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SYNGAS CAPABLE COMBUSTION SYSTEMS DEVELOPMENT FOR ADVANCED GAS TURBINES

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ABSTRACT

In the age of volatile and ever increasing natural gas fuel prices, strict new emission regulations and technological advancements, modern IGCC plants are the answer to growing market demands for efficient and environmentally friendly power generation. IGCC technology allows the use of low cost opportunity fuels, such as coal, of which there is a more than a 200-year supply in the U.S., and refinery residues, such as petroleum coke and residual oil. Future IGCC plants are expected to be more efficient and have a potential to be a lower cost solution to future CO₂ and mercury regulations compared to the direct coal fired steam plants.

Siemens has more than 300,000 hours of successful IGCC plant operational experience on a variety of heavy duty gas turbine models in Europe and the U.S. The gas turbines involved range from SGT5-2000E to SGT6-3000E (former designations are shown on Table 1). Future IGCC applications will extend this experience to the SGT5-4000F and SGT6-4000F/5000F/6000G gas turbines. In the currently operating Siemens' 60 Hz fleet, the SGT6-5000F gas turbine has the most operating engines and the most cumulative operating hours. Over the years, advancements have increased its performance and decreased its emissions and life cycle costs without impacting reliability. Development has been initiated to verify its readiness for future IGCC application including syngas combustion system testing.

Similar efforts are planned for the SGT6-6000G and SGT5-4000F/SGT6-4000F models.

This paper discusses the extensive development programs that have been carried out to demonstrate that target emissions and engine operability can be achieved on syngas operation in advanced F-class 50 Hz and 60 Hz gas turbine based IGCC applications.

New	Former
SGT5-2000E	V94.2
SGT5-3000E	V94.2A
SGT5-4000F	V94.3A
SGT6-3000E	W501D5
SGT6-4000F	V84.3A
SGT6-5000F	W501F
SGT6-6000G	W501G

Table 1. Siemens Gas Turbine Model Designation

INTRODUCTION

Dramatic increases in natural gas prices and concerns about availability, as well as significant advances in air separation, gasification and syngas cleanup technologies, have made coal and opportunity fuels based integrated gasification combined cycle (IGCC) plants a very competitive option for efficient and

environmentally benign power generation compared to direct fired coal plants and natural gas fired combined cycle (CC) plants. The main drivers for IGCC technology development and application are the low fuel costs, potential for significant reduction in harmful emissions and high efficiency in future advanced plants. The current IGCC plant capital costs are estimated to be 10 to 20% higher than conventional coal based options. However, the low prices, availability and abundance of coal, petroleum coke and residual oil, help to make up for the cost disadvantage when cost of electricity (COE) and total plant life cycle costs are taken into consideration. The IGCC plant economic viability can be improved further by co-production of hydrogen, methanol, sulfur, ammonia, etc. The plant capital cost and schedule can be reduced by developing a standard, optimized, integrated IGCC plant, while maximizing performance and reliability and minimizing emissions. A key prerequisite for the successful gas turbine integration into an IGCC plant is the development of a syngas capable combustion system.

Siemens has considerable syngas operational experience in IGCC plants, as well as gas turbine operation on blast-furnace gas, for a total of more than 450,000 total operating hours. Siemens industrial size gas turbines have accumulated more than 750,000 hours on syngas and refinery gas fuels containing high hydrogen levels. Siemens has several ongoing programs, some partially funded by the European Commission, to develop combustion systems for syngas and hydrogen operation and advanced IGCC concepts with and without CO₂ capture. 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 gas turbine for integration into an advanced, highly efficient, near zero emissions, coal-based IGCC plant.

