Field experience with the sequential combustion system of the GT24/GT26 gas turbine family

ABB advanced GT24/GT26 gas turbines, which are based on the unique sequential combustion system, achieve high cycle efficiency at moderate turbine inlet temperatures as well as optimal gas turbine exhaust temperatures for the steam cycle in combined cycle applications. The first GT24 (60 Hz, 165 MW-class) and GT26 (50 Hz, 265-MW class) machines have now been commissioned and are in commercial service. Extensive measurements under both design and off-design conditions demonstrate the high reliability of the turbines in operation and confirm the potential of the sequential combustion system for reducing NO_x emissions to even lower levels.

The sequential combustion cycle used by the GT24/GT26 family is a reheat process with two combustors which allows increased gas turbine output at high efficiency. Whereas the first combustor is based on proven EV-combustor technology, the lean premixed, self-igniting second combustor is the outcome of an extensive research and development programme.

The first GT24 to be operated commercially is installed at the Gilbert station of Jersey Central Power and Light (JCP&L) in the USA [1]. The first GT26 was installed and operated at the ABB gas turbine test center in Birr, Switzerland, the first commercial unit of this type having been ignited in the Rheinhafen power station at Karlsruhe, Germany [2].

GT24/GT26 performance data

Rated at 265 MW, the GT26 delivers about 50% more output than a conventional GT13E2 from essentially the same footprint. The higher output is the result of an increase in cycle pressure ratio and the sequential combustion cycle. Additionally, the exhaust temperature of the GT24/GT26 is about 610 °C (1130 °F) over the wide range of 50 to 100 % unit load, which is ideal for combined cycle (gas and steam turbine plant) operation.

The power density of the GT24/GT26 gas turbine family is approximately 20 % higher than for other units in this class. GT24/GT26 units feature a more compact design, shorter blade lengths, lower tip speeds and therefore lower stresses, leading to higher reliability.

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Sequential combustion system

GT24/GT26 units look very much like conventional gas turbines. They feature a straight through-flow design with cold-end generator drive, an air intake system which is perpendicular to the shaft, an axial turbine exhaust and horizontally split casings and vane carriers.

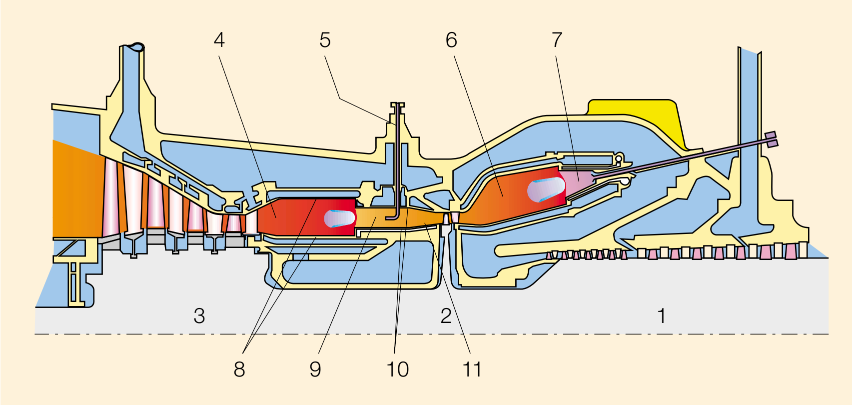
The advanced technology at the heart of the GT24/GT26 family is the sequential combustion system 1 [3]. An efficient 22-stage compressor [4] feeds combustion air into the first combustor – the annular EV combustion chamber – at a pressure ratio of 30 : 1, ie twice the pressure of conventional industrial gas turbines. Here, the fuel is mixed with the high-pressure air and ignited, producing the hot gases that drive the single-stage high-pressure turbine. Unlike conventional gas turbines, the GT24/GT26 has a second annular combustor – the SEV (Sequential EV) combustor – into which fuel is injected and ignites spontaneously, thereby reheating the air before its final expansion in four low-pressure turbine stages.

The thermodynamic cycle is characterized by a two-stage combustion process 2. During the so-called reheat process, energy is added to achieve a higher average temperature, resulting in a higher thermodynamic efficiency and higher power density than with a conventional single combustion gas turbine process in which the turbine inlet temperature stays the same. Thus, with sequential combustion a lower turbine inlet temperature can be used for the same power output.

GT24/GT26 operating concept

The GT24/GT26 turbines are optimized for combined-cycle operation. High thermal efficiencies and low emissions are achieved by the two combustors even during part-load operation with individual fuel control and three rows of adjustable inlet guide vanes. These vanes allow the combustion air flow to be reduced to 60% of the full load mass flow.

