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 overall purpose of this study was 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 work advanced earlier pilot plant testing with the Canadian Centre for Mineral and Energy Technology (CANMET) Energy Research Laboratories in Ottawa, Canada by running injection tests on the Herrin No. 6 coal under conditions that match the experimental conditions that are now being studied in the ironmaking industry. These conditions include oxygen enrichment of the blast air (up to 28% O₂), increased coal particle size (granular coal 1-3mm), and coal blends (in this case Herrin No. 6 coal and a higher BTU Appalachian coal). The results of the current research support the following conclusions: 1) The char burnout did not show the expected increase with increasing oxygen enrichment and suggests that oxygen enrichment may not be needed with Illinois coal; 2) although it is expected that the shock heating that granular coal experiences when it is injected will cause it to shatter into finer particles, this apparently did not happen in the current tests. The resulting extremely low burnouts for the granular coal indicate that the Herrin No. 6 is probably not suitable for granular coal injection. Previous test, however, have shown that the Herrin No. 6 is a very suitable for pulverized coal injection; 3) the calculated burnout of the 50/50 mix with Appalachian coal is as good as or even slightly better than the Herrin No. 6 sample alone. These results indicate that the Herrin No. 6 is quite acceptable as a blend component with higher rank coals for use in blast furnace injection. Also the reactivities of the Herrin No. 6 and the Herrin No. 6/Pittsburgh blend are similar. These results and the results of previous studies show that coal from the Illinois Basin have excellent combustion properties for use in blast furnace injection. The Illinois Basin coals burnout more completely and give a higher reactivity char than higher rank coals. These properties make them more desirable as a fuel for high injection rates. Results further indicate that the Herrin No. 6 coal can be blended at least up to equal proportions with higher rank coals with no significant change in the most desirable high burnouts and high char reactivities of the Illinois coal.
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 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. This proposal is a follow-up to one funded for the 1994-95 period. It is intended to advance earlier pilot plant testing with the Canadian Centre for Mineral and Energy Technology (CANMET) Energy Research Laboratories in Ottawa, Canada by running injection tests on the Herrin No. 6 coal under conditions that match the experimental conditions that are now being studied in the ironmaking industry. These conditions include oxygen enrichment of the blast air (up to 25% O₂), increased coal particle size (granular coal 1-3mm), and coal blends (in this case Herrin No. 6 coal and a higher BTU Appalachian coal). The reason for doing this work now is that as the industry attempts to go to higher and higher coal injection rates to cut the cost of using expensive coke, the coal char entering the blast furnace is accumulating to the point of interfering with the proper operation of the blast furnace. While the blast furnace operators have steps available to them to alleviate this problem, an additional step is to use coals such as those from the Illinois Basin, which produce a char that burns much faster in the blast furnace than the coals that are presently being used. An additional saving that some steel companies are studying is to eliminate the cost of pulverizing(-200 mesh, 0.075mm) the injected coal by injecting granular coal (1-3mm). Illinois Basin coals have not yet been used in this way and, therefore, a test at the CANMET facility is planned to show the suitability of the coal for this process.

As recently as 1992, the Amanda blast furnace of Armco Steel in Middletown, Ohio was the only one in north America injecting coal. Today there are eleven blast furnaces either injecting coal or about to come on line. There is also a great effort in the ironmaking industry to replace an ever increasing amount of metallurgical coke. This single-minded effort has led to new practices such as enriching the oxygen content of the blast air to enhance the coal combustion and using higher BTU coals and coal blends for a greater energy throughput. The disadvantages of these practices are the cost of the added oxygen and the much lower reactivity of the higher rank coals and their associated chars. An additional development is the introduction of the British granular coal injection system by the Bethlehem Steel Co. In this system granular coal (1-3mm) is used in contrast to the much finer pulverized coal (0.075mm) used elsewhere. In this case the savings in pulverization costs are gained, but at the expense of some combustion efficiency.

