SGT6-5000F (W501F) 3 MILLION HOURS FLEET OPERATIONAL EXPERIENCE

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ABSTRACT

This paper describes more than 3 million hours of fleet operational experience by the successful SGT6-5000F gas turbine. This 200 MW class gas turbine has been applied in peaking, intermediate and base load operational modes since its introduction in 1991. The 192 engines in operation have accumulated an impressive operational record. The continuous development efforts to improve its performance, operational flexibility and RAM, and to reduce emissions, operation and maintenance costs and capital costs have enhanced the SGT6-5000F and its value to current and future users. In addition to providing an overview of operational case histories with details on operating hours and starts, this paper describes developments in service interval extension, trip factor reduction, fast start capability, 9 ppm NOx combustion system development and low load turndown improvements. Recent developments of SGT6-5000F adaptation to Integrated Gasification Combined Cycle plant application and combustion system validation for liquefied natural gas fuel operation are described. Future performance, emissions and reliability enhancements are also outlined.

INTRODUCTION

The 60 Hz SGT6-5000F (formally W501F) heavy-duty gas turbine was designed for both simple cycle and combined cycle (CC) power generation in utility and industrial service (see Reference 1 and Figure 1). It is an advanced, highly efficient, low emission, high power density gas turbine able to operate on conventional fuels as well as coal-derived low BTU gas. Since its introduction in 1991, its performance, emissions, reliability and operational flexibility have been improved by enhancements, upgrades and technology cross flow from other Siemens' advanced gas turbines (see Reference 2). In simple cycle applications its output power and efficiency are now greater than 200 MW and 38%, respectively. In one on one CC operation the output power is about 300 MW and efficiency exceeds 57%.

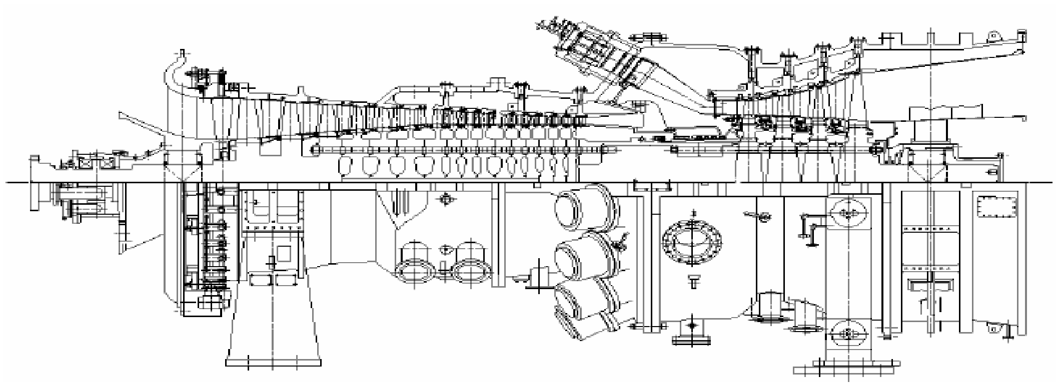

Figure 1. SGT6-5000F Longitudinal Section

192 SGT6-5000F engines are now employed in peaking, intermediate and continuous duty operation. The fleet has accumulated more than 3 million operating hours and has demonstrated excellent reliability, availability and starting reliability. The fleet leader has achieved more than 104,000 hours and there are over 114 engines with 8,000 or more operating hours. The fleet

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average reliability is about 99%, availability 95% and starting reliability 93%. These gas turbines have demonstrated successful operation on different fuels and in different modes of operation, including engines with numerous start cycles and engines with long run times between starts.

Increases in natural gas prices and the overcapacity in the US electric power market after 2002, significantly reduced the number of hours that the deregulated gas turbine-based plants could operate economically. Currently, many gas turbines run in a cyclic duty profile with daily start cycles fulfilling peak power requirements. To further enhance the gas turbine's operational flexibility, design changes were incorporated to reduce emissions (at full and part load), life cycle costs, and startup/cool down times while simultaneously improving performance and operational reliability (see Reference 3). This development was focused on operational/control modifications, combustion system enhancements, sealing improvements, tip clearance optimizations, cooling optimizations, hot path hardware durability improvements (especially as related to ability to operate in start-stop and cyclic modes) and exhaust system durability improvements. This effort provides a product that addresses market conditions, such as high fuel prices and requirements for cyclic/intermittent operational capability.

To take advantage of the low cost and secure U.S. coal supply, the SGT6-5000F has been adapted for incorporation into an Integrated Gasification Combined Cycle (IGCC) plant and has been proposed for several new IGCC plants targeted for 2010 operation (see References 4 and 5). The engine modifications required for IGCC operation were minor and retrofitable into existing engines. Only two components were impacted: the combustion system and the combustor cover plate, which were redesigned to accommodate syngas and natural gas fuels. Due to the changing natural gas supply market and especially the decline in domestic production, liquefied natural gas (LNG) imports are expected to increase significantly and several new LNG terminals have been announced for construction. Combustion test rig and engine field validation was carried out to demonstrate the combustion system capability for satisfactory LNG operation.

FLEET OPERATING EXPERIENCE

Operational Statistics

The 192 units in the fleet have amassed more than 3.25 million operating hours and demonstrated excellent reliability and availability. The lead engine has accumulated more than 104,000 operating hours and there are 114 engines with more than 8,000 operating hours. The fleet 12 month rolling average Reliability is about 99% and Availability over 95%, as of April 2006 (see Figure 2). The Starting Reliability has been improving steadily and is now approaching 93% (see Figure 3).

