Detailed Hot Section Mapping of Siemens SGT-600

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### Nomenclature

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>AF</td>
<td>Availability Factor</td>
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<tr>
<td>CBM</td>
<td>Condition Based Maintenance</td>
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<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
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<td>CMS</td>
<td>Condition Monitoring System</td>
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<td>CT</td>
<td>Compressor Turbine</td>
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<tr>
<td>Cx-factor</td>
<td>Stress factor</td>
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<tr>
<td>DLE</td>
<td>Dry Low Emission burner</td>
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<tr>
<td>EOH</td>
<td>Equivalent Operating Hours</td>
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<td>LCF</td>
<td>Low Cycle Fatigue</td>
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<tr>
<td>MD</td>
<td>Mechanical Drive</td>
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<tr>
<td>MTBF</td>
<td>Mean Time Between Failure</td>
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<tr>
<td>nBP</td>
<td>no Bypass (combustor bypass system turned off)</td>
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<tr>
<td>PG</td>
<td>Power Generation</td>
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<td>PT</td>
<td>Power Turbine</td>
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<td>RF</td>
<td>Reliability Factor</td>
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<td>SGT</td>
<td>Siemens Gas Turbine</td>
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<tr>
<td>TMF</td>
<td>Thermo Mechanical Fatigue</td>
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<tr>
<td>T51</td>
<td>Mixed turbine inlet temperature (according to ISO2314)</td>
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<tr>
<td>wBP</td>
<td>with Bypass (combustor bypass system turned on)</td>
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ABSTRACT
The 25-MW Siemens gas turbine SGT-600 (previously known as GT10B) is a mature product, which recently passed five million operating hours. The first engines were introduced in the mid-eighties, and currently over 230 SGT-600 have been sold. A four-year development project has been performed with the aim of enhancing knowledge of the SGT-600 lifing status, by mapping engine temperatures. The project started with an update of the models performed in 3D for CAD, aero, cooling and stress. Next, a thermo-crystal engine test at full load took place. 1741 thermo-crystals were used, measuring the gas temperature profile throughout the whole turbine and metal temperature distribution for blades 1-4 and vanes 1-2. The results were used to calibrate the aero, secondary air system and cooling models, in order to achieve more reliable stress calculations at full load. These models were also used as a base for sensitivity analysis concerning ambient temperature and power turbine matching. A second engine test using thermocouples was also performed. It covered a large number of cases, for example part and peak loads, start and stop cycles and effect of the combustor bypass system. The results were used to validate 3D calculations for the tested cases. The combination of computational models, measurements and field experience from the fleet has resulted in a substantial bank of knowledge of the lifing status of the SGT-600 turbine. One outcome of the project is that blade 3 turned out to have 50% longer life than was previously predicted. This and other conclusions will result in updated cycle-based maintenance plans, performance and design optimization, improvements of the Condition Based Maintenance product and possible extensions of the Time Between Overhaul.

INTRODUCTION
The SGT-600 was originally designed by the Swiss company Sulzer Escher Wyss and the machine was then known as Type 10. The first unit was in commercial operation in 1988. The rating was 22MW, which was considered as an introductory level. In 1990 this engine was transferred to Siemens Industrial Turbomachinery AB (at that time ABB Stal) where the first design change was to introduce a Dry Low Emission (DLE) burner with 25ppm NOx dry @15% O2 on gas, which now is standard (conventional burner is available as an option). The machine was then called GT10A.
A mature rating of 24.5 MW was introduced in 1992 (34.2% efficiency) and - excluding some minor changes - the rating has been the same since then. The machine was referred to as GT10B. Within the Siemens family the name of the machine today is SGT-600.

This twin-shaft machine is used both for Power Generation (PG) and Mechanical Drive (MD) applications. Over 230 units have been sold and the split between PG and MD is close to 50/50. The total accumulated operating hours is more than 5 million, whereof 80% is with DLE. The fleet leader is at the level of 140 000 hours.

This machine is now a well established product on the market with a high Reliability Factor (>99 %), Availability Factor (>97 %) and Mean Time Between Failure (>2000 h).

The AF, RF and MTBF figures are very important for a plant and every effort should be made to increase this further. This requirement, together with new state-of-the-art measurements and computational models, motivated extensive mapping to know the stresses of the machine for all operating conditions. The aims were among other things to optimize both cyclic and time-based maintenance programs. Consequently, new levels of AF, RF and MTBF are foreseen.

