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SGT-800 CONTINUOUS RELIABILITY, AVAILABILITY AND MAINTAINABILITY DEVELOPMENT IN CHANGING MARKET CONDITIONS

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Abstract

SGT-800 is an industrial single-shaft gas turbine originally developed for combined-cycle (CC) and combined heat and power (CHP) continuous and intermediate load applications. Its design features include the ability to maintain dry low emissions and a high exhaust heat flow on part load. The first fire of the SGT-800 industrial gas turbine took place in 1999. Since then more than 200 units have been sold for various applications including simple and combined cycle electricity production, CHP, industrial process applications and peaking power. The fleet leader has accumulated more than 100 000 Equivalent Operating Hours. SGT-800 has grown from its initial 45 MW, 37%/53% simple and combined cycle efficiencies to the current 50.5 MW and 38.3%/55.1% efficiencies through stepwise extensions of proven technology. Meanwhile total planned maintenance down time has decreased by up to 70% while availability and reliability have been improved and the specific maintenance cost has been reduced. In order to improve gas turbine reliability, availability and maintainability (RAM) and to adapt the gas turbine to changing market demands and new market segments there has been a continuous joint development of the gas turbine hardware and its maintenance concept.

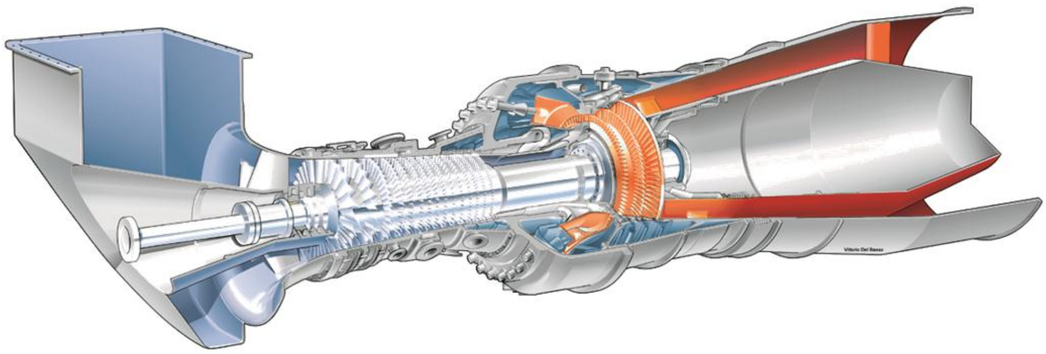

Figure 1: The SGT-800 gas turbine

1 Nomenclature

AF *Availability Factor* – probability that a unit, major equipment or component will be usable at a point in time [1]

CC *Combined Cycle* – Power plant configuration where the waste heat from the gas turbine is used to generate steam to a steam turbine thereby considerably increasing the plant electrical efficiency

CHP *Combined Heat and Power* – Power plant configuration where waste heat from power production is reused for other purposes e.g. district heating, process steam generating. CHP applications can provide thermal efficiencies in excess of 90% under the right conditions.

DLE *Dry Low Emissions* – combustion conditions that deliver low levels of nitric oxide and carbon monoxide pollutants without the addition of steam or water

EOH *Equivalent Operating Hours* – Normalized operation taking into account the impact of specific operation conditions on maintenance intervals

MW *Megawatt* – electric power output

Thermal efficiency Measure of the performance of a thermal process expressed as the total useful energy output divided by the total energy input.

RF *Reliability Factor* – probability that a unit, major equipment, or component will not be in a forced outage condition at a point in time [1]

SC *Simple Cycle* – Power plant configuration where the waste heat from the gas turbine is not used for energy recovery or other useful work

KPI *Key Performance Indicator* – Measure on how well a product or an organization performs. A gas turbine KPI can for example be its thermal efficiency or reliability.