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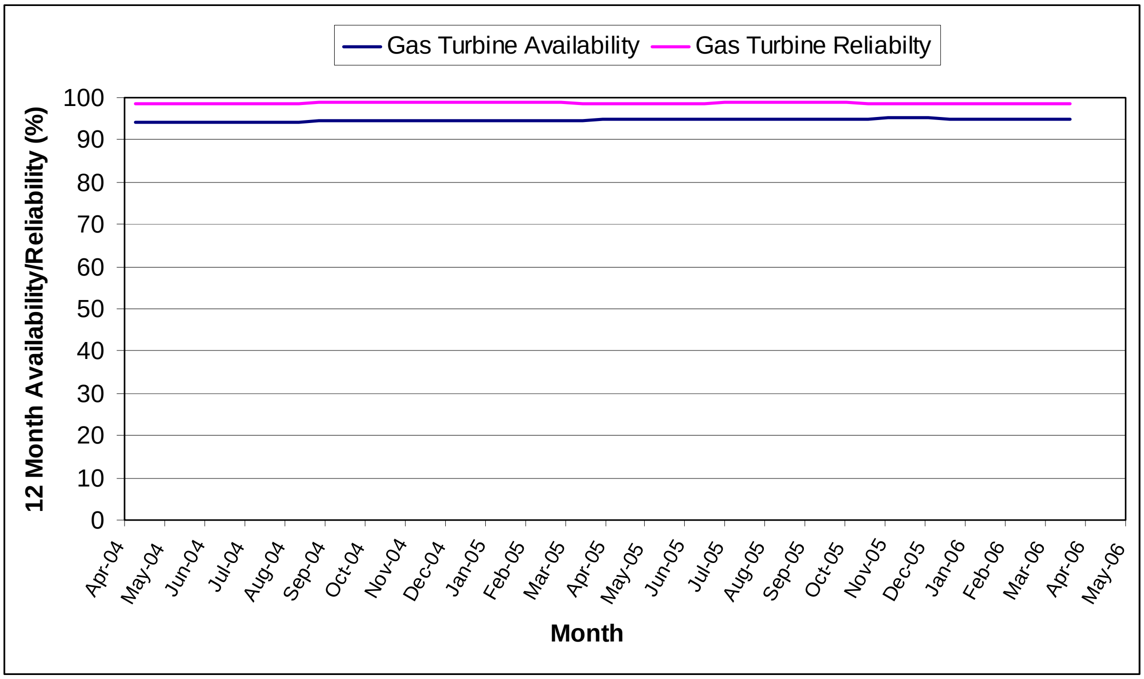

Figure 2. SGT6-5000F Fleet 12 Monthly Rolling Average Reliability and Availability

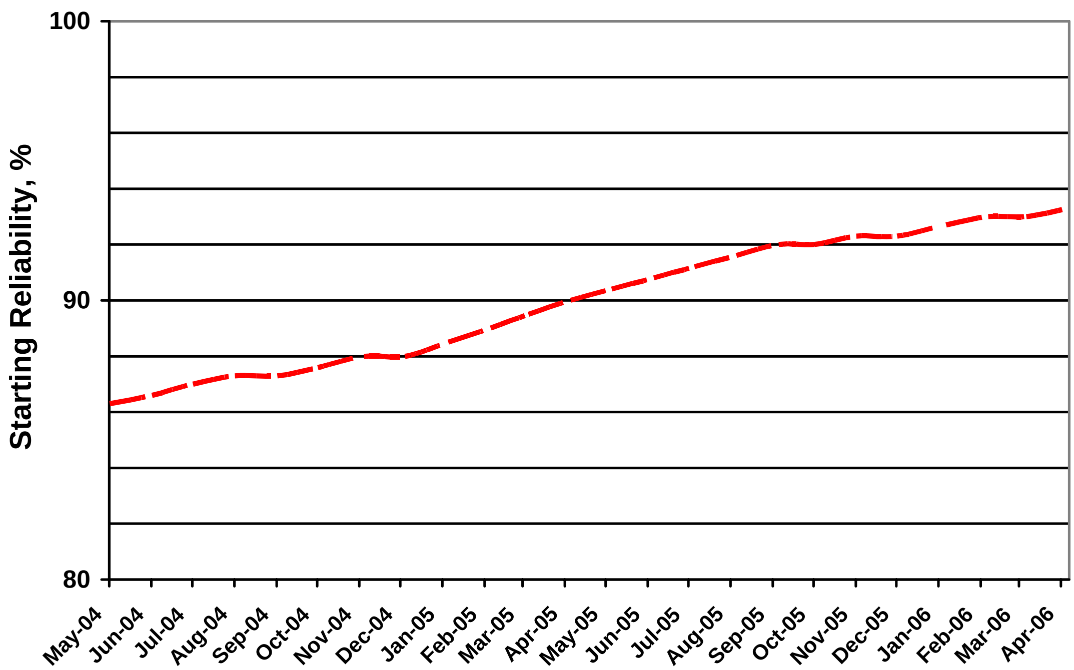

Figure 3. SGT6-5000F Starting Reliability Statistics

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Field Experience in Different Operating Modes

Described below are field operating experiences on several SGT6-5000F gas turbines employed in different operating modes.

One unit (Unit A) operating in a cyclic mode since 2001 has accumulated 1,896 equivalent starts (ES) and 424 equivalent base load hours (EBH). On inspection, the critical hot end hardware components were in an excellent condition. Figure 4 shows photos of the combustor basket (1,713 ES and 402 EBH), transition (1,896 ES and 424 EBH), first stage vane (1,896 ES and 424 EBH) and first stage blade (1,518 ES and 279 EBH). These components were in very good condition, with only minor TBC spallation on the vane inner airfoil fillet radii. All four components exceeded the target ES interval.