Because these developments are of current concern to the industry and, therefore, may have a bearing on the selection of coals for injection in the immediate future, an evaluation of behavior of Illinois coal under these conditions is proposed as the final phase of this project.
The results of previous research on the blast furnace injection properties of Illinois basin coal indicate that when it is injected under the same conditions as the Appalachian coal the Illinois Basin coals will give the more desirable results of putting less char into the raceway and that this char will burnout more quickly.

The results of the current research support the following conclusions:

1. The char burnout did not show the expected increase with increasing oxygen enrichment. Indeed, the purpose of enriching the oxygen content of the blast air is to achieve more complete combustion. While some limited experience with very low rank coals shows no enhanced combustion, results from tests using bituminous coal of slightly higher rank than the Herrin No. 6 coal have shown better combustion with the increased oxygen enrichment. Although these results could be interpreted as indicating that the Herrin No. 6 coal may not need oxygen enriched blast air, the results are still surprising and further oxygen enrichment tests are planned.

2. While it is expected that the shock heating that the coal experiences when it is injected will cause it to shatter into finer particles, this apparently did not happen in the current tests. When the particle size of the pulverized and granular chars are compared the major fraction of the char particles was in -60 to -200 mesh size for the granular char. For the pulverized coal the minor fraction of the char particles was in this range. The extremely low burnouts for the granular coal indicate that the Herrin No. 6 is probably not suitable for granular coal injection. Previous tests, however, have shown that the Herrin No. 6 is a very suitable for pulverized coal injection.

3. The calculated burnout of the 50/50 mix is as good as or even slightly better than the Herrin No. 6 sample alone. These results indicate that the Herrin No. 6 is quite acceptable as a blend component with higher rank coals for use in blast furnace injection. Also the reactivities of the Herrin No. 6 and the Herrin No. 6/Pittsburgh blend seem to be comparable. This latter result indicates that Herrin No. 6 coal can be blended at least up to equal proportions with higher rank Appalachian coals with no significant change in the more desirable high burnouts and high reactivities of the Illinois coal.

These results and the results of previous studies show that coal from the Illinois Basin have excellent combustion properties for use in blast furnace injection. The Illinois Basin coals burnout more completely and give a higher reactivity char than higher rank coals. These properties make them more desirable as a fuel for high injection rates. In addition, results indicate that the Herrin No. 6 coal can be blended at least up to equal proportions with higher rank Appalachian coals with no significant change in the more desirable high burnouts and high reactivities of the Illinois coal.
OBJECTIVES

This work was a follow-up to one funded for the 1994-95 period. It was intended to advance earlier pilot plant testing with the CANMET Energy Research Laboratories in Ottawa, Canada by running injection tests on the Herrin No. 6 coal under conditions that match the experimental conditions that are now being studied in the ironmaking industry. These conditions include oxygen enrichment of the blast air (up to 25% O₂), increased coal particle size (granular coal 1-3mm), and coal blends (in this case Herrin No. 6 coal and a higher BTU Appalachian coal). These tests have been run in the new and unique CANMET pilot plant test facility.

The specific objectives of this project were:

1. To test the blast furnace injection performance of the Herrin No. 6 in the CANMET pilot plant test facility with oxygen enrichment to about 25%.

2. To test the blast furnace injection performance of the Herrin No. 6 in the CANMET pilot plant test facility under conditions of granular coal injection (particle size 1-3mm).

3. To test the blast furnace injection performance of the Herrin No. 6 in the CANMET pilot plant test facility in an appropriate blend with an higher BTU Appalachian coal.

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

5. To determine the TGA reactivity of chars generated under blowpipe-tuyere conditions at simulated raceway conditions.

6. 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.

