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Safety Aspects and Environmental Considerations for a 10 MW Cogeneration Heavy Duty Gas Turbine Burning Coke Oven Gas with 60% Hydrogen Content

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INTRODUCTION

A customer of European Gas Turbines GmbH processes coal tar into chemical intermediate and final products. Continuous production throughout the year requires a peak electrical power of 10 megawatts and a continuous supply of approximately 30 tons per hour of superheated steam at a pressure of 41 bar. To cover these needs the customer chose a heavy duty gas turbine, type G3142J driving a generator. The exhaust gas from the gas turbine is fed to a waste heat boiler for steam production.

As a primary fuel, coke oven gas with over 60% hydrogen content and a lower heating value (LHV) of 4.78 kWh/m³ is available. The standby fuel is light distillate oil "EL" corresponding to DIN 51603. The high hydrogen content of the fuel gas required special design features for safety reasons. It was therefore considered necessary to provide an inert gas buffer, in this case nitrogen, which is inserted as a plug into the fuel gas system when changing over from liquid fuel to coke oven gas, in order to prevent formation of oxyhydrogen at the transition point. In addition to the complicated arrangement of valves for the nitrogen buffering, also the fuel oil nozzles need to be continuously purged with air during gas-fired operation, to prevent formation of condensate in the manifold and coking of the fuel nozzles.

Sophisticated control and regulation systems are necessary to monitor and control the sequencing of valves. Further measures were necessary because of the hazardous conditions and for explosion proofing. Redundant monitoring equipment and also extensive ventilation systems were installed.

To comply with current environmental requirements of the German clean air act (TA Luft) which limits emissions of nitrogen oxides and carbon monoxide, a part of the steam generated by the waste heat boiler was branched off and used for reduction of nitrogen oxides and augmentation of power output. This steam is injected into the combustion chamber. The high hydrogen content of the fuel gives a higher flame temperature than natural gas, therefore higher steam injection rates are required to reduce the nitrogen oxides. On the other hand, the CO_2 content of the exhaust gas is relatively low.

GENERAL LAYOUT OF PLANT

The principal components of the plant are the gas turbine, the load gear, the generator, the control and regulation systems, the waste heat boiler, and the combustion air filter system. These are shown in the block diagram of the plant, Fig. 1.

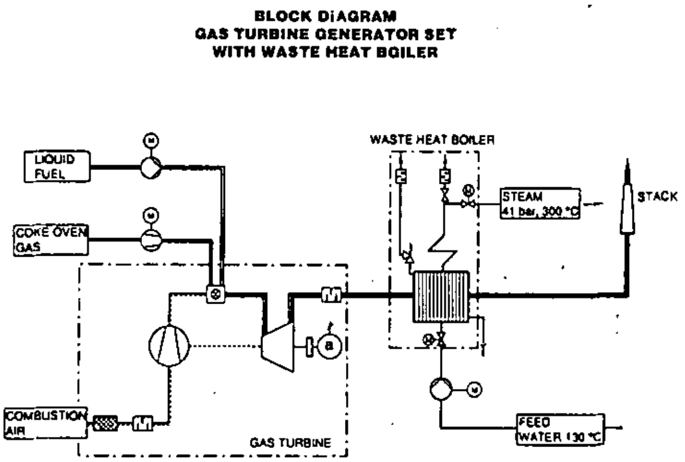

FIG. 1 BLOCK DIAGRAM

Presented at the International Gas Turbine and Aeroengine Congress and Exposition
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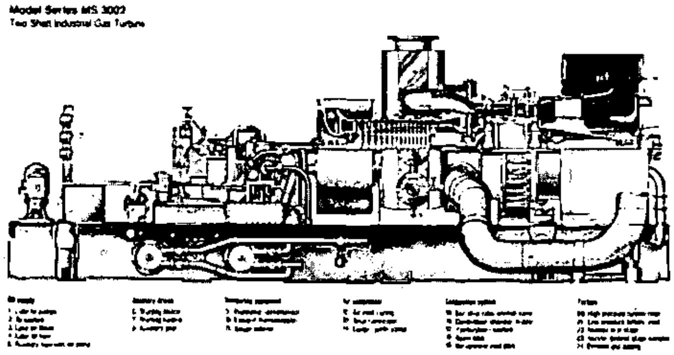

FIG. 2 G3124J GAS TURBINE

Fig. 2 shows a cross section of the turbine. More than 1000 of the G3142J gas turbines have been installed all over the world to drive natural gas compressors or electrical generators. This turbine is of proven reliability. The technical data of waste heat boiler, generator, and gas turbine, for this industrial application are summarised in Tables 1, 2, and 3. This power plant is a typical gas turbine installation with recovery of waste heat for industrial process use. Despite the conservatively chosen turbine firing temperature of 943°C, and an air compression ratio of 7.15:1, the good overall efficiency and the output shown in Table 3 are possible. The air throughput is 52 kg/s.

