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Project Title: **SUITABILITY OF ILLINOIS COAL FOR A MULTIPURPOSE COKE FACILITY**

ICCI Project Number: 07-1/ER5
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ABSTRACT

Although coke is an absolutely essential part of iron making and foundry processes, currently there is a shortfall of 5.5 million tons of coke per year in the United States. The shortfall has resulted in increased imports and drastic increases in coke prices and market volatility. This effort conducted a preliminary investigation of the suitability of using a blend of Illinois and conventional metallurgical coal for production of coke in a mine mouth or local multipurpose coking/gasification-liquefaction process. Previously, Illinois coal was a major component of the coal used to produce coke in northern Illinois and Indiana. As coke ovens became larger, issues with furnace wall integrity arose. When the industry adopted the Coal Strength Reactive (CSR) criteria for coke quality, use of Illinois coal for coke production was discontinued. Currently, over 8 million tons of coal are used per year to produce coke in northern Illinois and Indiana. This research is developing processes that will again allow Illinois coal to be used for coke production. These processes involve multiple value streams that reduce technical and economic risk. Initial efforts indicate that it will be possible to use blended coal in a non-recovery and possibly in a conventional coke oven to produce pyrolysis gas that can be selectively extracted and used for various purposes including the production of electricity, liquid transportation fuels, fertilizer, and hydrogen. The use of Illinois coal in this process will provide another source of coke for use in steel and other industries and thereby assist in stabilizing the coke market. A new market opportunity for Illinois coal will also be created through this effort. By using blending techniques investigated in this research effort, it will also be possible for industry to reduce the cost of coal used for production of coke since Illinois Basin coal is generally less expensive than typical metallurgical coals and transportation charges tend to be less due to closer proximity, except in cases were rail congestion or market conditions interfere.

EXECUTIVE SUMMARY

This project extended an ongoing study funded by the Center for Coal Technology Research at Purdue University to consider the use of Illinois Basin coal for production of coke used by steel and various other industries. This concept involves production of coke in non-recovery and possibly conventional ovens at mine mouth or at a local industrial site with partial gasification and heat recovery for production of electricity and other products. Additional uses for the pyrolysis gas produced in the coking process, such as the production of liquid transportation fuels, fertilizer, and hydrogen, were considered. A preliminary Computational Fluid Dynamics analysis of initial issues associated with the use of Illinois coal in the blend of coal used for the process was conducted. The research considered the feasibility and parameters for a conceptual design that will maximize the fraction of Illinois coal that can be used in the process.

Previously, Illinois coal was used as a major component in the blend of coals used to produce coke in northern Illinois and Indiana. One steel producer owned coal mines in Illinois and used their output for coke production. As coke ovens became larger, issues with furnace wall integrity arose, and with the adoption of the Coal Strength Reactive (CSR) criteria for coke quality in large blast furnaces, the use of Illinois coal for coke production was discontinued. This research is developing processes that will again allow Illinois coal to be used as part of the coal used for coke production. These processes involve multiple value streams that reduce technical and economic risk. Initial efforts indicate that it will be possible to use blended coal in a non-recovery or a conventional coke oven to produce pyrolysis gas that can be selectively extracted and used for various purposes including the production of electricity, liquid transportation fuels, fertilizer, and hydrogen. It is initially estimated that 25% or higher Illinois coal can be blended with conventional metallurgical coals for use in current design, large blast furnaces using the developed processes.

Figure 1 shows results from the pyrolysis of a typical Illinois coal sample. The coal used for this test consisted of a blend of 40% Illinois coal and 60% medium volatile Eastern coal. Blends of this type have been shown to meet CSR requirements for use in blast furnaces. The pyrolysis gas produced from this blend has a carbon monoxide to hydrogen ratio for the temperature range from 450 to 600ºC that would be suitable for use in production of liquid transportation fuels using the Fischer-Tropsch process with an iron catalyst. Currently, ongoing efforts are optimizing both physical coke properties and gas composition by adjusting the blending procedure for various types of coals.

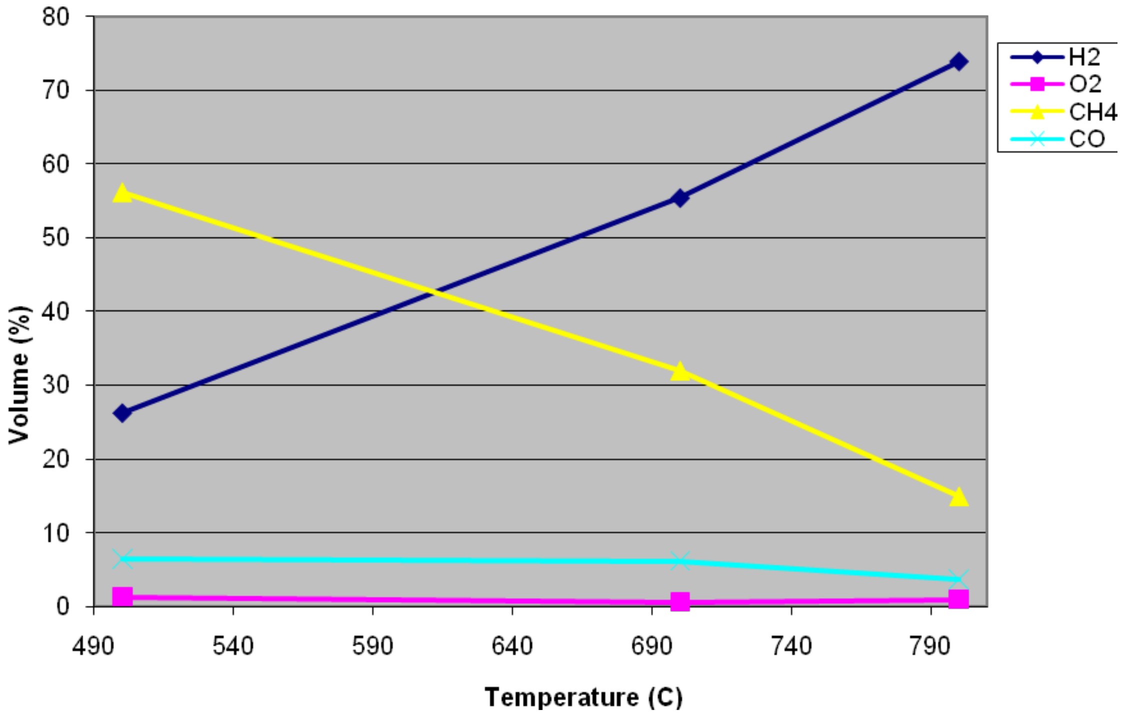

Figure 1: Pyrolysis Gas Molecular Composition for Illinois Coal Blend

Although coke is an absolutely essential part of iron making and foundry processes, currently there is a shortfall of 5.5 million tons of coke per year in the United States. The current shortfall of this critical raw material is being filled by imports, mainly from China and to a lesser extent Japan. Internationally, the shortfall has resulted in a sharp rise in recent coke prices. For example, coke delivered FOB to a Chinese port in January 2004 was priced at $60/ton, but rose to $420/ton in March 2004, and in September 2004 was $220/ton. This makes clear the likelihood that prices will remain high with considerable volatility. Current 2005 forecasts indicate that the United States will produce 11,500,000 net tons of coke, but will require 17,000,000 net tons for blast furnace, foundry, and related uses.[1] At present, essentially no Illinois coal is being used in coke production for the steel industry.

