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# CLEAN COAL TECHNOLOGY

# Blast Furnace Granular Coal Injection System Demonstration Project

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A report on a project conducted jointly under
a cooperative agreement between:

The U.S. Department of Energy and
Bethlehem Steel Corporation

Cover image: Burns Harbor blast furnaces at night

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# Executive Summary

The Clean Coal Technology (CCT) Demonstration Program is a government and industry co-funded effort to demonstrate a new generation of innovative coal utilization processes in a series of “showcase” facilities built across the country. These projects are carried out on a sufficiently large scale to prove commercial worthiness and generate data for design, construction, operation, and technical/economic evaluation of full-scale commercial applications.

The goal of the CCT Program is to furnish the U.S. energy marketplace with a number of advanced, more efficient coal-based technologies meeting strict environmental standards. These technologies will mitigate the economic and environmental impediments that limit the full utilization of coal. To achieve this goal, beginning in 1985, a multiphased effort consisting of five separate solicitations was administered by the U.S. Department of Energy (DOE). Projects selected through these solicitations have demonstrated technology options with the potential to meet the needs of energy markets while satisfying relevant environmental requirements.

This report discusses the demonstration of the British Steel and CPC-Macawber Blast Furnace Granular Coal Injection (BFGCI) Process at Bethlehem Steel’s Burns Harbor Plant in Burns Harbor, Indiana. The technology is installed on Blast Furnaces C and D, each of these units having a production capacity of 7,000 net tons of hot metal per day.

In the BFGCI process, granular coal is injected into the blast furnace as a fuel supplement. The coal, along with heated air, is blown into the lower part of the blast furnace through passages called tuyeres. The injected coal reduces the requirement for coke, the primary blast furnace fuel and reductant. BFGCI technology has the potential to reduce pollutant emissions because decreased coke production requirements result in a significant reduction of emissions of nitrogen oxides, sulfur dioxide, and air toxics. Coal can replace up to 40% of the coke.

DOE selected the BFGCI project in CCT Round III, and the cooperative agreement was awarded in November 1990. Construction began in September 1993 and was completed in January 1995; test operations commenced in November 1995 and were completed in 1999. The major conclusion of this project is that the injection of granular coal into a large blast furnace works very well and can reduce coke requirements on almost a pound-for-pound basis.

The higher blast furnace sulfur load and slag volume resulting from coal injection did not cause any operating problems. The chemistry of the furnace slag can be adjusted, without harm to overall operations, to accommodate the increased sulfur input.

BFGCI technology can be applied to essentially all U.S. blast furnaces and should be able to use any rank coal available in the United States. Since the gas leaving the blast furnaces is cleaned before being burned as fuel, injecting coal does not result in any increase in pollution from the blast furnace. The major environmental benefit from commercial application of the BFGCI process is a significant reduction of emissions from cokemaking due to decreased coke requirements.

Replacing a portion of the coke with coal offers increased furnace throughput as well as improved economics, since coal is cheaper than coke. Coal injection is also less expensive than natural gas injection as had been practiced at Burns Harbor prior to this demonstration project. The results of this work are being shared with other U.S. steel companies.

# Blast Furnace Granular Coal Injection System Demonstration Project

## Background

The Clean Coal Technology (CCT) Demonstration Program, which is sponsored by the U.S. Department of Energy (DOE) and administered by the Federal Energy Technology Center (FETC), is a government and industry co-funded technology development effort conducted since 1985 to demonstrate a new generation of innovative coal-utilization processes.

The CCT Program involves a series of "showcase" projects, conducted on a sufficiently large scale to demonstrate commercial worthiness and to generate data for design, construction, operation, and technical/economic evaluation of full-scale commercial applications. The goal of the CCT Program is to furnish the U.S. energy marketplace with advanced, more efficient coal-based technologies meeting strict environmental standards. These technologies will mitigate some of the economic and environmental impediments that inhibit the full utilization of coal as an energy source.

The CCT Program has also opened a channel to policy-making bodies by providing data from cutting-edge technologies to aid in formulating regulatory decisions. DOE and the participants in several CCT projects have provided the Environmental Protection Agency (EPA) with data to help establish NOx emissions targets for coal-fired boilers subject to compliance under the 1990 Clean Air Act Amendments (CAAA).

One of the major objectives of the CCT Program is to develop technologies that reduce emissions from industrial applications

Granular coal preparation building with blast furnaces in background

that use coal as a fuel or reactant. Conventional ironmaking requires the use of coke to provide a gas mixture, primarily carbon monoxide (CO) with some hydrogen ($H_2$), that reduces iron ore to molten iron. Coke is prepared from coal by means of a process that generates significant emissions of airborne toxic chemicals including nitrogen- and sulfur-based pollutants. The Blast Furnace Granular Coal Injection (BFGCI) System Demonstration Project described in this report replaces some of the coke by direct injection of coal into the blast furnace, thereby greatly reducing the amount of pollution associated with cokemaking.

In the blast furnace, sulfur in the coal is removed by reaction with the limestone added to the furnace and ends up in the slag. Since the gas leaving the furnace is cleaned by existing cyclones and wet scrubbers before being burned as fuel, injecting coal does not result in any increase in pollution. In addition to improved economics, the major benefit from application of the BFGCI process is the significant reduction of emissions from cokemaking due to decreased coke requirements.

The BFGCI technology was developed jointly by British Steel and Simon-Macawber (now CPC-Macawber) and installed at the Scunthorpe Works in England. However, the blast furnaces at Scunthorpe have only about one-half the production capability of the Burns Harbor blast furnaces, and one of the main objectives of the CCT test program at Burns Harbor was to determine the effect of coal injection on large, high-productivity blast furnaces. Another objective was to demonstrate BFGCI's effectiveness using a variety of U.S. coals.

## Chemistry of Blast Furnace Operation

A blast furnace is a shaft furnace in which iron ore, coke, and limestone are loaded at the top and air is injected at the bottom. Through a complex set of reactions, the iron ore is reduced to molten iron, which collects in a pool at the bottom of the furnace and is tapped off periodically. The following reactions are illustrative of the major reactions occurring during blast furnace operation and are not intended to be a complete representation of everything that occurs. At the tuyeres, oxygen in the air reacts with coke:

$C + 1/2\ O_2$ -----> CO

As the carbon monoxide rises through the blast furnace, it reduces the iron ore:

$Fe_2O_3 + CO$ -----> $2FeO + CO_2$
$Fe_3O_4 + CO$ -----> $3FeO + CO_2$
$FeO + CO$ -----> $Fe + CO_2$

Some of the carbon dioxide reacts with carbon:

$CO_2 + C$ -----> 2CO

Nonferrous oxides (mainly alumina and silica) in the iron ore and coke react with calcium oxide, produced from calcination of the limestone, and are removed as molten slag. Sulfur in the coke is also removed:

$CaCO_3$ -----> $CaO + CO_2$
$2CaO + Al_2O_3 + SiO_2$ -----> $Ca_2Al_2SiO_7$
S + CaO + C -----> CaS + CO

The composition of the slag is much more complex than shown above and can contain many other ions, such as Mg, Na, K, and Fe. In modern blast furnaces, supplemental fuel, such as natural gas or fuel oil, is frequently injected at the tuyeres to improve furnace performance and reduce coke requirements. These fuels result in the formation of both hydrogen and CO, as illustrated below:

$CH_4 + 3/2\ O_2$ -----> $CO + 2H_2O$
$H_2O + C$ -----> $CO + H_2$

The hydrogen thus formed can act as a reducing agent just as CO does in the above reactions, the only difference being that water is formed instead of $CO_2$. Some of the CO and $H_2$ produced does not react and leaves the top of the blast furnace as a low Btu fuel gas, which is used for a variety of purposes.

# Blast Furnace Operation

A blast furnace is a vertical, refractory-lined, nearly cylindrical vessel in which an ascending stream of hot gas passes through a descending column of solid raw materials (iron ore, coke, and limestone). Air needed for the combustion of coke to generate the heat and reducing gases for the process is preheated to 1500-2300°F. In many furnaces, the air is enriched with oxygen to enhance the combustion process.

The heated air enters the furnace through a series of pipes, called tuyeres. Molten iron and slag, which collect at the bottom of the furnace, are discharged through openings located below the tuyeres. The molten iron flows to refractory-lined vessels for transport to basic oxygen furnaces (BOF) or other steelmaking facilities.

