PHASED CONSTRUCTION OF AN IGCC PLANT WITH PRE-INVESTMENT IN THE CC PLANT

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ABSTRACT
After the Chernobyl accident in April 1986, most western countries have slowed down, suspended or sometimes stopped their nuclear programme. In many cases, natural gas has been regarded as the best alternative to nuclear fuel in the short and mean term and numerous countries have opted for CC plants. However, and it is the case in Belgium, decision-makers and operators want to diversify their fuel sources. Presently, CC plants are not multi-fuel and are the most efficient when fed with natural gas. A good strategy is to avoid a too strong dependence on this fuel, which would lead to a situation with natural gas similar to the one we previously experienced with oil. In that respect, the IGCC technique allows a come back to coal: starting with a CC plant, it is possible to add gasification units several years later and hence to switch from natural gas to coal. However, the price to pay will be capital cost but also a loss of performances of the resulting plant.

A first option which consists in adding a gasification unit to a genuine CC unit several years later has been investigated in a previous paper (4). In this paper, we examine a second option, when a CC plant is built with some of its components oversized in order to allow easy integration of the future connections from and to the gasification unit erected in the second stage of the construction. We calculate the performances of the CC plant for various pre-investment options, inside the heat recovery boiler, in the steam turbine and in the gas turbine. We compare the performances of the resulting IGCC plants when four types of gasifiers are used, i.e. Texaco, Shell, Dow and British-Gas-Lurgi. The performances of the same plants built in stages without pre-investment and built as genuine IGCC plants provide the yardsticks for comparison.

NOMENCLATURE
BGL : British Gas / Lurgi
CC : Combined Cycle
GT : Gas Turbine
HP : High Pressure
HRSG : Heat Recovery Steam Generation
IGCC : Integrated Coal Gasification in Combined Cycle
kWh : KiloWatt.Hour (3600000 J)
LHV : Low Heating Value (MJ/kg)
LP : Low Pressure
m : Mass Flow (kg/s)
mmWC : Millimetre of Water Column (0.0001 bar)
p : Pressure (bar)
P : Power Output (MW)
PFBC : Pressurized Fluidized Bed
PC : Pulverised Coal
Q : Fraction of Heat Transferred
ST : Steam Turbine
t : Temperature (°C)
t/d : Ton per Day (of dry coal)
TET : Turbine Entry Temperature (°C)
Δt : Temperature Difference (°C)

INTRODUCTION
After the Chernobyl accident in April 1986, several western European countries have slowed down, suspended or even stopped their nuclear programme. In particular, Belgium, second after France in the world ranking for the nuclear share in electricity production, has opted for a suspension of the erection of an eighth nuclear plant in december 1988. The alternative option was the installation of natural gas-fired power plants like combined-cycle plants. Two units rated at 450 MW each will normally be commissioned in 1993. More units are foreshed for this decade.

In order to diversify the fuel sources, the decision-makers have also planned to install classical pulverized coal power plants with deNOx and deSOx devices. However, the option to replace them, totally or partly, by IGCC plants is still open.
The great concern that the country could become too dependent on natural gas and would not be able to cope with a lack of this fuel led the decision-makers to assess the possible ways of phasing the construction of IGCC plants.

In practice, three main options are worth being analyzed in order to ensure a fuel flexibility to CC plants and in order to be able to switch from natural gas to coal when gas becomes unavailable or too expensive.

**First option.**
A new IGCC plant, optimized for operation on coal, is installed with a high degree of integration between the gasification unit and the CC plant. The performances of this new unit have then to be compared with those of a new PC plant of the same rated output.

**Second option.**
A new CC plant, optimized for operation on natural gas, has been built. Later on, the decision is taken to switch to coal. A coal gasification unit has to be added to the existing CC plant. In this option, the question is to know what type of gasifier should be selected and how it should be linked with the CC plant to minimize performance losses.

**Third option.**
The decision-makers initially decide to build an IGCC plant in stages. They start with a CC plant, no longer optimized on natural gas operation only. Therefore, they have to pre-invest for an overshielding of some components like heat exchangers in the recovery boiler, steam turbine, gas turbine burners... so that the system can accommodate the gasification unit later on. A loss of performance is accepted during the first stage but the subsequent operation on coal might compensate for it.

