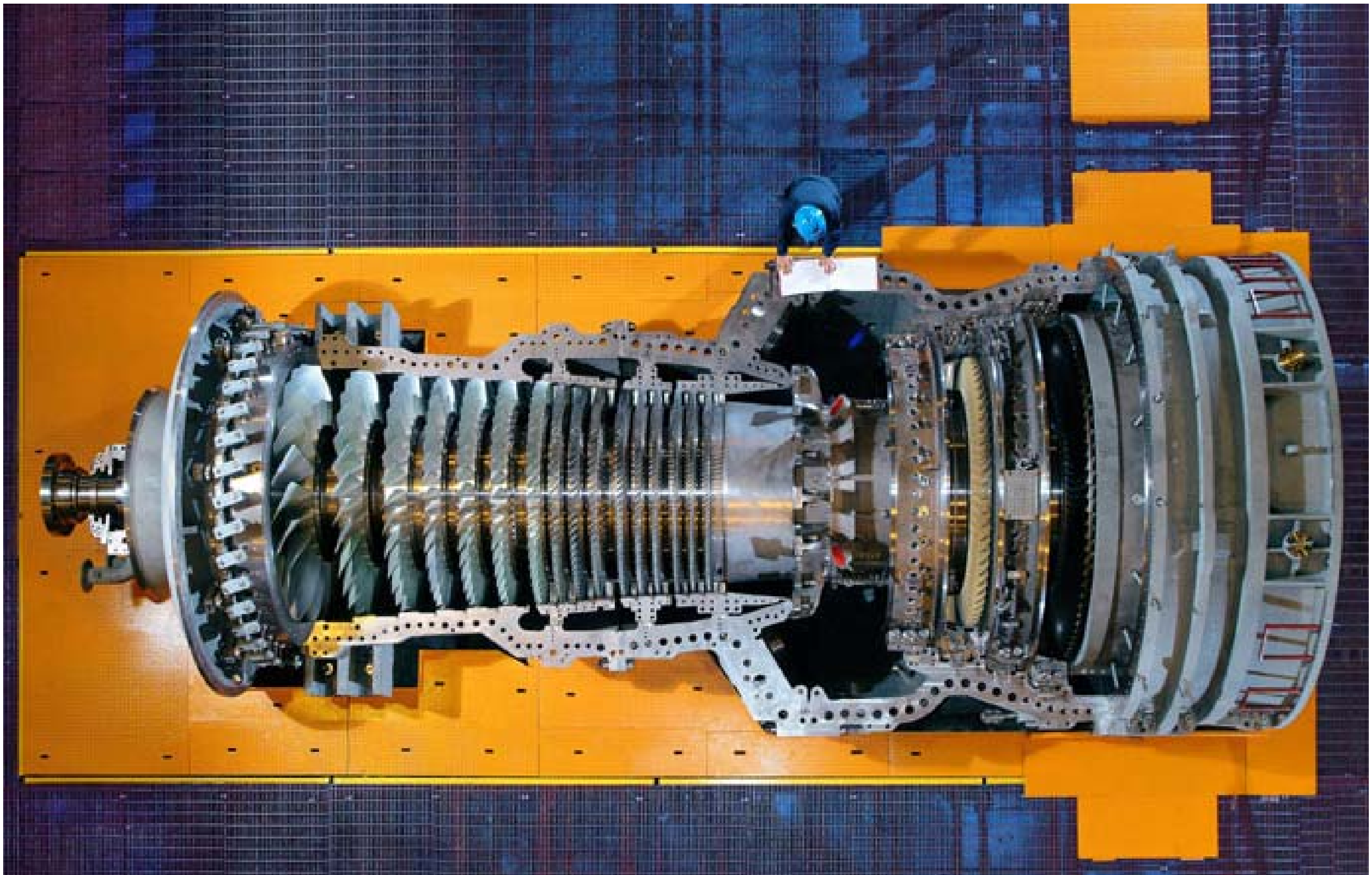

SGT6-5000F (W501F) Engine Enhancements to Improve Operational Flexibility

John Xia
- Engineering Manager, SGT6-5000F Frame

Josh Kovac
- GT Frame Engineering Manager

Gerry McQuiggan
- GT Product Analysis Program Manager

Ben Wolfe
- GT Product Line Manager

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Abstract

This paper describes recent changes made to the SGT6-5000F gas turbine (previously named W501F) to enhance its operational flexibility. The engine is designed for a wide range of operating modes, such as peaking, intermediate and continuous duty. The changes incorporated will further enhance its demonstrated record in flexible operation demanded by the current US market conditions of overcapacity and high fuel prices. This paper describes benefits resulting from these changes, as well as verification testing carried out to validate them. The changes focused on engine operation, performance, component mechanical integrity and combustion system improvements. The paper also summarizes the SGT6-5000F field experience over the 15 years since its introduction and outlines planned improvements for the near future.

Introduction

In the 40 years prior to the SGT6-5000F design, aviation and land-based gas turbines experienced evolutions in performance and design leading to improved mechanical integrity and reliability. During that period our engineers made significant contributions in developing heavy-duty gas turbine technologies. Heavy-duty gas turbines remained at 1093°C (2000°F) rotor inlet temperature levels in the decade before the SGT6-5000F introduction. The introduction of F-class firing temperatures (1260°C / 2300°F) represented a step change made possible by advancements in manufacturing, material processing, improved analytical techniques and advanced cooling technology. Significant improvements in thermal performance were achieved simultaneously with gas turbine emissions reductions through dry low NOx technology.

