Development & Operating Experience with SGT-800, a SIEMENS 45 MW Industrial Gas Turbine for various Applications

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Abstract

This paper describes the development steps of the advanced industrial gas turbine SGT-800 (former GTX100) - including initial driving factors, selection of design principles, performance & emission data, features/benefits, validation testing and commercial introduction. It also highlights the experience and status of the current fleet of plants in commercial operation as well as results from the latest inspections, carried out during year 2004/2005.

Introduction

The concept study of SGT-800 started year 1994 - a result of an extensive market survey of customer requirements, general market trends, potential future sales volumes and competition. Our conclusion from this survey was that there was room for another gas turbine in the 35-50 MW class, provided that it had attractive features and a strong organization to support the product. The selling volume was at a level of 100+ units/year with just a few strong players on the supply side. The forecast showed a rising trend for deliveries in the above-mentioned size range, with Combined Heat and Power/Combined Cycle-applications for electric power and hot water/steam production dominating in the long term perspective.

Since the commercial launch of the SGT-800 in May 1997, 32 units have been sold to 12 countries (Belgium, France, Germany, Italy, Latvia, Portugal, Russia, Sweden, Turkey, UK, USA and Venezuela). The accumulated number of equivalent operating hours for 12 units in commercial operation is 200 000+, with 9 units above 15 000 and the "fleet leader" 30 000+ (as per May 2005). Remaining units are in manufacturing or at site in erection/commissioning phase.

Driving factors influencing the final design outline

The customer requirement part of the market survey gave important input to the development project and these requirements coincides with those which are the focus of in a normal Total Cost of Ownership analysis.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>&quot;Buzz&quot; words</th>
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<tbody>
<tr>
<td>First investment cost for the Plant</td>
<td>Cash flow, IRR, NPV = design to cost (IRR = Internal Rate of Return, NPV = Net Present Value)</td>
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<td>Quick delivery from order to commercial operation</td>
<td>Cash flow, IRR, NPV = standardization, supply logistics</td>
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<tr>
<td>Reliability Availability Maintainability (RAM)</td>
<td>&quot;Uptime&quot;, design simplicity, durability, service concept</td>
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<tr>
<td>Cycle efficiency</td>
<td>Cost of fuel, &quot;greenhouse&quot;, CO₂ taxes</td>
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<tr>
<td>Emissions (NOₓ, CO, VOC, UHC, PM10..)</td>
<td>BACT, Air permits, hourly/daily/yearly caps (BACT = Best Available Control Technology)</td>
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<td>Operational flexibility without restrictions in the load range</td>
<td>Base/intermediate/peak operation, DLE simplicity, stable controls</td>
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<td>Full load rejection capability without trip</td>
<td>Single shaft for inertia, island mode capability</td>
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<td>Fuel capability</td>
<td>Wobbe-index range for gas fuel, gas/liquid fuel capability with quick changeover &quot;on the fly&quot;</td>
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<tr>
<td>Service life &amp; component life</td>
<td>Long time between inspections/overhauls, maintenance cost</td>
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All these requirements and "buzz" words were addressed in the design criteria for the development project.
Design considerations to meet the driving factors

Initially, there were a number of important technical "power string" decisions to make, based on the information available from the market and in-house knowledge. Some of these decisions were difficult ones with "pros and cons" to be evaluated and concluded.

- **Power Output**
  - Matching the market demand and the competition at the time of commercial launch and also having a growth capability in the design

- **Heat rate (efficiency)**

- **Emissions**
  - 15 ppmv/natural gas and 42 ppmv/diesel #2 (without wet injection) @ 15% O₂ in the 50-100% power range, with capability to go to single-digit in the future without change of DLE combustion system.

- **Pressure ratio and TIT.**
  - A pressure ratio/TIT combination selected to optimize the heat rate (efficiency) for the promoted applications. The importance of a low pressure ratio was also recognized as it is linked to the required engine gas fuel pressure and the possible need for a "boosting" compressor in the external gas fuel system (extra auxiliary power consumption).

- **1- or 2-shaft gas turbine.**
  - 1-shaft unit promotes simplicity in design (1 compressor, 1 combustion chamber, 1 turbine and 2 bearings), compactness and has high inertia to handle large load steps up and down plus island mode operation without trip.
  - 2-shaft is normally quicker to start, needs less starting power and is more suitable for MD operation (variable speed on power shaft).