In the furnace, the partially reduced ore melts and passes downward through layers of coke. The coke layers provide the permeability needed for the hot gases to rise to the upper portion of the furnace. Permeability is a measure of the ability of gas to pass through the bed of solid materials in the furnace; the higher the permeability, the better the furnace burden movement and the better the reducing gas flow through the furnace.

The hot gas leaving the top of the furnace is cooled, cleaned, and used to fire the stoves that heat the injected air, with the excess being used to generate steam and power for other uses within the plant.

Sometimes supplemental fuel (natural gas, fuel oil, or coal) is injected into the blast furnace through the tuyeres to supply some of the heat and reducing gas, thus decreasing the coke requirement. Since coke cost is one of the major expenses associated with blast furnace operation, there

## The Indiana Dunes

Only a few miles from Bethlehem Steel's Burns Harbor plant are the Indiana Dunes National Lakeshore and the Indiana Dunes State Park. The State Park was established in 1926, followed by establishment of the adjacent National Lakeshore in 1996. Together, these two parks span about 20 miles along the southern shore of Lake Michigan.

The Indiana Dunes consist of large sand dunes at the lake's edge, behind which is an area of dunes whose plant cover has evolved to mature forests. With 1,445 native plant species present, the area is a botanist's dream, with variety exceeded in the United States only by the Grand Canyon and Great Smoky Mountains National Parks. Overlapping ranges of plant species converge at the dunes, where plants usually found in warmer climates (orchids, cacti, and carnivorous plants) grow alongside species more typical of Canadian forests and the tundra (Arctic bayberry, jack pine, and northern rose).

This unusual diversity of plant life serves to attract a wide variety of wildlife to the area. For example, nearly 350 species of birds have been sighted in the dunes, ranging from waterfowl (geese, ducks, and swans) to raptors (hawks, falcons, and eagles). The National Lakeshore staff even manages a nearby heron rookery.

From 1895 to 1934, the Indiana Dunes served as the laboratory for Henry C. Cowles, a professor at the University of Chicago who was eulogized as being America's first professional ecologist. At the Indiana Dunes, Dr. Cowles studied the effects of geological formations on plant communities and the transformation of habitat by those communities.

Amidst the kaleidoscope of plant communities found at the dunes, Cowles recognized some patterns. As the habitat changed, proceeding inland from beachfront to forested dunes, he observed a succession of plant communities -- ranging from grasses that colonize the beachfront dunes to increasingly complex cottonwood, pine, oak, and beech-maple forests. This principle of ecological succession is important enough that when ten European botanists were asked what sites they wanted to see on their trip to America in 1913, they responded, "The Grand Canyon, Yosemite, and the Indiana Dunes." Scientific investigations are still performed at the Indiana Dunes, largely under the auspices of a staff of scientists at the National Lakeshore.

It is fitting that the BFGCI demonstration project is located near this environmentally sensitive area. In addition to reduced emissions, the project includes extensive environmental monitoring.

is considerable economic incentive to reduce coke usage. Also, if less coke has to be loaded into the blast furnace, more iron ore can be processed. However, not all the coke can be replaced with other fuels, since coke is critical in maintaining the integrity and permeability of the burden.

## Clean Coal Technologies for Industrial Applications

When coal use is considered, electric power production immediately comes to mind. However, there are many applications using coal that do not directly involve power production, and one of the objectives of the CCT Program is to address pollution problems and other barriers associated with coal use in the industrial sector. CCT projects are directed at demonstrating both continued coal utilization and the introduction of coal use in various industries where it is not now used. Problems addressed include the dependence of the steel industry on coke, the reliance of the cement industry on low-cost and, often, high-sulfur coal, and the need for many boiler operators to consider switching to coal to reduce costs.

One of the critical environmental concerns addressed by the CCT Program is the pollutant emissions resulting from producing coke from coal for use in steel making. Two approaches to mitigate or eliminate this problem are being demonstrated. In one project, which is featured in this Topical Report, about 40% of the coke is displaced through direct injection of granular coal into a blast furnace. The coal burns in the blast furnace to produce reducing gases. Because of conditions in the blast furnace, pollutant emissions are readily controlled (as opposed to first coking the coal). The other project precludes the need for cokemaking by using a direct iron making process that involves introducing raw coal into a vertical smelt reduction vessel where the carbon in the coal directly reduces iron ore to molten iron.

The Blast Furnace Granular Coal Injection (BFGCI) System Demonstration Project described in this report accomplishes decreased emissions by reducing the amount of coke needed to produce a ton of iron. Reducing the amount of coke used automatically reduces the emissions from the cokemaking process.

The BFGCI technology was developed jointly by British Steel and Simon-Macawber (now CPC-Macawber) and installed at the Scunthorpe Works in England. Since the blast furnaces at Scunthorpe have only about one-half the production capability of the Burns Harbor blast furnaces, one of the main objectives of the CCT test program at Burns Harbor was to determine the effect of granular coal injection on large high-productivity blast furnaces. Another objective was to determine the effect of various types of U.S. coals on blast furnace performance.

In 1989, the BFGCI System was selected under Round III of DOE's CCT Program for commercial-scale demonstration. The project was carried out under a cooperative agreement between DOE and the Bethlehem Steel Corporation.

# Project Description

Prior to initiating the BFGCI Project, natural gas was injected at Bethlehem Steel's Burns Harbor Plant as a fuel supplement to decrease coke requirements. However, two significant problems with the use of natural gas are high cost and the limited amount that can be injected, which limits the reduction in coke usage. Studies at Burns Harbor indicated that injecting coal instead of natural gas would permit a larger reduction in coke usage and would lower the cost of iron production. This led Bethlehem to submit a CCT proposal to DOE to conduct a comprehensive assessment of coal injection on the Burns Harbor blast furnaces.

This proposal was accepted in 1989 as one of the CCT Round III projects, and a Cooperative Agreement was signed in November 1990. Construction started in September 1993 and was completed in January 1995. The major objectives of the test program, which began in November 1995, were to evaluate the effect of coal injection on the operation of large blast furnaces, study the effect of the particle size of the injected coal, determine the maximum coke replacement level, and try a variety of U.S. coals.

A major reason for evaluating coal injection on U.S. blast furnaces is the fact that U.S. cokemaking facilities are rapidly aging. A high capital investment will be required to rebuild these facilities to meet emissions requirements under the CAAA. Increasingly stringent environmental regulations and the continuing decline in domestic cokemaking capability will cause significant reductions in the availability of coke over the coming years. Due to this decline in availability and the increase in operating and maintenance costs for domestic cokemaking facilities, coke prices are projected to increase more than general inflation. Blast furnace injection of coal will allow domestic integrated steel producers to maintain production while minimizing their dependence on coke.

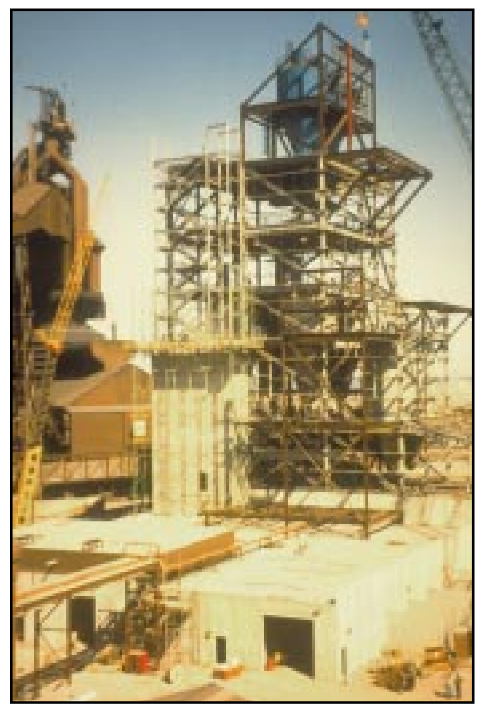
# Project Site

The BFGCI System Demonstration Project is located at Bethlehem Steel's Burns Harbor Plant in Burns Harbor, Indiana, located on the southern shore of Lake Michigan, about 30 miles east of Chicago. The site is immediately adjacent to the Indiana Dunes National Lakeshore, an area that is particularly sensitive from an environmental standpoint. The Burns Harbor Plant is an integrated operation that includes two coke oven batteries, an iron ore sintering plant, two blast furnaces, a three-vessel BOF shop, and two twin-strand slab casting machines. These primary facilities can produce over five million tons of raw steel per year. The steel finishing facilities at Burns Harbor include a hot strip mill, two plate mills, a cold tandem mill complex, and a hot dip coating line. The BFGCI technology is installed on both Blast Furnaces C and D. Each of these units has a production capacity of 7,000 net tons of hot metal (NTHM) per day.