The SGT6-5000F heavy-duty gas turbine was designed for both simple cycle and combined cycle (CC) power generation in utility and industrial service. This engine represented the next model in the family of successful W501 gas turbines (see Reference 1). It is an advanced, efficient, low NOx, powerful gas turbine able to operate on all conventional fuels as well as coal-derived low Btu gas. The introductory design, in 1990, carried a simple cycle rating of 145 MW of power and 34.1% net thermal efficiency. In CC applications, the introductory net plant efficiency was more than 53% with 200 MW of power.

In 2005, 185 SGT6-5000F engines are employed in peaking, intermediate and continuous duty operation. The fleet has amassed more than 2.5 million operating hours and has demonstrated excellent reliability, availability and starting reliability. These units, plus an additional 38 under contract, represent the highest number of any one model of 60 Hz Siemens gas turbines sold. Due to design enhancements, development efforts and technology cross flow from other Siemens' advanced gas turbines, the simple cycle output has increased from 145 MW to 200 MW and its efficiency from 34.1% to 38%. In one on one CC applications, the net plant output and efficiency are now 293 MW and 57%, respectively.

SGT6-5000F 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. Due to increases in natural gas prices and the overcapacity in the US electric power market after 2002, conditions shifted such that the nuclear and coal-based plants have become the lowest cost electricity producers. This 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.

The focus of this development included 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.

Engine Design Features

SGT6-5000F design was based on fundamental time-proven design concepts used in earlier models as well as new concepts and technologies incorporated to increase efficiency, reduce emissions and allow reliable operation (see Reference 2). Figure 1 illustrates the engine longitudinal section.

To develop a highly reliable gas turbine, reliability/availability/maintainability (RAM) principles were applied to the SGT6-5000F design and development. These principles were focused not only on the gas turbine and its components, but also on auxiliaries and controls, since they have a significant impact on overall plant reliability and availability. The RAM approach involved systematic and iterative evaluations of the design, comparison against design objectives and recommendations for design enhancements, using a full range of tools, such as reliability allocations, modeling and Failure Mode and Effects Analysis (see Reference 3). The current SGT6-5000F fleet average availability has reached world class levels, currently at 95% on a 12 month rolling average basis.

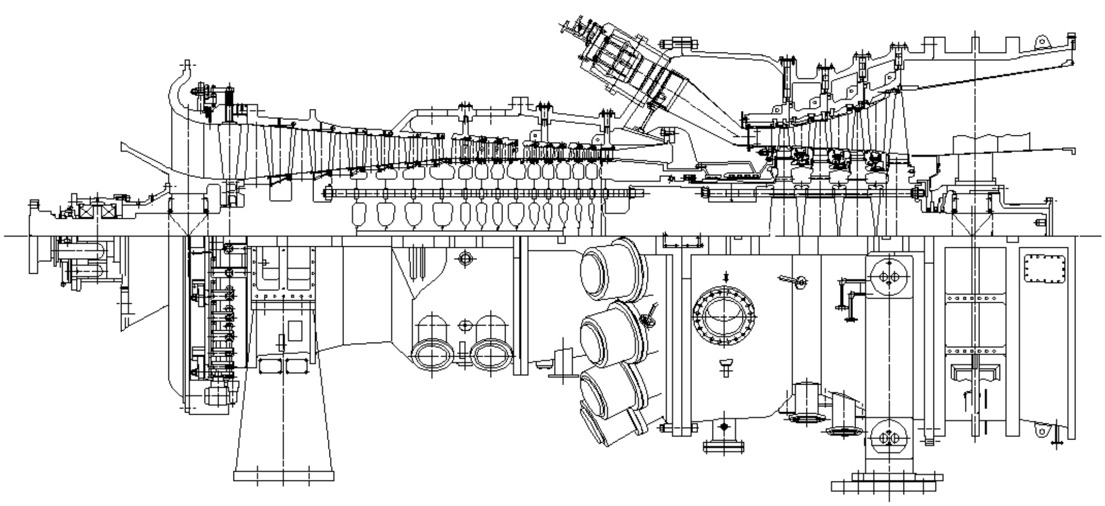

Figure 1. SGT6-5000F Longitudinal Section

Component and Engine Verification Tests

All the new advanced technology, incorporated into SGT6-5000F design, was validated for engine use by extensive rig and fully loaded engine shop tests. This verification test program included rotating blade vibration, combustion system, turbine aerodynamics, cooled turbine component heat transfer, and other shop tests (see References 5-7) The latest improvements have been fully tested and validated in the 235 MW test bed located at the Siemens factory in Berlin. This test bed which uses a water brake to absorb the full power of the SGT6-5000F engine is a unique facility for the testing of large gas turbines and allows operation of the engine at full power and off frequency to fully map out the mechanical and aerodynamic operating envelope for the engine.

Field Experience

The measure by which a gas turbine model is judged to be successful is its field operating experience. The specific criteria for success include performance, emissions, mechanical integrity, (as defined by RAM and starting reliability), life cycle costs and operational flexibility. All of the above are important, but in the current competitive and changing market environment, operational flexibility and adaptability to this environment have assumed a much greater importance. To be economically viable, the electricity generating plant must respond quickly, efficiently and reliably to any required changes in operating conditions such as load demand, start-stop operation, and different fuels, etc. The SGT6-5000F has demonstrated over the last 12 years its success in this environment, providing its operators with exceptional service.

