

# **ADVANCED F CLASS GAS TURBINES CAN BE A RELIABLE CHOICE FOR IGCC APPLICATIONS**

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## **ABSTRACT**

With the increase in natural gas fuel prices, customer interest in IGCC plants is growing as an alternative to the traditional coal plants. Future IGCC plants are expected to be more efficient, use less water, produce significantly less emissions, and have the potential to be a lower cost solution to address future CO<sub>2</sub> and Hg regulations compared to the direct coal fired steam plants. Since IGCC plants' availability is a widely documented industry concern, this paper will summarize how the integration of the Siemens SGT6-5000F (formerly W501F) into future 60 Hz IGCC plants will address this issue.

Siemens has over 300,000 hours of successful IGCC gas turbine operating experience in the United States and Europe and has supplied a range of products for many of today's IGCC plants. Currently in the Siemens 60 Hz natural gas based operating fleet, the SGT6-5000F gas turbine has the largest number of operating engines and the most cumulative operating hours. Several advancements to this frame have increased its power and efficiency while decreasing emissions and life cycle costs without impacting reliability. Development programs, including syngas combustion system testing, were initiated to verify the SGT6-5000F readiness for future IGCC applications.

This paper addresses the results of the comprehensive development program initiated to allow syngas operation of the SGT6-5000F in IGCC applications while maintaining the gas turbine system's availability and reliability at levels expected by the industry.

## **INTRODUCTION**

Escalating natural gas prices in the U.S., as well as recent advances in gasification, air separation and syngas cleanup technologies, have made coal and opportunity fuels based integrated gasification combined cycle (IGCC) plants an economically superior option for efficient and environmentally benign electricity generation when compared to conventional steam plants or even natural gas fired combined cycle (CC) plants. Current IGCC plant capital costs are higher than for conventional steam plant options, but the higher plant efficiencies that are expected with IGCC and the ability to lower CO<sub>2</sub> emissions more cost effectively are forecasted to more than make up for this disadvantage when total plant life cycle costs are considered. The IGCC plant viability can be enhanced further by co-production of commercial products, such as hydrogen,

ammonia, methanol, sulfur, etc. Developing a standard optimized, fully integrated IGCC plant design is a prerequisite in reducing capital cost and schedule, while achieving maximum possible plant performance and reliability. The SGT6-5000F based IGCC plant design is targeted to achieve these goals.

Siemens has considerable experience in gas turbine operation in IGCC plants, with over 10 years of operating experience in the 50 Hz European market and over 4 years in the 60 Hz U.S. market, for a total of more than 300,000 hours on syngas. In addition, Siemens industrial size gas turbines have accumulated more than 750,000 hours burning fuels containing high levels of hydrogen. Recently, the U.S. Department of Energy has awarded Siemens a research contract for Phase 1 of a 10-year program to develop the SGT6-6000G (formerly W501G) gas turbine for integration into an advanced, super efficient, near zero emissions, coal-based IGCC plant.

SGT6-5000F is the most successful model in the 60 Hz Siemens heavy duty product line with 189 units operating in peaking, intermediate and base load applications. It has demonstrated excellent performance, reliability, availability and operational flexibility, as well as low emissions, in more than 3.5 million total fleet operating hours. This engine has all the attributes required to be a suitable platform for integration into an advanced IGCC plant.

The SGT6-5000F based IGCC plant utilizes a 2X1 combined cycle plant incorporating two syngas capable gas turbines and generator packages, each coupled to a heat recovery steam generator (HRSG). The HRSGs generate steam to power the two-case reheat steam turbine with a double flow low pressure turbine. The gas turbines are integrated with a conventional air separation unit (ASU) and an oxygen-blown gasifier in a 2X1 configuration.

