

# **ASSESSMENT OF THE QUALITY OF INDIANA COALS FOR INTEGRATED GASIFICATION COMBINED CYCLE (IGCC) PERFORMANCE**

**FINAL REPORT TO THE CENTER FOR COAL TECHNOLOGY RESEARCH  
November 2008**

By

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Agnieszka Drobniak  
John Rupp  
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## CONTENT

Page

SUMMARY	8
1. INTRODUCTION	9
1.1 Importance and justification of the proposed study	9
1.2 IGCC process overview	10
1.3 IGCC technologies overview	13
1.3.1. Entrained-flow gasifiers	13
1.3.1.1 Dry-fed gasifiers	13
1.3.1.2 Slurry-fed gasifiers	14
1.3.2. Fluidized bed gasifiers	15
1.3.2.1. Circulating fluidized bed gasifiers	15
1.3.2.2. Hybrid systems	15
1.3.3. Moving bed gasifiers	16
2. OBJECTIVES OF THIS STUDY	17
3. SUMMARY OF COAL QUALITY PARAMETERS MOST RELEVANT TO IGCC TECHNOLOGY	18
3.1 Identifying properties of Indiana coals that are of major importance for IGCC performance	18
3.2 Database of coal properties to assess IGCC performance	20
4. EVALUATION OF INDIANA COAL FOR IGCC	22
4.1 Evaluation based on basic coal quality parameters	22
4.2 Evaluation based on the ability of coal and coal char to gasify (reactivity)	23
4.3 Evaluation of slagging based on mineral matter characteristics	24
5. GRADING OF INDIANA COALS FOR IGCC SUITABILITY	26
6. AVAILABILITY OF INDIANA COALS FOR IGCC	26
7. DISCUSSION	27
8. SUMMARY AND CONCLUSIONS	30
REFERENCE CITED	32

## List of figures

- Figure 1. Generic gasification system showing a variety of end products (Williams, 2004).
- Figure 2. Three types of gasifiers: A. – fixed (moving) bed gasifier; B – fluidized-bed gasifier; C – entrained-flow gasifier.
- Figure 3. Map of southwestern Indiana showing the heating value (dry basis) of the Danville coal.
- Figure 4. Map of southwestern Indiana showing the heating value (dry basis) of the Hymera coal.
- Figure 5. Map of southwestern Indiana showing the heating value (dry basis) of the Springfield coal.
- Figure 6. Map of southwestern Indiana showing the heating value (dry basis) of the Seelyville coal.
- Figure 7. Map of southwestern Indiana showing the moisture content of the Danville coal.
- Figure 8. Map of southwestern Indiana showing the moisture content of the Hymera coal.
- Figure 9. Map of southwestern Indiana showing the moisture content of the Springfield coal.
- Figure 10. Map of southwestern Indiana showing the moisture content of the Seelyville coal.
- Figure 11. Map of southwestern Indiana showing the ash content (dry basis) of the Danville coal.
- Figure 12. Map of southwestern Indiana showing the ash content (dry basis) of the Hymera coal.
- Figure 13. Map of southwestern Indiana showing the ash content (dry basis) of the Springfield coal.
- Figure 14. Map of southwestern Indiana showing the ash content (dry basis) of the Seelyville coal.
- Figure 15. Map of southwestern Indiana showing the total sulfur content (dry basis) of the Danville coal.
- Figure 16. Map of southwestern Indiana showing the total sulfur content (dry basis) of the Hymera coal.
- Figure 17. Map of southwestern Indiana showing the total sulfur content (dry basis) of the Springfield coal.
- Figure 18. Map of southwestern Indiana showing the total sulfur content (dry basis) of the Seelyville coal.
- Figure 19. Map of southwestern Indiana showing the chlorine content (% , whole coal basis) of the Danville coal.
- Figure 20. Map of southwestern Indiana showing the chlorine content (% , whole coal basis) of the Hymera coal.
- Figure 21. Map of southwestern Indiana showing the chlorine content (% , whole coal basis) of the Springfield coal.
- Figure 22. Map of southwestern Indiana showing the mercury content (ppm, whole coal basis) of the Danville coal.
- Figure 23. Map of southwestern Indiana showing the mercury content (ppm, whole coal basis) of the Hymera coal.
- Figure 24. Map of southwestern Indiana showing the mercury content (ppm, whole coal basis) of the Springfield coal.
- Figure 25. Map of southwestern Indiana showing the mercury content (ppm, whole coal basis) of the Seelyville coal.
- Figure 26. Relationships between fuel ratio and char reactivity (after Zevenhoven and Hupa, 1997)
- Figure 27. Relationships between O/C ratio and char reactivity (after Zevenhoven and Hupa, 1997)
- Figure 28. Map of southwestern Indiana showing the fixed carbon content (dry basis) of the Danville coal.
- Figure 29. Map of southwestern Indiana showing the fixed carbon content (dry basis) of the Hymera coal.
- Figure 30. Map of southwestern Indiana showing the fixed carbon content (dry basis) of the Springfield coal.
- Figure 31. Map of southwestern Indiana showing the fixed carbon content (dry basis) of the Seelyville coal.
- Figure 32. Map of southwestern Indiana showing the volatile matter content (dry basis) of the Danville coal.
- Figure 33. Map of southwestern Indiana showing the volatile matter content (dry basis) of the Hymera coal.

- Figure 34. Map of southwestern Indiana showing the volatile matter content (dry basis) of the Springfield coal.
- Figure 35. Map of southwestern Indiana showing the volatile matter content (dry basis) of the Seelyville coal.
- Figure 36. Map of southwestern Indiana showing the fixed carbon content to volatile matter content (daf basis) of the Danville coal.
- Figure 37. Map of southwestern Indiana showing the fixed carbon content to volatile matter content (daf basis) of the Hymera coal.
- Figure 38. Map of southwestern Indiana showing the fixed carbon content to volatile matter content (daf basis) of the Springfield coal.
- Figure 39. Map of southwestern Indiana showing the fixed carbon content to volatile matter content (daf basis) of the Seelyville coal.
- Figure 40. Map of southwestern Indiana showing the O/C value (daf basis) of the Danville coal.
- Figure 41. Map of southwestern Indiana showing the O/C value (daf, molar) of the Danville coal.
- Figure 42. Map of southwestern Indiana showing the O/C value (daf basis) of the Hymera coal.
- Figure 43. Map of southwestern Indiana showing the O/C value (daf, molar) of the Hymera coal.
- Figure 44. Map of southwestern Indiana showing the O/C value (daf basis) of the Springfield coal.
- Figure 45. Map of southwestern Indiana showing the O/C value (daf, molar) of the Springfield coal.
- Figure 46. Map of southwestern Indiana showing the O/C value (daf basis) of the Seelyville coal.
- Figure 47. Map of southwestern Indiana showing the O/C value (daf, molar) of the Seelyville coal.
- Figure 48. Map of southwestern Indiana showing the SiO<sub>2</sub> to Al<sub>2</sub>O<sub>3</sub> ratio of the Danville coal.
- Figure 49. Map of southwestern Indiana showing the SiO<sub>2</sub> to Al<sub>2</sub>O<sub>3</sub> ratio of the Hymera coal.
- Figure 50. Map of southwestern Indiana showing the SiO<sub>2</sub> to Al<sub>2</sub>O<sub>3</sub> ratio of the Springfield coal.
- Figure 51. Map of southwestern Indiana showing the SiO<sub>2</sub> to Al<sub>2</sub>O<sub>3</sub> ratio of the Seelyville coal.
- Figure 52. Map of southwestern Indiana showing the silica ratio of the Danville coal.
- Figure 53. Map of southwestern Indiana showing the silica ratio of the Hymera coal.
- Figure 54. Map of southwestern Indiana showing the silica ratio of the Springfield coal.
- Figure 55. Map of southwestern Indiana showing the Fe<sub>2</sub>O<sub>3</sub> + CaO of the Danville coal.
- Figure 56. Map of southwestern Indiana showing the Fe<sub>2</sub>O<sub>3</sub> + CaO of the Hymera coal.
- Figure 57. Map of southwestern Indiana showing the Fe<sub>2</sub>O<sub>3</sub> + CaO of the Springfield coal.
- Figure 58. Map of southwestern Indiana showing the Fe<sub>2</sub>O<sub>3</sub> + CaO of the Seelyville coal.
- Figure 59. Map of southwestern Indiana showing the critical temperature (in °F) of the slag viscosity of the Danville coal.
- Figure 60. Map of southwestern Indiana showing the critical temperature (in °F) of the slag viscosity of the Hymera coal.
- Figure 61. Map of southwestern Indiana showing the critical temperature (in °F) of the slag viscosity of the Springfield coal.
- Figure 62. Maps showing suitability of the Danville Coal for IGCC with regard to A) ash content; B) critical temperature of slag viscosity; C) SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> ratio; D) Fe<sub>2</sub>O<sub>3</sub>+CaO; and E) silica ratio; F) grading of coal taking into account the parameters shown in A-E.
- Figure 63. Maps showing suitability of the Hymera Coal for IGCC with regard to A) ash content; B) critical temperature of slag viscosity; C) SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> ratio; D) Fe<sub>2</sub>O<sub>3</sub>+CaO; and E) silica ratio; F) grading of coal taking into account the parameters shown in A-E.
- Figure 64. Maps showing suitability of the Springfield Coal for IGCC with regard to A) ash content; B) critical temperature of slag viscosity; C) SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> ratio; D) Fe<sub>2</sub>O<sub>3</sub>+CaO; and E) silica ratio; F) grading of coal taking into account the parameters shown in A-E.
- Figure 65. Maps showing suitability of the Seelyville Coal for IGCC with regard to A) ash content; B) SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> ratio; C) Fe<sub>2</sub>O<sub>3</sub>+CaO; D) grading of coal taking into account the parameters shown in A-C.
- Figure 66. Map of southwestern Indiana showing the extent of the Danville Coal Member, the Pennsylvanian System, and distribution of the Danville coal surface and underground mines.

