EUROPEAN COMMISSION
DIRECTORATE GENERAL XVII - ENERGY

PROVISION OF SERVICES FOR ASSISTANCE WITH CO-ORDINATION AND TECHNICAL SCIENTIFIC MONITORING

ENERGY FROM BIOMASS AND WASTE; TARGETED PROJECTS

TTM CONTRACT No. 6.75151/M/98-010

Technical Report

on

MITIGATION OF GAS TURBINE PROBLEMS AND PERFORMANCE FOR BIOMASS IGCC: EXPERIENCES IN EUROPE AND US. LESSONS LEARNT FROM COAL IGCC

Prepared by

CRE Group Ltd

CRE Ref No. 7996/3 April 1999

MITIGATION OF GAS TURBINE PROBLEMS AND PERFORMANCE FOR BIOMASS IGCC: EXPERIENCES IN EUROPE AND US. LESSONS LEARNT FROM COAL IGCC

Executive Summary

The objective of this study was to determine the experiences gained from the utilisation of gas turbines in coal fired integrated gasification combined cycle (IGCC) systems. Then to transfer the lessons learnt to benefit the development of biomass IGCC (BIGCC) systems. There are a number of BIGCC now under development world-wide. BIGCC is at an earlier stage of development than Coal IGCC (CIGCC). Because of this, there are a number of areas where BIGCC can benefit from the experiences already learnt in CIGCC projects. One area in particular, is low calorific value gas combustion in modified gas turbines.

To achieve the study objective, a detailed review of the operating performance from all the major coal IGCC (CIGCC) projects completed to date, 8 in total within the EU and the USA, has been completed. The lessons learnt from the review of the CIGCC projects are as follows:

- Gas turbines have been successfully modified on CIGCC plant to burn low calorific value gases. Gases with CVs as low as 4.5 MJ/m^3, e.g. comparable to those likely to be produced in BIGCC plants, have been successfully burnt for over 10,000 hours in a gas turbine integrated into a combined cycle system.

- In general, the can annular type combustion system with diffusion burners has experienced less operational difficulties. The silo type combustor systems such as those used by Siemens, and ABB, had significant operational problems in their early stages of introduction. However, it must be noted that at Buggenum, these problems have now been successfully overcome.

- The gas turbines that have performed most effectively from the commencement of the test programmes were all tested off line prior to installation. In this way, the burners are, therefore, modified and performance tests completed before installation on the plant. This approach greatly reduces the risk of later operational problems with the gas turbine combustors, which can lead to significant gas turbine down times and loss of revenue.

- The emissions of NOx produced by the gas turbines meet all the necessary environmental requirements. The technique of injecting diluent water or nitrogen to reduce peak flame temperatures in the gas turbine combustors to control NOx has performed extremely well.

- The use of particle filters before the turbine is a useful back up tool to prevent extraneous material in the syngas duct work damaging the turbine. Also, the use of in-duct particle monitors to give early warning of dust leaks to allow the turbine to be switched to back up fuel seems to be an extremely useful piece of additional instrumentation.

- Whilst not a direct turbine issue, careful attention to the operation of the gas clean up system prior to the gas turbine is essential to prevent damage to the gas turbine and reduce operational down time.

- All of the plants have separate start up fuels and the capability to switch from syngas to the back up fuel as necessary. Many of the plants regularly switch to their back up fuel to maintain their generation of electricity to the grid. This practice assures continued income generation for their plants in the event of gasifier or other plant problems.

- Syngas is both toxic and explosive and adequate attention must be paid to the special safety features that are required both during the design and operating phases of the CIGCC plant. Detailed safety procedures to prevent explosions and operator exposures need to be put in place and back up monitoring undertaken to ensure that procedures are being followed closely.

- The control logic for the turbine must be fast enough to deal with instantaneous plant changes. The control procedure for the turbine must be linked to a fast data acquisition system and the control procedures for the turbine integrated fully with the control systems and logic for the other CIGCC plant constituent components

The conclusions drawn, give confidence that gas turbines can be successfully modified for use with air blown gasification plant that are used in BIGCC systems. The main lessons that can be transferred to BIGCC systems, based on the CIGCC experiences, are as follows:

1. Turbines for projects should be sourced from manufacturers with experience and expertise in the combustion of low calorific value fuel gases and who are aware the necessary safety requirements for syngas handling.

2. Diffusion burners are the accepted industry standard for combustion of low CV gas and should be the preferred choice for all projects.

3. To gain confidence in the satisfactory performance of the turbine and to minimise operating risk gas combustion trials should be completed off-line prior to the formal selection of the turbine as an Approval stage. The costs for this activity need to be built into the project development costs or covered by the manufacturer as part of their sales package to the customer.

4. Careful attention to the operation and maintenance of the gas clean up system is essential to maintain the integrity of the gas turbine during the plants operating life.

5. Consideration should be given to building in fail safe devices such as, particle filters, dust and/or tar monitors before the turbine to prevent extraneous material from downstream operations contaminating and damaging the turbine.

6. In the case of current BIGCC plants NOx emissions are expected to be low, because of the presence of some 35-45% nitrogen in the fuel gas due to the fact that the gasifiers will be air not oxygen blown typically.

7. The control system for the gas turbine needs to be fast enough to deal with fast transient conditions from the gasifier, manual control is too slow. The control loop for the turbine needs to be integrated into the control philosophy for the whole plant.

BIGCC is at an earlier stage of development than CIGCC. It does, however, share many common development issues, in particular low calorific value combustion and firing in combined cycle systems. Eight Biomass IGCC plants have been identified world-wide, 4 in the EU, 3 in the USA and one in Brazil. Of the EU plants, three (Energy Farm, North Holland and ARBRE) are supported by the Thermie programme. Only one plant (the Värnamo plant in Sweden) is operational as a complete cycle; all the rest are in the planning/construction stage. Most of the new plants will not come on stream before the turn of the century. The non European projects are all being phased with installation of the gasifier and proving trials on the gasifier proceeding before the introduction of the gas turbine. One positive point to note is that it would appear that concerns regarding the use of turbine manufacturers with direct experience of low calorific value syngas have been addressed by most of the current project developers. Also, where there are uncertainties in the operation of the gas turbine combustor that proving trials, effectively 'acceptance tests', have been completed, or are planned, before the turbine is installed. This approach should reduce future down time due to combustion related issues in the gas turbine.

There are a number of lessons from the current BIGCC plants that raise areas for concern for future BIGCC projects that need to be noted. One area of concern for the turbine manufacturers would appear to be the variability in the syngas composition with different biofuels. This is particularly relevant where multiple sources of biofuel will be used in BIGCC plants. The turbine manufacturers need to be aware at an early stage in the project the likely ranges in syngas quality that can be expected.

A second area of concern, particularly relating to pressurised gasifiers, is the use of ceramic candle filters for dust removal prior to the gas turbine. Experience at Värnamo with the candle filters (persistent breakage's) was consistent with early problems with these systems encountered at the Buggenum and Wabash River CIGCC plants. The collective experiences of the CIGCC operators in candle filter design should be pooled for benefit of the development of future pressurised BIGCC projects. Where ceramic candle filters are employed, it is strongly recommended that serious consideration should be given to building in fail safe devices such as, extra particle filters and/or dust monitors before the turbine to prevent extraneous material from downstream operations damaging the turbine.

The issue of syngas nitrogen concentrations (ammonia and hydrogen cyanide) on overall plant NOx emission is an area of concern for BIGCC plant based on pressurised gasifiers. The Värnamo experience shows that some fuels can generate very high syngas ammonia and hydrogen cyanide concentrations. To minimise NOx emissions in this case there are two options: addition of an ammonia/hydrogen cyanide removal system into the process flowsheet or modification of the combustor design as at MnVAP. At Värnamo, they have a separate side stream experiment to study the selective oxidation of fixed nitrogen species in the syngas to nitrogen. Side stream tests began in late 1998. Results from this and the MnVAP project should be collected and disseminated at the earliest opportunity.

An area of concern for BIGCC plants based on atmospheric pressure gasifiers must relate to the tar cracker. It is essential that this system operates effectively otherwise damage to the turbine will occur. In some of the CIGCC plants, dust detectors are installed upstream of the turbine as a "fail safe" device in the event of dust carryover. These devices, then allow the turbine to be switched to back up fuel to avoid dust ingress and subsequent damage occurring. Similar such devices should be considered for tar carry over, if they are developed suitably for commercial application, until such time that commercial confidence in the operation of the tar crackers renders them unnecessary

It is recommended that, for future BIGCC projects, based on the collective experiences of CIGCC and the new BIGCC projects, it should be possible to develop a code of practice or best practise guide for developers. This code of practise should include advise on areas such as: selection of critical components (gasifier, gas cleaning system and gas turbine), selection requirements for specific components such as the gas turbine, guidelines on safety related issues regarding use of syngas, guidelines on appropriate safety procedures for plant and monitoring procedures and guidelines on control system integration. The code of practice should be developed in close collaboration with equipment manufacturers, project developers and the safety industry.

MITIGATION OF GAS TURBINE PROBLEMS AND PERFORMANCE FOR BIOMASS IGCC: EXPERIENCES IN EUROPE AND US. LESSONS LEARNT FROM COAL IGCC

Contents

Page Nos.

0. EXECUTIVE SUMMARY

Tables

Figures

MITIGATION OF GAS TURBINE PROBLEMS AND PERFORMANCE FOR BIOMASS IGCC: EXPERIENCES IN EUROPE AND US. LESSONS LEARNT FROM COAL IGCC

Bibliography

ABB	Asea Brown Boveri
Ar	Argon
ARBRE	Arable Biomass Renewable Energy
ASU	Air separation unit
BIGCC	Biomass Integrated Gasification Combined Cycle
BTU	British thermal unit
CH_4	Methane
CIGCC	Coal Integrated Gasification Combined Cycle
CRE	CRE Group Ltd
CO	Carbon monoxide
CO_2	Carbon dioxide
CFBC	Circulating Fluidised Bed Combustion
CFBG	Circulating Fluidised Bed Gasifier
CV	Calorific value
DG XVII	Directorate General Seventeen
EC	European Commission
EPRI	Electric Power Research Institute
EPZ	Elektriciteits Productiemaatschappij Zuid Nederland
EU	European Union
FERCO	Future Energy Resources Co. (USA)
FGD	Flue Gas Desulphurisation
GE	General Electric
GT	Gas turbine
H_2	Hydrogen
H_2O	Water
HRSG	Heat Recovery Steam Generator
IGCC	Integrated Gasification Combined Cycle
IGT	Institute of Gas Technology (Chicago, USA)
KRW	Kellogg Rust Westinghouse
kWe	Kilowatt electrical
kWh	Kilowatt hour
KWU	Kraftwerk Union AG
LHV	Lower heating value
MHI	Mitsubishi Heavy Industry
MJ/m^3	MegaJoules per cubic metre
MnVAP	Minnesota Valley Alfalfa Producers
MPa	Megapascal
MW	Megawatts
MWe	Megawatts electrical
N_2	Nitrogen
NOx	Nitrogen Oxides
O_2	Oxygen
PFBC	Pressurised Fluidised Bed Combustion
PICHTR	Pacific International Center for High Technology Research
Ref.	Reference
scf	Standard cubic feet
SIGAME	Wood Gasification Integrated System for Electricity Generation

STP	Standard temperature and pressure
SO_2	Sulphur Dioxide
Syngas	Synthesis gas
TPS	Thermiske Processor
USA	United States Of America
USDoE	United States Department of Energy
vppm	Parts per million by volume
wt.	Weight

MITIGATION OF GAS TURBINE PROBLEMS AND PERFORMANCE FOR BIOMASS IGCC: EXPERIENCES IN EUROPE AND US. LESSONS LEARNT FROM COAL IGCC

1.0 INTRODUCTION AND BACKGROUND

1.1 Introduction

CRE Group Ltd (CRE) has been contracted by the European Commission DG XVII for Energy to supply services to the Thermie programme. These services are to be supplied under the contract: **Provision of Services for Assistance with Co-ordination and Technical Scientific Monitoring, Energy from Biomass and Waste; Targeted Projects**, TTM Contract no. 6.75151/M/98-010.

As part of this contract CRE have been asked by the EC Co-ordinator (Dr Kyriatos Maniatis) to provide technical support to the EC in the form of a series of study reports, initially. The first study report requested cover's gas turbine issues relating to coal and biomass Integrated Gasification Combined Cycles (IGCC). This report, provides the first contract deliverable of the TTM Services contract referenced above.