The 200 MW class SGT6-5000F is the most successful 60 Hz Siemens heavy duty gas turbine model with 185 units operating in peaking, intermediate and base load duty (Scalzo et al., 1989, Xia et al., 2005). It has demonstrated excellent performance, reliability, availability and exceptional flexibility, as well as low emissions. In the fourteen years since its introduction, it has accumulated more than 3.5 million operating hours. The 270 MW class SGT6-6000G has 20 operating units, which have accumulated more than 250,000 operating hours (Southall and McQuiggan, 1995, McQuiggan, 1996, Bancalari and Chan, 2005). The 91 unit 300 MW class 50 Hz SGT5-4000F and 39 unit 185 MW class 60 Hz SGT6-4000F gas turbines have more than 1,825,000 and 766,000 equivalent operating hours, respectively. All four advanced gas turbine models have all the required attributes for successful integration into future IGCC plants. To enable this integration, extensive combustion development programs have been carried out or are in progress to develop reliable, low emissions

combustion systems capable of operation on a broad range of coal and opportunity fuels derived syngas.

SIEMENS SYNGAS OPERATING EXPERIENCE

Siemens has more than 300,000 hours of successful IGCC plant operational experience on heavy duty gas turbines (Morrison and Pillsbury, 1989, Geoffroy and Amos, 1991, Karg et al., 2000, Huth et al., 2000, Hannemann et al., 2000). This experience was derived from long time operation on syngases from gasification and other low heat content gases, such as blast-furnace gas. In addition, small industrial size gas turbines have more than 750,000 operating hours on syngas and high hydrogen content refinery gas fuels.

The IGCC plant in Buggenum, the Netherlands, which started syngas commercial operation in 1998, employs the SGT5-2000E gas turbine. The gas turbine, which has vertical silo-type combustion chambers, is in a single-shaft arrangement with the steam turbine and the 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 gas turbine. Syngas operation started in 1998. The ISAB IGCC plant in Priolo, Italy, is equipped with two SGT5-2000E gas turbines. The plant uses Texaco gasifiers with downstream quench to convert high sulfur asphalt into syngas. It was first fired in 1999. SGT5-2000E, in Servola, Italy, has accumulated more than 38,000 operating hours in a CC plant operating on steel-making recovery gas.

Two SGT6-3000E gas turbines were integrated into the LGTI IGCC project, based on the Dow (the predecessor to today's E-Gas technology) 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 2 summarizes Siemens' experience on syngas and high hydrogen content fuels.



Figure 1. High Pressure Combustion Test Rig

Gas Turbine	Plant Location	Main Features	Fuel	Startup
SGT-200	Many Locations		80-85% H ₂	
SGT-500/600	Many Locations		20-90% H ₂	
VM5	Dortmund, Germany	Compressor Drive GT	Blast-Furnace Gas	1960
VM5	Handan, China	Compressor Drive GT	Blast-Furnace Gas	2000
CW201	Chicago, USA		Blast-Furnace Gas	1960
V93	Luenen Germany	First CC plant in the world with integrated LURGI coal gasification	Syngas	1972
2XSGT6-3000E	Plaquemine, USA	CC plant with integrated DOW coal gasification	Syngas	1987
4XSGT6-3000E	Sweeney Cogeneration L.P., USA	CC Plant	0 – 30% H ₂	1998
SGT5-2000E	Buggenum, Netherlands	CC plant integrated with coal gasification (hard coal and biomass blend)	Syngas	1994/5
V94.3	Puertollano, Spain	CC plant integrated PRENFLO coal gasification (coal and petroleum coke blend)	Syngas	1997/98
2XGT5-2000E	Priolo Gargallo, Italy	CC plant with integrated TEXACO heavy-oil (asphalt gasification)	Syngas	1998/99
SGT5-2000E	Servola, Italy	CC plant with steel-making recovery gas	Steel-Making Recovery Gas	2000
SGT5-2000E	Sannazzaro, Italy	CC plant with integrated SHELL heavy-oil gasification	Syngas	2005

Table 2. Operating Experience with Syngas and H2 fuels

COMBUSTION SYSTEM DEVELOPMENT

High Pressure Combustion Test Facility

Combustion system testing to demonstrate capability for syngas operation was carried out in the Single Burner Full Pressure Combustion Test Rig. The test facility was modified for syngas operation. It had capability for superheated steam generation, which was required for syngas and natural gas dilution purposes. Additional syngas constituents, such as H₂, CO, CH₄, CO₂ and N₂, were supplied to the test site. The syngas constituents were then mixed, in a special mixing module, at the required concentrations to simulate the various syngas compositions used in the test program. Figure 1 shows the combustion test rig.