- Figure 67. Map of the southwestern Indiana showing the areas where the Danville Coal Member is available for surface mining and where surface mining is restricted (after Conolly and Zlotin, 2000).
- Figure 68. Map of the southwestern Indiana showing the areas where the Danville Coal Member is available for underground mining and where underground mining is restricted (after Conolly and Zlotin 2000).
- Figure 69. Map of the Danville Coal showing combination of the grading of the coal for IGCC and availability of the coal for surface mining.
- Figure 70. Map of the Danville Coal showing combination of the grading of the coal for IGCC and availability of the coal for underground mining.
- Figure 71. Map of southwestern Indiana showing the extent of the Hymera Coal Member, the Pennsylvanian System, and distribution of the Hymera coal surface, and underground mines.
- Figure 72. Map of southwestern Indiana showing the areas where the Hymera Coal Member is available for surface mining and where surface mining is restricted.
- Figure 73. Map of southwestern Indiana showing the areas where the Hymera Coal Member is available for underground mining and where underground mining is restricted.
- Figure 74. Map of the Hymera Coal showing combination of the grading of the coal for IGCC and availability of the coal for surface mining.
- Figure 75. Map of the Hymera Coal showing combination of the grading of the coal for IGCC and availability of the coal for underground mining.
- Figure 76. Map of southwestern Indiana showing the extent of the Springfield Coal Member, the Pennsylvanian System, and distribution of the Springfield coal surface, and underground mines.
- Figure 77. Map of southwestern Indiana showing the areas where the Springfield Coal Member is available for surface mining and where surface mining is restricted (after Conolly and Zlotin, 1999).
- Figure 78. Map of southwestern Indiana showing the areas where the Springfield Coal Member is available for underground mining and where underground mining is restricted (after Conolly and Zlotin, 1999).
- Figure 79. Map of the Springfield Coal showing combination of the grading of the coal for IGCC and availability of the coal for surface mining.
- Figure 80. Map of the Springfield Coal showing combination of the grading of the coal for IGCC and availability of the coal for underground mining.
- Figure 81. Map of southwestern Indiana showing the extent of the Seelyville Coal Member, the Pennsylvanian System, and distribution of the Seelyville coal surface and underground mines.
- Figure 82. Map of southwestern Indiana showing the areas where the Seelyville Coal Member is available for surface mining and where surface mining is restricted (after Conolly, 2001).
- Figure 83. Map of southwestern Indiana showing the areas where the Seelyville Coal Member is available for underground mining and where underground mining is restricted (after Conolly, 2001).
- Figure 84. Map of the Seelyville Coal showing combination of the grading of the coal for IGCC and availability of the coal for surface mining.
- Figure 85. Map of the Seelyville Coal showing combination of the grading of the coal for IGCC and availability of the coal for underground mining.

## List of tables

Table 1. Options in IGCC plant design (from Innes, 1999).

Table 2. Existing coal-based IGCC plants.

Table 3. Fixed-bed gasifiers.

Table 4. Fluidized-bed gasifiers.

Table 5. Entrained-flow gasifiers.

Table 6. Data availability for selected coal properties for Indiana coal beds.

Table 7. Suitability of selected parameters for IGCC suggested for Indiana coals.

## List of appendices

- 1) Coal Supply and Demand in Indiana, 2006. IGS Miscellaneous Map 72 by Drobniak, A., Mastalerz, M., and Shaffer, K.
- 2) Coal, Electricity, and Gas Transportation Systems in Indiana, 2006. IGS Open-File Study 06-03 by Drobniak, A., Mastalerz, M., and Shaffer, K.
- 3) Major point sources of CO<sub>2</sub> emissions and conceptual geological sequestration strategies in Indiana, 2007. IGS Open-File Study 07-01 by Drobniak, A., Rupp, J., Mastalerz, M., and Shaffer, K.
- 4) Indiana Railroad System. 2007. IGS Open-File Study 07-04 by Drobniak, A., Pfitzer, C. and Mastalerz, M.
- 5) Assessment of the quality of Indiana coals for Integrated Gasification Combined Cycle (IGCC) Performance; The Danville Coal Member.
- 6) Assessment of the quality of Indiana coals for Integrated Gasification Combined Cycle (IGCC) Performance; The Hymera Coal Member.
- 7) Assessment of the quality of Indiana coals for Integrated Gasification Combined Cycle (IGCC) Performance; The Springfield Coal Member.
- 8) Assessment of the quality of Indiana coals for Integrated Gasification Combined Cycle (IGCC) Performance; The Seelyville Coal Member.
- 9) Coal quality database (CD)

## **SUMMARY**

This document is a final report of the project “Assessment of the quality of Indiana coals for Integrated Gasification Combined Cycle (IGCC)” funded by the Indiana Center for Coal Technology Research (CCTR). This has been a two-year-project following a scoping study on the same topic. The objectives of this project included:

- 1) Identification of the properties of Indiana coals that are of major importance for IGCC performance;
- 2) Assessment of the availability of data on coal properties important for IGCC performance;
- 3) Identification of the areas in which more data are necessary to adequately assess coal performance for IGCC;
- 4) Generation of new data; and
- 5) Assessment of the potential of Indiana coals to be used in IGCC technology.

During this project, four major coal beds: the Danville, Hymera, Springfield, and Seelyville Coal Members have been investigated. New data for these coals were generated, with a special emphasis on the characteristics of the mineral matter in the coal. These data have been integrated with the previously available data into a database that accompanies this report. This updated database was used to map those properties of the coals that are most important for IGCC application. These maps are the basis for grading Indiana coals for IGCC. Evaluation of the coals has been divided into three groups: a) Evaluation based on basic coal quality parameters such as heating value, moisture content, ash yield, and sulfur content; b) Evaluation of the ability of coal and coal char to gasify (reactivity); and c) Evaluation of slagging based on mineral matter characteristics. Grading of the coals for IGCC was based on mineral matter characteristics. In the final phase, we combined grading with coal availability information for the four coal beds studied.

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## 1. INTRODUCTION

### *1.1. Importance and justification of the proposed study*

There are several reasons to evaluate the applicability of Indiana coals for IGCC technology. First, more than 90 percent of Indiana's electricity comes from coal. The overwhelming majority of the coal mined in Indiana (73 percent) is used for generating electricity. Annually, Indiana uses twice as much coal as it produces (70 million short tons used versus 34 million short tons produced). Most of the non-Indiana coal that is consumed within the state is imported from Wyoming. These simple facts demonstrate that coal is vital to the economy of our state.

Secondly, Indiana has significant coal reserves (~ 57 billion short tons); approximately 17.5 billion short tons are available for either surface or underground mining (Mastalerz et al., 2004) which, at the current level of production, can suffice for hundreds of years. However, most Indiana coals are high in sulfur (average sulfur content for all coal beds is 3.1 percent) and, as such, cause significant SO<sub>2</sub> emissions from power plants upon combustion. Wet scrubbers have to be used in power plants to reduce these emissions. In addition, recent mercury regulations from coal-fired power plants (EPA, 2000, 2005) force the plants to search for the most efficient and least costly ways to address these issues.

Thirdly, IGCC units are much cleaner than standard power plants; they can achieve greater than 99 percent SO<sub>2</sub> removal. Another benefit is the possibility of removing mercury and carbon dioxide upstream of the combustion process at a lower cost than conventional plants. The technology uses less water than a conventional coal-fired power plant which currently requires pollution control equipment. Although, the total cost of an IGCC plant is high, this option however, becomes especially attractive when additional installations of new pollution control devices become necessary.

Lastly, IGCC technology is continuously gaining momentum both nationally and internationally. The first IGCC plant with CO<sub>2</sub> capture is being planned in Australia [http://pepei.pennnet.com/Articles/Article\\_Display.cfm?Section=ONART&PUBLICATION\\_ID=6&ARTICLE\\_ID=335692&C=PRODJ&dcmp=rss](http://pepei.pennnet.com/Articles/Article_Display.cfm?Section=ONART&PUBLICATION_ID=6&ARTICLE_ID=335692&C=PRODJ&dcmp=rss), and several IGCC plants are being considered in China. Two IGCC power plants currently operate in the US, and more are being planned. Duke Energy is currently constructing a 630 MW ICGCC at Edwardsport, Indiana that employs the GE Reference Plant design. The plant is scheduled to be on line in 2011.

### ***1.2. IGCC Process Overview***

IGCC technology is becoming increasingly more competitive and is becoming the technology of choice in the future of electricity generation. In the IGCC process, plants turn coal to gas, removing most of the sulfur dioxide and other emissions before the gas is used to fuel a combustion turbine generator. The hot gases are then used to generate steam, driving a steam turbine generator.