The report is structured as follows:

- Chapter 1 provides a general background to the need for the development of IGCC for both biomass and coal.
- Chapter 2 provides a summary of the details of the coal IGCC projects completed to date with particular emphasis placed on gas turbine related issues and raises issues that should be considered for low calorific value (syngas) gas use in biomass IGCC projects.
- Chapter 3 provides details of the status of current biomass IGCC projects and draws reference to any notable gas turbine development issues with reference to those highlighted in the coal IGCC review.
- Chapters 4 and 5 cover the study conclusions and recommendations.

1.2 Background to the Development of IGCC

IGCC has been developed by the coal and oil industry to meet an increasing demand for high efficiency fossil fuelled power plant with low environmental emissions. Unless such “clean burning” technologies are developed coal, and to a lesser degree oil, cannot compete with the latest generation of gas fired combined cycle power plants, whose electricity generation efficiencies are some 55%. Within the European Union (EU) there are still significant reserves of coal (some 200 years supply), whilst reserves of natural gas are less significant (50 years supply). The EU will, therefore, be dependent on coal for its energy supply long after the natural gas has been utilised. However, to reduce the impact of coal burning on the regional and global environment it is essential that when coal is burnt in the future, it is burnt as cleanly and as efficiently as possible. Conventional power generation technologies, based on combustion techniques, generate electricity at an efficiency of some 38%. Coal IGCC (CIGCC) on the other hand has the potential to increase the electrical generation efficiency to 45%. This 7 percentage point increase in efficiency means less CO_2 emitted per kWh of electricity generated and helps preserve the EUs fossil fuel reserves. CIGCC plants also reduce significantly the emissions of NO_x, SO_2 and particulates compared to conventional plants, thus reducing acid gas emissions and the ecosystem damage it causes.

Whilst fossil fuels are still expected to play a significant role in the EU’s energy supply in the future other renewable fuels have significant potential. Amongst the range of renewable energy resources, biomass has significant potential. The EUs TERES report estimated the overall potential for biomass energy to be 180 million tonnes of oil equivalent of final energy consumption for the 12 member states. This was by far the largest renewable energy resource identified within the EU.

There are a number of notable environmental advantages for the utilisation of biomass that include:

- **CO_2 neutral**

  Biomass power is one of the most attractive options for addressing global CO_2 concerns. Both biomass growth and conversion involve the recycling of atmospheric carbon, resulting in no net addition of CO_2 to the atmosphere.

- **Reduced acid gas emissions**

  Acid gas emissions from biomass, when it is burnt, are considerably lower than that of coal. The constituents of biomass generally contain much less sulphur and nitrogen than coal, leading to reduced emissions of SO_2 and NO_x compared to coal fired plant.

- **Lower ash production**

  The ash content of biomass is considerably lower than that of coal, therefore during its utilisation much less ash is generated. The ash produced is considered to be non-hazardous and has the potential to be recycled back to the land to act as a growth promoter.

Despite the obvious environmental advantages of utilising biomass, there are a number of market barriers to its introduction. These barriers include:

- The price of the fuel is not competitive with other fossil fuels,
- Fossil fuels prices are stable currently,
- Biomass supplies cannot compete with fossil fuels,
- Biomass has a lower energy content than fossil fuels, therefore, greater masses need to be transported.

Many governments world-wide recognise the benefits of using biomass and also are aware of the market barriers to its introduction. Many of these countries have now introduced subsidies, including direct market support initiatives, tax exemptions and tradable tariffs amongst others to aid the entry of biomass technology into the market place. These actions are aimed at the longer term market, when fossil fuel prices rise and the developed biomass technologies become more competitive and market confidences in the technologies are established.

However, if biomass is to ever compete in the electricity market against fuels such as natural gas, it must be burnt in the most efficient manner possible. Conventional boilers although technically and commercially proven are capable of efficiencies of some 20%. Biomass based IGCC cycles, however, have the potential to generate electricity at efficiencies up to 45%. There is, therefore, considerable interest in the development of Biomass IGCC (BIGCC) throughout the world.

2. COAL BASED IGCC

2.1 Basic Principles of Coal Integrated Gasification Combined Cycle

CIGCC is one of the newer technology developments for power generation. CIGCC is based upon the application of gasification technology with integrated gas and steam turbines in a combined cycle system. Gasification technology is a coal conversion technology that can be further sub divided into three generic types. Each generic type has its own advantages and disadvantages. These generic gasifier types can be classed as:

- Entrained flow gasifiers
- Fixed Bed Gasifiers
- Fluidised Bed Systems

Each type of gasifier differs in the characteristics of the zone where the gasification reaction takes place between the fuel and a restricted amount of air or oxygen, usually in the presence of steam.

In IGCC coal is converted to a fuel gas (mainly carbon monoxide and hydrogen) by reaction with oxygen or air and steam. The fuel gas is cleaned and burned in a gas turbine that generates power. Heat from the gas turbine exhaust and the gasification and gas cleaning plant is used to generate steam that is fed to a steam turbine, generating additional power.

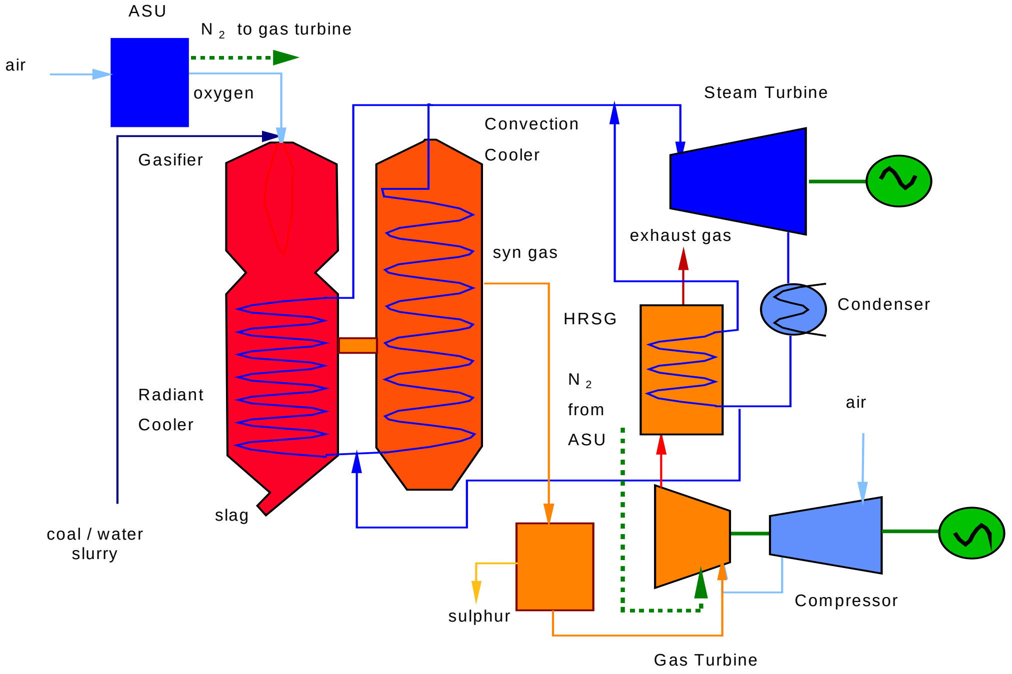


Figure 1 Schematic Representation of a CIGCC Plant

Figure Notes; ASU - Air Separation Unit, HRSG - Heat Recovery Steam Generator

CIGCC is capable of giving even higher efficiencies and lower emissions than other clean coal technologies such as circulating fluidised bed combustion (CFBC) or pressurised fluidised bed combustion (PFBC) with average efficiencies predicted to be over 43%.

CIGCC plants have the lowest environmental impact of all coal based power generation technologies. The designs of the gas clean up system differs depending on the gasification technology used, but the emissions are predicted to be broadly similar. The predicted emissions are:

- 99% sulphur retention.
- NO_x levels of 120-300mg/m^3.
- particulates - negligible.

A comparison of emissions with conventional coal fired plant is given below:

Technology	**CO_2 kg/kWh**	**SO_2 g/kWh**	**NO_x g/kWh**
IGCC	0.78	0.22[1]	0.62
Pulverised fuel plant with FGD	0.87	0.6-0.74[2]	1.76[3]

Notes: 1 - Data based on 1.5% S coal
2 - Data based on two coals of 1.1 and 1.4% S for 500MW plant
3 - Data based on low NOx burners only for 500 MW plant.

Solid wastes from CIGCC plants will potentially be the lowest of all power generation technologies. This is in part due to their higher efficiency reducing the amount of ash produced per unit of electricity generated, but also many of the gasification technologies used reduce the volume of ash produced by slagging the ash in the gasifier producing a non-hazardous vitrified waste stream.

Unlike other power generation technologies, CIGCC technology can be regarded as at the introductory commercial scale. A review of publicly available literature has identified some 23 CIGCC projects world-wide. Many of these projects are still in the planning and design stage.

Figure 2

Thermie Supported ELCOGAS CIGCC Plant at Puertollano in Spain

Within the EU there are two major CIGCC demonstration projects now underway. Two notable points about the European IGCC projects are:

- The largest CIGCC plant to date in the world has just been constructed by ELCOGAS at Puertollano in Spain, with commissioning now underway. The plant, based on PRENFLO gasification technology, (developed by Krupp Uhde of Germany) will have a capacity of 340 MWe and will burn hard coal and pet coke. The ELCOGAS plant is supported by the Thermie programme.

- The most successful of the current CIGCC demonstration plants in the world is the Demkolec plant at Buggenum in the Netherlands. The plant was financed by Demkolec the Dutch utility company. The plant is based on Shell dry feed entrained flow coal gasification technology. The plant uses internationally traded bituminous coal with a sulphur content of 1.5% and has a power output of 253 MWe. Construction started in 1990 and was completed on schedule by late 1993. Since that time the CIGCC plant has completed over 10,000 hours of operation. The plant passed its commercial acceptance trials with the Dutch Electricity Board and has been operating as a commercial power plant within the Dutch electricity grid since 1/1/98.

Figure 3

The Demkolec CIGCC Plant at Buggenum in Holland

2.2 Gas Turbine Developments for CIGCC

Large industrial and aero-derivative gas turbines have been applied and developed for coal IGCC applications since the mid 1970's, albeit in small numbers. The main development area in the development of gas turbines since the mid 1970's has been to increase the efficiency of the gas turbine itself thus maximising the efficiency of the overall IGCC cycle to make it as attractive as possible compared to other coal fired power generation systems. To increase the efficiency of the turbine the inlet gas temperature to the first stator and rotor stage has been progressively increased from 800°C in the early machines to temperatures approaching 1450°C in currently available machines. MHI are now developing a new machine with a turbine inlet temperature of 1415°C using a specially developed alloy for manufacturing the turbine blades. This unit known as the 'G' series machine will be tested in commercial operation in mid 1999. This increase in temperature has required the development of new cooling techniques and metals of construction as well as the application of ceramic liners. GE have developed a new 'H' series machine that uses selected turbine section aerofoils that are steam cooled by an integrated stream cooling system to raise the inlet gas temperature to 1430°C. The first commercial unit will be in operation on natural gas in 2001. Materials technology is currently limiting the scope for further increases in gas turbine inlet temperatures. New design of turbines with ceramic blades that are now in development in the USA will eventually allow another step forward in turbine technology to be made by the middle of this century.

One other controlling factor in the development of high efficiency gas turbines has been NOx emissions. As the firing temperature increases, so does the amount of NOx generated from the conversion of nitrogen chemically bound in the fuel gas, known as "thermal NOx". Since thermal NOx formation is a strong function of flame temperature it can be controlled by controlling the temperature at which the flame burns. Flame temperatures can be controlled by air staging so that high combustion temperatures are reached in stages. This technique avoids sudden peaks of localised temperature resulting from rapid combustion energy release and the achievement of a high temperature in a very small cross sectional area.

The application of low calorific syngases in CIGCC applications has also resulted in a number of developments. The syngases contain high concentrations of CO and H_2. If burnt alone these gases result in very high stoichiometric flame temperatures that would produce much higher NOx emissions than fuels with lower flame temperatures such as natural gas. For syngas applications diffusion burners are used. With diffusion burners' diluents can be injected into the reaction zone to reduce the reaction (stoichiometric flame) temperature. Steam or water injection can be used to control NOx temperatures. As NOx regulations have become increasingly more stringent, higher and higher diluent injection became required to achieve lower flame temperatures, however limitations were found associated with corrosion of combustion parts and thermal performance losses became unacceptable. Reduction of flame temperature (with high rates of diluent injection) can also cause issues relating to combustion stability, particularly in turn down conditions. At low loads the reaction temperature becomes extremely low causing inefficient and unstable combustion. In an extreme condition, this operating mode can lead to 'flame out', which can cause hazardous results in the event of re-ignition before purging of the gas turbine and heat recovery boiler is accomplished. In some cases to maintain stable conditions and prevent the possibility of potentially damaging 'flame out', very low CV gases can be "trimmed" (i.e. mixed) or co-fired with better quality gases, such as natural gas to maintain reliability of performance.

