ABSTRACT

A potentially new use for Illinois coal is its use as a fuel injected into a blast furnace to produce molten iron as the first step in steel production. Because of its increasing cost and decreasing availability, metallurgical coke is now being replaced by coal injected at the tuyere area of the furnace where the blast air enters. The purpose of this study was to evaluate the combustion of Illinois coal in the blast furnace injection process in a new and unique pilot plant test facility. This investigation is significant to the use of Illinois coal in that the limited research to date suggests that coals of low fluidity and moderate to high sulfur and chlorine contents are suitable feedstocks for blast furnace injection. This study was the first examination of the suitability of Illinois Basin coal for use in blast furnace injection. The study has integrated both laboratory techniques and pilot plant testing using samples of Illinois Basin coals, chars made from these coals, as well as coal, char and coke from active blast furnaces. Petrographic analysis of material taken from active blast furnaces shows that in actual practice not all of the coal is combusted in the tuyere where it is injected. This is a significant finding in that it indicates that the reactivity of the coal char in the blast furnace is a factor that must be considered. The reactivity experiments run under a range of pertinent conditions show that the Illinois Basin coals have a higher reactivity in both air and carbon dioxide than coke or the char from higher rank coals. This indicates that the Illinois Basin chars should survive in the raceway of the blast furnace for a shorter time than the chars of other coals now in use. This higher reactivity should be an important advantage at the high rates of injection that the industry is now trying to achieve. The computer modeling results also show that the Illinois Basin coal is comparable to other coals now in use in its cooling characteristics, permissible injection rates, replacement ratios, and coke rates. Finally, the results of the pilot plant testing show that the Illinois Basin coals performed just as well or slightly better than an Appalachian coal now being injected. In summary, all of the results of this study indicate that coals from the Illinois Basin are suitable for blast furnace injection and may even have some advantages at high rates of injection.
EXECUTIVE SUMMARY

A potentially new use for Illinois coal is its use as a fuel injected into a blast furnace to produce molten iron as the first step in steel production. Because of its increasing cost and decreasing availability, metallurgical coke is now being replaced by coal injected at the tuyere area of the furnace where the blast air enters. The purpose of this study was to evaluate the combustion of Illinois coal in the blast furnace injection process in a new and unique pilot plant test facility. This investigation is significant to the use of Illinois coal in that the limited research to date suggests that coals of low fluidity and moderate to high sulfur and chlorine contents are suitable feedstocks for blast furnace injection. This study was the first examination of the suitability of Illinois Basin coal for use in blast furnace injection. The study has integrated both laboratory techniques and pilot plant testing using samples of Illinois Basin coals, chars made from these coals, as well as coal, char and coke from active blast furnaces. Until now the limited experience in North America with coal injection systems has resulted in a lack of research and published literature on the subject. This has not been the case outside of North America, however. Coal injection research has been particularly strong in the United Kingdom and Japan. Blast furnace coal injection has been successful around the world and its use is expanding rapidly. Coal injection results in: 1) reduced demand for metallurgical coke; 2) increased blast furnace efficiency; 3) reduced operating costs. It has also been reported that in regard to the feed coal, low fluidity was desirable. While there are no major problems at the current rates of coal injection, the complete combustion of the injected coal is a problem for operation at greatly increased rates of injection. This serious lack of understanding about the behavior of injected coal must be overcome, if higher injection rates are to be achieved.

This phase of this study involves the testing of barrel quantities of two IBCSP samples - IBCSP 110 (Springfield No. 5 Seam) and IBCSP 112 (Herrin No. 6 Seam) in the CANMET Pilot Plant Test Facility and a final synthesis of all of the data collected. For comparison, an Appalachian coal that is currently being used for blast furnace injection was also tested at the CANMET facility.

Petrographic analysis of material taken from active blast furnaces shows that in actual practice not all of the coal is combusted in the tuyere where it is injected. This is a significant finding in that it indicates that the reactivity of the coal char in the blast furnace is a factor that must be considered. The reactivity experiments run under a range of pertinent conditions show that the Illinois Basin coals have a higher reactivity in both air and carbon dioxide than coke or the char from higher rank coals. This indicates that the Illinois Basin chars should survive in the raceway of the blast furnace for a shorter time than the chars of other coals now in use. This higher reactivity should be an important advantage at the high rates of injection that the industry is now trying to achieve. The computer modeling results also show that the Illinois Basin coal is comparable to other coals now in use in its cooling characteristics, permissible injection rates, replacement ratios, and coke rates. Finally, the results of the pilot plant testing show that the Illinois Basin coals performed just as well or slightly better than an Appalachian coal now being injected. In summary, all of the results of this study indicate that coals from the Illinois Basin are suitable for blast furnace injection and may even have
some advantages at high rates of injection. The results of this study summarized above support the following conclusions:

1. The results of computer modeling of lower rank bituminous coals, including coal from the Illinois Basin, show that they compare well in their injection properties to a variety of other bituminous coals, although the replacement ratio improves with increasing rank.

