IGCC – Clean Power Generation Alternative For Solid Fuels

Norman Z. Shilling, Product Line Leader, IGCC
norman.shilling@ps.ge.com
Dan T. Lee, Manager, Application Engineering
dan.lee@ps.ge.com

GE Power Systems
Energy Products
General Electric
1 River Road
Schenectady, NY 12345

ABSTRACT

Environmental performance is a key benchmark for contemporary Integrated Gasification Combined Cycle (IGCC) plant designs. IGCC boasts high marks in environmental performance derived in part from both the fundamental environmental characteristics of the process as well as advances in gas turbine combustion technology. The earliest commercial-scale coal IGCC plants are still achieving levels of criteria pollutants lower than those of recently permitted direct combustion plants. Additional advancements are providing further improvement in environmental performance as well as capability to deal with a broadening range of applications.

IGCC systems provide significant environmental benefits through lower solids production, lower criteria pollutant emissions, and income from byproduct sales when applied to the clean conversion of opportunity fuels such as petroleum coke, refinery residuals and biomass. In addition, the capability of gas turbine combustion systems to accommodate a wide variety of fuel gas compositions allows for effective process integration with gasification systems enabling “poly-generation” of hydrogen and steam, with provisions for cost effective “pre-combustion” CO\textsubscript{2} removal.

The future viability of IGCC is ensured by its capability to meet developing standards in Mercury and HAPS reduction. IGCC also has promising process paths and economics for low CO\textsubscript{2} power enabled by the capability of gas turbines to combust high-hydrogen, carbon-free gaseous fuel.

The robustness of the gasification process to handle a wide range of solid and liquid fuels has been demonstrated in applications using coal and refinery wastes in roles of power and chemical co-production. Current gas turbine combustion control systems provide for full and/or co-firing of synthesis gas with natural gas or distillate fuel providing high power availability with extensive operational flexibility needed to serve today’s dynamic energy markets. The high power and chemical production availabilities demanded by refineries can be achieved by IGCC system design through multiple gasifier and power trains, combined with the gas turbine’s capability to use backup fuels with seamless transfer between fuel sources.

Continuous improvements in gas turbine technology and performance are rapidly driving IGCC systems costs down the learning curve. The fuel cost sensitivity curve shows IGCC to be a viable commercial contender for low cost opportunity fuels and high sulfur coal as natural gas prices continue to trend upward.

GE gas turbines have accumulated more than 500,000 fired hours on a broad range of synthesis fuels, which to a large degree have been enabled by continuous developments in gas turbine technology. Fuel flexibility and high system reliability afforded by today’s gas turbines are critically important to the economic success of solid fuel based IGCC projects. IGCC plant designs currently enjoy compelling environmental advantages for waste fuel conversion to economical poly-generation products, and provide additional system flexibility and growth potential to meet future regulatory challenges.
Introduction

Natural gas prices are rising, environmental requirements are becoming more stringent, and there is an urgent need to diversify the U.S. fuel supply. In addition, energy demand is surging in developing countries like China and India even as pressure builds to reduce greenhouse-gas emissions worldwide.

To meet this challenging need, Integrated Gasification Combined Cycle (IGCC) system designs have demonstrated their capability to meet today’s power generation needs through a combination of high environmental performance, competitive cost-of-electricity and broad fuel flexibility using a variety of coals and other low value solid opportunity fuels. The capability of IGCC systems to accommodate wide variation in plant operations including associated fuel and power requirements illustrates that considerable system design optimization and process integration are paramount to achieving project objectives. Several solid fuel IGCC projects have met these design challenges with exceptional performance and fuel flexibility.

General Electric gas turbines have been employed in 14 IGCC projects, with four more planned to become operational within the next five years. These projects utilize the GE product line of commercially available heavy duty gas turbines resulting in IGCC plants ranging in size from 40 to 550 MW in net output capacity. GE gas turbines have accumulated over 500,000 fired hours of syngas experience to date. Power generation availability has also been excellent, in excess of 90%, due to the ability of GE gas turbines to switch and co-fire multiple fuels under load. The design and operational experience gained from these facilities has played a key role in the continued advancement of IGCC systems.