3 summarizes the operational concept of the GT24/GT26. The machine is started and accelerated with the EV combustor in operation. Diffusion-type pilot flames are used for the EV burners to ensure maximum stability. At approximately 20% relative machine load the EV burners switch to premix operation and the SEV combustor is ignited. During loading the EV combustor operates with a con-

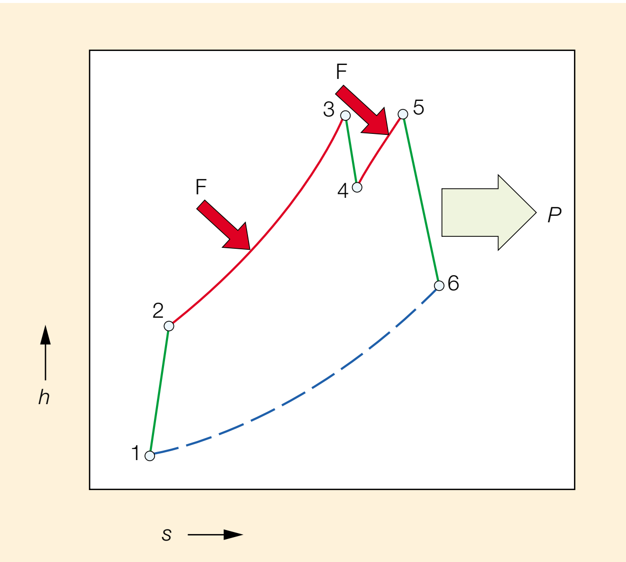


Sequential combustion system used in GT24/GT26 gas turbines **1**

1 *Low-pressure turbine*
2 *High-pressure turbine*
3 *Compressor*
4 *SEV combustor*
5 *Fuel injector*
6 *EV combustor*
7 *EV burner*
8 *Convective liner cooling*
9 *Mixing zone*
10 *Vortex generators*
11 *Effusion-cooled burner*

Thermodynamic cycle of the sequential combustion system **2**

h *Enthalpy*
s *Entropy*
F *Fuel input*
P *Power to generator*

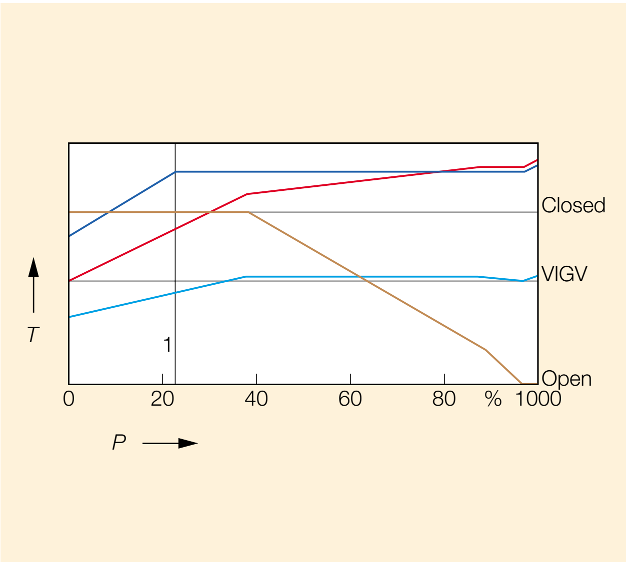


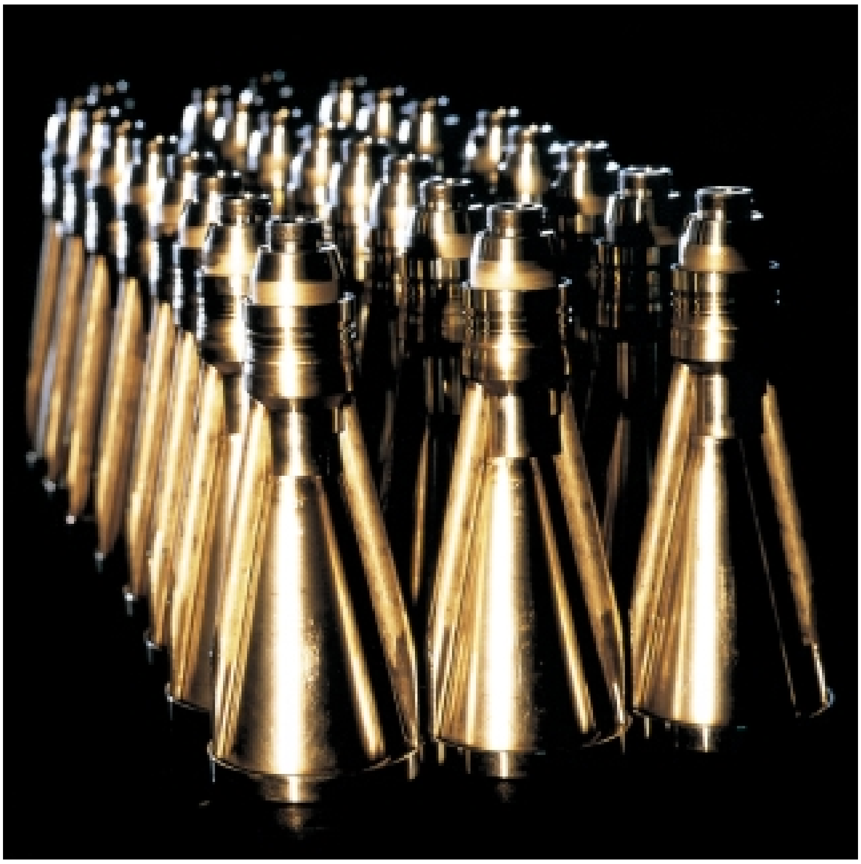
Operating concept of the GT24/GT26 **3**