The significant shortfall of needed coke has placed an enormous strain on local steel industries. Resolution and/or mitigation of this formidable problem through the use of Illinois Basin coal in a mine mouth or a local, environmentally friendly, high efficiency coking/coal gasification facility would increase coke supply and production while at the same time reducing costs for the steel and foundry industries. In addition, such a high efficiency coking facility would produce electricity for sale to the wholesale electric market, thereby reducing costs and environmental emissions and, at the same time, enhancing electric system reliability.

Expansion of the capability to produce coke is being planned by the steel industry located in the Illinois/Indiana region and at present, essentially all of the coal used in the coking process is imported from outside Illinois. Recently it has been reported that a subsidiary of the Russian steel giant, OAO Severstal, plans to invest $140M to rebuild aging coke ovens at the Wheeling-Pittsburgh Steel Corporation's Follansbee site.[2] After the renovation, Severstal plans to retain 50% of the coke output for their use. Such an investment by an international steel producer is an indication of the crucial nature of coke for the steel industry.

This report addresses a new concept for producing coke that would use Illinois Basin coal as a significant portion of the feed stock for coke production. The research has developed a preliminary assessment of the suitability of using Illinois coal in coke production. In addition to direct production of coke, the process will selectively use pyrolysis gas produced at various stages of the coking process for a variety of purposes including electricity generation, production of liquid transportation fuels through a Fischer-Tropsch process, and production of fertilizer and bulk hydrogen. Such use will provide a path for Illinois coal to be an active participant in a highly profitable expanding market. The approach does not involve rebuilding an aged technology, but the development and utilization of a cutting-edge technology that will be especially relevant to the future of the industry.

OBJECTIVES

The objectives of this research effort were focused on tasks associated with a preliminary investigation of the suitability of using a blend of Illinois and conventional metallurgical coal for the production of coke in a mine mouth or local multipurpose coking/gasification-liquefaction process. This research is developing processes that will again allow Illinois coal to be used for coke production. These processes involve multiple value streams that reduce technical and economic risk. Initial efforts indicate that it will be possible to use blended coal in a non-recovery coke oven to produce pyrolysis gas that can be selectively extracted and used for various purposes including the production of electricity, liquid transportation fuels, fertilizer, and hydrogen. The use of Illinois coal in this process will provide another source of coke for use in steel and other industries and thereby assist in stabilizing the coke market. A new market opportunity for Illinois coal will also be created through this effort.

The following tasks were completed as part of this effort:

1. A detailed plan was developed establishing a clear understanding of work activities, schedules, and reporting requirements for all parties to the project.
2. New industrial contacts were established and existing contacts were further developed. Communication and information exchange procedures were established that provided assistance in assuring the success of the project.
3. Illinois coal mines were contacted and coal samples were obtained. Analysis and evaluation of pyrolysis gas properties from these Illinois coal samples as well as blends of Illinois coal with other coals were performed. A literature survey was conducted to find information regarding chemical and physical characteristics of Illinois coal available in the open press.
4. Analysis of pyrolysis gas produced during coke production from Illinois coal samples was performed and an appraisal of the suitability of blends of Illinois and other coals for use in a multipurpose coke production facility was conducted.
5. Technical and economic feasibility factors were evaluated.

INTRODUCTION AND BACKGROUND

A viable supply of iron is one mainstay of economies throughout the world. Issues associated with the supply and price of iron, which is used to produce steel, play either a direct or indirect role in all modern business operations. The lower Lake Michigan region is home to approximately 22% of the base steel production for the United States and consequently there is enormous incentive to assure the supply, quality, and price of raw materials used in its production. One of the major components used in the iron making process is coke.

Coke is a solid fuel and carbon source used to melt and reduce iron ore. Coke production begins with pulverized, bituminous coal. In current operations, coal itself cannot be used in place of the central placement of coke in a blast furnace because it would not form a permeable bed of sufficient strength and porosity to support the weight of material in the blast furnace.

Coal is fed into a coke oven which is sealed and heated to about 1100^{o}C (2000 ^{o}F) for 14 to 36 hours. Coke is produced by heating particulate coals of very specific properties in a refractory oven in the absence of oxygen (or with limited oxygen at the top of the coal bed in the case of non-recovery coke ovens). As temperature increases inside the coal mass, it melts or becomes plastic, fusing together as devolatilization occurs. Ultimately it resolidifies and condenses into particles large enough for blast furnace use. During this process, much of the hydrogen, oxygen, nitrogen, and sulfur are released as volatile by-products, leaving behind a partially crystalline and porous carbon product. The quality and properties of the resulting coke are inherited from the selected coals, as well as how they are handled and carbonized in coke plant operations.

Heat is often transferred from one coke oven to another to reduce energy requirements. After the coke is finished, it is moved to a quenching tower where it is cooled with a water spray. Once cooled, the coke is moved directly to an iron melting furnace or into storage for future use. Currently, Illinois Basin coal is not used in coke production.

Coke production is traditionally one of the major sources of pollution from steel production. At present, there are two main methods of producing coke. First, a recovery process in which the coal is heated in a completely reduced atmosphere and volatile products are recovered in an associated chemical processing plant. Major issues associated with this process include the complexity of chemical processing and the production of potentially hazardous compounds. There is also a major concern with tar that is left after processing. This material is also potentially hazardous and is generally stored on site, thus presenting a significant future disposal concern. The complexity of chemical processing introduces added cost and operational details that have restricted the use of this option for coking and simultaneous power production in the past.

Air emissions such as coke oven gas, naphthalene, ammonium compounds, crude light oil, sulfur, and coke dust are released from many coke ovens. Emissions control equipment can be used to capture some gases and heat can be captured for reuse in other heating processes. But traditionally, some gases escape into the atmosphere as the coke oven ages. Air and water emissions from coke production can be reduced by using a non-recovery coke battery. In traditional plants, by-products can be recovered. In non-recovery batteries, pollutants are combusted in the coke oven itself, which is often maintained at a negative pressure. This technique consumes the by-products, eliminating much of the air and water pollution.