2. The results of the successful pilot plant testing of Illinois Basin coals shows that they behave as well or slightly better than Appalachian coals now being injected into blast furnaces.

3. The results of petrographic analysis of material collected from an active blast furnace, show that coal derived char is entering into the raceway of the blast furnace.

4. The results of reactivity experiments on a variety of coal chars at a variety of reaction temperatures show that coals from the Illinois Basin yield chars with significantly higher reactivities in both air and CO₂ than chars from higher rank Appalachian coals and blast furnace coke. These results indicate that the chars from the lower rank coals should have a superior burnout rate in the tuyere and should survive in the raceway environment for a shorter time. These coals, therefore, will have important advantages at high rates of injection that may overcome their slightly lower replacement rates.

5. In summary, all of the results of this study indicate that coals from the Illinois Basin are suitable for blast furnace injection and may even have some advantages at high rates of injection.
OBJECTIVES

Because of its increasing cost and decreasing availability, metallurgical coke is now being replaced by coal injected at the tuyere area of the furnace where the blast air enters. The purpose of this study was to evaluate the combustion of coal during the blast furnace injection process and to delineate the optimum properties of the feed coal with particular reference to the coals from the Illinois Basin. The main feature of this evaluation was the testing of Illinois coals in a new and unique pilot plant test facility. The specific objectives were:

1. To test the blast furnace injection performance of both the Herrin No. 6 and Springfield No. 5 in the CANMET pilot plant test facility.

2. To collect from the test facility samples of the injected coal, the combustion char, and slag at intermediate and final stages for chemical analysis, scanning electron microscopy and optical microscopic analysis, char microstructure analysis, and coal burnout analysis (ash technique).

3. To determine the TGA reactivity of chars generated under blowpipe-tuyere conditions at simulated raceway conditions (temperature 1500°C, gas composition: CO₂ 10%, O₂ 2%, N₂ 88%; and CO₂ 10%, O₂ 5%, N₂ 85%).

4. To evaluate the cooling and coke replacement characteristics of coal used for blast furnace injection through the use of a computer model of the blast furnace/coal injection process.

5. To synthesize and evaluate the data gathered from the pilot plant tests and to compare it with the results of the studies at both the Armco and Inland steel companies.

6. To use all of these results to demonstrate the suitability of Illinois coal for use in blast furnace injection using both analysis results and computer models.

INTRODUCTION AND BACKGROUND

A potentially new use for Illinois coal is its use as a fuel injected into a blast furnace to produce molten iron as the first step in steel production. Because of its increasing cost and decreasing availability metallurgical coke is now being replaced by coal injected at the tuyere area of the furnace where the blast air enters. The overall purpose of this study is to evaluate the combustion of Illinois coal during the blast furnace injection process and to determine the suitability of Illinois coal to become a feed coal in this process. This investigation is significant to the use of Illinois coal in that the research to date suggests that coals of low fluidity and moderate to high sulfur and chlorine contents are suitable feedstocks for blast furnace injection.
THE BLAST FURNACE PROCESS

A major step in steel making is changing iron ore into a form that can be used to make the various kinds of steel. This is primarily done in the blast furnace, which basically receives iron ore and reduces it to molten iron saturated with carbon (4.5-5.0%) which can then be processed to make steel.

The blast furnace (see Figure 1) is a steel shell, lined with brick, where iron ore, coke and limestone are charged into the top, and very hot air is blown into the bottom. A pool of molten iron and slag accumulates in the bottom where it is drawn off every few hours. Once started, the furnace operates continuously, usually for a campaign of ten years or more. The average North American furnace produces about 4000 tons of molten iron per day. Large furnaces are capable of producing 10,000 tons per day or more. The ore must be heated to a very high temperature and chemically purified. Coke, a carbon product made in large ovens from coal, serves to remove oxygen from the iron oxides and provides additional heat for the furnace process. Limestone helps remove the impurities and form a slag, which then separates from the molten iron.

