TECHNOLOGY STATUS REPORT

GASIFICATION OF SOLID AND LIQUID FUELS FOR POWER GENERATION

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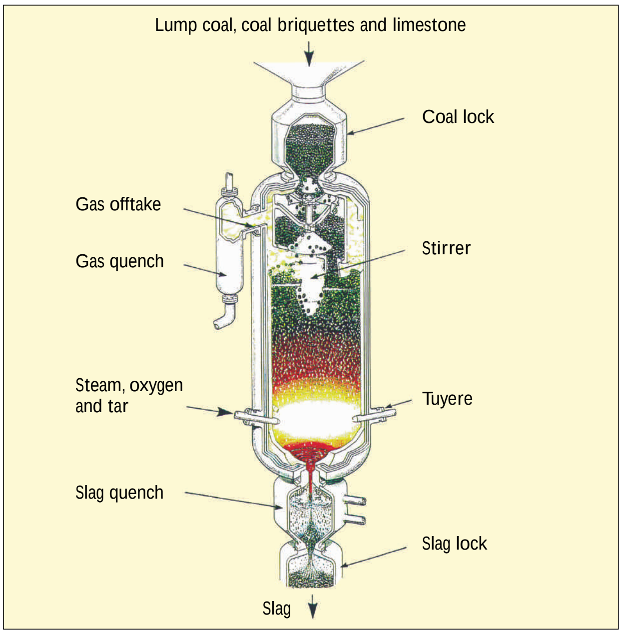

Figure 1. The BGL gasifier (courtesy of BG plc)

SUMMARY

Gasification is the conversion of solid and liquid materials (eg coal or oil) into a gas whose major components are hydrogen (H_2) and carbon monoxide (CO). Gasification has been employed for over a hundred years with the gas produced being used for various applications such as domestic heating and lighting ('Town Gas'), chemicals manufacture, eg ammonia (NH_3) or methanol, and the production of petrol- and diesel-substitutes.

In recent years, there has been interest in using gasification to generate electricity. The initial reason for this was the development of large, efficient gas turbines. It was soon realised that the gasification of coal, coupled with a gas turbine, could potentially generate power as efficiently as the most modern conventional coal-fired power plant, but with much lower emissions. The first experimental integrated gasification combined cycle (IGCC) power plant was built in the early 1970s in Germany, and today there are several coal-fired demonstration plant worldwide.

IGCC power plant can also be fired with oil-derived feedstocks such as heavy oils and tars. These products are formed during oil-refining processes. Traditionally, these products have been used to manufacture heavy fuel oils for use in power station boilers and as marine fuel. However, the market for heavy fuel oil has declined rapidly in recent years, and some refineries now have a surplus of such products. Gasifying these heavy oils can provide both power for the refinery, and for export, and H_2 which can be used within the refinery to upgrade and clean other products, such as diesel and petrol. There are at least four major oil IGCC projects active in Europe.

Both biomass and wastes can be gasified; however, IGCC technology tends to favour large, centralised power plant whilst biomass and wastes are best exploited using smaller plant close to their source. An alternative, therefore, is to gasify the biomass or waste in a small gasifier adjacent to an existing power plant and use the gas produced to partially replace the coal or oil being fired. This allows an existing power station to utilise biomass and wastes as and when they are available. Some gasifier technologies allow biomass and wastes to be co-gasified with coal. Several biomass and waste gasification projects are currently going ahead, mostly in Europe, with several of the most important in the UK.

IGCC plant are still at the demonstration stage and nearly all of the projects so far have required some form of Government support.
The technology has three major deficiencies that need to be remedied before it becomes widely used:

i IGCC plant are expensive to build, costing significantly more than conventional coal-fired plant with environmental protection equipment.

ii IGCC plant have so far suffered from relatively poor reliability.

iii The operational flexibility of IGCC plant at least those with oxygen (O_2) plant - has yet to be fully proven; in particular, the start-up times for IGCC plant are measured in days rather than hours.

Further development work is required to overcome these obstacles to the uptake of the technology. When they have been overcome, IGCC plant should take a significant market-share of new coal-fired power plant worldwide.

BENEFITS OF THE TECHNOLOGY

Gasification technologies offer the following benefits:

- highly-efficient and clean generation of power from coal
- clean generation of power from oil residues with substantial scope for integration with refinery activities
- environmentally-benign disposal of solid and liquid wastes with scope for further energy recovery
- utilisation of biomass for power production.

DEPARTMENT OF TRADE AND INDUSTRY SUPPORT

Since 1990, the Department of Trade and Industry (DTI) has supported 49 projects associated with gasification for power generation, contributing £10.9M to a total projects cost of £36.6M.

INTRODUCTION

Gasification

Gasification is the conversion of a carbon-containing solid or liquid substance into a gas in which the major components are H_2 and CO. This gas can then be used as a fuel or as a chemical feedstock from which products such as NH_3 or methanol can be made.

The defining chemical characteristic of gasification is that it entails the partial oxidation of the feed material; in combustion, the feed is fully oxidised, whilst in pyrolysis, the feed undergoes thermal degradation in the absence of O_2.

The oxidants for gasification are O_2 or air and, usually, steam. Steam helps to act as a temperature moderator, as the reaction of steam with the carbon in the feed is endothermic (ie it absorbs heat). The choice of air or pure O_2 depends on a number of factors such as the reactivity of the feed material, the purpose for which the gas is to be used and the type of gasifier.

The first major application of gasification was to convert coal into a fuel-gas for domestic lighting and heating. This application has gradually died out in most places due to the availability of natural gas, although gasification is still used for this purpose in China (and until recently in Eastern Europe). For the last few decades, the main application of gasification has been in the petrochemical industry to convert various hydrocarbon streams into 'synthesis gas', eg for the manufacture of methanol, the supply of H_2 for NH_3 production or the hydrodesulphurisation or hydrocracking of oil streams. Other, more specialised uses of gasification have included the conversion of coal into synthetic motor fuels (as practised in South Africa) and the manufacture of substitute natural gas (SNG) (not practised commercially at present but given serious consideration in the late 1970s and early 1980s).

Gasification for Power Generation

In the past ten years, the power generation industry has been transformed by the availability of large gas turbines for power production. These gas turbines, whether used by themselves (open cycle gas turbine, OCGT) or in conjunction with a heat recovery boiler and steam turbine (combined cycle gas turbine, CCGT), have proved to be a highly-efficient, clean and easy-to-operate means of generating power. The main disadvantage of gas turbines for power generation is that they can be fired only with clean fuels that either are gaseous (eg natural gas) or can be easily vaporised (eg distillate fuels and liquid petroleum gas, LPG). Gas turbines cannot be fired with coal or heavy fuel oil, the mainstays of the conventional power generating industry.

Gasification acts as a 'bridge' between conventional fuels such as coal and fuel-oil and gas turbines. Gasification of such fuels generates a fuel-gas which, after cleaning, can be used in a gas turbine power plant. Gasification therefore enables the advantages of gas turbine technology to be accessed using any fuel, whether solid or liquid. Furthermore, since the fuel-gas produced can be cleaned to remove particulates and sulphur and nitrogen compounds, before firing in a gas turbine, the emissions from a gasification-based power plant (GPP) are significantly lower than from a conventional power plant. A combination of gasification with a combined cycle (ie an IGCC) is the only coal-based technology that can approach the environmental performance of natural gas-fired systems. Moreover, the thermal efficiency of IGCC is as good as, if not better than, conventional coal-fired plant based on boilers and steam turbines.

A typical IGCC plant for generating power from coal is shown schematically in Figure 2. Pulverised coal is fed into a gasifier at a pressure of ~30bar, together with O_2 from an air separation unit (ASU). The raw fuel-gas is produced in the gasifier at about 1300°C and is cooled to about 200°C before being scrubbed with water to remove dust and compounds such as NH_3 and hydrogen chloride. It is then further cooled and scrubbed with a solvent to remove sulphur compounds such as hydrogen sulphide. The cleaned gas is then fired in a gas turbine. Ash in the coal is recovered as a mineral slag from the gasifier and the sulphur compounds removed from the gas are recovered as sulphur. Nitrogen from the ASU is typically added to the fuel-gas in the gas turbine to control nitrogen oxides (NO_x) emissions.

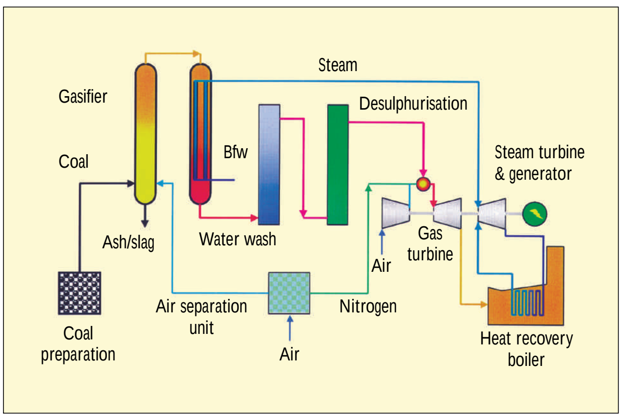

Figure 2. Schematic of a typical gasification combined cycle unit

A further reason for the current interest in gasification is its suitability as a means of waste disposal and biomass utilisation. Gasification offers a way of converting wastes into a fuel-gas which can then be used for small-scale power generation, or alternatively to partly displace the coal or oil-fuel in an existing boiler. Biomass may be exploited in a similar fashion. Whereas conventional pulverised fuel (pf) boilers cannot handle wastes or biomass directly, by converting these fuels into fuel-gas it is possible to co-fire the fuels in existing power station boilers. This is of particular importance where carbon dioxide (CO_2) emissions are of concern. A number of projects of this type are in operation or under development, mostly in Northern and Central Europe.