In a typical IGCC unit, coal gasification takes place in the presence of a controlled 'shortage' of air/oxygen, thus maintaining reducing conditions. The process is carried out in an enclosed pressurized reactor, and the product is a mixture of CO + H<sub>2</sub> (called synthesis gas, syngas, or fuel gas). The product gas is cleaned and then burned with either oxygen or air, generating combustion products at high temperature and pressure. The sulfur from the coal reacts to form H<sub>2</sub>S that can be readily removed from the system and beneficially used afterwards. No NO<sub>x</sub> is formed during gasification.

A typical IGCC process is shown in figure 1. For IGCC plants, there are various design options regarding coal preparation, coal gasification, gas cleaning, combined cycle system, air delivery, etc. A summary of these options is presented in Table 1.

Several options are in use for controlling the flow of coal during gasification, namely fixed-bed, fluidized-bed, and entrained-flow systems, with oxygen being used as an oxidizing medium in most units. Specifics about these techniques can be found elsewhere, for example, in Durie and Smith (1975) and Radulovic and others (1995); below we provide their brief characteristics.

Table 1. Options in IGCC plant design (from Innes, 1999).

Primary operations	Design options
<i>Coal preparation</i> <ul style="list-style-type: none"> <li>Delivered coal is milled to desired size specifications and, if necessary, combined with a flux</li> </ul>	<ul style="list-style-type: none"> <li>Slurry feeding</li> <li>Dry pneumatic feeding</li> <li>Fine coal briquetting</li> </ul>
<i>Coal gasification</i> <ul style="list-style-type: none"> <li>Coal is fed into a high temperature and pressure environment where it undergoes partial oxidation with air, Oxygen, or steam</li> </ul>	<ul style="list-style-type: none"> <li>Gasifier design</li> <li>Oxidant type</li> </ul>
<i>Gas cleaning</i> <ul style="list-style-type: none"> <li>Raw fuel gas undergoes a series of physical and chemical processing steps to eliminate particulates, alkali metals, sulfur and ammonia from the gas</li> </ul>	<ul style="list-style-type: none"> <li>Hot or cold gas cleaning</li> <li>Sulfur removal system</li> <li>Ammonia removal</li> </ul>
<i>Combined cycle system</i> <ul style="list-style-type: none"> <li>Clean fuel gas is mixed with compressed air and undergoes combustion with expansion through a gas turbine (GT)</li> <li>The hot combustion gases pass through a heat recovery steam generator (HRSG) to produce superheated steam to drive a steam turbine (ST) generator</li> </ul>	<ul style="list-style-type: none"> <li>Air compressor integration</li> <li>NO<sub>x</sub> emissions reduction system</li> </ul>
<i>Air delivery</i> <ul style="list-style-type: none"> <li>Air undergoes compression before entering gasifier and combustor or;</li> <li>Air undergoes separation to produce high purity oxygen and nitrogen. Oxygen is fed to the gasifier; nitrogen and compressed air are fed to the GT combustor</li> </ul>	<ul style="list-style-type: none"> <li>Gasifier oxidant type</li> <li>Air separation unit (ASU) selection</li> <li>Level of integration between ASU and remainder of IGCC plant</li> </ul>
Auxiliary operations	
<i>By-product solids &amp; water treatment</i> <ul style="list-style-type: none"> <li>Slag and fly ash disposal systems</li> <li>Process water cleaning systems</li> <li>Brine removal systems</li> </ul>	<ul style="list-style-type: none"> <li>Pneumatic or slurry removal</li> </ul>
<i>Sulfur recovery</i>	<ul style="list-style-type: none"> <li>Present or absent</li> </ul>

**Fixed (moving) bed gasifiers** closely resemble a blast furnace (Fig. 2A). They operate at 26 bar (377 psi) and coal and fluxes are placed on the top of a descending bed in a vessel. Moving downwards, the coal is gradually heated and put in contact with an oxygen-enriched gas flowing upwards. Pyrolysis, char gasification, combustion and ash melting occur sequentially. The temperature at the top of the bed is typically 450°C (842°F) and at the bottom 2000°C (3632°F). All coal mineral matter melts and is tapped as slag. Ash melt characteristics influence bed permeability, and fluxes may need to be added to modify slag flow characteristics.

Fixed bed gasifier offgas contains tar that must be condensed and recycled. This production of tar makes downstream gas cleaning more complicated compared to other IGCC gasifiers. The gas

residence time of a fixed bed gasifier is 30 minutes to one hour, which is longer compared to other types of gasifiers.

**Fluidized bed gasifiers** are reactors in which fine particles are kept in suspension by a gas and, consequently, the whole bed exhibits a fluid-like behavior (Fig. 2B). This type of reacting system is characterized by high heat and mass transfer rates between the solid and gas. In such a gasifier, rising oxygen-enriched gas reacts with suspended coal at a temperature of 950-1100°C (1742-2012°F) and pressure 20-30 bar (290-435 psi). To ensure stable fluid operation, gasification temperatures are kept below the ash fusion temperature (AFT) of the coal. Above this temperature, particles become sticky, agglomerating, resulting in bed defluidization. Low temperature operation limits the use of fluidized bed gasifiers to reactive and predominantly low rank coals.

Most fluid bed gasifiers have a high level of entrained fines recycled to achieve 95-98% conversion.

To reduce the size of the fines in recycle stream, it has been proposed that the gasifier is linked with a fluid bed combustor (Air Blown Gasification Cycle). In this process, the coal is first gasified to 70-80% carbon conversion. The unreacted char is then fed to the combustor where generated heat is used for steam production. This cycle enables the use of low reactivity, high ash fusion temperature coals.

**Entrained flow gasifiers** – this is the most aggressive form of gasification, with pulverized coal and oxidizing gas flowing simultaneously (Fig. 2C). High reaction intensity is provided by a high pressure (20-30 atm, 293-440 psi) and high temperature (>1400°C, 2552°F) environment. Extremely turbulent flow causes significant back-mixing of the coal particles, and the residence time is as short as seconds.

Entrained flow gasification is specially designed for low reactivity coals and high coal throughput. Single pass carbon conversions are in the range of 95-99%. To have a smooth operation, the gasifier temperature must be above the ash fusion temperature (AFT), otherwise fluxes which lower the melting temperature of the coal mineral matter must be used.

Entrained flow and fluidized bed gasifiers are selected for the majority of IGCC plants. Selection of one over the other depends on the feed coal, desired system capacity, and other considerations.

### ***1.3 IGCC Technologies Overview***

Below we present a brief overview of IGCC technologies. A more detailed description and discussion of these technologies can be found elsewhere (e.g., Collot, 2002; 2006). Main existing IGCC plants that use coal to generate electricity are listed in Table 2.

#### **1.3.1. Entrained flow gasifiers**

Entrained flow gasifiers are regarded as the most versatile gasifier type because they can use both liquid and solid fuels and operate at high temperatures, ensuring high carbon conversion and syngas free of tars and phenols. Dry-fed and slurry-fed gasifiers have been commercially used.

##### **1.3.1.1 Dry-fed gasifiers**

*Babcock Brosig Power (Noel, originally BBPl) technology* – developed in 1975 for the gasification of lignite in a 3 MW pilot plant in the former East Germany. Afterwards, a full-scale (130MW) plant was built to produce syngas and town gas. The only Noell gasifiers in commercial operation today are those located in Germany (Schwarze Pumpe) and a relatively new one in the UK (Middlesbrough). Although tested on various coal feeds in the past, currently they process wastes and there is no coal gasification plant operating with this technology now.

*Hitachi technology* – used in the EAGLE project in Japan. The gasifier is oxygen-blown, with two-stage spiral flows in the gasification chamber and it can process up to 150 tons of coal a day. The operation started in 2002 and a wide range of imported coals have been tested.

*Mitsubishi Heavy Industries (MHI)* – This technology is used in the Nakoso project in Japan, established in 2001. It is an air-blown two-stage gasifier. Fuel capacity is 1700 tons of coal a day. It is designed to use various coals including low rank coals. The planned end of the IGCC plant construction was 2007.

*PRENFLO (Pressurized Entrained Flow) technology* – the only commercial-scale unit based on this technology is located in Puertollano in Spain. It is the largest unit in the world that is based on solid fuels (320MWe). The plant has been operating since 1998 and can process 2600 tons of solid fuels a day (coal and coal/coke mixtures). Syngas is produced at a temperature of 1600°C

*Shell Coal Gasification technology* – this technology uses a single stage gasifier and is used in a plant in Buggenum (the Netherlands). The gasifier operates at a temperature of ~1500°C and pressure of 2-4 MPa. It can process ~2000 tons of fuel a day. It can use coals of various types and ranks. Currently it uses blend of coal and biomass. Another plant of this type was built in Italy (Sulcis) in 2006. Several plants are being planned in China (Yingcheng, Liuzhou, Dongting, Hubei, Yantai) for the production of syngas for ammonia and H<sub>2</sub> for other chemical plants, using coal as feedstock.

