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DESIGN AND EARLY DEVELOPMENT OF THE SGT-300 TWIN SHAFT GAS TURBINE

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Abstract

In order to meet the challenge of the effects of global warming and the growing pressure to reduce the impact on the environment, improvements in gas turbine efficiency and combustion capability have been shown as major drivers behind Siemens Energy's development of a twin shaft variant of the SGT-300 gas turbine. Technical focus was on providing a design offering high reliability and efficiency, commensurate with achieving the most stringent environmental regulations. A twin-shaft turbine derived from the single-shaft SGT-300 has been designed, built on the heritage of Siemens Energy's industrial gas turbine and applying proven technology from across the gas turbine range. The twin-shaft SGT-300 offers a highly efficient, robust design capable of meeting both mechanical drive as well as power generation duty.

The design process covering concept decisions through the detailed design phase and early validation is described in this paper. The need for a robust product led to key decisions being made with regard to material selection as well as turbine construction and assembly to aid the serviceability of the machine. This covers the gas turbine core and it interfaces with the package design. The turbine package shares many common features with its larger sibling, the SGT-400, featuring in-cell maintenance capability as well as a modular approach to construction, further aided by factory testing of components prior to package installation.

In parallel to the design program, a detailed compressor-blade validation was performed using a compressor rig as well as an SGT-300 single-shaft engine. Mapping the compressor across a wide range of speeds and loads allowed operational stability and potential high-cycle-fatigue risks to be addressed, especially in the compressor speed range of 70- 105%. Building on the proven fuel flexibility and good emissions signature of the single-shaft turbine, further work was completed to modify the combustion design in order to achieve the stringent environmental requirements required today and into the future. Comprehensive use of a high-pressure combustion facility was made, allowing a full size combustor to be evaluated at full engine pressures and temperatures across the complete range of ambient conditions.

1 Introduction

The Siemens SGT-300 gas turbine was introduced to the market in 1995, entering commercial operation in 1998. The single-shaft gas turbine has gained a reputation as a robust combined heat and power generation machine. More recently the SGT-300 has proven its outstanding capability in operating on lower Wobbe Index fuels whilst still meeting the most stringent emissions requirements.

Building on this success Siemens embarked on the development of the twin-shaft variant which is the subject of this paper.

The development programme followed the Siemens Product Development Process (PDP) utilising a variety of tools, such as Six Sigma, to support the conceptual design and decision making. Various detailed concepts were assessed against key success factors such as reliability, operability, serviceability, durability and performance. These key success factors will be discussed within this paper. Fault tree analysis methodology, as applied in other industries, was used on aspects of the package design focusing on reliability.

The overall design approach can be described as conservative, resulting in a moderate turbine inlet temperature in line with the SGT-300 single-shaft and the application of proven designs and technology as used in other Siemens gas turbines.

This enabled the design team to achieve the overall objective of a robust gas turbine, capable of providing high efficiency whilst meeting the most stringent demands of the mechanical drive and power generation applications in the Oil & Gas industry. This engine is also available to the industrial power generation market, offering an efficient simple-cycle and combined heat and power (CHP) solution.

2 Gas Turbine

The SGT-300 twin-shaft gas turbine has been released as a mechanical driver with a PT speed range of 5,750 to 12,075 rpm (50 -105% of nominal speed, nominal: 11,500rpm) chosen to allow for direct speed matching to the driven unit.

The power generation version with its 503^{0}C exhaust temperature is capable of raising 17t/h steam of 1.2MPa and 200^{0}C without supplementary firing.

Power and Efficiencies are as follows:

	Power (MWth)	Power (MWe)	Efficiency (%)	Heat Rate (kJ/kWh / BTU/kWh)
Mechanical Driver Package	8.2		34.6	10,405 / 9,869
Power Generation Package		8.5	33.6	10,714 / 10,162

All figures ISO, zero intake and exhaust loss, Power Generation includes gearbox and generator losses