![Diagram of a blast furnace]

Figure 1. Cross-section of a typical blast furnace. Note the location of the tuyeres around the base of the furnace (after Long 1968).
Another main ingredient is air, thirty-five to forty-five thousand cubic feet per ton of iron produced. The air is heated in large stoves and is then injected as a hot blast into the lower part of the furnace. The hot air fans the coke, the coke burns and reduces the ore from oxides of iron to metallic iron, which then will flow and settle to the bottom of the furnace.

The process in the furnace generates great quantities of hot, dirty gas. The gas exits at the top and is directed down to gas cleaning and cooling equipment. The gas is then suitable to be burned to heat the stoves or redirected for other uses in the steel plant.

There are usually three or four stoves to supply the hot blast to the furnace. The stoves are tall steel cylinders, lined with brick and nearly filled with a type of brick called checkerwork. The checker bricks store heat produced by burning the by-product gas from the furnace. The hot gas passes through the many small passageways in the bricks until they are thoroughly heated. Then combustion is stopped and a cold blast of clean air is blown through the stove, picking up the heat to make the hot blast for the furnace. The stoves are alternately cycled in this manner, one "on blast" while the others are "on gas" so there is always a continuous hot blast for the furnace.

**BLAST FURNACE INJECTION**

Hydrocarbons, oil, natural gas, and coal, have been injected into blast furnaces for over forty years to decrease coke demand and increase furnace productivity. While all injected fuels have an endothermic effect that reduces the temperature at the tuyere, coal has the smallest such effect of all injected fuels and is, therefore, the most suitable for use. For example, a flame temperature compensation of 100°F is typically required for the injection of 40 pounds of coal, 24 pounds of fuel oil, and 15 pounds of natural gas (Carmichael 1992). Coal is the only injected fuel that has the ability to reduce coke use rates by as much as 40% and on a $/pound basis coal has the lowest cost.

In all systems of coal injection, the coal is fed into the hot blast air in the tuyere where the coal, in the ideal case, is combusted before it enters into the raceway of the furnace (see Figure 2). Thus, ideally, only the products of combustion - CO2 and heat - leave the tuyeres. However, in practice the combustion is not always complete and both uncombusted coal and char as well as ash are produced.

The suitability of coal for blast furnace injection is influenced by its combustibility, flame temperature (cooling effect) and coke replacement properties. Carbon, hydrogen, oxygen, volatile matter and ash (amount, composition, fusion temperature) have been recognized as major factors. The most suitable coals have low cooling effect on the raceway, good combustibility and generate chars with high reactivity. Low cooling effect allows the injection of large quantities of coal without blast temperature compensation. Good combustibility and char reactivity result in efficient utilization of coal as a replacement for coke and for high productivity of the furnace.
Coals have different combustion properties and cooling effects, and the selection of a coal with the right characteristics is essential to efficient blast furnace operation. Volatile matter (VM) content is no longer considered sufficient to characterize coal for blast furnace injection. Other factors such as tar yield, char microstructure, maceral composition and catalytic effect of mineral matter must also be considered.

Figure 2. Cross-section of a tuyere with coal injection.

CANMET PILOT PLANT COAL COMBUSTION FACILITY

The Canadian Centre for Mineral and Energy Technology (CANMET) Energy Research Laboratories in Ottawa offer unique services to coal producers and researchers. The services include a confidential evaluation service to determine the suitability of particular coals for blast furnace injection and an evaluation report which can assist in the marketing of suitable coals to blast furnace operators.

CANMET's pilot plant coal combustion facility simulates blowpipe-tuyere conditions in an operating blast furnace, including blast temperature (900°C), flow pattern (hot velocity 200 m/s), geometry, gas composition, coal injection velocity (34 m/s) and residence time (20 ms). This facility is fully instrumented to measure air flow rate, air temperature, temperature in the reactor, wall temperature, preheater coil temperature and flue gas analysis.

Cooling and coke replacement characteristics of coal used for blast furnace injection depend on carbon, hydrogen and oxygen contents. They are influenced by a complex interplay of chemical and physical processes and they can be predicted through the use of a computer model of the blast furnace/coal injection process.
CANMET's computer model is based on principles of conservation of mass and energy for the steady state continuous blast furnace process. It includes mass balance equations which account for carbon, oxygen and iron as well as enthalpy balance equations which account for chemical reactions in the bottom zone of the furnace as well as combustion zone.