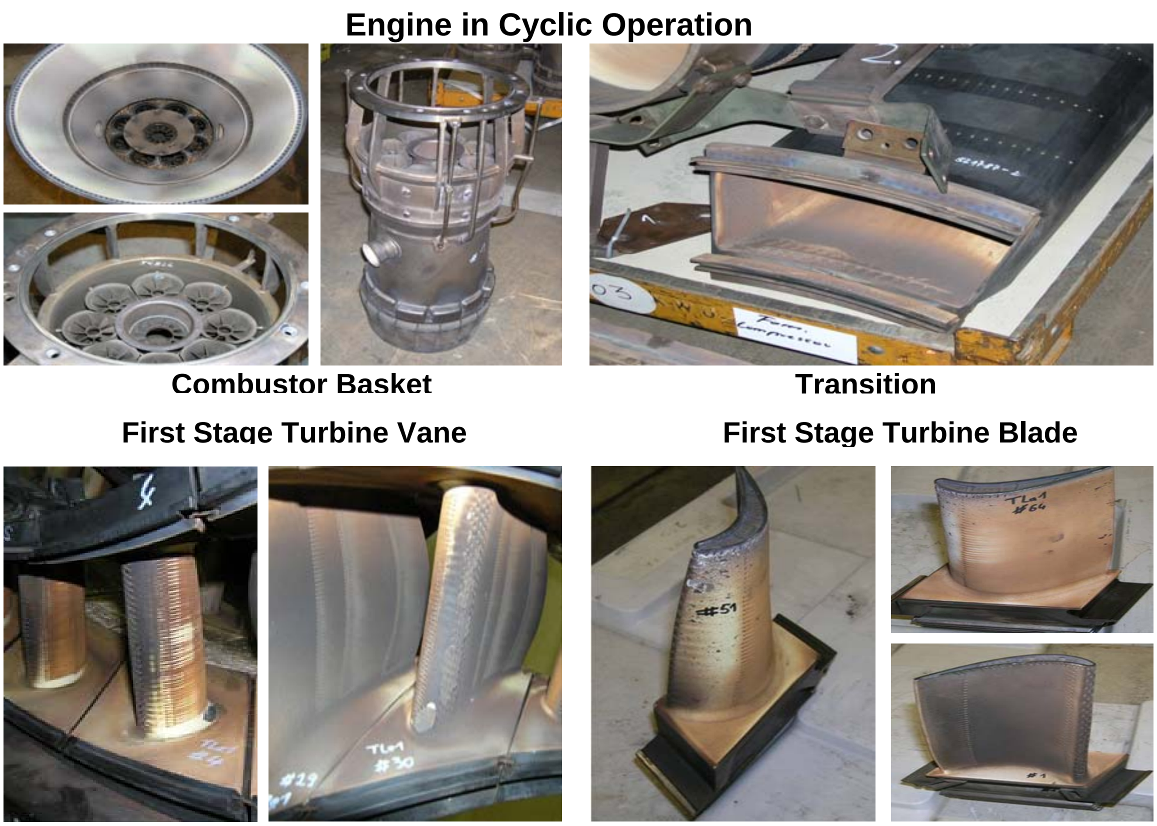

Figure 4. Photos of Critical Hot End Components on Unit A

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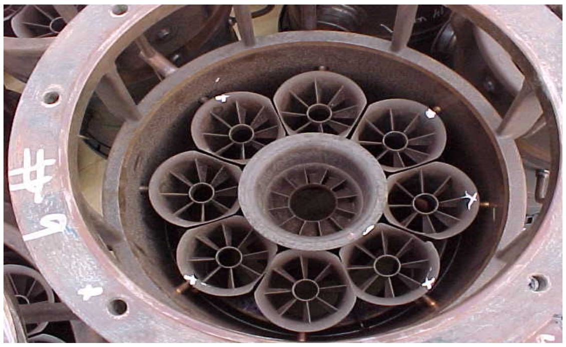
Another unit (Unit B), which has been operating in the intermediate mode since 2001, has accumulated 402 ES and 14,435 EBH. Figure 5 shows the critical hardware components' photos taken during inspection. When inspected after 225 ES and 4,944 EBH, the combustor baskets were in good condition. The transition (261 ES and 7,727 EBH) made the service interval with minor TBC spallation. The first stage turbine vane achieved 402 ES and 14,435 EBH without repair.

Engine in Intermediate Operation



Combustor Basket

Transition

First Stage Turbine Vane

First Stage Turbine Blade

Figure 5. Photos of Critical Hot End Components on Unit B

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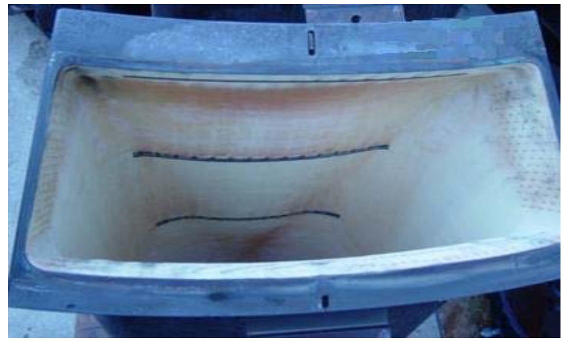
A unit (UNIT C) in base load operation since 2002 has accumulated 523 ES and 31,959 EBH, with 99.1% Reliability, 93.1% Availability and 90% Starting Reliability. Figure 6 shows the critical hot end parts after inspection. The combustor baskets (203 ES and 9,319 EBH) and transitions (134 ES and 8,454 EBH) exceeded their EBH inspection intervals and were in a very good condition. The first stage blades (453 ES and 23,996 EBH), were in excellent condition.