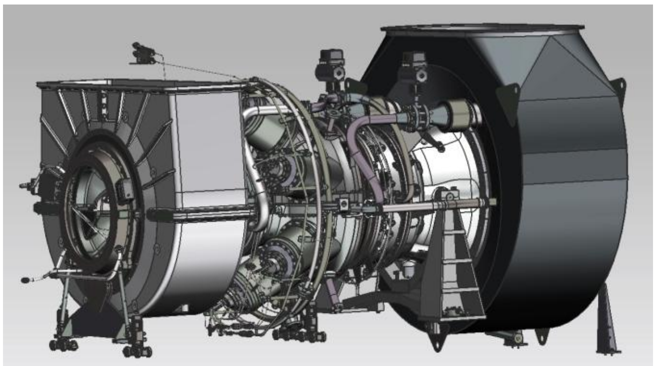

Figure 1: *SGT-300 Twin-shaft Core Engine*

The gas turbine has evolved from the SGT-300 single-shaft with which it has the compressor and combustor in common. This approach has been further expanded to encompass proven design features from other Siemens industrial products described throughout this paper.

2.1 Compressor

The gas turbine employs the latest version of the SGT-300 compressor, a proven transonic, axial compressor with customized multiple circular arc 3D bladed aerofoils in stages 1 and 2 and customized controlled-diffusion style 3D blading in stages 3 to 10, figure 2.

Figure 2a: *SGT-300 compressor rotor with high efficient 3D aerofoil design*

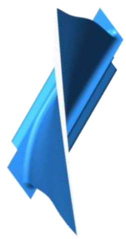

Figure 2b: *Customized multiple circular arc aerofoil*

The gas generator comprises a 10 stage axial compressor running on tilting pad journal bearings in the inlet housing and the centre casing with a 2-stage overhung turbine. A thrust bearing is located in the inlet module to accommodate rotor axial movement. 3 stages of variable geometry, in addition to the inlet guide vane (IGV), are used with an interstage bleed to preserve engine surge margin during starting, stopping and transient operation of the machine.

Using the single-shaft compressor in twin-shaft application was one of the early fundamental conceptual decisions, which required verifying before implementing. Thorough analysis followed by engine verification was completed to ensure the compressor blade vibration characteristics were not compromised by the extended speed range of the twin-shaft machine. Further details are given in Section 4 “Validation”.

2.2 Combustor

The SGT-300 twin-shaft is equipped with the proven pre-mix Dry Low Emissions (DLE) combustion system as used on the SGT-100 to SGT-400 product range, figure 3.

The SGT-300 DLE combustor has the capability to operate over a wide Wobbe Index range of gaseous and distillate fuels whilst still meeting the most stringent emissions requirements /1/.

The SGT-300 twin-shaft combustor has minor changes from the single-shaft combustor to reflect the variations in mass flow and pressure that occur under twin-shaft conditions.

Full use was made of a dedicated combustion rig to ensure the combustor satisfied the emissions and operational requirements. This resulted in the combustion system being optimized to guarantee <15ppm NOx and <10ppm CO over a wide ambient range and down to 50% load and being a dry combustion system without the need for water injection.

As on the SGT-300 single-shaft the combustor has full dual-fuel DLE capability.

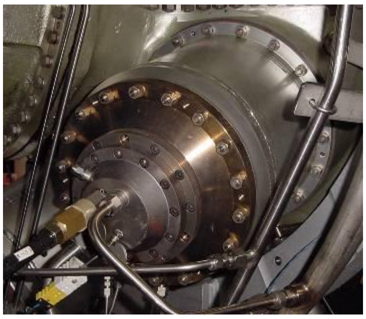

Figure 3a: *Pre-mix DLE combustor, for fuel flexibility and low emissions*

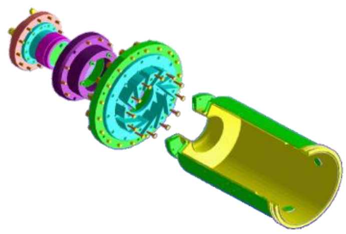

Figure 3b: *DLE combustor - Assembly model*

2.3 Compressor Turbine

The compressor turbine (CT) comprises 2 overhung stages.

Siemens advanced 2D- and 3D-tools and design methods were applied to perform the aerodynamical optimization with complete 3D through-flow analysis resulting in moderately and evenly loaded subsonic aerofoils for optimized stage efficiencies.