ENVIRONMENTAL

IGCC is the cleanest solid fuel technology. Coal IGCC provides superior performance in all key metrics of total environmental performance – criteria pollutants, organic HAPS, inorganic HAPS, and waste generation. Compared to conventional direct combustion technologies that primarily depend on end-of-pipe control, IGCC is a pollution prevention approach. Pollution prevention is achieved through source reduction – deep pre-combustion removal of pollutants followed by clean combustion. This pollution prevention perspective has been the guiding precept for GE’s emphasis on low emission combustion. IGCC offers thermodynamically favorable conditions of high pressure, high concentration of contaminants and low volumetric flow of syngas – as little as 1/100 of combustion products obtained in flue-gas cleaning. This allows economical deep cleaning of the syngas which currently provides exceptional sulfur and particulate removal, and which also can be expanded to deal with mercury and CO₂. Another significant benefit is the realizable future potential for continued -- even dramatic -- improvement in environmental performance. This derives from both IGCC’s fundamental process characteristics and continuing advances in gas turbine combustion technology. This has been convincingly demonstrated by the performance of the Polk and Wabash IGCC plants that, despite having entered operation 6-7 years ago, are still superior to current combustion coal plants. A comparison of a contemporary design IGCC plant with direct combustion plants having the lowest SOx and NOx emissions as cited by Power Magazine are shown in Table 1. IGCC is seen to be more effective in achieving simultaneous control of both NOx and SOx.

Table 1. Coal criteria pollutants.

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Direct Combustion</th>
<th>IGCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOx</td>
<td>Ammonia-based SCR</td>
<td>Deep pre-combustion removal</td>
</tr>
<tr>
<td>SOx</td>
<td>Direct Combustion</td>
<td>Deep pre-combustion removal</td>
</tr>
</tbody>
</table>

Pollution Prevention: End-of-pipe controls incur unintended collateral environmental, cost and operational impacts, which must be included in a total cost evaluation (Table 2).

NOx: Direct combustion coal plants use ammonia-based SCR to approach -- but not achieve -- the low NOx levels from IGCC plants. This comes at an environmental cost. Despite
advances in low-NOx combustors for direct combustion, high efficiency SCR is still required to achieve regulatory limits for NOx. High (95%+) levels of NOx reduction require ammonia injection to be nearly equal to the stoichiometric quantity required for complete reaction. The potential for ammonia slip exists even with over-sized SCR units due to spatial variability in ammonia concentration, gas temperature and gas velocity distribution. The challenge is further complicated by the uptake of ammonia by flyash. The temperature-reactivity characteristic of catalysts requires that ammonia injection and the SCR be located in the “dirty” flyash-laden gas stream prior to particulate removal. Flyash will adsorb and retain ammonia and remove it from participation in the NOx removal process.

Table 2. Collateral environmental effects.

Contamination of flyash with ammonia can render it unsuitable for commercial use as a byproduct by virtue of odor and/or reaction and potential mobilization of chemical components in the ash. By contrast, IGCC generates a glassy, vitrified solid that immobilizes metals and inorganic contaminants. IGCC product is also more suitable in size distribution for use as construction aggregate.

The reaction of free ammonia with SO₂ and SO₃ will form fine, sticky ammonium sulfate and sulfate salts which can add to the particulate load, or cause filter cleaning problems or air heater pluggage.

With certain SCR materials, spent catalyst may require disposal as a hazardous waste.

SO₂: Conventional combustion technology generates significant solid waste (Figure 1). This derives from the scrubbing reaction of SO₂ in the combustion stream with either limestone or lime. The products will be similar for both pulverized coal and CFB plants using a limestone bed. This results in approximately (depending upon scrubber stoichiometry) 4 ½ lbs (dry basis) of gypsum or 3 ¼ lbs of calcium sulfite for each lb of sulfur in the fuel. However, residual moisture will be present to typically 50% after dewatering, so the mass ration will be closer to 7.5 – 8.5 lbs of sludge per lb of sulfur. Further preparation by admixing of lime or ash is typically required to produce stable material suitable for landfill. Mist carryover with entrained solids from wet flue gas desulfurization adds to particulate loading.