In this paper, we investigate the third option and look for the most suitable gasifier among the four following ones: Texaco, Shell, Dow and British-gas/Lurgi gasifiers, together with the best pre-investment strategy. These gasifiers are selected because they are thought to be the most technically mature and are the most used and developed in pilot or already existing plants.

**ASSESSMENT OF GENUINE FULLY INTEGRATED IGCC PLANTS**
The various options for phasing an IGCC construction and the resulting performance penalties for the final plant strongly depend on two main parameters, namely the fuel LHV and the degree of integration, i.e. on the connections between gasification and CC units.

Without going into details, the connections between chemical and electrical units may mainly consist of:

- streams of feedwater flowing from the HRSG to syngas coolers and coming back to the HRSG either as saturated or as superheated steam;
- streams of feedwater to and from syngas humidifier or saturator;
- stream of water or steam from HRSG into gasification region;
- stream of feedwater to the coal slurry preparation (Texaco and Dow);
- stream of bled air from the GT compressor to the air separation unit and possible return of nitrogen into the GT combustion chamber;
- stream of syngas from the gas cooling and cleaning set up to the burners of the GT combustion chamber.

In a previous paper (1) the performances of genuine IGCC plants were assessed on the basis of the four considered gasifiers, using 150 MW-class gas turbines, with dual pressure HRSGs.

As a result of our computational modelling, figure 1 shows how the energy cascades between the different units of the four considered IGCC power plants. All figures are quoted according to the reference [coal LHV * coal mass flow = 100] and represent energy flows.

Table I gathers the main design point characteristics for the four power plants, but in absolute terms (and for one gas turbine). It was assumed that the gas turbines could be modified so that they could cope with the effect of low heating value gases at best. The CO₂ emissions are cut by almost the same amount as the increase in efficiency.

The IGCC efficiency still has a big potential of improvement coming from the performance improvements on the gas turbine side. It is currently thought that efficiencies around 46 % could be reached with advanced GTs. Because an IGCC plant is very modular (the modules are the steam cycle, the heat recovery steam generator, the gas turbines, the gasifiers and their cleaning devices, the air separation units, ...), it is possible to phase its construction and hence to plan a switch from natural gas to coal. Phasing the construction is also phasing the investment and following the growth of electricity demand more closely. When a gasification unit is added to a CC plant, the issue is the level of integration and consequently the loss of performances of the final plant compared with a new genuine IGCC one.
without requiring any bleeding when running with the design TET value. The effects of burning low LHV fuels on the gas turbine performances and behaviour are analyzed in (2) and (3).

From figure 1, it can be seen that the integration levels are quite different, especially between entrained bed technologies (Shell, Texaco, Dow) and fixed bed technology (BGL).

It is remarkable that, with such different technological options and integration levels, the four IGCC plants have very similar efficiencies as illustrated by table I. Therefore, it can be said that performance is not the leading criterion when choosing a gasification technology for an unphased construction.

These unphased IGCC plants provide the yardsticks for the appraisal of the phased options based on the same gasifiers.