185 SGT6-5000F engines are currently operating in peaking, intermediate and base load modes. Figure 2 shows the number of engines plotted versus the year of initial operation. The fleet has amassed more than 2.5 million operating hours (see Figure 3) and demonstrated excellent reliability and availability (see Figure 4). The fleet 12 month rolling average reliability* is currently over 99%, and availability* over 95%, as of May 2005. The lead engine has accumulated more than 94,000 operating hours. The simple cycle output power and efficiency for the latest model is 200 MW and 38%, respectively, and in CC application 293 MW and 57%, respectively . NOx and CO emissions of <9 ppm are available. The SGT6-5000F engine has demonstrated its operational flexibility and excellent performance through a continuous improvement & dedicated product development effort carried out since its introduction.* This data includes the gas turbine, generator, mechanical auxiliaries (lube oil, fuel, etc.), electrical components and control system.

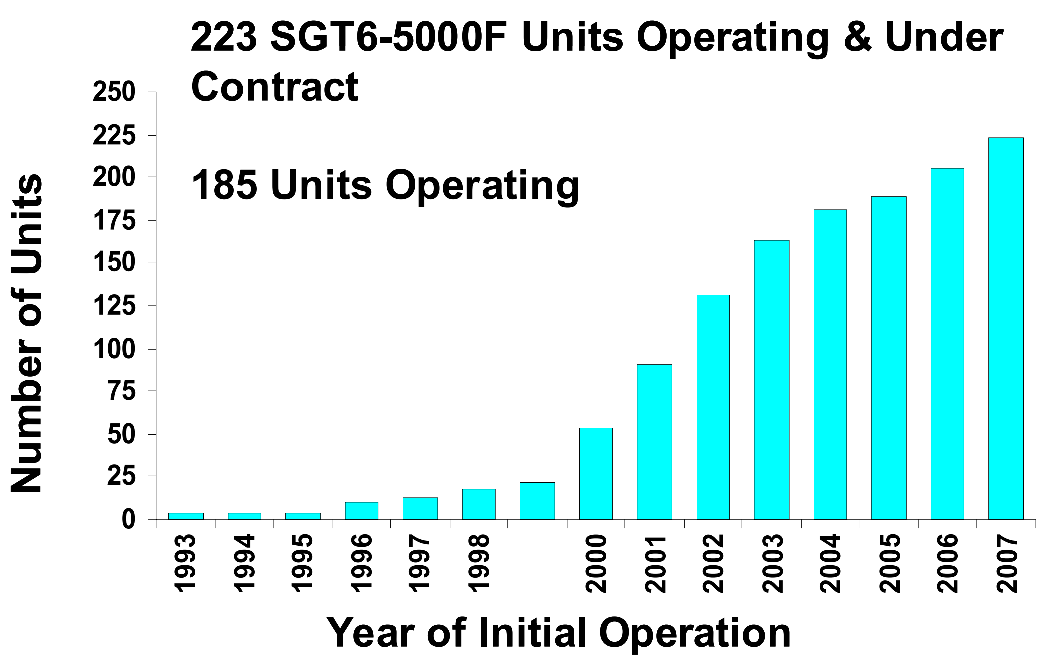

Figure 2. SGT6-5000F Engines in Operation

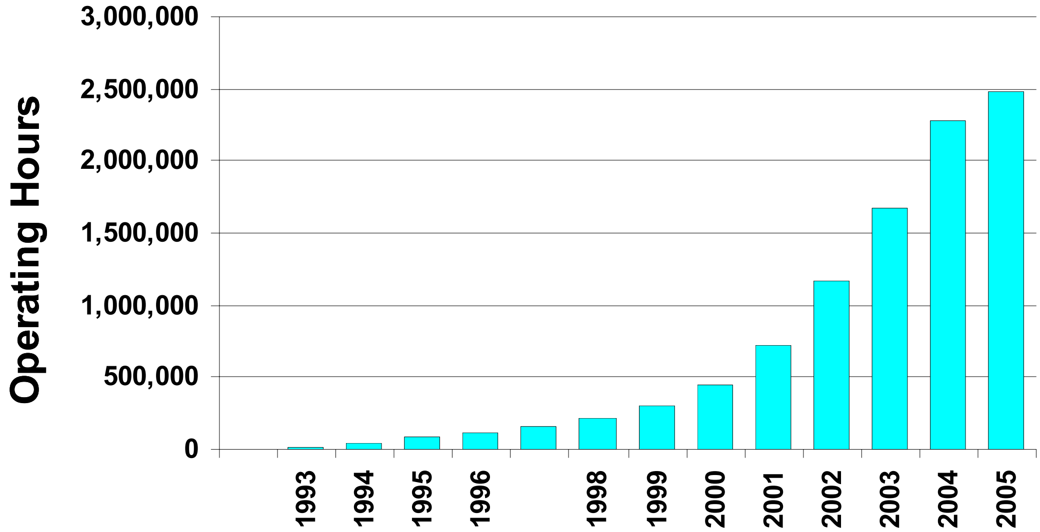

Figure 3. SGT6-5000F Fleet Cumulative Operating Hours

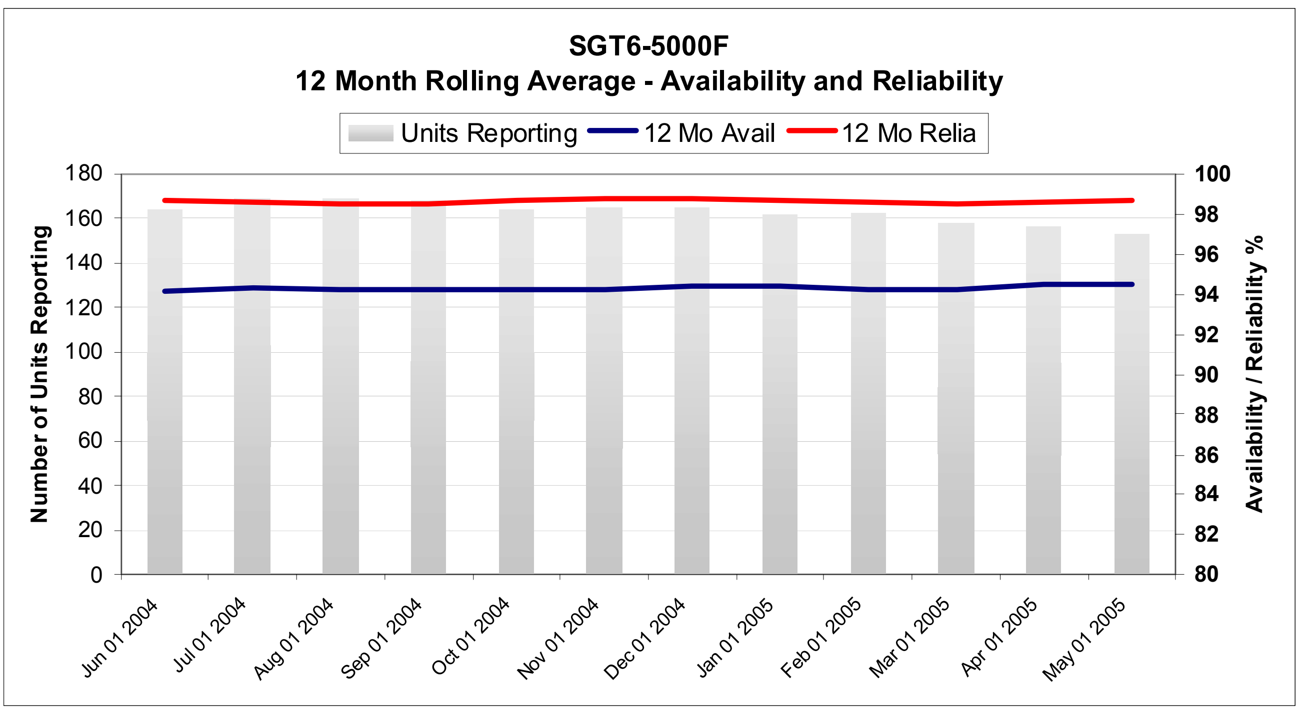

Figure 4. SGT6-5000F Fleet 12 Monthly Rolling Average Reliability and Availability

The first SGT6-5000F application was in North America in a repowering project. The repowered plant was based on four SGT6-5000F engines and two existing steam turbines in 2 on 1 CC applications. Commercial operation started in May, 1993. A field test was carried out to verify turbine blade vibratory