SR *Start Reliability* – probability that a unit will reach an in-service state through a starting attempt to the in-service state within a specified period

MTBF *Mean Time Between Failure* – Average time between events which initiate a forced outage

1 Product and market overview

SGT-800 was originally developed as GTX100, a 43 MW gas turbine optimized for high reliability, long overhaul intervals, good turndown characteristics, excellent combined-cycle performance and top-of-the-line dry low emissions performance. Prototype operation began in 1999 and was quickly followed by the first delivery units. In 2003 simple cycle power output was increased to 45 MW, followed by the 47,5 MW rating in 2007 and the 50,5 MW rating in 2011. In 2004 several insurance companies decided that SGT-800 was mature enough to allow insurance without special restrictions. An additional performance milestone was the confirmation of 94% combined heat and power thermal efficiency.

Table 1: SGT-800 product overview

	No. units†	SC Power [MW]	CC Power [MW]	SC eff. [%]	CC eff. [%]	Main design changes
43 MW (intro)	25*	43		~37		Original
45 MW (mature)	35	45	63,9	37	53	Minor design tuning
47,5 MW	108+6¤	47,5	66,5	37,7	53,8	Increased mass flow, hot section tuning
50,5 MW	25	50,5	71,4	38,3	55,1	Increased mass flow, new turbine stage 1 & 3

* = All modified to 45 MW version.
¤ = Units upgraded from previous ratings.
† = May 2013 numbers

During its current life span SGT-800 has seen a major market shift with the historical base load – peaking market changes into a more diverse and challenging market with intermediate, load following and part load regimes becoming much more important. The increased importance of start performance led to an increase in the internal start reliability requirements in 2005 to >95%, a goal that was met within two years. A series of other modifications were also introduced to increase performance in cyclic duty. A summary of operation KPIs and fleet size development are given in Table 2.

Table 2: SGT-800 product KPIs

	AF [%]	RF [%]	SR [%]	MTBF [hours]
Total fleet (2004)	93,9	99,2	72,5	*
Total fleet (2006)	96,1	98,3	91,8	1376
Total fleet (2008)	95,5	98,9	97,1	1642
Total fleet (2010)	97,7	99,9	96,8	5280
Total fleet (2011)	96,9	99,8	97,7	4658

* = No comparable figures available

2 Gas turbine maintenance development

Together with the product performance increase two aspects of the maintenance concept have also been improved. Basic maintenance is designed to fit most customers and will in general ensure safe operation even under quite harsh conditions. The hot section disassembly interval for basic maintenance is 20000 equivalent operation hours. For customers that operate under near-base-load conditions, with at least sixty running hours per start or approximately two starts per week on average, limited running time on liquid fuel and ensure adequate inlet air quality at all times, hot section inspection disassembly intervals can be extended to 30000 equivalent operation hours. This results in an availability increase by around 0.65% with no negative impact on reliability. This improvement was realised through careful examination of actual causes of unreliability on SGT-800 and other gas turbines, 3D aerodynamics and component mechanical calculations and full-scale engine tests in accordance with in-house calculations and validation requirements. The integration of collective experience and improved maintenance technology into the single lift gas turbine package allows further down time reductions if requested.

Necessary requirements to reach 30000 EOH hot section inspection interval with unchanged reliability have been identified and include minimum requirements on hardware, inlet air filtration system capability, maintenance routines and mode of operation. All units delivered with 47.5 and 50.5 MW ratings do typically meet the requirements or can be modified to meet them.

Table 3 below shows examples of standard maintenance for SGT-800 under various conditions. In practice very few units will be operated according to the standard conditions over its life span. Maintenance is therefore tailored to the needs for each specific unit to optimize operation for maximum life cycle profit.

Table 3. SGT-800 maintenance KPI development†

Maintenance concept†	Relative down time [%]
Basic 1-shift *	100
Basic 2-shift	77
Basic 2-shift module swap	67
Extended 1-shift	67
Extended 1-shift 50.5 MW	57
Extended 2-shift	53
Extended 2-shift module swap	47
Extended single lift	22

† = Actual figures will vary dependent on actual unit configuration, working conditions etc.
* = Reference conditions.

The second area of development was a major improvement of the maintenance tool sets. Experiences and suggestions from field service personnel and engineering identified a series of opportunities for improvements that resulted in lighter, fewer and more flexible and efficient maintenance tools. The primary benefit is that the same tools can now be used for many more components and component versions while they are at the same time lighter, safer and generally easier to work with. This reduces the need to keep multiple tool sets available, allows more efficient yet safer on-site maintenance work and makes it much easier to provide correct replacement tools should a tool be damaged. The benefits of these improvements can for example be observed in the shortened maintenance times for the 50.5 MW product version and as improvements in Siemens internal work processes.