REVIEW OF LITERATURE

Until now the limited experience in North America with coal injection systems has resulted in a lack of research and published literature on the subject. This has not been the case outside of North America, however. Coal injection research has been particularly strong in the United Kingdom and Japan.

The most recent review article by Carmichael (1992) concludes that the success of coal injection systems coming on line in the next two years should act as a stimulus for the rest of the North American steel industry to introduce the systems in the next five years. The UK work, (Wilmers 1989, Atkinson and Willmers 1990, Gathergood and Lochrie 1990, and Gathergood 1991), done mostly at British Steel generally concluded that the positive effects of improved blast furnace operation and reduced coke demand offset the minor problems of incomplete coal combustion and the carryover of fine particles. Other European work (Koen et al. 1985, Graffeville et al. 1985, Poos and Ponghis 1990, and deLassat dePressigny et al. 1990) agree on the success of the coal injection but warn that the process of the coal combustion is the major limiting factor to the increase in the amount of coal injected. They recommend more research on the behavior of coal in these systems. A report on some Chinese experience (Shyng et al. 1990) again support the success of their coal injection system. They also report that the sulfur content of the hot metal decreased. The Japanese (Saino et al. 1990, Uenaka et al. 1990, and Takeda et al. 1990) experienced similar success. Takeda et al. also report that a low fluidity, high volatile bituminous coal seems to have advantages over other coals. Investigations into blast furnace injection of coal have also been reported by Hunty et al. (1991) in Canada and by Burgess et al. (1987) in Australia.

In summary, blast furnace coal injection has been successful around the world and its use is expanding rapidly. Coal injection results in:

1. Reduced demand for metallurgical coke;
2. Increased blast furnace efficiency;
3. Reduced operating costs;

It was also reported that in regard to the feed coal low fluidity was desirable. While there are no major problems at the current rates of coal injection, the complete combustion of the injected coal is a problem for operation at greatly increased rates of injection. This serious lack of understanding about the behavior of injected coal must be overcome, if higher injection rates are to be achieved.
EXPERIMENTAL PROCEDURES

RESEARCH APPROACH

This phase of the study involves the testing of barrel quantities of two IBCSP samples - IBCSP 110 (Springfield No. 5 Seam) and IBCSP 112 (Herrin No. 6 Seam) in the CANMET Pilot Plant Test Facility and a final synthesis of all of the data collected. For comparison, a Appalachian coal that is currently being used for blast furnace injection was also tested at the CANMET facility. To accomplish the objectives stated above, the work was broken down into two tasks:

Task I - Pilot Plant Testing

The samples were tested in CANMET's pilot plant coal combustion facility that simulates blowpipe-tuyere conditions in an operating blast furnace, including blast temperature (900°C), flow pattern (hot velocity 200 m/s), geometry, gas composition, coal injection velocity (34 m/s) and residence time (20 ms). This facility is fully instrumented to measure air flow rate, air temperature, temperature in the reactor, wall temperature, preheater coil temperature and flue gas analysis. Samples were taken at intermediate and final stages to evaluate coal burnout (ash technique) and TGA method was used to evaluate char reactivity under simulated raceway conditions.

Task II Computer Model Evaluation

Cooling and coke replacement characteristics of coal used for blast furnace injection depend on carbon, hydrogen and oxygen contents. They are influenced by a complex interplay of chemical and physical processes and they can be predicted through the use of a computer model of the blast furnace/coal injection process. CANMET's computer model is based on principles of conservation of mass and energy for the steady state continuous blast furnace process. It includes mass balance equations which account for carbon, oxygen and iron as well as enthalpy balance equations which account for chemical reactions in the bottom zone of the furnace as well as in the combustion zone.

The computer model determines:

* cooling characteristics of specific coals: raceway adiabatic flame temperature (RAFT) change related to 1 kg of injectant (°C/kg);
* permissible amount of injected coal (kg/100°C change of RAFT);
* permissible injection rate relative to natural gas and oil at constant RAFT;
* replacement ratios of specific coals (defined as the ratio of mass of coke saved to the mass of an injected coal needed to replace it); and
* blast furnace response to specific coals: coke rate, RAFT, top gas composition.
Task III - Final Evaluation of Illinois Coal

At the completion of tasks I, and II, the results of the testing on the two Illinois coals were evaluated and compared to the results from work done in the earlier phases of this study.