#### **1.3.1.2 Slurry-fed gasifiers**

*E-Gas (Destec) technology* – this is a two-stage gasifier and the coal is injected as a pre-heated slurry. The gas exiting in a gasifier has temperature of ~1050°C. Wabash River Gasification Plant is the only gasifier of this type currently in operation. It was designed to use local coals with sulfur content up to 5.9%. Currently petroleum coke is used as the sole feedstock. More detailed description of this plant was given in our previous study (Mastalerz et al., 2005).

*Texaco technology* – this is a one stage slurry fed gasifier. The Eastman Chemicals and Polk Power Station are examples currently in operation. The Polk Station is a 250MW plant (~2000 tons of fuel per day) opened in 1996 as a DOE IGCC demonstration project. Feed has changed over the years. Petroleum coke (60%), Venezuelan coal (25%), and Illinois #6 coal (15%) were used for a couple of years. The current feed consists of petroleum coke and South American coal. More detailed descriptions of these two plants were given in our previous study (Mastalerz et al., 2005).

### 1.3.2. Fluidized bed gasifiers

#### **1.3.2.1. Circulating fluidized bed gasifiers**

*BHEL* – this technology is used in a 6.2 MWe plant built in Hyderabad, India to process Indian coals that have high ash content and very finely dispersed (and not removable during washing) mineral matter. It can process 168 tons of fuel a day. The gasifier operates at 1000°C temperature and 1.3 MPa pressure to generate a coal gas of a net calorific value of 9.8 MJ/kg.

*High temperature Winkler (HTW)* – this process was developed first in Germany to gasify lignites. The temperature of the bed is kept at 800°C, and higher temperature (900-950°C) is used to decompose undesired by-products formed during gasification. The operating pressure may vary from 1 to 3 MPa. Over the years some plants operated in Germany (Wesseling) and Finland. Currently a 400 MW IGCC plant of this type is operating in Vresova in the Czech Republic on lignites.

*Integrated Drying Gasification Combined Cycle (IDGCC)* – this technology was developed to gasify high moisture low rank coal in Australia. The gasifier is a 5 MW air-blown pressurized bed pilot plant that is fed with coal. The gasifier operates at 900°C under 2.5 MPa pressure.

*Kellog Rust Westinghouse (KRW)* – Pinon Pine in Nevada is the only large-scale (100 MWa) IGCC plant that uses this technology. It was designed to use Utah bituminous coal, but many other coals were tested as well. It has never operated in a steady state, however.

*Transport Reactor Gasifier* – the transport reactor developed by Kellog Brown and Root Inc at power System development Facility (PSDF) in Alabama is a demonstration scale gasifier. It operates at temperatures between 870°C and 1000°C and pressure up to 1.5 MPa. Coals ranging from lignites to bituminous have been tested.

#### **1.3.2.2 Hybrid systems**

*Air Blown Gasification Cycle (ABGC)* – this system was developed by the Coal Technology development Division of British Coal. The gasifier operates at temperatures of 900-1000°C and pressures up to 2.5 MPa. A variety of British and foreign coals have been tested.

### 1.3.3. Fixed (moving) bed gasifier

*BHEL's technology* – this technology was developed at the Trichy unit in India in 1988, as part of research program to gasify high ash Indian coals for the production of electricity. The drawback of the moving bed technologies is that they produce tar-laden gas, which prevents efficient heat recovery of the raw gas.

*British Gas/Lurgi (BGL) technology* – the internal temperature of this slagging gasifier is ~2000°C, which causes ash to melt. The molten ash is tapped off and quenched with water to solidify it. The resultant product gas exits the gasifier at a temperature of 450-500°C. The following facilities use this technology: the Westfield facility (UK), Schwarze Pumpe complex (Germany), and the Kentucky IGCC project (540 MWe).

*Lurgi dry ash gasifiers* – South Africa is the largest user of this technology. Low rank and high inertinite coals of South Africa are the feed. The great Plains synfuel plant (Dakota Gasification Co) is a commercial-scale coal gasification plant that can process up to 18000 tons a day of lignite. A 351 MWe IGCC plant was repowered in 1996 at Vresova, Czech Republic and also processes lignite. A few gasification plants of this type have also been operating in China.

Table 2. Major existing coal-based IGCC plants.

<b>Facility</b>	<b>Company</b>	<b>Location</b>	<b>Feedstock</b>	<b>Capacity</b>	<b>Gasifier technology</b>
Willem Alexander Centrale	Nuon	Buggenum The Netherlands	Coal/biomass	253 MW	Shell
Wabash River	SG Solution	Terre Haute, IN	Coal/pet coke	260 MW	ConocoPhillips
Polk Power Station	Tampa Electric	Mulberry, FL	Coal/pet coke	250 MW	GE Energy
Puertollano	ELCOGAS	Puertollano, Spain	Coal/pet coke	320 MW	Prenflo

## 2.0 OBJECTIVES OF THIS STUDY

In an earlier study (Mastalerz et al, 2005), we:

1. Identified properties of Indiana coals that are of major importance for IGCC performance;
2. Analyzed the availability of data on coal properties needed to assess IGCC performance;
3. Identified the areas in which more data are needed to adequately assess coal performance for IGCC; and
4. Provided a preliminary assessment of Indiana coals for IGCC.

One of the main recommendations of that study was the necessity to generate more data on mineral matter characteristics.

Following that earlier evaluation and recommendations, the main objectives of this study were to:

- 1) Perform new analyses and integrate them into a coal quality database (this database is included with this report)
- 2) Map various coal quality parameters;
- 3) Using several IGCC-important parameters, grade the coals with regard to their suitability for IGCC; and
- 4) Combine coal quality information with the availability of the coal for surface and underground mining.

All these above elements are presented and discussed in this report. In addition to the new data collection and the evaluation of coals for IGCC, four maps were generated during the project, and they include:

- 1) Coal Supply and Demand in Indiana, 2006. IGS Miscellaneous Map 72 by Drobniak, A., Mastalerz, M., and Shaffer, K.
- 2) Coal, Electricity, and Gas Transportation Systems in Indiana, 2006. IGS Open-File Study 06-03 by Drobniak, A., Mastalerz, M., and Shaffer, K.
- 3) Major point sources of CO<sub>2</sub> emissions and conceptual geological sequestration strategies in Indiana, 2007. IGS Open-File Study 07-01 by Drobniak, A., Rupp, J., Mastalerz, M., and Shaffer, K.
- 4) Indiana Railroad System. 2007. IGS Open-File Study 07-04 by Drobniak, A., Pfitzer, C. and Mastalerz, M.

These maps are included in this report as Appendices 1-4.

### 3. SUMMARY OF COAL QUALITY PARAMETERS MOST RELEVANT TO IGCC TECHNOLOGY

#### *3.1. Identifying properties of Indiana coals that are of major importance for IGCC performance*

In our initial study (Mastalerz et al., 2005) we identified several parameters of coal quality that are important for the performance in an IGCC system including:

- a) *Moisture content* influences gasifier efficiency and can help to determine whether the process should be dry or slurry fed.
- b) *Heating value* influences generation capacity. To obtain the same energy from a lower heating value coal (for example, Western coal), a greater tonnage must be gasified.
- c) *Mineral matter properties* such as ash content, ash fusion temperatures (AFT), and slag viscosity have a number of critical impacts on an IGCC system. In general, low ash content (<10 percent) coals are preferable for IGCC. Ash fusion temperature is very important, but its influence varies drastically between different plant designs. For example, for entrained flow gasifiers, AFT should be below 1500°C (2732°F), whereas for fluidized bed gasifiers temperatures above 1100°C (2012°C) are preferred.
- d) *Volatile matter and char reactivity* determine the extent and rate of gasification reactions. Coal consumption during gasification consists of two steps: volatile pyrolysis (fast process) and char gasification (slow process). Generally, the higher the char yield and the lower the char reactivity, the longer the time required for complete gasification. Therefore coals that have low char yield and high char reactivity are generally preferred, although these requirements vary depending on the gasifier type.

Other important parameters include the sulfur, nitrogen, and chlorine contents.

In our initial study (Mastalerz et al., 2005) we also presented a summary (included in this report as Tables 3-5) of how various coal properties influence IGCC behavior and what the requirements are for three types of gasifiers: fixed-bed gasifier (Table 3), fluidized-bed gasifier (Table 4) and entrained-flow gasifier (Table 5). This summary needs to be considered as a general guidelines only, because specific requirements can vary between individual units.

Table 3. Fixed-bed gasifiers.

Parameter	Importance	Requirements
<b>Moisture</b>	- influences gasifier efficiency - determines if process must be dry or slurry fed	- for dry feed – 2% - for slurry feed – 10%
<b>Volatile matter</b>	- determine the extent and rate of gasification reactions	- a range of volatile matter contents are used
<b>Heating value</b>	- determines plant dimensions - influences generation capacity	- a range of heating values are used
<b>Ash content</b>	- lowers system efficiency - increases slag production and disposal cost	<15%
<b>AFT (flow, reduction)</b>	- influence melting ability of discharged slag (it needs to be melted below performance temperature)	<1400°C (2552°F)
<b>Slag viscosity at 1400°C (2552°F)</b>	- viscosity must be sufficiently low to ensure smooth slag flow between packed bed particles	<5Pa-s (pascal second) <50 poise
<b>Char reactivity</b>	- influence the extent of carbon conversion	- a range of reactivities can be used because of high operational temperature
<b>Sulfur</b>	- can cause corrosion of heat exchanger surfaces	- preferred S <1.5%
<b>Nitrogen</b>	- contributes to NOx emissions	
<b>Chlorine</b>	- forming HCl can poison gas cleaning system catalysts - HCl can cause chloride stress corrosion	<0.4% (air dry) <0.2% preferred

Table 4. Fluidized-bed gasifiers.