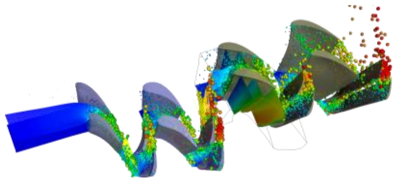

Figure 4: *3D through-flow, based on Siemens' advanced tools and methods*

Materials for blades and vanes, along with the cooling systems were carefully chosen for reliable operation; also under sub-optimum conditions. All the aerofoils are cooled, with the blades manufactured in directionally solidified IN6203 alloy with a diffused aluminium coating. The choice of IN6203; a nickel-based superalloy, offers enhanced corrosion resistance due to its 22% Cr content. Siemens has gathered extensive experience with this material in its SGT-100 and SGT-300 products. Both CT1 and CT2 rotor blades have fir tree roots with high-pressure cooling air entering the base of the blade via a pre-swirl supply and rim holes in the turbine disc (as per the SGT-300 & SGT-400). The CT1 has a double-passage cooling design with a dedicated leading edge channel providing cooling air to the tip region, the rear passage exits via trailing edge ejection. The CT2 blade has a simple triple pass arrangement similar to the existing SGT-400 CT2 blade design.

The first-stage stator comprises 18 double vane segments made from MarM247 castings with full thermal barrier coating (TBC), whilst the second stage is cast as 17 double-vane segments from IN939 with a diffused aluminium protective coating. Improved sealing is incorporated on the nozzle segments to increase CT efficiency and support the key design parameters set for the project. The CT blades run against tip seal segments with a high temperature abradable coating for clearance control, a system successfully used on other Siemens gas turbines.

The compressor turbine is coupled to the compressor rotor through curvic couplings with multi-bolt fixings. This design facilitates easy servicing, allowing in-situ removal and change-out of the compressor turbine module without removing the gas generator from the package. The CT module contains the discs, blades, nozzle and outer casing as a sub-assembly, as shown in figure 5.

Figure 5: *Service friendly compressor turbine module, replaceable in-situ*

The CT casing also includes a bleed-/blow-off system to support combustion turndown and power generation load-shedding. Variable control of the bleed valves allows low emissions, particularly CO emissions, to be achieved over a wide range of engine operation. For power generation application a valve with fast response is fitted to provide rapid evacuation of the air to avoid the PT rotor overspeeding if the generator circuit breaker opens under fault conditions.

2.4 Power Turbine

The Power Turbine of the SGT-300 twin-shaft has evolved from power turbines that are well proven in other Siemens products with features such as interlocked shrouded blades and curvic coupling with multibolts.

The 2-stage overhung rotor is mounted on a 2-bearing arrangement with a single-piece shaft with its thrust bearing at the output end of the bearing chamber. Stage 1 comprises 13 triple-nozzle segments made in IN792 with a diffused aluminium coating and 61 rotating blades made from MarM247 with a diffused chrome aluminide coating. Stage 2 has 9 quad-nozzle segments made from IN939 and 73 rotating blades made from IN792. The stage 2 nozzle and rotor blades do not require coatings. Both stages of PT rotor blades have shrouds that run against honeycomb tip segments and an anti-wear treatment on the shroud interlock surfaces.

The PT shaft has been extended so the output flange is more readily accessible. This also delivers a very stable high-speed coupling, with rotor health monitored by bearing thermocouples and vibration sensors. The fundamental instrumentation sensors can be removed without necessitating a major strip of the power turbine.

Like the Compressor Turbine, the Power Turbine is a modular arrangement. The main PT cartridge consists of the discs, blades, nozzles and casings as a sub-assembly which can be replaced without separating the PT structure from the exhaust, figure 6. In addition the shaft, labyrinths and bearings can be replaced in-situ as well as a further sub-assembly.

Figure 6: *Service friendly power turbine module, replaceable in-situ*

Following the same approach as for the CT, the PT discs are secured to the rotor with multibolts and curvic couplings. This compact arrangement has been designed so that the PT is aerodynamically close coupled to the CT eliminating the need for a separate turbine interduct. Cooling air for the PT disc cavities comes from the compressor interstage bleed through an air distribution system fully contained within the PT module.

The exhaust consists of a cast steel spoked frame that forms the rear engine mounting, carries the bearing chamber, and forms the first section of the exit diffuser. The rest of the diffuser is built into a fabricated collector box which achieves good pressure recovery and exits vertically or horizontally through a stretched circular outlet flange.

2.5 Gas Turbine Operability

The SGT-300 twin-shaft is available for mechanical drive and power generation.