- **Compressor**
  - Subsonic or transonic inlet? The use of a transonic compressor inlet results in fewer compressor stages for a given pressure ratio, i.e. a more compact compressor. The current trend today for compressors is to use a transonic inlet, however with a conservative Mach-number for surge margin and acceptance of fouling.
  - Electron Beam-welded (one-piece) or stacked rotor with heated central tie-bolt or hydraulically stretched tie-bolts on a radius.
  - EB-welded rotor gives low vibrations, straight-forward torque transfer, good control of blade tip clearances and still the possibility to replace individual blades in-situ, provided that casings in the compressor section have a longitudinal split.
  - Stacked rotor with tie-bolts allows casings to be non-split at compressor assembly/disassembly, smaller pieces to repair/replace in case of damage, better inspection possibilities at overhauls, requires detailed analysis to avoid loose fits between individual parts during start, steady state and shutdown.

- **Combustion system**
  - Conventional or Dry Low Emission or both concepts?
  - Conventional. Good fuel flexibility, higher emissions
  - DLE. Moderate fuel flexibility, lower emissions
  - Both concepts. Alternative variants on core engine and the rest of the package can contribute to lower availability for the overall fleet – more options to handle for the supporting organization.
  - Annular or can-annular type?
  - Annular requires less cooling air due to less hot surface area and gives a better flow inlet into the turbine. Simple cross-ignition during start-up. Acoustics due to flame
instability at ultra-low emission levels can be more difficult to cure. Maintenance concept must be adapted for single piece removal.

- Can-annular requires more cooling air, cross-over tubes for start-up alternatively one igniter per can, transition ducts for flow inlet to the turbine. Single cans can normally be removed without removal of the turbine module.

- **Turbine**
  - 3- or 4-stage?
  - **3-stages** less cooling air, slightly lower turbine efficiency, lower production cost.
  - **4-stages** more cooling air, slightly higher turbine efficiency, higher production cost.
  - The overall gas turbine efficiency becomes equal in the SGT-800 case.

- **Flexible service concept**
  - Service in situ without moving engine from its supports and/or engine swap, i.e. customer choice (please see picture below).

- **2-pole or 4-pole AC generator**
  - An early decision was taken to use a 4-pole AC generator for compact plant foot-print, sub-critical speed operation and lower production cost for the rated power.

- **Starting arrangement through the AC generator or separate arrangement on the power shaft**
  - A separate arrangement was favored to give flexibility on selection of generator brand and type and also the possibility to serve the mechanical drive market with alternative driven objects, without a major redesign.

The final selection of design principles for the core engine is shown later in this paper.
The General Arrangement drawing for the Simple Cycle version with dimensions is shown below.

In Combined Heat and Power/Combined Cycle, the exhaust is cut off at the flange downstream of the turbine diffuser and connected to either a diverter valve for by-pass stack applications or directly to the Waste Heat Recovery Boiler. The location of the exhaust silencer is often customized for CHP/CC-applications, depending upon site space and noise requirements. The Electrical and Control module seen on the right hand side picture is optional as a Central Control Room for the whole plant is often used to collect all E&C equipment at one place.
Main features of the SGT-800 core engine are illustrated below.

The design philosophy has been based upon simplicity, robustness and the use of proven technology. The SGT-800 has a frame design with a minimum number of parts in a single-shaft arrangement. The compressor rotor and the three-stage bolted turbine module form a single shaft, which rests in two hydrodynamic bearings of the tilting pad type. The 4-pole generator is driven through a speed reduction gear from the cold end of the gas turbine which allows for a simple and efficient exhaust arrangement. Modularization, few parts, long component life and easy inspection ensure long time between overhauls and low maintenance costs.