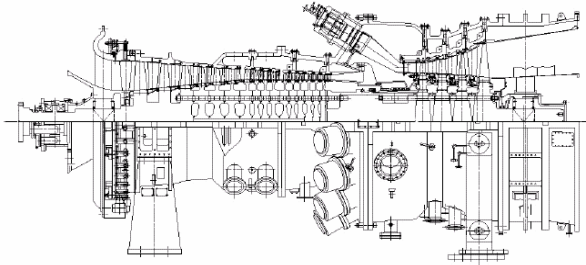
The SGT6-5000F gas turbine was modified for IGCC application. A syngas combustion system was developed to use syngas as the primary fuel from 30% load to maximum rated power, with natural gas or distillate oil as the secondary fuels. The only identified gas turbine components requiring modification were the combustor baskets and fuel nozzles, as well as some auxiliary systems and controls. It should be pointed out that, after a thorough analysis, it was concluded that adequate compressor surge margin could be maintained without first stage turbine vane restagger. All of the modifications are completely retrofitable into existing units to allow future conversion to IGCC operation.

SGT6-5000F performance, reliability and operational flexibility have been improved and its emissions and life cycle costs reduced steadily since its introduction through planned development programs. Siemens is committed to continuous enhancements in the future for both new and in-service plants.

## **ENGINE DESCRIPTION**

The SGT6-5000F design was based on fundamental time-proven concepts used in earlier models as well as new concepts and technologies incorporated to increase efficiency, reduce emissions and allow reliable operation at the increased design firing temperature (Scalzo et al., 1989). Its basic design and development since its introduction in 1990 provided it with exceptional operational flexibility demanded by the current market conditions (Xia et al., 2005). Figure 1 shows the engine longitudinal

section. It incorporates an advanced 13-stage axial compressor, 16-basket lean premixed dry low NO<sub>x</sub> combustion system, 4-stage turbine with first three stages air cooled and an axial exhaust with 6 tangential struts. The cylinders are horizontally split for easy maintenance and rotor removal.



**Figure 1. SGT6-5000F Longitudinal Section**

## **SIEMENS EXPERIENCE IN SYNGAS OPERATION**

IGCC is a technology that can conserve primary energy sources and can significantly limit air emissions, while avoiding use of high cost and scarce fuels, such as natural gas or distillate oil. The IGCC plant can utilize a variety of low cost and abundant fuels, such as coal, petroleum coke, bio-mass and oil/tar residue to produce a wide range of valuable products, including power, heat, hydrogen, ammonia, methanol, sulfur, aggregate, etc. This concept is the most economically viable approach to clean coal technology and when combined with an advanced, high firing temperature, high efficiency gas turbine technology, as represented by the SGT6-5000F engine, it is believed to be the most efficient method for coal or other low-grade opportunity fuel utilization for electricity generation. Recent combustion system technology developments to allow efficient syngas operation have made gas turbines ideally suited for integration in advanced IGCC plants. The market challenge is to reduce capital costs and emissions while improving fuel flexibility, efficiency and operating reliability. The capital cost reduction goal can be addressed by increased gas turbine capacity, optimized integration into the IGCC plant and decreased overhead expenditures, such as engineering and project management costs. Fuel flexibility entails the ability to burn syngas fuels with very low and varying heat content; being able to operate on different fuels during starting and fuel transfers; ability to maintain stringent emissions limits over the operating range; and ability to co-fire with natural gas or distillate oil over a wide output power range. The SGT6-5000F syngas combustion system development and incorporated modifications are designed to meet the above requirements.

Siemens has more than 300,000 hours of successful IGCC operational experience on heavy duty gas turbines in European (Karg, et al., 2000, Hannemann, et al., 2003) and U.S. (Geoffroy and Amos, 1991) IGCC plants. Siemens IGCC experience originates from long time operation on syngases from gasification and other low heat content gases, such as blast-furnace gas. In addition, Siemens industrial gas turbines have accumulated more than 750,000 hours burning syngas and refinery gas fuels containing high hydrogen fuels.

The IGCC plant in Buggenum, the Netherlands, which started commercial operation in 1998, employs the V94.2 (now the SGT5-2000E) gas turbine. The gas turbine, which has vertical silo-type combustion chambers, is in a single-shaft arrangement with a steam turbine and a common generator. The syngas burner is a modified Siemens hybrid burner with an additional coal gas supply line. The plant is based on the oxygen-blown SHELL entrained flow coal gasifier.