The hot-section mapping project was initiated in October 2004. An overview of the project is seen in Figure 2. The project started with an update of models performed in 3D for CAD, aero, cooling and stress. The project covered cyclic and creep lifetimes for turbine blades 1-4, turbine vanes 1-2 and CT discs 1-2. In 2005 a thermo-crystal engine test at full load took place. The results were used to calibrate the aero, secondary air system and cooling models, in order to achieve more reliable stress calculations at full load. A second engine test using thermocouples was performed in 2006. It covered among other things part and peak loads,
start, stop and trip cycles and the effect of the bypass system. The results were used to validate 3D calculations for the tested cases.

![Figure 2: Project overview.](image)

TESTS

The crystal test was performed in October 2005, and the transient test in December 2006. This section describes test instrumentation and tested cases.

**Thermo-crystal Test**

Temperature measurement with thermo-crystals is a Russian technique, developed at the Kurchatov Institute. Before the measurements, the thermo-crystals are exposed to neutron radiation. The radiation increases the distance between the atomic planes in the atomic lattice. When the crystals are exposed to heat, relaxation changes the atomic lattice, which is fixed at the highest temperature the crystals are exposed to. The relaxation is temperature and time-dependant, so by knowing the time and lattice angle from measurements by X-ray diffractometer, the temperature can be calculated. The Kurchatov Institute guarantees an accuracy of ± 12 °C. Oven tests were performed in Finspong to control this, and they confirmed the accuracy.

A 15-minute steady-state full-load test was performed. Thermo-crystals were used for measuring the gas-temperature profile throughout the turbine and metal temperatures for vanes 1-2 and blades 1-4. In total 1741 thermo-crystals were used, with a larger portion on stages 1 and 2. Besides the crystals and the standard instrumentation, the turbine was also
instrumented with additional thermocouples and thermal paint for blade and vane metal-temperature measurements. Figure 3 shows the distribution of thermo-crystals for metal temperature on blade 1 and thermal paint on vane 1. As seen in Figure 3, the components were covered with thermo-crystals.

![Figure 3: Metal temperature measurements on CT blade 1 (left) and vane 1 (right).](image)

Supplementary temperature and pressure probes were also installed in the secondary air system.

The gas temperature profile was measured throughout the whole turbine by thermo-crystals attached to small ceramic pins on different radii on the leading edges. This gave a unique picture of the temperature attenuation for each stage. Figure 4 shows how the gas-temperature profile was measured in front of blade 1.
Figure 4: Gas temperature measurement on ceramic pins on the leading edge of blade 1.

**Transient Test**
A transient and part load test was performed in December 2006. Tests were carried out for one week, covering for example:

- Transient start and stop
- Part loads
- Effect of combustor bypass for start, stop and part loads
- Peak loads
- Trip from 50% and 100% load

Tested cases were chosen to cover typical operation situations, for which the CMS should be able to predict lifetimes. Beyond the standard instrumentation, the engine was instrumented with additional pressure probes and thermocouples of type S and N measuring:

- Gas temperature in front of vane 1, vane 3 and in the exhaust
- Metal temperature on vane 1-2, blades 1-2 and discs 1-2
- Secondary air temperatures and pressure

In addition to the standard instrumentation, 225 thermocouples were used for metal temperature measurements, 36 were used to measure gas temperature in front of vanes 1 and
3 and 56 measurement probes were used in the secondary air system. On top of that, the engine was equipped with additional exhaust temperature probes with 6 thermocouples on different radii, to catch the temperature profile from the bypass system.

Figure 5 illustrates the gas temperature measurements. Figure 6 shows an overview of the gas turbine instrumentation.

The gas temperatures were measured by thermocouples placed in small tubes, attached to the leading edge mid-radius. The tubes protected against heat transfer by radiation.

Metal temperature was measured by thermocouples being flame-sprayed onto the metal surface. Telemetry was used for measurements on the disks and blades. In total there were 96 measurement points on rotating parts.
Figure 6: Instrumentation overview for Transient & Part Load test.

- $T_{\text{metal}}$ components
- $T_{\text{gas}}$ components
- SAS cavities $T_{\text{air}}$ & $P_{\text{air}}$
CALCULATIONS

The life of turbine components is predicted by both calculations and field experience. This section focuses on the calculation models used for the SGT-600, and how they are calibrated and validated to test data. The calculation work flow is shown in Figure 7. Mechanical Integrity analysis included TMF, LCF, creep and oxidation.