7. 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 new use for Illinois coal is 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 was 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. This work was intended to advance earlier pilot plant testing with the Canadian Centre for Mineral and Energy Technology (CANMET) Energy Research Laboratories in Ottawa, Canada by running injection tests on the Herrin No. 6 coal under conditions that match the experimental conditions that are now being studied in the ironmaking industry. These conditions include oxygen enrichment of the blast air (up to 25% O₂), increased coal particle size (granular coal 1-3mm), and coal blends (in this case Herrin No. 6 coal and a higher BTU Appalachian coal). The reason for doing this work was that as the industry attempts to go to higher and higher coal injection rates to cut the cost of using expensive coke, the coal char entering the blast furnace is accumulating to the point of interfering with the proper operation of the blast furnace. While the blast furnace operators have steps available to them to alleviate this problem, an additional step is to use coals such as those from the Illinois Basin which produce a char that burns much faster in the blast furnace than the coals that are presently being used. An additional saving that some steel companies are studying is to eliminate the cost of pulverizing (-200 mesh, 0.075mm) the injected coal by injecting granular coal (1-3mm). Illinois Basin coals have not yet been used in this way and, therefore, a test at the CANMET facility is planned to show the suitability of the coal for this process.

THE BLAST FURNACE PROCESS

A major step in steelmaking 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 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 (see figure 1). 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.

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.

The base of the furnace is enclosed by the cast house, where the molten iron is "cast", by drilling an opening in the tap-hole, an opening in the furnace hearth filled with clay. The clay is replaced after the completion of the cast until enough iron accumulates to be cast again. The iron flows out into runners and is directed to railroad cars that are large, brick-lined tank cars (pugh ladles). The slag is skimmed from the molten iron in the runner and directed into slag pits or slag ladles located next to each 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 and enter the raceway.
Figure 2. Cross-section of a blast furnace tuyere with coal injection.  
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.

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.

A 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 most recent review article by Poveromo (1996) details the latest operational considerations for using coal as an injectant. 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, Grasseville 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, Matsuo et al. 1997) 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, 1993, 1995) in Canada and by Burgess et al, (1987) in Australia. Results of studies showing that Illinois basin coals are
suitable for injection have been published by Crelling (1995, 1996)

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 (Poveromo, 1996). This serious lack of understanding about the behavior of injected coal must be overcome, if higher injection rates are to be achieved.

CANMET PILOT PLANT COAL COMBUSTION FACILITY

The 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.

RECENT DEVELOPMENTS IN BLAST FURNACE INJECTION PRACTICE
As recently as 1992, the Amanda blast furnace of Armco Steel in Middletown, Ohio was the only one in north America injecting coal. Today there are eleven blast furnaces either injecting coal or about to come on line. There is also a great effort in the ironmaking industry to replace an ever increasing amount of metallurgical coke. This single-minded effort has led to new practices such as enriching the oxygen content of the blast air to enhance the coal combustion and using higher BTU coals and coal blends for a greater energy throughput. The disadvantages of these practices are the cost of the added oxygen and the much lower reactivity of the higher rank coals and their associated chars. An additional development is the introduction of the British granular coal injection system by the Bethlehem Steel Co. In this system granular coal (1-3mm) is used in contrast to the much finer pulverized coal (0.075mm) used elsewhere. In this case the savings in pulverization costs are gained, but at the expense of some combustion efficiency.

Because these developments are of current concern to the industry and, therefore, may have a bearing on the selection of coals for injection in the immediate future, an evaluation of behavior of Illinois coal under these conditions was the final phase of this project.

**RELEVANCE AND SIGNIFICANCE**

There are several relevant and significant aspects to this study:

1. This study is unique in that it is the first North American scientific effort to directly determine the nature of the combustion of coal injected into a blast furnace.

2. The CANMET pilot plant test facility which just started operations in 1993 is unique in North America, indeed, the Northern Hemisphere. Because it is so well instrumented, it is superior in many aspects to actual blast furnace systems which are designed for production and, therefore, lack much in state of the art instrumentation.

3. The work is on the cutting edge of the field. There is at this time a great effort in the ironmaking industry to replace an ever increasing amount of metallurgical coke. This single-minded effort has led to new practices such as enriching the oxygen content of the blast air to enhance the coal combustion and using higher BTU coals and coal blends for a greater energy throughput. Illinois Basin coals have never yet been tested under these conditions.