T *Normalized temperature*
P *Relative machine load*

1 *SEV combustor ignition*

Brown *VIGV setting*
Dark blue *HP turbine inlet temperature*
Light blue *Gas turbine outlet temperature*
Red *LP turbine inlet temperature*





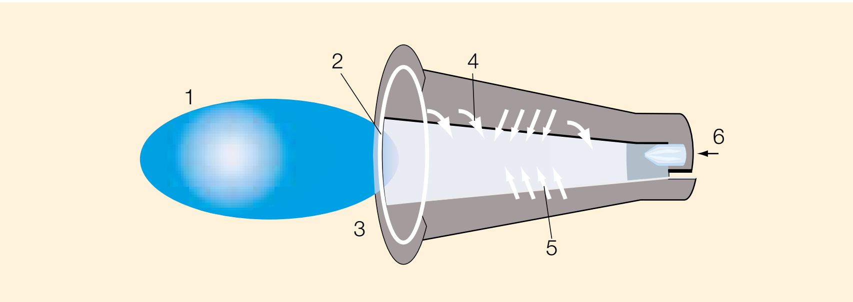
EV burner set **4**

stant exit temperature, while the SEV combustor temperature is increased. At close to 40% relative unit load the variable inlet guide vane (VIGV) is opened and more fuel is supplied to the two combustors. The exhaust temperature of the turbine is then kept constant until full load is reached. This is achieved by means of a last small increase in the combustor temperatures with the VIGV fully open.

The described concept allows a high degree of flexibility over the entire operating range. The EV burners operate under optimal design conditions from 25% load up to full load with just a premixed flame, ie without pilot flames. Also, the SEV combustor exit temperature and the VIGV position can be adjusted to optimize the emissions and the efficiency of the gas turbine or combined cycle.

EV burner mass flow **5**

1 *Flame front*
2 *Vortex breakdown*
3 *Ignition*
4 *Combustion air*
5 *Gas injection holes*
6 *Liquid fuel / pilot gas*



Emissions behaviour of the sequential combustion system

The NO_x formation depends on the temperature, pressure and residence time in the high-temperature zones of the combustion chamber. Since all the combustion air is premixed with the fuel there are no zones inside the combustor where the flame temperature is higher than the combustor exit temperature. In both the EV and SEV combustors high-temperature residence times are at least 50% shorter than in conventional combustors. This advantage of the sequential combustion system is the result of the second combustor burning all of the CO and UHC from the EV combustor in less time due to the high inlet temperature. The design of the SEV combustor also has another advantage: since the O_2 content of the incoming hot gas is considerably lower than that of normal air, less oxygen is available for the NO_x formation. Also, the SEV air is at a much higher temperature than conventional combustion air, allowing the flame temperature to be reached with less heat. Both of these NO_x-reducing phenomena are known from other combustion technologies which employ exhaust gas recirculation. Given that a large amount of the fuel is burned in the SEV combustor with ultra-low NO_x formation, the NO_x emission values (measured as vppm 15% O_2) are lower at the SEV exit than at the SEV inlet. This phenomenon is due to the consumption of oxygen in the SEV combustor with minimal NO_x production.

Design features of the EV combustor

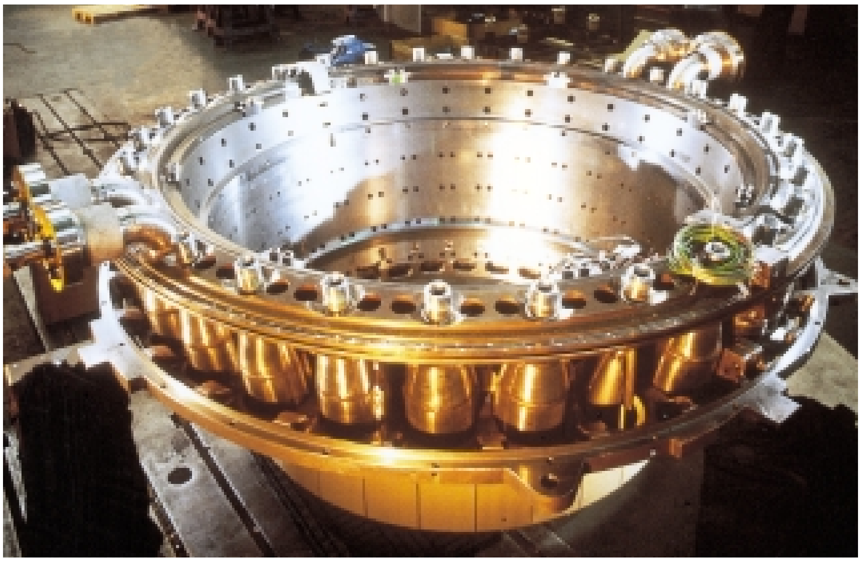
The first combustor is an annular combustion chamber with 30 proven dry low-NO_x EV burners [5].

