

THE USE OF PLASMA TORCHES IN BLAST FURNACE IRONMAKING*

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Abstract

Development work on the use of plasma torches in blast furnace ironmaking was completed in the 1980s. The technology developers planned to reduce blast furnace coke consumption using electrical energy and large scale coal injection through the tuyeres. Since this time, Westinghouse Plasma Corporation has improved torch reliability with industrial experience in solid-waste-to-energy facilities, as well as metallurgical applications. As coke makes up one-third of the hot metal cost, savings efforts frequently seek to lower coke consumption by increasing process efficiency or replacing coke with cheaper fuels. Alter NRG and Hatch assessed the merits of using plasma torch technology to superheat the hot blast. Coke rate savings, electrical purchase requirements, and a financial analysis to implement the torches are presented.

Keywords: Blast furnace; Coke consumption; Plasma torch technology.

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1. INTRODUCTION

Extensive development work on the use of plasma torches in blast furnace ironmaking was completed in the 1980s. The technology developers planned to reduce blast furnace coke consumption using electrical energy and large scale coal injection through the tuyeres. Plasma torches were identified as an alternative technology to large scale oxygen enrichment which was considered too expensive at the time. Ultimately, plasma technologies were not implemented largely due to concerns with plasma torch reliability in the steel plant environment. Westinghouse Plasma Corporation has since improved torch reliability with industrial experience in solid-waste-to-energy facilities, as well as metallurgical applications. Since coke makes up one-third of the hot metal cost, savings efforts frequently seek to lower coke consumption by increasing process efficiency or replacing coke with cheaper fuels. With an increasing focus on lowering greenhouse gas emissions, plasma torches offer the opportunity to lower both coke rate and carbon dioxide emissions from the blast furnace by using a greater amount of electrical energy. Alter NRG and Hatch assessed the merits of using plasma torch technology to superheat the hot blast and reduce coke consumption in blast furnace operations. Coke rate savings, coal consumption, electrical purchase requirements for hot blast superheating, and a financial analysis to implement the torches are presented.

2. HISTORY OF PLASMA TORCH USAGE IN BLAST FURNACE IRONMAKING

2.1 Early Developments

Plasma torches are electric arc gas heaters that utilize a high temperature, ionized, and conductive gas to achieve direct heat transfer from the arc [1,2]. The technology was first developed in 1878 by W. Siemens when he used a direct current furnace for the bulk melting of metals. Early large-scale applications of plasma heaters were developed in Norway in the early 1900s to make nitrogen fertilizer from atmospheric air [2-4].

Westinghouse Plasma Corporation's (WPC) plasma technology was developed over a period of 30 years with an estimated \$100 million invested in research and development (R&D). The WPC technology was initially developed in collaboration with NASA to produce clean high enthalpy gas flows to simulate reentry as part of the Apollo space program [1,3,5]. These early aerospace applications required plasma arcs at extremely high temperatures, and since testing for reentry did not require extended operation for many hours, long electrode life was not required for these testing systems.³ The proliferation of low power torches for cutting or welding applications led to smaller devices with more dependable operation and longer electrode life.³ Since the process energy from plasma is provided by direct heat transfer from an electric arc, gases of widely varying chemical composition can be heated. Plasma torches have the unique ability to increase the energy contained in a process gas by 2 to 10 times higher than that of conventional combustion equipment. The ability to use plasma torches to add large amounts of energy under controlled conditions led to their use across multiple industries [6].

2.2 Metallurgical Applications

Plasma technology has been applied in metallurgical processing to superheat process gases, direct smelting of ores and plant waste materials, as a combustion replacement, and for high temperature material testing [5,7]. The technology is especially appealing in ironmaking with its large energy consumption to smelt iron ores and produce molten iron and slag [1].