Prior to releasing the power generation concept an in-depth transient analysis of the engine's operational behaviour was required to ensure safe operation and grid code compliance.

The dynamic model proved the casing design, with its low residual volume, makes rapid evacuation in the event of load rejection possible. Staying well within the 10% PT-overspeed limit ensures safe coast down of the PT rotor for high and low load inertia conditions.

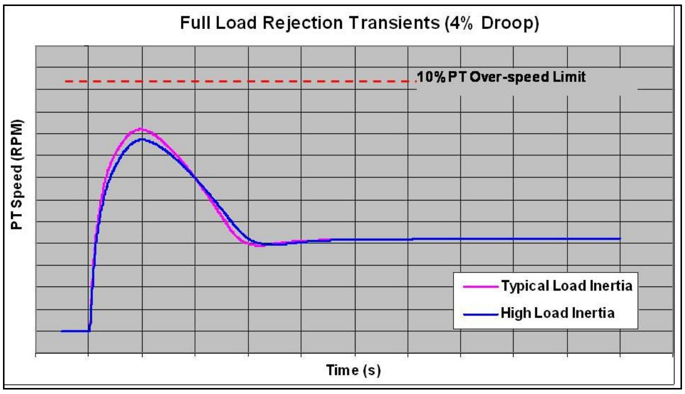

***Figure 7:** Full load rejection transients*

As a consequence the bleed system sizing of the mechanical driver core engine could be maintained when used in conjunction with rapid acting valves.

The engine can govern PT speed in droop or isochronous mode.

3 Package

The SGT-300 twin-shaft package is proven in service as the core engine shares the latest package standard with the SGT-400.

***Figure 8a:** SGT-400 package as being used for SGT-300 TS for improved serviceability*

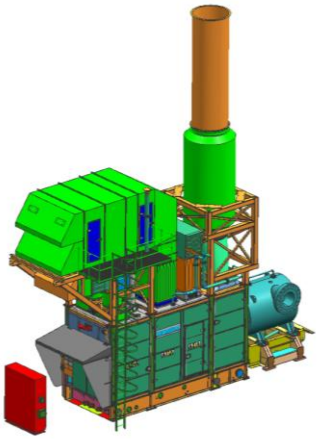

***Figure 8b:** SGT-300 TS package for compressor drive application*

This includes Siemens' PCS7 control system, the acoustic enclosure with the fire & gas system, the bedplate with its integrated lube-oil tank as well as the fluid systems modules such as the gas fuel, liquid fuel and lube oil module.

The package comes with a hydraulic start system as standard, which provides reliable operation.

All fluid systems are designed and manufactured as modules with onskid controls and complete electrical wiring. The drop-in systems are shop-tested with appropriate quality certification issued prior to assembly.

All systems and components that are specific to mass flows and torque or power are sized for the SGT-300 twin-shaft.

Options are available for static and pulse filter with HEPA filtration capability for prolonged service intervals.

The bedplate is equipped with rail tracks to allow necessary CT- and PT-module maintenance task in-situ. The tracks allow the gas generator to be moved laterally creating sufficient space for performing in-cell maintenance.

The modular package design supports a reduced number of lifts during its installation at site. In conjunction with the factory pre-testing of modules the entire duration for installation and commissioning has been reduced relative to earlier package designs.

The adoption of Reliability Engineering Methodologies during the project execution has proven beneficial. A robust methodology in support of an educated probabilistic prognosis on the effect of package design changes with respect to reliability improvement has been developed. As a first step the existing package design was transferred into a Fault Tree Model with corresponding Markov Chains to benchmark its theoretical Mean Time Between Forced Outage (MTBFO) with field data. In a second step sources of increased unreliability were minimised or rectified and the systems improved with the result that the model based MTBFO improved by 10%. This was possible through consequent simplification of design, measuring the right parameters in combination with the careful selection of redundant systems /2/.

This package standard in combination with the core engine features described above supports a 24hr core engine exchange or PT module change-out.

Package Dimensions and Weights are as follows:

	Length (m / ft)	Height (m / ft)	Width (m / ft)	Weight (kg / lbs)
Mechanical Driver Package	7.0 / 22.97	4.0 / 13.12	2.8 / 9.19	31,000/ 68,400
Power Generation Package	13.5 / 42.29	4.0 / 13.12	2.8 / 9.19	85,000/187,500

4 Validation

Product and design validation is a critical, quality assuring element in Siemens' Product Development Process (PDP). It comprises not only full engine and package validation but also necessitates the verification of critical conceptual decisions throughout the development project. The most prominent decision that needed verifying was the application of the single-shaft compressor in twin-shaft speed mode. The importance here lies in the assessment of the mechanical integrity of the blades under different excitation conditions due to a wider operating speed range of the gas generator.