TECHNICAL DATA OF WASTE HEAT BOILER	
• MANUFACTURER :	STANDARD KESSEL
• FEED WATER TEMPERATURE :	130 °C
• STEAM PRESSURE :	41 BAR
• STEAM TEMPERATURE :	300 °C
• STEAM CAPACITY :	29,7 T PER HOUR
• PINCH POINT :	20 °C
• EXHAUST GAS TEMPERATURE :	532 °C
• NATURAL CIRCULATION	
• TOTAL WEIGHT :	200 T

TABLE 1 WASTE HEAT BOILER

LIQUID AND GASEOUS FUELS

However, the most uncommon and most technically interesting feature of this plant is the fuel, it uses: coke oven gas containing a high percentage of hydrogen. The coking of coal produces coke oven gas and also tar, ammonia, and crude benzol. The proportion of coke oven gas produced depends on the proportion of volatile constituents in the coal: low-gas coals give a higher proportion of hydrogen in the coke oven gas than high-gas coals having a high volatile content. Coke oven gas is obtained as crude gas, and then cleansed to give so-called clean gas, free of hydrogen sulphide, hydrogen cyanide (HCN) and residual ammonia (NH_3).

TECHNICAL DATA OF GENERATOR	
• TYPE	: AEG - DKBL 807 /04
• PROTECTION	: IP44
• NOMINAL CAPACITY	: 12.6 MVA
• NOMINAL COS PHI (POWER FACTOR)	: 0.8
• NOMINAL VOLTAGE	: 10.5 KV
• NOMINAL CURRENT	: 693 A
• NOMINAL FREQUENCY	: 50 HZ
• NOMINAL SPEED	: 1500 RPM
• TOTAL LOSSES	: 288 KW
• *EFFICIENCY (100% LOAD AND COS PHI = 1)*	: 98%
• EXCITATION SYSTEM (ROTATING DIODES)	: ROTADUCT
• AIR COOLED	

TABLE 2 GENERATOR

TECHNICAL DATA OF GASTURBINE	
• TYPE	: G3412J
• TWO SHAFT	
• 15 COMPRESSOR STAGES	
• 2 TURBINE STAGES	
• DUAL FUEL SYSTEM	
• COMBUSTION CHAMBERS	: 3 RIGHT, 3 LEFT
• LOAD GEAR	: 6500/1500
• NOMINAL SPEED GAS TURBINE	: 6500 RPM
• ELECTRICAL MOTOR FOR START - UP	
• COMPRESSOR RATIO	: 1:7.15
• TURBINE INLET TEMPERATURE	: 943 °C
• EXHAUST GAS TEMPERATURE	: 532 °C
• NOx EMISSION at ISO - BASE LOAD, COKE OVEN GAS and 1.11 kg/s STEAM INJECTION	: 150 mg/Nm³ (15% O_2)
• OVERALL PLANT EFFICIENCY (STEAM AND ELECTRICAL OUTPUT)	: 77.1 %
• POWER OUTPUT AT ISO CONDITIONS	: 10.6 MW
• TURBINE CONTROL PANEL	: SPEEDTRONIC MK IV

TABLE 3 GAS TURBINE

COMPARISON OF FUEL GASES		
CONSTITUENTS	ANALYSIS OF COKE OVEN GAS (PERCENT, VOLUME)	ANALYSIS OF USUAL GERMAN NATURAL GAS (PERCENT, VOLUME)
CO_2	1.20%	0.13%
N_2	5.40%	0.96%
O_2	0.60%	-
H_2	61.6%	-
CO	6.0 %	-
CH_4	23.0%	97.90%
C_2.	2.20%	1.01%
H_2S	< 1.0 mg/m³	-
LOWER HEATING VALUE (LHV)	4.78 kWh/m³	9.978 kWh/m³
RELATIVE DENSITY (air = 1)	0.329	0.568

TABLE 4 FUEL GASES

HCN and also NH_3, contain fuel-bound nitrogen which can raise the emissions of nitrogen oxides in the turbine exhaust gas. Then it would not be possible to reduce these nitrogen oxides in the combustion process in the turbine by steam injection.

Coke oven gas is used as the main fuel. Liquid fuel, in this case light distillate "EL" corresponding to DIN51603, is used only for starting the turbine or as standby if the supply of coke oven gas fails.

Table 4 shows the composition of the coke oven gas used. For comparison, the table also shows the composition of the natural gas commonly used in Germany. The most striking difference seen is the high percentage of hydrogen in the coke oven gas, over 60% by volume. Of course, a heavy duty gas turbine can burn a very wide range of different liquid or gaseous fuels. When using hydrogen, however, there are important safety aspects to be recognised and complied with to prevent explosions. The lower heating value of coke oven gas is about 50% of natural gas, however firing temperature and standard combustion controls had not to be altered.