The EV burner offers the advantage of low-NO_x combustion when run on gas without water or steam injection but can also be operated on liquid fuel. The burner is shaped like two half-cones, slightly offset sideways to form two inlet slots of constant width running the full length of the component **4**.

The combustion air enters the cone through the slots while the main gaseous fuel is injected through a series of fine holes in the supply pipe situated next to the air inlet slots. The gaseous pilot fuel and the liquid fuel are injected through nozzles at the cone tip **5**. This arrangement ensures that the fuel and air spiral into a vortex form and are mixed intensively.

EV burners were first applied commercially in 1990 in the silo combustor system of the GT11N gas turbines. In 1993 the EV burner was utilized in the annular combustor arrangement of the GT13E2 gas turbine [6] and later also in types GT8, GT11N2 and GT10. In the meantime, over 800,000 hours of operation have been logged on these units.

The annular design **6** is advantageous because it provides a perfect, even and circumferential temperature profile, resulting in improved cooling, longer blade life and lower emissions. Radial temperature uniformity is accomplished by premixing virtually all the incoming air with the fuel in the EV burner and by the absence of film cooling in the convection-cooled combustor walls. This produces a single, uniform flame ring in the free space of the EV combustion chamber. Another benefit is that the flame has no contact with the walls of the burners.



EV combustor arrangement **6**

Design features of the SEV combustor

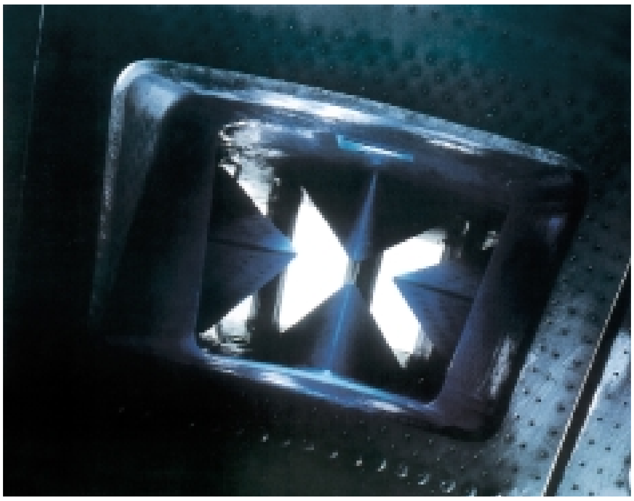
The combustion process in the annular SEV combustor is similar to that in the EV combustor: vortex generation, fuel injection, premixing and vortex breakdown. The SEV combustor consists of 24 diffusor-burner assemblies arranged around the circumference, followed by a single, annular combustion chamber surrounded by convection-cooled walls. The exhaust gas from the high-pressure turbine enters the SEV combustor through the diffusor area. Combustor temperature uniformity in the SEV is determined, as in the EV, by the spatial homogeneity of the fuel/air mixture, which is again accomplished by means of vortices. Each SEV burner has delta-shaped wings which swirl the combustion air into vortices. These wings, which are shaped like ramps, are located on all four interior walls of the burners **7** [7].

24 air-cooled fuel nozzles inject the fuel and distribute it in such a way that a perfect fuel/air mixture is formed prior to combustion. Cool carrier air surrounds the fuel jet and delays spontaneous ignition until the combustion chamber, which follows the burner area, is reached. Due to the elevated temperatures of the HP turbine exhaust gases, the fuel/air mixture ignites by itself under the influence of the carrier air. As in the EV combustor, combustion takes place in a single flame ring, operation of which remains stable over the entire load range.

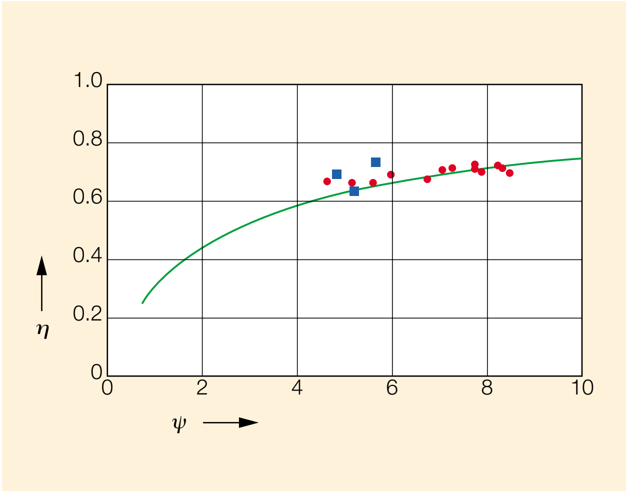
Development of the lean, self-igniting reheat combustor was supported by an extensive research and development programme. The design of the burner and the combustor was based on wind tunnel and water channel experiments, CFD-calculations and combustion tests under atmospheric and high-pressure conditions. Validation tests were carried out on engine parts under real machine conditions [3].