Another test that determined the scope of the combustor work was the benchmark of the SGT-300 single-shaft combustor against twin-shaft operating conditions.

4.1 Compressor

The compressor used for the SGT-300 twin-shaft is identical to the latest version of the SGT-300 single-shaft compressor. Blade aerofoil design is based on customized 3D blade designs which delivered improved compressor efficiency over a wide range of operating conditions. To ensure the compressor achieved the project objective, a SGT-300 development engine was operated at a number of off-design conditions thus simulating conditions the SGT-300 twin-shaft would routinely meet. This enabled the compressor surge margin to be evaluated under the MD requirements including the requirements for compressor exit bleed. During this test period optical probe-tip timing technique was used, allowing the blade response to the various off-design conditions to be monitored and recorded.

Subsequent analysis demonstrated the compressor blades needed no design changes, only optimisation of the variable guide vane schedule.

The test programme defined the compressor characteristic through the compressor speed range – circa 70% to 105% along with investigating the effects of variable guide vane schedule and interstage bleed on the performance characteristics. Finally an assessment to determine if there was sufficient surge margin during start-up and through the operating envelope was completed. All of these tests proved that the existing blade design met the design's mechanical integrity demands.

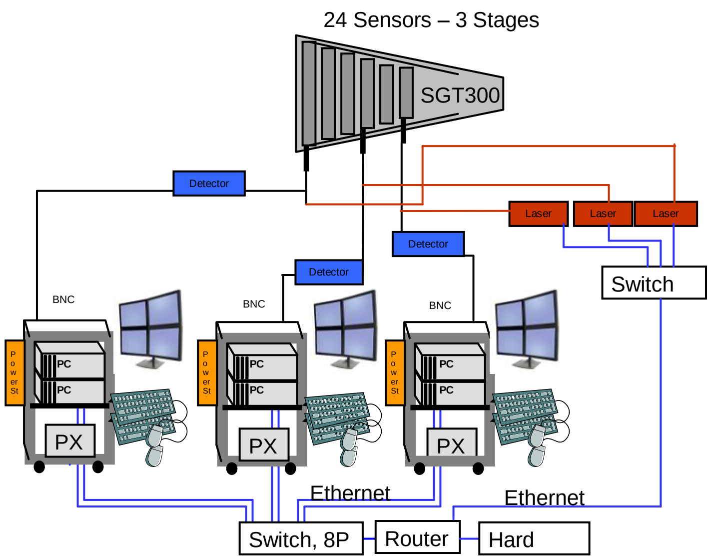

Figure 9: *Blade Tip Timing Instrumentation Hardware Layout*

For this program, three of the front six compressor rotor stages deemed critical were fitted with eight optical probes per stage to sit over the blade tip at a given axial location, figure 10. As the blade tips pass the optical probes, the system registers a time of arrival for each blade. Knowing the rotational velocity of each blade and the radius of the measurement probe, time of arrival data can be converted to deflection. Data from all of the probes at a particular axial location can then be used to calculate parameters such as frequency, amplitude, phase and other vibration characteristics. The vibration characteristics of these stages were monitored in real time through the test program covering a range of operating conditions through the speed and load range.

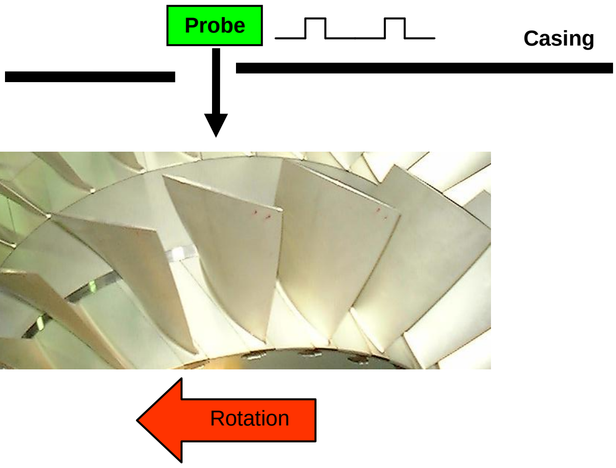

Figure 10: *Tip Timing Laser Probe Position*

Plotting the frequency data onto a Campbell Diagram confirmed that mode frequencies and engine-orders revealed no areas of concern within the operating speed range. Hence the blades were approved for production.