The Puertollano, Spain, IGCC plant is based on the oxygen-blown Krupp PRENFLO entrained flow gasifiers and uses the V94.3 (now the SGT5-4000E) gas turbine. Syngas operation started in 1997/8. The ISAB IGCC plant in Priolo, Sicily, is equipped with two V94.2K (now the SGT5-2000E) gas turbines. The plant uses GE gasifiers with downstream quench to convert high sulfur asphalt into syngas. It was first fired in 1999. Two W501D5 (now the SGT6-3000E) gas turbines were integrated into the LGTI IGCC plant, based on the ConocoPhillips E-Gas (originally Destec/Dow) coal gasification system, at Plaquemine, Louisiana. The principal modifications incorporated to provide syngas burning capability included specially modified fuel nozzles to accommodate larger fuel gas flow quantities. Table 1 summarizes Siemens' experience on syngas and high hydrogen content fuels.

<b>Turbine</b>	<b>Size</b>	<b>Fuel</b>	<b>Operating Hours</b>
SGT-200	7 MW	80-85% H <sub>2</sub>	250,000
SGT-500, 600	17-25 MW	20-90% H <sub>2</sub>	500,000
2XSGT6-3000E	208 MW	40-60% H <sub>2</sub>	85,000
SGT5-2000E	253 MW	Syngas	48,500
SGT5-2000E	300 MW	Syngas	26,600
2XSGT5-2000E	521 MW	Syngas	109,000 EOH
SGT5-2000E	180 MW	Syngas	38,000 EOH

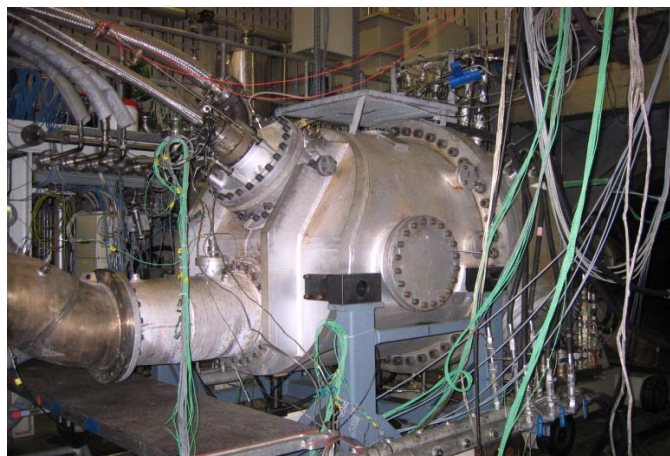
**Table 1. Operating Experience on Syngas Fuels**

## **COMBUSTION SYSTEM DEVELOPMENT**

Developing a syngas capable combustion system is a prerequisite for the successful gas turbine integration into an IGCC plant. This system must operate reliably on a broad range of syngas fuels, as well as secondary fuels, such as natural gas and distillate oil. It must do so efficiently and cost effectively while restricting emissions to the target values. The secondary fuel will be used for starting and loading the gas turbine while the ASU and the gasifier are brought online, as well as in emergencies. The system allows complete fuel transfer from secondary fuel to primary fuel anywhere

between 30% to 90% of maximum rated power on the respective secondary fuel. Fuel transfer times will be minimized to improve engine availability at maximum power. The SGT6-5000F combustion system development demonstrated that it is capable of operating successfully in the IGCC application and achieving its emissions, performance, reliability and operational flexibility goals.

Combustion system development testing to demonstrate capability for syngas operation was carried out in the Siemens High Pressure Combustion Test Facility. This facility was upgraded for syngas operation. The facility had capability to generate superheated steam for syngas and natural gas dilution purposes. Other syngas constituents, such as H<sub>2</sub>, CO, CO<sub>2</sub>, N<sub>2</sub> and CH<sub>4</sub>, were supplied to the facility in bottles. The constituents were then mixed at specified concentrations to simulate various syngas compositions. Figure 2 shows the test rig. The IGCC combustor test objectives were to demonstrate: operability on natural gas from ignition to 100% load and on syngas from 30% to 100% load; fuel transfers from natural gas to syngas (between 30% and 90% load) and vice versa; and natural gas and syngas co-firing (between 30% and 90% load). The emissions targets were: (1) ≤15 ppm NO<sub>x</sub> (at 15% O<sub>2</sub>) from 50% to 100% load and ≤10 ppm CO from 70% to 100% load, when operating on syngas, and (2) ≤25 ppm NO<sub>x</sub> (at 15% O<sub>2</sub>) from 70% to 100% load and ≤10 ppm CO from 70% to 100% load, when operating on natural gas.