The first IGCC plant was built in the early 1970s but since then progress has been slow. The first large-scale demonstration units have come into operation in Europe and the USA in the last five years. The early experience of these units has been rather mixed. The emissions performance and efficiency have been as good as expected, but it has become clear that there are three major barriers to be overcome before IGCC becomes widely adopted:

i The capital costs of IGCC plant are very high, significantly (~20-30%) more than those of conventional coal- and oil-fired units. This is partly because of the complex technologies involved, and partly because the technology is not yet 'off-the-shelf'. This means that design and manufacturing costs are greater than will be the case once IGCC is fully commercialised.

ii The reliability of current IGCC plant has been lower than anticipated and certainly lower than is desirable for a commercial power station. One reason for this is that some of the individual component parts have yet to be fully optimised for use in an IGCC; another is that the overall design of the IGCC is rather complex and problems with one part of the plant can rapidly cascade into other areas.

iii The operational flexibility of IGCC plant is poor compared with other power generating technologies. Start-up times from cold are very long, typically 40-50h (in contrast with a conventional boiler, which takes perhaps 8-10h). The ability to follow load has yet to be fully demonstrated.

Apart from these technical issues, the other reason why IGCC has yet to make a significant impact on power generation is that currently most of the increase in coal-fired capacity is in countries such as India and China. In these parts of the world, there is a particularly strong emphasis on reliability and cost, which are not currently IGCC strong points. In contrast, in Europe and North America, where emissions and efficiency are becoming increasingly more important (and where IGCC would be favoured), there are few if any coal-based projects going ahead, due to the widespread availability of cheap natural gas.

The current status of IGCC is therefore that it is clean and efficient but expensive and unreliable. A comparison of IGCC with a conventional (supercritical) coal-fired plant, fitted with flue gas desulphurisation (FGD), is given in Table 1.

	IGCC	Pf boiler with FGD
Efficiency (%)	45	43
Availability (%)	75	90
Emissions (mg Nm^{-3} @ 6% 0_2)		
SO_x	30	100
NO_x	65	150
Particulates	10	20
Capital cost (£ kW^{-1})	>1000	800

Table 1. Comparison of IGCC with supercritical pf plant

Factors favouring the selection of IGCC in the future are likely to be:

- an absence of cheap natural gas
- tight emissions limits
- high coal prices, demanding high efficiency
- the opportunity for co-gasification of wastes and biomass.

The factors likely to hinder its uptake, unless these are addressed, will be:

- high capital cost
- poor availability
- poor operational flexibility.

GASIFICATION PROCESSES

Types of Gasification Process

There are many different gasification processes on offer. These differ considerably in terms of, for example, technical design, scale, reference experience and fuels handled. The most useful way of classifying them is by flow regime, ie the way in which the fuel and oxidant flow through the gasifier.

Just as conventional solid-fuel boilers may be divided into three basic types (namely pf-fired, fluidised bed and grate-fired), gasifiers fall into three groups: entrained flow, fluidised bed and moving bed (sometimes called, somewhat erroneously, fixed bed). Fluidised bed gasifiers are exactly analogous to fluidised bed combustors; entrained flow gasifiers are similar in concept to pf-firing; and moving bed gasifiers bear some resemblance to grate firing. Characteristics of each are compared in Table 2.

	Entrained flow	Fluidised bed	Moving bed
Fuel types	Solid and liquid	Solid	Solid
Fuel size (solid)	<500µm	0.5-5mm	5-50mm
Fuel residence time	1-10s	5-50s	15-30min
Gas outlet temperature	900-1400ºC*	700-900ºC	400-500ºC

*Will be lower if there is a quench stage included within the overall gasifier vessel itself.

Table 2. Comparison of gasifier types

Entrained Flow Gasifiers

In an entrained flow gasifier, pf or atomised oil flows co-currently with the oxidising medium (typically O_2). The key characteristics of entrained flow gasifiers are their very high and uniform temperatures (usually more than 1000°C) and the very short residence time of the fuel within the gasifier. For this reason, solids fed into the gasifier must be very finely divided and homogeneous, which in turn means that entrained flow gasifiers are not suitable for feedstocks such as biomass or wastes, which cannot be readily pulverised. The high temperatures in entrained flow gasifiers mean that the ash in the coal melts and is removed as a molten slag. Entrained flow gasifiers are well suited to gasifying liquids, and the primary application of such gasifiers today is in refineries, gasifying oil-feedstocks.

Entrained flow gasifiers have been selected for nearly all the coal- and all the oil-based GPPs currently in operation or under construction. Entrained flow gasifiers include the Texaco gasifier, the two variants of the Shell gasifier (one for coal, the other for oil), the Prenflo® gasifier and the Destec gasifier. Of these, both the Texaco gasifier and the Shell oil gasifier have over 100 units in operation worldwide.

Fluidised Bed Gasifiers

In a fluidised bed, solids (eg coal, ash) are suspended in an upwardly flowing gas stream. In a fluidised bed gasifier, this gas stream comprises the oxidant (normally air rather than O_2). The key feature of the fluidised bed gasifier (like the fluidised bed combustor) is that the fuel ash must not be allowed to become so hot that it melts and sticks together; if the fuel particles stick together, the bed will defluidise. The use of air as the oxidant keeps the temperature below ~1000°C. This in turn means that fluidised bed gasifiers are best suited to relatively reactive fuels, such as biomass.

Advantages of the fluidised bed gasifier include the ability to accept a wide range of solid feeds, including household waste (suitably pre-treated) and biomass such as wood. It is also to be preferred for very high ash coals, particularly those in which the ash has a high melting point, because other gasifier types (entrained flow and moving bed) lose significant amounts of energy in melting the ash to form slag.

Fluidised bed gasifiers include the High Temperature Winkler (HTW) and that developed by British Coal Corporation and now marketed by Mitsui Babcock Energy Ltd (MBEL) as part of the Air Blown Gasification Cycle (ABGC). There are relatively few large fluidised bed gasifiers in operation. Fluidised bed gasifiers are not suitable for liquid feeds.

Moving Bed Gasifiers

In a moving bed gasifier, the oxidant (steam and O_2) is blown into the bottom of the gasifier. The raw fuel-gas produced moves upward through a bed of solid feedstock, which gradually moves downwards as the feed at the bottom of the bed is consumed. The defining characteristic of moving bed gasifiers is therefore counter-current flow. As the raw fuel-gas flows through the bed, it is cooled by the incoming feed, which in turn is dried and devolatilises. There is therefore a very pronounced temperature profile in the gasifier, from 1000°C or more at the bottom to perhaps 500°C at the top. The devolatilisation of the fuel during the gasification process means that the outgoing fuel-gas contains significant amounts of tarry compounds and methane. This raw fuel-gas is therefore washed at the outlet with water to remove the tars. As a consequence of this, the fuel-gas does not require high-temperature cooling in a syngas cooler, as it would if from an entrained flow reactor. Moving bed gasifiers were designed for coal, but can accept other solid fuels, such as wastes.

There are two main moving bed gasifier technologies. The Lurgi dry-ash gasifier was originally developed in the 1930s and has been used extensively for Town Gas production and in South Africa for chemicals from coal. In this gasifier, the temperature at the bottom of the bed is kept below the ash fusion point so the coal ash is removed as a solid. In the 1970s, Lurgi and the then British Gas Corporation (now BG plc) developed a slagging version in which the temperature at the bottom is sufficient for the ash to melt. This gasifier is referred to as the BGL (BG-Lurgi) gasifier. Several BGL gasifiers are currently being installed into plant for gasifying solid wastes and co-gasifying coal and waste.

SPECIFIC GASIFIERS

Some of the most important and well-known gasification processes are described below in alphabetical order.

BGL Gasifier (Moving Bed)

The BGL gasifier was originally developed in the 1970s to provide a syngas with a high methane content in order to provide an efficient means of manufacturing SNG from coal. It was developed over about 15 years at British Gas' Westfield Development Centre in Fife, initially to test the process for applicability to SNG manufacture and later for IGCC.

Lump coal and a flux such as limestone are fed into a lockhopper which periodically discharges into the top of the gasifier (Figure 1). A slowly rotating distributor plate distributes the coal evenly over the top of the bed. For caking coals, the distributor is connected to a stirrer which also keeps the bed even and prevents the coal from agglomerating. As the bed descends the gasifier, it undergoes a number of reactions. These reactions can be grouped into three zones at different heights in the fuel bed: in the upper zone coal is dried and devolatilises; in the middle zone it is gasified; and in the lower zone it is combusted, the CO_2 produced acting as a gasification agent in the middle section. O_2 and steam are added at the bottom of the bed through nozzles (tuyères). The molten slag produced forms a pool in the bottom of the gasifier and is periodically removed.