4.2 Combustor

The SGT-300 single-shaft combustor was benchmarked for operation under twin-shaft condition which means variation in mass flow and compressor discharge pressure and temperature.

Validation and confirmation of the combustor design took place in the high-pressure combustion rig facility, figure 11, which allows single combustor testing to take place at true engine flows, pressures and temperatures. It is able to operate across the full load spectrum at a wide range of ambient temperatures. Besides the recording of emissions, such as NOx, CO and UHC species, component temperatures, combustion dynamics and temperature profiles were some of the other parameters measured and recorded.

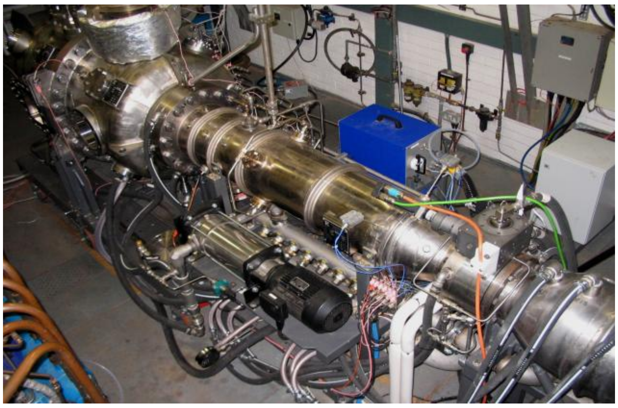

Figure 11*: High-Pressure Combustion Rig*

Changes to the existing SGT-300 hardware were found necessary in order to address the changes in combustion stoichiometry associated with the SGT-300 twin-shaft operating envelope. The overall length of the combustion casing has been reduced commensurate with a reduction in the height of the main swirler. The resultant NOx emissions recorded from the HP rig were within the specification requirements, figure 12.

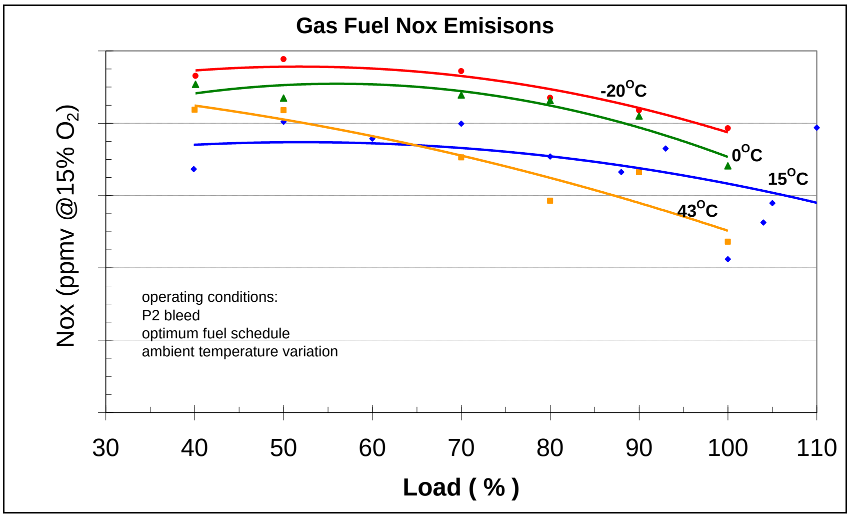

Figure 12: *NOx emissions recorded on the High Pressure rig facility*

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References

/1/ G Bulat*, K Liu, G Brickwood, V Sanderson, B Igoe: Intelligent operation of Siemens (SGT-300) DLE gas turbine combustion system over an extended fuel range with low emissions - Proceedings of ASME Turbo Expo 2011: Power for Land, Sea and Air GT2011 June 6-10, 2011, Vancouver, CanadaGT2011-46103

/2/ C Engelbert, A Sutor, M Nilsson & F Montrone: Application of a Reliability Model to Gas Turbine Design – ASME Power 2008 - POWER2008-60100

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