The positive operation statistics and the confirmed durability of the main structural parts also allowed a considerable extension of the standard maintenance with maintained reliability and availability and foreseeable maintenance cost.

2.1 Single-lift installation

In order to simplify gas turbine installation in remote environments and considerably reduce commissioning time Siemens has developed the single-lift package with reduced weight and a 50% footprint size. The single-lift package is delivered to site in a single skid-mounted package including gas turbine, gearbox, alternator and mechanical auxiliary systems with turbine controls, generator control panel, control centre for package motors and variable-speed drive for starter motor normally supplied in an external control module or as separate items. In addition to the shortened erection time the package enables features such as string test ability, quick engine exchange and considerable footprint reduction. Cold-climate and hot-climate options are available if required.

3 Maintaining highly reliable operation

While robust and easy-to-maintain design can ensure suitable conditions for high reliability, user feedback regarding every little disturbance is what makes it possible to maintain very high reliability for any equipment throughout its life cycle by ensuring that lessons learned are distributed among end users and that operation and maintenance instructions and spare parts recommendations are continuously improved. The user feedback further helps making sure that the implemented actions had the desired effect and is also a source of ideas for further improvements in particular when it comes to daily operation and maintenance. A selection of improvements driven by fleet feedback and changing market requirements are described below. The backbone of the successful improvement work is the collection of customer real-life operation experience, bringing isolated incidents and small pieces of information into the big picture and ensuring that the correct conclusions will be drawn. To meet future product expectations this hard work must continue, bringing new technology, solid knowledge and modern IT together.

3.1 Operations feedback and monitoring

Siemens product development is governed by market driven improvement requirements, customer requests, field service findings and operating statistics. Swift and adequate management of product non-conformance is ensured using a six sigma process adapted for gas turbines called the Product Improvement Process. The process dictates how to collect, categorize, analyse, mitigate and confirm the successful closure of suspected deficiencies. Each suspected deficiency is traced using so-called fault reports, and short term and long term mitigation strategies are implemented as modification orders that are directed towards the specific affected units. Dependent on the source of the disturbance the modifications may be hardware and/or software changes for the specific unit(s) concerned, generic design improvements, upgrade packages, improved maintenance instructions or any combination thereof. Priority and timing of improvements is determined by the severity of deficiency consequences, the impact on equipment operability and impact on product KPIs. A summary of accumulated fleet operation experience is found in Table 3.

Table 3: SGT-800 operating fleet and experience base

	Units in operation	# sold units	Total running hours [millions]	Total starts [1000s]	Accumulated number of major overhauls
Total fleet (2004)	11	28	0,15	3,1	0 (5 hot gas path inspections)
Total fleet (2006)	19	48	0,3	5,0	(19 hot gas path inspections)
Total fleet (2008)	36	85	0,65	8,8	5
Total fleet (2010)	53	116	1,3	12,5	15
Total fleet (May 2013)	>100	193	2,2	20	27

3.2 Combustion system – pulsation damping and operations and fuel flexibility

SGT-800 has an annular combustor with 30 dry-low-emission fuel premix burners of single-gas or dual-fuel design. The original SGT-800 combustion system fulfilled aggressive emissions targets when operating at base load conditions but was sensitive to external operation disturbances and combustor humming that sometimes initiated emergency shut downs in particular when operating at less typical conditions and with non-standard fuels. Combustor repair requirements were occasionally also much more extensive than originally expected. A series of improvements of hardware, controls and monitoring were developed to address some of these issues.

The different hardware and software generations and their main characteristics are listed in Table 4.

