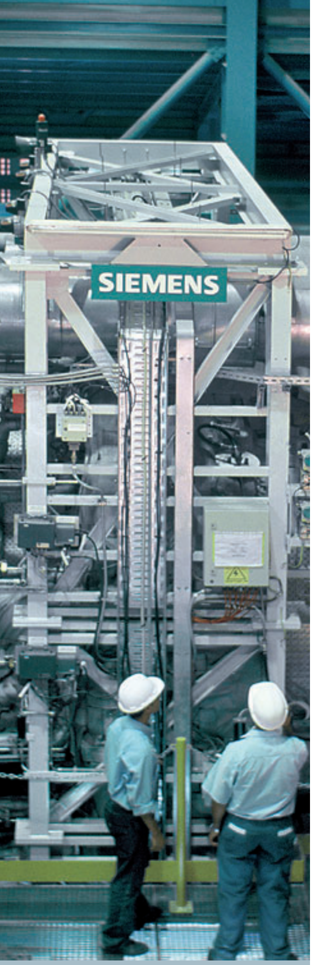

Latest performance upgrade of the Siemens gas turbine SGT5-4000F

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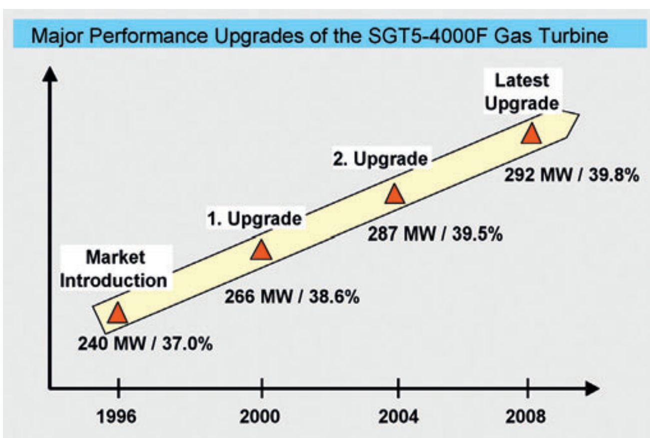
Introduction

Combined-cycle power plants using natural gas emerged as the outstanding trend in electricity production in the 1990´s. The trend is still continuing. Pacemaker for this development remains modern gas turbine technology. High efficiency, reliability and operating flexibility at low emissions and investment, together with short construction times provide extremely attractive value to the customer.

In response to the upcoming market needs and customer requirements, Siemens developed a further performance upgrade of the existing well proven SGT5-4000F gas turbine which has meanwhile more than ten years operating experience. The guiding principle was to use proven technology as the basis, while improving evolutionary cooling, blade coating and combustion technology. The figure below shows the major steps in performance upgrading over the time.



Aligned to the gas turbine development, a continuous optimization of the overall plant takes place. The gas turbine as key component of the Siemens Reference Power Plants is implemented in single- and multi-shaft configurations. Also the development of the plant is adjusted to operational experiences and customer requirements driven by changing market conditions.

Both the gas turbine upgrade and the corresponding plant optimization contribute to the performance improvement of at least 8 MW and 0.3 percentage points per unit in a combined-cycle power plant, which has already been demonstrated in the field. These figures bring about a significant increase in customer value of between EUR 13 and 15 million, depending on project-specific conditions. With the above-mentioned efficiency improvement, customers who operate the SGT5-4000F gas turbine in its latest version on the one hand save fuel and thus make an outstanding contribution to environmental protection. More than 100,000 tons of CO_2 could be saved over the entire lifetime of a power plant, a fact which helps to protect our planet. On the other hand, the plant can be operated more flexibly, this is also of value to our customers. In a situation where climate change and environmental concerns are important topics, our improved-design SGT5-4000F gas turbine can help to meet future challenges.

The mentioned performance upgrade has been developed in accordance with the well established Product Development Process (PDP) to create a competitive and reliable product focusing on market and customer requirements. The market introduction of this upgrade is also led by this process ensuring commercialization only after successful test and validation under real operational conditions in an existing power plant.