SGT6-5000F Combustion System

The SGT6-5000F combustion system development test objectives were to demonstrate: (1) that the following emissions targets could be achieved: <15 ppm NO_x (at 15% O₂) and <10 ppm CO (at 15% O₂) on syngas; and <25 ppm NO_x (at 15% O₂) and <10 ppm CO (at 15% O₂) on natural gas, (2) operability on natural

gas and on syngas over the load range, (3) fuel transfers from natural gas to syngas, and (4) natural gas and syngas co-firing.

The combustion system development test program included the following tests: (1) syngas testing with reduced syngas fuel Lower Heating Value (LHV) to meet NO_x target, (2) premixed natural gas and steam testing to meet NO_x target, (3) CO emissions measurement, (4) flame stability and flashback determination, and (5) fuel nozzle pressure drop management.

The test program consisted of combustion test rig commissioning, baseline combustor verification testing to ascertain that the rig/instrumentation functioned correctly, syngas test phase and natural gas test phase.

The syngas testing included emissions dependence on combustor pressure, different syngas compositions (also pure H₂ and CO fuels), steam/nitrogen injection limits, lowest turndown emissions points, and fuel stages tuning. The main syngas fuels tested are given in Table 3. A similar test program was carried out on natural gas, including syngas/natural gas co-firing and fuel transfers.

Extensive measurements recorded in real time were: emissions, gas temperatures, combustor/transition liner metal temperatures, combustor dynamics and vibrations. Two combustor/fuel nozzle variants were selected for testing on different syngas fuels. Initial test results demonstrated that one variant was by far superior and extensive syngas and natural gas testing was performed on this combustor/fuel nozzle combination (see Figure 2). The syngas capable design was a diffusion type combustor derived from the successful DF42 concept which has demonstrated reliable operation on natural gas and distillate oil on the SGT6-5000F over the last 14 years.

The diluent type and syngas fuel heating value were determined to have a strong effect on NOx emissions. NOx emissions increased steadily from low single digits with increasing heating value and diluent usage was minimized when using steam (see Figure 3). Figures 4 and 5 demonstrate that NOx emissions were well within target values for both coal and petroleum coke derived syngases.