With fuels with high levels of diluent nitrogen such as those from air blown gasifiers, relatively low flame temperatures are achieved without additional diluent and inherently low NOx. The same is true for oxygen blown gasifiers where the syngas is diluted upstream of the turbine by the addition of N_2 or through direct injection of N_2 in to the gas turbine combustor.

One benefit of using low calorific value fuels is a significant performance benefit. The turbines are able to generate a greater power output than on traditional fuels due to the higher flow rate (relative to natural gas) of hot combustion gases expanding through the turbine. GE quote their turbines burning syngas to have a 20-25% higher power rating than on natural gas.

Most of the modern aero-derivative gas turbine designs feature can annular combustor type arrangements, such as those manufactured by GE. This design was principally developed to minimise space requirements, to keep the aeroplane’s weight and drag as low as possible. It is noted that Siemens have now moved away from their traditional silo type combustion system to an annular combustion arrangement, called a “hybrid burner ring”, on their latest generation of high firing temperature (1250°C) Vx4.3A family turbines for combined cycle operation. Siemens predict coal IGCC cycle efficiencies of 46% with the new V94.3A turbine. ABB have also moved toward annular type combustors in their large gas turbine designs. The main reasons for the design change are even flame fronts and temperature distribution combined with more controllability at low NOx levels.

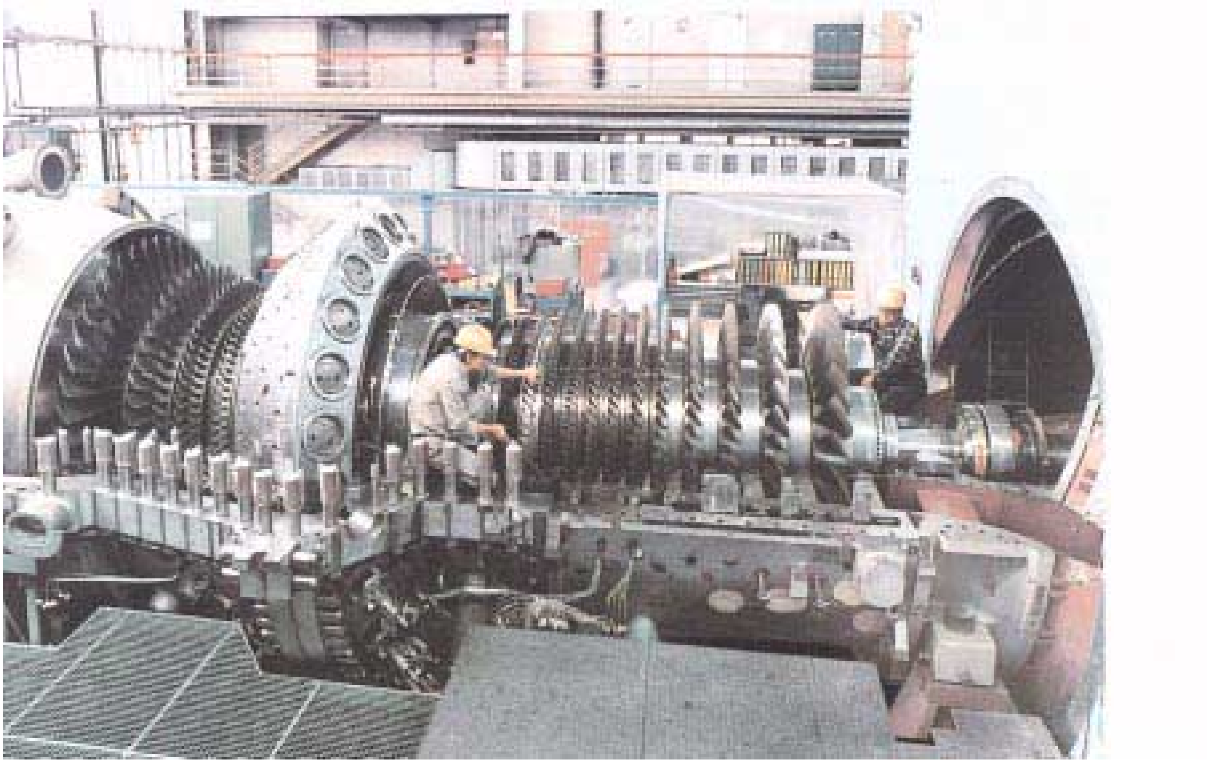


Figure 4

Siemens V84.3A Gas Turbine with Annular Combustion Chamber

Another significant advantage of increasing turbine efficiency and power outputs will be to reduce the net investment for IGCC per kWe. The current oxygen blown CIGCC demonstration plants have installed costs of 1520 - 2711 Euro/kWe ($1640 - $2400 per kWe), which is between 40 and 100% higher than the investment costs for conventional pulverised fuel power plants fitted with FGD. For air blown IGCC the cost differential is even higher.

2.3 History of CIGCC Development and Lessons Learnt.

CIGCC was first demonstrated in the mid 1970s and by 1987 three "first generation" IGCC plants had been built. The first CIGCC demonstration project was the Lünen plant in West Germany that used Lurgi gasification technology. The Lünen plant was built in 1972 and operated until 1977 for a total of 10,000 hours. The power generation output was 170 MW. The longest on-stream operating period was 2,400 hours. Until like most of the later generation CIGCC plant the Lurgi gasifiers were operated with air. The calorific value of the gas produced was 7.8 MJ/m^3. The overall efficiency of the Lünen plant was 34% (HHV basis). This high an efficiency was considered to be a considerable achievement at this stage of IGCC development based on the low efficiency of the gas turbine used compared to more modern designs.

The Cool Water project in the USA, which used Texaco technology plant was the second large scale CIGCC demonstration project. This plant ran from 1984 to 1988. Until the end of 1998, 24,000 hours of operation had been achieved. As operational experience grew so did operational availability. In 1984 on stream availability was 43%, whilst in 1988 it was 92%. The gross power production was 117 MWe and the output was 96 MWe. The electrical generation efficiency was 31% (on a lower heating value basis) which was lower than that achieved at Lünen. The lower efficiency was attributed to lower thermal efficiency in the gasifier and higher auxiliary power consumption costs because oxygen was used instead of air. The low gasifier efficiency is attributed to the use of fuel slurries in the Texaco process. Investment costs were high at $3000/kWe

The third demonstration was the Louisiana Gasification project in the USA using Destec entrained gasification technology. This plant had a gross electrical output of 184 MWe and an output of 160 MW. It ran from 1987 to 1995, and operated for some 42,000 hours over that period (overall availability 60%). As with the Cool Water Plant operational availability improved significantly with time. The electrical generation efficiency at 34-37% was significantly improved over Lünen and Cool Water, but lower than most theoretical predictions for CIGCC technology.

Of particular interest to this study are the developments and experiences in gas turbines that accompanied these early CIGCC developments.

The turbine used at Lünen was a commercially available large industrial turbine supplied by KWU rated at 74 MWe. The gas turbine operating conditions were; turbine entry temperature 810°C and pressure 1 MPa. These operating conditions can be considered modest by modern standards. The standard KWU (now Siemens) gas turbine had two silo combustors connected to the main engine casing by two ducts. The turbine was modified by increasing the air offtake from the compressor (needed because of the large air volume required) and the size of the combustors was increased. Both modifications were needed because of the large air and gas volumes required in this application compared to gas and oil fired models. The combustors were further modified to use steam generating tubes for flame containment rather than the usual air cooled liners and ceramic tiles. By placing superheat surface in the high temperature region of the combustor, heat by-pass was introduced so that necessary additional heat was put into the steam cycle to ensure high steam quality without the need for supplementary firing in the gas turbine exhaust.

The operational problems experienced with the gas turbine at Lünen were corrosion related. The corrosion problem was attributed to carry over of liquids from the scrubbing towers used to clean the fuel gas prior to combustion in the turbine.

At Cool Water a standard General Electric (GE) Frame 7E gas turbine was used. The turbine inlet temperature was 1085°C, considerably higher than that at Lünen. The GE Frame machines use a can annular type of combustion chamber, which consists of a number of small combustor cans centred on the main combustion chamber. The turbine combustors used at Cool Water were specially designed to burn the low calorific value gas (9.2 MJ/m^3 or 265 Btu/Scf) produced from the process. The gas combustors were designed based on trials using a high pressure burner test facility at the GE Schenectady facility in the USA. The burner test facility at Schenectady allows full scale combustor can trials to be completed at high pressure and with synthetic gas mixtures comparable to those to be used on the real plant. Full scale burner development can therefore be undertaken at this plant and any likely problems resolved before the turbine is installed on the IGCC plant. To control NOx emissions the fuel gas was saturated with low grade steam, giving a total water vapour content of 25% prior to combustion. The gas turbine generated some 65 MWe.

Details of the modifications to the gas combustors at Cool Water were not available in public domain documents, despite it being a US DoE supported project. EPRI on behalf of the US Doe undertook an extensive review of the problems encountered during the Cool Water operational programme. The principal problems related to the gasifier and radiant syngas coolers. Turbine associated problems were minimal and there were no reports of any combustion or flame stability problems with the turbine combustors.

The Plaquemine facility used two existing gas turbines designed for natural gas firing on the Dow Chemicals Site. The turbines were Westinghouse 501 machines, which were modified to burn natural gas as well as syngas. The Westinghouse turbine was similar in design to the GE machines in that it has a can annular combustion arrangement. The turbines were able to run on all syngas or natural gas and mixtures in between. NOx control was achieved using water saturation of the fuel gas, as at Cool Water.

The Plaquemine standard gas turbine required several modifications to burn syngas, that included:

- enlargement of fuel delivery components were made to accommodate the higher flow of syngas,
- co-axial injectors were added to allow natural gas to be fired through the centre annulus with steam and/or syngas in the outer annulus,
- an exchanger was added to reheat syngas as a defence against possible corrosion, especially critical during start up,
- a knock out pot and particulate filter were added before the turbine.

The turbine was designed to operate from 0 to 100% on either natural gas or syngas, which required the control logic to be modified to protect the compressor from surge in the event of excessive turbine mass flow requirements.

Two principal problems were encountered. The first problem involved excessive wall temperatures in the gas combustor, which were deemed to be significant enough to reduce the adequate service life of the metal components of the turbine. The overheating was overcome by reducing the velocity of the syngas through the injection nozzles by increasing their diameter. This modification prevented the syngas flame from impinging on the combustor can walls. The second problem involved excessive noise and a non synchronous vibration in the turbine. The source of the combustion behaviour was the switch between natural gas and syngas flow in the centre and annulus passages of the burner. This problem was corrected by increasing the angle of natural gas injection to modify the primary air recirculation flow relative to the momentum vectors associated with fuel and steam injection.

In summary the data available from the first generation CIGCC plants indicates the following key points:

1. Standard industrial gas turbines were successfully modified to operate on medium CV (9-10 MJ/m^3)syngases from oxygen blown gasifiers and lower CV syngases from air blown gasifiers (7.8 MJ/m^3). There were no significant problems reported with flame stability.

2. NOx control was achieved by saturating the fuel gas in the oxygen blown gasifier case. No additional NOx control was used on the air blown gasifiers at Lünen.

3. Close attention to the design of the gas treatment plant and its operation were critical to the operation of the gas turbine.

4. Full scale testing of the syngas combustors prior to installation of the turbine on the CIGCC plant has the potential to significantly reduce operational down time due to turbine related firing problems during later plant operations.

5. The use of additional filters prior to the turbine as a “belt and braces” approach may be considered appropriate.

2.4 Current Coal IGCC Demonstration Projects

There are currently some 23 Coal IGCC projects proposed world-wide. Most of these projects are at the early stages of planning and development. There are, however, 5 major IGCC demonstration projects in operation from which experiences in turbine performance can be drawn. These projects include:

- The Demkolec project at Buggenum in Holland
- The ELCOGAS project at Puertollano in Spain
- The Wabash River repowering project in Illinois in the USA
- The Tampa Electric project in Florida, USA
- The Pinon Pine project in Nevada, USA

Details of these projects are summarised in Table 1 overleaf.