Table 4: SGT-800 combustion system generations

Combustor	Burner	Introduction	Burner characteristics	Combustor characteristics	Controls features
Original	Original	Original	2-way gas	100% air combusted	Original
Gen-2	Gen-2	2006	3-way gas	Passive damping	No staging, improved pulsation monitoring
	Gen-3	2009	Pilot premix		Improved response to disturbances
Gen-3	Gen-4	2012	Gen-2 pilot premix	Exhaust ring redesign	Miscellaneous

3.2.1 Combustor damping and more robust pulsation monitoring

The first and most noticeable reliability improvement was the introduction of a modified combustor in 2006 that featured passive pulsation damping in the front panel. The modified combustor was implemented together with improvements of the pulsation monitoring system making it less sensitive to condensation and temperature gradients to increase measurement reliability. These design improvements have direct reliability impact since it eliminates the root cause of the most frequent operation disturbance. The main design improvements were supported by stepwise modifications of the control and monitoring systems that are further described below. Figure 2 shows emergency shutdowns caused by various systems during the time period when the improved combustion system was implemented into the operating fleet. As can be seen pulsations went from a maximum of 35% of all emergency shutdowns to around 5%. At the same time, as shown in Table 2, the mean time between operation disruptions increased from around 1500 hours to more than 4500 hours.

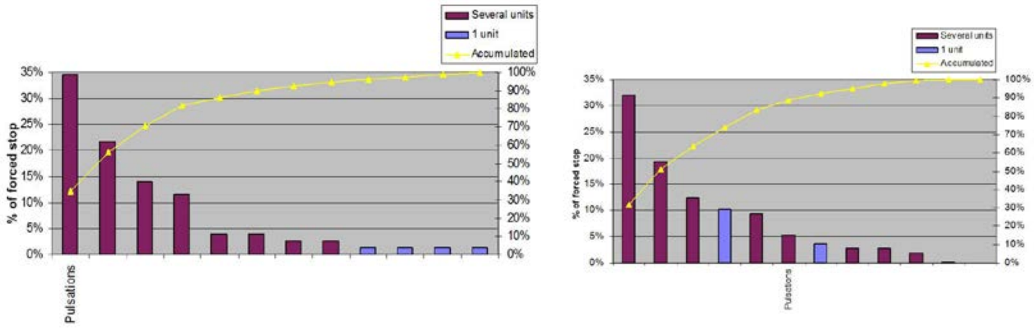

Figure 2: Change in emergency shutdowns caused by combustor pulsations from 2008 to 2011

3.2.2 Improved fuel and turndown flexibility and part load emissions

SGT-800 has a third-generation dry low emission DLE combustion system with a lean pre-mixed main flame supported by a pilot flame to stabilize the main combustion zone from outside. The original combustion system was optimized for near-full-load operation and required burner staging to allow acceptable emissions levels down to 70% load for some fuel and running condition combinations. Investigations showed that natural gas characteristics could be improved by adding a third fuel supply flow in addition to the main and pilot flows, namely central gas, to stabilize combustion. The central gas is released in the centre of the burner mixing tube and provides an “anchor point” for the main combustion flame thereby vastly reducing the need for pilot air to stabilize the flame from outside.