![Figure 1. Solid waste generation.](image)

In bold contrast, IGCC produces either elemental sulfur or sulfuric acid as a sellable byproduct. The economic choice is dependent on the local demand for chemical feedstock. The effectiveness and economics of sulfur removal from IGCC plants benefits from the lower relative volume gained by treating high-pressure synthesis gas versus final dilute combustion products. Sulfur removal efficiency levels of 98+ are easily achieved by IGCC.

Mercury: Increasing attention is being focused on Mercury from fossil coal power, and at the time of this writing, regulatory consideration is focused on developing standards for mercury control. Varying mercury speciation in combustion processes and for varying coal types makes effective capture especially problematic.

In contrast, the method of mercury control in combustion plants depends highly on the speciation of the mercury. It should be noted that mercury control has not been commercially demonstrated for coal combustion plants. Mercury control in coal combustion plants is...
expected to be accomplished either through activated carbon injection into the flue gas stream or by additives to the WFGD system. Since the carbon must be captured, injection must either be done upstream of the particulate collection device. As another example of collateral effects, the injection of activated carbon can also degrade the byproduct usefulness of flyash from the presence of both carbon and captured mercury. If the flyash is to be used for cement, activated carbon can compromise both the strength as well as “spoil” the effectiveness of cement additives by absorbing them during mixing. In the case of capture in the WFGD system, concern will focus on the stability and availability of the Mercury in the scrubber sludge. This may dictate disposal versus byproduct sale as gypsum for wallboard manufacture.

Fortunately, the reducing conditions in gasification strongly favor conversion of fuel mercury to its elemental form. Elemental mercury can be reliably and cost-effectively removed by sulfinated activated carbon as has been achieved in long-term commercial operation at the Eastman Chemical acetate plant at Kingsport, TN (Figure 2).

\[ \text{Figure 2. Mercury removal from IGCC} \]

In IGCC, the majority of HAPS are effectively partitioned and captured in the gas cleaning process. Low volatility, high boiling point metals are captured and effectively immobilized in the vitreous slag. Medium volatility metals will be condensed and captured by syngas scrubbing. The effectiveness of metals reduction in IGCC is shown in the summary of stack testing data performed by GE on representative coal plants given in Figure 3. High volatility metals can be removed in activated carbon beds in the same manner as mercury.

CO\textsubscript{2}: Pre-combustion de-carbonization of syngas combined with the demonstrated capability of gas turbines to efficiently combust high-hydrogen syngas favors IGCC for low-CO\textsubscript{2} power production. The comparative economics of IGCC when configured for CO\textsubscript{2} capture has been the topic of numerous studies. One such comparison as provided by the DOE is shown in Figure 4 which shows that IGCC provides a net COE approximately 20% lower net O&M and capital costs than that of a conventional combustion plant. It should be noted that IGCC is already utilized in refinery applications (Figure 5) where hydrogen is generated to upgrade final products.

The syngas derived from decarbonization will be high in hydrogen content. The capability of gas turbines to combust high-hydrogen fuel is key to integrating CO\textsubscript{2} control within IGCC. GE gas turbines have already been successfully applied

\[ \text{Figure 3. Power plant metals emissions.} \]

\[ \text{Figure 4. Pre-versus-post combustion decarbonization.} \]
in applications with fuel hydrogen ranging from 60% to as high as 95% (Figure 6) and have already amassed over 500,000 hours on high hydrogen syngas operation. While these applications have used E-class gas turbines, GE has moved forward with successful combustion testing at advanced machine firing temperatures that demonstrates the capability to control NOx to as low as single digit levels through the use of diluent injection. GE has completed feasibility testing for 100% H₂ and 100% CO fuel to define the entire combustion map (Figure 7). The H₂-only case is representative of pre-combustion removal of CO as CO₂ for Enhanced Oil Recovery (EOR) or sequestration and allows CO₂-free power plants. Ratios of 50/50 hydrogen/nitrogen can produce very low NOx as well as provide enhanced output in a modern IGCC gas turbine.