stresses, combustor pressure fluctuations, combustion and transition metal temperatures, first stage blade cooling effectiveness and key engine operating parameters (i.e. performance, emissions and vibration) (see Reference 8). The four units met all contract guarantees for output power, efficiency and emissions. A rotor inspection, after 80,000 operating hours, showed the unit to be in excellent condition.

Over the last 12 years, enhancements were incorporated in the SGT6-5000F to improve its performance and reliability, and to reduce its emissions. Figure 5 shows its performance evolution. The improvements focused on compressor redesign, cooling and leakage air reduction, blade tip clearance reduction, improved thermal barrier coatings on some turbine airfoils, fourth stage turbine vane and blade redesign, and combustion system development.

The compressor was redesigned using a combination of hardware design and internal secondary flow changes. The compressor airfoils were redesigned using controlled diffusion airfoil design to increase inlet flow and efficiency, and cooling air was reduced. Brush seals were incorporated in the 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. The dry low NOx (DLN) combustion system, which reduced NOx emissions on natural gas fuel from >25 ppmv down to <9 ppmv (Reference 9) and was successfully demonstrated on a service unit in 2004. The combustion bypass valve, which was instituted for part load stability control, was eliminated without affecting operability, but reduced component and maintenance costs. Capability to operate on liquefied natural gas has also been demonstrated in field operation.