Further details are summarised as follows:

Table 2	Summary details of the gas turbines used and their operating conditions,
Table 3	Gas turbine inlet gas composition data
Table 4	Summaries of gas turbine operating problems encountered.
Table 5	Gas Turbine emissions' data for IGCC demonstration plants.

With regard to the turbines used in these projects, the European projects use Siemens machines whilst all the American projects use GE machines. With regard to Coal IGCC these two manufactures of large aero-derivative combined cycle turbines have the market lead. In the case of the GE turbines these are the current ‘state of the art’ high firing temperature turbines.

It is noted that there are a number of refinery residue IGCC projects under development. The turbine suppliers to these projects are principally Siemens and GE again, but ABB are installing a large syngas turbine for one of these projects. Other manufacturers are therefore developing turbines capable of burning syngas as well as Siemens and GE.

Table 1

Summary Details of Current Main CIGCC Projects

Project	Country	Plant Electrical Output (Net)	Electrical Generation Efficiency	Gasification Technology	Gas Turbine	Degree of Air Extraction from GT Compressor	Installed Cost	Project Status
Demkolec	Holland	253 MWe	43.2% LHV	Shell oxygen blown, dry feed entrained flow process	Siemens V94.2	100%	$1640/kWe (1522 Euro/kWe)	In commercial operation since 1/1/98.
ELCOGAS	Spain	297 MWe	44% LHV	PRENFLO oxygen blown, dry feed entrained flow process	Siemens V94.3	100%	$2400/kWe (2228 Euro/kWe)	Commissioning of plant sub components underway
Wabash River	Indiana, USA	262 MWe	38% LHV	Destec, oxygen blown, wet feed entrained flow process	General Electric Frame 7 FA	0%	$1660/kWe (1541 Euro/kWe)	Plant in operation since November 1995
Tampa Electric	Florida, USA	250 MWe	41.7% LHV Design Figure	TEXACO, oxygen blown, wet feed entrained flow process	General Electric Frame 7 FA	0%	$2000/kWe (1857 Euro/kWe)	IGCC operation commenced in October 1996
Pinon Pine	Nevada, USA	100 MWe	43% LHV	KRW air blown fluidised bed process	General Electric Frame 6 FA	0%	$2920/kWe (2711 Euro/kWe)	Commissioning in progress

Table 2

Summary of Gas Turbine Details for Current Main CIGCC Projects

Project	Gas Turbine	Combustor Type	Degree of Air Extraction from GT Compressor	Gas Turbine Power Output	Gas Turbine Inlet Temperature	GT Efficiency (LHV)	NOx Control Method	Start Up fuel	GT Problems Encountered
Demkolec	Siemens V94.2	Diffusion Burners with Vertical Silo Combustors	100%	156 MWe	1050° C (ISO)	34.5%	Nitrogen injection before GT combustor and water saturation	Gas	Yes
ELCOGAS	Siemens V94.3	Diffusion Burners with Horizontal silo Combustors	100%	195 MWe	1120°C (ISO)	38.5%	Nitrogen injection before GT combustor and water saturation	Gas	Yes
Wabash River	General Electric Frame 7 FA	Diffusion burners with Can Annular Combustors	0%	192 MWe	1288°C	36.2%	Water saturation	Oil	Yes
Tampa Electric	General Electric Frame 7 FA	Diffusion burners with Can Annular Combustors	0%	192 MWe	1288°C	36.2%	Nitrogen mixing in GT combustor	Oil	Yes
Pinon Pine	General Electric Frame 6 FA	Diffusion burners with Can Annular Combustors	0%	61 MWe	1288°C	34.2%	None - gasifier air blown	Gas	Too early in project

Table 3

Gas Turbine Inlet Gas Compositions

Project	**Demkolec***	**ELCOGAS***	**Wabash[#] River**	**Tampa Electric^**	**Pinon Pine[+]**
Major Composition, % by vol.					
H_2	12.3	10.7	28.0	33.8	14.5
CO	24.8	29.2	38.0	48.3	23.9
CO_2	0.8	1.9	10.0	10.0	5.5
N_2	42.0	53.1	1.0	6.1	48.6
CH_4	0	Trace	1.0	0.2	1.4
Ar	0.6	0.6	-	1.1	0.6
H_2O	19.1	4.2	22.0	0.5	5.5
O_2	0.4	0.3	-	-	-
Calorific Value, LHV					
MJ/m^3 (STP)	4.46	4.85	8.29	9.91	5.44
Trace Components, vppm					
Sulphur Compounds	N/A	N/A	100	135	20
Ammonia					200

Notes:

N/A	not available
*	gas composition represents mixed nitrogen and syngas mixture fired in the turbine combustor.
#	gas composition represents steam saturated and syngas mixture fired in the turbine combustor.
^	gas composition represents syngas prior to addition of diluent nitrogen.
+	gas composition as produced from air blown gasifier.

Table 4

Summary of Gas Turbine Problems Encountered And Actions Taken

Project	Gas Turbine	GT Problems Encountered	Actions Undertaken	Problems Solved	Comments
Demkolec	Siemens V94.2	1. Physical damage to turbine from construction debris 2. Gas turbine vibration and noise 3. Damage due to loose burner components	1. GT and compressor blading repaired. 2. Extensive burner modifications undertaken 3. Turbine repairs made	1. Yes 2. Yes 3. Yes	After turbine humming/vibration overcome, no further problems encountered
ELCOGAS	Siemens V94.3	1. Gas turbine vibration and humming	1. Modifications to combustors made to introduce Buggenum experience	1. Status unknown	Limited data on operational status of gas turbine available in public domain.
Wabash River	General Electric Frame 7 FA	1. Turbine flow sleeve cracking 2. Syngas purge control 3. Cracking in Turbine Liners	1. Expansion bellows redesigned and replaced 2. Solenoids replaced 3. Fuel nozzles and liners changed	1. Yes 2. Yes 3. Yes	Early Frame engine problems overcome with no recurrences
Tampa Electric	General Electric Frame 7 FA	1. Y Strainer cracking 2. Turbine damage due to dirty fuel gas because of gas/gas heat exchanger failure.	1. New Y strainer fitted 2. Failed gas/gas heat exchanger removed	1. Yes 2. Yes	Y strainers refitted and particulate leak detector installed to protect turbine
Pinon Pine	General Electric Frame 6 FA	Too early in operating stage	-	-	-

Table 5

Environmental Performance Data

Project	Gas Turbine	Sulphur Retention Efficiency	NOx Emissions	Particulate Emissions
		%	vppm	vppm
Demkolec	Siemens V94.2	98.5	19-33	Negligible
ELCOGAS	Siemens V94.3	Operating data not available		
Wabash River	General Electric Frame 7 FA	99%	13-20	Negligible
Tampa Electric	General Electric Frame 7 FA	96%	17-20	Negligible
Pinon Pine	General Electric Frame 6 FA	Operating data not available		

The projects also fall into a geographical divide with regard to the degree of air extraction used from the turbine. For the projects in the USA there is zero air extraction, but the European projects all use full air side integration. The reason for this partly relates to the turbines used; the Siemens machines are designed for full air extraction only, whilst the GE machines are not. Another factor is fuel price variations between the continents. In the USA, coal prices are lower than in the EU, therefore, the highest efficiency is not necessarily required. Within the EU, coal prices are much higher than in the USA and, therefore, for coal to be competitive with natural gas combined cycle plants then the highest efficiency plant is essential.

In the full integration case, all the air from the ASU is taken from the gas turbine compressor. The gas turbine must start up on back up fuel first before the process of starting up the gasifier train can begin. This procedure can lead to lengthy start up times. The compressed nitrogen from the ASU is then added to the gas turbine for NOx control. In the zero integration case, all the compressor air comes from a separate start up compressor. Zero integration adds to capital costs, because a separate start up compressor is required. The advantages are reduced operational complexity and reduced start up times. In terms of efficiency, full integration is more efficient than zero integration.

The trend in the Coal IGCC market however is to move towards partial integration. In the partial integration case, only a part of the air from the ASU is taken from the gas turbine compressor, while all or part of the nitrogen is sent back to the gas turbine. The advantage of partial integration is that the ASU can start up without the gas turbine running and the configuration offers more operational flexibility. A recent study by Air Products and Shell has suggested that partial integration may be 1 % more efficient than full integration. It is interesting that at Buggenum they have installed a separate start up compressor to meet 50% of the ASU air requirements to reduce start up times. Also, that Siemens have now developed a new turbine range, the Vx4.2AK, that is capable of operating with zero and partial integration, because this is perceived to be the future market requirements.

Of course, the air blown Coal IGCC at Pinon Pine does not require air side integration because there is no ASU.

The main turbine issues at the five demonstration IGCC plants are summarised overleaf

Demkolec

The turbine used at Buggenum was the Siemens V94.2 machine. This turbine uses eight syngas burners situated in each of two silo combustors. This design allowed the syngas burners to be installed into completely unmodified standard flame tubes. Each burner consists of multi annular passages with syngas and natural gas injected via separate passages. Syngas is injected on the outside and natural gas, with steam for NOx control, injected in the centre annulus. The syngas passage contains a swirler, this allows the burners to operate on both syngas and natural gas as required. The gas turbine and combined cycle systems were successfully commissioned on natural gas, with no reported operating problems.

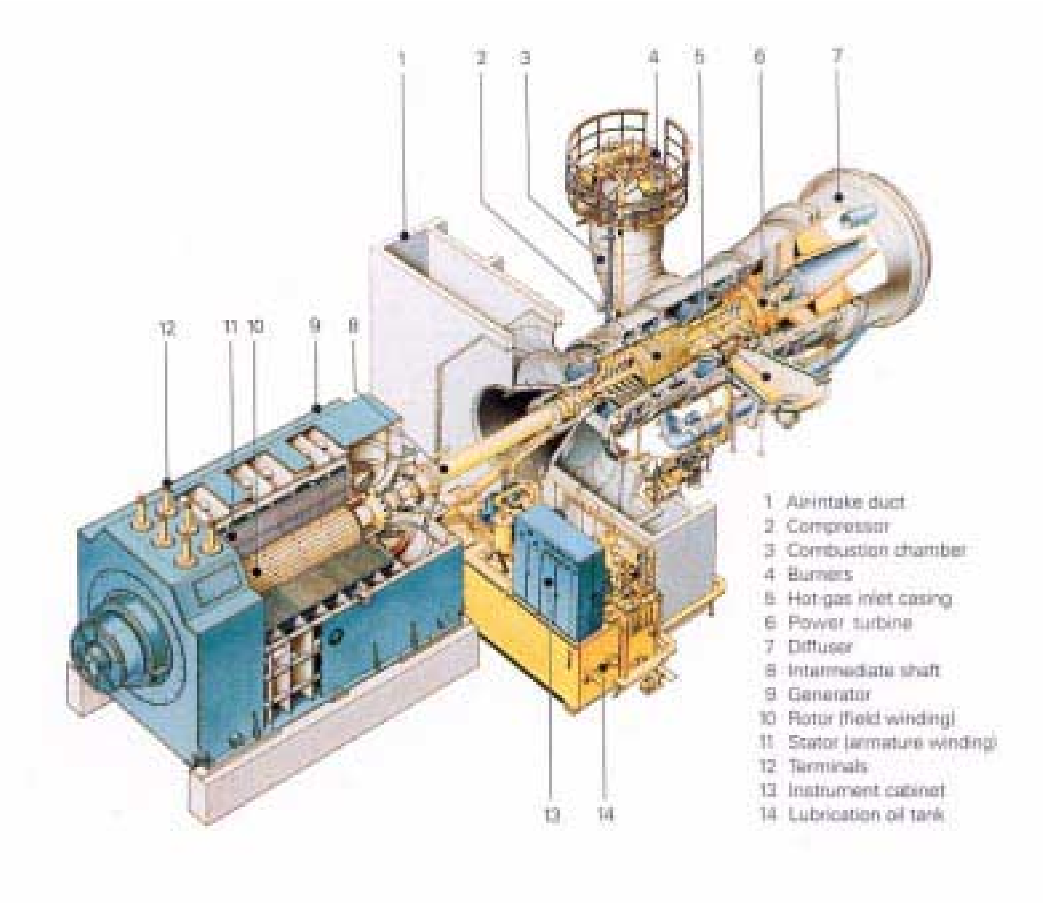


Figure 5

Siemens V94.2 Gas Turbine

In order to burn syngas, the gas turbine combustion and fuel systems had to be modified to accommodate a volume flow that could be more than 3 times the flow experienced with natural gas or liquid fuels. The Buggenum design uses natural gas for start-up and as a back-up fuel so the combustor design has to be able to operate at full load on either fuel. While all conventional aspects of combustion behaved as predicted, the syngas operation was not entirely free of flame induced pressure oscillations that led to unacceptable noise levels. These oscillations occurred first at low load operations and then reoccurred at high load operations on syngas.