RESULTS AND DISCUSSION

COMPUTER MODEL EVALUATION

Comparison of Injectants

Hydrocarbons, oil, natural gas, and coal, have been injected into blast furnaces for over forty years to decrease coke demand and increase furnace productivity. While all injected fuels have an endothermic effect that reduce the temperature at the tuyere, coal has the smallest such effect of all injected fuels and is, therefore, the most suitable for use. For example, a flame temperature compensation of 100°F is typically required for the injection of 40 pounds of coal, 24 pounds of fuel oil, and 15 pounds of natural gas (Carmichael 1992). Coal is the only injected fuel that has the ability to reduce coke use rates by as much as 40% and on a $/pound basis coal has the lowest cost. Figure 3 shows the typical cooling characteristics of the various injectants on the basis of degree C change in the Raceway Adiabatic Flame Temperature (RAFT) per kilogram of injectant. In Figure 4 the same injectants are plotted against the amount of injectant required to reduce the RAFT by 100°C. In both figures the desirability of coal is clear. This same feature is also shown in Figures 5 and 6 where the permissible injection rates relative to oil and natural gas are shown. These two figures clearly show that larger amounts of coal can be injected than either oil or natural gas for a given RAFT change. The significance of this effect is indicated in Figure 7 which shows the replacement ratio, the ratio of the mass of coke replaced by the mass of the injectant, of the various injectants. It is clear that although natural gas and especially oil have higher replacement ratios than coal, more coal can be injected for a given RAFT change. It should be noted that the replacement ratio increases as the rank of the coal increases.

Desirable Properties of Injected Coal

The suitability of coal for blast furnace injection is influenced by its combustibility, flame temperature (cooling effect) and coke replacement properties. Carbon, hydrogen, oxygen, volatile matter and ash (amount, composition, fusion temperature) have been recognized as major factors. The most suitable coals have low cooling effect on the raceway, good combustibility and generate chars with high reactivity. Low cooling effect allows the injection of large quantities of coal without blast temperature compensation. Good combustibility and char reactivity result in efficient utilization of coal as a replacement for coke and for high productivity of the furnace.

Coals have different combustion properties and cooling effects, and the selection of a coal with the right characteristics is essential to efficient blast furnace operation. Coal rank alone is no longer considered sufficient to characterize coal for blast furnace injection. Other
Figure 3. Predicted cooling characteristics of various injectants on the basis of °C change in RAFT per kilogram of injectant based on computer modeling.

Figure 4. Predicted cooling characteristics of various injectants on the basis of amount of injectant required to reduce the RAFT by 100°C based on computer modeling.
Figure 5. Predicted permissible injection rate of various coals of different rank relative to oil based on computer modeling.

Figure 6. Predicted permissible injection rate of various coals of different rank relative to natural gas based on computer modeling.
Figure 7. Predicted replacement ratios of various injectants based on computer modeling. Note the increase with increasing coal rank.

Factors such as tar yield, char microstructure, maceral composition and catalytic effect of mineral matter must also be considered.

Six Illinois Basin coals from the Illinois Basin Coal Sample Program (IBCSP) were analyzed with the CANMET model and compared with other bituminous coals from the Appalachians, France, Poland, South Africa, and Colombia. Some of the results of that analysis are shown in Figures 8 - 13. Figure 8 shows the typical cooling characteristics of the various coals on the basis of degree C change in the RAFT per kilogram of injectant and Figure 9 shows the same coals plotted against the amount of injectant required to reduce the RAFT by 100°C. It should be noted that the Illinois basin coals plot in the same range as the other coals. The same is true when the permissible injection rates relative to oil and natural gas are plotted in Figures 10 and 11. The replacement ratio, the ratio of the mass of coke replaced by the mass of the injectant, of the various coals is shown in Figure 12. The Illinois coals again plot with the other coals studied. Figure 13 shows the predicted coke rate in kilograms of coke per ton of hot metal at various injection rates. In all of these cases the Illinois coals compare well with the other coals except for the Polish coal which is much higher in rank. Based on the results of the computer modeling, it is clear that the lower rank bituminous coals, including coals from the Illinois Basin, compare well in their injection properties with a variety of other bituminous coals, although the replacement ratio improves with increasing rank.
Figure 8. Predicted cooling characteristics of various coals (IL-Illinois Basin, SA-South Africa, CO-Columbia, PO-Poland, FR-France, AP-U.S. Appalachian) on the basis of °C change in RAFT per kilogram of injectant based on computer modeling.