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

Table 3. Syngas Fuel Compositions



Figure 2. Syngas Capable Combustor and Fuel Nozzle

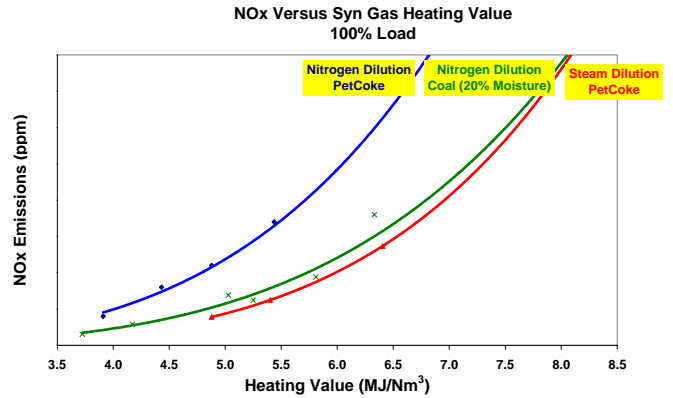


Figure 3. Effect of Syngas Heating Value on NOx Emissions

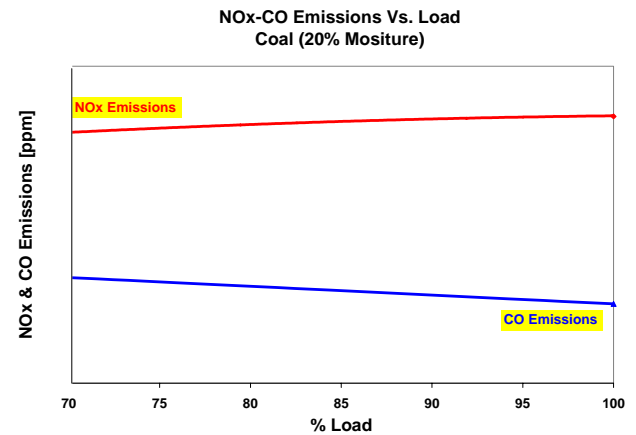


Figure 4. NOx and CO Emissions vs. Load for Coal (20% Moisture) Syngas

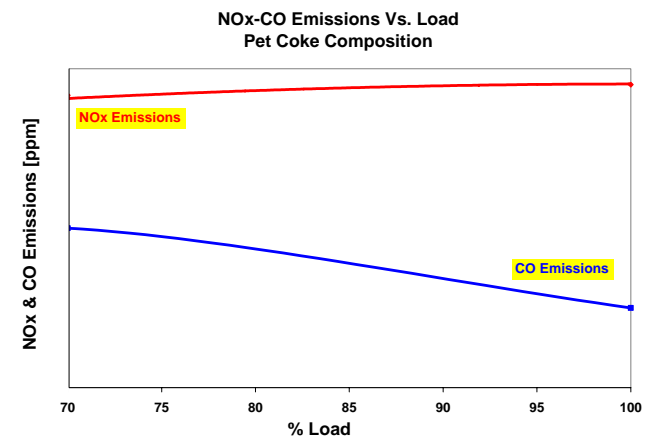


Figure 5. NOx and CO Emissions vs. Load for Petroleum Coke Syngas

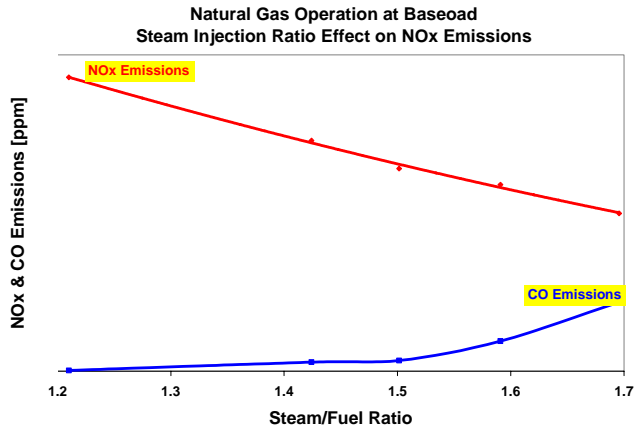


Figure 6. Steam Injection Impact on Emissions on Natural Gas

Fuel		Emissions, ppm	
		Expected Engine Results	Test Rig Results
PetCoke Syngas	NOx	15	<15
	CO	10	<<10
Coal (20% Moisture) Syngas	NOx	15	<15
	CO	10	<<10
Natural Gas	NOx	25	<25
	CO	10	<<10
Pure H2	NOx	25	<<25
	CO	0	0
Operational Considerations			
	% Load	SG – NG % Heat Input Ratio	
		Expected Engine Results	Rig Test Results
Syngas-Natural Gas Co-Firing Capability	30%	67 – 33	67 – 33
		33 - 67	33 - 67
	100%	67 – 33	67 – 33
		33 - 67	33 - 67
	Fuel	% Load	
		Expected Engine Results	Rig Test Results
Syngas-Natural Gas Fuel Transfer Capability	SG to NG	Above 30%	30%
		Below 90%	90%
	NG to SG	Above 30%	30%
		Below 90%	90%

Table 4. SGT6-5000F Combustion Test Results Summary

Tests on natural gas demonstrated that the <25 ppm NOx and <10 ppm CO emissions targets were achieved with considerable margin over the required load range. Figure 6 shows the impact of steam injection on NOx emissions with natural gas fuel. The test results established the steam/fuel injection range within which both the NOx and CO emissions could be achieved.