The calculations within this project can be divided into three sets:

1. Calculations before the tests, with calculated boundary conditions
2. Calculations after the Crystal Test
3. Calculations after the Transient & Part Load test

The project started in 2004 with an update of models for CAD, secondary air system, aero, cooling and MI, based on calculated boundary conditions. The turbine inlet temperature used in the global 3D aero calculation was estimated by the department for combustor development. Results from 3D aero and the SAS calculations were used as input for 3D-cooling calculations. The temperature fields from the cooling calculations were used as input in the MI calculations.

After the full load crystal test, all models were calibrated to measurement data. SAS models were calibrated to thermocouples in the secondary air system. Results from the SAS models were used as input to both 3D aero and 3D cooling calculations.

Figure 7: Calculations work flow overview.
Concerning 3D aero, the turbine inlet temperature in a global model was calibrated to measured gas temperature profile. However, the temperature profiles in downstream stages did not coincide with measured profiles to the needed accuracy. Therefore local models for each component were created and calibrated to measurements. A clear trend was seen; the measured gas temperature profiles in front of the components were flatter than the calculated one. That was altered during calibration of the local models. Gas temperature profile in front of blade 3 is shown as an example of this in Figure 8. Results from the local aero models were used as boundary conditions for the 3D cooling calculations. [1]

![Relative total temperature at blade 3 LE](image)

**Figure 8 : Relative total temperature at leading edge, Blade 3.**

Each instrumented blade and vane was cold-flow tested after the crystal test. The information was used to calibrate the flow characteristics in the 1D SAS models and the 3D thermal models. [2]

The calibrated aero and SAS results were used as input to the 3D thermal models. In general, calculated metal temperature agreed well with that measured on the airfoil mid-radius. On shrouds, platforms and airfoil suction sides however, calculated metal temperatures often differed from measured ones. This was due to difficulties predicting the mixing of sealing air with the gas flow in the CFD code. In general the influence of cooling air on platforms and
shrouds was larger than predicted. This was altered in the thermal model by decreasing the gas temperatures locally in these regions. During calibrations, the results from thermal paint and thermocouples were used to confirm the temperature field distribution from thermo-crystals.

The crystal test also showed in detail how the sealing air is mixed with gas on the suction sides of the blades. This is difficult to predict with 3D CFD. See the example in Figure 9, which shows the metal temperature difference before and after calibration to crystal measurements. The white circles indicate the predicted sealing-air mixing before the crystal tests. Other useful facts learned from these measurements were information about how effective the internal cooling air system is in different regions.

![Figure 9: CT blade 1. Δ T_{metal} = After minus Before calibrating to thermo-crystals.](image)

In addition to 100% load ISO calculations, the calibrated models were used for sensitivity studies concerning ambient temperature and PT matching.

Two examples of important MI results after the thermo-crystal test concern blade 1 and blade 3. The ambient-temperature sensitivity study showed that blade 1 was more sensitive to hot
ambient conditions than expected [3]. Therefore a separate project was initiated to improve the blade for these conditions. Blade 3 on the other hand turned out to have 50% longer creep life than that predicted before the tests, due to lower metal temperatures at mid-radius, see Figure 8 [4].

A comprehensive set of calculations were performed after the Transient and Part Load test. Calculations for part and peak loads, transient start, stop and trip were carried out, and also calculations to investigate the effect of bypass. 1D aero and SAS calculations were calibrated to pressure and temperature measurements in the secondary air system, for each case. Concerning 3D thermal calculations, the models previously calibrated to the thermo-crystals were used as a base for these new off-design calculations. The gas temperature profile was assumed to be the same in the two engine tests, except when the bypass system was on. Each off-design case was validated to thermocouple measurements.

Major focus was put on evaluating the effect of the bypass system. This is a unique system, designed to reduce CO-emissions at part loads, by increasing the flame temperature. Compressor air bypasses the combustion chamber at loads up to 95%, and then re-enters before the turbine. This will change the gas temperature profile. The bypassed air will press the hot combustion air towards the inner radius which leads to a warmer inner radius and a colder outer radius. An overview of the bypass system is seen in Figure 10.