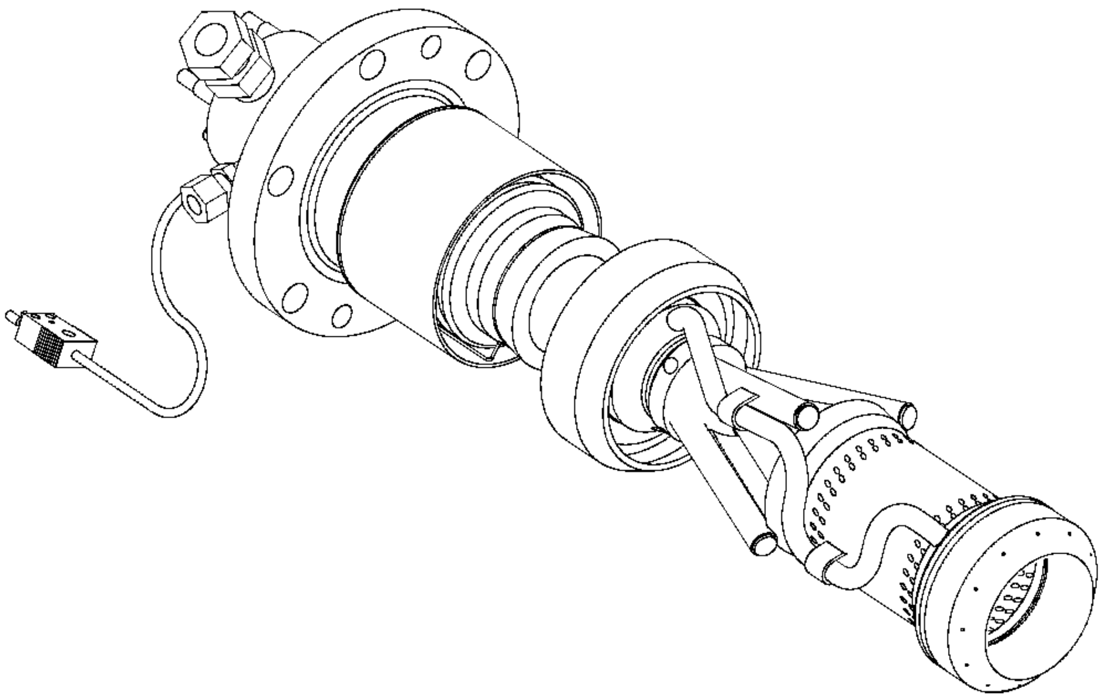

Figure 3. 2nd generation SGT-800 DLE burner

With this improvement stable low emission operation without burner staging was possible down to around 70% load resulting in a considerable increase in fuel flexibility. This improvement was implemented as part of the second-generation SGT-800 burner.

To further reduce emissions performance it turned out that it was necessary to premix not only the main fuel supply but also the pilot air. This improvement was released in 2009 and allowed full load emissions of nitric oxides, carbon monoxide and uncombusted fuels to be maintained down to around 50% load. Further details of some of the background research work can be found in [2].