In the 1970s, the use of plasma technology to superheat the blast air to very high temperatures emerged as an opportunity to replace coke [1]. This led to a number of laboratory and pilot-scale tests that included injection of superheated gas into blast furnace tuyeres, and blast furnace wind superheating with plasma energy [7]. Pilot scale tests conducted at the Centre de Recherches Metallurgiques (CRM), Belgium used three (3) 20 kW torches to produce a heated reducing gas – natural gas reformed with CO₂ at temperatures above 1,750°C. Electrode life was over 400 h, with 80% efficiency at a 2 MW power level, and no electrical network problems were experienced [1]. These tests showed that the blast furnace process did not change if gases produced from reactions with coke and air were replicated with another gas of similar composition and temperature [1].

In 1980, Westinghouse Electric Corporation – in conjunction with Cockerill Steel, S.A, Belgium – designed and implemented a 3,500 kW single-phase plasma torch system for the injection of superheated air and natural gas into the tuyeres of a blast furnace. During single tuyere tests, a coke rate reduction was observed, and the study proved that plasma torches could indeed be used to superheat reducing gases for co-injection with hot blast air into the blast furnace. The torches provided an opportunity to use alternative fuels such as natural gas, coke oven gas or fuel oil without oxygen enrichment. The combination of high arc rotation speeds and large gas throughput velocities provided excellent heat transfer, thereby increasing overall process thermal efficiency [5].

In 1993, BHP used an electric resistance heater in conjunction with a 150 kW nitrogen plasma torch to heat the blast to 1,300°C in a tuyere simulator at its Newcastle Laboratory. BHP recommenced research to use pulverized coal injection (PCI) in 1996, with successful tests resulting in the tuyere injection of PCI at the Port Kembla blast furnaces in mid-2002 [8,9].

2.3 Issues Using Plasma Torches in Commercial Scale Blast Furnace Plants

In the 1980s, the returns on investment for plasma heating were similar to those for oxygen enrichment. While pilot and lab scale tests were successful, commercial success in the blast furnace was limited due to inadequate electrode life, torch performance issues in the steelworks' dirt-laden/wet environment, and the need for simple maintenance procedures to maintain electrode integrity [6,7]. The combined use of high levels of oxygen enrichment with pulverized coal injection and/or natural gas proliferated as this practice reduced coke consumption without the electrode life and efficiency concerns of plasma torches. Oxygen enrichment and fuel injection rapidly increased on a global basis.

Recognizing that additional coke savings could be achieved with plasma technologies, Westinghouse addressed the plasma torch performance issues that were identified in the early plant trials. In the intervening years, WPC torches were commercially deployed in over 34 different industrial applications in a wide variety of uses such as metals recycling, catalyst re-forming, heating of cupolas, and cleaning

of industrial gases. From 1989 to 2008, the General Motors' Powertrain plant located in Defiance, Ohio, used a plasma fired cupola (PFC) to produce gray iron for engine blocks and automotive castings. The foundry successfully used six (6) MARC 11H plasma torches to increase the melt yield. Operating experience suggested that plasma technology is economically suitable for iron melting as the PFC provided a strong reducing atmosphere in the melting zone. No major changes to foundry operations were required to employ the PFC system. Key benefits for this system included reduced process gas velocities for the PFC compared to conventional cupolas due to lower coke usage [10].

3. ALTER NRG AND WESTINGHOUSE PLASMA TORCHES

Alter NRG acquired WPC in 2007 and has further developed the plasma torches to provide a clean source of heat to industrial processes. The plasma torch system along with its subsystems, including the arc heater, power supply components, cooling water system, gas system, and instrumentation and control system were improved [5]. The plasma unit was containerized to function better in the hostile blast furnace environment. The high voltage terminals were tightly sealed, and the container could be easily removed to provide access to the internal components for servicing and inspection.⁷ The improved plasma torch proved to be sufficiently rugged and durable to withstand the demands of industrial use [5].

The MARC 3A plasma torch was originally conceived as an experimental torch for pilot plants and R&D applications. The design then became a standard for lower power applications between 80 and 300 kW. The MARC 11L and MARC 11H plasma torches were developed primarily for metal melting applications (Figure 1).