When originally put into service, the Burns Harbor Plant could produce all the coke required for the two blast furnaces operating at 10,000 NTHM per day (total). However, improved practices and raw materials have resulted in a blast furnace operation that can now produce over 14,000 NTHM per day. Since the coke oven batteries are not able to produce the coke required for this level of blast furnace output, other sources of coke and energy have been used to fill the gap. Over the years, coke has been shipped to Burns Harbor from other Bethlehem plants and from outside coke suppliers. In addition, auxiliary fuels such as coal tar, fuel oil, and natural gas have been injected into the blast furnaces to reduce the coke requirements. The most successful auxiliary fuel through the 1980s and early 1990s was natural gas. It is easy to inject and, at moderate injection levels, has a highly beneficial effect on blast furnace operations and performance.

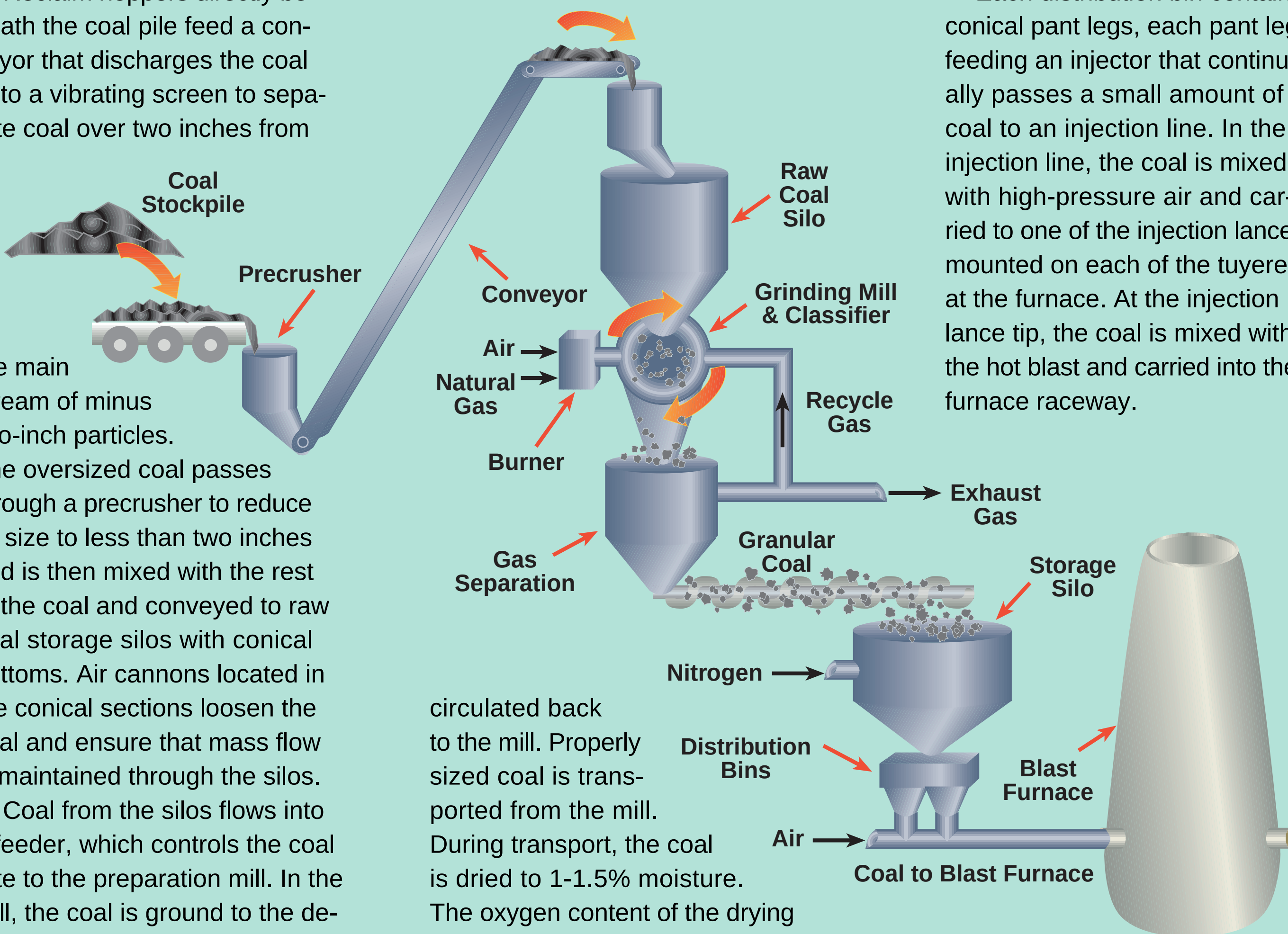
Panoramic view of the Bethlehem Steel plant at Burns Harbor with Indiana Dunes National Lakeshore in background

In 1994, the C furnace was relined. During this reline, the furnace was enlarged slightly, and the refractory cooling system was upgraded to a high-density plate cooling configuration. The furnace stack region on C has closely spaced cooling plates that are not on the D furnace. This high-density cooling was specifically designed for the rigors of high coal injection rates and to provide for increased production capacity.



BFGCI  demonstration facility under construction

## BFGCI Technology




Reclaim hoppers directly beneath the coal pile feed a conveyor that discharges the coal onto a vibrating screen to separate coal over two inches from the main stream of minus two-inch particles. The oversized coal passes through a precrusher to reduce its size to less than two inches and is then mixed with the rest of the coal and conveyed to raw coal storage silos with conical bottoms. Air cannons located in the conical sections loosen the coal and ensure that mass flow is maintained through the silos.

Coal from the silos flows into a feeder, which controls the coal rate to the preparation mill. In the mill, the coal is ground to the desired particle size. Flue gas from a natural gas fired burner is mixed with recycled air from the downstream side of the process and swept through the mill's grinding chamber. The hot gas lifts the ground coal from the mill vertically through a classifier where oversized particles are circulated back to the mill. Properly sized coal is transported from the mill. During transport, the coal is dried to 1-1.5% moisture. The oxygen content of the drying gas is controlled to stay below the combustion limit.

The dried coal is screened to remove any remaining oversized material and then sent by screw conveyors to storage silos. From the storage silos, a weigh hopper dumps batches into the distribution bins, which are part of the coal injection facility.

Each distribution bin contains conical pant legs, each pant leg feeding an injector that continually passes a small amount of coal to an injection line. In the injection line, the coal is mixed with high-pressure air and carried to one of the injection lances mounted on each of the tuyeres at the furnace. At the injection lance tip, the coal is mixed with the hot blast and carried into the furnace raceway.