The selection of the early V 94.2 turbine for syngas operation may have introduced a possible problem because for a given compressor mass flow, there is a significant increase in turbine mass flow when firing a low CV fuel. This difference between turbine and compressor mass flow might cause surge problems. The solution was to use the surplus air as the total air supply to the air separation unit i.e. total air-side integration that also resulted in the highest efficiency. To offset some heat loss, the syngas was diluted with nitrogen and saturated with water vapour that would not only recover some low grade heat but also increase power output and help to reduce NOx. It was found that the dilution nitrogen could only be made available after syngas had been introduced to the gas turbine and the ASU integrated with the gas turbine. During the period when dilution nitrogen was not available, it had to be replaced by steam.

Initially, Siemens attempted to resolve the burner problems without a complete rebuild of the turbine combustors. However, after several months of on site testing, the burners were removed and significant modifications were made. The final modifications to the burners were made in September 1996. The modifications made consisted of modified fuel nozzles that disturb the annular symmetry of the syngas flame. After this the burners were operated on synthesis gas at full output for several months to prove their operation. During this period, the combined cycle unit was run at full load without any flame induced oscillation. The problem had therefore been solved. The fuels were also successfully switched in both directions at base load conditions. The gas turbine has also proven to be highly flexible e.g. in cases of a sudden trip of the dilution nitrogen supply or a trip of the ASU.

Since the final burner modifications the Buggenum plant has been operated extensively with no reoccurrence of the humming problems. It must be considered that the problems with the gas turbine combustors on the Siemens V94.2 gas turbine have been successfully overcome.

The redesign of the gas turbine burners took more time because the problems related both to the turbine design and the associated total integration concept that was chosen. To assist start up in this period a separate air compressor capable of meeting 50% of the ASU demand was installed by Demkolec to decrease plant start-up times.

ELCOGAS

The gas turbine was commissioned on natural gas and no operational problems were noted. The main problem encountered occurred with the combined cycle operating on syngas. When the gas turbine was switched to operation with syngas problems humming and vibration similar to those experienced at Buggenum were apparent.

The V94.3 turbine used at Puertollano uses a different combustor arrangement to that at Buggenum that uses a V94.2 turbine (see Figure 6 overleaf). In the V94.3, the eight burners fire into the silo combustor that is horizontal to the turbine rotors and stators; there are two silos. In the V94.2, the silos are horizontal with the gas burners firing downwards. The changed design however did not overcome the firing problems with syngas experienced by Siemens before. Minor modifications to the burners made in-situ at Puertollano by Siemens have not been successful in overcoming these problems. A major redesign of the burners on the V94.3 turbine was underway in August 1998 to incorporate the design features used to overcome the humming/vibration problems at Buggenum. Restart of the turbine was expected in early September.

Wabash River

The gas turbine and combined cycle were commissioned first on fuel oil. No problems were recorded on the turbine. At Wabash River, the combined cycle operates as a separate generating station, operated by PSI Energy, with syngas from the gasifier sold ‘over the fence’ as required. PSI

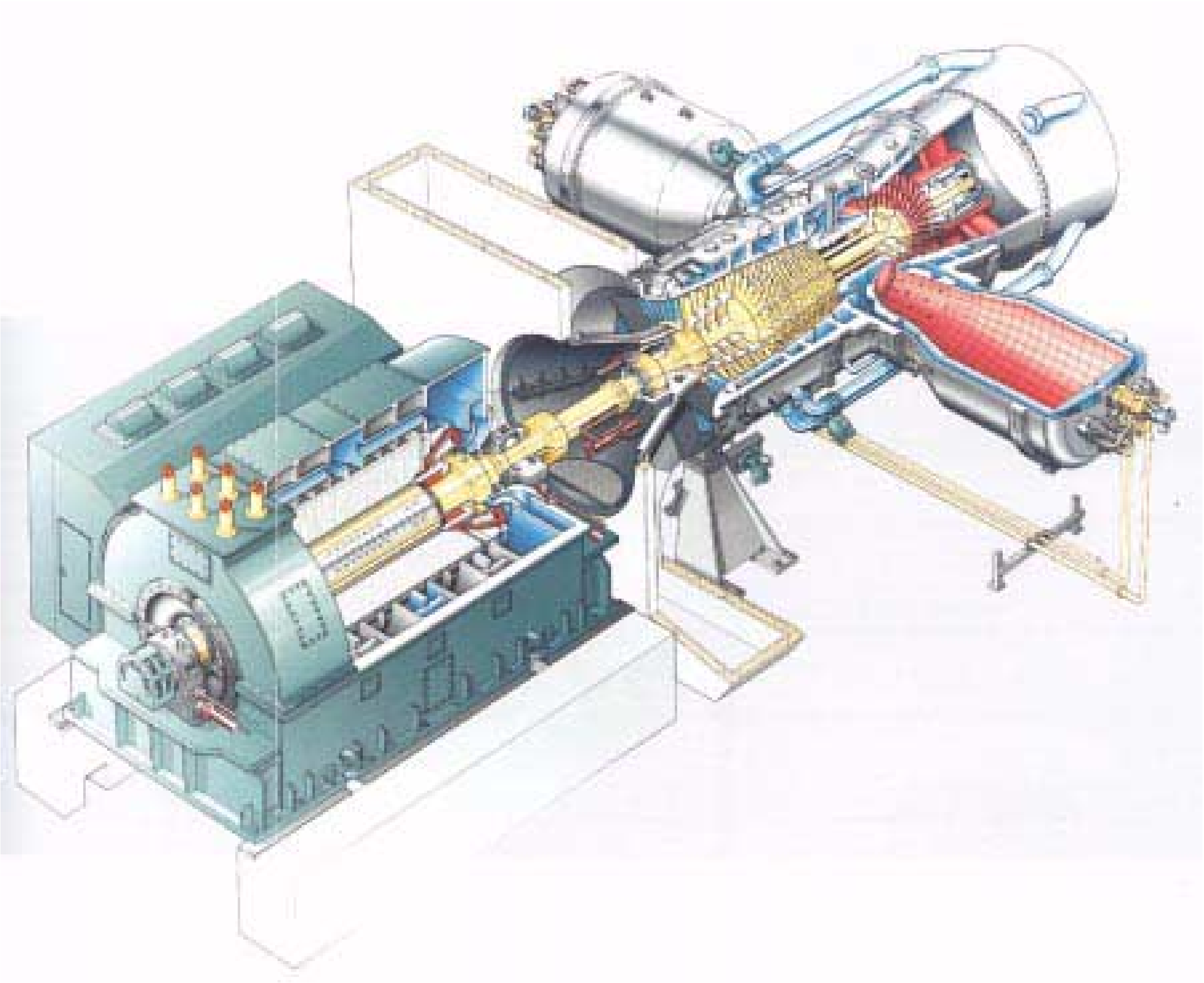


Figure 6

Siemens V94.3 Gas Turbine Used at the ELCOGAS CIGCC Plant

Energy gained authorisation from the local grid to despatch electricity on oil and frequently revert to oil use to maintain their electricity despatch to the grid. In that way generating revenue is maintained if there are problems with the gasification train.

On the combined cycle side the gas turbine experienced three areas of additional work after the acceptance of syngas. The first was in the syngas module and the piping from the module to the gas turbine. Expansion bellows required redesign and replacement to eliminate cracking in the flow sleeves. This problem was corrected by GE efforts in early syngas runs. The second problem was in the syngas purge control. These problems were primarily related to field devices such as solenoid valves and flow measuring devices. The solenoids were redesigned and replaced by GE. The third area was that the turbine required 2-3 spacer modifications.

The second year of commercial operation identified cracking problems with the combustion turbine combustion liners. Several outages resulted to allow weld repair of cracked liners. The cracking was located near the head end of the liner and around cooling holes. Evaluation of cause resulted in a changeout of the fuel nozzles and liners as a warranty item for GE.

Tampa Electric

At Tampa, the gas turbine and combined cycle were commissioned first on natural gas, with no reported problems. The Tampa plant was accepted for operation by the local grid on gas firing and frequently reverts to gas use to maintain their electricity despatch to the grid. In that way, generating revenue is maintained if there are problems with the gasification train, as occurs at Wabash River.

The problems encountered with the gas turbine arose due to a particulate problem in the syngas, which in turn arose from corrosion problems encountered in the convective gas/gas heat exchanger. In August and September 1996, on three occasions the gas/gas heat exchanger was plugged due to ash deposits that resulted in corrosion of the heat exchanger walls. On a routine inspection of the ‘Y’ strainers before the turbine in February 1997 cracks were observed; the strainers were removed and operations continued while they were repaired. For clarification, the ‘Y’ strainers are coarse particle filters situated before the gas turbine inlet to prevent turbine damage in the event of extraneous material being present in the duct work. In March 1997, a tube in the gas/gas heat exchanger failed (due to stress corrosion cracking) and dirty gas entered the turbine. The turbine had to be shut down cleaned and repaired. A second tube failure occurred on restart, but damage to the turbine was avoided because the leak detector indicated the presence of dust in the gas line before the turbine was switched from distillate to syngas. The particle leak detectors were fitted by Tampa Electric to give an early time indication of dust in the syngas line. The time indication is sufficient to switch the turbine to back up fuel operation and thus prevent turbine damage. Later in March 1997, a further sequence of events led to a tube failure in the gas/gas heat exchanger and again the turbine had to be shut down, cleaned and repaired. The strainer was refitted on restart this time. To avoid future problems, the gas/gas heat exchanger was removed from service. The plant has continued to operate to date with the heat exchanger removed with no operational problems with the gas turbine.

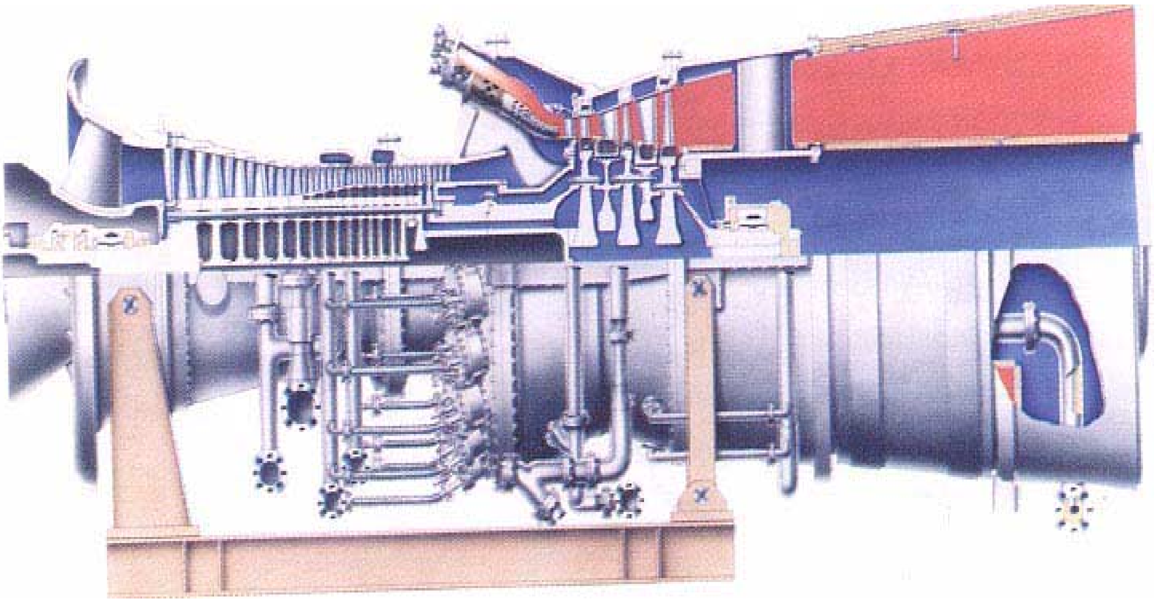


Figure 7

General Electric MS7001F Turbine used at Tampa Electric CIGCC Plant

Pinon Pine

At Pinon Pine the gas turbine was commissioned on natural gas with no reported problems. The combined cycle has been operated throughout the gasifier commissioning programme on gas to generate operational income for the utility owner.