Engine in Base Load Operation

Combustor Basket



Transition

First Stage Turbine Blade

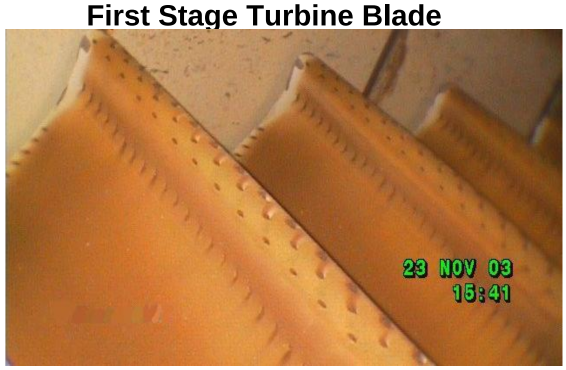


Figure 6. Photos of Critical Hot End Components on Unit C

Power Diagnostics^{TM} Centers

The three Siemens Power Diagnostics^{TM} Centers, one located in Orlando and the other two in Erlangen and Mülheim, Germany, have been operating for over 5 years to provide technical support to Siemens' gas turbine customers and to obtain operational feedback from the customers. The Centers monitor over 200 operating units world wide and provide engineering service and instrumentation/controls support. This allows rapid access to comprehensive operating data anywhere in the world. The customers also benefit from the rapid access to technical support and advice on how to resolve operational issues before they develop and impact the safe engine operation. The benefit to Siemens is in the ability to track and monitor its gas turbine fleet, collect operational data, identify any potential issues and provide resolutions before they develop into more serious incidents. These Centers are very helpful in providing feedback on the SGT6-5000F operation and statistics, thus aiding in issues resolution as well as indicating the direction for further engine development and enhancements.

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Parts Life Experience

Recent hot end component redesigns, some of which were carried out to extend the service interval to 12,500 EBH, have improved service lives of combustor baskets, fuel nozzles, transitions, stages 1-3 turbine vanes and stage 1 and 2 turbine blades. An extensive study was undertaken to determine the condition of major components based on field data analysis. The analysis covered combustor baskets, combustor support housings, fuel nozzles, transitions and all eight turbine airfoil rows. These hot gas path components were analyzed in terms of survivability, forced outages and scrap rates during parts refurbishment. Survivability focused on the mean time at which a component is removed from the engine fleet. The analysis identified the main causes for early part removal from engines and provided statistics on mean time between parts removal and scrap rates. This information will be used to further improve the hot end parts' service lives. The efforts described above have reduced scrap rates on some critical components to low single digits.

Service Interval Extension

Extending the combustion system and gas path inspection intervals significantly reduces the maintenance costs and increases the gas turbine availability, thus enhancing plant profitability. Combustor basket and fuel nozzle mechanical design and manufacturing processes were improved and the transition aerodynamic shape and cooling design were enhanced. These improvements allowed an increase in the combustion inspection interval by 56% on an hours based maintenance cycle from 8,000 equivalent base load operating hours to 12,500 hours and by 125% on starts based maintenance cycle (from 400 Equivalent Starts [ES] to 900 ES). As with the improved trip factor, this will also lengthen the interval between maintenance inspections while improving operational flexibility for units that incorporate the upgrade package. An advanced design available for offering will extend the combustor inspection interval from 400 ES to 900, and the equivalent base load hours (EBH) to 12,500. The current hot gas path inspection interval is at 900 ES and 25,000 EBH, while the major inspection is done at 1,800 ES and 50,000 EBH.

Trip Factor Reductions

Trip factor is the number of equivalent starts when the engine experiences a trip. For instance, trip factor of 8 means that each trip is equivalent to 8 starts. Each engine trip, especially if it is an emergency trip from base load, causes hot end components to experience severe thermal gradients over a short time interval (the turbine airfoil metal temperatures may decrease hundreds of degrees in seconds). The result is a negative impact on hot end parts' mechanical integrity and life. Startups, on the other hand, are slower and turbine components experience a moderate rate of temperature increase and hence much lower thermal gradients. Thus, originally each trip was considered equivalent to 20 starts as to its effect on the gas turbine cyclic life and the inspection interval. Maintenance intervals are calculated using operational data in a mathematical formula, one component of which is the number and type of trips experienced. Thus a high trip factor means more frequent inspection intervals. For the SGT6-5000F the maximum full load trip factor was reduced from 20 to 8 equivalent starts due to improved turbine and combustor components, with corresponding reductions in trip factors from part load conditions. This change allows the operator to run the engine longer between maintenance inspections, enhance the operational flexibility and thereby reduce life cycle costs.

Fast Startup Capability

In the original SGT6-5000F engine, startup time from initiation to full power took approximately 30 minutes. The improved start time capability is as follows: 5 minutes from start initiation to minimum load, and then the gas turbine is loaded at 30 MW/minute. This permits 150 MW within 10 minutes (see Figure 7). The reduction in starting time is over 60%.

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To achieve the improved start capability the following steps were taken:

1. Static frequency converter (SFC) (static start, where generator operates as a motor) replaced the mechanical starter motor. SFC allows more efficient and faster rotor acceleration than the equivalently sized mechanical starting motor.

2. Turning gear (TG) speed was increased from 3 rpm to 120 rpm. The higher TG speed enables the generator rotor wedges to lock up, thus preventing wear exhibited at low TG speed.