The gasifier vessel is refractory-lined to prevent excessive heat loss from the bed. The refractory does not experience high temperatures as it is insulated from the hottest part of the bed (at the tips of the tuyères) by the coal bed itself.

The gas exiting the gasifier is at a temperature of 450-500°C and contains tars and oils produced by the devolatilisation of the coal, together with coal dust elutriated from the bed. This is removed by a quench vessel located at the gas exit. The gas is simultaneously cooled and cleaned by a water quench. The gas then passes to a further chain of exchangers that cool the gas to ambient temperature prior to being desulphurised. The tars and water removed from the gas pass to a separator, from which the tars and coal dust are recycled to the tuyères of the gasifier (a portion may be added to the top of the gasifier to suppress the elutriation of coal dust).

The BGL gasifier has a very high cold gas efficiency; ie, compared with other gasifiers, a larger portion of the original calorific value (CV) of the coal appears as chemical energy in the gas as opposed to thermal energy. Thus, the BGL gasifier does not feature high-temperature heat exchangers as required by Shell and Texaco systems amongst others. The gasification island and CCGT unit is therefore less closely coupled as the gas-cooling train is not intimately integrated into the steam turbine cycle. In a BGL system more of the power is generated by the gas turbine and less by the steam turbine than in an entrained flow system.

The BGL gasifier can handle a significant quantity of fines (ie <6mm) in the lump feed to the top of the gasifier, depending on the caking characteristics of the coal; eg with a high-swelling, high-caking coal such as Pittsburgh No.8, up to 35% of the coal can be fed as fines. However, run-of-mine (RoM) coal typically contains 40-50% fines by weight. Hence, whereas for an entrained flow gasifier all of the coal would first be milled, in the BGL system the coal is first screened. BG tested a number of ways of utilising the fines in the gasifier, feeding the fines to the tuyères either dry or as a slurry or alternatively briquetting them using bitumen as the binder.

The existing, mothballed gasifier at Westfield is currently being recommissioned by Fife Power as part of a plant that will generate $120MW_e$ from coal and sewage sludge. Fife Power has applied for permission to build a second, larger ($400MW_e$) plant, to gasify coal and municipal solid waste (MSW).

Destec (Entrained Flow)

The Destec process is a slurry-fed, pressurised, two-stage process.

The process was originally developed by Dow Chemicals in the 1970s. Following pilot-scale and prototype trials, in 1984 the decision was taken to build a commercial unit at Dow's Plaquemine (Louisiana) chemicals complex; this went into operation in 1987. In 1989, Dow spun off its gasification and other power interests into a separate company, 80% owned by Dow, named Destec. Meanwhile, the technology has been chosen for a repowering IGCC at Wabash River, Indiana.

The gasifier (Figure 3) consists of a pressure shell lined with uncooled refractory.

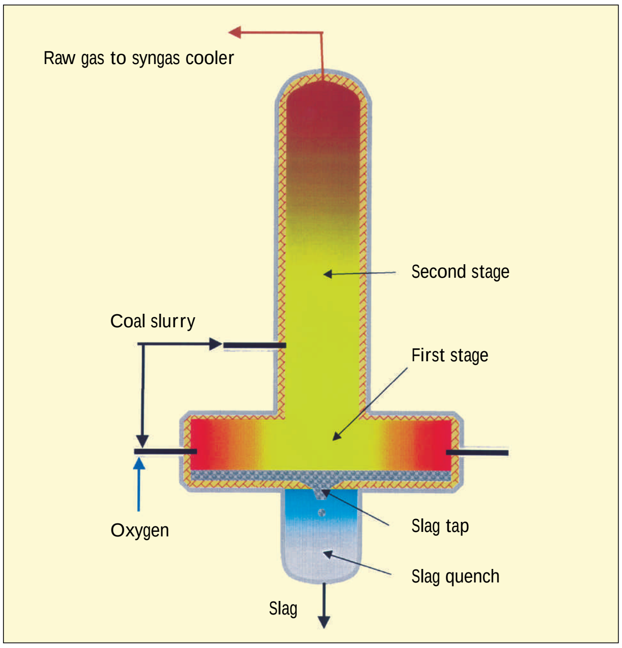

Figure 3. The Destec gasifier

Two gasification burners are located in the lower (first) stage of the gasifier, with a further injection point for coal in the upper stage. Coal is slurried to about 60% solids (by weight). About 80% of the slurry is injected into the gasifier in the two burners located in the lower stage, together with O_2, and is partially combusted at a temperature of about 1350-1400°C and a pressure of about 30bar. The ash in the coal melts, runs down the vessel and is removed through a taphole into a water quench. The fuel-gas formed in the first stage flows upwards into upper second stage of the gasifier, where the remaining 20% of the coal slurry is injected and reacts, undergoing pyrolysis and gasification and cooling the gas to about 1050°C. This two-stage process has the effect of increasing the CV of the syngas. The crude syngas is then cooled in a firetube syngas cooler.

The cooled syngas is then cleaned using filters that remove large ash and char particles. The char can be recycled to the gasifier.

The only operational Destec gasifier is at the Wabash River IGCC which runs on bituminous coal. Extensive tests have been carried out over the years on sub-bituminous coals and petroleum coke.

High Temperature Winkler (Fluidised Bed)

The HTW process is a development of the old Winkler fluidised bed gasification process. The original Winkler process was first developed and used in the 1920s and was an atmospheric-pressure process.

The HTW process was developed by Rheinbraun which owns and operates several lignite mines in Germany's Ruhr region. The HTW process was originally developed to produce reducing gas for iron ore; interest then switched to the production of synthesis gas, then to power generation. All these applications were based on the gasification of lignite. The current emphasis is on the gasification of waste plastics. Rheinbraun is still responsible for the development of the HTW process, with Krupp Uhde undertaking the marketing and supply.

Rheinbraun built a pilot plant at Frechen, which ran from 1978 to 1995. It was rated at 10bar and 1.8 tonnes per hour (tph). In 1985 a demonstration unit was built at Berrenrath near Cologne. This ran at 10bar, the syngas produced being piped to a methanol synthesis plant at nearby Wesseling. The Berrenrath plant used steam and O_2 as the gasification media.

In 1989 a 25bar pilot plant was started at Wesseling with the intention of developing the process for power generation. At that time, gasification of lignites, combined with a fluidised process to pre-dry the lignite before gasification, was seen as the most promising means of generating power from the Rheinish lignites in an efficient and clean way. The work culminated in the design of an IGCC based around an air-blown HTW gasifier and termed KoBRA (KOmbikraftwerk mit Integrietier BRAunkohlvergasung - combined cycle with lignite gasification). The initial KoBRA plant was due to be built at the Goldenberg power station near Cologne; however, economic considerations intervened and the project has now been dropped. High-efficiency conventional pf boilers are now favoured for the next generation of lignite-fired plant.

Following the demise of the KoBRA IGCC project, the emphasis switched to the gasification of wastes. Tests were carried out at the Berrenrath plant to investigate the gasification of waste plastics and sewage sludges. Krupp has now developed a process, referred to as PreCon®, in which the HTW gasifier is combined with pre-treatment of the wastes and post-treatment of the ash to produce a syngas for chemicals manufacture or power production.

The HTW gasifier is shown schematically in Figure 4.

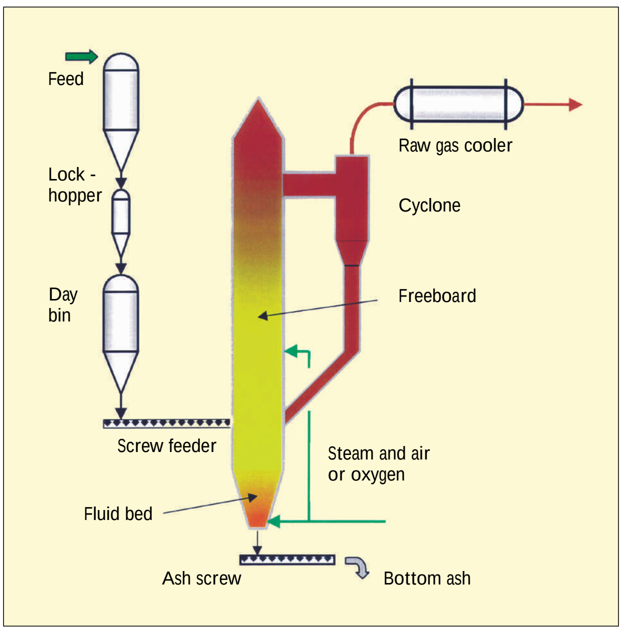

Figure 4. HTW gasifier

Fuel is pressurised in a lockhopper and then stored in a day- or charge-bin before being fed by screw into the gasifier. The bottom part of the gasifier itself comprises a fluidised bed, the fluidising medium being air or O_2 and steam. Gas plus elutriated solids flow up the reactor, with further air/O_2 and steam being added in this region to complete the gasification reactions. The crude syngas is then dedusted in a cyclone and cooled. The solids removed in the cyclone are returned to the gasifier base. Ash is removed from the base of the gasifier by means of an ash screw.