Unfortunately, there are no operating data yet for the gas turbine on syngas, due to serious operational problems with the gasifier during commissioning.

2.5 Other Issues

Safety

One point of issue regarding safety with syngases is the fact that they are both highly toxic and explosive. Correspondingly, the fuel system designed for use with syngases must meet a higher safety standard than that for natural gas. This feature must be taken into account at the project design stage.

System safety features that must be considered include;

- The integrity of piping, flanges and joints must be such to prevent air ingress and minimise the risk of explosions,
- Electrical zoning of relevant plant areas and the use of suitable electrical equipment to prevent explosion risks,
- Complex purging procedures are required with inert gases to pipelines carrying syngas to avoid the risk of operator exposure or explosion,
- A comprehensive system of permitting is required for entry to and clearance of syngas systems for operational and maintenance purposes,
- All system vents are connected to a central flare system, no venting must allowed,
- A comprehensive system of ambient leak monitoring with alarm indications and both operator and work place monitoring will be required to avoid personnel exposure.

Control Procedures

Of particular interest are the switching procedures between syngas and back up fuels, both in stable operation and in response to plant outages. The control logic must be fast enough to deal with instantaneous plant changes. Manual control is not fast enough. The control procedure for the turbine must be linked to a fast data acquisition system and the control procedures for the turbine integrated fully with the control systems and logic for the other CIGCC plant constituent components.

2.6 Lessons Learnt

The principal lessons learnt from the coal IGCC projects that have been completed to date are as follows:

1. Gas turbines can be successfully modified to burn low calorific value gases. Gases with CVs as low as 4.5 MJ/m^3 have been successfully burnt for over 10,000 hours in a gas turbine integrated into a combined cycle system.

2. In general, the can annular type combustion system with diffusion burners has experienced less operational difficulties. The silo type combustor systems such as those used by Siemens, and ABB, had significant operational problems in their early stages of introduction. However, it must be noted that at Buggenum, these problems have now been successfully overcome. With Siemens latest

development of a similar system on the turbines, this arrangement now appears to be the adopted industry standard for the utilisation of low CV gases in the CIGCC industry.

3. The gas turbines that have performed most effectively from the commencement of the test programmes were all tested off line prior to installation. GE have a test stand at its facility at Schenectady in the USA where full scale burner trials can be undertaken. The burners are therefore modified and performance tests completed before installation on the plant. This approach greatly reduces the risk of later operational problems with the gas turbine combustors. Siemens do not operate such a high pressure test facility currently and have had to make modifications to the burner's in-situ, which has resulted in significant gas turbine down times and loss of revenue.

4. The emissions of NOx produced by the gas turbines meet all the necessary environmental requirements. The technique of injecting diluent water or nitrogen to reduce peak flame temperatures in the gas turbine combustors to control NOx has performed extremely well.

5. The use of particle filters before the turbine at Tampa looks to be a useful back up tool to prevent extraneous material in the syngas duct work damaging the turbine, as occurred at Buggenum. Also, the use of in-duct particle monitors to give early warning of dust leaks to allow the turbine to be switched to back up fuel seems to be an extremely useful piece of additional instrumentation.

6. Whilst not a direct turbine issue, careful attention to the operation of the gas clean up system prior to the gas turbine is essential to prevent damage to the gas turbine and reduce operational downtime.

7. There is a move within industry, to reduce the degree of air side integration to improve operational flexibility and ease of start up. A maximum air side integration of some 40% is now favoured.

8. All plants have separate start up fuels and the capability to switch from syngas to the back up fuel as necessary. Many of the plants regularly switch to their back up fuel to maintain their generation of electricity to the grid and ensure income generation for their plants in the event of gasifier or other plant problems.

9. Syngas is both toxic and explosive and adequate attention must be paid to the special safety features that are required both during the design and operating phases of the CIGCC plant. Detailed safety procedures to prevent explosions and operator exposures need to be put in place and back up monitoring undertaken to ensure that procedures are being followed closely.

10. The control logic for the turbine must be fast enough to deal with instantaneous plant changes. The control procedure for the turbine must be linked to a fast data acquisition system and the control procedures for the turbine integrated fully with the control systems and logic for the other CIGCC plant constituent components

3.0 BIOMASS IGCC

BIGCC is at an earlier stage of development than Coal IGCC. It does, however, share many common development issues, in particular low calorific value combustion and firing in combined cycle systems. One notable dissimilarity between BIGCC and coal IGCC is the unit scale. For BIGCC, the size of the plant is dictated by the available biomass resource; in most cases this tends to constrain the power plant to a size of 25 MWe or less. Significant economies of scale and improvements in generation efficiency could be gained by going to 50 to 75 MWe plants. However, such increases in plant scale would require some portion of the feedstock to come from dedicated fuel supply systems, such as short rotation forestry or herbaceous energy crops.

The development of the biomass gasification component of the IGCC plants has taken a different development route to coal. The higher reactivity of biomass compared to coal means that lower operating temperature gasifiers can be used. Air is more typically used as the gasification medium, since it is more cost efficient than oxygen at this scale of operation. The gas produced has a calorific value (5-6 MJ/m^3) similar to that of the diluted fuel gases used in the gas turbines in the large scale coal IGCC projects. In that sense, the adaptation of turbine technology to burn these fuels has preceded the introduction of BIGCC, thanks to the development work completed for the CIGCC projects.

Another different feature is the use of air blown gasification plants. Without the need for a costly ASU, all the systems have effectively zero air side integration.

3.1 Review of Status of Biomass IGCC

Eight Biomass IGCC plants have been identified world-wide, 4 in the EU, 3 in the USA and one in Brazil. Of the EU plants, two (Energy Farm, North Holland and ARBRE) are supported by the Thermie programme. Only one plant (the Värnamo plant in Sweden) is operational as a complete cycle; all the rest are in the planning/construction stage. Most of the new plants will not come on stream before the turn of the century. The non European projects are all being phased with installation of the gasifier and proving trials on the gasifier proceeding before the introduction of the gas turbine.

Details of the biomass IGCC (BIGCC) projects under development world-wide and their operational status is summarised in Table 6 overleaf. Details of the gas turbines to be used on these plants are given in Table 7.

In 5 out of the eight cases, the gasification technology is based on atmospheric pressure systems, two including Värnamo use pressurised gasifiers.

There is limited efficiency data published for the projects and difficulty was experienced on quoting efficiencies on a common basis. Without a common basis; comparison of the different project efficiencies could not be made. The ARBRE and Energy Farm projects quote efficiencies of 31 and 32% respectively, which is a significant improvement over combustion processes burning biomass. The efficiency of BIGCC is approaching that of conventional power generation plant, typically 36-38%. The efficiency difference between BIGCC and CIGCC in the cases quoted can be explained by the use of atmospheric pressure gasification. In the atmospheric pressure gasification cycle, the syngas must be compressed before it is fed to the turbine, whereas in pressurised gasification the air fed to the gasifier is compressed. Depending on the fuel-to-air ratio, the power requirement of fuel gas compression can be twice that of air compression, which accounts for the difference in efficiency. The air compression

Table 6

Summary Details of Current Main Biomass IGCC Projects

Project & Developer	**Country**	**Biofuel**	**Plant Output**	**Electrical Generation Efficiency**	**Gasification Technology**	**Installed Cost***	**Project Status**
Värnamo Bioflow Ltd	Värnarmo, Sweden	Forest residues	6 MWe	40-45%	Foster Wheeler pressurised CFBG	5601 Euro/kWe	In operation, 1500 hours completed.
Energy Farm Bioelletrica SpA	Pisa, Italy	Agric.by-products and wood	17 MWe	32% LHV	Lurgi Air blown CFBG	N/A	Under Construction
ARBRE Yorkshire Water	Eggborough UK	Coppice wood	8 MWe	31% LHV	TPS Air blown CFBG	5215 Euro/kWe	Under construction
North Holland EPZ	Holland	Wood & Forestry residues	N/A	N/A	?	N/A	Project expected to become a non BIGCC project
WPB/SIGAME Various	Brazil	Wood	30 MWe	42-44%	TPS Air blown CFBG	3973 Euro/kWe	Project in planning stage. Possibility project may be cancelled.
MNVAP	Minnesota, USA	Alfalfa stems	75 MWe	N/A	Carbona/Kaverner, air blown pressurised bubbling fluidised bed gasifier	2475-3178 Euro/kWe	Plant due on line in 2001
Vermont Project USDoE/FERCO	Vermont, USA	Wood	56 MWe (net)	36.4%	Batelle 'indirect' gasification process	1000 Euro/kWe[1]	Gasifier built and tested, turbine to be added in next phase.
PICHTR US DoE and State of Hawaii	Hawaii, USA	Sugar cane bagasse	5 MWe	N/A	IGT pressurised fluidised bed gasifier	9.2m Euro for Phase 1 only (1842 Euro/kWe)	Project now cancelled due to continuing problems with the gasifier island

Notes:

N/A	not available
*	Cost data not normalised to common base year.
1	Data excludes turbine costs
Agric.	Agricultural

Table 7

Summary Gas Turbine Details for Current Main BIGCC Projects

Project & Developer	Gas Turbine (GT)	Burner Design	GT Rating	GT Inlet Gas Temp. °C	GT Efficiency (LHV)	Manufacturers Previous Experience of Low CV Gas	Comments
Värnamo Bioflow Ltd	ALSTOM Energy modified Typhoon Class turbine	Multiple annular burners diffusion type ?	4.2 MWe	1100°C	30.2%	ALSTOM Energy experience via Licenser GE, some off line combustion testing completed	Reference data indicates turbine operating on 90% syngas and 10% natural gas. Obviously some flame stabilisation required ?
Energy Farm Bioelletrica SpA	Nuovo Pignone PGT10B	Diffusion burner with single can reverse flow combustor	10.9 MWe	N/A	32.0%	Nouvo Pignone has some experience on low CV gas and experience from licenser GE.	Extensive turbine combustion proving trials completed at GE's test facility in USA
ARBRE Yorkshire Water	ALSTOM Energy modified Typhoon Class turbine	Multiple annular burners diffusion type ?	4.2 MWe	1100°C	30.2%	GT used at Värnamo	GT selected with proven track record
WPB/SIGAME Various	GE LM2500	Multi annular diffusion burner	22 MWe	820°C	38%	GE has extensive low CV gas experience.	Proving trials on GT underway as part of phased development programme.
MnVAP	Westinghouse 251B12	Multi annular diffusion burner	50 MWe	N/A	32.8%	Westinghouse has Low CV gas experience own work +Siemens	-
Vermont Project USDoE/FERCO	Turbine to be decided	-	~ 15 MWe	-	-	-	-
PICHTR US DoE and State of Hawaii	Turbine not selected ?	-	~2 MWe	-		-	-

issue also accounts for the difference in efficiencies quoted for ARBRE, Energy Farm and Värnamo that uses a pressurised gasifier. The efficiency of +40% quoted for the SIGAME project is inconsistent with the other efficiency data quoted for the European atmospheric gasification based BIGCC plants. At Värnamo the quoted cycle efficiency is 40-45%, it is assumed that this figure relates to a fully optimised plant. This BIGCC efficiency compares favourably with some of the CIGCC projects. It is again noted that the BIGCC plants are at the early stage of development and that the same degree of optimisation of the cycles that has been undertaken with CIGCC has not yet been carried out. The first generation BIGCC plant should obtain sufficient data to allow further cycle optimisation to be completed.

The project costs vary considerably and can be as high as twice the installed cost per kilowatt of electricity produced than that of coal IGCC. Significant development of Biomass IGCC is, therefore, required to reduce plant costs and make the technology competitive with fossil fuels. The cost quoted for the Vermont IGCC project looks uncharacteristically low; it is considered that this cost may only reflect the installation of the gasification phase of the project and not the whole IGCC system.

All of the plants will have a separate start up fuel, but it is not clear from the available data whether they propose to switch fuels to maintain their outputs or not.