<table>
<thead>
<tr>
<th></th>
<th>BGL</th>
<th>SHELL</th>
<th>TEXACO</th>
<th>DOW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Input as coal (MW)</td>
<td>508.1</td>
<td>590.7</td>
<td>612</td>
<td>662.1</td>
</tr>
<tr>
<td>Coal requirements (t/d) (approx.)</td>
<td>1570</td>
<td>1820</td>
<td>1890</td>
<td>2040</td>
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<tr>
<td>Make-up water capacity (kg/s)</td>
<td>5.13</td>
<td>6</td>
<td>29.5</td>
<td>20.7</td>
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<tr>
<td>Condenser heat load (MW)</td>
<td>156.6</td>
<td>247.4</td>
<td>209.4</td>
<td>247.6</td>
</tr>
<tr>
<td>Syngas mass flow (kg/s)</td>
<td>34.1</td>
<td>36.6</td>
<td>46.7</td>
<td>56.3</td>
</tr>
<tr>
<td>Treated syngas LHV (MJ/kg)</td>
<td>13.75</td>
<td>12.2</td>
<td>8.16</td>
<td>8.545</td>
</tr>
<tr>
<td>Cooled Gas Efficiency (0-1)</td>
<td>.898</td>
<td>.782</td>
<td>.763</td>
<td>.739</td>
</tr>
<tr>
<td>Gas turbine output (MW)</td>
<td>155.8</td>
<td>155.5</td>
<td>185.3</td>
<td>172.5</td>
</tr>
<tr>
<td>Gas turbine efficiency (%)</td>
<td>33.2</td>
<td>33.2</td>
<td>35.1</td>
<td>34.3</td>
</tr>
<tr>
<td>Gas turbine exhaust temperature (°C)</td>
<td>551.9</td>
<td>551.6</td>
<td>553.7</td>
<td>553.3</td>
</tr>
<tr>
<td>Gas turbine exhaust mass flow (kg/s)</td>
<td>531.5</td>
<td>534</td>
<td>562.1</td>
<td>553.7</td>
</tr>
<tr>
<td>HRSG stack temperature (°C)</td>
<td>113.9</td>
<td>114.5</td>
<td>104.5</td>
<td>106.2</td>
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<tr>
<td>Steam turbine output (MW)</td>
<td>129.3</td>
<td>107.2</td>
<td>134</td>
<td></td>
</tr>
<tr>
<td>Output radio [ST / (ST + GT)]</td>
<td>.342</td>
<td>.454</td>
<td>.366</td>
<td>.437</td>
</tr>
<tr>
<td>Gross output (MW)</td>
<td>236.8</td>
<td>284.9</td>
<td>292.5</td>
<td>306.6</td>
</tr>
<tr>
<td>Auxiliary requirements (MW)</td>
<td>23.6</td>
<td>36.3</td>
<td>32.7</td>
<td>26.8</td>
</tr>
<tr>
<td>Net output (MW)</td>
<td>213.2</td>
<td>248.5</td>
<td>259.5</td>
<td>279.8</td>
</tr>
<tr>
<td>Net efficiency (%)</td>
<td>42.0</td>
<td>42.1</td>
<td>42.4</td>
<td>42.2</td>
</tr>
</tbody>
</table>

Table I - Genuine IGCC Plants - Main Characteristics

Figure 1 - Energy flows in the four unphased IGCC Plants
Gas Turbine Data

The gas turbine represents a typical 150 MW-class machine:

- TET : 1110°C
- pressure ratio : 10.7
- inlet mass flow : 497.4 kg/s
- net power output : 145.8 MW
- net efficiency : 32.48%
- compressor isentropic efficiency : 0.9
- turbine isentropic efficiency : 0.93
- exhaust mass flow : 506.9 kg/s
- exhaust temperature : 552°C

under the conditions:

- inlet pressure : 1 bar
- inlet temperature : 15°C
- inlet pressure drop : 10 mbar
- exhaust pressure drop : 25 mbar (=250 mmWC) (including HRSG)
- fuel : natural gas, LHV = 42.4 MJ/kg

HRSG Data

- HP drum pressure : 75 bar
- HP superheater discharge flow temperature : 515°C
- HP superheater mass flow : 66.5 kg/s
- HP evapo pinch point : 10°C (*)
- HP econo approach point temperature difference : 4°C (*)

- LP drum pressure: 7 bar
- LP superheater discharge flow temperature : 200°C
- LP superheater mass flow : 12.2 kg/s
- LP evapo pinch point : 8°C (*)
- LP econo approach point temperature difference : 4°C (*)

feedwater heating : econo-type circuit on the deaerator
stack temperature : 107.6°C

Steam Cycle Data

- HP turbine isentropic efficiency : 0.8
- LP turbine isentropic efficiency : 0.85
- condenser pressure : 50 mbar
- net output : 80.2 MW

Overall Performance

- net plant output : 260 MW
- net plant efficiency : 50.35%

(*) selected according to current industrial practice

Table II - Original combined cycle characteristics.

PHASED IGCC PLANTS WITHOUT PRE-INVESTMENT

This has been studied in a previous paper (ref 4) and is summarized here for comparison purposes.

First phase : the Combined Cycle

The first phase of the operation is a combined cycle unit running on natural gas, based on two 150 MW-class gas turbines with their associated heat recovery steam generators (HRSGs) and one corresponding steam turboset. This system is optimized and sized for natural gas operation in its initial design.

Table II summarizes the main design assumptions and performances of this very classical state-of-the-art natural gas fired combined cycle plant.
Second Phase: The IGCC Plant
The second phase of operation is characterized by the existing CC plant transformed into an IGCC plant, operating on coal.