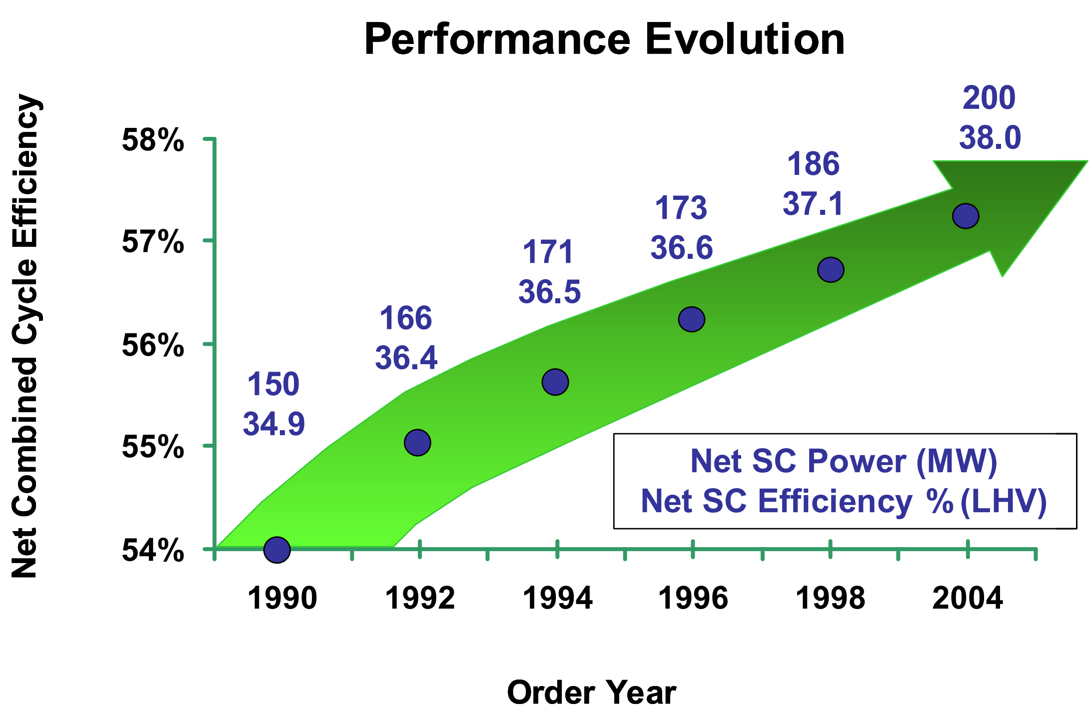

Figure 5. SGT6-5000F Performance Evolution

References 10 to 12 provide additional information on SGT6-5000F operational experience.

To enhance the SGT6-5000F plant output power and/or efficiency, additional design options are available. These options, which can be applied to the SGT6-5000F, include steam and water injection, inlet air chilling, evaporative cooling, fogging and fuel heating. Proper selection from these options will result in a power plant which is optimized on cost and performance (see Reference 13).

Market Drivers for Operational Flexibility

Electricity generation market conditions changed significantly from the late 1990's to present. From the mid-1990's to 2000 there was a steady reduction in US electric power reserve margins and the belief that deregulation, along with clean and efficient combined cycle plants, would replace old base load generation, such as nuclear and coal-based plants. Increasing demand for electricity and high electricity prices caused a surge in new orders for both simple cycle and combined cycle plants. The result was a dramatic growth in total generated electricity capacity and an increase in reserve margins in all U.S. regions, as well as a decrease in CC Capacity Factor (defined as the unit operating hours divided by the hours the unit is available for operation). The capacity factor reduction forced operators to run their gas turbines in Peaking and Intermediate modes rather than Base Load, thus increasing demand for cyclic operation capability.

Demand growth, economic dispatchability and operational flexibility are the key factors that determine the electricity-generating plant's ability to improve its dispatch rate (i.e. the order in which it is dispatched as demand for electric power increases during the day). Due to current overcapacity and increase in reserve margins, the units that excel in economic dispatchability and operational flexibility will dispatch in higher order compared to other competing units. The dispatch order is determined by the unit's VPC (variable production cost). Fuel cost and variable Operation and Maintenance (O&M) cost are used to calculate VPC. Small changes in VPC can significantly affect the unit's dispatch order. Fuel cost is directly impacted by the gas turbine's efficiency, thus increased efficiency improves not only the revenue per megawatt hour, but also increases the unit's total dispatch hours. Reduced O&M costs will also lower VPC, improve dispatchability and increase net cash flow. Units that are operationally flexible and can load follow, economically cycle on and off, and possess other flexibility attributes, will have improved dispatchability and a competitive advantage in the current market. Design improvements specifically implemented into the SGT6-5000F, enhanced its economic dispatchability, due to increased efficiency and lower life cycle costs (hence reduced VPC), and improved its operational flexibility.

Engine Adaptation for Enhanced Flexibility

Operational Flexibility Attributes

In order to maintain competitiveness, it is important that the SGT6-5000F provide our current and future customers with operational flexibility, which is demanded by fluctuating market conditions and rising fuel prices. Operational flexibility not only includes the capability to operate safely, efficiently and with minimum emissions in different operating modes, but also the ability to run on different fuels, start reliably when required, reach the demanded output in the shortest time possible and minimize cool down time so that inspection can start early. It is important that this flexibility not negatively impact performance, parts' lives, maintainability, life cycle costs and intervals between inspection/service. In response to changing market conditions and more emphasis on cyclic or even start-stop operation, design enhancements/ changes were introduced into the SGT6-5000F to further improve its already amply demonstrated operational flexibility. These enhancements focused on starting reliability, fast start capability, reduced part load CO emission, inlet heating, exhaust temperature optimization, Trip Factor reduction, increased time between inspections, and new component design features to improve performance and durability.

The following sections describe in detail how the SGT6-5000F was adapted to improve its operational flexibility by enhancements which are grouped in two categories: (1) engine operational/control modifications, and (2) component design changes. All these enhancements/modifications are retrofitable into existing engines.

Engine Operational/Control Modifications

Starting Reliability

Starting reliability is being improved by implementing the advanced Closed Loop Ignition Control (CLIC™) system. To improve engine starting reliability, an investigation was carried out to determine root causes for failure to start each time when ignition was initiated. Based on the investigations the CLIC™ system was developed, validated and implemented. The control logic was also changed to allow more time for ignition before aborting the start and the fuel filter was enhanced to reduce likelihood of blockage. These changes have been implemented on multiple engines and to date have resulted in improved starting reliability.

Start up Time.

The original 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 GT is loaded at 30 MW/minute. This permits 150 MW within 10 minutes (see Figure 6).

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 .

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.

Part Load CO Emission Reduction

Reduced low load CO emissions were 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 & operational changes, CO is kept to <10 ppm down to between 45% and

50% load This CO reduction will reduce total CO mass emissions by 70% per startup-shutdown cycle (see figure 7).