One potential problem in BIGCC, in particular those cycles based on atmospheric pressure gasification plants, that does not feature in CIGCC, is tar. In CIGCC, the gasifiers operate at high temperatures (>1000°C) because of the lower reactivity of the fuel. The high operating temperatures effectively destroy all the tar vapour in the fuel gas. In the lower operating temperature atmospheric pressure biomass gasifiers, high concentrations of tar are produced. These tars must be completely removed from the fuel gas otherwise they will cause lacquering problems on the turbine blades. All the atmospheric gasification technologies have incorporated a tar removal system into the flow sheet either in the form of a tar cracking reactor, or an acid scrubber. In high pressure gasifier, such as that used at Värnamo, the gas is cleaned at high temperatures (>400°C) and enters the gas turbine without further cooling. The tar in this case remains in the vapour phase and should not cause problems in the gas turbine. High temperature gas cleaning also increases the overall plant efficiency.

For the purposes of this study, tar was highlighted because it can be regarded as a new problem for the gas cleaning industry in power generation applications. Other gas cleaning issues of course may arise depending on the biomass fuels used. Straw for instance, can contain high concentrations of alkali's and chlorine, which can themselves cause severe problems.

From the details available for those projects that have selected their turbines, all the turbine manufacturers have experience either directly or through their relationships with their product licensees (GE and Siemens) of syngas utilisation. The standard burner adopted is the diffusion burner, as per CIGCC experience. Extensive testing of the burners for the turbines has been completed by Nouvo Pignone for the Energy Farm Project and by GE for the SIGAME project. For Project ARBRE, the turbine selected, the ALSTOM Gas Turbine Typhoon, has already been operated on syngas on the Värnamo project.

3.2 Performance of BIGCC and Key Experiences Learnt to date.

As noted earlier not many of the BIGCC plants are in operation, therefore direct experience of gas turbine problems are limited. However, the experiences from plant operations and combustion trials learnt to date can be summarised as follows:

Värnamo

The Värnamo process involves initially drying of the wood using a flue gas dryer to 5-20% moisture. The dried wood is then fed to the gasifier, via pressurised lock hoppers, using screw conveyors. The gasifier is a pressurised circulating gasifier operating at 900 to 1000°C and 18 bara. The gasifier is air blown, with some 10% of the fluidising air extracted from the gas turbine compressor. The gas leaving the gasifier first enters a cyclone, from which solids are circulated to the gasifier. After the cyclone the gas passes to a gas cooler and the gas is cooled to 350-400°C. After the cooler the gas enters a candle filter for de-dusting. From the candle filter the gas passes to the gas turbine where it is burnt. The hot flue gases exiting the gas turbine are cooled in a HRSG to produce steam for the steam turbine. During start up and lean gas production the gas is flared rather than put through the gas turbine.

Commissioning of The Värnamo plant was completed on liquid fuel in March 1993**.** The gasification plant was commissioned on wood in the spring of 1995, later than expected. The gas turbine was commissioned on liquid fuel in September 1995, with the first test runs on syngas completed in October 1995. To date the gas turbine has completed over 1500 hours of operation on syngas.

Figure 8
The Värnamo BIGCC Plant

The main operating issues learnt that reflect on the gas turbine are as follows:

1. An acceptable gas calorific value has been achieved, the hydrogen content was lower than expected but this was offset by an increase in methane concentration. The gas CV has varied between 5.3 and 6.3 MJ/m3.

2. High concentrations of ammonia and hydrogen cyanide have been measure in the syngas. Concentrations of ammonia up to 1450 vppm have been recorded. Whilst concentrations of thermal NOx from the gas turbine are low, due to the high nitrogen content and low peak flame temperatures. The overall NOx emissions were higher than on liquid fuel because of the high ammonia and hydrogen cyanide concentrations in the syngas. NOx emissions from the turbine as high as 130 vppm have been recorded on bark and as low as 40 vppm on bark. The base line NOx release on diesel was 70-75 vppm.

It is noted that the diesel NOx emission was higher than expected and was accompanied by smoke emissions. The NOx and smoke emission issue on diesel are under investigation by the turbine supplier ALSTOM gas turbines.

3. The recorded alkali levels were below 0.1 ppm wt. and should not pose any problems in the gas turbine.

4. The ceramic candle filter has been prone to breakage’s and to prevent turbine damage a metallic police filter has been installed after the candle filter to detect candle filter breakage’s and allow the gas turbine to be taken off-line. This “early warning” system seems to have been effective.

Overall, Sydkraft have not observed any adverse effects on the turbine hardware, combustion performance or turbine behaviour on syngas.

Project ARBRE

It is noted that this plant is yet built and therefore there is no operational data to comment upon. However, based on the Värnamo results it is worth reflecting on the difference in configuration of the ARBRE process and how that may impact on the main points observed at the Värnamo plant.

The process flow sheet for the ARBRE plant is given in Figure 9, overleaf.

The ARBRE plant will use wood chips and forestry residues, similar fuels to those at Värnamo. Some variation in the fuel gas composition such as that observed at Värnamo can be expected. However, the impact on NOx emissions from the gas turbine will be reduced. The ARBRE flowsheet includes a wet gas scrubber after the gasifier unit, this gas scrubber will remove any ammonia or hydrogen cyanide before combustion in the turbine. Overall NOx emissions should, therefore, be lower than those observed at the Värnamo plant. The ARBRE plant uses an atmospheric pressure gasifier and therefore includes a tar racking stage before the gas compressor. The tar cracker is a second CFB reactor operating at a temperature slightly above that of the gasifier itself and incorporates dolomite as the bed material. The dolomite acts as a catalyst in the cracking of the tars. The scrubber will also remove traces of residual tar and alkali metals, the gas entering the turbine should, therefore, be of acceptable quality.

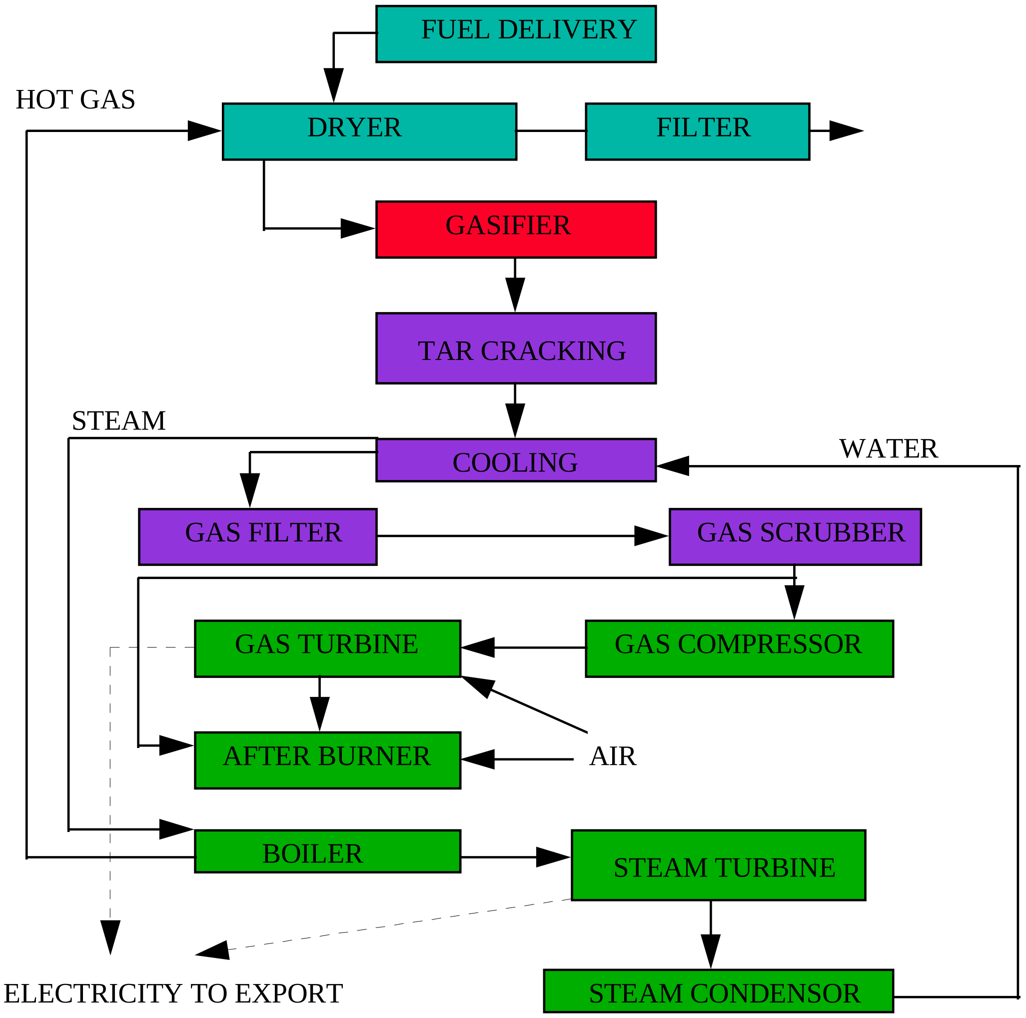


Figure 9

Process Flowsheet for ARBRE BIGCC Plant

The Energy Farm Project

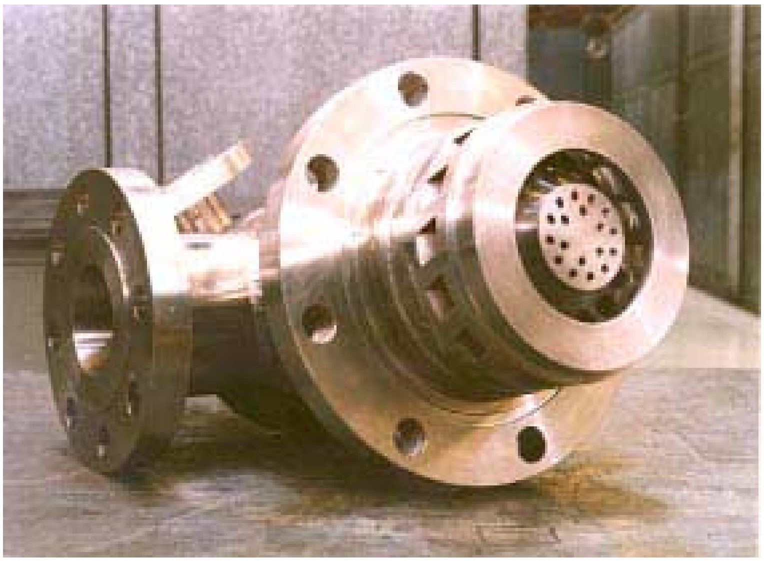
The Energy Farm (TEF) project has a similar flow sheet to ARBRE and again uses an air blown atmospheric pressure gasifier, designed by Lurgi GmbH. The turbine selected for this project was a standard industrial single shaft turbine the PGT10B manufactured by Nuovo Pignone. Nuovo Pignone are GE licensees and therefore have access to the combustion testing rig at Schenectady used by GE for their combustion can design work. Nuovo Pignone have completed as series of combustion trials on simulated syngas to establish confidence in the use of a single diffusive burner (see Figure 10, overleaf) for application with the PGT 10B gas turbine. The combustion system design was tested down to a CV of 4.3 MJ/m3 and showed good flame stability and blow out characteristics.

The test results showed that

- NOx emissions as low as 21 vppm (@15% oxygen) were demonstrated on syngas,

- No combustion instability problems were observed over the range of loads to be operated under,
- The combustion system pressure drop was within the expected limits,
- Combustor can metal temperatures were acceptable
- Combustion dynamics for the single nozzle design were comparable to those on other fuels.

Overall, no problems with flame stability or flame out are expected when the gas turbine is operated on syngas in earnest.



(Picture Supplied Courtesy of Nuovo Pignone)

Figure 10

Nuovo Pignone Single Diffusive Burner

MNVAP

The MnVAP project uses a pressurised fluidised bed gasifier and hot gas clean up system similar to that at Värnamo. The fuel used is alfalfa, which due to its low sintering temperature must be gasified below 750°C. Initial gasifier tests indicated that ammonia concentrations of up to 2% by volume were present in the syngas. This high ammonia concentration will have a significant effect on overall NOx emissions from the plant, as observed at Värnamo. Alkali vapours in the fuel gas were measured at 0.02-0.05 wppm. These concentrations are lower than could be expected from the low sintering temperature of the alfalfa, which is normally associated with high sodium and potassium salt concentrations.

MnVAP have selected a Westinghouse turbine and combustion trials have been completed. The turbine uses a Multi Annular Swirl Burner. The combustor was specifically designed to burn low CV syngas with high ammonia concentrations. Burner trials have been completed on a synthesised syngas, which are reported to have produced low NOx emissions. This is attributed to the rich-quench-lean design of the burner. The combustor is quoted as having a unique design feature, an internal air damper. This damper is externally adjustable to permit the modulation of the primary and secondary air flows inside the combustor during operation.