Parameter	Importance	Coal Requirements
<b>Moisture</b>	- influences gasifier efficiency (higher moisture - lower efficiency)	- a range of moisture contents are used
<b>Volatile matter</b>	- determine the extent and rate of gasification reactions	- a range of volatile matter contents are used
<b>Heating value</b>	- determines plant dimensions - influences generation capacity (higher heating value – higher capacity and efficiency)	- a range of heating values are used
<b>Ash content</b>	- influences net cycle efficiency - influences flux addition rate	<40%
<b>AFT (flow, reduction)</b>	- since mineral matter is expelled as ash, it is important that AFT is higher than operation temperature for the ash particles not to become sticky and agglomerate	>1100°C (2012°F)
<b>Slag viscosity</b>	- not much of concern	
<b>Char reactivity</b>	- fundamental importance	- low reactivity chars are not suitable because of low carbon conversion at relatively low temperature
<b>Sulfur</b>	- can cause corrosion of heat exchanger surfaces	- preferred S <1.5%
<b>Nitrogen</b>	- contributes to NOx emissions	
<b>Chlorine</b>	- forming HCl can poison gas cleaning system catalysts - HCl can cause chloride stress corrosion	<0.4% (air dry) <0.2% preferred

Table 5. Entrained-flow gasifiers.

<b>Parameter</b>	<b>Importance</b>	<b>Coal Requirements</b>
<b>Moisture</b>	- influences gasifier efficiency (higher moisture - lower efficiency)	- a range of moisture contents are used
<b>Volatile matter</b>	- influences the extent and rate of gasification reactions	- a range of volatile matter contents are used
<b>Heating value</b>	- determines plant dimensions - influences generation capacity (higher heating value – higher capacity and efficiency)	- a range of heating values are used
<b>Ash content</b>	- influences net cycle efficiency (higher ash – lower efficiency) - influences flux addition rate	<25%
<b>AFT (flow, reduction)</b>	- influence melting ability of discharged slag (it needs to be melted below performance temperature) - influences operating costs (higher temperature – higher costs)	<1500°C (2732°F)
<b>Slag viscosity</b>	- viscosity must be sufficiently low to ensure smooth slag flow down the gasifier walls	- <15Pa-s (150 poise) - Used up to 25 Pa-s (250 poise)
<b>Char reactivity</b>	- influence the extent of carbon conversion (higher reactivity – higher cycle efficiency) - influences oxygen consumption	- a range of reactivities can be used because of higher operational temperature
<b>Sulfur</b>	- can cause corrosion of heat exchanger surfaces - influences operating costs (higher sulfur – higher costs)	- preferred S <1.5%
<b>Nitrogen</b>	- contributes to NOx emissions	
<b>Chlorine</b>	- forming HCl can poison gas cleaning system catalysts - HCl can cause chloride stress corrosion	<0.4% (air dry) <0.2% preferred

### *3.2. Database of coal properties to assess IGCC performance*

In the early phase of this study, we built a database of Indiana coal characteristics (Mastalerz et al., 2005) that included parameters that are of primary importance to IGCC. From the database available in 2005, the averages of the following parameters: moisture, heating value, fixed carbon, volatile matter, ash yield, ash fusion temperatures, and chlorine content were calculated. Some parameters (for example, moisture content, ash yield, heating value, volatile matter content, and fixed carbon) had good coverage of data for all major Indiana coal beds. For some of the other parameters, for example, ash fusion temperatures and slag viscosity, data were limited to nonexistent.

During the course of this project, following recommendations of the scoping study, we generated new data and a summary for the Danville, Hymera, Springfield, and the Seelyville Coal Members based on the current database. The summary of selected parameters is provided in Table 6. These four coal beds are the targets of this evaluation. The Lower Block Coal is also included for comparison.

Table 6. Data availability for selected coal properties for selected Indiana coal beds. n – number of data points available.

	DANVILLE				HYMERA				SPRINGFIELD				SEELYVILLE				LOWER BLOCK			
	Min.	Max.	Ave	n	Min.	Max.	Ave	n	Min.	Max.	Ave	n	Min.	Max.	Ave	n	Min.	Max.	Ave	n
M [ar]	1.9	28.2	11.3	253	0.8	23.5	10.3	134	0.5	34.7	9.9	654	0.8	29.2	9.9	81	0.7	27.1	13.8	139
A [dry]	4.9	41.1	13.0	255	6.8	72.7	14.5	135	4.9	54.2	12.2	663	6.7	35.6	14.9	88	4.1	31.0	9.0	148
S [tot, dry]	0.33	7.62	2.65	163	1.20	5.34	3.10	36	0.30	12.19	3.27	443	2.50	9.84	5.02	28	0.55	7.0	1.36	111
Btu [dry]	7651	17314	13050	253	2520	13734	12042	134	8362	20648	13214	663	8494	13810	12149	83	9677	14702	13267	147
FC [dry]	32.0	58.2	48.4	131	11.7	54.0	46.7	110	29.0	70.7	48.0	308	19.0	61.1	44.4	73	35.5	59.5	52.6	93
VM [dry]	26.9	46.1	39.1	131	15.6	45.8	38.5	110	19.9	62.0	40.9	308	31.2	65.4	41.4	73	33.5	47.5	38.5	94
Slag viscosity temp. (°F)	2156	2900	2559	30	2150	2900	2421	15	2150	2720	2345	41	2150	2630	2273	9	2150	2900	2649	38
Cl [%]	0.01	0.10	0.03	25	0.02	0.07	0.04	23	0.01	0.24	0.15	31	0.08	0.17	0.11	3	0.01	0.06	0.02	42
SiO <sub>2</sub> [%]	31.0	60.0	48.3	34	17.00	55.00	39.13	20	21.0	53.0	38.6	48	19.0	45.0	31.0	14	0.4	61.7	47.2	39
Al <sub>2</sub> O <sub>3</sub> [%]	14.0	26.0	20.9	34	9.10	28.40	18.00	20	9.2	28.0	18.2	48	8.5	25.0	17.2	14	16.4	34.0	25.3	39
Fe <sub>2</sub> O <sub>3</sub> [%]	3.5	37.0	16.3	34	4.60	41.00	22.95	20	6.5	49.0	23.3	48	9.2	55.0	35.8	14	3.3	47.2	15.1	39
CaO [%]	0.5	10.0	2.9	34	0.43	27.00	4.80	20	0.3	16.0	4.3	48	0.5	8.2	3.1	14	0.5	7.1	1.9	39
MgO [%]	0.6	1.7	1.2	34	0.37	1.50	0.85	20	0.3	1.4	0.8	48	0.4	0.9	0.5	14	0.3	1.0	0.6	39
SiO <sub>2</sub> / Al <sub>2</sub> O <sub>3</sub>	1.75	2.73	2.31	34	1.60	2.93	2.22	20	1.46	2.59	2.16	48	1.44	2.42	1.85	14	0.02	2.52	1.89	39
Fe <sub>2</sub> O <sub>3</sub> + CaO	4.01	38.50	19.26	34	5.12	42.00	27.75	20	7.60	53.80	27.42	48	10.4	58.0	38.84	14	4.80	47.66	16.51	39
Silica ratio*	0.44	0.92	0.71	34	0.28	0.90	0.58	20	0.30	0.86	0.58	48	0.25	0.80	0.45	14	0.02	0.92	0.73	39
AFTR INIT	2095	2540	2275	12	-	-	-	-	2095	2103	2099	2	-	-	2185	1	1970	2800	2430	28
AFTR SOFT	2155	2610	2375	12	-	-	-	-	2131	2151	2141	2	-	-	2275	1	2040	2800	2477	28
AFTR HEM	2210	2665	2436	12	-	-	-	-	2181	2187	2184	2	-	-	2353	1	2080	2800	2525	28
AFTR FINAL	2250	2735	2502	12	-	-	-	-	2208	2232	2220	2	-	-	2425	1	2170	2800	2558	26
AFTO INIT	2340	2705	2535	12	-	-	-	-	-	-	2528	1	-	-	2668	1	2425	2740	2578	9
AFTO SOFT	2370	2730	2570	12	-	-	-	-	-	-	2576	1	-	-	2701	1	2470	2765	2589	7
AFTO HEM	2395	2765	2594	12	-	-	-	-	-	-	2596	1	-	-	2716	1	2495	2780	2608	7
AFTO FINAL	2415	2795	2626	12	-	-	-	-	-	-	2611	1	-	-	2728	1	2540	2800	2638	7

\* Silica ratio: SiO<sub>2</sub>/(SiO<sub>2</sub>+Fe<sub>2</sub>O<sub>3</sub>+CaO+MgO)

## 4. EVALUATION OF INDIANA COAL FOR IGCC

In this chapter, we present an evaluation of the Indiana coals for IGCC based on all the data currently available to us. There are two things of special importance for coal gasification: 1) the ability of coal and coal char to gasify, and 2) the ability of slag to be removed from the system. To address these two aspects, we divided this chapter into three sections: 1) Evaluation based on basic coal quality parameters such as heating value, moisture content, ash yield, and sulfur content; 2) Evaluation of the ability of coal and coal char to gasify (reactivity); and 3) Evaluation of slagging based on mineral matter characteristics

### *4.1 Evaluation based on basic coal quality parameters*

Heating value (presented on dry basis, Fig. 3-6) shows a range from less than 10,500 to greater than 13,500 Btu/lb for the four coal beds presented, with large portion of the resource having heating values higher than 12,000 Btu/lb. The heating value of the feed coal determines IGCC plant dimensions and its generating capacity. To obtain the same energy from a lower heating value coal, a greater tonnage must be gasified, contributing to higher costs. Therefore, lower heating value coals such as, for example, Powder River Basin sub-bituminous coals or lignites are economically less desirable for IGCC than bituminous coals, such as those from Indiana and the entire Illinois Basin.