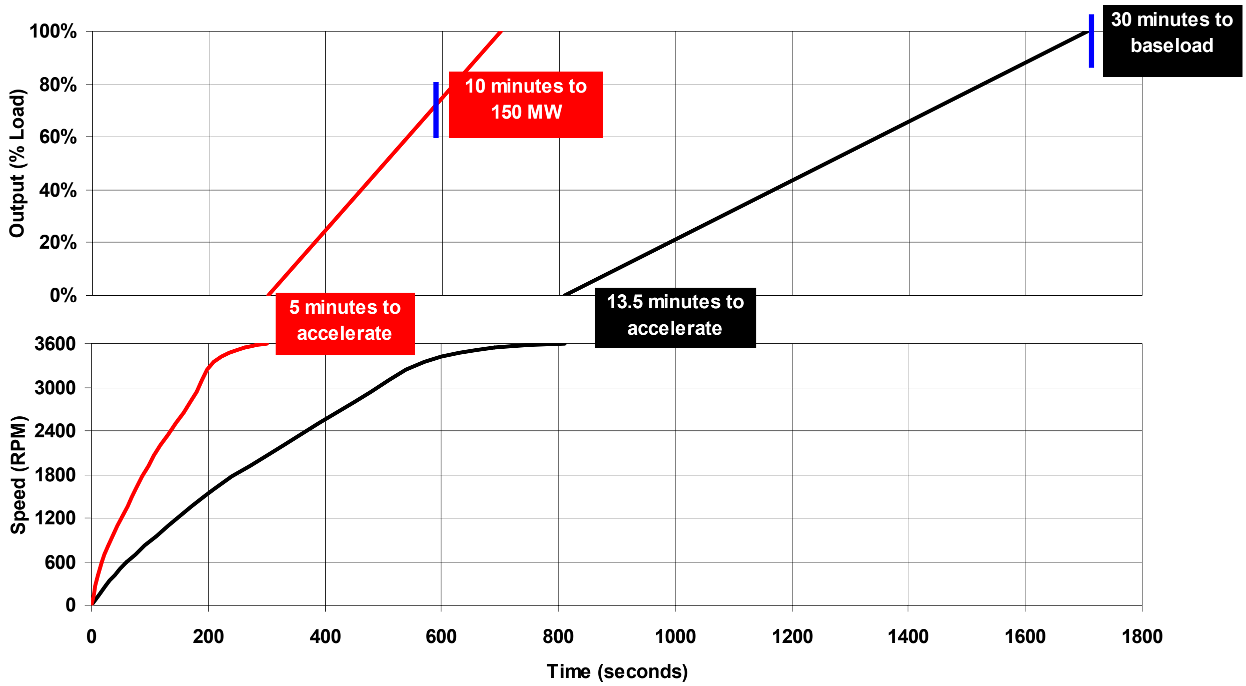

Figure 6. Fast Start / Fast Load Rate Reduces Startup Time By Over 60%

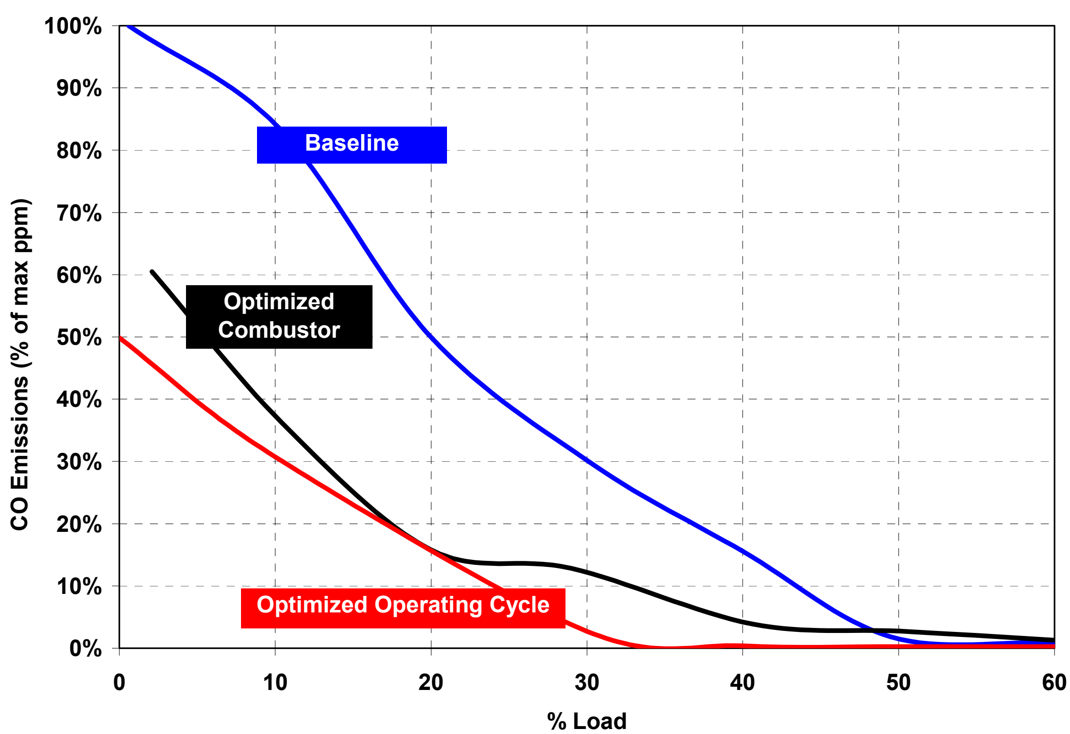

Figure 7. CO Emissions at Startup & Low Load

Outlet Temperature Control

The original SGT6-5000F engine control was based on a function of exhaust temperature versus combustor shell pressure. This relationship defined the turbine base load firing temperature to which the engine was controlled. This has now been changed to a relationship of exhaust temperature versus compressor inlet temperature. This Siemens system is called the Outlet Temperature Control (OTC), which has been used successfully on the V-series engines for over 20 years, and results in a tighter control on the IGV settings. Benefits due to operation on OTC control can include an improvement in average part load (60-95% load) plant efficiency, reduced drift in NOx at part load operation and no requirement for seasonal combustion tuning.