The temperature in the base of the gasifier is kept at about 800-900°C; this is controlled to ensure that the temperature does not exceed the ash softening point; the temperature in the freeboard above the bed itself can be significantly higher. The operating pressure can vary between 10bar (for syngas manufacture) and 25-30bar (for IGCC).

Lurgi Dry Ash (Moving Bed)

The Lurgi dry-ash gasification process was developed by Lurgi GmbH in the early 1930s as a means of producing Town Gas. The first commercial plant was built in 1936. Until 1950, the process was mostly restricted to lignites, but in the 1950s Lurgi and Ruhrgas collaborated to develop a process suitable for bituminous coals as well. Since then the Lurgi gasification process has been widely used worldwide for producing Town Gas and syngas for a variety of purposes (eg NH_3, methanol, liquid fuel production). In addition to plant supplied by Lurgi itself, Lurgi-type gasifiers have been built in Eastern Europe and the former Soviet Union.

The first ever GPP, at Lünen in Germany, used the Lurgi system (unusually, the gasifiers were air-blown). Other significant installations using the Lurgi system are the Great Plains SNG plant in North Dakota, USA, and the SASOL synfuels plant in South Africa.

The process itself is shown schematically in Figure 5.

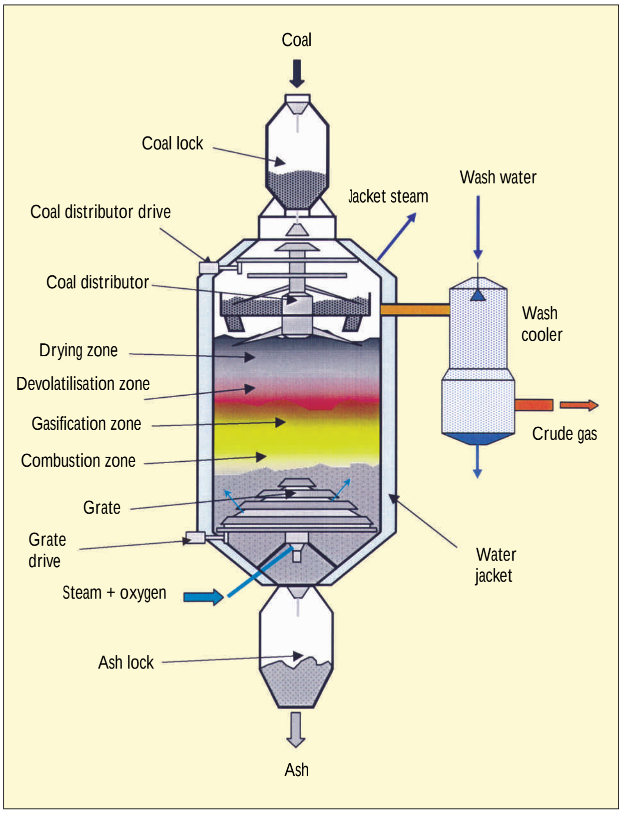

Figure 5. Lurgi dry-ash gasifier

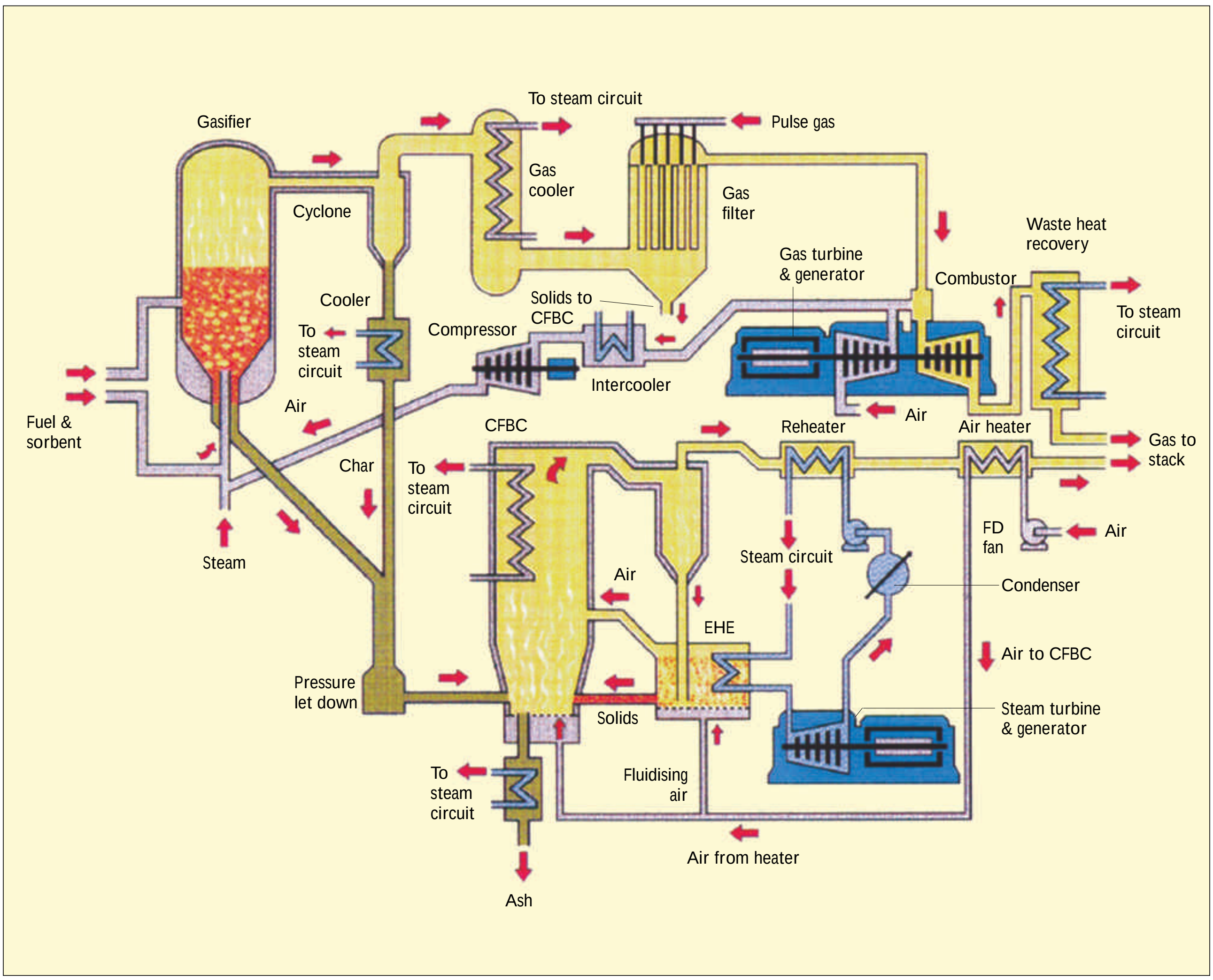

Figure 6. ABGC incorporating the MBEL gasifier

The major features of the process are that it is a moving bed process that uses steam and (normally) O_2 as the oxidants. Like the BGL gasifier, it runs on lump coal rather than pf and, like the BGL system, it produces tars. The major difference between the Lurgi dry-ash gasifier and the BGL slagging gasifier is that the former uses a much greater ratio of steam to O_2 as oxidant (perhaps 4-5:1 for the former compared with ~0.5:1 for the latter). The result of this is that the temperature in the dry-ash system is kept sufficiently low at all points that the ash does not melt but is removed as a dry ash. The lower temperature of the dry-ash system means that it is suited more to reactive coals, such as lignites, than to bituminous coals.

Lump coal is fed into the lockhopper at the top of the gasifier and pressurised before entering the gasifier itself. A rotating coal distributor ensures even distribution of coal around the reactor. The coal moves slowly down the gasifier. As its does so, it is warmed by the fuel-gas flowing upwards through the bed; thus the coal is sequentially dried and devolatilised (the devolatilisation forms tars and phenols), then gasified. The very bottom of the bed, immediately above the grate, is the hottest part of the gasifier (~1000°C) and there any remaining coal is burned. The CO_2 produced reacts with carbon higher in the bed to form CO. The ash is removed by a revolving grate and depressurised in a lockhopper. Steam and O_2 are blown up through the grate to provide the oxidant for the gasification process. The gas produced exits the gasifier at a temperature of 300-500°C and is cooled and washed using a water quench. The gasifier is surrounded by a water jacket that raises steam which can be used by the process.

MBEL Gasifier (Fluidised Bed)

MBEL now owns the rights to the gasifier that was originally developed by British Coal Corporation at its Coal Research Establishment as part of the ABGC process (Figure 6). The gasifier is an air-blown, pressurised system designed to attain about 80% carbon conversion, the remaining carbon being burned in a fluidised bed. A 0.5tph pilot-scale gasifier was built and operated at Stoke Orchard in Gloucestershire. Further development of the process, and the ABGC as a whole, is now in the hands of a consortium comprising MBEL, Alstom and Scottish Power which has plans to build a ~100MW_e demonstration unit at Kincardine in Fife.