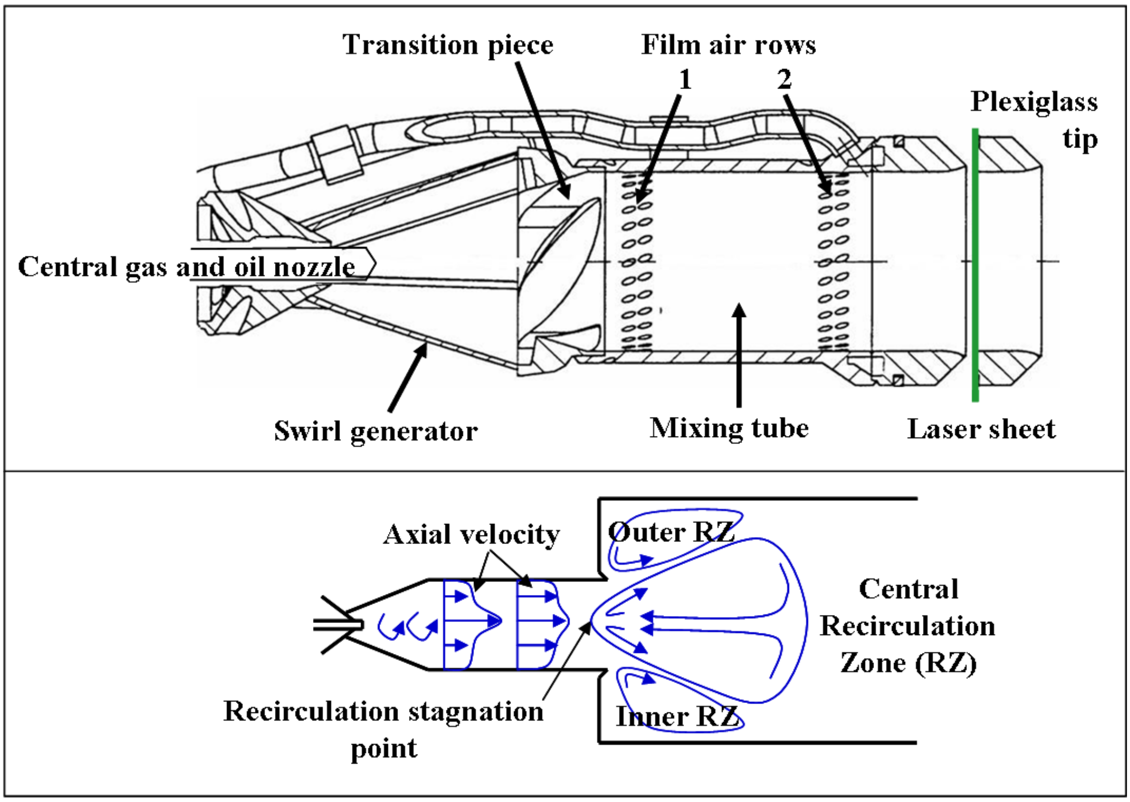

Figure 4. Cross section of test setup during validation tests of central gas burner

3.2.3 Resistance to external disturbances and condition changes

Changes in fuel composition and supply pressure, power requirements, grid disturbances like load oscillations, grid frequency variations, loss of grid connection and even large weather changes will move the operation point of the gas turbine. While the original engine protection system prevented major equipment damage, the allowable operation regime sometimes became very small and operation could sometimes not be maintained without on-site tuning and increased emission levels or not at all. The introduction of second-generation combustor resulted in a much more disturbance-tolerant environment, and the introduction of third-generation burners in 2009 together with more reliable pulsation monitoring systems opened up the opportunity to use feedback from the pulsation monitoring system to fine-tune the pilot flow level on-line to compensate for disturbances thereby allowing operation at lowest possible nitric oxide emission levels within a large operation regime. The narrow-band pulsations frequency monitoring introduced in 2010 and a self-check ability that confirms that readings are “realistic” made it even easier to quickly detect early symptoms of pulsations, further increasing the performance of the system and introduced into the combustion pulsation monitoring system. In 2010 the combustion stability was further improved by the addition of narrow-band pulsation frequency monitoring.

3.3 Variable guide vane mechanism

Variable guide vane systems are used as one of the mechanisms to control the gas turbine operation point by effectively changing the inlet area to the gas turbine compressor. It is particularly important to ensure adequate compressor operation during starts and stops and off-design operation conditions. In the SGT- 800 the variable guide vane system is also part of the emissions control system.

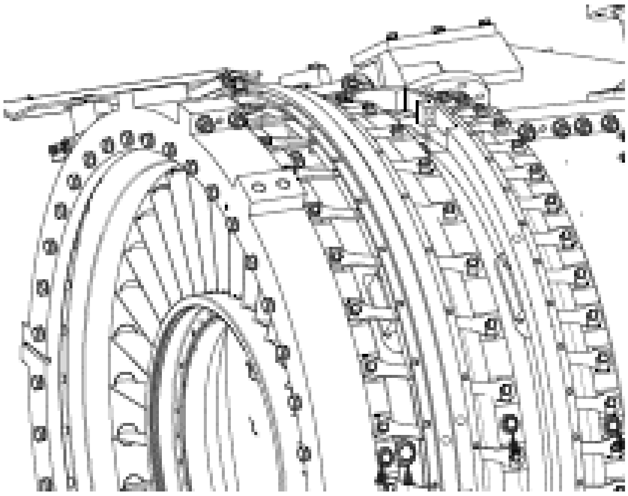

Figure 5. Variable guide vane mechanism

The variable guide vane mechanism is a system of levers and adjusting rods that connect the three stages of variable guide vanes to the single actuator that moves the guide vanes to the desired position as function of load. Based upon customer operation experience feedback, showing sufficient operation disturbance to motivate further work, root cause investigations were initiated for the variable guide vane system in a similar way like for the combustion system.

The investigation revealed three different faults behind the disturbances, namely wear of system components, drifting variable guide vane positions, and the system getting stuck in one position unable to move. The information also revealed that the reasons were highly interrelated and generally showed that the system could, dependent on operation, be sensitive to corrosion, high amounts particles in the air and the selection of compressor washing detergents to various degrees. The outcome was modifications of the hardware, control logics and maintenance procedures.