Turbine instrumentation

To confirm the design, about 1,500 locations on the prototype machines were selected for measurement [1]. Combustor performance data were obtained by measuring the emission and hot-gas temperatures behind both the HP turbine and the LP turbine: three emission probes



SEV burner with vortex generators, viewed from the SEV combustor **7**



Measured cooling effectiveness of the SEV combustor liner **8**

η	*Cooling effectiveness*	Blue	*Machine*
ψ	*Coolant mass flow function*	Red	*Rig test*
		Green	*Ideal trend*

and 24 hot-gas probes are positioned behind the HP turbine to measure the circumferential distribution, while 30 thermocouples behind the LP turbine allow exhaust temperature measurements at three radial and 10 circumferential positions. Additionally, material temperatures were measured on all relevant parts, ie the combustor liners and the burners. Each combustor was fitted with a pulsation probe for monitoring the pulsation behaviour.

The measurement of emissions in front of and behind the SEV combustor enabled the NO_x formation to be determined separately for both the EV and SEV combustors. For the purpose of comparison, the NO_x emissions were also calculated relative to the amount of fuel added to each combustor. Additionally, the NO_x, CO and smoke emissions were monitored at the stack.

Test procedure

Due consideration was given to the described operating concept during the tests. The combustor firing temperatures and VIGV settings were varied at different loads to examine the influence of these parameters on engine performance and emission behaviour.

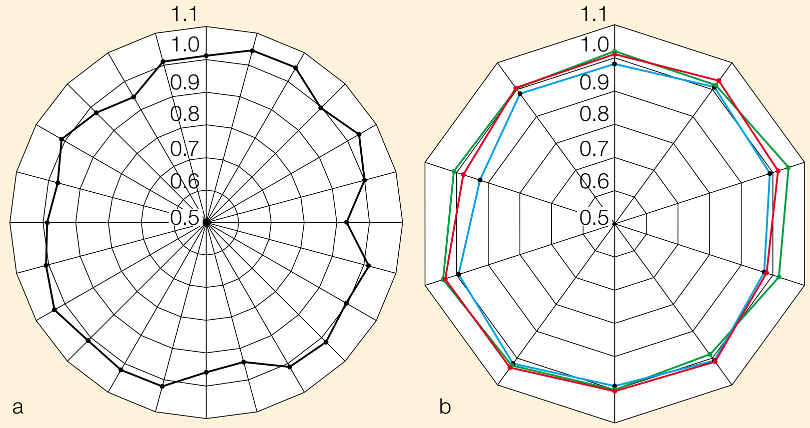
Combustor cooling technology

All the air from the compressor can be used to cool the EV combustor as it passes to the burner after being used to cool the liner. This is an example of pure convective cooling. The amount of leakage air flowing directly into the combustor is minimized by designing the liner segments as large parts. Each of the 30 burner segments consists of two liner segments with thermal barrier coating (TBC) and one impingement-cooled front panel around the burner.

An innovative cooling mechanism was developed that meets all of the requirements of the self-igniting premixed SEV combustion chamber. Minimization of the cooling air used by the combustor was an important goal during development of the sequential combustion system because the cooling air of the SEV combustor bypasses the HP turbine. This requirement contrasts with that of a convective-cooled combustor in a standard cycle gas turbine, where the pressure drop must be minimized and therefore the maximum amount of air must be used for cooling. Special attention was also paid to the construction of the hardware, which was required to be robust, and to ensuring that variations in the boundary conditions would have only a minimal effect on the effectiveness of the cooling.

Essentially, a counterflow cooling system with full heat recovery is used in which virtually all the cooling air is mixed with the hot gas from the HP turbine ahead of the flame. After having cooled the combustor liner walls via convective cooling, the cooling air is again used in the effusion cooling scheme of the SEV burner. This means that the full amount of cooling air is mixed into the combustion air upstream of the flame, thereby lowering the flame temperature and therefore also the NO_x formation.

8 gives the measured effectiveness (ie, the dimensionless wall temperature) of the SEV liner cooling as a function of the coolant mass flow function. This function is defined as the ratio of the heat capacity rate of the cooling air to that of the hot-gas wetted surface, and therefore as the inverse of the number of heat transfer units used in heat-exchanger theory [8]. In high-pressure tests under real machine conditions, all combustor liner temperatures remained well below 800 °C, thus supporting the modelling of the heat transfer process.



Hot-gas temperature distribution behind the HP turbine in the middle of the hot gas channel (a) and behind the LP turbine at three radial positions in the hot gas channel (b), in each case relative to the average outlet temperature (GT26 operated at full load with gas as fuel) **9**

Blue *Hub*
Green *Tip*
Red *Mid-radius*

Gas temperature profile at the turbine exit

The temperature distribution at the combustor outlet is influenced by the quality of both the fuel distribution system and the burner air flow. Air leakages also influence the temperature distribution.