**Figure 2. High Pressure Combustion Test Rig**

The following development approach was used in the test program: (1) syngas testing with reduced fuel Lower Heating Value (LHV) to meet NO<sub>x</sub> target, (2) premixed natural gas and steam testing to meet NO<sub>x</sub> target, (3) CO emissions measurement, (4) flame stability determination, and (5) fuel nozzle pressure drop management. The test program consisted of natural gas and syngas phases. Natural gas testing involved: (1) emissions dependence on combustor pressure, (2) natural gas/steam mix variation (steam injection limits, steam premix injection limits, and nitrogen), (3) lowest turndown emission points, (4) natural gas/syngas co-firing at 30% load (67% - 33% heat input between natural gas and syngas, and vice versa) and at 100% load (15% - 85% heat input, and vice versa), and (5) syngas/natural gas transfer at 30% and 100% load. The

syngas testing involved: (1) emissions dependence on combustor pressure, (2) syngas fuel composition variation (different coal and petroleum coke compositions, H<sub>2</sub>/CO ratio sweep, 100% H<sub>2</sub> syngas fuel, pure CO syngas fuel, and steam and nitrogen injection limits), (3) lowest turndown emissions points, and (4) fuel stages tuning. The main syngas fuel composition ranges used in the testing are given in Table 2. Note that the final fuel LHV was lowered for NO<sub>x</sub> reduction by nitrogen and steam injection. Other syngas compositions were also tested at 50% pressure conditions. The measurements taken during the testing, all in real time, were: emissions, combustor/transition liner temperatures, combustor dynamics, etc.

	H <sub>2</sub> %	CO%	CH <sub>4</sub> %	CO <sub>2</sub> %	N <sub>2</sub> %	H <sub>2</sub> O%	LHV MJ/Nm <sup>3</sup>
<b>Coal</b>	25-30	30-40	0-5	10-15	0-3	15-25	7-10
<b>PetCoke</b>	25-30	50-60	5-10	5-10	0-2	0-2	11-14

**Table 2. Syngas Fuel Composition Ranges**

The test program started with two combustor/fuel nozzle variants. Initial testing showed one variant to be superior and an extensive testing on natural gas and syngas was carried out on this combustor. Figure 3 shows this combustor and the fuel nozzle. Test results demonstrated that the selected combustor/fuel nozzle combination will meet its design goals.