Scope and Objectives
Phased IGCC plants, based on the four considered gasifiers and on the previously described combined cycle, are analyzed. From figure 1 and table I, it is quite obvious that the gasification techniques require different integration levels with the combined cycle unit in order to give the best possible performance. These physical links between gasification and combined cycle are illustrated on figures 2, 5 and 8. When phasing the construction, the connections that both improve the efficiency and do not prevent the HRSG from working are implemented.

When a substantial amount of high pressure steam is produced by the gasification process, a separate steam turbine is installed in the gasification unit, together with its condenser. This separate steam turbine is supposed to have an isentropic efficiency of 82% (with a 1% efficiency loss by % of moisture content by mass in the two-phase zone), whilst the condenser has a vapour pressure of 80 mbar.

The computational model which is used provides detailed results for the gas turbine, steam turbine and HRSG which are described in ref. 4.

The effect of low LHV gaseous fuels on gas turbines is described and discussed in ref. (2) and (3). Both the output and the pressure ratio increase when natural gas is replaced by syngas if the regulation keeps the TET constant. A constant TET which provokes an unacceptable or dangerous rise in output and pressure ratio appears as a quite academic assumption. When studying the phased IGCC plants without pre-investment, it has been demonstrated (ref 4) that the use of VIGVs was the best strategy to counteract these effects of low LHV fuel. Therefore, performances are derived with the VIGV position as a variable, and the operating points characterized by the gas turbine output and pressure ratio equal to their design values are computed.

The performances of the four resulting plants under those assumptions are summarized in table III.

<table>
<thead>
<tr>
<th>Integration</th>
<th>BGL</th>
<th>SHELL</th>
<th>TEXACO</th>
<th>DOW</th>
</tr>
</thead>
<tbody>
<tr>
<td>HP process steam</td>
<td>weak</td>
<td>medium</td>
<td>strong</td>
<td>strong</td>
</tr>
<tr>
<td>unphased IGCC output (MW)</td>
<td>213.2</td>
<td>248.5</td>
<td>259.5</td>
<td>279.8</td>
</tr>
<tr>
<td>- efficiency (%)</td>
<td>42.0</td>
<td>42.1</td>
<td>42.4</td>
<td>42.2</td>
</tr>
<tr>
<td>phased IGCCs without pre-investment</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. gas turbine with design TET</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>plant output (MW)</td>
<td>212.5</td>
<td>246.6</td>
<td>252.8</td>
<td>263.97</td>
</tr>
<tr>
<td>- efficiency (%)</td>
<td>41.8</td>
<td>41.75</td>
<td>41.30</td>
<td>39.9</td>
</tr>
<tr>
<td>2. gas turbine with design pressure ratio (VIGV regulation)</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>plant output (MW)</td>
<td>200</td>
<td>232.5</td>
<td>227</td>
<td>n.a.</td>
</tr>
<tr>
<td>- efficiency (%)</td>
<td>41.65</td>
<td>41.6</td>
<td>40.8</td>
<td>n.a.</td>
</tr>
<tr>
<td>Penalty in efficiency (unphased IGCC - case 2) (%)</td>
<td>0.35</td>
<td>0.50</td>
<td>1.6</td>
<td>n.a.</td>
</tr>
</tbody>
</table>

Table III - Phased IGCC Plants - Summary of Characteristics

PHASED IGCC PLANTS WITH PRE-INVESTMENT
Possible Pre-investment
The comparison of genuine IGCC plants and phased IGCC plants without pre-investment helps the identification of the possible pre-investments.

Gas turbine and generator. The gas turbine will have to be adapted when switching to syngas because of the differences in combustion properties, mainly in LHV. These modifications will affect the combustion process. From the performance point of view, ref (2) and (3) demonstrate that, if the gas turbine is not redesigned, the effect of the low LHV fuel can be counteracted by the use of VIGVs. All 150 MW-class machines are fitted with these and hence, no pre-investment with an impact on performance is required on the gas turbine.

The gas turbine generator may be slightly oversized, in order to sustain the additional power produced by the gas turbine when it is VIGV-controlled with the pressure ratio equal to its design
value. In that case, there is an improvement compared with the case when both the pressure ratio and the output have to be equal or less than their design value.