The ABGC is based on the partial gasification of coal in the MBEL gasifier at pressures of 20-25bar and a temperature of ~1000°C. About 70-80% of the coal is converted to a low CV fuel-gas that is cooled to ~400°C and then cleaned using ceramic filters. Limestone is used to remove the majority of the sulphur in the coal as calcium sulphide. The fuel-gas produced in the gasifier is fired in a gas turbine and the turbine exhaust gas is used to raise steam in a heat recovery steam generator (HRSG). Solid residues from the gasifier (ash, char and sulphided sorbent) are depressurised, cooled and passed to a circulating fluidised bed combustor (CFBC) which operates at atmospheric pressure. In the CFBC, the residual char is burned and the calcium sulphide is oxidised to calcium sulphate, a more environmentally benign substance. The heat produced in the CFBC adds to the steam system of the HRSG and the steam produced is used to run the steam turbine. Tests at Stoke Orchard proved the ability of the gasifier to run with a variety of coals and sorbents and to achieve 90% desulphurisation in the gasifier.

An evaluation of the ABGC system suggests that, using current technologies, the system would attain an efficiency of 44.7% (higher heating value basis).

Prenflo® (Entrained Flow)

The Prenflo® (Pressurised Entrained Flow) gasification process has been developed by Krupp Uhde. It is a pressurised, dry feed, entrained flow process. Krupp built a 48 tonne per day (tpd) unit at Fürstenhausen in Saarland, Germany. Following this work, the Prenflo® process was selected for the Puertollano IGCC plant in Spain. The process is shown in Figure 7.

Coal is ground to ~100μm and pneumatically conveyed by nitrogen to the gasifier. The gasifier structure is unusual in that it incorporates both the gasifier itself and the syngas cooler. The coal is fed through burners located in the lower part of the gasifier, together with O_2 and steam. Syngas is produced at a temperature of up to 1600°C. However, it is quenched at the gasifier outlet with recycled cleaned syngas to reduce its temperature to about 800°C. The syngas then flows up a central distributor pipe and down through evaporator stages before exiting the gasifier at about 380°C. Slag formed during the gasification process is quenched in a water bath and removed through a lockhopper system.

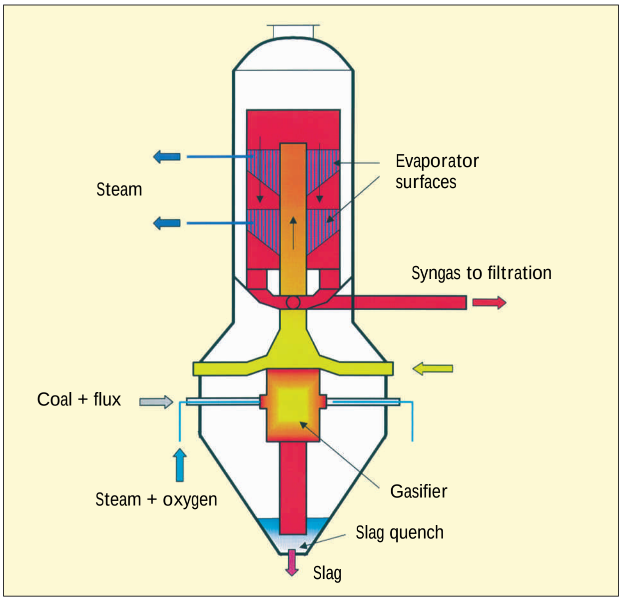

Figure 7. Prenflo® gasifier

Shell Gasification Process (Entrained Flow)

The Shell Gasification Process (SGP) was developed in the 1950s as a means of converting a wide variety of hydrocarbon feedstocks into clean synthesis gas. The SGP is not used for coal gasification, for which Shell has a separate process (the Shell Coal Gasification Process, SCGP).

The gasifier itself is a refractory-lined vessel which operates at about 25-30bar (in an IGCC context; for H_2 manufacture, pressures of about 65bar are typical) and 1300°C. Fuel, O_2 and steam are injected at the top of the gasifier through a co-annular burner. Gasification takes place, with a small amount of soot and ash being formed (~0.5-1% of the carbon in the feed is converted to soot). The crude syngas and impurities exit at the bottom of the gasifier and are cooled in a syngas cooler, which consists of spirally-wound gas tubes in parallel, immersed in a vertical steam generator. This arrangement produces saturated steam at ~100bar. The gas is cooled from ~1300°C at the syngas cooler entrance to <400°C at the exit. The gas may then be further cooled before being cleaned of soot and ash. This is carried out in a quench pipe, where the raw gas is sprayed with water to remove the majority of the solid particles present. The entrained particles are removed as a sludge in the separator. The gas then passes to a scrubber, where two packed bed sections are used to lower the particulate concentration to <1 mg m^{-3}. The raw syngas is then suitable for desulphurisation and use.

The ash and soot removed from the gas are treated in a soot ash removal unit developed by Shell and Lurgi. The sludge is filtered and the carbonaceous filter cake is incinerated to give a high-vanadium ash residue.

Key differences between the SGP and the SCGP are:

- uncooled gasifier
- fire-tube syngas cooler
- no recycle of cool syngas for quench
- lower temperatures in the gasifier.

The only GPP using the SGP is the Per+ complex at Shell's refinery in Rotterdam. Three SGP trains produce syngas from residue; 67% of the syngas is used for H_2 production and the remainder for power generation.

Shell Coal Gasification Process (Entrained Flow)

Shell's experience with gasification dates back to the 1950s, when the first SGP units were commissioned. In 1972, Shell started development work on a gasification process for coal. Following experience with a 6tpd pilot plant in Amsterdam, in 1978 Shell started operation of a 150tpd demonstration plant operated by Deutsche Shell at Harburg near Hamburg, Germany. Shell used the experience gained to construct a plant at its existing petrochemicals complex at Deer Park in Houston, USA. This plant was sized to gasify 220tpd (250 US tons per day) of bituminous coal or 365tpd (400 US tons per day) of high-moisture, high-ash lignite.
The Deer Park gasifier went into operation in 1987, and proved the ability of the SCGP to gasify a wide range of coals.

In 1989 it was announced that the SCGP had been chosen for an IGCC plant at Buggenum, the Netherlands; this remains the only commercial plant using the SCGP.

The Shell gasifier is shown in Figure 8.

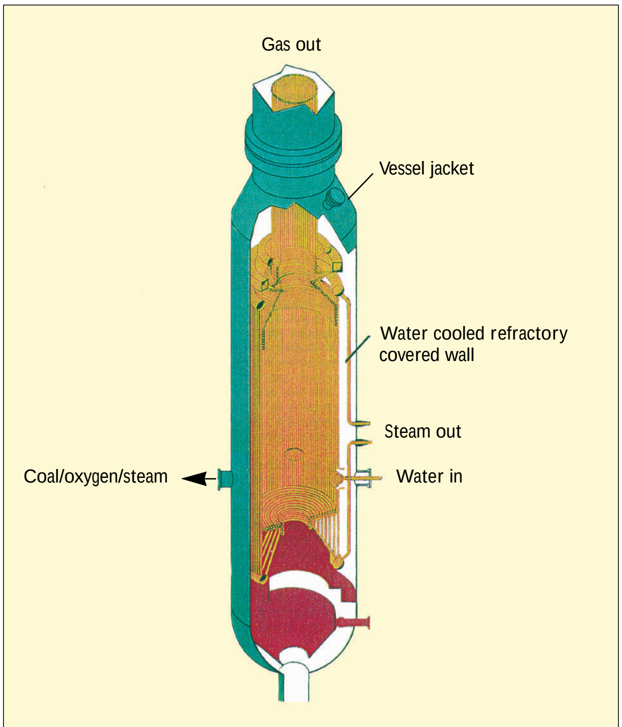

Figure 8. The Shell coal gasifier (courtesy of Shell)

The gasifier vessel consists of a carbon steel pressure shell, within which is a gasification chamber enclosed by a refractory-lined membrane wall. Water circulated through the membrane wall is used to control the temperature of the gasifier wall and raises saturated steam. Dried pf, O_2 and steam are fed through opposed burners at the bottom of the gasifier, which operates at ~25-30bar. Gasification occurs at temperatures of 1500°C and above, which ensures that the ash in the coal melts and forms a molten slag. The slag runs down the inner surface of the gasifier wall and is quenched in a water bath at the bottom of the gasifier. A portion of the slag adheres to the wall of the gasifier and cools, forming a protective layer.

Gasification of the coal forms a raw fuel-gas that is predominantly H_2 and CO with a little CO_2 and some entrained slag particles. At the gasifier outlet, the raw gas is quenched with recycled, cooled fuel-gas to lower the temperature to ~900°C; this cooling 'freezes' the slag particles, rendering them less sticky and less prone to fouling surfaces.

The fuel-gas is then cooled to ~300°C in the syngas cooler, raising high- and medium-pressure steam. In contrast to the syngas cooler for Shell's oil gasification process, the SCGP syngas cooler has the gas on the shell side. The syngas cooler thus has a complex tube bundle comprising various economisers, medium- and high-pressure evaporators and some superheaters.

The cooled syngas is filtered using ceramic filters. About 50% of the cooled syngas is then recycled to the top of the gasifier to act as the quenching medium for the gas. The remainder is washed to remove halides and NH_3 and then passed to the desulphurisation unit.