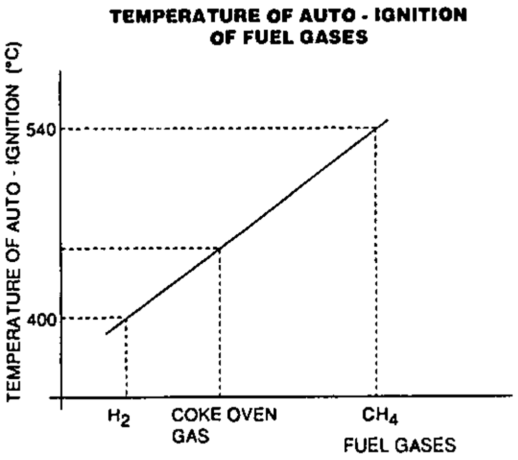

FIG. 3 TEMPERATURE AUTO-IGNITION

The auto-ignition temperature of hydrogen is much lower than that of natural gas. Fig. 3 shows the figures for hydrogen, coke oven gas, and methane. Not only is the lower explosion limit lower, but also the range of explosive concentrations in the air is much wider for hydrogen (4% to 74.5%) and for coke oven gas than for methane (5.3% to 14%). Any hydrogen mixture with air (see Fig. 4), in the range between 4% and 74.5% at ambient temperature is highly explosive.

DESIGN CONSIDERATIONS

To minimize the safety risk, the turbine design takes account of the following special requirements:

- the turbine is always started on light distillate oil (risk of explosion during a restart if the previous start failed using coke oven gas).

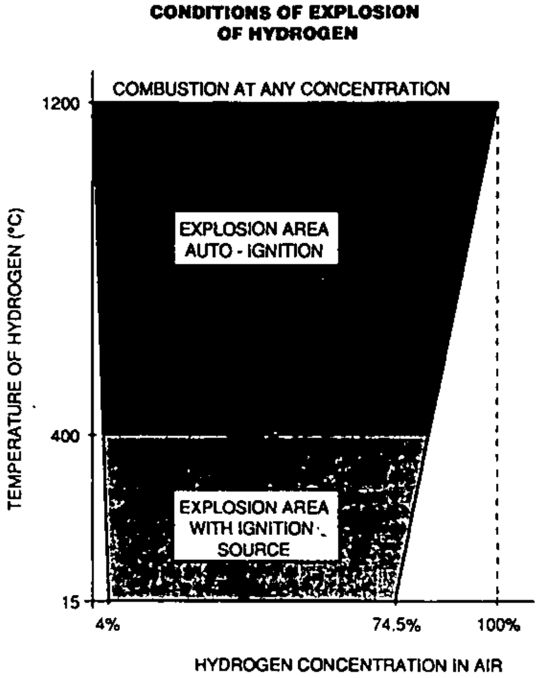

FIG. 4 CONDITIONS OF EXPLOSION

- longer purging cycle of turbine, exhaust duct system and waste heat boiler before each start and after each stop
- forced ventilation of turbine rooms by underpressure and overpressure respectively
- explosion proofing of turbine room and fuel gas cabinet according to VDE 0165, ZONE 2, which corresponds to NEC Class I, Group B, Division II
- exhaust ducts run vertical to be self-ventilating
- avoid any "dead pockets" in the exhaust ducts where coke oven gas could collect
- nitrogen buffering of combustion gas system
- redundant arrangement of gas sensors
- redundant system of flame detectors and ignition spark-plugs
- all gas pipework is leaktight welded, i.e. there are not flanged joints
- electrically ground all pipes and ducts
- special consideration of those materials and seals which come into contact with the coke oven gas
- double-flooding CO_2 fire extinguishing system

- the supply pressure of the coke oven gas is 12-14 bar and the supply temperature 100°C. The dewpoint of the coke oven gas is minus 106°C. The fuel gas is heated to 100°C due to process. Condensate forming which could attack the turbine components is not expected.

VENTILATION SYSTEMS

Special attention was paid to the independent ventilation systems for the accessory compartment, turbine compartment, generator compartment and the fuel gas valve cabinet. Fig. 5 shows a schematic of these ventilation systems. Since coke oven gas is lighter than air, the following design criteria were imposed:

Compartments containing gas pipe flanges or valves are fitted with an underpressure ventilation system (slightly below atmospheric pressure). This means that any leakage is immediately blown out into the atmosphere. Compartments containing no possible leakage sources are held at overpressure (slightly above atmospheric). This prevents any gas-laden air from entering. A common noise hood covers all the compartments, which are separated from one another by bulkhead partitions.

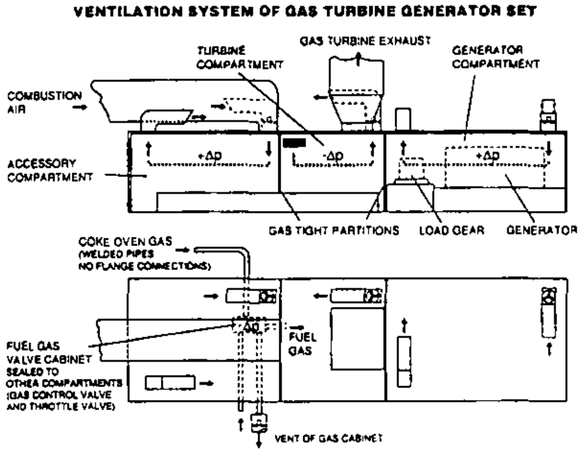

FIG. 5 VENTILATION SYSTEM

The accessory room has an independant overpressure ventilation system.