Figure 9. Predicted cooling characteristics of various coals (IL-Illinois basin, SA-South Africa, CO-Columbia, PO-Poland, FR-France, AP-U.S. Appalachian) on the basis of amount of injectant required to reduce the RAFT by 100°C based on computer modeling.
PERMISSIBLE INJECTION RATE
VARIOUS COALS RELATIVE TO NATURAL GAS

Figure 10. Predicted permissible injection rate of various coals (IL-Illinois basin, SA-South Africa, CO-Columbia, PO-Poland, FR-France, AP-U.S. Appalachian) relative to oil based on computer modeling.

PERMISSIBLE INJECTION RATE
VARIOUS COALS RELATIVE TO OIL

Figure 11. Predicted permissible injection rate of various coals (IL-Illinois basin, SA-South Africa, CO-Columbia, PO-Poland, FR-France, AP-U.S. Appalachian) relative to natural gas based on computer modeling.
REPLACEMENT RATIO
VARIOUS COALS

Figure 12. Predicted replacement ratios of various coals (IL-Illinois basin, SA-South Africa, CO-Columbia, PO-Poland, FR-France, AP-U.S. Appalachian) based on computer modeling. Note the increase with increasing coal rank.

COKE RATE, kg/tHM
VARIOUS COALS

Figure 13. Predicted coke rate (kg of coke per ton of hot metal product) of various coals, including Illinois Basin coals, at different injection rates based on computer modeling. Note that the coke rates decrease with both increasing coal rank and injection rate.
Pilot Plant Testing

A significant part of this study was the testing of samples in CANMET's pilot plant coal combustion facility that simulates blowpipe-tuyere conditions in an operating blast furnace, including blast temperature (900°C), flow pattern (hot velocity 200 m/s), geometry, gas composition, coal injection velocity (34 m/s) and residence time (20 ms). This facility is fully instrumented to measure air flow rate, air temperature, temperature in the reactor, wall temperature, preheater coil temperature and flue gas analysis. Samples were taken at intermediate and final stages to evaluate coal burnout (ash technique) and TGA method was used to evaluate char reactivity under simulated raceway conditions. The samples tested were barrel quantities of two IBCSP samples - IBCSP 110 (Springfield No. 5 Seam) and IBCSP 112 (Herrin No. 6 Seam) and for comparison, an Appalachian coal that is currently being used for blast furnace injection.

All three samples were successfully tested and all three gave similar results. For example, the coal burnout percentage, the portion of the coal that actually combusted in the test, was about the same for the Herrin No. 6 and Appalachian coal and a little higher for the Springfield No. 5 coal as shown in Figure 14. The reactivity of the chars from the tests were also determined and show similar results. As shown in Table 1 the non-isothermal reactivities for all of the runs were about the same, while the burnout temperatures and burnout temperature range were slightly higher.

FINAL EVALUATION OF ILLINOIS COAL

In addition to the computer modeling and pilot plant testing completed this year substantial petrographic and thermal gravimetric analysis of coals, cokes, and chars related to blast furnace injection were completed in earlier work on this project. These results are summarized below.

Petrographic Analysis

In all systems of coal injection, the coal is fed into the hot blast air in the tuyere where the coal, in the ideal case, is combusted before it enters into the raceway of the furnace. Thus, ideally, only the products of combustion - CO₂ and heat - leave the tuyeres. However, in practice the combustion is never complete and both uncombusted coal and char as well as ash enter the raceway of the blast furnace.

As part of this study samples of raceway material from an active blast furnace into which coal was being injected were obtained and examined petrographically. Because the size of the injected coal was <200 mesh (<75 micrometers) only this size fraction of the samples was studied. In all samples there was evidence of uncombusted coal and coal char derived from the injected coal. Photomicrographs of this char are shown in Figures 15 - 18. Figure 15 shows some uncombusted coal and Figures 16 and 17 show char cenospheres derived from the vitrinite components in the injected coal. Figure 18 shows unfused coal char derived from
the inertinite (fusinite) components of the injected coal. The presence of char inside the furnace shows that not all of the coal is being totally combusted upon injection and that the reactivity of the char in the reducing environment of the blast furnace needs to be considered, because the purpose of coal injection is to produce heat and carbon monoxide.