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, as well as syngas to natural gas transfers (and vice versa) at base load. 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 combustor liner and transition piece metal temperatures were well within design limits for all tests. The test results demonstrated that the selected combustor/fuel nozzle combination will meet its design goals for syngas operation in an IGCC application. Table 4 summarizes the test results.

SGT6-6000G Combustion System

SGT6-6000G combustion system is almost the same as in the SGT6-5000F engine. The main hardware differences are larger fuel nozzle holes, no cross-flame tubes and steam cooled transitions in the SGT6-6000G. Steam cooling eliminates the need for air and hence helps to reduce NOx emissions. The operational differences are the higher firing temperature, air flow and pressure in the SGT6-6000G combustor. Any combustion system advancements developed on the SGT6-5000F are directly transferable to the other engine model. Initial syngas testing carried out at the SGT6-6000G operating conditions was very encouraging. Further SGT6-6000G syngas emissions testing is planned for the near future.

SGT5-4000F/SGT6-4000F Combustion System

Siemens has formed a strong consortium for the development of advanced burner technology for the SGT5-4000F. The three-year project, titled “High Efficiency Gas Turbine for Syngas Application” (HEGSA), is sponsored by the European Commission. The project coordinator is Siemens Power Generation. The project team also includes Ansaldo Energia, several European utilities and research institutes, all of which will contribute their knowledge and experience. The work scope includes modifications necessary to the proven silo-type combustor for its integration into the advanced SGT5-4000F as well as NOx emissions reduction and improved operation/fuel flexibility on syngas operation.

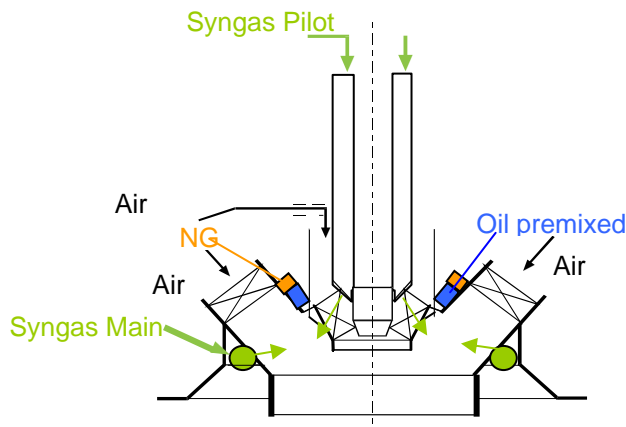


Figure 7. SGT5-4000F Triple-Fuel Syngas Burner.

In existing syngas combustion systems the backup fuel, either natural gas or distillate oil, is usually burned in diffusion mode. For the advanced high firing temperature combustion system, special effort has to be taken to keep the NO_x emission for backup fuel operation below the currently acceptable limit as well as introduce the potential for further reduction. Therefore, a premix passage for the backup fuel needs to be introduced and has to be integrated into the advanced syngas burner with the lowest possible, or even without, dilution. The low NO_x emissions requirements combined with the demand to minimize the amount of diluents for the syngas are the main drivers for developing a triple-fuel premixed combustion system for the fuel oil, natural gas and syngas. Based on the proven hybrid burner design of F-class engines combined with the syngas experience obtained with silo combustor engines, a new prototype syngas system has been developed for F-class gas turbines within the scope of the HEGSA project. The design includes an additional ring annular premixed passage for non-diluted or partly-diluted syngas. During syngas operation the main syngas flame is stabilized by a small syngas pilot flame (see Figure 7).