4. The principal investigator has a 24 year-long record of experience in the use of coal and coke in the steel industry. He was in charge of the Coal and Coke Petrology Laboratory at the Homer Research Laboratories of the Bethlehem Steel Corporation for five years and since then has taught, conducted research, and published in this area. He has recently conducted successful research projects on blast furnace injection and has also established a good working relationship with the scientific staff at the CANMET facility.

5. This project clearly fills the general ICCI mandate of finding new markets/uses for Illinois coal.
6. The significance for the Illinois coal industry is that all of the published work to date and all of the industrial experience to date suggests that Illinois coal is an ideal feedstock for blast furnace injection and that some of the commercial drawbacks of Illinois coal such as its rank and high sulfur and chlorine content may not be a disadvantage for use in blast furnace injection. Specifically:

**Rank** - the low rank of Illinois bituminous coal has limited its use as a coking coal in the steel industry. The published literature suggests that the low rank and consequent low fluidity are desirable for coal injection.

**High Sulfur Content** - while this is the biggest problem in marketing Illinois coal, the high sulfur content is not perceived as a major problem for blast furnace injection. Experience in the industry using high sulfur fuel injectants (oil and coal) suggests that the sulfur in the injected coal has an increased tendency to enter the slag instead of the iron compared with sulfur in coke charged into the top of the furnace. The Japanese report mentioned above also supports this idea.

**High Chlorine Content** - while the high chlorine content of Illinois coals is recognized as a growing problem, it should not be a drawback and may even be an advantage in coal injection. This is because chlorine is commonly added to the blast furnace in the form of CaCl₂ to control alkali content.

7. This research was successful and it has shown that, as expected, Illinois coal is suitable for coal injection, the size of the potential market becomes important. At this time most of the steel companies injecting coal (Inland Steel, Bethlehem Steel, and U.S. Steel) are located near Chicago along Lake Michigan in immediate proximity to the Illinois Basin coalfields. At this time about 2-3 million tons of coal are being injected into these blast furnaces and higher usage rates are anticipated in the future.

**RESULTS OF PREVIOUS RESEARCH AT SIUC**

Previous work done by Professor Crelling has examined the petrography and combustion reactivity of the chars derived from injected coal as well as testing three coals in the CANMET pilot plant facility. The results show the coal from the Illinois Basin has cooling and replacement characteristics equal to or better than those of the higher rank coals now being injected. Results from the previous pilot plant tests show that the Illinois Basin coals also have superior burnout and char reactivity properties. Specific results are given below:

1. **Petrography**
   The results of petrographic analysis of material collected from an active blast furnace at Armco Steel, clearly show that coal derived char is entering into the raceway of the blast furnace.

2. **Computer Modeling**
All of the Illinois Basin Coal Sample Program (IBCSP) samples were analyzed in CANMET's computer model, which is based on principles of conservation of mass and energy for the steady state continuous blast furnace process. The CANMET model compared the IBCSP samples with other bituminous coals from the Appalachians, France, South Africa, and Colombia. The results of that analysis show that cooling characteristics of the Illinois coals, on the basis of degree C change in the Raceway Adiabatic Flame Temperature (RAFT) per kilogram of injectant, the amount of injectant required to reduce the RAFT by 100°C, the replacement ratio, and the predicted coke rate in kilograms of coke per ton of hot metal, compare well with the other bituminous coals.

3. Reactivity
   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.

4. Pilot Plant Testing
   In this investigation, three coals, including two Illinois Basin coals (IBCSP-110 and IBCSP-112) and an Appalachian coal, were experimentally tested in terms of their combustibility in the CANMET Energy Research Laboratory’s coal injection facility. Work has focused on measuring the burnout of the three coals under simulated blowpipe-tuyere conditions and determining char reactivity under simulated raceway conditions and comparing these results with those of coke using thermo-gravimetric techniques. The most significant conclusions based on the results of this study are:

   A) Both coals from the Illinois Basin showed higher combustion rates resulting in higher coal burnout than the Appalachian coal tested under the same conditions.