The turbine room, too, has an independant ventilation, and is held at slight underpressure. Gas-tight bulkhead partitions separate it from the accessory room and the generator room.

On the generator compartment roof a fan is mounted to create slight overpressure in the room. This fan supports the cooling of the generator.

The fuel gas cabinet contains the gas control valve, the trip throttle valve, and control and monitoring instrumentation. It is sealed gastight, and has forced ventilation. All equipment in the gas cabinet is explosion proofed. The room contains a gas sensor which is linked to the turbine control. If any gas is detected, a rapid shutdown of the turbine occurs immediately and gas pipes are vented. The gas pipe running from outside the gas cabinet to the turbine room has welded joints with no flanges.

FUEL SYSTEM

A dual fuel system with gaseous fuel and light distillate oil is a combination often used for gas turbines. In our case, the distillate oil is used only for starting and as a standby supply. The turbine can be automatically switched form gaseous to liquid fuel or vice versa. When switching from gas to distillate, sufficient time is needed for the fuel pump to run up to speed, and when switching from distillate to gas, sufficient gas pressure has to be available.

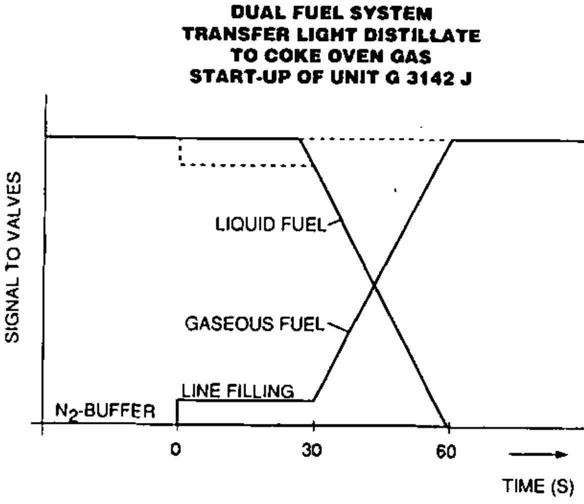

FIG. 6 FUEL TRANSFER

Fig. 6 shows a typical transfer from distillate oil to coke oven gas. The control system of the turbine has the aim to perform this changeover smoothly, without any substantial jerks in the load. After the switchover is completed and the turbine is running on gas, the oil system is purged with compressed air generated by the atomizing air compressor. Oil nozzles are continuously purged with atomizing air during coke oven gas operation.

Here too, sudden jerks in load must be avoided by means of a controlled purging operation, to bring the remaining fuel oil slowly into the combustion chamber. Sudden changes in load during switchover should be held to within 5 to 10% of ISO rated load. Apart from this task, the atomizing air compressor is used mainly to atomize the liquid fuel entering the combustion chamber through the fuel nozzles.

The G3142J gas turbine has six combustion chambers, three on left and three on the right (see Fig. 7), at right angles to the turbine axis. This not only makes it easier for inspection and maintenance of the combustion chambers, but makes it much easier to accomodate the large number of piping systems which a coke oven gas turbine needs. The photographs (Fig. 8 and Fig. 9) show the turbine in the test bed; at this stage not all the systems have been installed. In Fig. 9 the fuel nozzles can also be seen. Each combustion chamber is fitted with a dual fuel nozzle. In the sectional view (Fig. 10), one can see the dual fuel nozzle, part of the combustion chamber, and part of the flame tube. The central nozzle is fed solely with distillate oil. The air atomizing passage forms a ring shape around the oil feed in the front of the nozzle body. At the outermost diameter of the tip of the nozzle, the coke oven gas nozzles are arranged and lead the fuel gas to the swirler.