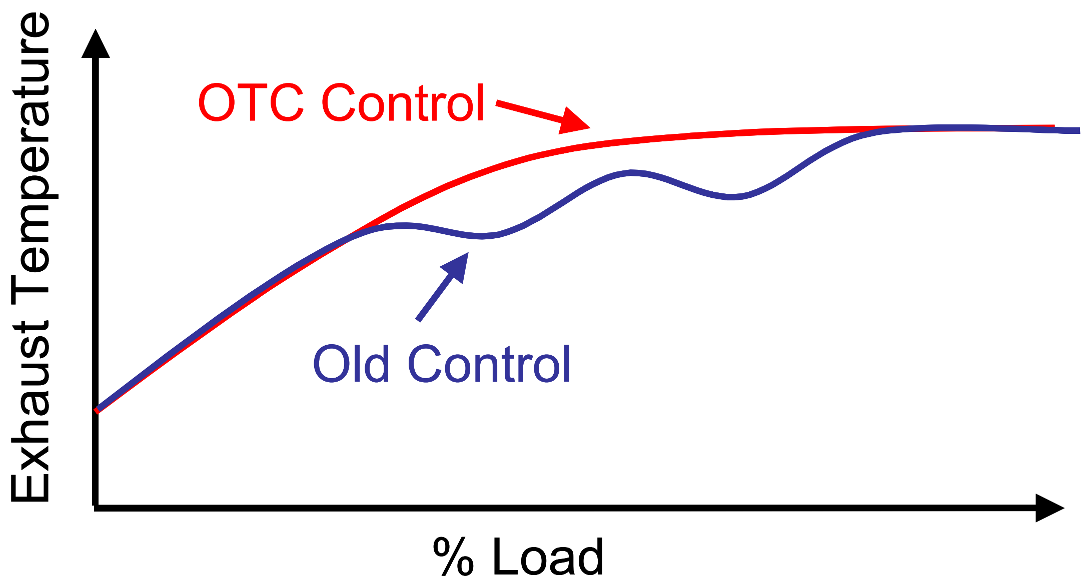

Figure 8. OTC Control Effect on Exhaust Temperature

Trip Factor Reduction

Maintenance intervals are calculated using operational based data in a mathematical formula. One component of this equation that accounts for rapid temperature changes experienced by the turbine hardware is the number and type of trips experienced. A "trip factor" is assigned a value depending on the severity of the trip ranging throughout the load range. 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.

Increased Combustion System Inspection Interval

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 over 50% on an hours based maintenance cycle from 8,000 equivalent base load operating hours to 12,000 hours, and by 100% on a starts based maintenance cycle (from 400 Equivalent starts to 800 Equivalent starts). As with the improved Trip Factor, this will also lengthen the interval between maintenance inspections while improving operational flexibility for units that incorporate upgrade package.

Component Design Enhancements

Design enhancements were incorporated to improve performance, mechanical durability and operational flexibility, while reducing emissions and life cycle costs (LCC). Performance enhancements were achieved in the combustor, turbine, and exhaust components. These include transition, turbine airfoil and exhaust diffuser/manifold aerodynamic redesigns, as well as leakage and turbine blade tip clearance reduction and cooling design optimization, with a NOX emission reduction primarily due to reduced cooling and leakage air flows. Mechanical durability improvements were made possible by turbine airfoil cooling optimization and mechanical design enhancements, and fourth stage blade and exhaust duct redesigns.

Compressor

Compressor sealing was improved by the use of a new seal design which provides better leakage control over the complete operating range .

Combustor

The combustor baskets, fuel nozzles (both pilot and mains) and fuel nozzle support housing were redesigned to improve mechanical integrity and reduce costs. The new components are designed to have a 12,000 hour or 800 Equivalent start inspection interval.

Continuous Dynamic Monitoring Systems have been implemented. Combustion dynamics sensors, which use transistors to measure dynamic pressure, were installed in the combustors to detect low and high frequencies. In the passive system, when dynamic fluctuations exceed a preset value, an alarm is sounded and the operator takes remedial action (such as unloading the engine or adjusting the fuel to the various fuel stages). In the Active Continuous Dynamic Monitoring System, when combustion instabilities are detected, the control system will tune the combustor away from the instability.

Transition

The transition was redesigned with optimized aerodynamic shape and enhanced cooling. It incorporated a three layer construction with an advanced TBC. This design is currently in service and has an excellent operational record. The new transitions are designed to have a 12,000 hour inspection interval or 800 Equivalent starts.

Turbine

Airfoils on the first two stages and the third stage vane were redesigned for increased efficiency, power output and service life and/or lower part/repair costs. The fourth stage vane and blade were redesigned for improved efficiency and maximum power output.

Exhaust System

The exhaust cylinder was redesigned to improve the pressure recovery and engine performance. Additionally, the two manways in the exhaust manifold were eliminated. This design change improved performance and component reliability.

IGCC Application

SGT6-5000F has been adapted for incorporation into IGCC plant and has been proposed for several new IGCC plants targeted for 2010 operation. These changes are primarily concerned with the design of a modified combustor and fuel nozzle. These components have been successfully rig tested and demonstrated excellent start up and full load parameters and emissions. The high maximum power output of the engine makes it ideal for IGCC applications.