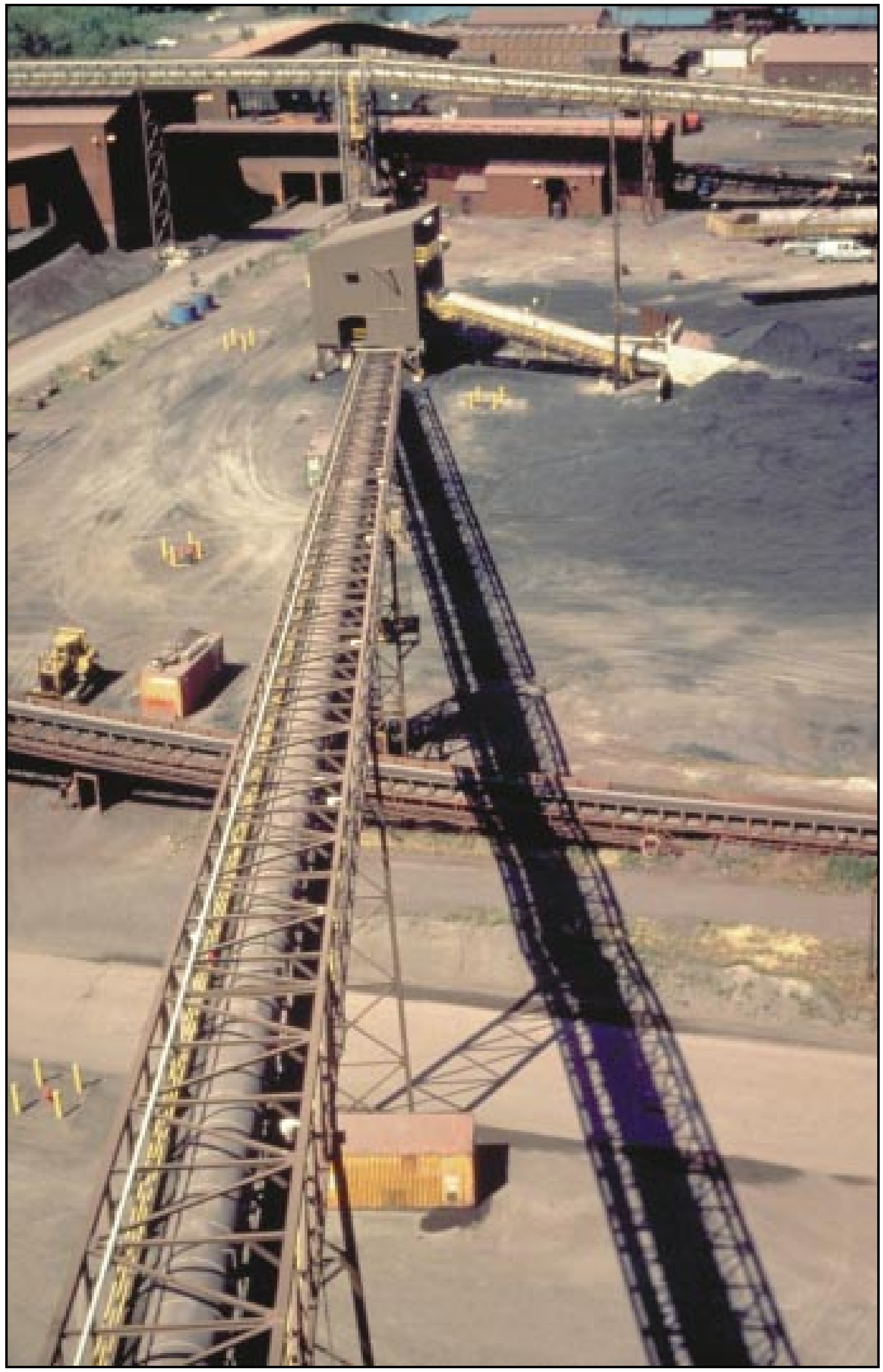
# Technology Description

An important factor relative to coal injection into a blast furnace is the particle size of the injected coal. Two coal sizes are commonly used: (1) finely powdered coal, referred to in this report as pulverized coal and defined as 70-80% passing through a 200-mesh screen; and (2) a less finely ground coal, referred to as granular coal and defined as only 10-30% of the particles passing through a 200-mesh screen. Pulverized coal is similar in particle size to face powder, while granular coal is similar to granulated sugar. Bethlehem decided to use the BFGCI system because, unlike more widely used systems that can inject only pulverized coal, the BFGCI system is also capable of injecting granular coal. Thus, an additional objective of the CCT project at Burns Harbor was to compare injection of pulverized coal with that of granular coal.

The BFGCI system has advantages that make it very attractive for application in the U.S. basic steel industry:

- The capital and operating costs for a granular coal preparation system are significantly less than those for the same capacity pulverized coal preparation system.
- Granular coal is easier to handle in pneumatic conveying systems, since granular coal is not as likely to stick to conveying pipes.
- Coke replacement ratios (decreased pounds of coke required per pound of coal injected) obtained by British Steel using BFGCI are as high or higher than those achieved by other systems.
- System availability has exceeded 99% during several years of operation at British Steel.
- The unique variable speed, positive displacement injectors provide superior flow control and measurement compared to other coal injection systems.
- The injection system can be used with both granular and pulverized coal; no other system has operated over this wide a range of coal particle sizes.

Installation of BFGCI technology at Burns Harbor required adding raw coal handling, coal preparation, and coal injection equipment.



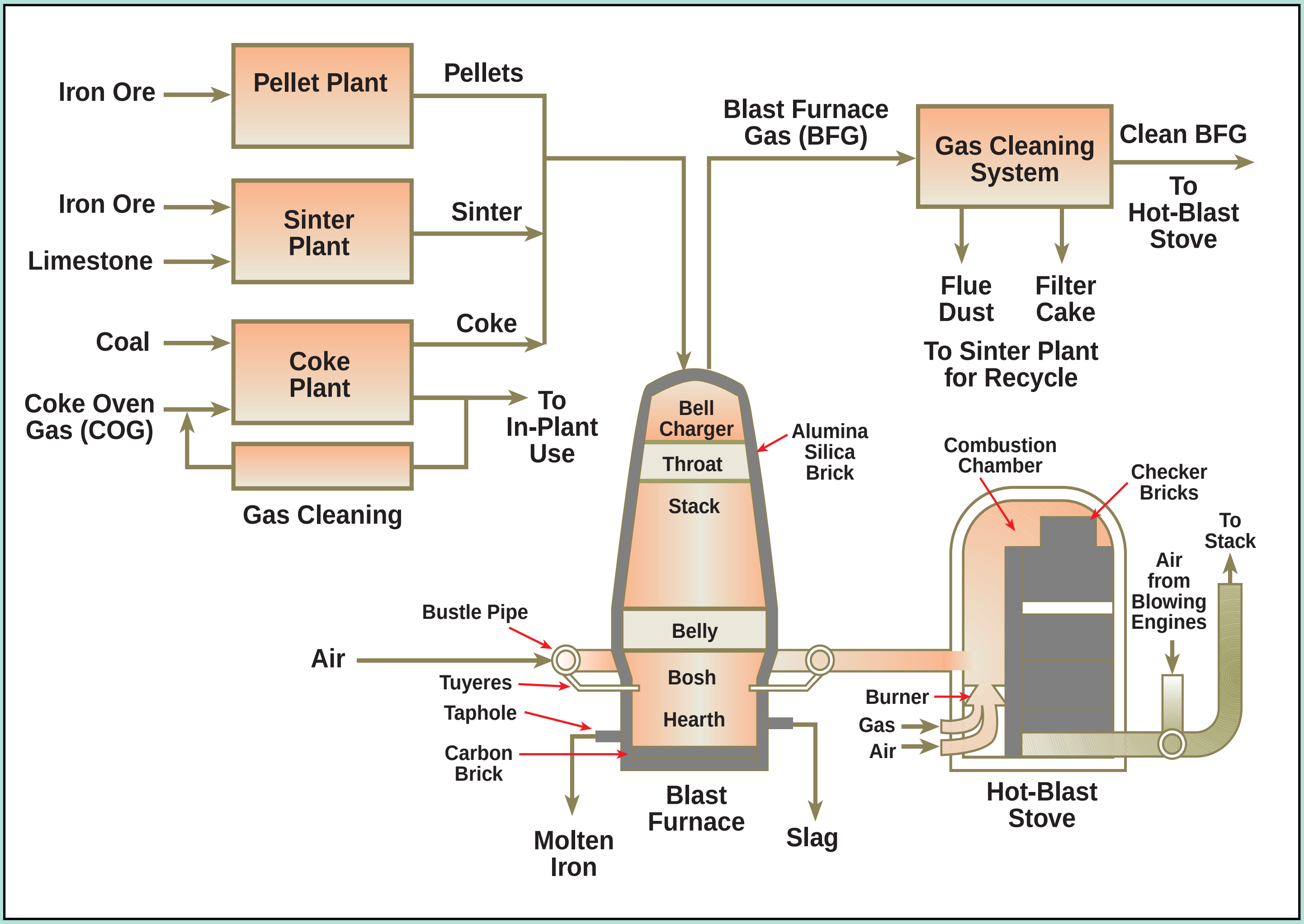
**Conveyor from coal storage area to coal preparation building**

## Blast Furnace Operation

The ironmaking blast furnace is at the heart of integrated steelmaking operations. Basically, the blast furnace is a countercurrent heat and oxygen exchanger in which rising combustion/reducing gas loses most of its heat on the way up, leaving the furnace at about 300-500°F, while descending iron oxides are converted to metallic iron. To ensure smooth flow of the iron ore, it is sintered and pelletized prior to being fed to the furnace. Sintering involves heating to agglomerate fines, thereby producing feed of suitable size.