4 Repair, parts cost and inspection requirements improvements

The market change from mostly base load to intermediate and part load operation profiles means of course that component loads and damage mechanisms of parts have changed in comparison with initial foreseen requirements. In particular most parts are nowadays much more exposed to fatigue than initially anticipated. While design life times in general were met with acceptable confidence, repair yield particularly in operation with many starts has not been satisfactory, and inspection requirements for peaking units during primarily the latter part of the standard maintenance cycle and beyond was recognized as not meeting internal and external expectations. Mitigation strategies and design improvements were developed to reduce the inconvenience and to adapt the current design to current and anticipated future market requirements. There is also a general desire to cut costs of new parts as well as parts repairs to further increase the equipment value and the user's Life Cycle Profit.

4.1 Burners and combustor

While the original SGT-800 burners fulfilled emissions requirements it was very expensive especially in dual fuel version. Considerable investigations resulted in improvements of the burner tip section including the addition of Thermal Barrier Coating, TBC, and material changes to increase the ability to cope with fatigue damage due to many more starts and stops than anticipated. The second generation of burners showed higher repair yield, resulting in reduced maintenance cost and the need for fewer sets of burners during the equipment standard maintenance cycle. In many cases this configuration was backwards compatible and could be implemented as a repair upgrade to previous burners through a replacement of the burner tip. However there was still potential for considerable improvement of in particular repair cost in applications with many starts. In the design of the fourth-generation burner detailed studies, including feedback from operation and engine tests, identified the potential for even further improvements of the burner tip section. As a result this burner can serve for longer intervals, be repaired multiple times with excellent repair yield and is much more durable than its predecessors in cyclic operation.

The SGT-800 combustor has a similar history, meeting requirements for the intended application but with unsatisfactory repair yield and high sensitivity to combustor humming. The second combustor generation was released together with the second generation of burners in 2006, providing adequate repair yield through the redesigned rear end wall providing both increased fatigue durability and passive pulsation damping, and redesign of attachment features prone to fatigue cracking. A third combustor generation was released together with the 50,5 MW rating, providing further improved repair yield in particular in applications with many starts primarily through design modifications in the exhaust area.

4.2 Turbine hot parts repairability improvements

In addition to tracking the performance of the gas turbines Siemens also monitors repair yield and scope of repair work for hot parts that are considered potential objects for repair, e.g. turbine blades and vanes. Again, while repair yield was in general acceptable in base load operation, both scope and yield were not at desired levels in intermediate and daily starts applications. Further some findings regarding e.g. thermal barrier coating behavior and the failure patterns of post-service single crystal superalloy blades did not match expectations and required considerable development to understand as previously presented in e.g. [4]. In order to make the repairs as efficient as possible from customer and Siemens perspective many different improvements were investigated. The improvements introduced so far include both redesigns to increase fatigue resistance, modifications of repair materials and coatings to make repairs simpler to perform while meeting or exceeding original design durability requirements, and modifications of the overall maintenance to make maximum use of the improvements. Figure 6 shows a section of the SGT-800 turbine inlet while Figure 7 shows a modification introduced to reduce the tangential stiffness of turbine guide vane 3. With the introduced modification fatigue inspections of this part will not influence the hot section maintenance intervals. The stepwise measures taken to design and implement suitable improvements ensure transparency in technology evaluation and the ability to rapidly and adequately respond to unforeseen deficiencies. At the same time this makes it possible to make improved technologies available to customers at an acceptable rate.