### TABLE 1. Results of Non-Isothermal Reactivity Analysis

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<th>Injection Rate, kg/h</th>
<th>Burnout Range dC</th>
<th>Burnout Temp. dC</th>
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<tr>
<td><strong>Average</strong></td>
<td><strong>IBCSP 112</strong></td>
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<td><strong>898</strong></td>
<td></td>
<td><strong>0.34</strong></td>
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<td><strong>77</strong></td>
<td><strong>906</strong></td>
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<td><strong>0.36</strong></td>
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Figure 14. Amount of coal burnout in the blowpipe-tuyere pilot plant tests. The Herrin No. 6 and Eastern Kentucky coal had about the same burnout while the Springfield No. 5 had a more complete burnout.
Figure 15. Photomicrograph of partially reacted coal (two irregularly shaped particles at center) from the raceway of a blast furnace. Width of the field is approximately 300 micrometers.

Figure 16. Photomicrograph of a char cenosphere (center) from the raceway of a blast furnace. Width of the field is approximately 300 micrometers.
Figure 17. Photomicrograph of a char cenosphere (upper center) from the raceway of a blast furnace. Width of the field is approximately 300 micro-meters.

Figure 18. Photomicrograph of an unfused char particle derived from the inertinite (fusinite) components of the injected coal. Width of the field is approximately 300 micrometers.
Reactivity Analysis

Reactivity, the rate at which a material burns, is of considerable interest in the injection of coal into the blast furnace because the purpose of injecting coal is to provide heat and carbon monoxide and not char to the blast furnace. Therefore, there is a general belief that injected coals that have lower char reactivities are more desirable than those with higher char reactivities, if all other conditions are similar. Three experimental conditions needed to simulate blast furnace injection conditions were considered. The first is the heating rate. Heating rates of $10^4 \, ^\circ\text{C} \, \text{s}^{-1}$ or higher are desired and, fortunately, these can be realized in an entrained flow reactor (EFR) or a wire mesh reactor. All of the chars generated for this study to date have satisfied this condition. The second condition is the pyrolysis (charring) temperature. While temperatures of up to 1000°C can be obtained without difficulty in a good thermogravimetric analyzer (TGA) and this temperature is approximately the same as the blast air going into the furnace through the tuyere, the flame temperature in the tuyere and the raceway of the furnace is higher. Thus, higher temperatures of up to 2000°C are appropriate to simulate coal injection conditions. Chars formed (pyrolyzed) at 1000°C, 1400°C and 1800°C were used in these experiments. The third condition is the temperature of the combustion/gasification reaction of the char with the air or gas mixture inside the furnace. Most of the experiments for this project have been run in TGA units isothermally in the range of 1000°C to 1400°C. However, one set of experiments was run under non-isothermal conditions.

The three coals analyzed were SIU 2360, IBCSP sample - 112 (Herrin No. 6 seam) from the Illinois Basin Coal Sample Program, and two coals that are actually being used for injection, SIU 2380 an Indiana coal and SIU 2359, an Appalachian coal. In addition, a sample of coke being used in blast furnace operations was also analyzed for comparison.

The results of the reactivity experiments on chars from both Illinois and Appalachian coals produced at 1000°C in a nitrogen atmosphere in an entrained flow reactor (EFR) and then reacted in a thermogravimetric analyzer (TGA) in air and carbon dioxide at temperatures ranging from 1000 to 1400°C show that in air the chars and blast furnace coke are similar and show only a mild trend (a slight increase in reactivity with increasing temperature). However, in carbon dioxide all three samples show a marked temperature dependence of similar trend.

The results of experiments with chars from Illinois, Indiana, and Appalachian coals produced at 1400°C in a nitrogen atmosphere in an entrained flow reactor (EFR) and then reacted in a thermogravimetric analyzer (TGA) in air and carbon dioxide at 1400°C. As seen in the lower temperature work, the coke has the lowest reactivity of the sample set and the mid-western coals have the highest reactivities. In the CO$_2$ atmosphere all three coals have about the same reactivity. However, care must be taken when comparing the results in the two atmospheres. While the actual values of the data suggest that the reactivities in CO$_2$ are higher than in air, this is actually not the case. The concentration of the reacting gas (oxygen) in air is only 20%, while the concentration in the reacting gas in the CO$_2$ is 100%.
In an additional experiment, a set of chars of these same samples were produced in nitrogen at the extreme temperature of 1800°C in an experimental wire mesh reactor at Imperial College in London. Although this experiment is still continuing, some initial results on the combustion properties of these very high temperature chars is available. The weight loss profiles, plots of the normalized rate of weight loss in a TGA against temperature in an atmosphere of 7% O₂ in N₂ show that the two mid-western coals achieve maximum reactivity well before the char from the Appalachian coal, which achieves its peak well before the coke. From these experiments it is clear that the reactivity of the mid-western coals is about twice that of the Appalachian coal and the reactivity of the Appalachian coal is again about twice that of the coke.