Higher TG speed also helps the engine cool down faster, because the turbine parts are cooled faster and tip clearances are similar to the cold tip clearance. The fast start capability has been field validation tested and implemented.

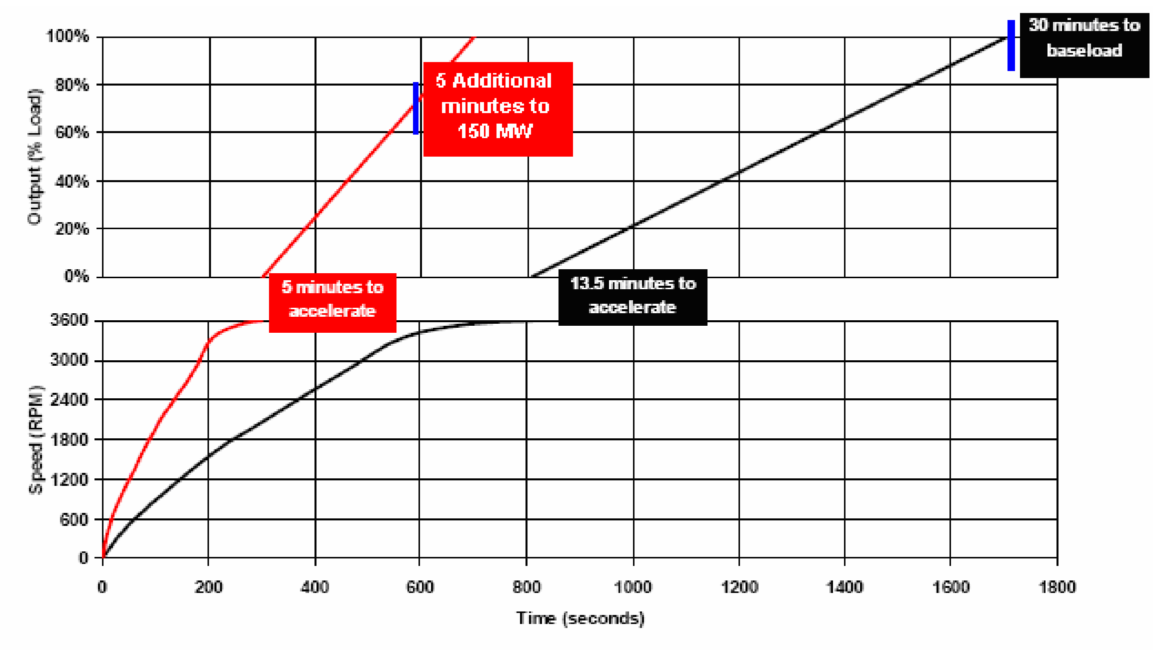

Figure 7. Fast Start/Fast Load Rate Capability (10 Minutes – Turning Gear to 150 MW)

PERFORMANCE

The SGT6-5000F gas turbine, which was designed for both simple cycle (Econopac) and combined cycle (CC) operation, has undergone in the last 15 years a dramatic evolution in performance, emissions and reliability. The improvements focused on compressor redesign, combustion system development, coating enhancements, thermal barrier coating application on some turbine airfoils, leakage air reduction, cooling enhancements, and fourth stage turbine vane and blade redesign. The compressor was redesigned using a combination of hardware design and internal secondary flow changes. The compressor airfoils were redesigned using a controlled diffusion airfoil design to increase inlet flow and efficiency. Brush seals were incorporated in the turbine interstage locations to reduce leakage, and disk cavity cooling flow modulation was instituted to reduce cooling flows. The fourth stage turbine vane and blade were redesigned to reduce the turbine exit swirl and flow Mach number, thus reducing exhaust diffuser loss and improving engine performance. As a result of these enhancements, the simple cycle introductory performance of 150 MW and 34.9% efficiency was improved to 200 MW and 38%, respectively. The net CC efficiency was improved from 54% to 57.3%. In 2x1 CC applications, the output

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power is now about 600 MW. Figure 8 shows the CC efficiency evolution. The engine maximum output power limit was increased from 185 MW to 235 MW, so as to provide its operators increased power production on cold days. In field performance acceptance tests, SGT6-5000F engines have met or exceeded their performance guaranties.