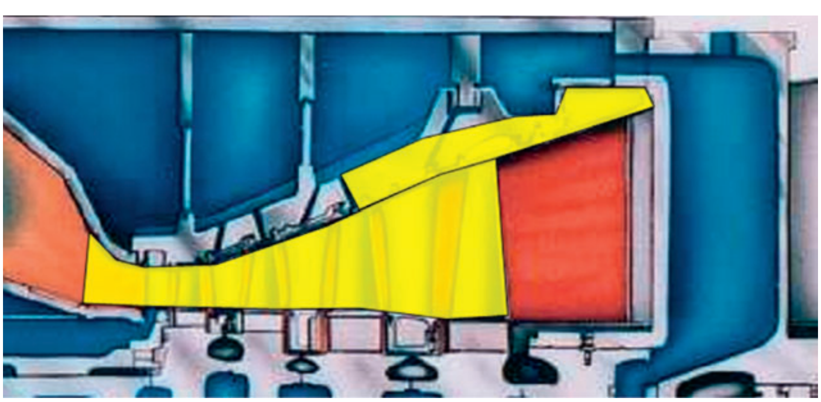
This paper shows the evolution of Siemens F-class gas turbine technology and the last performance upgrade together with the comprehensive testing and validation approach implemented for save and reliable engine operation

1 Upgrade Program

The requirements on heavy duty gas turbines in the global market are continuously increasing in terms of power output and efficiency as well as regarding the operating regime. Consequently the evolutionary design approach within Siemens gas turbine engineering uses current field experiences, identifies improvement potentials and provides design solutions based on latest material technology and design knowledge considering the increased requirements. A further requirement within the Siemens design philosophy is to limit changes of geometry and/or material specifications as far as possible.

The main targets for the latest design step of the SGT5-4000F were performance improvement, improved engine cycling capability as well as an extended service life for parts combined with an increased robustness. The main boundary condition for the upgrade is the ability to retrofit the new design to the former design. This ensures a fast, easy and reliable installation of the parts. The validation is reliable as it allows a direct comparison of the former and the latest design. Furthermore this boundary condition ensures that the vast majority of interfaces remain unchanged and additional risks are thus avoided. Consequently the engine is expected to operate at the same reliability level. And last but not least the ability to retrofit allows implementation of the new design in the existing fleet.

The outstanding reliability of the hot gas path components of the SGT5-4000F fleet contributes to a world class overall engine reliability. The parts' robustness is also a key to flexibilizing the operational regime of this gas turbine in future applications. Therefore the field experiences gained in the last ten years have been reviewed intensively in order to identify further potentials for improvement of the robustness (even if these potentials are only of local nature). The potentials for cooling air savings in areas which are excessively cooled represent a key to the engine performance improvement. The saved cooling air in the turbine causes a reduction of flame temperature and increased performance at the same time. The consequential reduction of the hot gas temperature in the front rows is beneficial for the service concept flexibility.

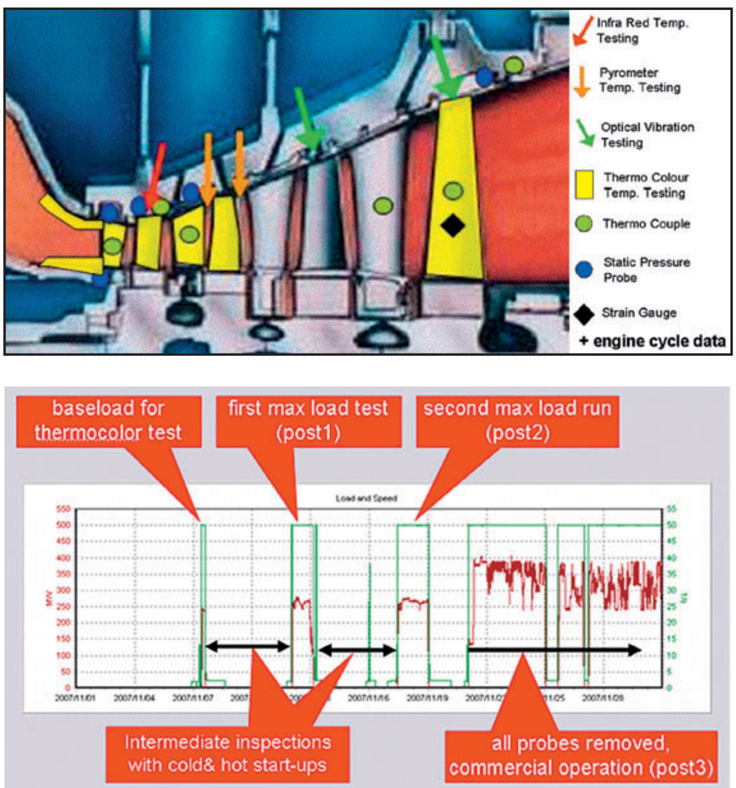


Upgrade components of latest SGT5-4000F design: Metallic combustor heat shields and turbine blades and vanes