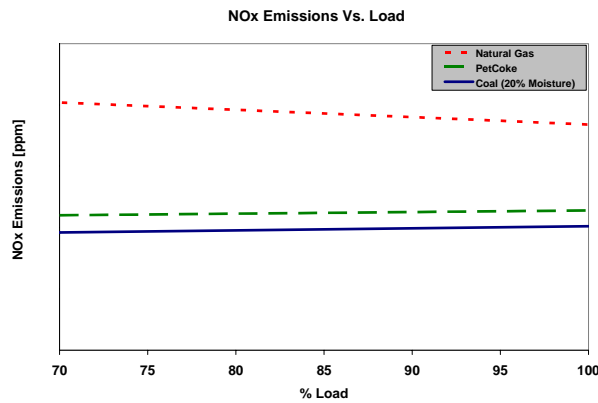


**Figure 3. Syngas Capable Combustor and Fuel Nozzle**

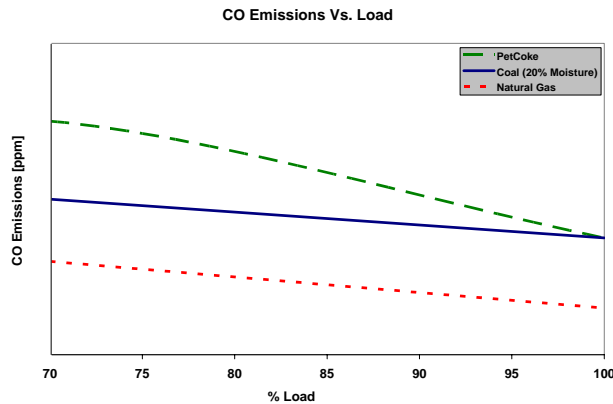
Figure 4 shows NO<sub>x</sub> emissions versus percent load on natural gas and two syngas fuels derived from coal and petroleum coke. Natural gas NO<sub>x</sub> emissions target ( $\leq 25$  ppm) would be achieved over the operating range with the appropriate steam to fuel (S/F) injection ratio and syngas targets would be achieved with appropriate dilution. The effect of steam and nitrogen dilution on NO<sub>x</sub> emissions was established for coal and

petroleum coke derived syngas fuels with varying heating values. Figure 5 shows CO emissions versus percent load (70% to 100%) for the tested natural gas, coal and petroleum coke derived syngas fuels. In all cases the NOx and CO emissions met the target values, respectively.

The IGCC combustion system testing was completed successfully and all the emissions and operational targets have been demonstrated. Stable combustion was achieved on both the syngas and natural gas fuels. Syngas to natural gas transfers (and vice versa) at base load were achieved with stable combustion. Syngas/natural gas co-firing (both ways) at base load and 30% load was achieved with stable combustion. Ambient temperature variation was determined to have a minimal effect on NOx and CO emissions. Combustion dynamics and combustion/transition liner metal temperatures were well within design limits for all tests. Table 3 summarizes the test results.



**Figure 4. NOx Emissions vs. Load**



**Figure 5. CO Emissions vs. Load**

Fuel	% Load	Emissions, ppm	
			Expected Engine Results
PetCoke Syngas	50-100	NOx	≤15
	70-100	CO	≤10
Coal (20% Moisture) Syngas	50-100	NOx	≤15
	70-100	CO	≤10
Natural Gas	70-100	NOx	≤25
	70-100	CO	≤10

**Table 3. Combustion Test Results Summary**

## MODIFICATIONS FOR IGCC APPLICATION

### Engine Modifications

Modifications and analyses on all critical components were carried out to ensure that the SGT6-5000F would meet all the requirements for syngas operation and optimized integration into the IGCC plant. The basis for this endeavor was as follows:

1. Gas turbine should be able to operate on a wide range of syngas compositions, caused by variation in gasifier suppliers and feedstocks, with minimal impact on performance or emissions.
2. Combustor to operate on syngas fuel with a Lower Heating Value as low as 4.31 MJ/kg [US Units (general comment)] or 4.9 MJ/Nm<sup>3</sup>.
3. Capability to co-fire backup (secondary) fuel and syngas.
4. Operation syngas between 30% load and base load and natural gas and distillate oil as the backup fuels.
5. Provision to be made for up to 50% air side integration.
6. Bleed air extraction points to be located so as to minimize flow maldistribution to the combustor baskets.
7. No impact on the engine's external physical interfaces, with the exception of the combustion system.
8. Retrofittable into the current SGT6-5000F fleet without modifications to the physical interfaces.
9. Component design criteria for operation on natural gas were to be adhered to for operation on syngas.

The analysis/verification of existing and redesigned engine components was done for the worst case scenario, for each individual component, to ensure that all design limits and criteria would be satisfied for the IGCC application. This process involved aerodynamic, structural, stress, heat transfer, cooling, frequency, vibration and life cycle



analyses. The components analyzed were the compressor, turbine, rotor and casings. The combustion system components were redesigned based on results from an exhaustive syngas combustion development and testing program.