In the non-recovery process, air is introduced above the top of the coke bed in the oven and volatiles are combusted. The Environmental Protection Agency has stated that new ovens must meet non-recovery standards. Hot gases from the oven can then be used in a heat recovery boiler to produce steam and subsequently generate electricity. Relatively small amounts of hydrogen are produced in this process and are recirculated to the bottom of the furnace to provide heat for the process. Figure 2 depicts coke at the conclusion of the coking process in a conventional slot oven. Figure 3 depicts coke after it has been pushed from a slot oven.[3] Figure 4 depicts a non-recovery coke oven.[4]

Figure 2: Coke in a Slot Coking Oven

Figure 3: Coke from Slot Oven

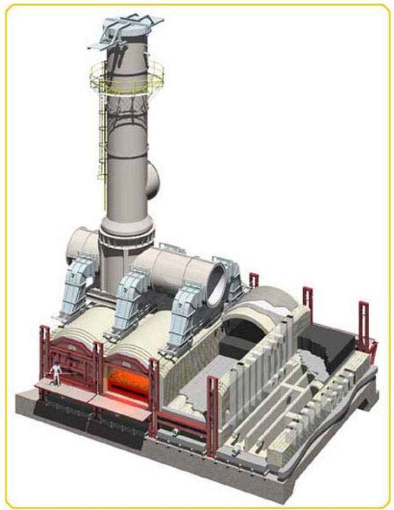

Figure 4: Non-Recovery Coke Oven

In the iron making process, iron ore, coke, heated air and limestone or other fluxes are fed into a blast furnace. Heated air causes coke to combust, which provides heat and a source of carbon for iron production. Limestone or other fluxes may be added to react with and remove acidic impurities from molten iron in the form of slag. A typical blast furnace operation indicating the location of coke is depicted in Figure 5.[5]

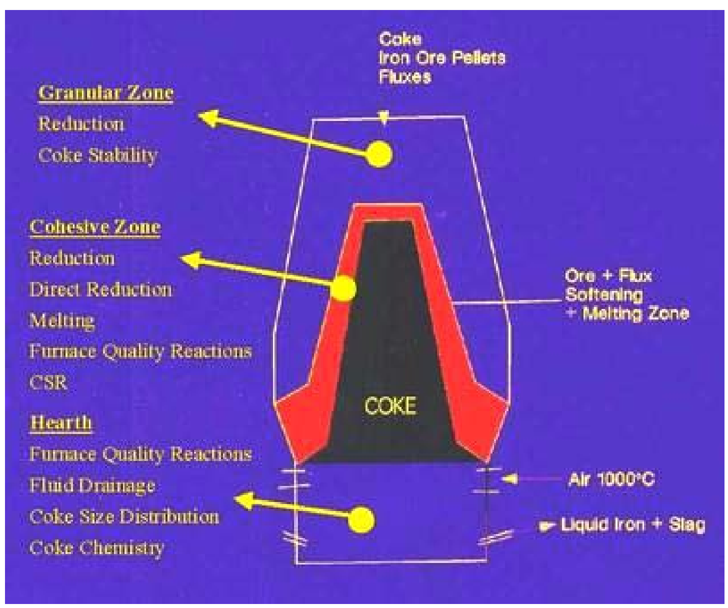

Figure 5: Typical Blast Furnace Zones

One key issue in blast furnace iron making is the coke strength.[6] Coke produced from Illinois Basin coal has less strength than coke produced from current metallurgical coal sources and consequently is smaller in size. This means that it will be used in upper portions of the blast furnace. Typical characteristics of coke used in blast furnace operations are shown in Table 1.[7]

Table 1: Typical Blast Furnace Coke Characteristics

Physical Characteristic: (measured at the blast furnace)	**Mean**	**Range**
Average Coke Size (mm)	52	45-60
Plus 4” (% by weight)	1	4 max
Minus 1” (% by weight)	8	11 max
Stability	60	58 min
CSR	65	61 min
Ash (% by weight)	8.0	9.0 max
Moisture (% by weight)	2.5	5.0 max
Sulfur (% by weight)	0.65	0.82 max
Volatile Matter (% by weight)	0.5	1.5 max
Alkali (K_2O+Na_2O) (% by weight)	0.25	0.40 max
Phosphorus (% by weight)	0.02	0.33 max

This report details research that was conducted to preliminarily consider the applicability of using Illinois coal as part of the blend of coals used for production of coke for modern large blast furnaces. Specifically, using Illinois coal in a Multipurpose Coke Facility located at a local mine or at an existing industrial facility was considered. The Multipurpose Coke Facility includes gasification and production of liquid transportation fuels, electric power, fertilizer and bulk hydrogen. Results of this study indicate that there is a high potential to use Illinois coal for coking as well as other industrial purposes both within and outside Illinois. A flow diagram of the concept for the Multipurpose Coke Facility is depicted in Figure 6.