Texaco Gasification Process (Entrained Flow)

The key feature of Texaco's process is the very wide range of feedstocks that have been successfully gasified using the same basic technology. This range encompasses gases, oils, Orimulsion™, petroleum coke and a range of coals. Texaco is additionally working on pre-treatment processes that will allow waste plastics and scrap tyres to be gasified.

The Texaco Gasification Process was originally developed in the late 1940s. The initial focus of the work was to develop a process for reforming natural gas so as to make synthesis gas for conversion into liquid hydrocarbons. Soon, the emphasis shifted to producing syngas for NH_3 production. During the 1950s, work was carried out to extend the process to gasify oils and, to a lesser extent, coal. When the oil crisis occurred in 1973, work on coal gasification was re-commenced, and the first commercial plant gasifying coal began operation in 1983 at Eastman Chemicals' plant at Kingsport, Tennessee, USA. In 1984 the Cool Water IGCC plant went into operation. Currently operational GPPs using the Texaco process are El Dorado (petroleum coke) and Polk (coal); the Texaco process has also been selected for the majority of oil-residue IGCCs being built or planned.

There are two basic variants of the process, which differ in the method used to cool the raw syngas. In the quench variant, the raw syngas from the bottom of the gasifier is shock-cooled with water. In the full heat recovery variant, the raw syngas is cooled using a syngas cooler. The Texaco quench gasifier is shown schematically in Figure 9 and the full heat recovery version in Figure 10.

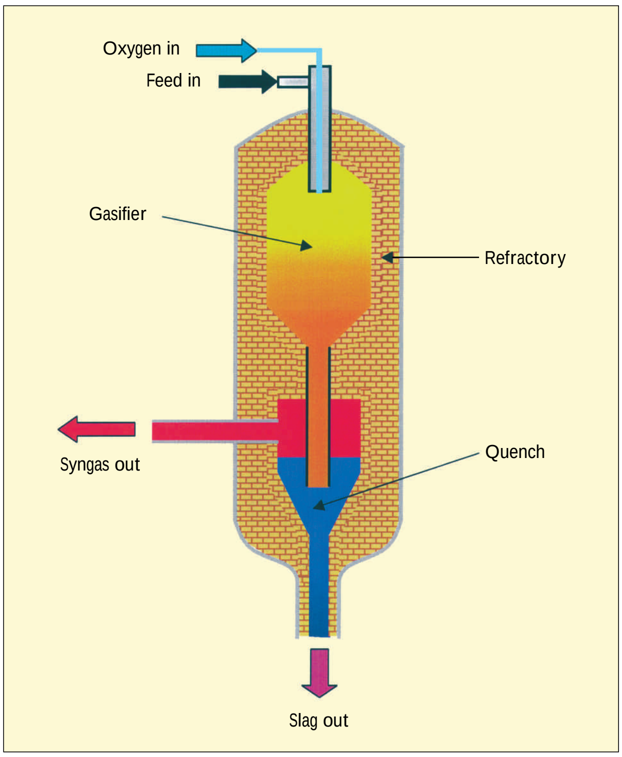

Figure 9. Texaco quench gasifier

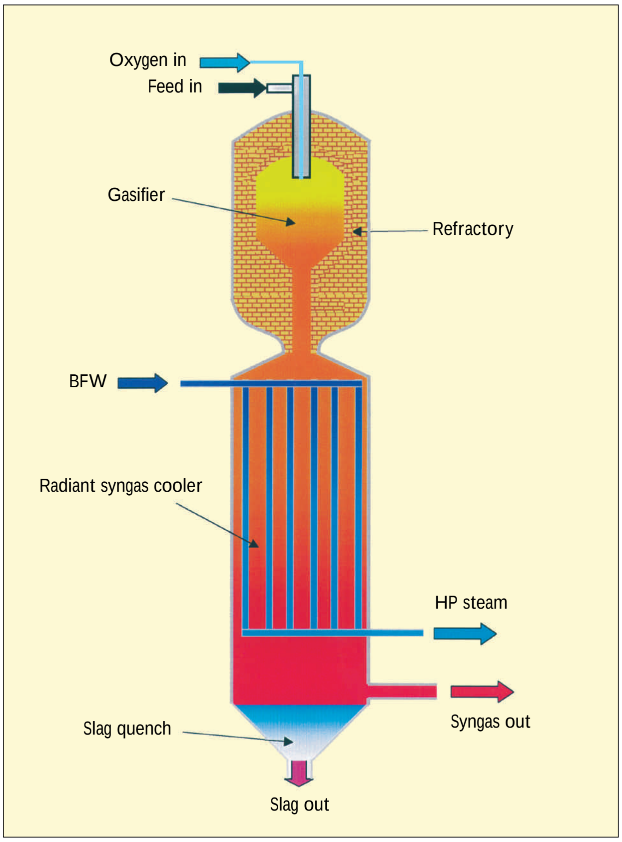

Figure 10. Texaco gasifier with full heat recovery

Irrespective of the syngas cooling method used, the actual gasification process is the same. The feedstock, together with O_2 and (usually) steam, is introduced into the top of the gasifier. The steam acts as a temperature moderator. Solid feedstocks, such as coal or petroleum coke, are slurried and finely ground before being introduced into the gasifier; the water used in the slurry replaces steam as the moderator in this instance. The gasifier itself is a refractory-lined pressure vessel. Gasification takes place at temperatures of ~1250-1450°C. The operating pressure depends on the use to which the syngas is to be put: ~30bar for IGCC (although it can be higher) and 60-80bar for chemicals manufacture. The crude syngas, plus any ash (as slag) and soot (in the case of oil gasification), exits the gasifier at the bottom.

In the quench variant, the crude syngas leaves the bottom of the gasifier through a quench tube, the bottom end of which is submerged in a pool of water. In passing through this water, the crude gas is cooled to the saturation temperature of the water and is cleaned of slag and soot particles. The cooled, saturated syngas then exits the gasifier/quench vessel through a duct on the sidewall. Depending on the application and the feedstock used, the crude syngas will then be further cooled and/or cleaned before use.

In the full heat recovery variant, the raw syngas leaves the gasifier section and is cooled in a radiant syngas cooler from ~1400°C to ~700°C, the heat recovered being used to raise high-pressure steam. Molten slag flows down the cooler and is quenched in a bath at the bottom, from where it is removed through lockhoppers. The partly-cooled syngas leaves the bottom of the gasifier and is then further cooled in convective coolers before being cleaned and used.

Most Texaco gasifiers used to-date have employed the quench variant. The major advantages of the quench variant over the full heat recovery design are that it is cheaper and more reliable; the major disadvantage (for IGCC) is that it is less thermally efficient. Most gasifiers in operation are in fact used for chemicals production where thermal efficiency is not an issue and so the quench variant is preferred. A further useful feature of the quench variant, for oil gasification, is that it helps to scrub oil-soot particles from the syngas. It is notable that the oil-based IGCC projects using Texaco gasifiers have mostly used quench gasifiers whilst the coal-based Texaco IGCC projects use syngas coolers.

SELECTION OF GASIFICATION PROCESSES

Many different factors affect the selection of a gasifier for a specific project. Commercial factors are paramount and political considerations may also be important. The technical issues that influence the choice of gasifier include the characteristics of the material to be gasified and the scale of the project.

Coal

All three main types of gasifier (ie entrained flow, fluidised bed and moving bed) can be used to gasify coal. Characteristics of the coal that can influence gasifier selection include ash content and melting point and coal reactivity. The size of the project may also have an effect.

All the gasifiers reviewed in the previous Section, with the exception of the Shell SGP, have been proven on coal.

Entrained flow reactors, and the BGL gasifier, rely on the coal ash being melted and converted into a fluid, molten slag. If the ash-melting point or slag viscosity is too high, they can be lowered using a suitable fluxing agent, usually limestone. The amount of limestone required depends on both the ash-melting point and the amount of ash present in the coal. So a very high-ash coal with a high ash-melting point will require considerable quantities of limestone. Conversely, fluidised bed gasifiers, as well as the Lurgi dry-ash gasifier, depend on the ash not melting. Consequently, low ash content and low ash-melting point tend to favour the selection of a slagging gasifier; high ash content and high ash-melting point favour the selection of a non-slagging gasifier.

Reactivity is another issue. The lower gasification temperatures of the fluidised bed gasifiers make them very suitable for reactive lignites but less suitable for less-reactive coals.

Entrained-flow gasifiers have been built for power plant of about $300MW_e$ and larger sizes are possible. In comparison, fluidised bed and moving bed gasifiers tend to be smaller, so a large power plant project would require multiple gasifiers. This has the disadvantage of losing some economies of scale, though an advantage is that multiple gasifiers may allow one to be taken out of service for maintenance whilst the plant as a whole is still in operation.

A further consideration when selecting a gasifier for coal is whether to use a process which utilises air or O_2 as the oxidant. Generally, fluidised bed systems use air whilst other gasifiers use O_2. Using air as the gasification medium has the advantage of not requiring an ASU, which is an expensive item of plant; against this, since the use of air means that the fuel-gas is diluted with nitrogen, the downstream processing equipment needs to be larger.