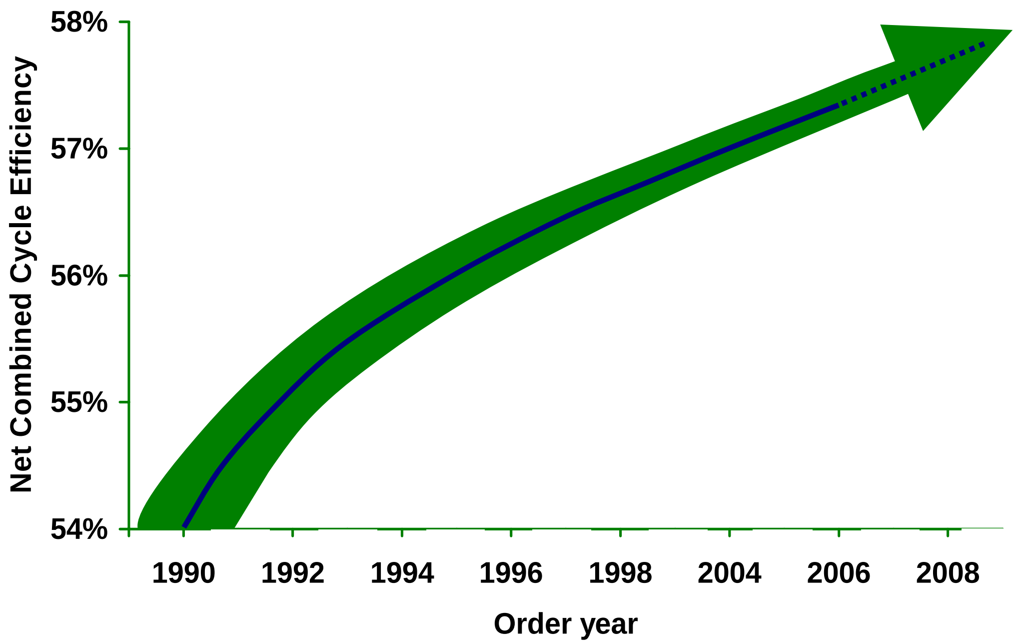

Figure 8. SGT6-5000F CC Efficiency Evolution

EMISSIONS

NOx Emissions

The original SGT6-5000F gas turbine incorporated diffusion flame DF-42 combustors with 42 ppm NOx (@ 15% O_2) emission. Through continuous combustion system development, NOx emission was reduced to 15 ppm with the premixed dry low NOx (DLN) combustors and now to <9 ppm with the ultra low NOx (ULN) combustors. In addition to reducing NOx, the ULN combustion system controls CO, volatile organic compounds (VOC) and particulate emissions. This development also addressed the fuel flexibility issues, as more LNG enters the U. S. market, and expanded operating range (turndown), where low CO emissions are required.

The starting point for this development was the premixed DLN combustor (see Figure 9). The NOx reduction was achieved through temperature and heat release strategy modification by staging the combustion process (see Reference 6). The current DLN combustor design uses 4 fuel stages to mix the natural gas with combustion air. These stages come on line independently as the engine is ramped up in power. At all loads the fuel is injected continuously through the pilot nozzle and is not premixed, thus limiting the achievable minimum NOx emissions. The modifications required to achieve 9 ppm NOx in the ULN system concentrated on a premixed pilot design and support housing design changes. The pilot and the main premixers on the combustor support housing now employ swirler fuel injection, where the fuel is injected off the swirler vanes, thus providing more injection points and hence better mixing. The ULN combustion system validation included CFD modeling, high pressure single basket rig testing and full-scale engine test in the Berlin Test Bed (BTB), which allowed testing over a wide load range. The value of the

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BTB facility was demonstrated in the field engine validation where the ULN system operated within the design emissions and dynamics parameters on the first day of testing. The new combustor design is very stable, since emissions and combustion dynamics exhibit virtually no effect with fuel temperature variations, such as when the engine loses the fuel heater and the fuel temperature drops. The thermal loading on the hot parts, such as the combustor liner, transition and the first stage turbine vane, is very similar to the existing 15 ppm NOx system. Therefore, durability will be unaffected by this combustor design.

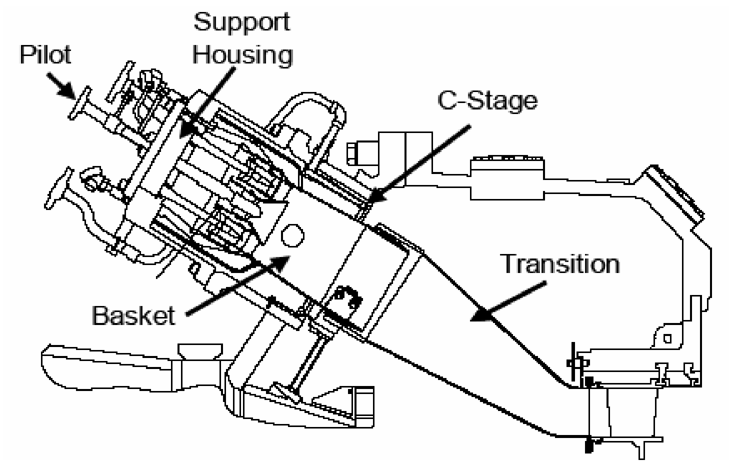

Figure 9. Premixed DLN Combustor Cross Section

Part Load CO Emissions Reduction

It is very important for gas turbine operators to minimize CO emissions on startup as well as part load operation to stay within the permitted levels. The SGT6-5000F low load CO emissions reduction was achieved by operational modifications which include a second modulating circuit added to turbine cooling air supply. When load is reduced, the second modulating circuit is opened, bypassing additional cooling air around the combustor. Bypassing air around the combustor increases combustor flame temperature and, hence, limits CO production. There are other measures which can be taken to reduce CO if necessary, including changes to valve scheduling to allow compressor air to be bypassed into the exhaust. With this equipment and operational changes, CO is kept to <10 ppm down to 40% load. This CO reduction will decrease total CO mass emissions by more than 70% per startup-shutdown cycle (see Figure 10).