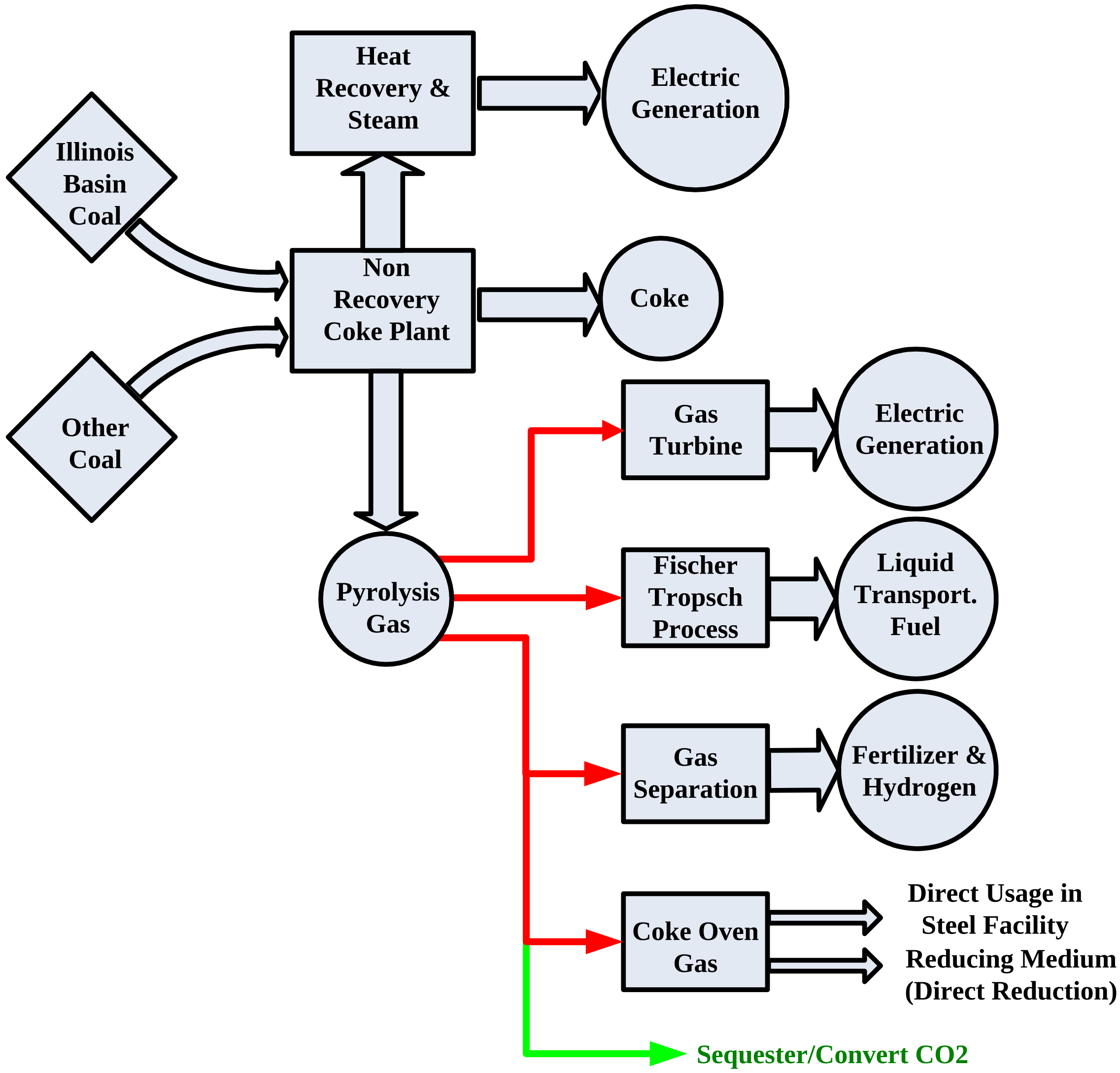

Figure 6: Initial Concept Description

Coke produced from Illinois Basin coal has less strength than coke produced from conventional metallurgical coal and this results in coke sizes that fall into two general classes. One class, often referred to as Buckwheat or Nut coke, is on the order of 1-inch x ¼-inch as compared to conventional blast furnace coke, which is on the order of 1-inch x 4-inch. The other class is called coke breeze and is much finer. It is used as a source of carbon in steel making, for palletizing and sintering, as well as in the elemental production of phosphorous. It can also be made into briquettes and used to feed blast furnaces in combination with iron ore pellets. Other industries that use coke breeze include cement, paper and fertilizer. Buckwheat/Nut coke is classically used in the steel industry as a carbon source for electric furnaces, in the production of ferromagnesium and ferrosilicon products, and in the production of elemental phosphorous.

Blends of Illinois and other coals have been used successfully to produce coke. Several steel manufacturers have expressed interest in considering how Illinois Basin coal might be used for various production processes. They also indicate that they have considered and/or are currently considering using Illinois Basin coals, usually at low levels, in blends.

Previously Illinois coal was a major component of the blend used to produce coke in northern Illinois and Indiana. One steel producer owned coal mines in Illinois and used their output for coke production. As coke ovens became larger issues with furnace wall integrity arose. When the industry adopted the Coal Strength Reactive (CSR) criteria for coke quality in large blast furnaces, use of Illinois coal for coke production was discontinued. This research is developing processes that will again allow Illinois coal to be used for coke production. These processes involve multiple value streams that reduce technical and economic risk.

One approach to increasing the percentage of Illinois Basin coal used for coke production is to blend different types of coals until a mixture is obtained that meets coke quality requirements. Results from this research effort indicate that it will be possible to use blended coal in a non-recovery or conventional coke oven to produce pyrolysis gas that can be selectively extracted and used for various purposes including the production of electricity, liquid transportation fuels, fertilizer, and hydrogen. It is initially estimated that 20% or higher Illinois coal can be blended with conventional metallurgical coals for use in current design, large blast furnaces using processes developed in this work. Efforts to extend blending to also consider optimizing the composition of pyrolysis gas produced in the coking process are also underway. By optimizing both aspects simultaneously, it will be possible to obtain coke of acceptable quality for use in blast furnaces and other applications and at the same time obtain a supply of pyrolysis gas that can be used for production of liquid transportation fuels in a Fischer-Tropsch process, as well as fertilizer and bulk hydrogen.

Before the coke property called CSR (coke strength after reaction with CO_2) was implemented in the USA during the 1970s, Illinois coal was used extensively at a local steel company in blends as follows. For wet charged coke batteries, a blend of 60% Illinois coal and 40% Eastern medium volatile coal was used. For preheat coke batteries, a blend of 70% Illinois coal and 30% Eastern medium volatile coal was used. These blends produced coke with high cold strength properties (stability, hardness, impact resistance, and abrasion resistance). But, the hot strength property, CSR, was poor. For small blast furnaces, poor CSR values did not cause operating issues, but as furnace sizes increased dramatically in the late 1970s, issues started to arise with furnace component and wall integrity. To improve CSR, blends were modified to 30% Illinois coal, 30% Eastern high volatile coal, and 40% Eastern medium volatile coal for wet charged batteries and 43% Illinois coal, 25% western Canadian high/medium volatile coal, and 32% Eastern medium volatile coal for preheat charged batteries. Optionally, for preheat charged batteries a blend of 43% Illinois coal, 25% western Canadian high/medium volatile coal, and 32% western Canadian medium volatile coal was used. With increased emphasis on CSR as an operating parameter, the use of Illinois coal was discontinued for production of coke. This research preliminarily indicates that Illinois coal can be used as part of a blend for production of coke in the Multipurpose Coking Facility currently being developed with properties suitable for use in modern large blast furnaces.

EXPERIMENTAL PROCEDURES

An important aspect of the use of Illinois coal in a Multipurpose Coke Facility is the molecular composition of the gas produced during the coking process. Tests with Illinois coal were conducted to understand the molecular composition of pyrolysis gas produced during the coking process as a function of temperature. This composition is important since various processes that will use this gas, such as production of liquid transportation fuel by the Fischer-Tropsch process, have gas composition requirements like the ratio of carbon monoxide to hydrogen. By understanding the molecular composition of gas produced for various temperature ranges, it is possible to selectively extract gas streams with the desired molecular composition for that particular process.

The apparatus depicted in Figure 7 was used to extract pyrolysis gas from coal samples at various temperatures. This gas was then analyzed in a Varian Micro Gas Chromatograph to determine molecular composition.

Coal samples were placed in a test vessel. A vacuum was then pulled on the vessel and it was filled with dry nitrogen. This process was repeated three times. At the conclusion of the initial nitrogen fill, the pressure of the vessel was set to one atmosphere. The furnace was then set to ramp up the temperature to a maximum of 850ºC. This was the maximum temperature used because of integrity concerns with the 316 stainless steel test vessel. As the coal in the test vessel was heated, it released various gases as part of the slow pyrolysis process. The temperature of the coal in the vessel was recorded by a thermocouple placed in the coal sample. At temperatures of 500, 600, 700, and 800ºC, gas samples were extracted from the apparatus with a gas tight syringe from a septa connected to the exit gas piping. Prior to extracting the sample, a partial vacuum was pulled on the test chamber and the chamber quickly returned to a slight positive pressure. A check valve in the exit gas line maintained the pressure in the test vessel below 1 psig. Gas samples were then analyzed in a Varian Micro Gas Chromatograph. At the conclusion of the test, coke was removed from the vessel and stored for subsequent analysis.