The latest upgrade step was achieved by the following main technical measures:

- The application of the latest high performance thermal barrier coatings which have been proven in different Siemens gas turbine types and also in the Siemens Gas Turbine Test Bed in Berlin.
- The coating thickness distribution was modified and/or increased to a level which was proven in similar Siemens gas turbines for more than 50,000 EOH in total.
- Furthermore minor casting changes have been applied, while the proven and successful aerodynamic design remains unchanged.
- Already existing and proven design features such as Vane Sealing Plates have been applied to other components.

The performance improvement of the latest SGT5-4000F as well as the parts behaviour were validated in an extensive testing program in November 2007. The major testing means and locations are illustrated in the figure below.



Testing program for SGT5-4000F upgrade

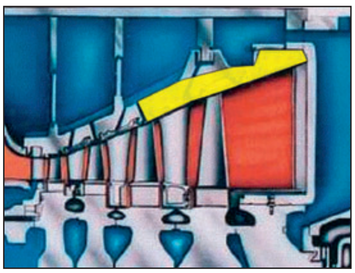
The latest upgrade design has been tested successfully under all relevant operating conditions, such as, base load and turn-down operation. Cold-, warm- and hot start-ups have been performed. The short testing periods have been followed by intermediate inspections. The inspections were used for thermal paint evaluation and adjustment of testing devices as well as for safety reasons. After completing the testing phase successfully, the engine was handed over to the customer for commercial operation. The long term validation phase started in November last year with two planned intermediate inspections after 2,000 EOH and 4,000 EOH in February and June 2008 respectively. As expected the upgrade parts were found in excellent condition during the first inspection. This sequence of inspections illustrates the conservative approach Siemens is following within the validation phase.

2 Detailed Design Description

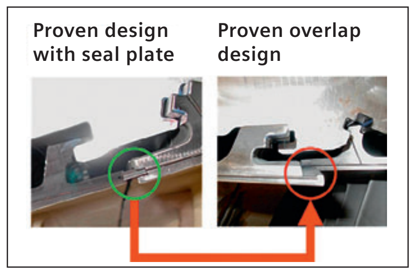
The following examples illustrate the evolutionary approach which uses local experiences and technology improvements and incorporates these in the latest upgrade.

Leakage air reduction

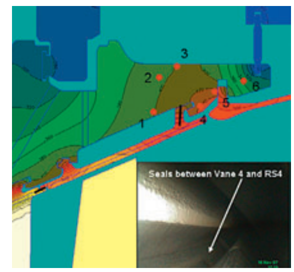
The modification of the sealing system of the rear turbine stages takes advantage of the experiences with the sealing concept in the front stages of the turbine which has been used since the first SGT5-4000F and its derivatives. The operating experience with this design feature has clocked up more than 5,200,000 EOH. The sealing effectiveness is well known from the design in the front stages and therefore the resulting leakage air reduction could be predicted accurately.



Modified area of turbine vane carrier and rear turbine vanes



Tranfer of proven features to other components



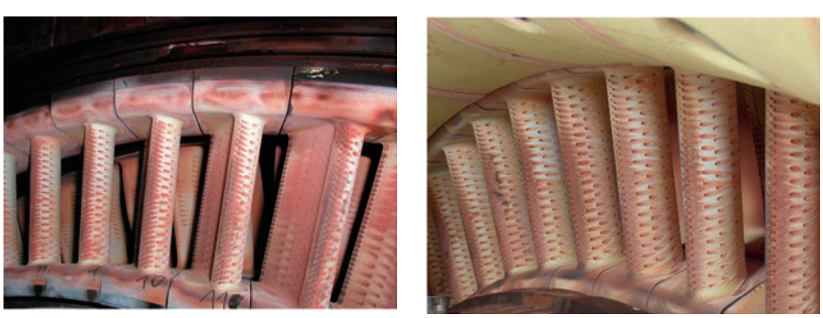
Whole engine model of rear turbine end

The impact of the new sealing concept on the thermal transient expansion of the turbine vane carrier and thus on the turbine clearance was predicted by means of a 2D rotationally symmetric whole engine model. Thermocouple measurements have been performed in order to validate the model and the measurement data clearly confirmed the design results.