The furnace itself is a tall, vertical shaft that consists of a steel shell with a refractory lining of firebrick and graphite. Five sections can be identified. At the bottom is the *hearth*, where liquid metal and slag collect. This is surmounted by an inverted truncated cone known as the *bosh*. Heated air is blown into the furnace through *tuyeres*, which are water-cooled nozzles made of copper and mounted at the top of the hearth close to its junction with the bosh. A short vertical section called the *belly* connects the bosh to the truncated upright cone that is the *stack*. The fifth and topmost section, through which the charge enters the furnace, is the *throat*.

The raw materials, consisting of sintered/pelletized iron ore, crushed limestone, and coke, are charged batchwise

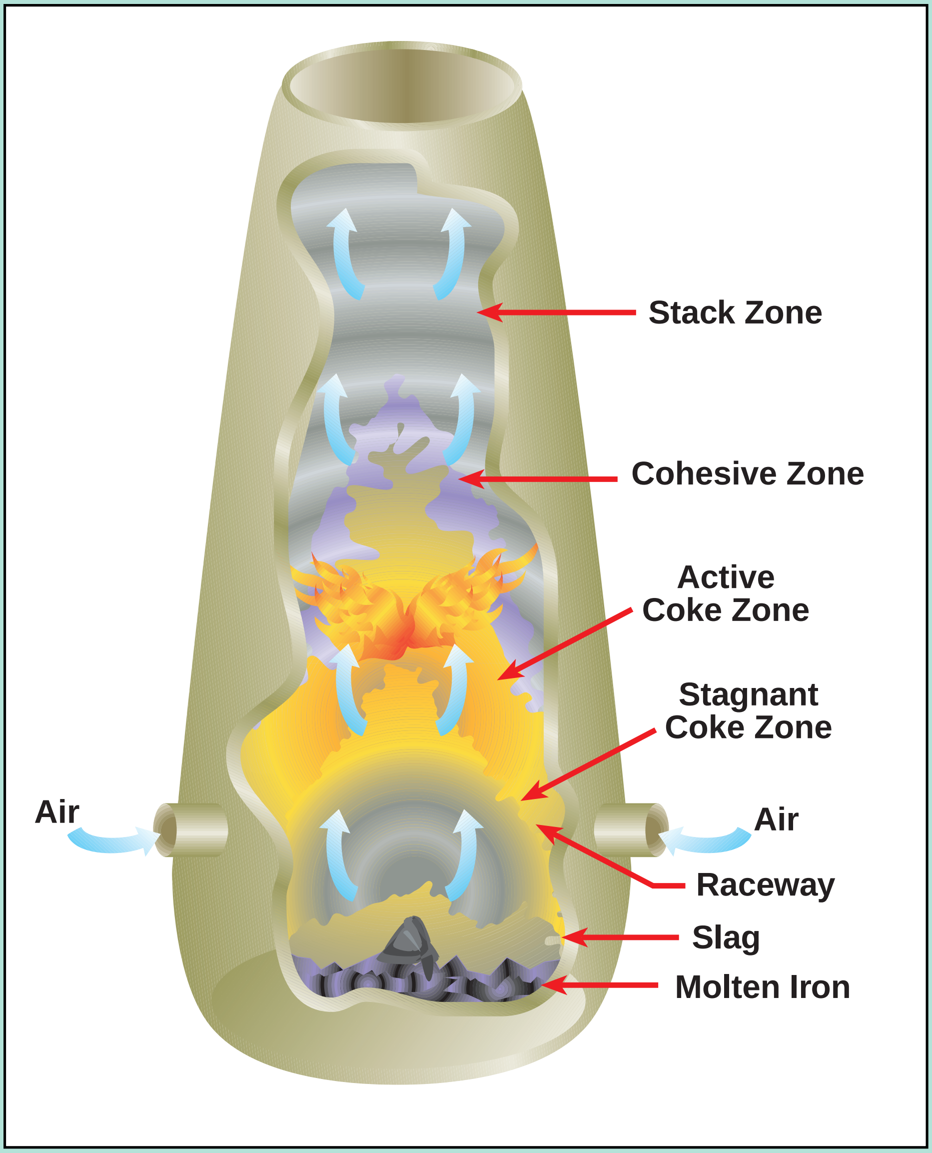


to the top of the furnace through a bell charger to prevent the escape of pressurized hot reducing gases. Air needed for the combustion of coke to generate the heat and reducing gases for the process is passed through regenerative heaters called *stoves*, where it is heated to 1500-2300ºF. The stoves, which are alternately heated and cooled, consist of a combustion chamber and a checkerwork of firebricks that absorb heat during the combustion part of the cycle.

Blast furnace gas is normally used as fuel. When a stove has reached the desired temperature, combustion is stopped and cold air is blown through in the reverse direction so that the checkerwork surrenders its heat to the air. Each furnace has three or four stoves to ensure continuous flow of heated air, which is referred to as *hot blast*.

The hot blast is conveyed to a refractory-lined *bustle pipe* located around the perimeter of the furnace. From the bustle pipe, it enters the furnace through the tuyeres. The injected hot blast creates a channel, called a *raceway*, around the bottom of the furnace. Molten iron and slag are discharged through openings, known as *tapholes*, located below the tuyeres. The molten iron flows to refractory-lined vessels for transport to basic oxygen furnaces or other steelmaking facilities.

The solids, referred to as the *burden*, flow through the furnace as discrete layers of ore and coke. As the hot blast reacts with and consumes coke at the tuyeres, the burden descends. A molten pool of iron collects on the hearth, and molten slag floats on top of the molten iron. Reduction of the descending ore occurs by reaction with the rising hot reducing gas that is formed by combustion of the coke.




The *cohesive zone* above the tuyeres is so called because it is in this area that the partially reduced ore is melted and passes through layers of coke. The coke layers provide the permeability needed for the hot gases to pass through this zone to the upper portion of the furnace. Unlike coal, coke has the high temperature properties needed to retain its integrity in this region; this is the reason that blast furnaces cannot be operated without coke in the burden.

The hot gas leaving the top of the furnace is cooled and cleaned to remove particulates, which are recycled to the sintering plant. Since the gas has a significant heating value (80-100 Btu/scf), it is used to fire the hot blast stoves, with the excess used to generate steam and power for use within the plant.

**Transport piping to carry coal from preparation area to tuyeres**

## *Raw Coal Handling*

Coal used for blast furnace injection is received at the existing facilities used to handle coal sent to the coke ovens. The coal is unloaded using the existing railroad car dumper, which is part of the blast furnace material handling system. The existing conveyor was modified to enable the coal to be sent either to the coke ovens or to a pile used to store the coal destined for furnace injection. The coal pile is formed by a radial stacker or bulldozer. The coal pile has ten days storage (approximately 28,000 tons). The material handling system from the car dumper to the coal storage pile is sized at 2,300 tons per hour, which matches the output of the car dumper.

A raw coal reclaim tunnel was constructed beneath the coal storage pile and contains four reclaim hoppers directly beneath the coal pile. These hoppers feed a conveyor that transports coal at a rate of 400 tons/hr to the south end of the storage pile and discharges the coal onto a vibrating screen to separate coal over two inches from the main stream of particles less than two inches. The oversized coal passes through a precrusher to reduce its size to less than two inches and is then mixed with the rest of the coal and conveyed to the top of the building that houses the coal preparation facilities.

## *Coal Preparation*

The new coal preparation facility contains two cylindrical steel raw coal storage silos with conical bottoms. These silos are entirely enclosed with a vent filter on top. Each silo holds 240 tons of coal, which is a four-hour supply at maximum injection rate. Air cannons are installed in the conical section to loosen the coal and ensure that flow is maintained through the silo.

Coal from the silos flows into a feeder which controls the coal rate to the preparation mill. In the mill, the coal is ground to the desired particle size. Flue gas from a natural gas fired burner is mixed with recycled gas from the downstream side of the process and swept through the mill's grinding chamber. The hot gas lifts the ground coal from the mill vertically through a classifier where oversized particles are circulated back to the mill.