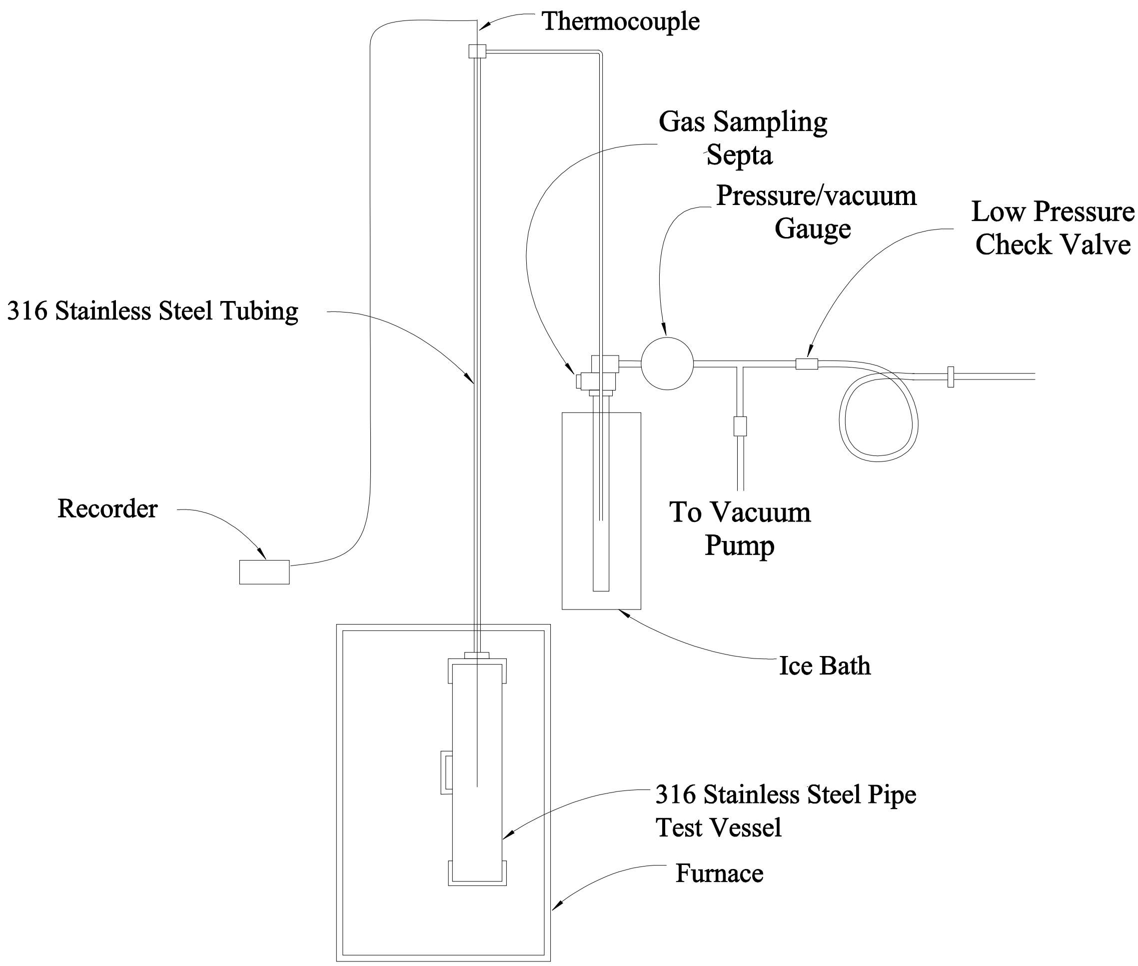

Figure 7: Pyrolysis Gas Apparatus

RESULTS AND DISCUSSION

Preliminary laboratory tests were conducted to determine the suitability of slow pyrolysis gas produced from Illinois coal for purposes of producing liquid transportation fuels, fertilizer, and hydrogen as part of the coke production process. As the temperature of coal is increased in the coke production process, pyrolysis gas of varying composition is released. In the proposed Multipurpose Coke Facility concept, it is anticipated that portions of this gas will be gathered from the coke process at specific temperature ranges with the proper composition for the production of liquid transportation fuels, electricity, fertilizer, and hydrogen.

A literature search conducted regarding properties and composition of Illinois coal found considerable non mine specific data, but limited mine specific information. Basic data regarding chemical composition was obtained for major Illinois coal mines by contacting ten Illinois coal mines and requesting coal samples for testing. Two samples were received from Knight Hawk Coal, LLC. Figure 8 shows average results of repeated pyrolysis gas trials for Illinois coal. Figure 9 shows average results of repeated pyrolysis gas trials for a blend of 40% Illinois coal and 60% medium volatile Eastern coal.