Combustion tests were performed under full pressure engine conditions in the Single Burner Full Pressure Combustion Test Rig with various syngas compositions (see Table 5). The main test objectives were to demonstrate flashback resistance with these highly reactive fuels, while keeping the low emission features of the proven burners when operating on single fuels. The combustion system development test program included the following tests: (1) baseline test with standard hardware on natural gas premixed operation with a hardware change to syngas burner, (2) premixed natural gas operation to verify NO_x emissions in DLN mode, (3) syngas operation with various gas compositions, (4) sweep of syngas pilot fraction, (5) identifying the influence of nitrogen/steam as diluent on NO_x emissions

and flashback behavior, and (6) co-firing with natural gas. The baseline testing on natural gas showed that the hardware modifications had no impact on the dry low emissions performance. The emissions were similar to the standard natural gas burner on syngas operation. To reduce the high reactivity of the non diluted syngas, a small amount of steam was needed. From the combustion point of view, no further dilution by nitrogen was necessary. If the overall plant concept provides additional nitrogen, it can easily be mixed with the combustion air without any negative influence on the combustion performance. Furthermore, if needed, the syngas can be blended with natural gas. The rig test results demonstrated that on the tested syngas compositions, the measured NO_x emissions were below 5 ppm and CO <1 ppm (see Table 6).

	H2 %	CO%	CH4%	CO2%	N2%	H2O%	LHV MJ/Nm3
#1 Syngas	25 - 30	55 - 60	0	12 - 16	0	0	8 - 12
#2 Syngas	30 - 40	34 - 38	0	0	26 - 30	0	7 - 11
#3 Syngas	13 - 17	23 - 27	8 - 12	8 - 12	18 - 22	18 - 22	7 - 11

Table 5. Fuel Gas Compositions

Fuel	Diluent	Emissions, ppm@15%O ₂	
		Test Rig Results	
#1 Syngas	Steam	NO _x	<4
		CO	<1
#2 Syngas	Steam	NO _x	<4
		CO	<1
# 3 Syngas	Steam	NO _x	<4
		CO	<1

Table 6. SGT5-4000F Combustion Test Results

Summarizing the test results, it can be stated that for the selected syngas compositions a safe premixed combustion operation was demonstrated under full pressure F-class engine conditions with low NOx emissions, while maintaining the well proven performance on DLN operation with natural gas. This was achieved with minor burner design changes. Additional combustion tests are planned to demonstrate the potential for further minimizing the required dilution for flashback control in premix syngas mode, while keeping the fuel flexibility features of the standard hybrid burner.

MODIFICATIONS FOR IGCC APPLICATION

SGT6-5000F Modifications

Detailed analyses were carried out on all the affected SGT6-5000F gas turbine components that may have required modifications for its successful application in IGCC plants. The existing and redesigned components were analyzed for the worst case scenario, for each individual component to ensure that all design criteria and limits would be satisfied. Aerodynamic, heat transfer, stress, frequency, vibration and life cycle analyses were carried out on the compressor, turbine, rotor and casings. The combustion system components were designed to operate on syngas and natural gas. The cover plate was modified for syngas operation. The fuel nozzle was designed to accommodate multi-fuel operation, diluent injection, fuel transfers and co-firing.

Syngas operation has a significant impact not only on the combustor and the hot end components, but also on the compressor, since its surge margin changes due to the increased operating pressure ratio resulting from the increased syngas fuel mass flow. An extensive investigation was carried out on the compressor surge margin and the need to restagger the first stage turbine vane open to reduce the operating pressure ratio. Two vane open staggers and no restagger cases were considered. The detailed compressor analysis results showed conclusively that adequate surge margin would be maintained without restaggering the vane.

Turbine analysis concluded that all its components would meet the design requirements when operating on syngas and would not require any modifications. Combustion cylinder analysis showed that it was acceptable at the higher pressure. It did not require any modifications for air extraction, since the air required for the gasification process will be withdrawn through the two existing manway openings located on opposite sides of the combustion cylinder. No engine exterior physical interfaces were impacted with the exception of those on the combustor cover plate which was redesigned to accommodate syngas operation. All modifications for syngas operation in IGCC applications are completely retrofitable into existing engines. This will allow current

SGT6-5000F operators the option for future conversion to IGCC operation.