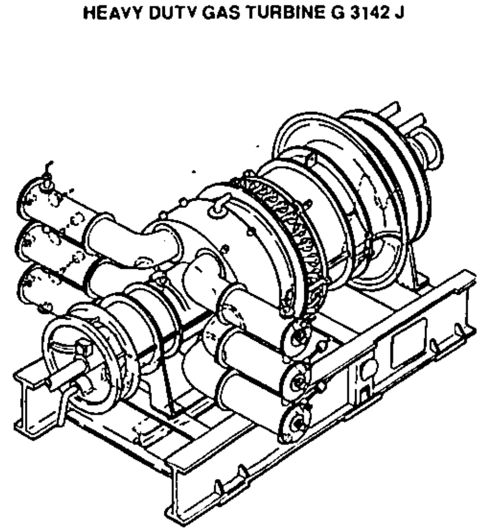

FIG. 7 HEAVY DUTY GAS TURBINE G3124J

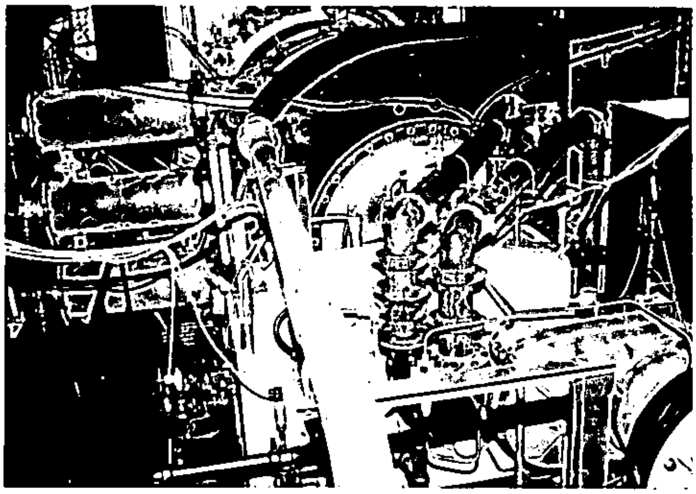

FIG. 8 TURBINE ACCESSORIES

The following pipework systems carrying fuel or other media are installed on the base frame:

- pipe system for coke oven gas
- pipe system for distillate oil
- pipe system for nitrogen buffering
- pipe system for steam injection
- pipe system for air purging, using discharge air from the axial compressor.
- pipe system for air purging, using air from atomizing air compressor.

These systems are easier to understand from a diagram (Fig. 11).

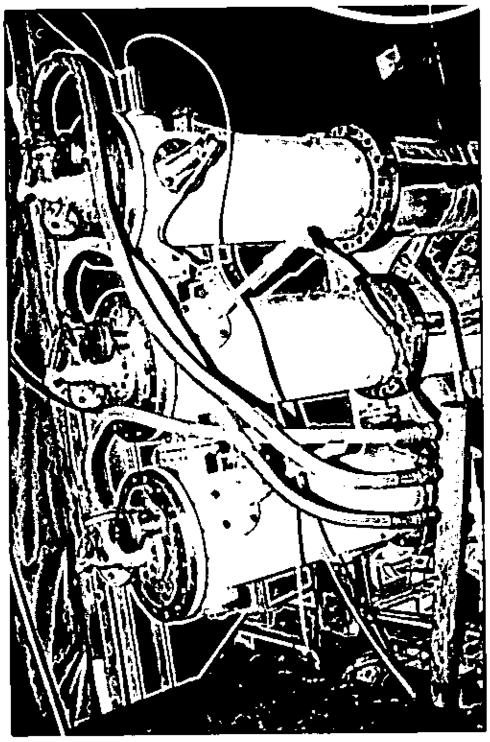

FIG. 9 COMBUSTION CHAMBERS

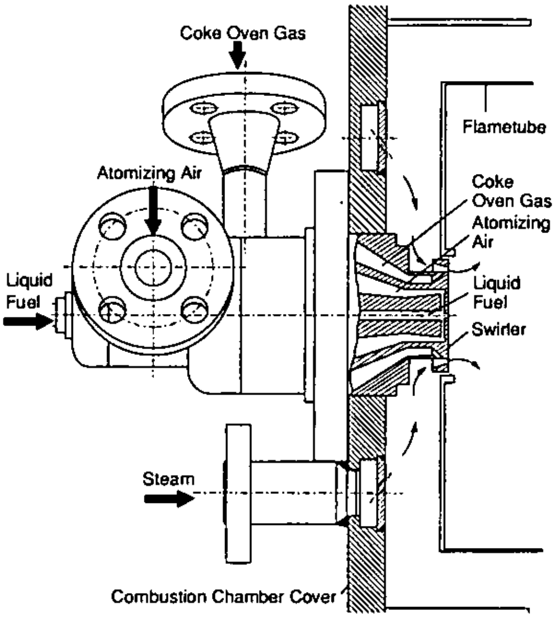

FIG. 1D DUAL FUEL NOZZLES

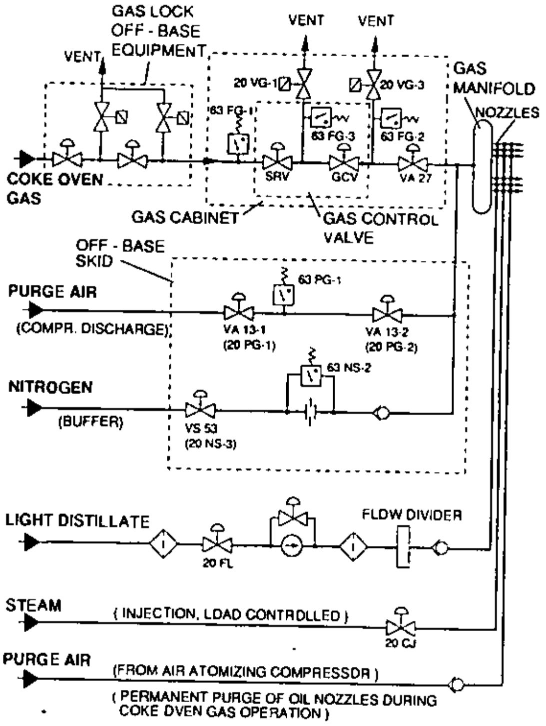

FIG. 11 FUEL DIAGRAM

The fuel system is fitted with an additional offbase gas lock, and there is an additinal shut-off valve (VA27) in the gas cabinet.