Moisture content (Fig. 7-10) in Indiana coal varies from less than 5% to, locally, more than 20%, with the highest moisture generally occurring close to the basin margin. Moisture content influences gasifier efficiency and can help to make a decision whether the gasification process should be dry or slurry fed. High moisture content is a problem, because, in order to maintain the gasifier temperature, additional coal and oxygen must be used to evaporate the water. Significant resources of Indiana coals have more than 10% moisture, which is somewhat high for IGCC use. However, considering moisture content, Indiana coals are better for IGCC than lower rank high moisture coals of the Powder River Basin (28% on average, Mastalerz et al., 2004).

Ash content distribution maps (Figs 11-14) show that the Danville and Springfield Coals have lower ash contents than the Hymera Coal, making them more suitable for IGCC. Low ash contents are favorable because lower coal volumes need to be gasified to get the same amount of energy, and also because the slag yield will be lower.

Significant resources of Indiana coals have high sulfur contents. In the Danville Coal, there is a split between low sulfur (<1.5%) areas in the north and high sulfur (>2.5%) in the south (Fig. 15). In the Hymera Coal (Fig. 16), sulfur content is dominantly high, although limited data are available. In the Springfield Coal, sulfur content is more than 3%, except for some areas in Gibson and Sullivan Counties (Fig. 17). The Seelyville Coal is also a high sulfur coal bed (Fig. 18). For IGCC plants, high sulfur content is not much of a problem. In fact, high sulfur coals are often preferred, because in the process, sulfur is transformed into sulfuric acid and high purity elemental sulfur, both profitably sold products. As a result of sulfur recovery, sulfur emissions from IGCC plants are minimal. For example, in the Polk Station IGCC plant and Eastman Gasification plant, the feed with ~3.5% is preferred, while feeds with up to 5.8% sulfur can be used. Thus, with regard to sulfur content, Indiana coals are good for IGCC.

Chlorine content in coal is of special concern because it may contribute to the formation of boiler and gasifier deposits and corrosion during gasification. For gasification chlorine contents less than 0.4% are required, and less than 0.2% are preferred. In the Danville Coal, chlorine content is <0.1%, but limited data are available (Fig. 19). Similarly low values occur in the Hymera Coal (Fig. 20). Springfield is characterized by higher Cl content, but still always below 0.3% (Fig. 21). For this coal, Cl content generally increases with depth, in southwestern direction.

Mercury content maps are presented in Figs 22-25. They have been generated because of the new mercury regulations from power plants.

#### **4.2 Evaluation based on the ability of coal and coal char to gasify (reactivity)**

No direct data on char reactivity are available for Indiana coals. However, it has been demonstrated that selected properties relate well to gasification rate and degree of conversion. Gasification rate is related to carbon content, decreasing when carbon content increases (Miura et al., 1989), and oxygen content (gasification rate increases with O content). For two-step char conversion, char reactivity correlates with fuel ratio (Fig. 26), expressed as a ratio of fixed carbon and volatile matter (negative correlation with  $R^2$  of ~0.85 within a range of fuel ratio of 0.25 to 1.7, (Zevenhoven and Hupa, 1997), and with O/C molar ratio of the parent fuel (positive

correlation with  $R^2$  up to 0.96, within a O/C range of 0.1 to 0.7, Fig. 27). For one step conversion (simultaneous devolatilization and char gasification), the values of char conversion will be modified, but the trends are expected to remain the same.

Maps of fixed carbon and volatile matter content are shown in Figs 28-31 and Figs 32-35, respectively, and maps of ratios of fixed carbon to volatile matter content (Fuel ratio) in Figs 36-39. Fuel ratio maps (Fig. 36-39) show a range of values from less than 1 to greater than 1.5. Because reactivity decreases with increasing fuel ratio (Fig. 26), the most reactive, and the most adequate in this respect for gasification would be the coal zones that have lower ratios. In the Danville Coal, it would be the areas in the most northern and most southern part of its extent (Fig. 36), whereas for the Springfield (Fig. 38) and the Seelyville (Fig. 39) these will be zones along the margins (relatively shallow). The Hymera Coal is characterized by a relatively high fuel ratio, suggesting that reactivity will be relatively lower than in the other coal beds (Fig. 37).

The ratios of O/C (molar and weight) are mapped in Fig. 40-47. These ratios show a positive correlation with reactivity, therefore areas with higher values would imply higher reactivity. As expected, the areas of higher O/C ratios (~higher reactivity), in general, coincide with the area of lower fuel ratio.

### **4.3 Evaluation of slagging based on mineral matter characteristics**

Slagging characteristics of the coal are very important in entrained-flow slagging gasifiers, because melting and subsequent smooth mineral matter removal is critical to the plant operation. Entrained-flow slagging gasifiers are the most common gasifier types in IGCC technologies worldwide, including the US and, therefore, evaluation of mineral matter properties and prediction of their behavior in the gasifier is of fundamental importance.

Previous studies (Patterson et al., 1996; 2004) of slagging behavior and its relationship to the gasification process suggested that the optimal characteristics of the coal would include:

- 1) Low ash flow temperature  $<1400^{\circ}\text{C}$  ( $2552^{\circ}\text{F}$ ) in reducing conditions
- 2) Relatively low ash content (around 10%)
- 3) Slag viscosity less than 15 Pa.s (150 Poise) at  $1400^{\circ}\text{C}$  ( $2552^{\circ}\text{F}$ ), with an upper limit of 25 Pa.s at  $1500^{\circ}\text{C}$  ( $2732^{\circ}\text{F}$ )

- 4) Little or no flux requirement (<3% CaCO<sub>3</sub> by weight of coal)
- 5) Low temperature of critical viscosity (T<sub>cv</sub>) - <1400°C (2552°F)
- 6) SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> ratio of about 2 – this minimizes limestone flux and prevents slag crystallization
- 7) Silica ratio (SR=SiO<sub>2</sub>/[SiO<sub>2</sub>+Fe<sub>2</sub>O<sub>3</sub>+CaO+MgO]) <0.70 – minimizes flux requirements;
- 8) Fe<sub>2</sub>O<sub>3</sub> +CaO content in ash >15% - minimizes flux requirements

In our evaluation of Indiana coals, several of these parameters were selected and mapped and, consequently, used to grade the coals with regard to performance in the slagging gasifier. These parameters, the selection of which depended to a large extent on the data availability, include: ash content, SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> ratio, silica ratio, Fe<sub>2</sub>O<sub>3</sub> +CaO content, and slag viscosity and Table 7 shows parameter ranges used in this study to characterize the best resource.

Table 7. Suitability of selected parameters for IGCC suggested for Indiana coals.

<b>Parameter</b>	<b>Optimal</b>	<b>Remarks</b>
Ash content (%)	less than 12.5	12.5% ash considered less suitable
SiO <sub>2</sub> /Al <sub>2</sub> O <sub>3</sub>	1.9-2.2	<1.9 and >2.2 considered less suitable
Silica ratio	less than 0.70	>0.70 considered less suitable
Fe <sub>2</sub> O <sub>3</sub> +CaO (% in ash)	15-35	<15 and >35 considered less suitable
Slag viscosity T (°F)	less than 2550	>2550 considered less suitable

With regard to the SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> ratio (Figs 48-51, the Hymera and Seelyville Coals have the highest proportion of the coals within a 1.9-2.2 range. Silica ratio values for the Danville, Hymera, and Springfield are within or close to optimal ranges (Figs 52-54); no map is available for the Seelyville Coal because of very limited data. Considering the Fe<sub>2</sub>O<sub>3</sub> +CaO contents (Figs 55-58), all of the coals have significant resources within the optimal value range. The same holds true for the temperature of the critical viscosity (Figs 59-61), although this is the parameter for which very limited data are available.

## **5. GRADING OF INDIANA COALS WITH REGARD TO IGCC SUITABILITY**

Applying the classification criteria listed in Table 7, and subdividing the coals into optimal and less suitable, a series of maps have been generated for each coal (Figs 62-65) that outline the best coal with regard to each parameter. These maps include:

- 1) Ash content map showing areas with ash content greater than 12.5% (optimal) and less than 12.5% (less suitable)
- 2) Slag viscosity temperature showing areas with less than 2550°F (optimal) and greater than 2550°F (less suitable)
- 3) SiO<sub>2</sub> to Al<sub>2</sub>O<sub>3</sub> ratio showing areas with the ratio within the range of 1.9-2.2 (optimal) and outside this range (less suitable)
- 4) Fe<sub>2</sub>O<sub>3</sub> +CaO content showing areas within a range of 15-35 (optimal) and outside this range (less suitable); and
- 5) Silica ratio showing areas with the ratio less than 0.7 (optimal) and larger than 0.7 (less suitable).