Properly sized coal is transported from the mill in a 52-inch pipe. During transport, the coal is dried to 1-1.5% moisture. The oxygen content of the drying gas is controlled to stay below the combustion limit. The gas passes through cyclones for particulate removal before being discharged to the atmosphere.

There are two grinding mills, each capable of producing 30 tons per hour of pulverized coal or 60 tons per hour of granular coal, thus permitting testing of both particle size ranges of coal.

The dried coal is screened to remove any remaining oversized material and then sent by screw conveyors to one of four 180-ton storage silos. From the storage silos, a weigh hopper dumps two-ton batches into the distribution bins that are part of the coal injection facility.

### *Coal Injection*

Because of capacity differences between the coal injection equipment and the blast furnaces, each furnace requires two parallel sets of equipment, each set consisting of one product coal silo, one weigh hopper, one distribution bin, and 14 injector systems. Thus, the coal injection facility includes four distribution bins (two for each furnace), each located under a weigh hopper. At the bottom of each distribution bin are 14 conical pant legs. Each pant leg feeds an injector through which a small amount of coal passes continually to an injection line. In the injection line, the coal is mixed with high-pressure air and carried approximately 600 feet to one of the 28 injection lances, one on each of the 28 tuyeres on each furnace. At the injection lance tip, the coal is mixed with the hot blast and carried into the furnace raceway. The 14 injectors at the bottom of each distribution bin feed alternate furnace tuyeres.

**Cyclone separators on coal grinding mills**

**Burns Harbor Blast Furnace D**

# Operating History and Test Results

The test facility achieved full operation in January 1995. The granular coal injected during startup operations was a high volatile Eastern Kentucky coal with 36% volatile matter, 8% ash, and 0.63% sulfur. After some initial problems, coal injection to both furnaces stabilized at 140 lb/NTHM. During the summer of 1995, the injection rate for C furnace was gradually increased until it reached 200 lb/NTHM during September through November. The injection rate on D furnace was maintained at 145-150 lb/NTHM during the last half of 1995. During December, a problem arose due to the condensation of moisture inside the granulated coal silos. This problem was solved by insulating the coal silos.

In order to determine the range of coal properties suitable for use with the BFGCI process, several tests were conducted during the course of this project. These included tests to compare granular coal with natural gas, high volatile bituminous coal with low volatile bituminous coal, high ash coal with low ash coal, and Western coal with Eastern coal.

In determining the value of an injected fuel in a blast furnace, the quantity of coke that is replaced is an important factor. The replacement ratio for a blast furnace injected fuel is defined as the reduction in the amount of furnace coke used divided by the amount of injected fuel, after correcting for other factors that affect coke rate.

### *High Volatile Coal Injection versus Natural Gas Injection*

The first comparison made was between coal injection and natural gas injection. It was found that 210 lb of coal was equivalent to 140 lb of natural gas; that is, 210 lb/NTHM of coal required the same coke rate as 140 lb/NTHM of natural gas. (Because of the ash and oxygen contents of the coal and its lower hydrogen content, more coal is required to achieve the same reduction in coke usage as a given amount of natural gas.)

There were several differences in operation when injecting coal rather than natural gas. First, the volume and sulfur content of the slag increased, due directly to the sulfur and ash content of the coal. This did not cause any operating problems, but in order to maintain the chemistry of the hot metal, the slag chemistry was slightly altered. Other differences were less hydrogen in the off gas and a decrease in furnace permeability. The lower permeability can be offset by increasing oxygen enrichment and increasing the amount of steam in the hot blast.

### *Test with Low Volatile Coal*

For initial testing of the system, high volatile coal was used. After eight months of operation with high volatile coal on both furnaces, six different low volatile coals were tested during the next seven months. The favorable operating results achieved with low volatile coals led to the decision to use Virginia Pocahontas coal as the standard for low volatile granular coal injection. The C furnace was designated as the granular coal test facility, due in large part to the improvements made to the furnace during the 1994 reline.

An important test with low volatile coal was conducted during October 1996. Virginia Pocahontas coal, with a volatiles content of 18.0%, 5.3% ash, and 0.78% sulfur, was used during this test. The carbon content was 87.1%, and the higher heating value (HHV) was 14,974 Btu/lb on a dry basis. The minus 200 mesh fraction of the granular coal was 14.6%.

The major conclusion from this test was that granular low volatility coal performs very well in large blast furnaces. The best fit line to a plot of adjusted coke rate versus injected coal rate gives a replacement rate of 0.96 lb of coke per pound of injected coal. This is an excellent replacement ratio and is significantly better than the 0.8-0.9 value reported by other operations.

### *Test with Higher Ash Coal*

The objective of this test was to determine the effect of coal ash content on blast furnace operations. Initially, low ash Buchanan coal was injected. Buchanan coal is from a different mine than Virginia Pocahontas, but from the same seam and has a very similar analysis. To supply coal

**Raw coal conveyor belt**

## Pollution Regulations in the Steel Industry

The CAAA of 1990 regulate emissions of a number of substances of concern in steelmaking, primarily certain hazardous air pollutants (HAPs) as well as $SO_2$, NOx, and particulates. For blast furnace operation, the major issue is control of particulates. There are no federal emission regulations that specifically cover blast furnaces. They are regulated at the state level as part of State Implementation Plans. These regulations are generally based on opacity limits (typically 20% opacity for varying frequencies and durations).

Cokemaking is the steel industry's area of greatest environmental concern. In response to increasingly stringent regulatory constraints, including the emissions standards for coke ovens promulgated in 1993 under the CAAA, U.S. steelmakers are turning to new, cleaner cokemaking technologies. Pollution prevention has focused on two areas: reducing coke oven emissions and developing ironmaking techniques that minimize or eliminate coke usage.

**CAAA Standards Applied to Cokemaking**

Standard coke ovens emit a variety of pollutants from different locations in the coking process, including leaks from doors, lids, and offtake pipes. These emissions are basically raw coke oven gas (COG), which is made visible by the condensation of vapors. These vapors include coal tar, pitch, creosote, methane, ammonia, hydrogen cyanide, hydrogen sulfide, carbonyl sulfide, and various hydrocarbons such as benzene, toluene, and xylene.

Additional emissions occur when coal is fed into the oven at the beginning of a new coking cycle. Since ambient temperature coal is dropped into ovens that are at about 2000°F, some of the same materials that exist in COG can be emitted during charging operations. However, the major emissions during charging are particulates, mainly coal dust.

Emissions also occur at the end of a coking cycle when the coke is pushed from the oven into a car and quenched with water. During normal pushing operations, when coke oven doors are opened, emissions consist primarily of CO and $CO_2$ from oxidation of the hot coke upon contact with air, along with particulate matter. The hot coke is quickly quenched with large volumes of water. The rapid evolution of steam releases particulate matter to the environment. In addition, any pollutants in the quench water can become airborne either as gas/vapor or fine particulates. If a push occurs before the coal is completely coked (green coke), enormous quantities of COG, particulates, and combustion products can enter the atmosphere.

Typically, cleaned COG is burned to provide the heat for the coking process; the combustion products exit the oven through a stack, thus resulting in potential emissions of NOx, $SO_2$, and particulate matter.

The major environmental concern is that COG contains a number of known carcinogens. Epidemiological studies of coke oven workers have reported an increase in cancer of the lungs, trachea, bronchus, kidney, bladder, prostate, and other organs. EPA has classified coke oven emissions as a Group A, human carcinogen. In addition to its carcinogenic properties, coke oven emissions can cause conjunctivitis, severe dermatitis, and lesions of the respiratory and digestive systems. In addition to the threat to health, coke oven emissions cause degradation of the environment, as would any source of particulate matter and odorous gases.

The CAAA set specific standards for HAPs that can be emitted from coke ovens. Pursuant to this legislation, EPA issued Maximum Achievable Control Technology (MACT) standards and Lowest Achievable Emission Rate (LAER) standards.