Syngas operation has a very significant impact not only on the turbine and the downstream equipment, but also on the compressor as its surge margin is reduced due to the increased operating pressure ratio resulting from the increased mass flow through the turbine. An extensive investigation was carried out into the compressor surge margin and the need to restagger the first stage turbine vane so as to reduce the operating pressure ratio. The compressor analysis involved aerodynamic and mechanical considerations. Calculations were carried out on aerodynamic loading on marginal stages, stall, surge margin and thrust balance. Three first stage turbine vane stagger cases were investigated. The case with most open stagger resulted in a very healthy surge margin, but resulted in a significant loss in output power and efficiency compared to zero stagger for both syngas and natural gas operation. The intermediate open stagger case had much less effect on performance and would not require design changes to the first stage blade. Detailed compressor analysis for the zero stagger case indicated that an acceptable surge margin could be maintained without affecting performance.

Turbine analysis covered aerodynamic, mechanical, heat transfer and cooling aspects on the turbine airfoils, rotor and disc cavities. Aerodynamic analysis carried out on the turbine showed that the flow conditions were satisfactory. First stage blade heat transfer analysis showed that it had adequate cooling. The conclusion was that the turbine components would maintain their lives in this application and would not require any design changes. There were no appreciable changes in operating conditions on the compressor, turbine and exhaust cylinders. The combustion cylinder was analyzed and found to be acceptable. It should be pointed out that air extraction for the gasification process will be through the two existing manway access openings located on opposite sides of the combustion cylinder. Their location and the air extraction flow were chosen so the air flow distribution to the combustor baskets will not be distorted.

The syngas combustor basket was designed to operate on syngas and natural gas. The combustor was developed to the minimum amount of diluent on both primary and secondary fuels. The cover plate was modified to accommodate continuous dynamics monitoring and a continuous online self tuning system. The fuel nozzle was designed to inject syngas and natural gas separately, syngas and natural gas simultaneously during fuel transfers, syngas and natural gas during co-firing, nitrogen as the primary diluent, steam mixed with syngas as the secondary diluent on syngas operation, and steam as the primary diluent on natural gas operation. The nozzle will be designed to operate on distillate oil in similar combinations as described above for natural gas.

In addition to the standard engine supervisory instrumentation the following will be required for the IGCC application: combustion dynamics monitoring sensors, online TBC monitoring sensors, syngas fuel condition sensors, backup fuel condition sensors, diluent condition sensors, extracted shell air condition sensors, a computer to determine syngas mass flow/gas constituents/LHV/HHV at a continuous rate entering the fuel nozzle manifold, and mass spectrometer to determine syngas heating value at the mixing station.

## **Auxiliaries / Controls**

The auxiliary systems that need modification or new design are: syngas/natural gas fuel injection skids, fuel/diluents manifolding, fuel/diluent valves, mixing stations for fuel heating value control, syngas/natural gas fuel saturation station, nitrogen flushing system, syngas/ diluent filtration systems, gas turbine ventilation and air separation unit (ASU) extraction air manifolding/piping/ valves.

The engine control systems will be updated (software and hardware) to accommodate the fuel transfers (primary to secondary fuel and vice versa) gas turbine/ ASU integration-IGV control (closed loop air extraction process), continuous fuel heating value and Wobbe Index control, and continuous control of the saturation unit and the enclosure fuel leak protection system.

## **RETROFITABILITY**

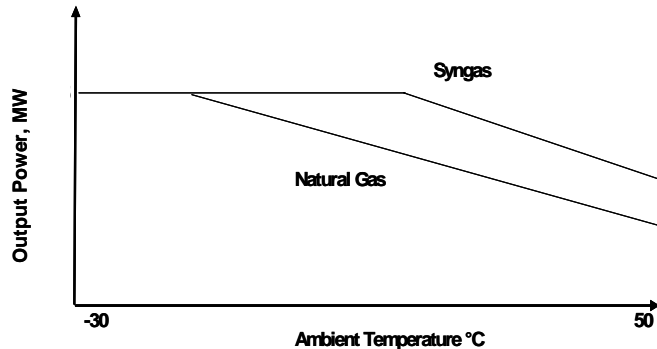
It should be emphasized that all the redesigned and modified engine components are retrofitable into the currently operating SGT6-5000F models (FD1 and FD2) without requiring a cover lift. No design or assembly modifications are required to the compressor or the turbine for the planned IGCC application. Also, both the combustor and the fuel nozzle are readily retrofitable. No engine exterior physical interfaces are impacted with the exception of those on the combustor cover plate, which was redesigned to accommodate syngas and natural gas operation. The cover plate and the associated piping are retrofitable into existing engines. The designed-in retrofitability allows many current SGT6-5000F operators the flexibility and option for future conversion to IGCC operation when market conditions warrant it.