Improvements of transition area between combustor exit and turbine vane 1

The design improvements of the transition area between the combustor exit and the turbine vane 1 benefit from the latest developments in thermal barrier coatings, field experience and proven design features from other parts.

The following figures show turbine vane 1 parts which have been in operation for approx. 25,000 EOH. The parts are in good condition and contribute to the excellent operational reliability of the fleet. However single engines show vanes with minor individual findings on the platforms and the potential to improve the part’s robustness in these locations.

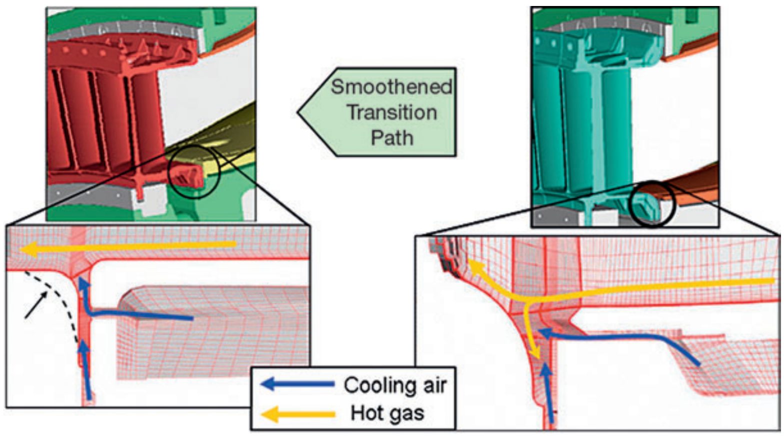


SGT5-4000F turbine; Vane 1 after 25,000 EOH of operation

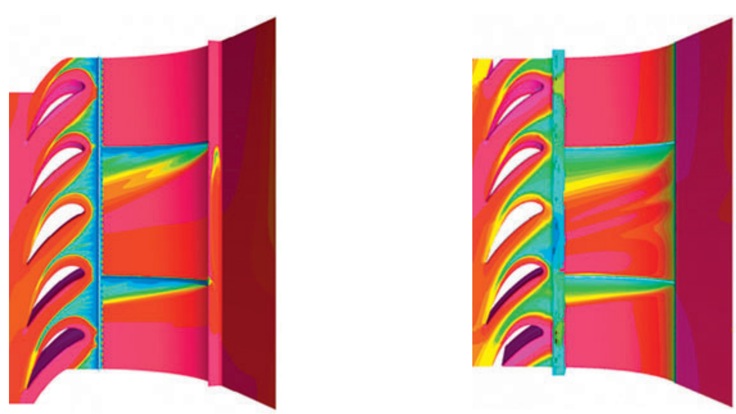
Consequently the design team's tasks were:

- Reduce the heat load of the vane 1 platform and improve the operational robustness.
- Save cooling air.

The leading edge is partly cooled by purging air which exits the gap between the combustor exit and turbine vane 1, as shown in the following figure.

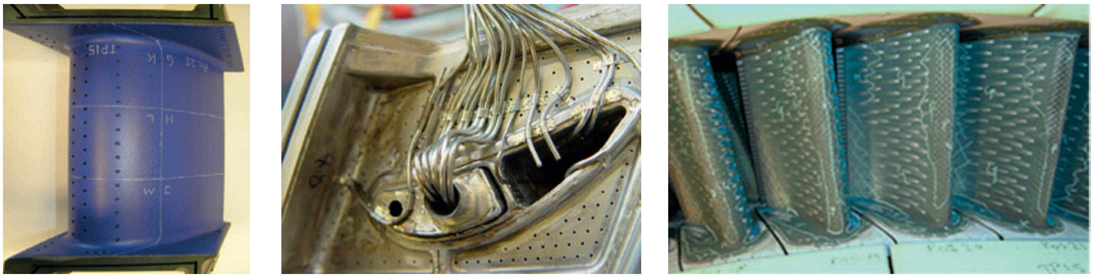


Latest Design *Former Design*



Temperature distribution on vane 1 platform
← Direction of flow

Through increased numerical capabilities the existing CFD and heat transfer calculation models could be matched to the field experience and confirmed hot spots of single vanes on the circumference of the turbine row one. This knowledge was the basis for an improved geometric design which allows for a reduction of purging air between the combustor exit and the turbine vane 1.