Oil

Only entrained flow gasifiers are suitable for gasifying liquid hydrocarbons such as heavy oils. Both the Shell SGP and Texaco gasifiers have a successful track record of operation on this type of feedstock. Selection between these two would therefore be made on commercial grounds.

Biomass

Biomass is very reactive, and biomass projects tend to be on a small scale (usually $<50MW_e$). There are several gasifiers that have been developed particularly for biomass; these often operate at atmospheric pressure, which makes feeding the biomass into the gasifier easier.

Wastes

Liquid wastes, such as waste oils, are best gasified in entrained flow reactors.

Solid wastes, such as MSW and sewage sludge, may be gasified in either fluidised bed or moving bed systems. Smaller projects, and projects which do not entail the co-firing of the waste with coal, tend to use fluidised beds. Larger projects and co-gasification projects favour moving bed systems.

CURRENT GASIFICATION POWER PLANT PROJECTS

There are currently at least 35 GPP projects in operation, commissioning, construction, design or planning. These vary in size from $500MW_e$ to less than $10MW_e$ and use a variety of fuels such as coal, heavy oil residues, waste woods, sewage sludge and sugar cane bagasse. A selection of these projects are reviewed below whilst a full list of operational and near-operational plant is given in Table 3.

Coal GPPs

Buggenum (Netherlands)

The Buggenum plant is the world's first commercial-sized ($253MW_e$), coal-fired IGCC (Figure 11). The IGCC is based around a Shell SCGP gasifier and a CCGT supplied by Siemens. The plant was started up in 1993. As well as being the first of the current generation of IGCC plant, the project is important in that it contains a number of advanced design features. The most significant of these is that the ASU and the gas turbine are very closely coupled together, with the gas turbine compressor supplying all the air to the ASU. This increases efficiency at the cost of making the plant more complex and less easy to start.

Figure 11. Buggenum IGCC (courtesy of Demkolec)

Name	Location	Output(MW)	Fuel	Gasifier	Power Island	1998 Status	Year
Buggenum	Netherlands	$253MW_e$	Bituminous coal	Shell	CCGT - V94.2	Operational	1995
Piñon Pine	USA	$100MW_e$	Bituminous coal	KRW	CCGT - GE 6FA	Commissioning	1998
Polk	USA	$250MW_e$	Bituminous coal	Texaco	CCGT - GE 7F	Operational	1996
Puertollano	Spain	$298MW_e$	Coal and petroleum coke	Prenflo®	CCGT - V94.3	Commissioning	1998
Vøesová	Czech Republic	$400MW_e$	Lignite	Lurgi	CCGT - 2xGE 9E	Operational	1995
Wabash River	USA	$262MW_e$	Bituminous coal	Destec	CCGT - GE 7FA	Operational	1995
El Dorado	USA	$40MW_e$ (gross)	Petroleum coke	Texaco	GT - GE 6B	Operational	1996
Falconara	Italy	$234MW_e$	Visbreaker residues	Texaco	CCGT - ABB 13E2	Construction	1999
GSK	Japan	$550MW_e$	Vacuum residue	Texaco	CCGT - 2xGE 9EC	Construction	2000
Pernis	Netherlands	$125MW_e$	Refinery residues	Shell SGP	CCGT - 2xGE 6B	Operational	1997
Priolo Gargallo	Italy	$521MW_e$	Refinery asphalt	Texaco	2xCCGT V94.2	Construction	1999
Saras	Italy	$550MW_e$	Visbreaker residue	Texaco	CCGT - 3xGE 9E	Construction	2000
Star	USA	$240MW_e$	Petroleum coke	Texaco	2xGE 6FA	Construction	1999
Amercentrale	Netherlands	$85MW_{th}$	Wood wastes	Lurgi CFB	Existing boiler	Construction	2000
ARBRE	UK	$8MW_e$	SRC willow	TPS CFB	CCGT - AGT typhoon	Construction	1999
Energy Farm	Italy	$12MW_e$	Short rotation forestry	Lurgi CFB	CCGT - Nuovo Pignone PGT10B/1	Construction	2000
Lahti	Finland	$70MW_{th}$	Wood wastes	Foster Wheeler CFB	Existing boiler	Operational	1998
McNeil	USA	$\sim15MW_{th}$	Wood chips	Battelle CFB	Existing boiler	Operational	1997
Värnamo	Sweden	$6MW_e$	Wood wastes	Foster Wheeler CFB	CCGT - AGT Typhoon	Operational	1993
Fondotoce	Italy	$1MW_e$	MSW	Thermo-select (moving bed)	Gas-motor generator	Operational	1994
Grève in Chianti	Italy	$6.7MW_e$ (gross)	Refuse - derived fuel	TPS CFB	Boiler and steam turbine	Operational	1992
New Bern	USA	$<60MW_{th}$	Black liquor	Chemrec (entrained flow)	Boiler and steam turbine	Operational	1997
Schwarze Pumpe	Germany	$60MW_e$	Assorted solid and liquid wastes	Noell, Lurgi BGL	CCGT - GE Frame 6	Operational. BGL to start-up in 1999	1997
Westfield	UK	120MW	Sewage sludge plus coal	BGL	CCGT - GE 6B	GT Operational on natural gas	1998
Zeltweg	Austria	$10MW_{th}$	Biomass/wastes	AE&E CFB	Existing boiler	Operational	1997

Table 3. Operational and near-operational GPPs

Since the plant has been put into operation it has suffered from two major types of problem: operability problems connected with the high level of integration, and gas turbine problems associated with burning the low-CV syngas in the gas turbine. Both of these have now been solved, but both required significant time to fully rectify.

Buggenum is among the cleanest coal-fired power plant in the world (depending on exactly how the figures are calculated), with overall NO_x and SO_x emissions lower than for a gas-fired CCGT (Table 4).

Emission	g GW^{-1}
SO_x	60
NO_x	60-120
Particulates	'virtually zero'

Table 4. Buggenum Emissions

Polk (USA)

Polk Power Station is located in Florida, near Tampa, and is owned and operated by Tampa Electric. It comprises one $250MW_e$ (net) IGCC incorporating a Texaco gasifier with full heat recovery and a GE 7F gas turbine. The project is supported by the US Department of Energy under its Clean Coal Technology Demonstration Program. In comparison with the Buggenum plant, Polk is much less integrated: the ASU is supplied by a separate air compressor, there being no off-take of air from the gas turbine compressor.

The plant entered commercial operation in 1996. Since then, it has generally run well. The major problem experienced relates to the heat exchangers, which are used to cool the raw syngas before the removal of sulphur compounds and reheat the cleaned syngas before it enters the gas turbine. Some deposition of fine ash occurred in these exchangers and this in turn led to repeated instances of corrosion, with the consequence that dust-laden syngas from the dirty side of the exchangers passed through to the clean side and into the gas turbine. These exchangers have now been removed, with cooling of the raw syngas and reheating of the clean syngas being carried out separately. These modifications have reduced the thermal efficiency of the plant, which is now <40% net.

Puertollano (Spain)

The Puertollano plant, located in southern central Spain, is a $300MW_e$ IGCC owned and operated by Elcogas, a consortium of European utilities and suppliers (Figure 12). Puertollano features a Prenflo® gasifier and a Siemens V94.3 gas turbine. The plant is very similar in design to Buggenum and, like Buggenum, has full integration of the gas turbine and ASU. The fuel is a mixture of petroleum coke and coal.

Figure 12. Puertollano IGCC during its construction (courtesy of Elcogas SA)

The plant is currently undergoing commissioning. As with Buggenum, problems have been experienced operating the very integrated design; there have also been combustion problems in the gas turbine.

Wabash River (USA)

The Wabash River power plant is owned by PSI Energy and is located in Western Indiana. It is the site of a $262MW_e$ IGCC which has been operational since 1995. The IGCC is unusual for two reasons:

i the unit repowers an existing, 1950s vintage steam turbine

ii the gasification island is owned and run by the technology vendor (Destec/Dynegy), which sells syngas 'over-the-fence' to the utility.

The plant contains a Destec gasifier and a GE7FA gas turbine.

The plant started operation at the end of 1995. There have been no major failures of plant or equipment. Minor problems which have been overcome include some ash deposition in the syngas cooler, cracking of part of the combustion liners in the gas turbine and failures of the ceramic filters used to remove fine ash from the gas (since replaced by metal elements).

Oil GPPs

Pernis (Netherlands)

Shell has recently installed a GPP at its Pernis refinery near Rotterdam. The GPP has three major functions: to provide a convenient means of processing high-sulphur oil residues; to provide H_2 for the refinery; and to generate power. The installation of the GPP, named Per+, is part of a wider scheme to upgrade the refinery to adjust for the tighter limits on sulphur content in automotive fuels.

The plant consists of three parallel gasification trains, each consisting of a Shell oil gasifier. Gas from two of the trains is processed to recover H_2 which is used in the refinery. The gas from the third train is used to fuel a gas turbine power plant. This third train is effectively a reserve, guaranteeing that if one of the trains comes off-line, H_2 production for the refinery can be kept at full-flow. The $125MW_e$ generated is therefore a by-product.

The plant started up in 1997 and no significant problems have been reported.