Data
Number of shafts 1
Drive shaft position Cold end
Type of compressor Axial flow, transonic inlet
Number of compressor stages 15 stages total (3 stages with variable guide vanes)
Number of compressor extractions 5 (3rd, 5th, 8th, 10th and 15th stage)
Pressure ratio 19:1 (at ISO and natural gas)
Type of turbine Axial flow
Number of turbine stages 3 (film cooled stage #1, convection cooled stage #2 and non-cooled stage #3)
Turbine inlet temperature 1180 °C // 2156 °F (ISO2314, average thermodynamic mixed gas temperature).
Engine weight 36000 kg // 79380 lbs
Engine rotor weight (incl. blades): 7860 kg // 17300 lbs
Rotor construction: Electron beam welded compressor, bolted turbine discs
Nominal engine rotor speed: 6600 rpm (after gear 1500 rpm/50 Hz & 1800 rpm/60 Hz)
with 4-pole Generator
Thrust bearing type: Tilting pad (forced lubrication)
Journal bearing type: Tilting pad (forced lubrication)
Type of combustion chamber: 3 P generation DLE (dry), annular combustion chamber
Number of burners: 30
Burners type: Single fuel or dual fuel
Nominal emissions:
- Natural gas: NOx: ≤ 15 ppmv @ 15% O2, CO: ≤ 5 ppmv
- Diesel #2: NOx: ≤ 42 ppmv @ 15% O2, CO: ≤ 5 ppmv
Performance:
- Simple cycle:
  - Nominal output, ISO, natural gas: 45 MW (net)
  - Nominal heat rate, ISO, natural gas: 9730 kJ/kWh (net)
  - Nominal efficiency, ISO, natural gas: 37.0 % (net)
- Combined cycle:
  - Nominal exhaust flow: 130,4 kg/s // 287,4 lbs/s (at ISO and natural gas)
  - Nominal exhaust temperature: 538 °C // 1001 °F (at ISO and natural gas)
The mechanical auxiliary systems for a dual fuel GTG set is shown below as an overview,
Development phases

The timeline of the development phases is shown above. After the first unit startup in November 1999 and the clearance of some initial issues a successful 500 hours endurance test was carried out in mid 2000. The plant in Helsingborg (Västhann) has been used during the summer seasons for validation of continuous improvements, mainly related to fine-tuning of emissions over a load range – but also for a "crystal test", which will be briefly explained later in this document (please see validation of design).

Validation of design

The initial design validation was done by cold and/or hot testing of core engine components and modules rather than a complete package to catch any issues as early as possible. The complete package was tested with 1550 extra instruments (approx. 200 through telemetry) at the end of 1999.

A number of component upgrades have been introduced since the original launch and a new fingerprint of the complete turbine section was taken during a comprehensive measurement in 2003.

Crystal test.
In mid 2003 a full engine test was carried out with a temperature-sensitive crystal technique, which gives an excellent mapping of the temperature distribution in turbine vanes and blades (Reference [1]). As it is possible to install many crystals on a single component, the temperature gradient can be established – which is essential for thermo-mechanical fatigue analysis of components with advanced cooling.
The instrumentation used in this test included more than 2300 measuring points, complemented with thermal paint. A total number of 1975 thermo-crystals, 237 thermocouples and 110 pressure taps were used for the test of the 3-stage turbine. The 1975 thermo-crystals measured both metal temperature (1855 off, yield rate during test 95%) and gas path temperature (120 off, yield rate during test 80%)

The metal temperatures were measured by installing crystals, using a thermo-cement technique to glue the crystals into the grooves and the gas path temperatures were measured by placing crystals on extended ceramic pins attached to the leading edge of rotating blades and stationary vanes.

The accuracy of the method is claimed by the crystal supplier to be +/- 10 C (+/- 18 F). This has been verified by blind tests for some crystals which had been put in an oven at our laboratory with accurate temperatures and holding times and afterwards sent away for evaluation. This experiment confirmed the claimed accuracy.

The measuring interval is from 200 C (390 F) to 1400 C (2550 F). For high temperatures the exposure time is limited and the full engine test was carried out for 20 minutes on full load.

The test showed that there was a good correlation between measured and calculated temperatures. For turbine blade stage 2, the largest difference found (max-min) for a single point was 35 C (63 F) and the average difference (max-min) for similar points at different blades was 10 C (18 F).

This test, discussed in detail in Reference [1], and the obtained results, enables us to further optimise the blade cooling for component life and cycle efficiency improvements.
Commercial introduction & status of fleet

The commercial launch to the market took place in May 1997 at four strategic places in the world and the first SGT-800 orders were placed in August 1998 (1 unit in Sweden and 2 units in France). The first commercial order reached full load in November 1999.

Since the commercial launch of the SGT-800 in May 1997, 32 units have been sold to 12 countries. The accumulated number of equivalent operating hours for 12 units in commercial operation is 200 000+, with 9 units above 15 000 and the "fleet leader" 30 000+ (as per May 2005).