## **OPERATIONAL CONSIDERATIONS**

The IGCC engine normal operating range is from -34.4°C to 50°C ambient temperature and sea level to 2,300 m altitude. Due to the increased mass flow through the turbine resulting from syngas operation, the gas turbine output approaches the maximum capability of the turbine under most ambient temperatures. The normal starting time from start initiation to baseload is 30 minutes on secondary (natural gas) fuel. The reliability, availability and maintainability (RAM) targets will be the same as for a standard natural gas fired engine. The combustion system inspection, turbine hot gas path inspection and major overhaul intervals will be the same as for the standard engine.



and capital plant cost targets, the IGCC plant levelized cost of electricity (COE) are projected to be half that of a natural gas fired CC plant operating with today's expensive natural gas and about the same as for a current direct fired coal steam plant. However, the IGCC plant will significantly reduce emissions. Figure 7 shows the output power variation with ambient temperature for both syngas and natural gas operation. Note the significant output power surplus on syngas operation.



**Figure 7. Output Power vs. Ambient Temperature**

## **FUTURE ENHANCEMENTS**

Siemens is committed to continuous product enhancement for both new and currently operating plants to improve its competitive position and to add value to its customers. The product enhancement process will continue in the future and will concentrate not only in emissions and performance but also on RAM, operational flexibility, longer component lives, lower life cycle costs, improved service factors and increased repair intervals. The planned SGT6-5000F enhancements, which will also be incorporated into the IGCC version, are: (1) improved turndown ratio, (2) increased service/ inspection intervals to reduce life cycle costs, and (3) reduced maintenance cost for service run components.

In addition to the planned gas turbine improvements, programs are in place to improve the gas turbine-IGCC plant integration and IGCC technology. Siemens is collaborating on a project, led by Air Products, to integrate ion transport membrane (ITM) ASU technology into IGCC plants based on the advanced SGT6-6000G. The ITM technology has the potential not only to improve the IGCC plant efficiency, but also to reduce its capital cost. Also, Siemens has been awarded a research contract for Phase 1 of a 10-year program to develop the SGT6-6000G gas turbine for integration into an advanced, more efficient, near zero emissions, coal-based IGCC plant.

## **SUMMARY**

An extensive investigation was carried out into the developments/redesigns required to integrate the SGT6-5000F gas turbine into an IGCC plant. The development effort focused on developing a combustion system capable of operation on syngas derived from coal or petroleum coke, while meeting all the design requirements. The system was developed to limit NO<sub>x</sub> to ≤15 ppm and CO to ≤10 ppm when operating on syngas,

and to  $\leq 25$  ppm NO<sub>x</sub> and  $\leq 10$  ppm CO on natural gas fuel. Fuel transfers (primary to secondary and vice versa) and co-firing (on primary and secondary fuels) capabilities were demonstrated. Detailed analysis of all other affected components (aside from the combustor baskets and fuel nozzles) indicated that no modifications would be required. However, modifications and additions to auxiliaries, supervisory instrumentation and control systems will be required. The modified combustion system components were designed to be completely retrofitable into currently operating engines. Therefore, the current SGT6-5000F customers will have the flexibility for future conversion to IGCC operation, if it is to their economic advantage. Engine operability and RAM were not affected by the modifications required for IGCC application.

In a 2X1 IGCC application, the plant net output power is expected to be greater than 625 MW and net HHV efficiency greater than 41%. The predicted levelized COE for a SGT6-5000F based IGCC plant will be 50% less than that for a natural gas fired CC plant operating on today's high priced gas. Future SGT6-5000F enhancements and improvements in IGCC technology will improve plant performance and reduce emissions and cost.

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