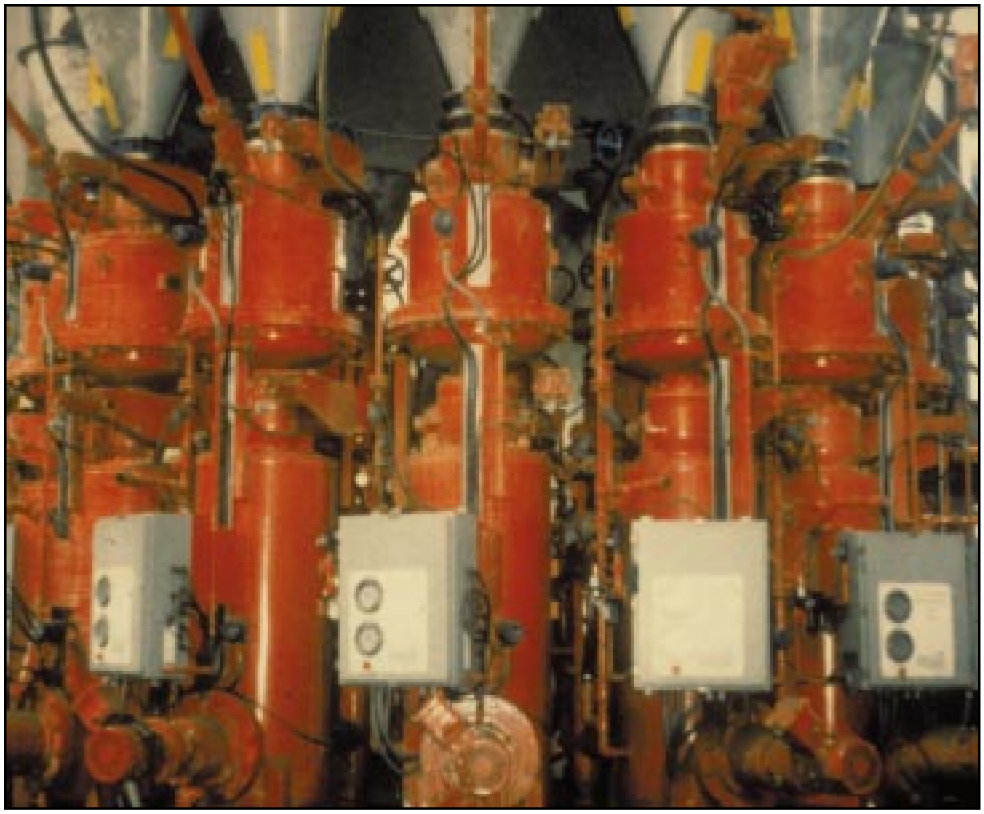
The coke industry faces technological and financial difficulties in meeting the CAAA emissions standards. The CCT Program, through projects such as that at Bethlehem Steel, represents one successful effort to address this issue.

for the higher ash test, the operators of the Buchanan mine increased the ash content of the coal by eliminating one of the steps in the coal cleaning process. The advantage of this is that only the ash content of the coal changed; the rest of the chemistry remained the same. The high ash Buchanan coal provided for this test had an ash content of 7.7% (compared to 4.7% for the low ash Buchanan coal). Other analyses were a volatiles content of 18.75%, 0.75% sulfur, 84.3% carbon, and a HHV (dry) of 14,425 Btu/lb. The test was conducted during June 1997. The conclusions from this test were:

- Coke usage increased slightly as the ash content of the injected coal increased (about 10 lb/NTHM for a 3% increase in ash content).
- Higher ash coal had no adverse effect on furnace permeability.
- Furnace productivity was unaffected by the 3% increase in coal ash at an injection rate of 260 lb/NTHM.
- Hot metal quality was unaffected by the increased ash content of the injected coal.

### *Western versus Eastern Coal*

The Western coal used for this test was high volatile Oxbow coal from Colorado. Its average volatile content was 37.1%, with 11.2% ash and 0.76% sulfur. Carbon content was 73.2%. The test, which was run during October 1998 on D furnace, compared high volatile granular Oxbow coal with low volatile granular Buchanan coal. For an Oxbow coal injection rate of 190 lb/NTHM, coke rate was 798 lb/NTHM. With the Buchanan coal at an injection rate of 250 lb/NTHM, the coke rate was 683 lb/NTHM. Part of the 115 lb/NTHM more coke required with the Oxbow coal is accounted for by the 60 lb/NTHM lower injection rate of the Oxbow coal, but this does not account for the whole difference. The rest of the difference is due to the lower carbon content (73.2% vs. 86.3%) and higher ash content (11.2% vs. 5.2%) of the Oxbow coal. The higher ash content resulted in an increase in slag volume from 430 to 461 lb/NTHM.



**Granulated coal injectors**

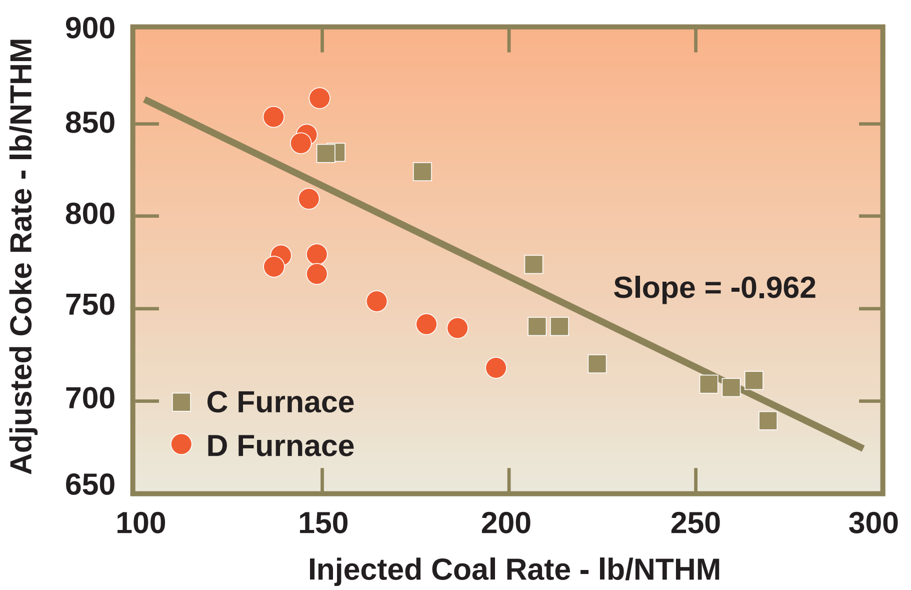
### *Granular versus Pulverized Coal*

This test was run on D furnace in November 1998, using the same Oxbow coal as in the above test, except that the mills were set for a much finer grind. For the test with granular coal, 24.9% passed through a 200-mesh screen; for the test with pulverized coal, 74% passed through a 200-mesh screen. After correcting for the factors that affect coke rate, comparison of the test with pulverized coal with the test for granular coal showed no significant difference in coke rate between the two. Furthermore, overall performance of the blast furnace was almost identical for the two tests. There was one major difference, however, between the two tests, and that was the amount of energy required to grind the coal. It required about 60% more energy to pulverize coal compared to granulating it. This results in a distinct economic advantage for granulated coal.

A previous attempt to use pulverized low volatility Buchanan coal was unsuccessful due to coal injection problems. The two major problems were an insufficient injection rate for the coal due to its low bulk density and plugging of the 1-1/4 inch diameter pipes that conveyed the pulverized coal to the tuyeres. Plugging was caused by a high content of very fine particles that deposited on the walls of the pipe. Several attempts were made with this coal, but none was successful.

## Cost/Demonstration Schedule

The total project cost is $194 million, of which DOE's share is $32 million or 16%. From the time of awarding the cooperative agreement, the project has required approximately eight years. Activities included design, permitting, construction, startup, and operation. Construction was started in September 1993 and was completed in January 1995. Startup operations began following completion of construction. Significant granular coal injection to D furnace occurred on January 19, 1995, when coal was injected through four tuyeres at a total rate of 20 lb/NTHM. Coal injection was initiated on C furnace on February 9, 1995, using four tuyeres at an overall rate of 25 lb/NTHM. The remaining 24 tuyeres used natural gas injection. Since startup, C furnace has achieved coal injection rates as high as 295 lb/NTHM.




Relationship between coal injection and coke rate

## Market Potential

BFGCI technology can be applied to essentially all U.S. blast furnaces. The technology should be applicable to a wide range of coals available in the United States. The environmental impacts of commercial application are primarily indirect and consist of a significant reduction of emissions resulting from diminished cokemaking requirements.