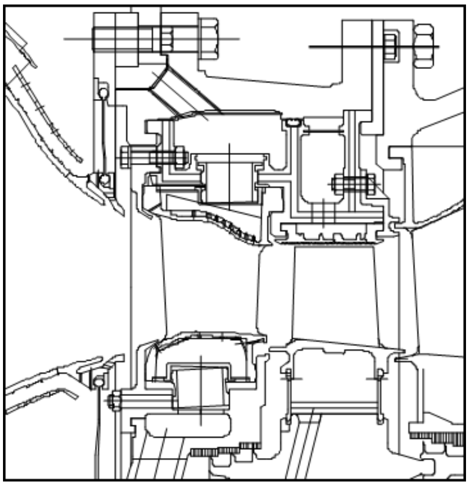

Figure 6. Turbine inlet section

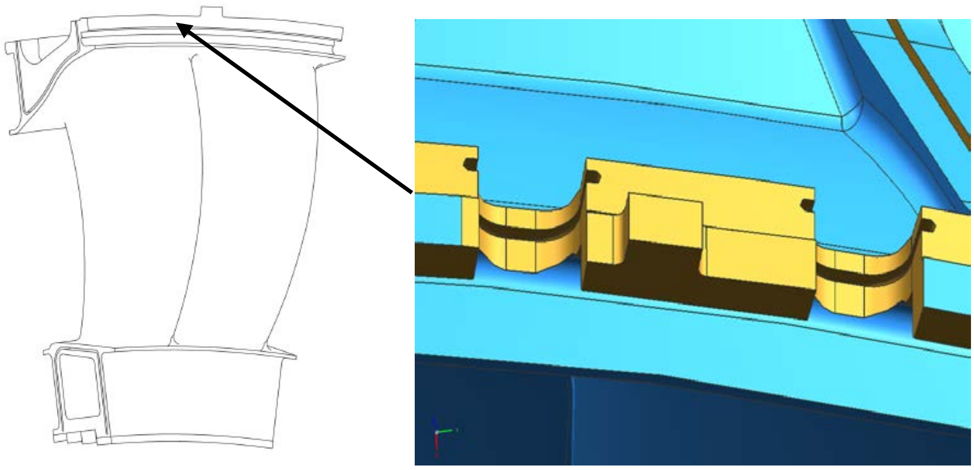

Figure 7. Turbine guide vane 3 segment outer platform tangential stiffness reduction

4.3 Casings and other structural parts

To fulfill market requirements on operational flexibility, reliability and availability casings and other structural parts were reassessed to ensure their durability and functionality under current and foreseeable future market conditions. The assessment indicated that the inspection requirements for the central casing, surrounding the gas turbine combustor, could impact maintenance down times in an undesired way. The central casing was therefore modified to improve fatigue durability without compromising its ability to withstand long term operation. The structural parts of SGT-800 can now meet the requirements for the extended major inspection intervals that are expected to be necessary in the future, together with increased demands on flexibility and ever-changing production requirements with no impact on availability.

The resulting highly durable design meets requirements for more than 200 000 running hours at all normal operation conditions with minimum inspection requirements.

5 The impact of remote monitoring and support tools on operations

Current technology makes information exchange much more efficient than ever before, potentially allowing swift and adequate customer support with virtually in-situ capability without the need for delays due to traveling. This results in considerable less inconvenience to the operator but even more important it makes it possible to use highly skilled engineers to efficiently share their time between urgent issues in remote locations far from the office and complex R&D tasks. One example is post-inspection field balancing where the exchange of one or more sets of rotating blades can cause a rotor imbalance that prevents operation. Instead of sending a vibrations expert to site to monitor the post-inspection commissioning, or gamble on a small change in rotor balance state, the expert can now stay at home and provide guidelines using remote support tools while the hands-on work is performed by the field service personnel on site. This not only increases the quality of the support but also bridges the traditional gap between field service personnel solving “real” problems and the design engineers providing long-term solutions and developing next-generation products. In-house experience shows that in excess of 80% of all reported minor operation disturbances can be solved remotely. This figure is expected to increase over the coming years, extending from monitoring of specific areas like emissions, vibrations and performance into more sophisticated health monitoring. While remote monitoring and support tools are already important tools to ensure top-quality performance of gas turbines these tools will be the backbone of the business in the future.

6 Conclusions and summary

Since its introduction in 1999 the SGT-800 gas turbine has undergone continuous development to meet ever-increasing market demands on increasing performance, operation flexibility and maintainability aiming at outstanding performance particularly in high-efficiency combined-cycle and combined heat and power applications. Actual reliability and availability have been maintained at 99.5% and >96.5% levels across performance upgrades and introductions of new technology through focused and stepwise introductions of improvements that are easy to validate making it possible to maintain a high development rate. The backbone of this success is the collection of customer real-life operation experience, bringing isolated incidents and small pieces of information into the big picture and ensuring that the correct conclusions will be drawn. To meet future product expectations this hard work must continue, bringing new technology, solid knowledge and modern IT together.

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