Summary

This study is the first examination of the suitability of Illinois Basin coal for use in blast furnace injection. The study has integrated both laboratory techniques and pilot plant testing using samples of Illinois Basin coals, chars made from these coals, coal, char and coke, from active blast furnaces. Petrographic analysis of material taken from active blast furnaces shows that in actual practice not all of the coal is combusted in the tuyere where it is injected. This is a significant finding in that it indicates that the reactivity of the coal char in the blast furnace is a factor that must be considered. The reactivity experiments run under a range of pertinent conditions show that chars from the Illinois Basin coals have a higher reactivity in both air and carbon dioxide than coke or the char from higher rank coals. This indicates that the Illinois Basin chars should survive in the raceway of the blast furnace for a shorter time than the chars of other coals now in use. This higher reactivity should be an important advantage at the high rates of injection that the industry is now trying to achieve. The computer modeling results also show that the Illinois Basin coal is comparable to other coals now in use in its cooling characteristics, permissible injection rates, replacement ratios, and coke rates. Finally, the results of the pilot plant testing show that the Illinois Basin coals performed just as well or slightly better than an Appalachian coal now being injected. In summary, all of the results of this study indicate that coals from the Illinois Basin are suitable for blast furnace injection and may even have some advantages at high rates of injection.

CONCLUSIONS

The results of this study summarized above support the following conclusions:

1. The results of computer modeling of lower rank bituminous coals, including coal from the Illinois Basin, show that they compare well in their injection properties with a variety of other bituminous coals, although the replacement ratio improves with increasing rank.

2. The results of the successful pilot plant testing of Illinois Basin coals show that they behave as well or slightly better than Appalachian coals now being injected into blast furnaces.
3. The results of petrographic analysis of material collected from an active blast furnace, show that coal derived char is entering into the raceway of the blast furnace.

4. The results of reactivity experiments on a variety of coal chars at a variety of reaction temperatures show that coals from the Illinois Basin yield chars with significantly higher reactivities in both air and CO₂ than chars from higher rank Appalachian coals and blast furnace coke. These results indicate that the chars from the lower rank coals should have a superior burnout rate in the tuyere and should survive in the raceway environment for a shorter time. These coals, therefore, will have important advantages at high rates of injection that may overcome their slightly lower replacement rates.

5. In summary, all of the results of this study indicate that coals from the Illinois Basin are suitable for blast furnace injection and may even have some advantages at high rates of injection.

ACKNOWLEDGEMENTS

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DISCLAIMER STATEMENT

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**REFERENCES**


PROJECT MANAGEMENT REPORT
June 1 through August 31, 1995

Project Title: PILOT PLANT TESTING OF ILLINOIS COAL FOR BLAST FURNACE INJECTION

DOE Cooperative Agreement Number: DE-FC22-92PC92521 (Year 3)
ICCI Project Number: 94-1/5.1A-2P
Principal Investigator: John C. Crelling, Department of Geology, Southern Illinois University at Carbondale
Project Manager: Frank I. Honea, Illinois Clean Coal Institute

COMMENTS

None.
### PROJECTED AND ESTIMATED EXPENDITURES BY QUARTER

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<th>Quarter*</th>
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*Cumulative by Quarter
COSTS BY QUARTER

Pilot Plant Testing of Illinois Coal for Blast Furnace Injection

![Graph showing cumulative costs by quarter with projected and actual expenditures marked.]

- ● = Projected Expenditures
- ▲ = Actual Expenditures

Total Illinois Clean Coal Institute Award $99,803
SCHEDULE OF PROJECT MILESTONES

Hypothetical Milestones:

A: Sample Collection
B: Sample Testing
C: Sample Analysis
D: Data Interpretation
E: Reporting

Begin
Sept. 1
1994