Fuel Flexibility

Fuel flexibility provides a hedge against potential “destroy-your-business” excursions in both fuel cost and availability. The robustness of gasification to deal with a wide range of solid and liquid fuels have been demonstrated in IGCC’s broad application to coal, RDF and refinery wastes in roles of power generation, cogeneration and co-production (Figure 8).

<table>
<thead>
<tr>
<th>Site</th>
<th>Country</th>
<th>G.T. Model No.</th>
<th>Year</th>
<th>Fuel Type</th>
<th>Main Design Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Casmar</td>
<td>US</td>
<td>MS600CB 1</td>
<td>1998</td>
<td>FG</td>
<td>Up to 60% H₂</td>
</tr>
<tr>
<td>Daesan</td>
<td>Korea</td>
<td>MS600CB 1</td>
<td>1997</td>
<td>RG</td>
<td>Up to 95% H₂</td>
</tr>
<tr>
<td>Schwane</td>
<td>Rurpe</td>
<td>MS600CB 1</td>
<td>1996</td>
<td>WAG</td>
<td>68% H₂</td>
</tr>
<tr>
<td>Catalonia</td>
<td>Spain</td>
<td>MS600CB 1</td>
<td>1994</td>
<td>RG</td>
<td>66% H₂</td>
</tr>
<tr>
<td>Tenerife</td>
<td>Spain</td>
<td>MS600CB 2</td>
<td>1993</td>
<td>70% H₂</td>
<td></td>
</tr>
<tr>
<td>San Roque</td>
<td>Spain</td>
<td>MS600CB 2</td>
<td>1993</td>
<td>70% H₂</td>
<td></td>
</tr>
<tr>
<td>Antwerp</td>
<td>Belgium</td>
<td>MS600CB 1</td>
<td>1993</td>
<td>76% H₂</td>
<td></td>
</tr>
<tr>
<td>Ranchoilo</td>
<td>Spain</td>
<td>MS600CB 1</td>
<td>1994</td>
<td>RG</td>
<td>Up to 52% H₂</td>
</tr>
<tr>
<td>La Coquina</td>
<td>Spain</td>
<td>MS600CB 1</td>
<td>1991</td>
<td>1991</td>
<td></td>
</tr>
<tr>
<td>Rotterdam</td>
<td>Holland</td>
<td>MS600CB 1</td>
<td>1990</td>
<td>59% H₂</td>
<td></td>
</tr>
</tbody>
</table>

The capability of the gas turbine to handle the syngas produced from these applications is measured according to the following requirements:

- Capability to deal with low heating value fuel containing varying hydrogen content
- Operability on a wide range of fuels, including startup, transfers and system upsets
- Capability to co-fire synthesis gas with natural gas over a wide total heat input
- Low emissions

The flowdown from these requirements in captured by the gas turbine combustor and its fuel control system.
**Combustor Design:** The GT combustor is the key process orifice for an entire IGCC plant. The standard IGCC combustor for GE gas turbines is derived from the Multi-Nozzle Quiet Combustor (MNQC - Figure 9). Since hydrogen is a typical constituent of synthesis gases, Dry Low NOx (DLN) combustors are not appropriate due to hydrogen’s high flammability and flame speed, which can initiate flashback and combustor failure. GE’s contemporary IGCC combustor has evolved to an increased diameter standard that allows a wider range of fuel constituents and cofiring capability. The lower specific calorific content of IGCC synthesis gas requires that the combustor be able to process more than 5X the fuel flow relative to a natural gas combustor. Also, combustion of 100% syngas would result in unacceptable NOx emissions, so dilution of the syngas with nitrogen, water, CO₂ or combinations is needed to achieve desired performance (Figure 10). Note that the quantity of diluent needed to achieve acceptable NOx concentrations is equal or greater than the quantity of synthesis gas. This means the flow of diluent plus fuel in the combustor may be eight times or more than that of a natural gas machine. The combustion engineer’s challenge is to deliver stable, low-noise combustion, acceptable liner temperatures and full fuel burnout despite relatively high fuel injection velocities. The key to achieving this is full-scale testing.