Additional Flexibility Considerations

The SGT6-5000F, due to its design features and implemented enhancements, has other qualities that further improve its operational flexibility. It has no restrictions on inlet fogging or compressor water washing, both stationary and on-line. This ensures continuous high performance level during operation. It has no special inspection requirements at specified intervals for the compressor rotor, compressor blades or turbine disks. There are no special maintenance factors applied to its rotor. This freedom from operational restrictions further enhances its already good operational flexibility.

Future Improvements

SGT6-5000F gas turbine performance, reliability and operational flexibility improved and its emissions and life cycle costs decreased steadily since it's introduction. This was accomplished by planned development programs, which facilitated the introduction of new technologies and concepts, as well as a structured process for field technical issue resolution. The result was 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. Near term planned enhancements are listed below:

1. Further Starting Reliability improvements
2. Improved CO emissions turndown performance
3. Longer service/inspection intervals.
4. Lower maintenance cost and reduced fallout rate for service run components
5. Increased use of common parts with other Siemens gas turbine models

Summary

The 185 SGT6-5000F gas turbines in service have established an impressive service record in the 12 years since the first engine went into commercial operation. The total fleet hours have exceeded 2.5 million and the lead unit has more than 94,000 operating hours. During its commercial lifetime it has demonstrated an excellent operational reliability record. In May, 2005, the fleet 12 month rolling average Reliability and Availability was 99% and 95%. Due to a concerted product development effort, its simple cycle output power has increased from the introductory rating 135 MW to 200 MW and the efficiency from 33.6% to 38%. In two on one CC applications its net output power and efficiency are now 595 MW and 57%, respectively. On natural gas fuel its NOx emission is <9 ppm and on distillate oil NOx emission is <42 ppm with water injection. This evolution in performance and reduction in emissions has benefited our customers. Right from its introduction, SGT6-5000F units have operated in very different duty cycles: Peaker, Intermediate and Base Load. Due to its intrinsic design features that provide its components mechanical durability and long cyclic lives, the engine has proven its capability for flexible operation. In response to the current market demand for more cyclic and stop/start operation, design enhancements were incorporated into the SGT6-5000F to further improve its already good operational flexibility. These enhancements included: 1) improved starting reliability; 2) reduced starting time; 3) turndown ratio reduced to 50% load; 4) heating for inlet icing prevention ; 5) outlet temperature control system; 6) Trip Factor reduced from 20 to 8; 7) transition and combustor inspection interval increased to 12,000 hours and 800 starts ; 8 hot end component redesign for improved performance and reduced life cycle costs; 9) fourth stage turbine redesign for improved exhaust performance; 10) exhaust duct redesign for improved performance and cyclic life, 11) maximum power limit was increased from 186 MW to 235 MW and 12) ability to operate on LNG, syngas and high hydrogen content fuel.

The SGT6-5000F gas turbine has demonstrated its capability in the current market conditions by its performance, reliability, availability, low emissions and operational flexibility. It is now, and will be in the future, a very efficient and reliable low cost electricity generator, which is very important in changing market conditions and rising fuel prices.

References

1. Scalzo, A.J., Bannister, R.L., DeCorso, M., Howard, G.S., 1994, "Evolution of Westinghouse Heavy-Duty Power Generation and Industrial Combustion Turbines", ASME Journal of Engineering for Gas Turbines and Power, **118**, pp. 316-330.

2. Scalzo, A.J. McLaurin, L.D., Howard, G.S., Mori, Y., Hiura, H., Sato, T., 1989, "A New 150-MW High-Efficiency Heavy-Duty Combustion Turbine", ASME Journal of Engineering for Gas Turbines and Power, **111**, pp. 211-217.

3. Engel, R.J., Tyler, P.J., Wood, L.R., Entenmann, D.T., 1991, "Reliability, Availability Usage in the Development of the 501F Combustion Turbine and Auxiliaries" ASME Paper No. 91-GT-366.

4. Smed, J.P., Pisz, F.A., Kain, J.A., Yamaguchi, N., Umemara, S., 1991, "501F Compressor Development Program", ASME Paper 91-GT-226.

5. Entenmann, D.T., North, W.E., Fukue, I., Mugama, A., 1990, "Shop Test of the 501F: A 150 MW Combustion Turbine", ASME Paper No. 90-GT-362.

6. Entenmann, D.T., Hultgren, K.G., Smed, J.P., Aogama, K., Tsukagoshi, K., Umemura, S., 1992, "501F Development Update", ASME Paper No. 92-GT-237.

7. Entenmann, D.T., Dedousis, G.S., 1993, "The 501F Advanced Combustion Turbine Development/Testing/Implementation", Presented at the Rotating Machinery Conference and Exposition (Rocon '93), Somerset, N.J.

8. Coslow, B.J., Sestito, J.J., Ruiz-Castaneda, 1993 "Field Testing of a Westinghouse 501F Combustion Turbine", POWER-GEN International 1993.

9. Antos, R.J., 1995 "Westinghouse Combustion Development, 1996 Technology Update", POWER-GEN 1995.

10. Aoki, S., Tsukuda, Y., Akita, E., Terazaki, M., McLaurin, L.D., Kizzer, M., 1994, "Uprated 501F Gas Turbine, 501FA", Paper No. 94-GT-474.

11. Entenmann, D.T., Moradian, A., Merrill, R.K. Plotkin, P., 1995, "501F Design Update and FPL Lauderdale Operating Experience", Presented at ASME Cogen Turbo Power '95, Anakeim, CA.

12. Antos, R., Diakunchak, I., Wolfe, B., 2002, "Product Enhancements and Operational Updates on Advanced Technology W501 Gas Turbines", POWER-GEN International 2002.

13. Alba, J., Briesch, M.S., 1994, "Design Options for Enhancing the Performance of Combined Cycle Power Plants", POWER-GEN International 1994.