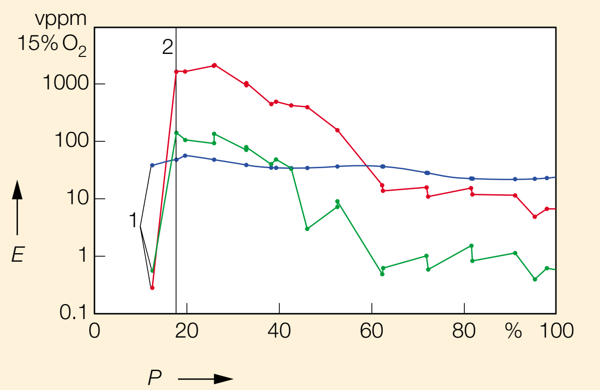
Uneven distribution of the combustor temperature results in increased NO_x or CO formation as well as an increase in the cooling air required by the turbines. To improve the situation it is therefore necessary to know at least the temperature distribution at the combustor outlet. The easiest way to assess the combustor outlet profile is to carry out measurements downstream of the turbine. However, since the cooling air added by the turbine blading, the platforms and the leakages as well as the secondary flows in the turbine stages even out the temperature profile, it is

Emissions measured when the gas turbine is operated with gas (first commercial GT24) **10**

E *Emissions*
P *Relative machine load*

1 *EV premix mode*
2 *SEV combustor ignition*

Blue NO_x
Red *CO*
Green *UHC*

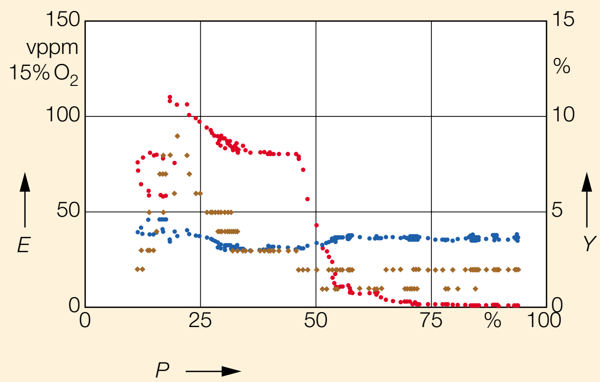


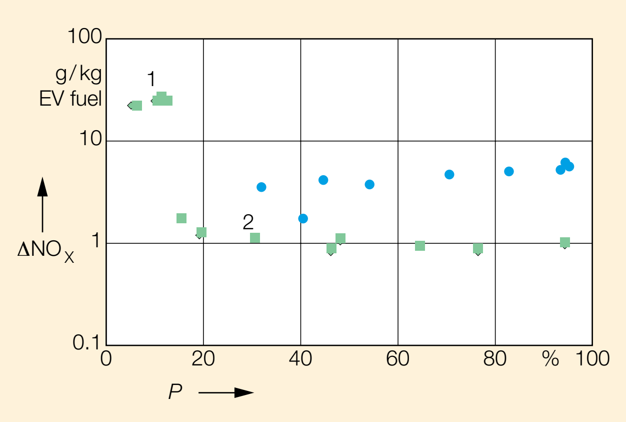
Emissions measured when operated with oil (first commercial GT24) **11**

$\dot{m}_{water}/\dot{m}_{oil}$ *EV = 1.2;* $\dot{m}_{water}/\dot{m}_{oil}$ *SEV = 1.0*

E *Emissions*
Y *Opacity*
P *Relative machine load*

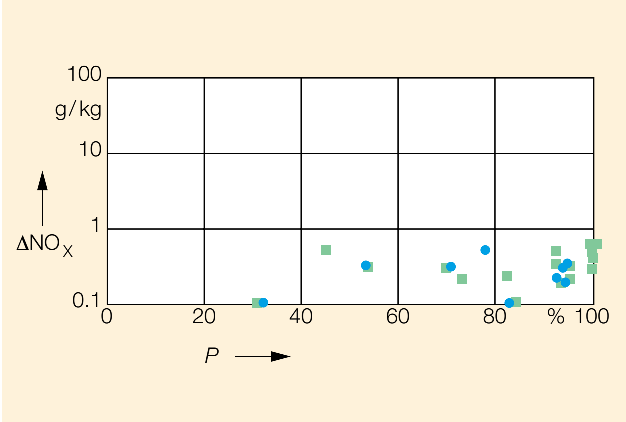
Blue NO_x
Red *CO*
Green *Opacity*





Measured NO_x formation in EV combustor **12**

ΔNO_x	*NO_x formation*
P	*Relative machine load*
1	*Gas pilot*
2	*Gas premix*
Green	*Operation with gas*
Blue	*Operation with oil ($\dot{m}_{water}/\dot{m}_{oil}$ EV = 1.2)*



Measured NO_x formation in SEV combustor (commercial machine) **13**

ΔNO_x	NO_x formation
P	*Relative machine load*
Green	*Operation with gas*
Blue	*Operation with oil ($\dot{m}_{water}/\dot{m}_{oil}$ EV = 1.2/1.4)*

difficult to calculate the distribution at the combustor exit.