Biomass GPPs

ARBRE (UK)

ARBRE (Arable Biomass Renewable Energy Ltd) is a joint venture between Yorkshire Water, Royal Schelde (Netherlands) and Termiska Processer (TPS) of Sweden. ARBRE is building a biomass IGCC at Eggborough. The plant will use a TPS gasifier and CCGT based around an Alstom Gas Turbines (AGT) Typhoon gas turbine, and will run on short rotation coppice (SRC) willow grown in the surrounding area. The plant is due to become operational in 1999. The project has support from the European Commission's Thermie Programme and the UK's NFFO (Non-Fossil Fuel Obligation). The plant will generate $10MW_e$ gross, $8MW_e$ net.

Waste- and Co-gasification GPPs

Lahti (Finland)

The Kymijärvi power plant in Lahti, southern Finland, is the site of a biomass gasification partial repowering project. In this project, wet biomass is gasified in an atmospheric circulating fluidised bed gasifier and the fuel-gas produced is used to partly replace coal in the existing coal-fired boiler. The purpose is to take advantage of cheap biomass fuels.

The Kymijärvi plant was built in 1976 as an oil-burning unit and was modified to burn coal in 1982. In 1997, construction of the gasifier was started and the gasifier started operating in the early months of 1998. The boiler has a maximum rating of $360MW_{th}$ and the syngas produced by the gasifier can supply $40\text{-}70MW_{th}$, ie up to about 20% of the total energy input.

Biomass, comprising wet wood wastes, dry wood wastes from local timber factories and recycled fuel (consisting of paper, wood and plastics), is gasified at atmospheric pressure and 800-1000°C. The syngas produced passes directly from the gasifier through an air preheater to the boiler, where it is fired in two burners located under the coal burners.

The burners have been specially designed for the syngas, which has a very low lower heating value - as little as 2.2MJ kg^{-1} when the biomass is very wet. The fuel is not dried before gasification.

Westfield (UK)

The site of British Gas' Westfield Development Centre in Fife is being developed by the US-based Fife Power. The existing BGL gasifiers on the site are being refurbished to gasify a mixture of coal and sewage sludge. When the plant is fully operational, it will generate ~120MW_e.

In a second project at the same site, Fife Power plans to build a 400MW_e unit, also using BGL gasifiers, to gasify coal and household refuse.

FUTURE PROSPECTS

Market Opportunities

Coal

The most important markets for new coal-fired plant over the next 10-15 years will be China and South and East Asia. However, overwhelmingly in these markets, the technology chosen will be conventional pf-fired boilers, as the primary pre-requisites for these markets are low capital cost and high reliability, as well as the need to locally-source equipment wherever possible. The most important markets for IGCC will be North America (8-16GW_e) and China (6-8GW_e), the former driven by stringent emissions limits, the latter by the sheer amount of new capacity required. The uptake of IGCC in Europe will be constrained by the widespread availability of cheap natural gas. Overall, coal-fired IGCC will represent no more than 10% of new coal-fired plant worldwide until its costs are significantly lowered and its reliability increased.

Oil and Petroleum Coke

There is considerable scope in the short-to-medium term for oil- and petroleum coke-fired IGCCs plant integrated with refinery processes. The key drivers are the refiners' need to find routes for the disposal of heavy oil residues and petroleum coke and their need for H_2 to upgrade other refinery products. There is scope for up to 14GW_e of oil-fired IGCC in the European Union (EU) by 2010 (based on the amount of heavy residue likely to be available). However, the actual oil-IGCC capacity in the EU will be constrained by the availability of natural gas, which is an alternative source of H_2. Another significant market may be India: there, the deployment of oil-IGCC will depend on being able to get reliable and secure power purchase agreements (PPAs). In the short-to-medium term, oil-IGCC plant may well out-number coal IGCC plant.

Biomass

Biomass is becoming increasingly important as a fuel in both the EU and the USA because of concerns over CO_2 emissions. For biomass GPPs to make headway, they will have to become more cost-competitive relative to biomass combustion plant. Typical projects will be combined heat and power schemes utilising agricultural and forestry residues, eg in remote areas of Scandinavia, China, Canada, India and Brazil.

Waste

Gasification is an excellent, if expensive, way to dispose of wastes such as MSW and sewage sludge, both 'neat' and co-gasified with coal. It has several significant advantages over waste incineration, such as producing only an inert solid residue and eliminating the potential for the production of dioxins. Waste gasification will first 'take off' in those parts of Europe with particularly strong environmental concerns over waste incineration, such as Germany and Switzerland. By 2010, perhaps 15% of new waste disposal plant in Europe will be based on gasification.

A further application of the gasification of biomass and wastes is the production of fuel-gas for the partial repowering of existing oil- and coal-fired boilers. Several schemes are already in operation. Biomass and wastes cannot be used directly in conventional boilers. Their low or negative cost can make them attractive fuels in principle but they cannot be fired, as they cannot be ground finely enough. Air-blown gasification converts them into a fuel-gas that can be fired in the boiler, providing a means of waste disposal.

Research and Development Needed

The current weaknesses of GPP technologies are high capital costs, poor reliability (at least for coal-fired IGCCs) and poor operational flexibility. The current strengths are high efficiency and environmental performance. It is therefore clear that, in the short-to-medium term, R&D effort needs to be focused on reducing costs and increasing reliability and operability. This R&D effort can be broken down into three major areas:

i research into the fundamentals of gasification

ii R&D to improve individual plant components

iii R&D into better overall process layout and design.

Research into the fundamentals of gasification is required to establish the fuel flexibility of IGCC technologies. This would be directed at understanding gasification reaction rates and carbon conversion and at predicting the gasifiability of individual coals and other fuels, ash/slag behaviour and the potential for sulphur capture in fluidised bed gasifiers.

R&D is required to improve the following components of IGCC, to make them more reliable and/or cheaper:

- gasifiers/syngas coolers
- pressurised coal feeding systems
- gas clean-up
- gas turbines
- ASUs.

The required R&D for gasifiers and syngas coolers is centred on the development of improved alloys and manufacturing processes to improve the corrosion resistance and lower the cost of these components.

Pressurised coal feeding systems (both dry pf systems and briquetting systems) need to be improved to increase reliability and lower costs.

The development of improved hot gas clean-up systems could lower the cost of IGCC by providing a cheaper alternative to the conventional low-temperature processes currently employed. R&D is required to improve the reliability of both hot gas filters and hot gas desulphurisation systems.

The highest priority gas turbine R&D for IGCC is the development of better combustion systems for low-CV syngas. Also required is the development of more rugged gas turbines, capable of reliably running on uncleaned or partly-cleaned syngas.

Further work is required to allow the successful integration of ASUs into an IGCC. The two areas requiring attention are improved control systems for, and better dynamic simulation of, highly integrated ASUs. There is also the need, in the longer term, for alternatives to conventional cryogenic ASUs in order to lower costs.

A key area of R&D for IGCC is optimisation of the overall plant configuration and layout. Specific issues that require study are:

- dynamic simulation
- start-up and shut-down strategies
- operability
- simplified designs which reduce cost
- optimum integration strategies
- combining operability assessments within existing thermo-economic optimisation techniques.

CONCLUSIONS

- The gasification of solid- and liquid-fuels and wastes to produce fuel-gas for power generation is potentially very attractive on the grounds of both efficiency and environment.
- A coal-fired IGCC, for example, could match or beat the efficiency of the most efficient pf boiler whilst attaining significantly improved emissions performance. However, coal-fired IGCCs are currently expensive to build and have relatively poor reliability and operational flexibility. These drawbacks will limit the uptake of IGCCs to about 10% of all new coal-fired plant over the next 10-15 years, with the USA and China being the principal markets.
- The gasification of heavy refinery residues and petroleum coke is in principle an attractive option for refiners faced with poorer quality crudes and more stringent specifications for the composition of their refined products such as diesel and petrol. The extent to which refinery-based IGCC projects will go ahead depends on the availability or otherwise of cheap natural gas and the local power market. Several projects based on heavy fuel oil are already under way in Europe with more to follow; India may also see significant refinery-residue IGCC projects, depending on the availability of acceptable PPAs. Several petroleum coke IGCCs are in construction or operation in the USA.
- Small-scale gasification plant may be an attractive option for utilising opportunity fuels such as biomass and wastes, particularly in isolated areas. However, these will need to be cost-competitive with other conversion options such as fluidised bed boilers. Gasification of biomass and wastes also allows such fuels to be co-utilised in existing boilers. The gasification of household wastes is very attractive environmentally and may play an important role in waste disposal in Europe over the next 10-15 years.
- There are many proven gasifiers available. These fall into three major types: entrained flow, fluidised bed and moving bed. Entrained flow gasifiers are well-suited to both coal and oil. Fluidised bed gasifiers are particularly suited to biomass and waste gasification and high-ash coals. Moving bed gasifiers are suitable both for coal and for solid wastes.
- The successful adoption of gasification technologies within the power generation industry will depend on costs being reduced and reliability and operational flexibility being improved. These are the key areas in which R&D needs to be focused. The most important R&D areas are:

i better understanding of fuel-gasification behaviour

ii improving the reliability and reducing the capital costs of key IGCC plant components

iii optimising the overall IGCC process design.

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