Owing to the can-annular design of GE turbines, a single can may be fully tested and proven at full airflow and pressure for many machines over the entire range of cycle conditions before releasing it to the field. The performance of new designs is subsequently verified in the field. In 2002, GE successfully commissioned its new IGCC combustion laboratory in Greenville, S.C. (Figure 11). This state-of-the-art facility includes two test stands dedicated solely to IGCC combustion development. Each single burner test stand is designed to simulate the internal flow patterns of a particular machine. Fuel blending tank farms and gas conditioning skids allow for simulation of fuel characteristics representative of all anticipated fuel and gasifier types. Compressor capability is capable of simulation of up to H-turbine combustor conditions.

**Combustion Testing**
- State-of-the-art combustion development facility at Greenville, S.C.  
- Capability to H-combustion conditions  
- Standard machines with optimal integration of turbine and gasification plant with gasification developers  
- Program to develop fuel-tolerant, lean-pre-mix combustor for <5 ppm NOx  
- At GE’s Global Research Laboratory – advanced concepts for low-NOx fuel flexible combustors

**Figure 9. MNQC combustor**

**Figure 10. LHV NOx control.**

IGCC machines require a start-up fuel because of the dangers of starting on fuels that contain hydrogen. This allows many plants to begin operation on backup fuel with introduction of IGCC and synthesis gas capability phased-in at a later date. Dual fuel capability has been developed into a standard co-firing feature so users can design plants for uninterrupted power output if syngas production is restricted, or if a plant is contemplating parallel or staged co-production for utilization of syngas.
Operability

The projects shown in Figure 12 reflect the wide combustion flexibility developed to date for syngas combustion. The top half of the chart shows the constituents from the gasifier. The bottom half shows the diluents needed to meet emission or power augmentation requirements. Hydrogen varies from 8.6% to 61% while other constituents vary widely with bothfeedstock and air-blown versus oxygen-blown syngas. By combining this combustion technology with output enhancement capability, designers can determine the most optimum and economic mix of diluents. The ability to use nitrogen economically is derived from elevated pressure ASU improvements and can be very important in obtaining flat output ratings at high ambient temperatures. Many process plants also produce co-products from the syngas and the GT must be able to accommodate the resultant tail gas in order to avoid flaring.

Mixed fuel operation or co-firing has become an important operating mode to enhance project economics. Co-firing was first used at the Texaco El Dorado IGCC plant in Kansas where the gasifier provides only one-third (1/3) of the size of the plant thermal input. Since starting in 1996 the El Dorado GT has performed at better than 97% power availability. More recently, Exxon Singapore has this feature. The standard types of fuel systems and operating characteristics are provided in Figure 13. For a dual fuel syngas/distillate machine the distillate can be controlled down to 10% while the syngas is generally used in the 70% range.

The broad feedstock flexibility of IGCC is enabled by the wide fuel and operability flexibility of gas turbines. Interest is increasing for the concept of multi-generation process plants. In this concept, an initial installation will utilize natural gas as the primary fuel, followed by IGCC and introduction of synthesis gas. As a final step, the plant is configured to produce hydrogen, where the gas turbine can either utilize the hydrogen directly, or be fired on a combination of tail gas from the hydrogen generation process, syngas or a mixture of synthesis and natural gas.

IGCC Economics

IGCC capital costs have declined down a distinct learning curve (Figure 14) by virtue of advances in technology, economies of scale, and the incorporation of lessons learned.
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PowerGen Asia, 2003

Figure 14. IGCC cost learning curve
Aggressive and optimum process integration and output enhancements have contributed to a 40% reduction over two decades. These improvements combined with standardization, larger plants and new technology integration such as ionic-transport air separation offer promising potential for future cost reduction.

Process Integration: GE has experience with both air-blown and oxygen-blown systems. Each system requires a different type of air integration for optimal performance. Most of the recent efforts have concentrated on high-to-medium pressure oxygen blown systems due to the large size of plants and particularly the co-production of chemical products. Various gasifiers require from 11% to 20% of the GT airflow for full air integration (Figure 15).