The conventional method is to measure the temperature distribution of the combustor behind the last stage of the turbines. Hot-gas thermocouples located downstream of the first turbine stage give a better picture of the temperature distribution behind the combustor. **9a** shows the circumferential distribution of the hot gas at the high- pressure turbine (first-stage) outlet relative to the average outlet temperature for full-load operation with gas. The deviation from the average lies within ±5 %.

Measured behind the machine, ie at the outlet of the LP turbine, the circumferential temperature distribution at the mid-radius is in the range of ±5 % **9b**. A radial temperature distribution is also visible due to the addition of platform cooling air of the turbine.

Although the deviation from the mean value is lower than 5 %, further improvements to the fuel distribution system and the sealing will be carried out.

Emissions

Results of GT24 tests at the Gilbert station

The emissions of the first commercial GT24 unit, measured in the stack during gas dry operation is shown in **10**. Between 50 % and 100 % relative machine load, the NO_x emissions are below 25 vppm (15 % O_2). The CO values, which were relatively high during the SEV ignition, decrease to below 100 vppm at 50 % load and further to less than 10 vppm (15 % O_2) at loads higher than 90 %, while the UHC emission is lower than 1 vppm (15 % O_2) for operating conditions above 60 % machine load. Tuning the SEV ignition and VIGV will shift the CO/UHC peak to the load range of 20 % to 50 % machine load, ie allow operation at more than 50 % load with emissions as measured in the 60 % to 80 % range. This has also been demonstrated by the machine tests carried out at the test center in Birr.

At loads lower than 20 % only the EV combustor in premix mode operates with low NO_x and CO/UHC emissions. During the ignition phase of the SEV, the CO/UHC values increase due to the low temperature rise in the SEV combustor. This small rise was chosen to obtain a smooth, robust acceleration without having to switch several burner groups or the VIGV.

When running on oil, the NO_x emissions are below 42 vppm (15 % O_2) over the entire load range, while the CO value remains well below 10 vppm (15 % O_2) at loads above 50 % **11**. The exhaust gases are visible for a short time only during SEV ignition at around 30 % load.

To evaluate the emissions formed in the EV and SEV combustors, the fuel-related values must be compared. Typical values of the NO_x emissions measured behind the HP turbine, in front of the SEV combustor, are shown in **12**. The premix flame of the EV burner produces about 1 g NO_x/kg EV fuel during operation with gas and about 5 to 7 g NO_x/kg EV fuel when running on oil, in each case over the entire operating range. The fact that NO_x

formation is practically independent of the pressure increase and VIGV opening between 40 % and 90 % load underscores the high quality of the mixing in the EV burners. NO_x emissions from the diffusion-type pilot flame are around 25 g NO_x/kg EV fuel.

The emissions formed in the SEV combustor can be determined separately since the NO_x emissions being measured in front of and behind the SEV combustor **13**. NO_x formation in the SEV is about 0.5 g NO_x/kg SEV fuel during operation with both oil and gas. This is half the value of the NO_x formed in the EV combustor during operation with gas and about ⅓th of the value formed when running on oil. These values clearly demonstrate the low NO_x-formation characteristic of a reheat combustor: small increases in combustor temperature plus a lower O_2 content in the burning air.

The machine measurements validate the rig measurements carried out during the development of the SEV combustor **14**. During the rig tests it was observed that increasing NO_x formation is dependent upon the temperature increase in the SEV combustor, while the machine measurements show that the machine load has practically no influence.

Results of GT26 tests in Birr/Switzerland

Special ultra-low-emission runs have been carried out with the first GT26 at the ABB test center in Birr to demonstrate the future emission potential of the sequential combustion concept **15**.

15 vppm NO_x (15 % O_2) with CO values below 5 vppm and UHC values below 1 vppm (15 % O_2) could be achieved without difficulty. These low emissions were obtained in the 50 % to 100 % load range.

Pulsation

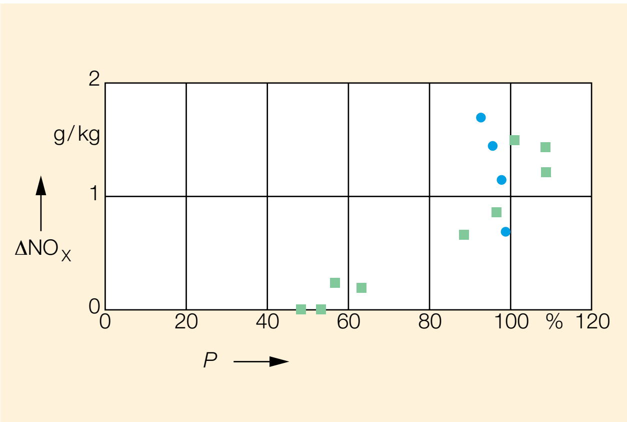
The occurrence of pressure pulsation in a gas turbine combustor can cause large machine parts (eg, the liner segments) to vibrate. If the pulsation amplitudes are high or if the design is inadequate, damage to the fixations can result. The design of the machine parts and their fixations therefore focused on, among other things, making sure that all of the large parts are connected and that there is forced damping. As a result, the robust construction of the GT24/GT26 turbines is able to withstand high vibration levels. In spite of this, the pulsation of the combustors is monitored by measuring the pressure fluctuation inside the combustor. The excited frequencies lead in most cases to standing waves, making it important to measure in regions where maximum amplitudes occur. These positions were determined by measurement of the pulsation at several locations along the combustor. The evaluation of the measurements allows the pulsation to be investigated, with one position taken as the standard measurement. The measurements are evaluated in the range of 1 to 1000 Hz.