The current Availability and Reliability is 95 % respectively 98 % (12 months rolling average, July 2004-June 2005) for the reporting fleet, which is in line with our expectations. These figures were achieved without any engine swaps. The starting reliability over the same period is 80%, with an improvement program ongoing to raise it to the "benchmark" 95%.

During the calendar period January 2000 - August 2005 the SGT-800 has had only two engine failures, one due to a loose honeycomb seal in turbine vane #2 (August 2000) and one due to a material deficiency (excessive carbon contamination) in one turbine blade #1 (January 2003), which caused the primary damage. This is a good record, considering the advanced technology level required to meet the stringent market requirements, which are continuously pushing the limits.

Maintenance Program and Inspection results 2004

Inspections and overhauls of the "core engine" are governed by an Equivalent Operating Hours (EOH) and an Equivalent Operating Cycles (EOC) formula on a Come-First basis. Continuous base load units are "triggered" by EOH, while frequent start and stop units are normally "triggered" by EOC.

The standard Maintenance Program over 120 000 EOH / 6000 EOC (approximately 15 calendar years) is shown below. The downtime for planned maintenance in a base-load application is ≤2% as an average over the 120 000 EOH period without use of a swap engine at Level B, C and D.
The vital hot section components (combustion chamber and blades/vanes), have a design life of 40 000 EOH/2000 EOC (with margin) and some of these components are coated, either by Thermal Barrier Coating (TBC) or by Pt-Al alternatively M-Cr-Al-Y, calling for "strip" and "re-coat" at half time. As a "strip" and "re-coat" activity takes time and short outages are essential, a change-out concept as outlined for "coated components" above is applied.

A swap of the complete "hot" turbine module is an attractive alternative for reduction of outage time at Level B, C and D interventions with some impact on the service cost.

Inspection results 2004/2005

The Level B-inspections at 20 000 EOH have been carried out on 6 units during year 2004/2005 according to the Maintenance program. Reconditioning of combustion chamber, turbine vane #1, turbine blade #1 and turbine vane #2 is scheduled at this event.

- Unit #1, season operation
- Unit #2, base-load operation
- Unit #3, season operation
- Unit #4, season operation
- Unit #5, base-load operation
- Unit #6, intermediate-load operation

The units were generally in good condition with only a few observations on parts not included in the ordinary Maintenance program - in excess of normal fouling, wear and tear:

- Unit #1
  - Small impact damages on 8 blades in compressor stage #12 - #15, excess wear on the end piece of one torch igniter (used for start-up), 6 burners had some material loss around the pilot gas injection holes. The deviating parts were corrected or exchanged as required.
- Unit #2
  - Dust inside the GT-enclosure due to failed ventilation inlet filter, dark color on tilting pads in bearing #1 and #2, some carbonized oil at bearing #2, some wear of the abradable coating in the stator at blade tips stage #5 to stage #15, some burners had clogging of pilot gas injection holes and minor cracks at this location, dust particles in the turbine area, small dents from foreign object on 4 blades in stage #2. The ventilation inlet filter, all burners and the 4 blades in stage #2 were replaced and the mineral oil was changed.
- Unit #3
  - 2 out of 3 pipes in the combustion chamber pulsation system broken, issues with propane ignition system, dents in caulked in sealing strips at bearing #2. The broken pipes were replaced and clamping changed, ignition system converted to run on natural gas (instead of propane) and sealing strips repaired.
- Unit #4
  - Oil leakage from bearing #1 through one of the struts in the compressor inlet, repaired by welding.
- Unit #5
  - No special remarks
- Unit #6
  - Loss of paint on the inlet bell-mouth, minor cracks in the external casing insulation, wear of cooling sleeves and heat shields in the turbine stator.
  - All parts with deviations were exchanged or repaired.
These observations were fed into the engineering department for further investigation of root cause and possible need for future improvement.

**Summary**

The introduction of the advanced industrial gas turbine and its route to maturity has been successful. After some initial "teething" issues at first startup in end of 1999, the commercial plants have been operating well. Some design updates have been done en route in the hot section part of the core engines for emission tuning over a load range and for increase of turbine stage #1 component life to the stated level in the Maintenance Program.

The latest Level B-inspections show that the life criteria of components are met as outlined in the Maintenance Program, with a few extra observations under investigation.

**References:**