MnVAP report that the low CV syngas burnt well in the combustor and less than 10% of the ammonia in the syngas was oxidised to NOx. It is noted that even at 10% oxidation this will still represent a significant NOx release.

FERCO Project

The FERCO project is at an early stage with limited operation of the gasifier completed to date. The CV of the syngas produced was 6.7 MJ/m^3 . The gas is burnt in a waste heat boiler. No problem with the burning of the syngas has been reported. The gas turbine will not be delivered before late 1999. No details on the turbine selection are available.

3.3 Areas of Concern To Be Raised For Future Projects

It would appear that concerns regarding the use of turbine manufacturers with direct experience of low calorific value syngas have been addressed by most of the developers. Also, where there are uncertainties in the operation of the gas turbine combustor that proving trials, effectively ‘acceptance tests’, are completed before the turbine is installed. This should reduce future down time due to combustion related issues in the gas turbine.

One area of concern for the turbine manufacturers would appear to be the variability in the syngas composition with different biofuels. This is particularly relevant where multiple sources of biofuel will be used in BIGCC plants. The results from Värnamo indicate significant variation in both major and minor syngas species between wood and bark. At a very early stage in the project design, the fuel sources and characteristics of the fuel needs to be firmed up. Trials on the selected gasifier need to be undertaken with the full range of fuels and the syngas characterised fully. This data can then be used by the turbine supplier to provide confidence in the combustors design to accommodate the changes in the syngas quality.

The issue of syngas nitrogen concentrations (ammonia and hydrogen cyanide) on overall plant NOx emission is an area of concern for BIGCC plant based on pressurised gasifiers. The Värnamo experience shows that some fuels can generate very high syngas ammonia and hydrogen cyanide concentrations. To minimise NOx emissions in this case there are two options:

- addition of a ammonia/hydrogen cyanide removal system into the process flowsheet,
- modification of the combustor design as at MnVAP.

The second approach appears to have been addressed at MnVAP. There will be considerable interest in the NOx data generated from this plant. At Värnamo, they have a separate side stream experiment to study the selective oxidation of fixed nitrogen species in the syngas to nitrogen. Side stream tests began in late 1998 and the results will be eagerly awaited.

A second area of concern relating to pressurised gasifiers is the use of ceramic candle filters for dust removal prior to the gas turbine. Experience at Värnamo with the candle filters (persistent breakage’s) was consistent with early problems with these systems encountered at the Buggenum and Wabash River CIGCC plants. At Buggenum the ceramic candle filter system was completely redesigned, from a top suspended system to a bottom mounted design. After this design change limited further problems with the dust filters were encountered. At Wabash River the ceramic filters were removed and metal filters installed to overcome breakage problems. A side stream experiment was put in place to study ceramic candle mounting issues and candle durability. The collective experiences of the CIGCC operators in candle filter design should be pooled for benefit of the development of future pressurised BIGCC projects. Where ceramic candle filters are employed, it is strongly recommended that serious consideration should be given to building in fail safe devices such as, extra particle filters and/or dust monitors before the turbine to prevent extraneous material from downstream operations contaminating the turbine.

Neither of the above issues (NOx emissions and particulates) are relevant to atmospheric BIGCC plant because they include a wet gas scrubber before the turbine to remove any residual particulates, tars or nitrogen species. One area of concern for BIGCC plants based on atmospheric pressure gasifiers must relate to the tar cracker. It is essential that this system operates effectively otherwise damage to the turbine will occur. In some of the CIGCC plants, dust detectors are installed upstream of the turbine as a "fail safe" device in the event of dust carryover. These devices, then allow the turbine to be switched to back up fuel to avoid dust ingress and subsequent damage occurring. Similar such devices should be considered for tar carry over, if they are developed suitably for commercial application, until such time that commercial confidence in the operation of the tar crackers renders them unnecessary.

With regard to the existing BIGCC plants, it is assumed that the safety related issues of handling syngas are being addressed. Similarly, it is assumed that the control and integration issues of the turbine and other plant components have been considered fully.

For future BIGCC projects, based on the collective experiences of CIGCC and the new BIGCC projects it should be possible to develop a code of practice or best practise guide for developers of BIGCC projects.

This code of practice would include advice on areas such as:

- General guidelines on the selection of critical components such as the gasifier, gas clean up system (in particular ceramic candle filters) and turbines, based on best available technology and practise
- Guidelines of selection requirements for specific components such as the gas turbine. These could include:
  - determine syngas composition in terms of CV and major constituents over full load range envisaged,
  - determine gasifier syngas contaminant compositions and compare with turbine manufacturer input gas requirements,
  - determine based on interaction with turbine manufacturers need for turbine combustor proving trials. The costs can then be built into project costs,
  - undertake proving trials or arrange visits to commercial operating plants.
- General guidelines on safety related issues regarding use of syngas,
- Guidelines on appropriate safety procedures for plant and monitoring procedures.
- Guidelines on control system integration

3.4 Scale Up of BIGCC

There are a number of issues to be considered to scale up BIGCC. Of course, the key determining factor will always be the availability of the fuel resource.

Scale up should allow greater cycle integration and scope for optimisation of the system configuration that should lead to increases in efficiency. With regard to the turbine, increasing the scale will allow the use of higher efficiency machines. The future development of BIGCC must take advantage of increases in the firing temperature, and hence turbine efficiency, as CIGCC is doing.

Scale up should lead to some economies of scale, which should lead to lower capital costs. At a point in size pressurised gasification based BIGCC should become more cost effective than atmospheric gasification based BIGCC. A detailed modelling study needs to be undertaken to assess the cut off size for atmospheric versus pressurised BIGCC.

4.0 CONCLUSIONS

A review of the gas turbine issues arising from CIGCC projects completed and in operation to date. The review lessons learnt from these projects are as follows:

1. Gas turbines have been successfully modified on CIGCC plant to burn low calorific value gases. Gases with CVs as low as 4.5 MJ/m^3, i.e. comparable to those likely to be produced in BIGCC plants, have been successfully burnt for over 10,000 hours in a gas turbine integrated into a combined cycle system.

2. In general, the can annular type combustion system with diffusion burners has experienced less operational difficulties. The silo type combustor systems such as those used by Siemens, and ABB, had significant operational problems in their early stages of introduction. However, it must be noted that at Buggenum, these problems have now been successfully overcome.

3. The gas turbines that have performed most effectively from the commencement of the test programmes were all tested off line prior to installation. In this way, the burners are, therefore, modified and performance tests completed before installation on the plant. This approach greatly reduces the risk of later operational problems with the gas turbine combustors, which can lead to significant gas turbine down times and loss of revenue.

4. The emissions of NOx produced by the gas turbines meet all the necessary environmental requirements. The technique of injecting diluent water or nitrogen to reduce peak flame temperatures in the gas turbine combustors to control NOx has performed extremely well.

5. The use of particle filters before the turbine is a useful back up tool to prevent extraneous material in the syngas duct work damaging the turbine. Also, the use of in-duct particle monitors to give early warning of dust leaks to allow the turbine to be switched to back up fuel seems to be an extremely useful piece of additional instrumentation.

6. Whilst not a direct turbine issue, careful attention to the operation of the gas clean up system prior to the gas turbine is essential to prevent damage to the gas turbine and reduce operational down time.

7. All of the plant have separate start up fuels and the capability to switch from syngas to the back up fuel as necessary. Many of the plants regularly switch to their back up fuel to maintain their generation of electricity to the grid and ensure income generation for their plants in the event of gasifier or other plant problems.

8. Syngas is both toxic and explosive and adequate attention must be paid to the special safety features that are required both during the design and operating phases of the CIGCC plant. Detailed safety procedures to prevent explosions and operator exposures need to be put in place and back up monitoring undertaken to ensure that procedures are being followed closely.

9. The control logic for the turbine must be fast enough to deal with instantaneous plant changes. The control procedure for the turbine must be linked to a fast data acquisition system and the control procedures for the turbine integrated fully with the control systems and logic for the other CIGCC plant constituent components

The conclusions drawn give confidence that gas turbines can be successfully modified for use with air blown gasification plant that is used in BIGCC systems. The main lessons that can be transferred to BIGCC systems based on the CIGCC data are as follows:

1. Turbines for projects should be sourced from manufacturers with experience and expertise in the combustion of low calorific value fuel gases and who are aware the necessary safety requirements for syngas handling.

2. Diffusion burners are the accepted industry standard for combustion of low CV gas.

3. To gain confidence in the satisfactory performance of the turbine and to minimise operating risk gas combustion trials should be completed off-line prior to the formal selection of the turbine as an Approval stage. The costs for this activity need to be built into the project development costs or covered by the manufacturer as part of their sales package to the customer.

4. Careful attention to the operation and maintenance of the gas clean up system is essential to maintain the integrity of the turbine during the plants operating life.

5. Consideration should be given to building in fail safe devices such as, particle filters, dust and/or tar monitors before the turbine to prevent extraneous material from downstream operations contaminating the turbine.

6. In the case of BIGCC plants, additional NOx control features in the turbine combustor are unlikely to be necessary because of the presence of some 35-45% nitrogen in the fuel gas due to the fact that the gasifiers will be air not oxygen blown typically.

7. The control system for the gas turbine needs to be fast enough to deal with fast transient conditions from the gasifier, manual control is too slow. The control loop for the turbine needs to be integrated into the control philosophy for the whole plant.

The key lessons learnt from the BIGCC demonstration plants and areas of concern for future projects are:

1. One area of concern for the turbine manufacturers would appear to be the variability in the syngas composition with different biofuels. This is particularly relevant where multiple sources of biofuel will be used in BIGCC plants. The turbine manufacturers need to be aware at an early stage in the project the likely ranges in syngas quality that can be expected.

2. A second area of concern, particularly relating to pressurised gasifiers, is the use of ceramic candle filters for dust removal prior to the gas turbine. Experience at Värnamo with the candle filters (persistent breakage's) was consistent with early problems with these systems encountered at the Buggenum and Wabash River CIGCC plants. The collective experiences of the CIGCC operators in candle filter design should be pooled for benefit of the development of future pressurised BIGCC projects. Where ceramic candle filters are employed it is strongly recommended that serious consideration should be given to building in fail safe devices such as, extra particle filters and/or dust monitors before the turbine to prevent extraneous material from downstream operations damaging the turbine.

3. The issue of syngas nitrogen concentrations (ammonia and hydrogen cyanide) on overall plant NOx emission is an area of concern for BIGCC plant based on pressurised gasifiers. The Värnamo experience shows that some fuels can generate very high syngas ammonia and hydrogen cyanide concentrations. To minimise NOx emissions in this case there are two options: addition of an ammonia/hydrogen cyanide removal system into the process flowsheet or modification of the combustor design as at MnVAP. At Värnamo, they have a separate side stream experiment to study the selective oxidation of fixed nitrogen species in the syngas to nitrogen. Side stream tests began in late 1998. Results from this and the MNVAP project should be collected and disseminated at the earliest opportunity.

4. One area of concern for BIGCC plants based on atmospheric pressure gasifiers must relate to the tar cracker. It is essential that this system operates effectively otherwise damage to the turbine will occur. In some of the CIGCC plants, dust detectors are installed upstream of the turbine as a "fail safe" device in the event of dust carryover. These devices, then allow the turbine to be switched to back up fuel to avoid dust ingress and subsequent damage occurring. Similar such devices should be considered for tar carry over, if they are developed suitably for commercial application, until such time that commercial confidence in the operation of the tar crackers renders them unnecessary

5. 5.0 RECOMMENDATIONS

It is recommended that for future BIGCC projects, based on the collective experiences of CIGCC and the new BIGCC projects it should be possible to develop a code of practice or best practise guide for developers.

This code of practice should include advice on areas such as:

- General guidelines on the selection of critical components such as the gasifier, gas clean up systems and turbines, based on best available technology and practise
- Guidelines of selection requirements for specific components such as the gas turbine. These could include:
  - determine syngas composition in terms of CV and major constituents over full load range envisaged,
  - determine gasifier syngas contaminant compositions and compare with turbine manufacturer input gas requirements,
  - determine based on interaction with turbine manufacturers need for turbine combustor proving trials. The costs can then be built into project costs,
  - undertake proving trials or arrange visits to commercial operating plants.
- General guidelines on safety related issues regarding use of syngas,
- Guidelines on appropriate safety procedures for plant and monitoring procedures.
- Guidelines on control system integration

The code of practice should be developed in close collaboration with equipment manufacturers, project developers and the safety industry.