The Springfield Coal (Fig. 64), specifically, shows extensive areas of the optimal values of the parameters used.

In order to outline the geographic areas within individual coal seams would be best when all the parameters are considered, the maps were overlain, and summary maps were created that show a grading of the coal from 1 to 3, where grade 1 is the best resource (Figs 62-64F, 65D). In maps constructed this way, Grade 1 indicates that all the considered parameters were within the optimal value ranges, Grade 2 indicates that some parameters were outside the optimal values ranges, whereas Grade 3 indicates that most parameters were outside the optimal values ranges.

## **6. AVAILABILITY OF INDIANA COALS FOR IGCC**

In addition to grading the coal with regard to its potential for IGCC, we have combined this information with that on the availability of coal for surface and underground mining. To convey this information, for each coal we provide a series of five maps that include:

- 1) extent of the coal with mined-out areas as well as currently active mines,
- 2) availability of the coal for surface mining,
- 3) availability of coal for underground mining,
- 4) coal grading map with areas available for surface mining, and

5) coal grading map with areas available for underground mining.

For the Danville, these maps are presented in Figs 66-70, for Hymera – 71-75, Springfield – 76-80 and Seelyville 81-85. The last two maps for each coal bed are of special importance here because they show what grade of coal occurs in the areas that are still available for surface and underground mining. This, together with the locations of the active mines for these coal beds (shown on the first map in each coal 5-map series) can help planning while searching for the resource for IGCC technologies. Series of these maps for each coal is also presented in a larger format as appendices.

In the Danville Coal, the best (Grade 1 and 2) coals available by surface mining methods occur in Warrick, Pike, and northern Vigo Counties (Fig.69). The coal available by underground methods is dominantly of Grade 3 (Fig. 70), except northern Pike County where there is coal of Grade 2. In the Hymera Coal, most of the coal available both for surface (Fig. 74) and underground (Fig. 5) mining is represented by Grade 3 and 2. In the Springfield Coal, the best coal for IGCC available by surface methods occur in Pike and Warrick Counties (Fig. 79), and there are large areas of excellent quality (Grade 1 and 2) coal available by underground methods (Fig. 80). In the Seelyville Coal, Pike, Vigo, and Warrick Counties contain Grade 1 and 2 coals available for surface mining (Fig. 84), and coals of Grade 1, 2, and 3 are available for underground mining in several counties (Fig. 85).

## 7. DISCUSSION

Coal quality parameters, coal reactivity and slagging characteristics of the Danville, Hymera, Springfield, and Seelyville coals indicate that these coals would constitute good feedstock for use in an IGCC system. In fact, the Illinois Basin coal is a proven feedstock in IGCC processes (Lizzio, 1997). High sulfur Indiana coals have been used in the two US gasification plants: the Wabash River Coal Gasification Plant in Indiana and Polk Station Power Plant in Florida. The Wabash River Gasification plan was designed to use a range of local Indiana coals having a maximum sulfur content of 5.9 percent. In Polk Station Power Plant in Florida, the Springfield, Hymera, and Danville Coals from Indiana, along with along with Illinois #6 coal (Herrin) were tested between 1997 and 2001

<http://www.tampaelectric.com/pdf/TENWPolkDOEFinalTechReport.pdf>).

Indiana coals performed well in the tests. Successful results were achieved also on blends of the Danville coal from Indiana with the South American coal and petroleum coke.

This study provides an analysis of the properties of Indiana coals that are important in IGCC technology. It shows that there is significant variability in coal properties in Indiana and the maps generated can help select the areas best suited for specific applications. The emphasis of this evaluation is placed on entrained-flow slagging gasifiers. Such an approach was chosen because entrained-flow slagging gasifier technology is the most common choice in IGCC plants; such gasifiers are powerful, designed for a large volume of the coal and relatively flexible with regard to the type of feed. Therefore, grading of coal has been based on mineral matter characteristics, critical for the behavior of the slag in the gasifier. This grading for IGCC, as described in chapter 5, takes into account several parameters that in this study, however, are assumed to have equal influence on IGCC process. This is an assumption that may not be accurate, but only further detailed studies of how individual parameters influence behavior of Indiana coals in the gasification process could prove or disprove its validity.

Although the emphasis of this work is on slagging gasifiers, no slag viscosity predictions have been attempted. Consequently, it is difficult to assess what will be actual viscosity of the slag generated from Indiana coals within the temperature range that is commonly used for slag tapping (2462-2822°F; 1350-1550°C), and what will be the influence of ash composition on the slag viscosity. There are two reasons for not including slag viscosity predictions in this study. One reason is that predictive models for testing on American coals are not available to us (they are usually kept confidential). The other reason is that such predictions are feed specific. Such modeling and slag viscosity predictions are routinely done at IGCC plants for a specific type of feed, and the results vary between different feeds. In Indiana coals, there is a wide range of mineral matter characteristics, and the aim of this study was to assist in the selection of the coal feed, rather than predict their specific behavior in the gasifier.

Grading of Indiana coals for IGCC introduced in this study shows that within each coal bed studied, there is a range from Grade 1 (optimal) to Grade 3 (least suitable) within the areas where coal is available for mining (surface or underground) (Fig. 69 and 70 for the Danville

Coal, Fig. 74 and 75 for the Hymera Coal, Fig. 79 and 80 for the Springfield Coal, and Fig. 84 and 85 for the Seelyville Coal). Coal classified as Grade 3 could still be used for IGCC, but in order to improve slag properties, blending of this coal with the coal of Grade 1 or 2 might be recommended. The blending decisions are IGCC-plant specific and will depend on numerous local factors, but here are some general guidelines to consider:

- 1) For the coals that have high ash fusion temperatures ( $>2550^{\circ}\text{F}$  used in this study), flux (e.g., limestone) needs to be added to lower melting temperatures and to reduce slag viscosity in order to get continuous slag flow. To reduce the need for the flux, such coals can be blended with the coals that have lower ash melting temperature. Depending on the composition of ash, such blends can minimize or even eliminate the need for the flux.
- 2) Blending of coals that have high ash melting temperatures with those that have lower melting temperatures may also prevent slag crystallization and, consequently, slag blockages, by lowering temperatures of critical viscosity ( $T_{cv}$ ).
- 3)  $T_{cv}$  can be also lowered by the addition of CaO and FeO, as shown for other coals (Patterson and Hurst, 1996). Therefore, blending with coal of high CaO and MgO would be especially beneficial.  $T_{vc}$  can also be lowered by increasing the  $\text{SiO}_2/\text{Al}_2\text{O}_3$  ratio, therefore blending with coals of high  $\text{SiO}_2/\text{Al}_2\text{O}_3$  ratio would be recommended. High  $T_{cv}$  seems to be associated with low ( $<1.9$ )  $\text{SiO}_2/\text{Al}_2\text{O}_3$  ratios.

In general, the main blend strategies that we suggest for Indiana coals are:

- A. Blending low  $\text{SiO}_2/\text{Al}_2\text{O}_3$  coals ( $<1.6$ ) with high  $\text{SiO}_2/\text{Al}_2\text{O}_3$  coals to yield of  $\text{SiO}_2/\text{Al}_2\text{O}_3$  of 1.0-2.2;
- B. Blending high flux ( $\text{Fe}_2\text{O}_3+\text{CaO}$ ) coals with lower flux coals to yield  $\text{Fe}_2\text{O}_3+\text{CaO}$  content of about 15-20%

As alternative to lowering  $T_{cv}$  is running the gasifier at higher temperatures, and this possibility needs to be evaluated versus blending and flux addition. For each coal there will be a trade-off between the benefits and the costs of the flux addition versus increasing the gasification temperature.

Although in this study, evaluation of the coal for IGCC is particularly suitable for entrained-flow slagging gasifiers, generated data and coverages can be valuable for other coal-processing

technologies as well. In addition to evaluation based on mineral matter characteristics (chapter 4.3) including evaluation of the coal/char reactivity (chapter 4.2) as well as analysis of coal quality parameters (chapter 4.1), this study can be used to guide the selection of coals for other gasification technologies as well as other clean coal technologies.

## **8. SUMMARY AND CONCLUSIONS**

1. The overall objective of this study was to evaluate Indiana coals for use in IGCC technologies. Specific aims included: 1) generating new analyses on coals and integrating them into a coal quality database; 2) mapping various coal quality parameters; 3) using several IGCC-important parameters, grading the coals with regard to their suitability for IGCC; and 4) combining coal quality information with the availability of the coal for surface and underground mining. Four coal beds are targeted in this study: the Danville, Hymera, Springfield, and Seelyville Coal Members.
2. This study includes an analysis of coal properties that are of major importance to IGCC technology and requirements with regard to these properties in all three types of gasifiers: fixed-bed, fluidized-bed, and entrained flow. The properties identified as having major impact on gasification process are, among others, heating value, moisture content, and ash content. A updated database of coal properties important for IGCC is available with this report.
3. Assessment of Indiana coals for IGCC is accomplished based on the analysis of: 1) basic coal quality parameters such as heating value, moisture content, ash yield, and sulfur content; 2) ability of coal and coal char to gasify (reactivity); and 3) mineral matter characteristics.
4. Basic coal quality characteristics such as heating value, moisture content, and ash content indicate that Indiana coals are a good feedstock for gasification. High sulfur content of the majority of Indiana coals does not create a problem because in IGCC plants sulfur is transformed into sulfuric acid and high purity elemental sulfur, both profitable products. Chlorine content in the coals studied is usually well below the IGCC-preferred 0.2% level, except some areas in the Springfield coal, where at places is a little higher but still below 0.3%. Chlorine content below 0.4% is required for gasification.