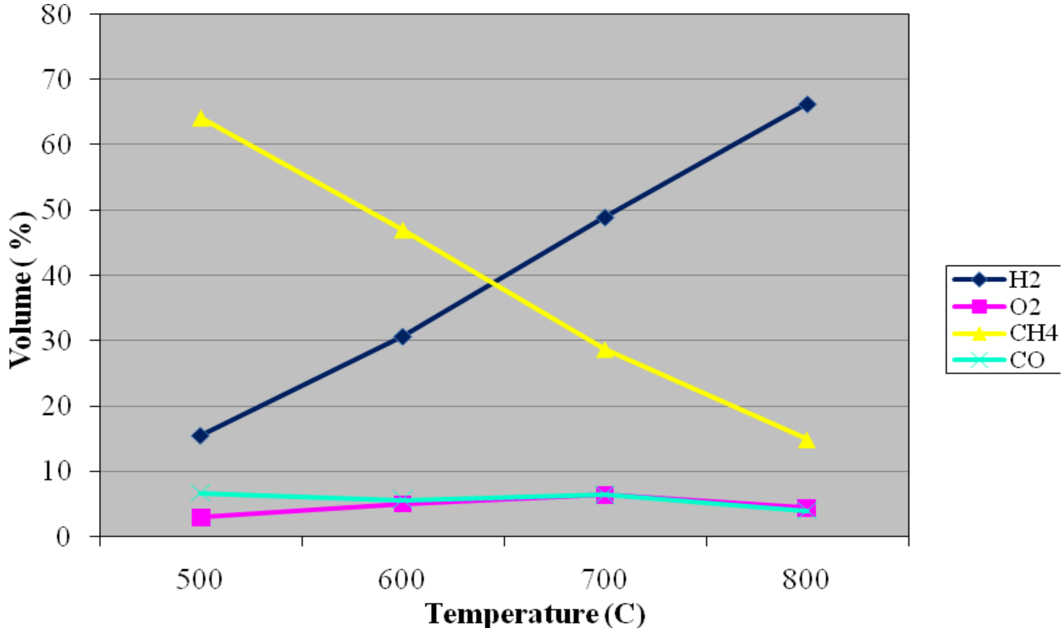

Figure 8: Gas Composition versus Temperature for Illinois Coal Samples

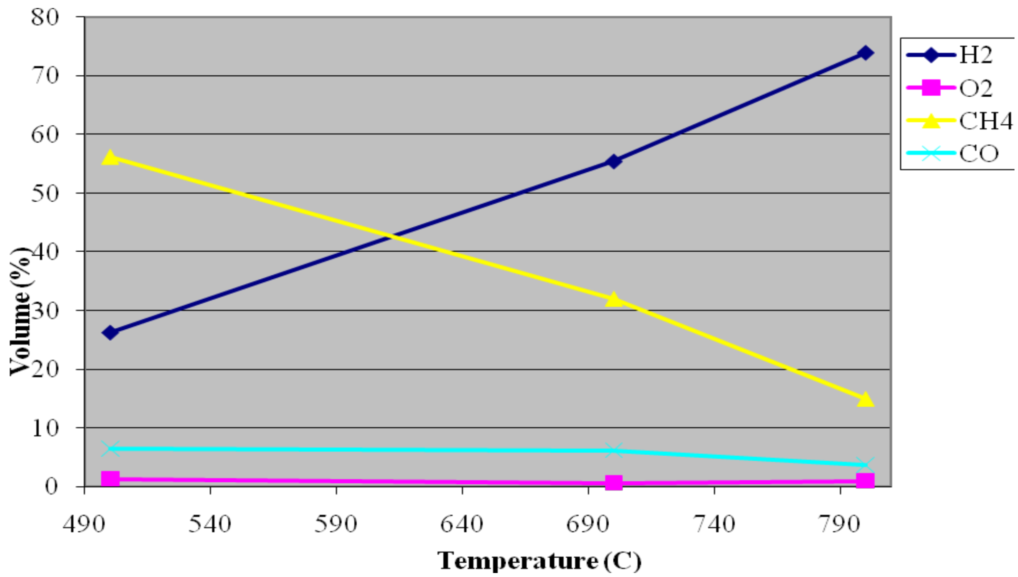

Figure 9: Gas Composition versus Temperature for Blended Coal

Figure 10 depicts results of repeated trials for randomized samples of medium volatile Eastern coal. The test was repeated on three separate days with randomized samples indicating that results are repeatable. Similar tests were performed periodically during the project to assure that systematic errors had not been introduced into the testing program and that equipment was functioning correctly. Periodically, calibration gas samples were processed as a further quality check on the apparatus and data.

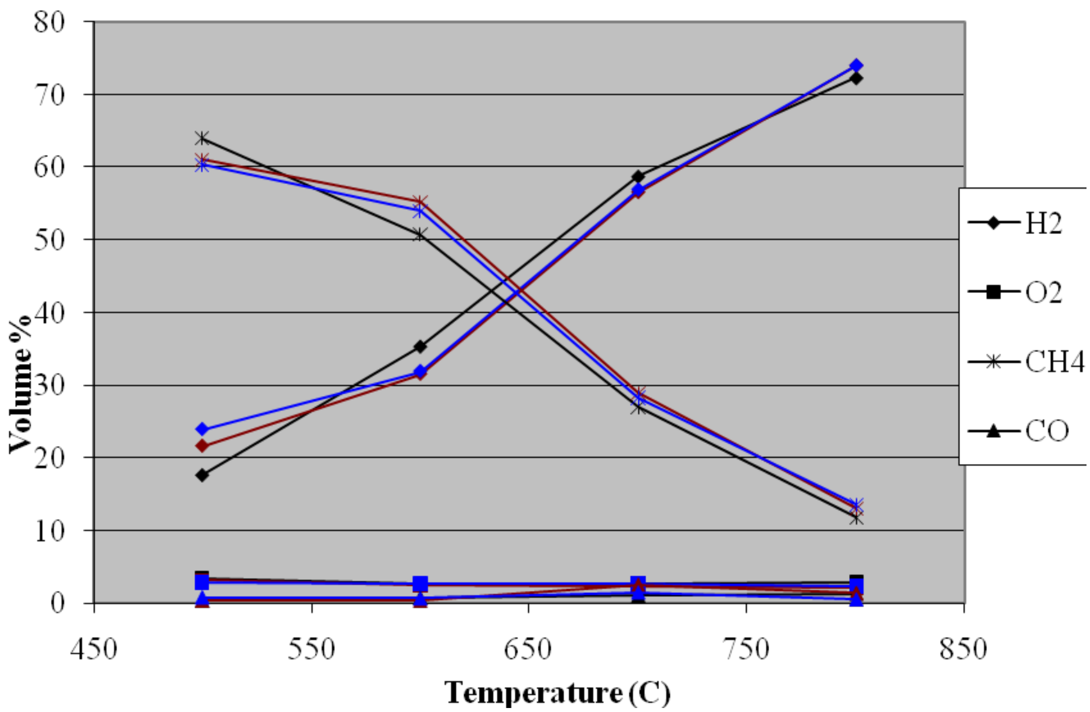

Figure 10: Gas Composition versus Temperature for Random Eastern Coal Samples

The blending mix used to produce the pyrolysis gas depicted in Figure 9 was estimated from previous coke tests using Illinois coal. Pyrolysis gas is produced principally from aliphatic compounds in the coal. Slow pyrolysis data is available for broad categories of coal types[8], but specific data for Illinois coal is not available in the published literature. For blending purposes it is necessary to know more detail regarding pyrolysis gas composition as a function of temperature. This effort has produced base line slow pyrolysis data that can be used to develop blending schemes that will both maximize CSR and molecular composition of the gas for ancillary purposes.

It is important to assure that any blend of coals used for coke production will have an acceptable CSR value. Previously, pilot oven tests were conducted to determining the influence of blending on CSR and other important coke characteristics, such as strength. An example of pilot oven tests conducted by industry is shown in Table 2.[9]

Table 2: Examples of Coke Quality

	100% Illinois Coal	30% Illinois, 30% Eastern HV, 40% Eastern MV
Moisture, %	8.8	2.9
Coke Stability	39	61
Coke Hardness	72	70
CSR*	22	61
Coke Size, mm	56.6	61.7
Coke Yield, %	65.6	73.6
Coking Time, hr	20.0	16.9
Max. Pressure, kPa**	6.54	5.65

Notes: *CSR = coke strength after reaction with CO2
**Max Pressure = maximum oven wall pressure
HV = high volatile
MV = medium volatile

Additional data from industry blending tests are shown in Table 3.[10] These tests further indicate the feasibility of using Illinois coal in blends for coke production. It can be observed that a blend of Illinois Basin and metallurgical coal can be used in a slot oven to produce acceptable coke quality. If such blends are carbonized in a Heat Recovery/Non-Recovery Coke Oven, it is anticipated that there will be similar or better performance in coke quality.

Modern large blast furnace operations generally require CSR values above 60. As can be observed in Table 2, the 100% Illinois coal sample does not have a sufficient CSR value. However, the blended sample exceeds the threshold CSR value.

One way to rank coals is by the amount of volatile matter they contain. At the simplest level, mid-range prime coking coals will produce the best coke and the farther a particular coal is away from prime coking coal, the less suitable it is. Coke from high volatile coals tends to be too weak and reactive to be used in the blast furnace. Also, carbonizing low volatile coals can produce unacceptably high pressures on oven walls for slot ovens.