For a dual-fuel machine with fuels containing more than 5% of hydrogen, buffering is compulsory. Buffering with an inert gas during switchover from oil to gas or gas to oil prevents any explosive mixture forming in the fuel gas manifolds between the shut-off valve (VA27) and the fuel gas nozzles. When the gas turbine is being run on liquid fuel, the gas system is purged with air from compressor discharge to prevent any flow back through the gas nozzle ducts into other combustion chambers. This compressor discharge air, which is hot, would form an explosive mixture with the coke oven gas, so that when changing over to gas it is necessary to purge with nitrogen for a brief period. This nitrogen plug is fed into the system near valve VA27 in adequate quantity at the right time.

The nitrogen buffering is needed both when starting up the turbine and during normal shut-down (light distillate oil is always used for starting-up and normal shutting-down the turbine).

The amount of nitrogen depends on the number of times fuel is switched between gas and oil (see Fig. 12) and can be calculated, i.e.:

$G_n = V_p \cdot n \cdot \varrho$ where
G_n = mass of nitrogen (kg) for one transfer
V_p = volume of the pipework to be purged (m³)
n = number of nitrogen changes (3x to 5x)

and ϱ = 1.25 kg/m³ (specific weight of nitrogen)

During both gas and oil operation, steam is injected into the combustion chambers depending on the load: this reduces oxides of nitrogen and increase the output.

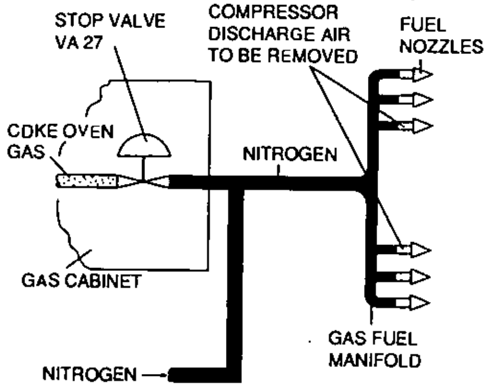

FIG. 12 NITROGEN BUFFER

The wide variety of different valves which the fuel sytstem needs and the sequence of opening and closing are controlled by the Speedtronic MK IV turbine control. Table 5 shows part of the sequence logic.

DUAL FUEL SYSTEM
LIGHT DISTILLATE / COKE OVEN GAS

TABLE OF VALVE POSITIONS VERSUS OPERATING MODES

OPERATION MODES / VALVE POSITIONS	SRV / GCV GAS CONTR. VALVE	VA 27 GAS STOP VALVE	VS 53 NITROGEN VALVE	VA 13-1 PURGE AIR VALVE	VA 13-2 PURGE AIR VALVE	20 VG-1 VENT VALVE	20 VG-3 VENT VALVE	20 FL LIGHT DIST. VALVE
STARTING CYCLE AND OPERATION WITH LIGHT DISTILLATE - GAS NOZZLE PASSAGE WAYS WILL BE PURGED WITH COMPR. DISCHAR. AIR DURING OPERATION	C 0	C 0	C 0	O 1	O 1	C 1	O 0	O 1
INITIATION TO TRANSFER FROM LIGHT DISTILLATE TO COKE OVEN GAS, NITROGEN BUFFER IN OPERATION	C 0	C 0	O TD 1	C 0	C 0	C 1	O 0	O 1
TRANSFER FROM LIGHT DISTILLATE TO COKE OVEN GAS, PURGESYSTEM (COMPR. DISCHAR.) IS OFF	O 1	O 1	C 0	C 0	C 0	C 1	C 1	O 1
GAS OPERATION, PURGE SYSTEM (COMPR. DISCHAR.) IS OFF. ATOMISING AIR THROUGH OIL NOZZLES IS ON.	O 1	O 1	C 0	C 0	C 0	C 1	C 1	C 0
TRANSFER FROM COKE OVEN GAS TO LIGHT DISTILLATE, PURGE SYSTEM (COMPR. DISCHAR.) IS OFF.	O 1	O 1	C 0	C 0	C 0	C 1	C 1	O 1
LIGHT DISTILLATE OPERATION, NITROGEN BUFFER IN OPERATION (SHORT INTERVALL)	C 0	C 0	D TD 1	C 0	C 0	O 0	O 0	O 1
LIGHT DISTILLATE OPERATION, PURGE SXSTEM (COMPR. DISCHAR.) IS ON FOR GAS PASSAGE WAYS.	C 0	C 0	C 0	O 1	O 1	O 0	O 0	O 1
NORMAL SHUT DOWN OF TURBINE	C 0	C 0	C 0	O 1	O 1	O 0	O 0	O 1
TRIP	C 0	C 0	C 0	C 0	C 0	D 0	O 0	C 0