5. Since no direct reactivity measurements were available, coal/char reactivity proxies such as fuel ratio (a ratio of fixed carbon and volatile matter) and O/C ratio were used to evaluate reactivity. The analysis indicates that the Danville Coal and the Springfield Coal will be more reactive than the Hymera Coal. Reactivity of coal/char is more important in gasifiers with two-step char conversion, such as the one used at Wabash Valley Gasification Plant, than in one stage gasifiers where gasification is a faster process.
6. Mineral matter characteristics are very important in entrained-flow slagging gasifiers. Entrained-flow slagging gasifiers are the most common gasifier types in IGCC technologies worldwide, including the US and, therefore, evaluation of mineral matter properties and prediction of its behavior in the gasifier is of fundamental importance. In this study, we propose the following ranges of parameters as the optimal for Indiana coals:

Ash content (%)	less than 12.5
SiO <sub>2</sub> /Al <sub>2</sub> O <sub>3</sub>	1.9-2.2
Silica ratio	less than 0.70
Fe <sub>2</sub> O <sub>3</sub> +CaO (% in ash)	15-35
Slag viscosity T (°F)	less than 2550

With regard to the SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> ratio, the Hymera and Seelyville Coals have the highest proportion of the coals within the 1.9-2.2 range. Silica ratio values for the Danville, Hymera, and Springfield are within or close to optimal ranges; no map is available for the Seelyville Coal because of very limited data. Considering the Fe<sub>2</sub>O<sub>3</sub> +CaO contents, all of the coals have significant resources within the optimal value range. The same holds true for the temperature of the critical viscosity, although this is the parameter for which very limited data are available.

7. Grading of coals for IGCC was accomplished by mapping the distribution of parameters listed in Table 7, overlying the maps, and outlining the areas with the best characteristics (Grade 1) and less desirable characteristics (Grade 2 and 3). Maps of coal grading were combined with maps of availability for the surface and underground mining. In the Danville Coal, the best coals (Grade 1 and 2) available by surface mining methods, occur in Warrick, Pike, and northern Vigo Counties. The coal available by underground methods is dominantly of Grade 3, except in northern Pike County where there is coal of

Grade 2. In the Hymera Coal, most of the coal available both for surface and underground mining is represented by Grade 3 and 2. In the Springfield Coal, the best coal for IGCC available by surface methods occur in Pike and Warrick Counties and there are large areas of excellent quality coal (Grade 1 and 2) available by underground methods. In the Seelyville Coal, Pike, Vigo, and Warrick Counties contain Grade 1 and 2 coals available for surface mining and coals of Grade 1, 2, and 3 are available for underground mining in several counties.

8. For Indiana coals, we recommend two main blending strategies when improvement in slagging characteristics is required: a) blending low  $\text{SiO}_2/\text{Al}_2\text{O}_3$  coals (<1.6) with high  $\text{SiO}_2/\text{Al}_2\text{O}_3$  coals to yield of  $\text{SiO}_2/\text{Al}_2\text{O}_3$  of 1.0-2.2; and b) blending high flux ( $\text{Fe}_2\text{O}_3+\text{CaO}$ ) coals with a lower flux coals to yield  $\text{Fe}_2\text{O}_3+\text{CaO}$  content about 15-20%
9. Although the evaluation of Indiana coals presented in this report is particularly suitable for entrained-flow slagging gasifiers, generated data and coverages can be valuable for other coal-processing technologies as well. By concentrating on the evaluation based on mineral matter characteristics, but including evaluation of the coal/char reactivity as well as analysis of coal quality parameters, this study can be used to guide the selection of coals for other gasification technologies as well as other clean coal technologies.

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## **REFERENCES CITED**

- Collot, A.-G., 2002. Matching gasifiers to coals. IEA Clean Coal Centre Report, CCC/65, London, 63pp.
- Collot, A.-G., 2006. Matching gasification technologies to coal properties. International Journal of Coal Geology 65, 191-213.
- Conolly, C.L., Zlotin, Alex, 1999. The availability of the Springfield Coal Member for mining in Indiana: Indiana Geological Survey Open-File Study 99-07, 49 p., 18 fig.
- Conolly, C.L., Zlotin, Alex, 2000. The availability of the Danville Coal Member for mining in Indiana: Indiana Geological Survey Open-File Study 00-01, 47 p., 18 fig.
- Conolly, C.L., 2001. The availability of the Seelyville Coal Member for mining in Indiana: Indiana Geological Survey Open-File Study 01-08, 52 p., 18 fig.

- Drobniak, A., Shaffer, K.R., Rupp, J.A., Mastalerz, M., 2007. Major point sources of CO<sub>2</sub> emissions and conceptual geological sequestration strategies in Indiana: Indiana Geological Survey Open-File Study 07-01.
- Drobniak, A., Pfitzer, C., and Mastalerz, M., 2007. Indiana's railroad system: Indiana Geological Survey Open-File Study 07-04.
- Drobniak, A., Mastalerz, M., Shaffer, K.R., 2006. Coal supply and demand in Indiana: Indiana Geological Survey Miscellaneous Map 72.
- Drobniak, A., Mastalerz, M., Shaffer, K.R., 2006. Coal, electricity, and gas transportation systems in Indiana: Indiana Geological Survey Open-File Study 06-03.
- Durie, R.A., and Smith, I.W., 1975. Production of gaseous and liquid fuels from coal. In Cook, A.A. (Ed) Australian Black Coal – Its occurrence, mining, preparation and use. Australasian Institute of Mining and Metallurgy, Illawara Branch, 161-172.
- EPA, 2000. Regulatory finding on the emissions of hazardous air pollutants from electric utility steam generating units. U.S. Federal Register 65 (245), 79825-79831.
- EPA, 2005. Standards for Performance for New and Existing Stationary Sources: Electric Utility Steam Generating Units; Final Rule. Federal Register. Part II. Vol. 70, No. 95. May 18, 2005.
- Innes, K., 1999. Coal quality handbook for IGCC. Technology Assessment Report 8. Cooperative Research Centre for Coal in Sustainable Development. Australia, 66p
- Lizzio, A.A., 1997. Methods to evaluate and improve the gasification behavior of Illinois coal. Final Technical Report. <http://www.icci.org/97final/finliz.htm>
- Mastalerz, M., Drobniak, A., and P. Irwin, 2005. Indiana Coal Quality Database (ICQD). ). IGS Open File-Study 05-02.
- Mastalerz, M., Drobniak, A., Rupp, J., and Shaffer, N., 2004. Characterization of Indiana's coal resource: Availability of the reserves, physical and chemical properties of the coal, and present and potential uses. IGS Open-File Study 04-02, 74p, 102 figures, 67 tables.
- Miura, K., Hashimoto, K., and Silveston, P.L., 1989. Factors affecting the reactivity of coal chars during gasification, and indices representing reactivity. Fuel 68, 1461-1475.
- Pashos, K., 2005. IGCC- An important part of our future generation mix. Presentation at IGCC Conference, October, 2005 <http://www.gasification.org/>
- Patterson, J.H., and Hurst, H.J., 1996. Slag characteristics of Australian bituminous coals for utilization in slagging gasifiers. Conference Proceedings – Impact of Coal Quality of Thermal Coal Utilisation, Brisbane, September 1-4, 1996.
- Patterson, J.H. and Do, T., 2004. Survey of the suitability of export thermal coals for IGCC use. Research Report 49, CSIRO Energy Technology, Pullenville, Qld, Australia. 75 pp.
- Radulovic, P.T., Ghani, M.U., and Smoot, L.D., 1995. An improved model for fixed bed coal combustion and gasification. Fuel 74, 582-594.
- Tampa Electric Polk Power Station Integrated Gasification Combined Cycle Project. Final report August, 2002, 260p  
<http://www.tampaelectric.com/pdf/TENWPolkDOEFinalTechReport.pdf>.
- Williams, R.H., 2004. IGCC: Next step on the path to gasification-based energy from coal. November 2004, [www.westgov.org/wga/initiatives/cdeac/IGCC-NEC-Chapter4.pdf](http://www.westgov.org/wga/initiatives/cdeac/IGCC-NEC-Chapter4.pdf), accessed June 2, 2005
- Zevenhoven C.A.P., and Hupa, M. 1997. Characterisation of fuels for second-generation PFBC. Proceedings of the 14<sup>th</sup> International Conference on Fluidized Bed Combustion, Vancouver, B.C., Macada, May 11-14, vol. 1, 213-227. F.D.S. Preto (Editor), ASME, New York.