The pressure pulsations measured inside the combustors with the GT24 running on gas are shown in **16**. During loading with EV pilot operation, the measured pulsation level was about 25 mbar rms. During the 1 s duration of the EV burner

Measured NO_x formation in SEV combustor (rig test) **14**

ΔNO$_x$ *NO_x formation*
P *Relative machine load*

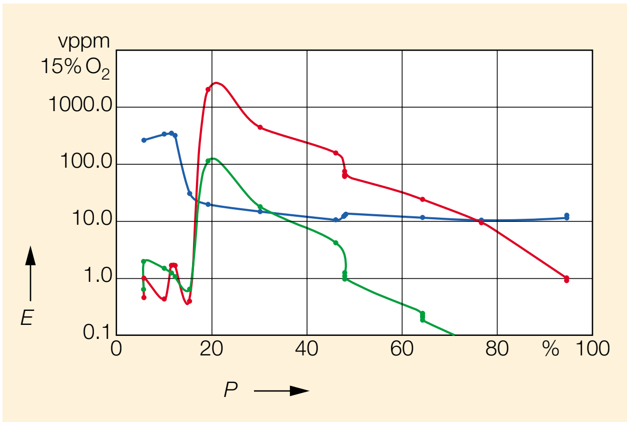
Green *Operation with gas*
Blue *Operation with oil*

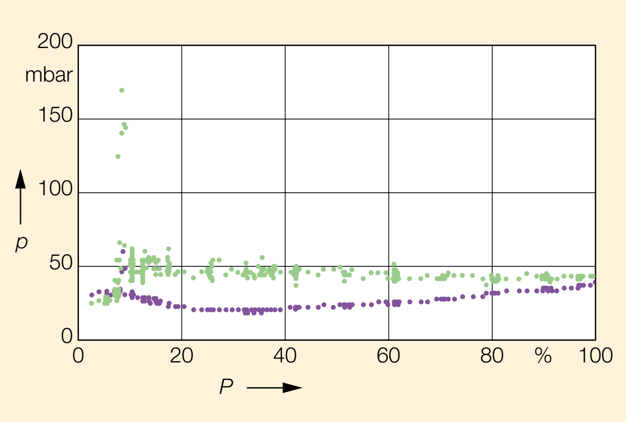


Emissions measured for a GT26 operated with gas at the ABB test center; ultra-low-emission run **15**

E *Emissions*
P *Relative machine load*

Blue *NO_x*
Red *CO*
Green *UHC*

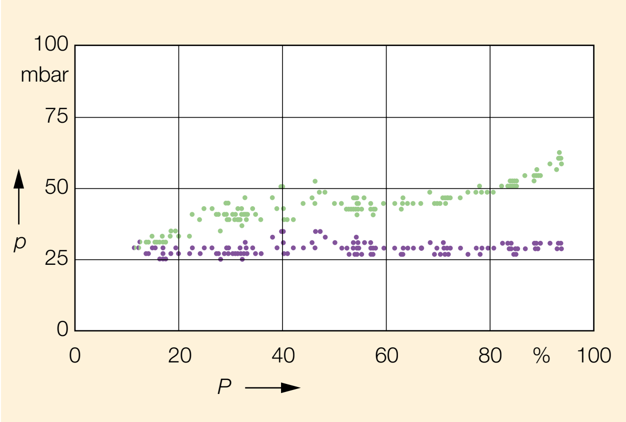




Measured pulsation for a GT24 operated with gas **16**

p *Pulsation (rms)*
P *Relative machine power*

Green *Pulsation in SEV combustor*
Purple *Pulsation in EV combustor*



Measured pulsation for a GT24 operated with oil **17**

$\dot{m}_{water}/\dot{m}_{oil}$ EV = 1.2; $\dot{m}_{water}/\dot{m}_{oil}$ SEV = 1.0

p *Pulsation (rms)*
P *Relative machine power*

Green *SEV combustor*
Purple *EV combustor*

switchover from pilot to premix operation, a short-time pulsation peak can be observed due to the change in location of the flame in the EV burner. During premix loading, the pulsations of the EV combustor are always below 50 mbar. Similarly, the pulsation levels of the SEV combustor are always below those of the EV combustor.

The pulsation levels during operation with oil can be seen in **17**. In the case of the EV combustor the pulsation levels remain always at about 30 mbar, while the SEV pulsations increase during loading from 30 to 60 mbar rms. All the measured pulsation levels are acceptable for long-term operation.

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