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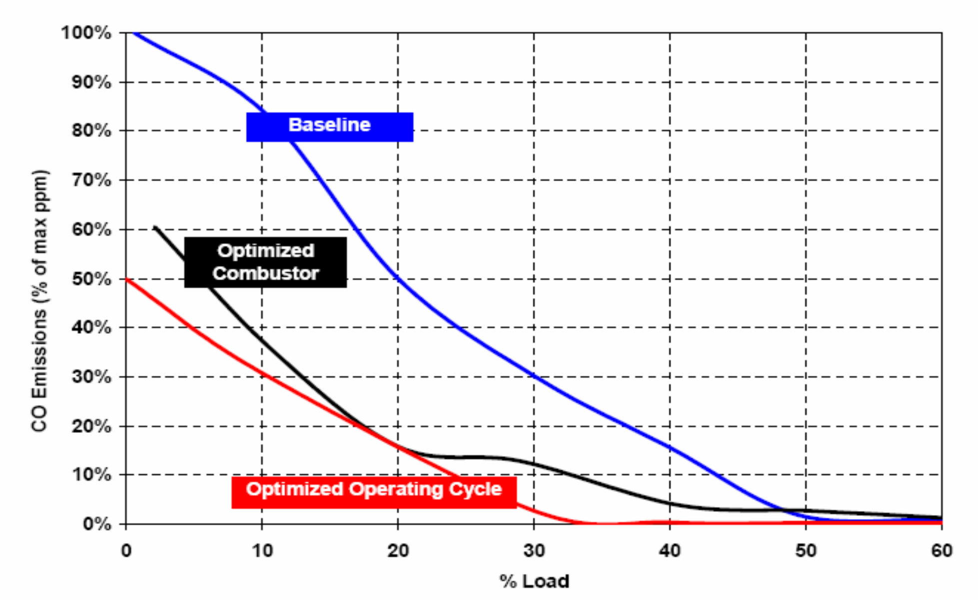

Figure 10. CO Emissions at Startup & Low Load

IGCC CAPABILITY

The SGT6-5000F has been adapted for incorporation into coal- and biomass-based IGCC plants to take advantage of abundant and low cost fuels and to provide the customer with additional fuel flexibility. 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, restrict emissions to the target values and meet the cost goal. The secondary fuel will be used for starting and loading the gas turbine while the air separation unit (ASU) and the gasifier are brought on line and as a backup fuel. The system must allow complete fuel transfer from secondary fuel to primary fuel anywhere between 30% to 90% of maximum rated power on the respective secondary fuel. The SGT6-5000F combustion system development demonstrated that it will operate successfully in the IGCC application and achieve its emissions, performance, reliability and operational flexibility goals (see Reference 5). A diffusion flame combustor and fuel nozzle were developed and validated for this application. This combustion system was developed with flexibility in mind to ensure that it could handle a wide range of feed stocks that have been processed with a variety of gasification technologies.

Analyses were carried out on all critical components to ensure that the SGT6-5000F engine would meet all the requirements for syngas operation and optimized integration into the IGCC plant. The components analyzed were the compressor, turbine, rotor and casing. Provision was made for up to 50% air side integration (i.e. up to 50% of ASU air requirement would be supplied by the gas turbine). The combustion system components were redesigned based on results of the exhaustive syngas testing program. The analyses results indicated that with the exception of the combustion system, no modifications to the engine components would be required. The modified combustion system components are retrofitable into existing engines.

Modifications to the Econopac for IGCC application will include additional piping (for syngas, air extraction and diluents systems) and controls for the additional systems. A flow computer and a mass spectrometer will be required to accurately measure and control fuel heating value as it enters the gas turbine. Active combustion dynamics monitoring systems will be incorporated. An optimized SGT6-5000F-IGCC plant design was produced to take advantage of multiple integration points (air, water, steam, fuel) and hence produce plant efficiency gains. Siemens past

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experience in integrating gas turbines into IGCC plants helped in establishing the practical design limitations on integration amount. The Power Block design was made flexible enough to accommodate a wide range of feed stocks and a variety of gasification technologies. The SGT6-5000F adapted for IGCC application is now being offered commercially.

The standard 2X1 SGT6-5000F-IGCC plant fired on coal-derived syngas will produce more than 609 MW net output power with 40.5% (HHV) net efficiency. Based on this performance and the expected plant availability, O&M cost and capital plant cost targets, the IGCC plant levelized cost of electricity (COE) is expected to be approximately 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 11 shows the output power variation with ambient temperature for both syngas and natural gas operation. Note the significant output power surplus on syngas operation.

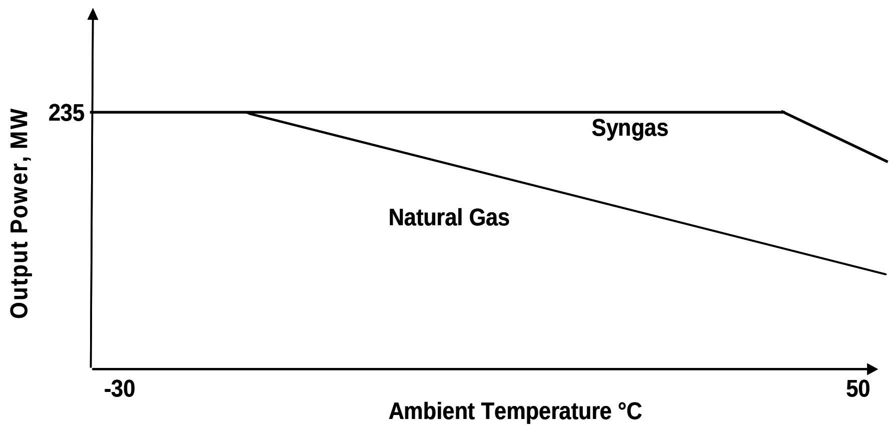

Figure 11. Output Power Vs. Ambient Temperature

In 2005 the U. S. Department of Energy awarded Siemens a contract for Phases 1 and 2 of a three Phase 10-year Advanced Hydrogen Turbine Development program to develop the SGT6-6000G (W501G) gas turbine for integration into a super efficient, near zero emissions, coal-based IGCC plant (see Reference 7). New or enhanced technologies developed under this program will be incorporated into the SGT6-5000F, as appropriate, to enhance its thermal performance, environmental performance, reliability, operational flexibility and optimize its integration into future IGCC plants.