   B) Both coals from the Illinois Basin showed higher char combustion reactivities than the Appalachian coal tested under the same conditions.

   C) These results indicate that when injected under the same conditions as the Appalachian coal the Illinois Basin coals will put less char into the raceway and that this char will burnout more quickly.
EXPERIMENTAL PROCEDURES

RESEARCH WORK PLAN

There are two major tasks required to accomplish the objectives of this project - pilot plant testing and coal and char characterization.

Task I. Pilot Plant Testing

**Samples Tested**

Two hundred to three hundred kilogram quantities of two different coals were tested. A sample from the Illinois Basin Coal Sample Program - IBCSP 112 (Herrin No. 6 Seam) crushed to two different sizes (1-3mm, -200 mesh, 0.075 mm) was tested because it is representative of the coal being mined in the Illinois Basin. For comparison, an Appalachian coal that is currently being used for blast furnace injection was also tested under the same conditions.

**CANMET Facility Test Procedures**

The 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 using the following conditions:

* 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 the TGA method was used to evaluate char reactivity under simulated raceway conditions. For the combustion tests, coal injection rates were 4.5 kg/h, 6.5 kg/h, and 8.5 kg/h. In an average size blast furnace, these correspond to injection rates of 50, 75, and 100 kg/tHM, respectively.

Three sets of tests were run under these conditions.

**Test 1. Oxygen Enrichment** - in this test the Herrin No. 6 coal was injected at the
highest injection rate with three levels of oxygen enrichment (tentatively 21%, 23%, 25%, and 28%). The value of this test was to determine the coal burnout and char reactivity characteristics and compare them to the results of previous tests of the same coal. Improved burnout and char reactivity properties were expected.

**Test 2. Granular Coal** - in this test the Herrin No. 6 coal was tested at the granular particle size (1-3mm). The results were compared to the results of previous tests on the same coal tested at a much smaller size (-200 mesh, 0.075mm).

**Test 3. Coal Blend** - in this test a 50/50 blend of Herrin No. 6 coal and the Appalachian coal previously studied was tested and the results were compared to the previous results on the individual coals. The value of this test was to show any catalytic or synergistic effects of blending as well as showing if the blending is a reasonable compromise between the desirable coke replacement ratio of the Appalachian coal and the desirable high char reactivity of the Illinois coal.

**TASK II. Coal and Char Characterization**

The chemical (proximate and ultimate) analysis and petrographic properties of all of the coal samples have already been analyzed. The combustion properties of the injected samples were assessed by determining the total burnout (TB) and Volatiles released/Burnout (VMB) in the BFI reactor where:

\[
\text{Total Burnout (TB)} = \frac{(1-\text{coal ash/char ash})}{(1-\text{coal ash})}
\]

\[
\text{Volatile released/Burnout (VMB)} = \frac{1-\text{char volatile matter/coal}}{\text{volatile matter x coal ash/char ash}}
\]

Thermogravimetric (TGA) methods were used to evaluate char reactivity under simulated blowpipe-tuyere conditions. The TGA experiments were run at 1300°C in two different gas mixtures. One mixture, 10% CO\(_2\), 5.06% O\(_2\), & 84.94% N\(_2\), simulates conditions at low injection rates and the other mixture, 10.1% CO\(_2\), 1.99% O\(_2\), & 87.91% N\(_2\), simulates conditions at high injection rates.