The BFGCI technology was developed jointly by British Steel and CPC-Macawber. British Steel has granted exclusive rights to market BFGCI technology world wide to CPC-Macawber. CPC-Macawber also has the right to sublicense BFGCI rights to other organizations throughout the world.

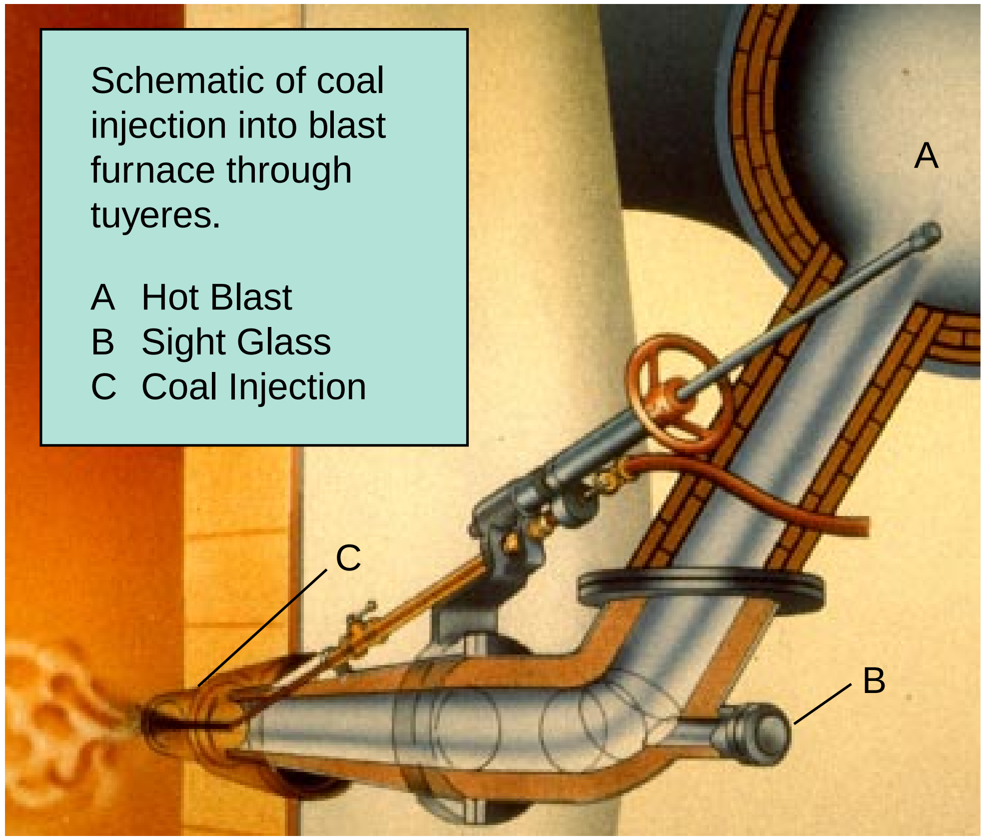
British Steel and CPC-Macawber have recently installed a similar facility at U.S. Steel's Fairfield blast furnace near Birmingham, Alabama, which operates at about 6,000 NTHM per day. This represents another successful application of the technology, with granular coal injection rates averaging about 260-270 lb/NTHM.

# Conclusions

The injection of granular coal into a large blast furnace works very well and can replace coke requirements on almost a pound for pound basis. There is no difference in results between granular coal and pulverized coal. However, granular coal has the advantage that it requires much less grinding energy.  Also, with some coals it may be impractical to inject pulverized coal because of a tendency to plug lines.

The higher sulfur load and slag volume on the blast furnace resulting from coal injection do not cause any operating problems. The chemistry of the furnace slag can be adjusted, without harm to overall operations, to accommodate the increased sulfur input.

Overall, this was a very successful project and should show substantial benefits to the steel industry.



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## The Clean Coal Technology Program

The Clean Coal Technology (CCT) Program of the U.S. Department of Energy (DOE), a model of government and industry cooperation, responds to DOE's mission to foster a secure and reliable energy system in the United States that is environmentally and economically sustainable. The CCT Program represents an investment of over $5.6 billion in advanced technology, with industry and state governments providing a significant share —66 percent—of the funding. With 23 of the 40 active projects having completed operations, the CCT Program has yielded technologies that can meet existing and emerging environmental regulations and compete in a deregulated electric power marketplace.

The CCT Program provides a portfolio of technologies that will enable continued use of the United States' economically recoverable coal reserves (over 270 years at current consumption rates) to meet the nation's energy needs in an environmentally sound manner.

Many CCT processes have reached commercial status, including cost effective devices to control sulfur dioxide ($SO_2$), nitrogen oxides (NOx), and particulate matter (PM). Also ready is a new generation of technologies that can produce electricity and other commodities, such as steam and synthesis gas, at high efficiencies consistent with concerns about global climate change. The CCT Program has taken a prevention approach as well, providing technologies that remove pollutants or their precursors from coal before combustion.

Additionally, new technologies have been introduced into major coal-using industries, such as steel production, to enhance environmental performance. Thanks in part to the CCT Program, coal—abundant, secure, and economical throughout much of the world—can continue in its role as a key component in world energy markets. CCT processes offer a cost effective means to mitigate potential environmental problems associated with unprecedented energy growth.

Most of the CCT demonstration projects have been conducted at commercial scale, in actual user environments. Each application addresses one of the following four market sectors:

- Advanced electric power generation
- Environmental control devices
- Coal processing for clean fuels
- Industrial applications

**Granulated coal injection control room**

# List of Acronyms and Abbreviations

BFGCI ........ Blast Furnace Granular Coal Injection
BOF ........ Basic oxygen furnace
Btu ........ British thermal unit
CAAA ........ Clean Air Act Amendments of 1990
CCT ........ Clean Coal Technology
CO ........ Carbon monoxide
$CO_2$ ........ Carbon dioxide
COG ........ Coke oven gas
DOE ........ U.S. Department of Energy
EPA ........ U.S. Environmental Protection Agency
FETC ........ Federal Energy Technology Center
HAPs ........ Hazardous air pollutants
HHV ........ Higher heating value; expressed as Btu/scf applied to blast furnace top gas and Btu/lb for coal
LAER ........ Lowest Achievable Emission Rate
MACT ........ Maximum Achievable Control Technology
NOx ........ Nitrogen oxides
NTHM ........ Net tons of hot metal
PM ........ Particulate matter
scf ........ Standard cubic feet
$SO_2$ ........ Sulfur dioxide
wt% ........ Percent by weight

# Glossary of Terms

Belly - short vertical section just above the bosh area of a blast furnace

Bosh - the area just above the tuyeres

Burden - the solid mixture of iron ore, coke, and limestone that descends through the furnace

Bustle pipe - a refractory-lined pipe that circles the blast furnace near its base

Cohesive zone - the zone above the tuyeres where the partially reduced iron ore melts and passes through layers of coke

Coke replacement ratio - lb of coke replaced per lb of coal injected

Granular coal - powdered coal with 10-30% passing through a 200-mesh screen

Hearth - bottom of furnace, where liquid metal and slag collect

Hot blast - heated air produced in the stoves and injected into the furnace

Lock hopper - a closed vessel, valved at top and bottom, designed to charge solid feed into the top of a blast furnace while preventing escape of process gases

Pant legs - vertical cones through which coal feed flows to the injectors for injection into the furnace

Permeability - a measure of the ability of the combustion/reducing gas to pass upward through the furnace burden

Productivity - net tons of hot metal produced (NTHM) per unit time, usually per day

Pulverized coal - powdered coal with 70-80% passing through a 200-mesh screen

Raceway - an internal channel around the bottom of the furnace, created by the injected hot blast

Reducing gas - gas produced by partial combustion of fuel in the furnace, primarily carbon monoxide but also some hydrogen, which reacts with iron oxides to form metallic iron

Slag residue - material remaining after reduction of iron ore to iron, primarily calcium and aluminum silicates plus oxides of other elements such as magnesium, sodium, potassium, iron, and sulfur

Stack - truncated upright cone above the belly

Stoves - vessels filled with brickwork, external to the furnace, where air is heated for injection into the furnace

Tapholes - openings below the tuyeres through which molten iron and slag are removed from the furnace

Throat - topmost section of the furnace, through which solid raw materials are charged

Tuyeres - openings through which the hot blast is injected into the furnace