Table 3: Coal Blending Test Data

	TC1931	TC1933	TC1935	TC1940	TC1941	TC1951	TC1952	TC1953	TC1954	TC1995
	30% Ill 30% EHV 40% EMV	30% Ind 30% EHV 40% EMV	80% Ind 20% PC	45% Ind 15% EHV 40% EM	45% Ind 15% EHV 40% WCM	30% Ind 30% EHV 40% WCM	30% Ill 30% EHV 40% WCM	20% Ind 10% PC 30% EHV 40% WCM	20% III 10% PC 30% EHV 40% WCM	50% Ind 50% LVM
Moisture (%)	**2.94**		**2.50**	**4.98**	**5.15**	**4.48**	**4.03**	**3.29**	**3.24**	**3.40**
Grind (%, -3.35mm)	**97.1**	**93.3**	**87.6**	**90.7**	**91.1**	**91.9**	**92.7**	**94.6**	**96.9**	**91.0**
Dry oven bulk density (kg/m^3)	**792**	**816**	**754**	**801**	**788**	**801**	**804**	**804**	**805**	**794**
Max oven wall pressure (kPa)	**5.65**	**6.27**	**2.55**	**4.62**		**3.45**	**4.07**	**4.07**	**3.58**	**7.23**
Coking time (h)	**16.87**	**16.37**	**16.05**	**17.13**	**17.03**	**17.05**	**17.00**	**16.60**	**16.10**	**17.02**
Stability	**61.0**	**60.0**	**42.0**	**58.0**	**63.0**	**57.0**	**61.1**	**60.5**	**60.7**	**62.0**
CSR	**61**	**68**	**24**	**57**	**65**	**65**	**70**	**72**	**71**	**66**
CRI	**30**	**22**	**44**	**32**	**24**		**21**	**20**		**28**
Hardness	**70.0**	**70.0**	**51.3**	**70.0**	**68.0**	**70.0**	**70.0**	**69.0**	**68.0**	**72.0**
Coke size (mm)	**61.73**	**65.53**	**70.90**	**70.74**	**69.30**	**62.80**	**59.00**	**61.30**	**64.20**	**62.60**
Coke yield (%)	**73.58**	**70.15**	**69.60**	**73.39**	**74.60**	**74.90**	**76.30**	**78.00**	**76.90**	**74.90**
SHO contraction %	**-7.99**	**-9.57**	**-11.94**	**-11.13**	**-10.14**	**-12.82**	**-7.93**	**-10.59**	**-12.93**	
Coke sulfur (%)						**0.66**		**0.93**		
Coke ash (%)						**11.1**		**8.9**		

Notes: Ill=Illinois; Ind=Indiana Brazil Formation; EHV=Eastern high volatile; EMV=Eastern medium volatile; WCM=western Canadian medium volatile; LVM=Alabama low volatile; PC=petroleum coke

When coal is viewed under a microscope, it can be seen to be composed of three main components, or macerals, analogous to minerals found in rocks.[11] The first of these, vitrinite, softens on heating. In association with the other components, liptinite and inertinite, it forms the coke matrix. These components reflect light at different intensities. In general, the reflectance of vitrinite is a measure of coal rank and is inversely proportional to volatile matter content. Usually, a coal blend for blast furnace coke should have a reflectance between 1.25% and 1.35%. The reflectance of coal blends tends to vary linearly, but having the average reflectance of a blend in this range is not sufficient to assure that the produced coke will have the desired qualities. For this reason the reflectance distribution is considered.

If reflectance values from a sample are plotted in a histogram, it is desirable to have a distribution that resembles a normal distribution with a standard deviation that is not too large. Unacceptable distributions have large standard deviations or have multiple peaks.[12] Attempts at using simple linear programming models to determine coal blends for coking have produced varying results due to the complexity of the coking process.[13] Modeling must also consider other characteristics such as dilatation and fluidity, which provide empirical measures of the extent of softening and fusion on heating in the blending process.

Due to the physical characteristics of Illinois Basin coal[14], coke produced from it will tend to be of a smaller size, but there are many opportunities to use this type of coke in blast furnaces and other operations. Concerns with the relative strength of coke produced from Illinois Basin coal can be reduced by carefully blending various types of coal. Through blending, many potential issues with coke characteristics can be reduced or eliminated. Classically, the process of coal blending for coke production has been considered an “art”. The research team for this project has had considerable experience in customizing coal blends used for coking processes in operating industrial coke production facilities. This experience was a valuable attribute in customizing the process to maximize the use of Illinois Basin coal. It is clear that Illinois coal can be used in blends with other coals for coke production purposes. The nature of the coal blend is a function of the coking process detail and will require additional research to determine optimal values.

Another approach to increasing the percentage of Illinois Basin coal for coke production involves locating that coke in upper regions of the blast furnace where higher reactivity is less of a concern. In this region there is also less mechanical pressure on the individual pieces of coke since there is less material above it. This would allow coke of reduced strength to be readily used in this region. Figure 11 depicts various zones and layering for a typical blast furnace.[15] Methods to use coke produced with an enhanced blend of Illinois Basin coal in the upper coke layers is currently under development.

A preliminary consideration of the influence of coke produced from blended coal on the blast furnace lining was conducted using CFD analysis. A blast furnace located in northwest Indiana was modeled and influences from changes in coke properties resulting from the use of blended coal were considered on an exploratory basis.

The geometry considered is depicted in Figure 12. The cohesive zone was modeled with 34 alternating layers of coke and ore. The ore layer’s porosity is assumed to be zero since the ore starts fusing and melting in the cohesive zone. The coke bed porosity in the cohesive zone is 0.5. The burden is treated as one zone with an effective porosity of 0.41. Various cases were run to find the effect of ore and coke porosity, and ore and coke particle diameters.