**RESULTS AND DISCUSSION**

**COMBUSTION TESTS WITH OXYGEN ENRICHMENT**

The oxygen enrichment tests were run with the pulverized Herrin No. 6 coal (IBCSP 112) injected at a distance of 75 cm from the tuyere at a rate of 8.5 kg/h with a blast air temperature of 900°C, and an air flow rate of 102 m\(^3\)/h. The oxygen contents of the various test were 21%, 23%, 25%, and 28%. The results of the tests are given in Table 1 and are plotted in figure 3. The surprising result is that in these tests the char burnout did not show the expected increase with increasing oxygen enrichment. Indeed, the purpose of enriching
the oxygen content of the blast air is to achieve more complete combustion. While some limited experience with very low rank coals shows no enhanced combustion, results from tests using bituminous coal of slightly higher rank than the Herrin No. 6 coal have shown better combustion with the increased oxygen enrichment. Although these results could be interpreted as indicating that the Herrin No. 6 coal may not need oxygen enriched blast air, the results are still surprising and further oxygen enrichment tests are planned.

Table 1. Results of Oxygen Enrichment Combustion Tests

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</tbody>
</table>

Figure 3. Variation of calculated burnout with oxygen concentration. Note the lack of change with increasing oxygen content.
COMBUSTION TESTS WITH GRANULAR COAL

The granular coal test were run with the Herrin No. 6 coal (IBCSP 112) crushed to 1-3 mm and injected at distances of 30 cm, 65 cm, and 75 cm from the tuyere at rates of 4.5, 6.5, and 8.5 kg/h with a blast air temperature of 900°C, an air flow rate of 102 m³/h, and an oxygen concentration of 21%. The results of the tests are given in Table 2 and are plotted in figure 4. The surprising result is that in these tests the char burnout is so low. It is expected that the shock heating that the coal experiences when it is injected will cause it to shatter into finer particles. This apparently did not happen in the tests. When the particle size of the pulverized and granular chars are compared the major fraction of the char particles was in -60 to -200 mesh size for the granular char. For the pulverized coal the minor fraction of the char particles was in this range. The extremely low burnouts for the granular coal indicate that the Herrin No. 6 is probably not suitable for granular coal injection. Previous test, however, have shown that the Herrin No. 6 is a very suitable for pulverized coal injection.

Table 2. Results of Granular Coal Combustion Tests

<table>
<thead>
<tr>
<th>Injection Rate, kg/h</th>
<th>Distance from Tuyere, cm</th>
<th>Ash in Sample, %</th>
<th>Total Burnout, %</th>
<th>Volatile Matter in Sample, %</th>
<th>Volatile Matter Burnout, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5</td>
<td>30</td>
<td>11.1</td>
<td>10.5</td>
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<td>12.8</td>
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<td>10.3</td>
<td>3.0</td>
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<td>6.4</td>
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<td>11.3</td>
<td>32.3</td>
<td>16.6</td>
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<td>8.5</td>
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<td>11.3</td>
<td>33.3</td>
<td>13.9</td>
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<tr>
<td>4.5</td>
<td>75</td>
<td>12.2</td>
<td>19.8</td>
<td>33.7</td>
<td>20.3</td>
</tr>
<tr>
<td>6.5</td>
<td>75</td>
<td>11.7</td>
<td>15.5</td>
<td>32.9</td>
<td>15.5</td>
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<td>8.5</td>
<td>75</td>
<td>11.0</td>
<td>10.3</td>
<td>33.5</td>
<td>12.5</td>
</tr>
</tbody>
</table>

COMBUSTION TESTS WITH A COAL BLEND

A 50/50 blend the high-volatile C Bituminous Herrin No. 6 coal (IBCSP 112) and the high-volatile A Bituminous Pittsburgh seam coal from western Pennsylvania was injected at distances of 30 cm, 65 cm, and 75 cm from the tuyere at rates of 4.5, 6.5, and 8.5 kg/h with a blast air temperature of 900°C, an air flow rate of 102 m³/h, and an oxygen concentration of 21%. The results of the tests are given in Table 3 and are plotted in figure 5. The results
Figure 4. Variation of Calculated burnout with injection rate for both pulverized coal and granular coal. Note the low burnout for the granular coal.

show that the calculated burnout of the mix is as good as or even slightly better than the Herrin No. 6 sample alone. These results indicate that the Herrin No. 6 is quite acceptable as a blend component with higher rank coals for use in blast furnace injection.
Table 3. Results of Combustion Tests with a Coal Blend