Vane 1: Coated with thermal paint, instrumented and after thermal paint test run

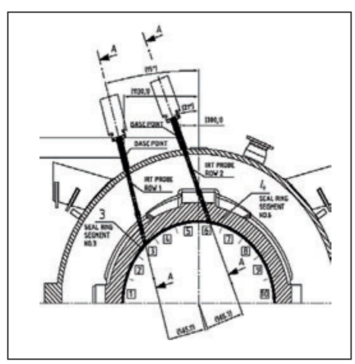
Several vane 1 parts were instrumented with thermocouples and thermal paint for validation purposes. The results of the thermal paint tests clearly confirm that hot spots are avoided with the new design. Furthermore the testing data shows further potential for cooling air saving.

Blade 1

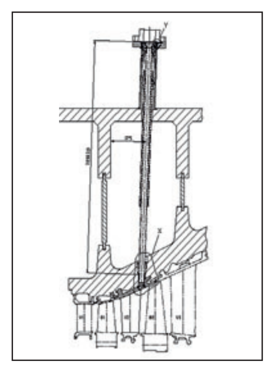
Similar to all other teams, the target for the blade 1 team was to save cooling air and increase the number of allowed operating hours and starts as well. The number of allowed starts for example was increased nearly by a factor of two.

This challenging target could be achieved by consequent review of field experiences, especially of frequent starters and application of proven technology. The review clearly indicated that the experiences from the SGT6-4000F fleet could be used, to adopt the 50Hz engine blade 1 casting accordingly and allow for start numbers which are proven already in the 60Hz fleet. The latest evolution in thermal barrier coatings was used to prepare the parts for operation at increased hot gas temperatures but also allow for cooling air saving, without compromising the cycling capability of the new casting.

Blade 1: Prepared for measurements and with stripes for identification during operation

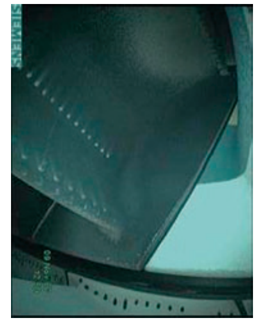


Schematic view on IR-camera installation

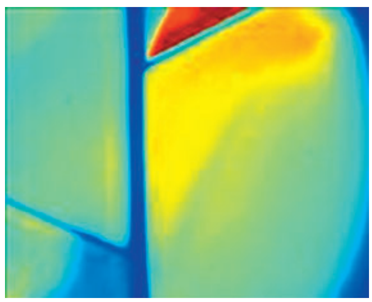


Pyrometry for temperature measurement of blade 2

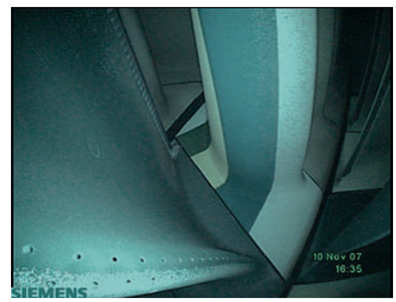
View on blade 1 pressure side during operation



Blade 1 with thermal paint and identification stripes after test run



Vane 2 and blade 2 platform during operation



Blade 2 with thermal paint and identification stripes after test run

Significant effort had to be undertaken in order to validate the highly thermally loaded blade 1 and blade 2. Siemens engineers used an infrared camera to measure the surface temperatures at different locations on the profile and the blade platform. The camera eye is able to change the perspective of view. The testing operation gave valuable results for the blade designers as thermal paint results could be directly compared to the IR-camera data or pyrometry data. Furthermore several experiences for improvement opportunities of the IR-camera itself have been collected.