NOTES: O = VALVE OPEN
C = VALVE CLOSED
0 = INDICATES SOLENOID OF VALVE DEENERGIZED
1 = INDICATES SOLENOID OF VALVE ENERGIZED
TD = VALVE FUNCTION TIME DELAYED

TABLE 5 OPERATING MODES

The design must not only cope with normal working sequences, but must also allow for the unexpected events. For turbine trip while it is running on coke oven gas, SRV, GCV and VA27 valves must close and 20VG3 must vent; then a brief purging with nitrogen has to be performed to remove remaining coke oven gas from behind VA27. Before a new start, a thorough purge of the turbine must be carried out.

EXHAUST EMISSIONS, POWER AUGMENTATION AND ENVIRONMENTAL ASPECTS

In the Federal Republic of Germany there a programmes for reducing both NO_x and CO emissions. In 1990, the federal government also passed measures to reach a 25% reduction of energy-related CO_2 emissions by the year 2005 taking 1987 as base year. It is intended that Germany shall play a pioneer role in preventing the so-called greenhouse effect and the threat to the world climate. It is planned to introduce a CO_2 levy to stimulate creative technological solutions and motivate users. German industry, however, does not share this view and fears that this CO_2 tax will distort competition. Certainly there is no simple political answer. But from a technical viewpoint:

- The primary way to reduce total CO_2 emissions is by improving the efficiency of electricity generating plants, and for users to be conscious, economical and avoid waste.
- A substantial contribution can be made by using fuels containing less carbon or none at all, i.e. hydrogen technology becomes very actual.

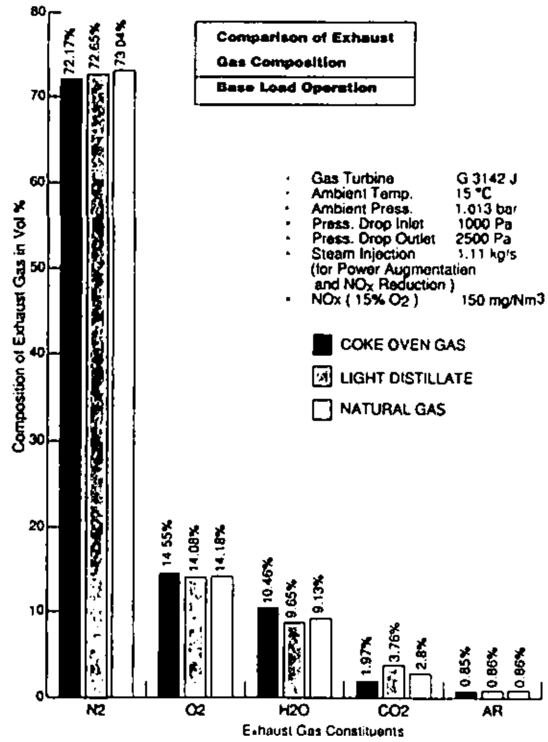

FIG. 13 COMPARISON EXHAUST GAS

The coke oven gas used as fuel for the G3142J turbine fulfils these requirements. Fig. 13 shows for comparison the composition of the exhaust gas when the turbine would be run on natural gas, distillate oil, or coke oven gas. Under these operating conditions, that is, 15°C ambient temperature and base load, the percentage of carbon dioxide in the exhaust gas is 2.80 % using natural gas as fuel, 3.76% using distillate oil, and 1.97% using coke oven gas.

Converting these figures to kilograms per hour the large difference in CO_2 emission can be seen.(table 6)

COMPARISON OF CO_2 EMISSIONS

BURNING DIFFERENT FUELS
IN GAS TURBINE G 3142 J
BASE LOAD, 15°C AMBIENT TEMPERATURE
PRESS. LOSS INLET/OUTLET: 1000/2500 PA

	LIGHT DISTILLATE	NATURAL GAS	COKE OVEN GAS
CO_2 IN PERCENT (VOL) OF EXHAUST GAS	3.76%	2.80%	1.97%
CO_2 IN KG / H	7285	5363	3794
DIFFERENCE IN PERCENT TO LIGHT DISTILLATE	—	26%	48%
DIFFERENCE IN PERCENT TO NATURAL GAS	—	—	29%

TABLE 6 CO_2 EMISSIONS

The percentage improvement by using coke oven gas instead of natural gas is 29%, and by using coke oven gas instead of distillate oil 48%. Comparing these CO_2 figures with the federal government's targets, it is clear that this is a step in the right direction.