Figure 15. Air-side integration
Tampa Polk is designed for 0% airside integration with no air extraction to the ASU but full nitrogen return to the GT. PIEMSPA has been designed for partial integration where some air is extracted for the ASU. Sierra Pacific is designed for full integration where all air demand from the ASU is extracted from the gas turbine. The IGCC combus tor allows extraction up to 20% (full integration) on Model 7F machines without affecting the cooling air. For systems such as gas-to-liquid (GTL) that require more air, a 9E medium air extraction (MAE) system at 37% is available. Overall IGCC optimization for a specific site depends upon the operating requirements and the fuel type to determine the kind of airside integration to be used, if any. In larger plants we have determined that operability can be enhanced with partial air integration by reducing the size of ASU compressors.

Output Enhancement: For natural gas machines, normal GT full load operation over the ambient range follows air density and falls off considerably at high ambient temperatures. We can counteract this with IGCC designs and frequently design the system to utilize the full winter capability, even at 90°F/32°C, which can be a major factor for IGCC viability. Figure 16 demonstrates the physics of this benefit. Natural gas fuel provides 2% of the flow through the turbine as compared to syngas at 16% flow due to its lower heating value. This allows the turbine to produce more power, up to a theoretical increase of 20%, when fired to the same temperature. Mechanical capability, surge margin and Mach number restrictions limit this capability differently for each machine setting a specific maximum output.

Figure 16. IGCC output enhancement
For GE units this limiting capability is usually the torque limit corresponding to a very low ambient temperature. If the syngas flow raises the GT above its maximum capability at an average ambient, inlet guide vanes are closed to restrict air and therefore output. As ambient increases, these guide vanes are opened to hold maximum output until the guide vanes are fully open. That ambient point is called the break point in the curve. Above that the output falls off. For Above that the output falls off. For Tampa Polk, the
break point is 90°F/32°C. This capability can strongly enhance project return based on either the higher market value that can be captured during high ambient temperature or reducing the need to dispatch less efficient, higher cost generation during periods of peak demand. We are constantly endeavoring to extend limits and enhancement of an expander turbine in the sour-gas (pre-sulfur removal) fuel system to maximize energy availability. HEQ can provide an additional 4% output. GE now has the ability to supply this expander and incorporate it into the plant guarantees. When added together, these output enhancements have been the major contributor to the significant plant cost reductions we are achieving in recent bids.

A comparison of cost-of-electricity for 7FA+e-based coal IGCC against coal and Natural Gas Combined cycle (NGCC) is given in Figure 17. It should be noted that all cases are based on an 80% capacity factor. In terms of the dispatch schedule, the capacity factor for a NGCC would likely be lower based on fuel costs, so that net COE would be higher than IGCC. Also, the fuel flexibility of IGCC to use lower rank (lower cost) coals or a mix of petroleum coke and coal as expect to make even more improvements in the next generation turbines for IGCC.

An important new system concept incorporates the latest GT improvements for a High Efficiency Quench (HEQ) design. This plant incorporates all of the features developed from previous plants and includes an additional output would be pursued by a cost-conscious utility is indicated by the spread that brings IGCC COE below that of conventional coal plants.

![Figure 17. COE - NG versus coal and refinery wastes](image)

**Figure 17. COE - NG versus coal and refinery wastes**

**SUMMARY**

IGCC has matured to the point where IGCC systems are commercially competitive with all other power generation options. Gas turbine improvements have come from operating experience in many applications over nearly two decades. IGCC is the clear choice where exceptional environmental performance is required. It is also the clear choice in a wide variety of new power generation applications utilizing low cost feedstocks. The ability of IGCC systems to use opportunity fuels to produce high value co-products along with power enhances the economic viability of new projects. The co-production of chemicals and other utility products required by refineries is a key advantage afforded by IGCC. By fully utilizing the capabilities of modern combined cycles, IGCC systems are able to achieve exceptional levels of environmental performance, availability, and efficiency at a competitive cost of electricity.