Blade 4

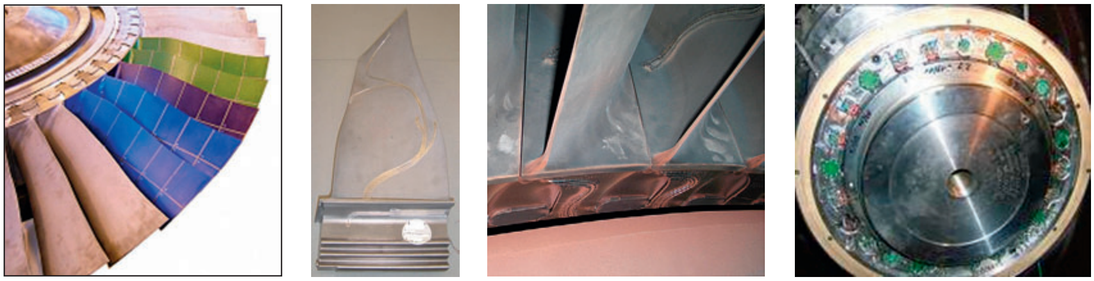
The target for the blade 4 team was to increase the part lifetime by up to 33% and provide a service-free part which requires increased robustness. This means that the long-term corrosion behavior and the creep of the part had to be improved.

In an extensive design concept phase 5 different options were investigated in order to meet the requirements. The team decided to stick to the proven aero-dynamic design and to apply a highly corrosion resistive coating. The additional coating weight was compensated by a mass re-distribution of the base material in order to keep the root-forces in the rotor disc unchanged at the proven level. The mass redistribution of the blade reduced furthermore the creep stress in the relevant areas of the blade which allowed the total service life to be increased..

The design change was mainly supported by improved casting technologies and a close collaboration of the design team with manufacturing experts and the experts from the vendor.

The modified mass distribution leads to a change of the blade frequencies which were validated on site. Optical blade vibration monitoring and strain-gage measurements using telemetry were used in a rainbow test to the standard and to the latest design. This was possible due to the ability to retrofit the design, which allows for direct comparison at absolutely same operating modes.

Also the testing data of blade 4 as the final part of the whole upgrade package clearly confirmed the design targets.



Instrumented blade 4 and blade vibration measurement device

3 Summary and Outlook

The SGT5-4000F gas turbine has been in the market for more than 10 years and the engine performance has steadily increased by evolutionary design improvements characterized by:

- step by step changes based on a well proven existing design
- high confidence and low risk through field experience and analytical design
- component testing in test rigs and validation in the field
- focused on retrofit-ability for field validation and service upgrades

The presented paper describes the implemented measures of the latest performance upgrade of the SGT5-4000F gas turbine. The respective performance data achieved by these evolutionary design improvements of the hot gas path components are shown in the following tables.

Performance data for the SGT5-4000F gas turbine and applications
*) All data for standard design at ISO ambient conditions

Siemens Gas Turbine	SGT5-4000F
Grid frequenzy (Hz)	50
Gross power output (MW)	292
Gross efficiency (%)	39.8
Gross heat rate (kj/kWh)	9,038
Gross heat rate (Btu/kWh)	8,567
Exhaust temperature (°C/°F9	577/1,071
Exhaust mass flow (kg/s)	692
Exhaust mass flow(lb/s)	1,526
Pressure ratio	18.2
Length x width x height (m)*	13x6x8
Weight (t)	308

Siemens Gas Turbine Package	SGT5-PAC 4000F
Net power output (MW)	288
Net efficiency (%)	39.5
Net heat rate (kJ/kWh)	9,114
Net heat rate (Btu/kWh)	8,638
Exhaust temperature (°C/°F)	580/1,075
Exhaust mass flow (kg/s)	688
Exhaust mass flow (lb/s)	1,516
Generator type	Air-cooled

Siemens Combined Cycle Power Plant	
Single Shaft	SCC5-4000F 1S
Net power output (MW)	423
Net efficiency (%)	58.4
Net heat rate (kJ/kWh)	6,146
Net heat rate (Btu/kWh)	5,842
Multi Shaft	SCC5-4000F 2x1
Net poer output (MW)	848
Net efficiency (%)	58.5
Net heat rate (kJ/kWh)	6,158
Net heat rate (Btu/kWh)	5,836

The latest upgrade of the SGT5-4000F hot gas path components has been tested successfully. The expectations have been fulfilled and the design even indicates potential for further improvements. This potential will be evaluated both through a detailed data evaluation as well as by compiling of mid term results. The upgrade is ready for broad market introduction within new apparatus business. It was successfully offered for a number of commercial projects and further units are expected for first firing shortly. The technology transfer for the service business application is underway. The successful long term trial operation under real conditions ensures that the upgraded SGT5-4000F remains a highly reliable and competitive gas turbine in the continuously growing F-class market.

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