The nitrogen oxide emissions from gas turbines have already for a long time been regulated by the "TA Luft" clean air regulations in Germany. The clean air regulations of 1986 are now modified by a dynamising clause of 1991, such that a gas turbine with a thermal output of less than 100 MWth must not emit more than 150 mg/Nm³ of NO_x, related to 15% oxygen in the case of gaseous fuels. The G3142J turbine falls in this category.

It is known that NO_x emissions are strongly dependent on the flame temperature and on the dwell time of the particles in the high temperature zone within the combustion chamber. Coke oven gas has a higher flame temperature than distillate oil or natural gas. Fig. 14 shows the relationships. Therefore the coke oven gas forms approximately 70% more NO_x in the combustion process than natural gas.

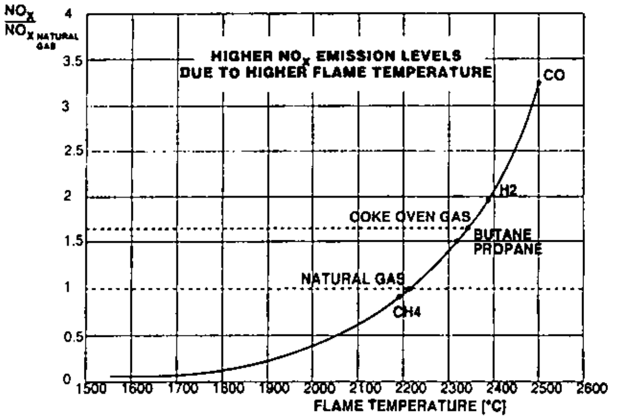

FIG. 14 EMISSION LEVELS

At present, the most economical way of reducing NO_x is to inject steam. This is particulary true if steam is available from a waste heat boiler, or if power augmentation of the turbine is desired to meet the electricity demand. In the present application, both these conditions apply. The output from the gas turbine is augmented by injecting steam, primarily because it raises the throughput of the turbine, but also more fuel is used, since it has to heat the steam to the temperature on the turbine inlet. This improves the thermal efficiency and augments the output power of the turbine. Fig. 15 shows this in comparison. Raising the amount of injected steam increases turbine output power and lowers NO_x emissions. At a steam input of 1.11 kg/s, we achieve the required limit of 150 mg/Nm³ NO_x in the exhaust gas, at 1.48 kg/s only 100 mg/Nm³ are emitted and the power increases are 6% respectively 9.4%.

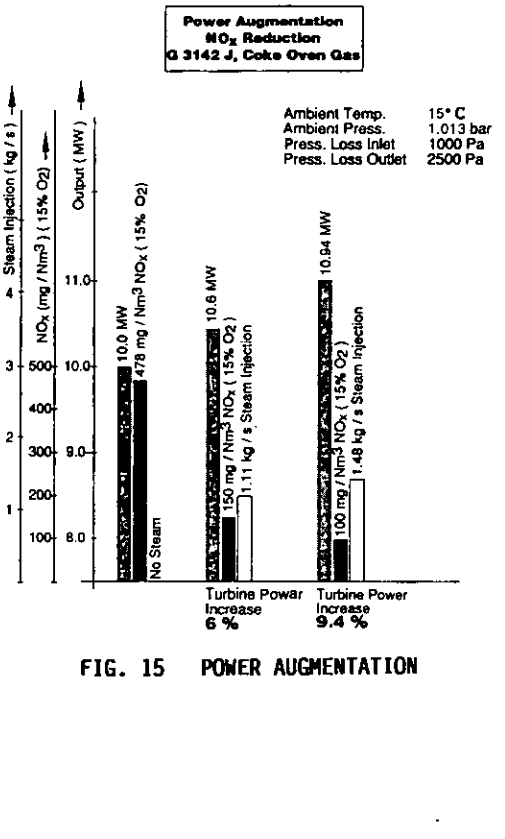

FIG. 15 POWER AUGMENTATION

SUMMARY

More than one thousand gas turbines of model G3142J have been built and installed. But the application described here is the first time the turbine is being operated with coke oven gas with over 60% hydrogen content. Special safety precautions in design, construction and operation of the whole plant demanded creative technical solutions.

As already mentioned, heavy duty gas turbines -rather than aircraft engines- can contribute to worldwide demands to reduce air pollution and prevent the global greenhouse effect by reducing CO_2 emissions. Worldwide, gas turbine manufacturers are spending large amounts on research and development to minimise emission of oxides of nitrogen and to improve the efficiency of the turbine sets. It is still cheaper to use non-renewable fossil fuels such as natural gas or mineral oil than pure hydrogen. New technologies must change this for the future.

Gas turbines of heavy duty design such as the G3142J are already today capable of generating electricity from low-carbon or zero-carbon fuels and producing low-CO_2 emissions. Production of coke oven gas is certainly economical at the present day, while generating hydrogen by electrolysis of water is not yet economical.

The high cost for the increased safety measures, when using hydrogen fuels, is necessary to protect the plant and personnel. Reducing NO_x, CO and CO_2 helps however preserve our environment.