**HRSG.** The HRSG heat transfer surfaces are different in the CC and IGCC plants both because the gas turbine exhaust has different composition and properties and because some of the connections between the gasification and the CC plant affect the HRSG.

It appears feasible to size some of these heat transfer surfaces with regard to the IGCC operation in phase two rather than with regard to the CC operation in phase one. There might be a performance penalty in phase one in that case.

**Steam turbines.** The steam mass flows are usually higher during the IGCC phase, so that the oversizing of the CC steam turbine may avoid the necessity of a separate steam turbine during the IGCC phase. Calculations will assess the performance penalty during the CC phase due to the fact that the turbine is running with substantially less steam than at design.

**Steam cycle cold end.** It may be interesting to oversize some of the steam cycle cold end components, like pumps and deaerators. From a performance point of view, sizing the condenser so that it is able to accommodate the additional flow from the separate steam turbine during the IGCC phase appears as an attractive pre-investment, because it enables the separate steam turbine to work with a condenser pressure similar to that of the CC steam turbine.

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**The BGL-based Phased IGCC Plant**

**Introduction.** The CC arrangement of the genuine BGL-based IGCC plant used as reference is illustrated by fig. 2. From table III, it appears that the performance penalty when phasing the construction of this plant, starting with a genuine CC plant, amounts to 0.35 percentage point when VIGVs are used to control the gas turbine.

This performance penalty is mainly due to the slight non-adaptation of the HRSG heat transfer surfaces to the IGCC mode.

**Performance analysis.** Connections 4 and 5 on figure 2 indicate that the HP economizer is the most affected transfer surface when running in the IGCC phase. Performances have been recomputed with this economizer sized for the IGCC phase. This corresponds to a 22% oversizing during the CC phase.

Rather than a performance penalty for the combined cycle plant, its efficiency goes up from 50.35% to 50.40%. In phase two, however, the phased IGCC plant efficiency increases from 41.65% to 41.78% when VIGV controlled.

If the gas turbine alternator is sized to sustain the output corresponding to the gas turbine running with its design pressure ratio, the phased IGCC plant efficiency is 41.84%.

Figure 3 compares the efficiencies of the phased plant with pre-investment with the two reference situations (unphased IGCC and phased IGCC without pre-investment). The same results are summarized by table IV.

Figure 4 compares the efficiency during the IGCC phase for the same options. The difference between the two curves is the effect of oversizing the HP economizer, whilst the benefit of oversizing the gas turbine alternator is illustrated by the difference between the two left-hand crosses on the continuous curve.

**Discussion of the results.** The genuine BGL-based IGCC plant had an efficiency of 42% (ref 1). Phasing its construction starting with a normal CC plant implies a 0.35 percentage point penalty (ref 2). This small figure was ascribed to the low integration level required by the process, which is described in ref. 5 and 6. Pre-investing on the HRSG HP economizer and on the gas turbine generator reduces this penalty by 50%, down to 0.16 percentage point. These recommended pre-investments do not jeopardize the phase one (CC) efficiency, which although no longer optimized on natural gas, even slightly increases from 50.35% to 50.40%.
The Shell-based Phased IGCC Plant

Introduction. The CC arrangement of the genuine Shell-based IGCC plant used as reference is illustrated by fig. 5. From table III, it appears that the performance penalty when phasing the construction of this plant, starting with a genuine CC plant, amounts to 0.50 percentage point when VIGVs are used to control the gas turbine.

Performance analysis. Figure 5 indicates that the HRSG is not affected on the water-steam side when going into the IGCC phase, because superheated steam is produced by the process (described in ref. 7). Hence, only the differences in gas turbine exhaust influence the HRSG transfer surfaces, which are quite similar in genuine CC and IGCC plants.

The performances have however been recomputed with the heat transfer surfaces sized with respect to the IGCC phase: the CC phase efficiency goes down from 50.35% to 50.21%, whilst the phased IGCC efficiency increases from 41.6% to 41.7% when VIGV controlled.

Pre-investment on the gas turbine alternator increases this figure up to 41.75% when only the gas turbine pressure ratio has to be kept at its design value.