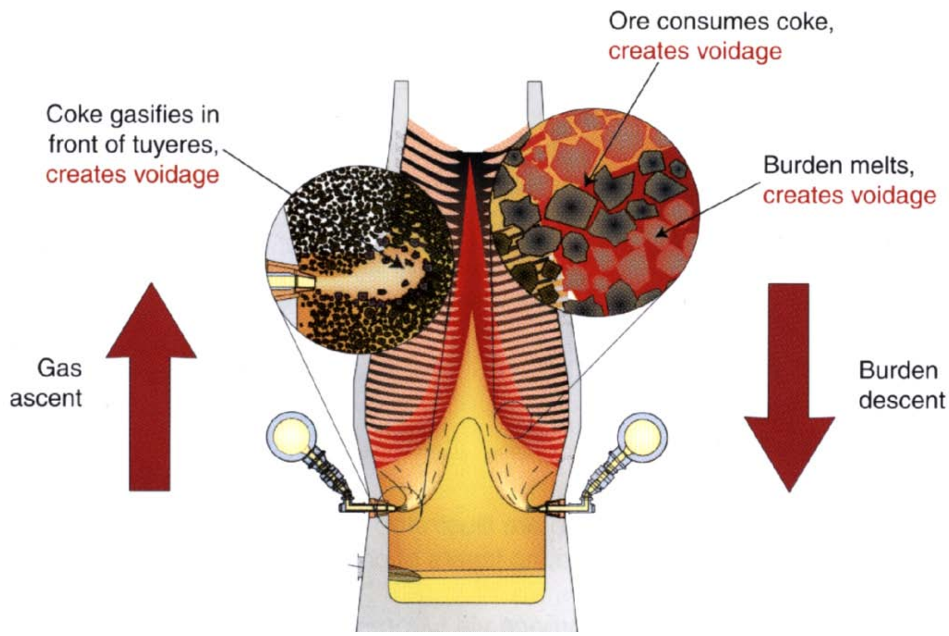

Figure 11: Blast Furnace Zones

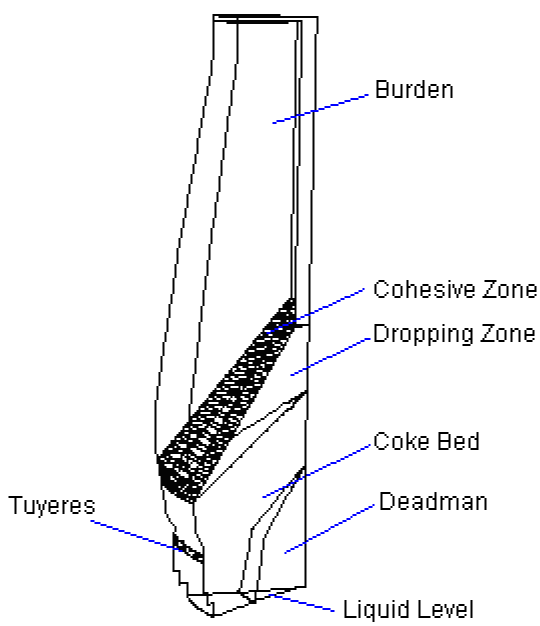

Figure 12: Model Geometry

The velocity profile was similar for all cases as shown in Figure 13. It can be observed that velocity decreases as we move away from the tuyere due to the effect of the porous zone in the coke bed. The gas flow is primarily upward. Velocity is uniform in other zones of the blast furnace.

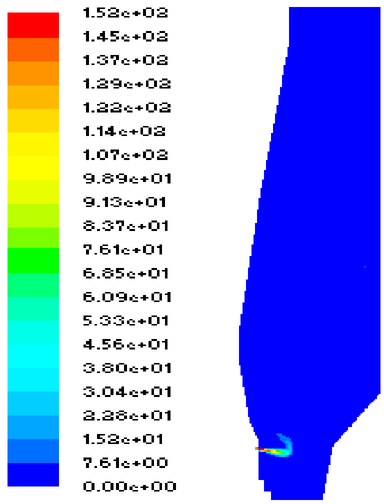

Figure 13: Velocity Profile

The pressure drop for different cases is depicted in Figure 14. It can be observed that as ore diameter, ore porosity, coke diameter and coke porosity increase, the pressure drop from the tuyere level to the top of the furnace decreases. The effect of the ore layer is more dominant as ore layer thickness is higher than coke layer thickness.

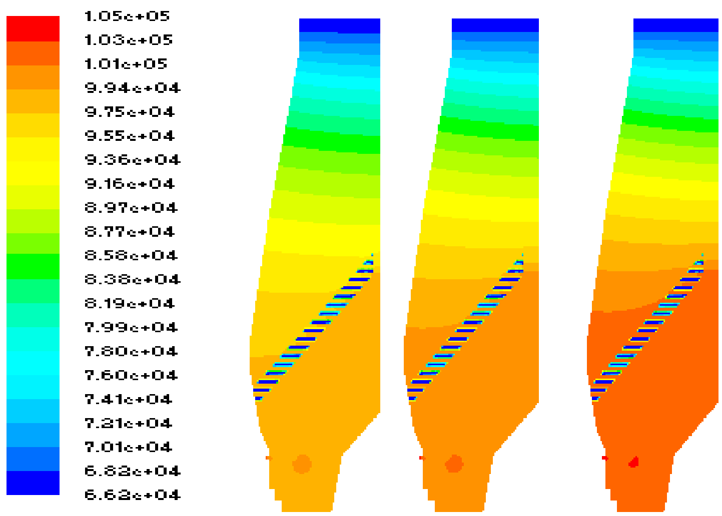

Figure 14: Pressure Loss for Ore Diameters of 0.02 m, 0.012 m, and 0.006 m

CONCLUSIONS AND RECOMMENDATIONS

This effort developed a new approach to coke production in which there are multiple value streams for the process. The research indicates that it is possible to use Illinois coal blended with other coals in a non-recovery coke oven. This process can also produce pyrolysis gas that can be selectively extracted and used for various purposes including the production of electricity, liquid transportation fuels, fertilizer, and hydrogen that provide further benefit and reduce risk. Use of Illinois coal in this process provides another source of coke for steel and other industries thereby assisting in stabilization of the coke market. A new market opportunity for Illinois coal is also created. By using the blending techniques investigated in this research effort, it is possible for the coke industry to reduce coke production costs since Illinois Basin coal is generally less expensive than typical metallurgical coal and transportation charges tend to be less due to closer proximity, except in cases were rail congestion or market conditions interfere.

Technological and financial risks of a Multipurpose Coke Facility will be reduced by leveraging existing process technology. Coke producers have developed efficient and reliable processes. Current coke production facilities are cost justified based on the production of coke. The inclusion of additional value streams such as production of liquid transportation fuels can add to the value of existing operations. Existing production facilities operate reliably on a continuous basis. Since a coke oven is essentially a coal gasifier, technical and financial risks for production of pyrolysis gas and associated processes for its use are greatly decreased. The multipurpose coke plant considered by this research can provide a new direction and approach for the production of coke in the future that optimizes value over multiple product streams while reducing business and technological risks, environmental emissions, and carbon foot print.

This study has produced preliminary recommendations for using Illinois coal in conjunction with a new approach to coke production – the Multipurpose Coke Facility. Prior to developing final blending schemes for actual coke production, it will be necessary to conduct further pyrolysis gas testing to better understand differences in Illinois coal characteristics and their temperature dependent pyrolysis properties. Further effort is needed for testing physical and chemical characteristics of coke produced by various blends and their suitability for use in modern large blast furnaces.

After characterization of multiple Illinois coal samples is completed, the next step would be the development of a multidimensional optimizing technique for simultaneously maximizing coke properties and pyrolysis gas properties for the various ancillary purposes considered. This will require testing larger samples. Currently, support is being pursued for development of a testing program at a facility that is capable of processing one ton of coal per test. Testing at this facility would involve online gas analysis as well as development of a Fischer-Tropsch column to test the suitability of gas streams extracted during the proposed process for liquid transportation fuel production. This level of testing would lead to the next stage involving testing of the developed technology at an operating industrial facility or coal mine.

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