<table>
<thead>
<tr>
<th>Injection Rate, kg/h</th>
<th>Distance from Tuyere, cm</th>
<th>Ash in Sample, %</th>
<th>Total Burnout, %</th>
<th>Volatile Matter in Sample, %</th>
<th>Volatile Matter Burnout, %</th>
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</thead>
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<td>59.6</td>
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<td>42.6</td>
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<td>63.1</td>
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<td>90.0</td>
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<td>19.0</td>
<td>62.1</td>
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<td>81.7</td>
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<td>---------------</td>
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<td>---------------------------</td>
<td>-------------------------</td>
</tr>
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<td>69.7</td>
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</table>

RESULTS OF REACTIVITY TESTS

A Cahn TG-171 Thermogravimetric Analyzer coupled to a Dell PC Pentium processor was used to measure weight changes in tuyere coke as well as PCI (pulverized coal injection) and GCI (granular coal injection) chars produced from IBCSP -112 and a Pittsburgh seam coal as a function of time and temperature. The char samples were collected at 75 cm from injection during pulverized (90% <75 micrometers) and granular coal (99%<1 mm) injection experiments of IBCSP 112 coal in the pilot scale unit at CANMET’s Energy Technology Centre. The reactivity of the chars was determined at 1300°C in gas mixtures consisting of 9.99% CO₂, 5.00% O₂, and 85.01% N₂ (vol. %), as well as 9.97% CO₂, 2.00% O₂, and 88.03% N₂ (vol. %). These mixtures simulate gaseous conditions in the raceway of a typical blast furnace during combustion of pulverized or granular coals at low and high injection rates, respectively. The rate of weight loss at 1300°C is provided by the TG analysis software. Sample reactivities reported here are expressed in units of weight % loss min⁻¹ and refer to dry ash free (daf) conditions. The results of the reactivity tests are reported in Table 4.

As seen in Table 4 higher char reactivity (20% on average) were obtained with gas mix 2 than with gas mix 1. This is expected on the basis of the higher oxygen content of mix 2. Because both mixtures have the same carbon dioxide content, it shows that the chars react preferentially with the oxygen and not carbon dioxide.
The reactivities of chars generated under granular coal injection conditions are found to be somewhat inferior (by a factor of 1.5) to that produced under pulverized coal conditions (see figure 6). The observed difference in reactivity between GCI and PCI chars is attributed to a difference in particle size distribution below -60 mesh for char samples collected under both cases. Reactivity tests conducted at CANMET have clearly indicated a dependence of char reactivity on particle size. These results have revealed an increase in char reactivity with decreasing particle size (larger surface area). The lower reactivity of GCI chars with respect to PCI chars would therefore be due to the fact that, for the former case, a greater fraction of particles lies in the -60 to -200 mesh size range. On the other hand for PCI chars, the smaller fraction of particles in the -60 to -200 mesh size range would lead to their enhanced reactivity, which is observed experimentally.

For either gas mix, the reactivities of PCI and GCI chars are higher than that of the tuyere coke. The fact that the reactivity of PCI and GCI chars are found to be higher than that of coke is important because it clearly indicates that in the real situation inside the raceway, where char particles and coke are in competition for the available O₂, char is the winner and will react faster than coke.

In the case of the Herrin No. 6 chars produced under conditions of oxygen enrichment, there appears to be no systematic change in the reactivities with oxygen enrichment.

Similarly the reactivities of the Herrin No. 6 and the Herrin No. 6/Pittsburgh blend seem to be comparable (see figure 8). This result indicates that Herrin No. 6 coal can be blended at least up to equal proportions with higher rank Appalachian coals with no significant change in the more desirable high burnouts and high reactivities of the Illinois coal.
Figure 5. Variation of calculated burnout with injection rate for the Herrin No. 6 coal and a 50/50 blend of Herrin No. 6 with the Pittsburgh seam coal.