A second possible pre-investment is the oversizing of the steam cycle cold end, in order to provide the separate steam turbine with a condenser pressure similar to that of the CC steam turbine. This, together with the previously described modifications, leaves the CC phase efficiency unchanged at 50.21%, but increases the IGCC phase efficiency up to 41.95%.
option 3

A third possible pre-investment is the oversizing of the CC steam turbine so that it can accommodate the additional flow when switching to the IGCC phase. This ensures an efficiency to the IGCC phase of 42% (very close to the genuine IGCC), but jeopardizes the CC phase performance, down to 47.13%. The reason is the inefficient expansion during the CC phase, in a highly oversized steam turbine.

Discussion of the results. If pre-investment has to be done on a CC plant in order to ease the integration of a Shell gasification process later on, we would recommend option two, i.e. sizing of the HRSG transfer surfaces and of the steam cycle cold end with regard to the IGCC phase. The oversizing of the CC steam turbine turns into an unacceptable efficiency penalty during the CC phase.

With that recommendation, the phase IGCC efficiency is 41.95%, to be compared with the genuine IGCC (42.1%) and with the phased construction without pre-investment (41.6%).

Figure 7 compares the efficiency during the IGCC phase for this recommended option. The difference between the two curves is the effect of oversizing the HRSG surfaces and the steam cycle cold end, whilst the benefit of oversizing the gas turbine alternator is illustrated by the difference between the two left-hand crosses on the continuous curve.

The Texaco-based Phased IGCC Plant

Introduction. The CC arrangement of the genuine Texaco-based IGCC plant used as reference is illustrated by fig. 8. From table III, it appears that the performance penalty when phasing the construction of this plant, starting with a genuine CC plant, amounts to 1.60 percentage point when VIGVs are used to control the gas turbine.

Figure 8 - unphased Texaco-based IGCC plant (CC part)
This performance penalty is mainly due to the important non-adaptation of the HRSG heat transfer surfaces to the IGCC mode and to the inefficiency of the expansion of saturated HP steam in the separate steam turbine.

Performance analysis. Figure 8 indicates that the HRSG is very much affected on the water-steam side when going into the IGCC phase, because saturated steam is produced by the process (described in ref. 8 and 9). Hence, the HRSG heat transfer surfaces in a genuine IGCC plant are very different from those in the original CC plant.

The performances have been recomputed with the heat transfer surfaces sized with respect to the IGCC phase: the CC phase efficiency goes down from 50.35% to 48.97%, whilst the phased IGCC efficiency increases from 40.8% to 41.0% when VIGV controlled.

Pre-investment on the gas turbine alternator increases this figure up to 41.15% when only the gas turbine pressure ratio has to be kept at its design value.

option 2
A second possible pre-investment is the oversizing of the steam cycle cold end, in order to provide the separate steam turbine with a condenser pressure similar to that of the CC steam turbine. This leaves the CC phase efficiency unchanged at 50.35%, but increases the IGCC phase efficiency up to 41.24% when VIGV controlled and with an oversized gas turbine alternator.

option 3
A third possible pre-investment strategy is to apply both option 1 and 2. The CC phase efficiency is similar to that of option 1 (48.97%), whilst the IGCC phase efficiency goes up to 41.47%.

Figure 9 compares the efficiencies of the three considered options of phased plant with pre-investment with the two reference situations (unphased IGCC and phased IGCC without pre-investment).

Discussion of the results. If pre-investment has to be done on a CC plant in order to ease the integration of a Texaco gasification process later on, we would recommend option two, i.e. sizing of the steam cycle cold end with regard to the IGCC phase. The sizing of the HRSG heat transfer surfaces turns into an unacceptable efficiency penalty during the CC phase.

Experience gained from the Shell process indicates that the oversizing of the CC steam turbine in order to accommodate the additional flow during the IGCC phase is not recommendable.

With that recommendation, the IGCC phase efficiency is 41.24%, to be compared with the genuine IGCC (42.4%) and with the phased construction without pre-investment (40.8%).

Figure 10 compares the efficiency during the IGCC phase for this recommended option with the two reference situations (unphased IGCC and phased IGCC without pre-investment). The difference between the two curves is the effect of oversizing the steam cycle cold end, whilst the benefit of oversizing the gas turbine alternator is illustrated by the difference between the two left-hand crosses on the continuous curve.
The Dow-based Phased IGCC Plant

The analysis of phased IGCC plants without pre-investment conducted in a previous paper (ref. 4) has demonstrated that the Dow process described by ref. 10 is characterized by the largest performance penalties when phasing its construction. This is due to the fact that the integration connections in the Texaco and in the Dow process are quite similar, but with a higher saturated HP steam mass flow for the Dow process. The inefficient expansion of HP saturated steam in a separate steam turbine is the major fact contributing to the performance penalty for these processes.