LNG CAPABILITY

Due to natural gas supply market volatility, increasing prices and declining domestic production, liquefied natural gas (LNG) is becoming an attractive alternative fuel choice for gas turbines. LNG imports are expected to increase in the future and several new LNG terminals' construction have been announced. LNG consists of methane, which is the main constituent in natural gas, along with heavier components, such as ethane, propane and butane. Depending on the level of heavier constituents, LNG could result in a higher or lower flame temperature than traditional natural gas and could impair the safe and environmentally sound operation of gas turbine plants, if the gas is not diluted or otherwise altered to meet the standards for pipeline-quality natural gas. Development of the SGT6-5000F combustion system was necessary to ensure that it would operate satisfactorily on LNG with acceptable emissions, combustion dynamics, reliability and parts life.

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Both single combustor rig tests and combustor tests in a field engine were carried out. To simulate LNG in the field test, a wide range of vaporized heavy constituents were blended with natural gas. An instrumented combustor basket and transition were installed in the test engine. Tests were conducted with varying amounts of heavier constituents and 70 to 100% load. Detailed measurements confirmed that the SGT6-5000F combustion system was capable of LNG operation with low emissions. Combustion dynamics were acceptable with tuning. Increased NOx emissions were observed with increasing heavy hydrocarbon concentrations (beyond the normal ranges present in LNG), but no negative impact on CO or Total Hydrocarbon emissions. Output power or heat rate were not affected by LNG operation. Post test hardware inspection showed the engine to be in excellent condition. It was concluded that for LNG fuels that exceed fuel specifications the minimum required modifications will include active combustion dynamics monitoring and fuel gas monitoring (Wobbe Index measurement). Depending on the specific engine configuration and operational requirements, the following additional modifications may be required: enhanced fuel control, gas thermal control (Wobbe Index), engine control adjustment to avoid load swings and newer designs for combustor parts, first stage turbine vanes and first stage turbine blades. The upgrade hardware will provide longer inspection intervals and parts service lives.

BERLIN TEST BED

The Siemens Berlin Test Bed (BTB) provides a world class facility for testing and validating advanced technologies, concepts and components (see Figure 12). A water friction brake absorbs the engine power and provides variable speed capability. This facility allows advanced designs to be extensively tested at full load before fleet implementation. Thus, any issues identified during testing can be rectified and then retested prior to field installation. The engine can be tested with a full load (up to 250 MW) on natural gas for extended periods, limited only by noise restrictions during the night. To obtain accurate measurements of performance, emissions, temperatures, pressures, vibration and tip clearances, there is provision for measuring more than 2,300 measurement points. These measurements include air/gas/metal thermocouples, pressure taps, flame monitors, dynamic strain gages, accelerometers, blade vibration monitors, optical pyrometry/thermography, tip clearance probes, etc. The following tests were conducted on the SGT6-5000F in the BTB facility: extended off-frequency operation range, compressor characteristics mapping, advanced combustion design, advanced design for enhanced engine power and efficiency, optimum operational control for reduced part load CO emission, faster engine startup, starting reliability improvement, reduction of trip factors and reduction in expected maintenance cost. Future SGT6-5000F enhancements will also be validated in the BTB facility.

Figure 12. Berlin Test Bed for Full Load Engine Testing

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RECENT ENHANCEMENTS

SGT6-5000F gas turbine performance, reliability and operational flexibility improved and its emissions and life cycle costs decreased steadily since its introduction in 1991. This was accomplished by planned development programs, which facilitated the introduction of new technologies and concepts. To improve the current engine model performance and mechanical reliability the sixteenth stage compressor blade was redesigned for enhanced aerodynamic performance, honeycomb seals were incorporated into the compressor to reduce leakage flow, advanced sealing designs were implemented into the turbine to reduce leakage and hot gas ingestion, and the fourth stage turbine and the exhaust diffuser were redesigned for enhance aerodynamic performance. The result is a more competitive product and added value to our customers.

Siemens is committed to continuous enhancement for the STG6-5000F gas turbine in both new and in-service plants. Thus, the product enhancement process will continue in the future and will concentrate, not only on performance and emissions, but also on operational flexibility, reliability/availability/maintainability, lower life cycle costs, longer component lives, improved service factors and increased repair intervals.

SUMMARY

The 192 currently operating SGT6-5000F gas turbines achieved an impressive record in the 13 years since the first engine went into commercial operation. The fleet has accumulated more than 3.25 million operating hours and the fleet leader more than 104,000 hours. During its service lifetime, the engine has demonstrated excellent mechanical integrity and operational reliability. The hot end parts lives have been steadily improved and the parts fallout rates in the repair cycle have been reduced. The fleet 12 month rolling average Reliability, Availability and Starting Reliability are 99%, 95% and 93%, respectively. The concerted and continuous engine performance evolution has improved the Econopac output power to 200 MW and efficiency to 38%. In two on one combined cycle applications the output power is now about 600 MW and the efficiency is 57.3%. The latest models are achieving <9 ppm NOx and <10 ppm CO down to 40% load. The combustion system inspection interval has been increased from 400 to 900 equivalent starts and from 8,000 to 12,500 equivalent base load hours. The SGT6-5000F has been adapted for IGCC application with very minor modifications, which are retrofitable into current engines. Combustor rig and engine field tests were carried out to demonstrate that the combustion system would operate satisfactorily on liquefied natural gas. The Berlin Test Bed facility was employed effectively to test and validate SGT6-5000F enhancements, such as ultra low NOx combustion system, reduced part load CO emissions, compressor and turbine performance improvements, starting reliability improvement and faster engine startup. To further improve the competitive position and customer value, future enhancements will be incorporated in the combustion system, transition, and turbine vanes and blades.

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