In addition to the engine modifications, the other systems of the SGT6-PAC 5000F were also evaluated. Modifications to supervisory instrumentation, auxiliaries and controls will be required to accommodate syngas operation.

SGT6-6000G Modifications

Conceptual modifications will be developed for the SGT6-6000G gas turbine operation on coal derived hydrogen and syngas fuels in IGCC plants. Performance, emissions and RAM will be evaluated and optimized. Cost impacts associated with the proposed component modifications and with the overall system will be evaluated. This will be done to ensure that the SGCC6-6000G IGCC plant concept will be economically viable. Detailed designs will then be carried out for the new components and any required gas turbine modifications. The standard Siemens Product Development Process will be used in the design to ensure that all functional, engineering and customer requirements are met.

FUTURE DEVELOPMENTS

Siemens has been developing a catalytic combustion system for the SGT6-5000F gas turbine over the past four years using the Rich Combustion Lean Burn design concept. Most of this effort has been focused on natural gas fuel, but recent development under the "Catalytic Combustor Development for Fuel-Flexible Turbine Program", co-funded by U.S. DOE, is making good progress in developing the catalytic system for operation on syngas fuel. Selected catalyst materials were identified, down selected and validated. The necessary design changes will be incorporated and the system will be scaled up to the SGT6-6000G. Verification tests will then be carried out to demonstrate the system viability for hydrogen, syngas and natural gas operation at the design temperatures and the required emissions targets.

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, highly efficient, near zero emissions, coal-based IGCC plant. Various combustor concepts will be evaluated for hydrogen/syngas fuel burning capability with minimum emissions. Some of these concepts include: catalytic, premixed dry low NOx and diffusion combustors. They will be tested, evaluated and down selected to one successful candidate, which will then be further developed for incorporation into future SGT6-6000G gas turbines.

The combustion system developments, described above, for syngas operation in IGCC applications will be coordinated so that any enhancements or new concepts developed in one program will be incorporated across

the Siemens gas turbine product line, as deemed applicable. By leveraging these R&D efforts Siemens will produce enhanced syngas capable combustion systems which will be fuel flexible, reliable, cost effective and produce minimum emissions.

SUMMARY

Combustion system developments were carried out on advanced Siemens' gas turbines to demonstrate their readiness for syngas operation in IGCC applications. Extensive testing on the SGT6-5000F combustion system proved its capability to operate on a range of syngas fuels. <15 ppm NO_x and <10 ppm CO emissions targets were achieved on a variety of syngas fuels over the expected load range. This combustion system also produced <25 ppm NO_x and <10 ppm CO on natural gas with steam injection. Stable combustion and excellent operability were demonstrated during fuel transfers (syngas to natural gas) and co-firing (syngas and natural gas). Feasibility tests performed at SGT6-6000G operating conditions indicated that its emissions and operational targets will likely be achieved.

The SGT5-4000F combustion system testing verified its capability for syngas operation at full pressure engine conditions. The measured NO_x and CO emissions on different syngases were <5 ppm and <1 ppm, respectively. The design changes required for syngas capability had no impact on the dry low emission performance of the standard burner.

Future combustion systems development under the U.S. DOE co-funded "Catalytic Combustor for Fuel Flexible Turbine Program" and the "Advanced Hydrogen Turbine for FutureGen" as well as the European Commission co-funded syngas/hydrogen/IGCC programs will enhance operability on a broad range of syngas compositions and high hydrogen content fuels with near zero emissions. Advanced IGCC technology developments will lead to improved plant performance, reduced capital costs and CO₂ sequestration. The Siemens' gas turbine product line will support the benefits from these developments and provide our customers with efficient, environmentally benign, reliable, and low cost power generation options.

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