Hence, no analysis of phased scenarios with pre-investment has been conducted for the Dow process.

<table>
<thead>
<tr>
<th>Integration</th>
<th>BGL</th>
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<th>DOW</th>
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</thead>
<tbody>
<tr>
<td>HP process steam</td>
<td>weak</td>
<td>medium</td>
<td>strong</td>
<td>strong</td>
</tr>
<tr>
<td>-</td>
<td>superheated</td>
<td>saturated</td>
<td>saturated</td>
<td></td>
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<tr>
<td>unphased IGCC output (MW)</td>
<td>213.2</td>
<td>248.5</td>
<td>259.5</td>
<td>279.8</td>
</tr>
<tr>
<td>- efficiency (%)</td>
<td>42.0</td>
<td>42.1</td>
<td>42.4</td>
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<tr>
<td>phased IGCCs</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. without pre-investment</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>gas turbine at design pressure ratio (VIGV regulation)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>plant output (MW)</td>
<td>200</td>
<td>232.5</td>
<td>227</td>
<td>n.a.</td>
</tr>
<tr>
<td>- efficiency (%)</td>
<td>41.65</td>
<td>41.6</td>
<td>40.8</td>
<td>n.a.</td>
</tr>
<tr>
<td>Penalty in efficiency (unphased IGCC - case 1) (%)</td>
<td>0.35</td>
<td>0.50</td>
<td>1.6</td>
<td>n.a.</td>
</tr>
<tr>
<td>2. with the recommended pre-investments</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>gas turbine at design pressure ratio (VIGV regulation)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>plant output (MW)</td>
<td>205</td>
<td>237.5</td>
<td>229</td>
<td>n.a.</td>
</tr>
<tr>
<td>- efficiency (%)</td>
<td>41.84</td>
<td>41.95</td>
<td>41.24</td>
<td>n.a.</td>
</tr>
<tr>
<td>Increase in efficiency (case 2 - case 1) (%)</td>
<td>0.19</td>
<td>0.35</td>
<td>0.44</td>
<td>n.a.</td>
</tr>
<tr>
<td>Remaining efficiency penalty (unphased IGCC - case 2) (%)</td>
<td>0.16</td>
<td>0.15</td>
<td>1.16</td>
<td>n.a.</td>
</tr>
<tr>
<td>Associated CC phase penalty (%)</td>
<td>-0.05</td>
<td>0.14</td>
<td>0.0</td>
<td>n.a.</td>
</tr>
</tbody>
</table>

Table IV - Phased IGCC Plants - Comparison of phasing strategies.
CONCLUSIONS
Various pre-investment strategies that reduce the performance penalty encountered when phasing the construction of an IGCC plant have been analyzed in this paper. This analysis demonstrates that:

- the integration of technologies which require a low level of integration (namely fixed bed gasifiers like BGL) can be eased in an existing CC if the HRSG heat transfer surfaces are adapted to the IGCC phase. This compensates for more than half the performance penalty associated with the phased construction;

- the integration of the processes producing HP superheated steam is eased by the sizing of the HRSG transfer surfaces and of the steam cycle cold end (condenser, pumps and deaerator) with respect to the IGCC phase. The oversizing of the CC steam turbines turns into an unacceptable efficiency penalty during the CC phase;

- The integration of those processes producing HP saturated steam into an existing CC plant is characterized by a quite important performance penalty during the IGCC phase, even with the oversizing of the steam cycle cold end, which appears to be the only feasible solution. Sizing the HRSG heat transfer surfaces with regard to the IGCC phase gives an unacceptable performance penalty to the CC phase in these processes.

In any case, the installation of a gas turbine generator capable of sustaining the power output of the gas turbine when it is VIGV controlled down to its design compressor pressure ratio appears attractive. The associated efficiency gain lies between 0.05 and 0.15 percentage point, depending on the syngas LHV.

With these recommendations, the economics of coal gasification (ref. 11 and 12) might make the phased construction of IGCC plants starting with adapted CC plants an attractive power generation option for the future.

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