![Figure 10 : SGT-600 bypass system overview.](image)
First, part load calculations without bypass were performed for 80 % and 90 % load. The gas temperature profile was scaled from the 100% load crystal case. The calculated temperatures were validated to measurement data, with good results.

Secondly, the effect of bypass for these part loads was investigated. For 80% load, the bypass had a visible effect on the metal temperature. New aero calculations were performed to simulate the gas temperature profile with bypass [5]. The aero results correlated well to measurements, see the example in Figure 10.

![Figure 11](image)

**Figure 11 : Vane 1 80% load. Gas temperature ΔT “With bypass” minus “No bypass”.

The new gas temperature profile was applied to the thermal 3D model, and the calculated metal temperatures were validated to measurement data with satisfactory results. The resulting temperature fields were used as input to MI calculations.

For 80% load, the bypass does decrease the component life somewhat for vane 1 and 2, due to more oxidation on the inner radius because of the higher gas temperature in that region. The effect of blade 1 is not significant, and for blades 2-4 the lifetime is actually increased, due to the colder temperature at the outer radius. [7]
At 90% load, all measurements showed that the bypass had no effect on the metal temperature and thus no effect on the component life.

Regarding the transient start, stop and trip cycles, the results agreed well with measured temperatures. Minor adjustments of the transient gas and cooling air temperatures were necessary to match the measured metal temperatures. The results from the transient MI calculations were used as a base for a new maintenance program based on cycles.

Peak load calculations were performed with stress factor (Cx-factor) 2 and 10. A stress factor of 2 or 10 means that the lifetime of the gas turbine is divided by 2 or 10 compared to the nominal lifetime. The criterion for stress factors 2 and 10 was an increase of T51 with 15 ºC and 40 ºC respectively. The aim was to learn more about the stress for each turbine component during these conditions. Noteworthy results were that for Cx=10, the individual creep stress factors were far below 10 for all components. Figure 12 shows an example for blade 3 at nominal ISO conditions.
Figure 12: Blade 3 peak load. $T_{\text{metal}}$ differences between 100% load and stress factor 2 (left) and 10 (right).

**BENEFITS FOR PRODUCTS ON THE MARKET**

The knowledge of the turbine life and temperatures is useful in a number of ways. A new maintenance program has been developed, with 30’ + 30’ equivalent operating hours, instead of today’s intervals of 20’+20’ hours. Another ongoing project using the output of the hot section mapping project is a lifetime extension program, to be used for engines that have passed 120’ hours. The lifetimes of a number of engines will be prolonged to 160’ hours. [8]

The Condition Based Maintenance product also benefits from these lifetime results and is continuously improved.
As mentioned above, the models and measurement data will also be useful in future site-related questions. Another plan is to use this information for further optimization of the SGT-600, and also for future uprating of the engine.

CONCLUSIONS

The 25-MW Siemens gas turbine SGT-600 is a mature product, which recently passed five million operating hours. A four-year development project has been performed with the aim of enhancing the knowledge of the SGT-600 lifing status, by mapping engine temperatures. Two engine tests with extensive instrumentation have been performed, covering a large number of cases, for example part and peak loads, start and stop cycles, trip and the effect of the combustor bypass system. The hot-section mapping of the SGT-600 has resulted in an extensive data base of measurements, and also a large number of steady state and transient computational models for aero, 3D thermal models and MI models for nominal cases and off-design. These models are all validated to measurements, and have already been useful tools in site-related questions.

This project has resulted in detailed information about the turbine metal-temperature distribution and the gas temperature profile throughout the turbine. Other important output is the improved understanding of how sealing air mixes with the gas flow, which is difficult to predict with CFD.

The hot-section mapping has significantly increased the knowledge of the lifing status for each turbine component. Turbine blade 3 for example, turned out to have 50% longer creep life than predicted before the mapping, due to lower metal temperatures at mid-radius than predicted before the crystal test. Another conclusion is that turbine blade 1 is more sensitive to hot ambient conditions than expected. Therefore a project was initiated to improve the blade for these conditions. The project also concluded that the bypass system’s effect on the turbine life is not critical.

Another output from this project is a new cyclic maintenance program, which is based on calibrated transient calculations. A lifetime-extension program has benefited from this project, as well as the Condition Based Maintenance product. Project calculations have also been used as a base for a new maintenance program with 30’ + 30’ EOH. In the future,
models and measurement data will be used for further optimization of the design and maintenance of the Siemens SGT-600.

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REFERENCES

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