Table 4. Results of Reactivity Analysis

<table>
<thead>
<tr>
<th>Char Sample</th>
<th>Oxygen Content in Blast Air, %</th>
<th>Reactivity in Gas Mix 1, wt. loss/m</th>
<th>Reactivity in Gas Mix 2, wt. loss/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tuyere Coke</td>
<td>21</td>
<td>1.59</td>
<td>2.02</td>
</tr>
<tr>
<td>GCI (IBCSP 112)</td>
<td>21</td>
<td>1.62</td>
<td>2.35</td>
</tr>
<tr>
<td>PCI (IBCSP 112)</td>
<td>21</td>
<td>2.72</td>
<td>3.24</td>
</tr>
<tr>
<td>PCI (IBCSP 112)</td>
<td>23</td>
<td>2.46</td>
<td>2.87</td>
</tr>
<tr>
<td>PCI (IBCSP 112)</td>
<td>25</td>
<td>2.52</td>
<td>3.07</td>
</tr>
<tr>
<td>PCI (IBCSP 112)</td>
<td>28</td>
<td>2.64</td>
<td>3.01</td>
</tr>
<tr>
<td>PCI (50% -112 + 50% Pittsburgh)</td>
<td>21</td>
<td>2.78</td>
<td>3.03</td>
</tr>
</tbody>
</table>
Figure 6. Comparison of the reactivities of tuyere coke, granular coal char, and pulverized coal char.

Figure 7. Comparison of the reactivities of Herrin No. 6 char and Char from a 50/50 mix of Herrin No. 6 and the Pittsburgh seam coal.
CONCLUSIONS AND RECOMMENDATIONS

The results of previous research on the blast furnace injection properties of Illinois basin coal indicate that when it is injected under the same conditions as the Appalachian coal the Illinois Basin coals will give the more desirable results of putting less char into the raceway and that this char will burnout more quickly.

The results of the current research support the following conclusions:

1. The char burnout did not show the expected increase with increasing oxygen enrichment. Indeed, the purpose of enriching the oxygen content of the blast air is to achieve more complete combustion. While some limited experience with very low rank coals shows no enhanced combustion, results from tests using bituminous coal of slightly higher rank than the Herrin No. 6 coal have shown better combustion with the increased oxygen enrichment. Although these results could be interpreted as indicating that the Herrin No. 6 coal may not need oxygen enriched blast air, the results are still surprising and further oxygen enrichment tests are planned.

2. While it is expected that the shock heating that the coal experiences when it is injected will cause it to shatter into finer particles, this apparently did not happen in the current tests. When the particle size of the pulverized and granular chars are compared the major fraction of the char particles was in -60 to -200 mesh size for the granular char. For the pulverized coal the minor fraction of the char particles was in this range. The extremely low burnouts for the granular coal indicate that the Herrin No. 6 is probably not suitable for granular coal injection. Previous tests, however, have shown that the Herrin No. 6 is a very suitable for pulverized coal injection.

3. The calculated burnout of the 50/50 mix is as good as or even slightly better than the Herrin No. 6 sample alone. These results indicate that the Herrin No. 6 is quite acceptable as a blend component with higher rank coals for use in blast furnace injection. Also the reactivities of the Herrin No. 6 and the Herrin No. 6/Pittsburgh blend seem to be comparable. This latter result indicates that Herrin No. 6 coal can be blended at least up to equal proportions with higher rank Appalachian coals with no significant change in the more desirable high burnouts and high reactivities of the Illinois coal.

These results and the results of previous studies show that coal from the Illinois Basin have excellent combustion properties for use in blast furnace injection. The Illinois Basin coals burnout more completely and give a higher reactivity char than higher rank coals. These properties make them more desirable as a fuel for high injection rates. In addition, results indicate that the Herrin No. 6 coal can be blended at least up to equal proportions with higher rank Appalachian coals with no significant change in the more desirable high burnouts and high reactivities of the Illinois coal.
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Koen, W., Vogel, R.B., Toxopeus, H.L., and Flierman, G.A., 1985, Injection of coal into the


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