Figure 1. WPC Torches – MARC 3A and MARC 115.

These torches have the ability to achieve temperatures beyond the limitations of combustion-based air heating. As such, the MARC 11 series of torches were specifically created for heating large quantities of blast air, and have a power rating up to 2.4 MW. The MARC 4.5 plasma torch fills the gap between the MARC 3 and MARC 11 series of torches; it is a robust, industrial torch capable of delivering over 500 kW of power to a process application. A summary of the WPC plasma torches is given in Table 1.

Table 1. Summary of WPC plasma torches

Type/ Features	MARC 3A	MARC 4.5	MARC 11L	MARC 11H
Power output	80-300 kW	280-530 kW	350-800 kW	860-2400 kW
Type of Control - Independent control of field coil and arc current?	No - Field coil in series with arc current	Yes - power controlled by changing either arc current, field current or process gas flow	Yes - power is controlled by changing either the arc current, field current or the process gas flow	
Design Characteristics/ Challenges	Flexible cylindrical design; length of torch can be modified to suit process needs.	Flexible cylindrical design; plasma torch can be inserted into hot zone of a furnace.	Fixed design; torches typically used externally; mounting limitations.	

4. USE OF PLASMA TORCHES IN THE BLAST FURNACE

In blast furnace ironmaking, the largest cost savings opportunity is to lower coke consumption by increasing process efficiency or replacing coke with less expensive replacement fuels. Using plasma torches to superheat the blast air to very high levels that are not possible with combustion processes offers a unique opportunity to further reduce the coke consumption to levels approaching the minimum coke rate. Hatch considered the impact of aggressive air superheating on the blast furnace process to understand potential benefits. Implementation would require additional engineering analysis to define the best plasma torch locations and verify the maximum temperature that the hot blast delivery system could achieve in existing facilities. The plasma technology could be phased in; this allows incremental benefits as the best superheating arrangement is developed.

To illustrate the impact of using plasma torches to superheat the blast air in a blast furnace operation, the cases listed in Table 2 were developed.

Table 2. Summary of coke replacement cases studied

Case	Details
1	Base case – typical blast furnace
2	Increase blast temperature to 1,200°C
3	Increase blast temperature to 1,400°C
4	Increase blast temperature to 1,600°C
5	Increase blast temperature to 1,800°C

4.1 Case 1: Base case

The base case representing a typical blast furnace was developed using Table 3.

Table 3. Base case summary

Parameter	Units	Value
Sinter	kg/t HM	404
Pellets	kg/t HM	1,093
Coke	kg/t HM	387
PCI	kg/t HM	128
Fuel rate*	kg/t HM	502
Specific blast volume	m ³ (S.T.P.)/t	990
Blast temperature	°C	1,065
Flame temperature	°C	2,220
O ₂ content in blast	%	26

*Fuel rate = Coke rate + (0.9×PCI rate)

Subsequent cases were developed by superheating the blast air, while maintaining a top gas temperature between 120°C and 130°C, a constant metallic feed, hot metal chemistry, and raceway adiabatic flame temperature (RAFT). Coke and PCI rates were adjusted to satisfy both furnace heat and reduction requirements.

4.2 Cases 2 to 5: Using plasma torches to increase the blast temperature

The blast temperature was increased from the base case of 1,065°C up to 1,800°C using plasma energy. The coke rate associated with the maximum blast air temperature of 1,800°C (178 kg/t HM) approaches the minimum coke rate needed for iron carburization and ferrous burden support – a plasma superheated blast could enable the blast furnace to minimize coke close to theoretical minimum rates. At such temperatures, the burden distribution in the furnace would need to be adjusted to account for the lower coke rate. Further consideration and research would be required to understand the impact of gas flow within the furnace at very low coke rates. The major changes for all cases are presented in Figure 2 below.

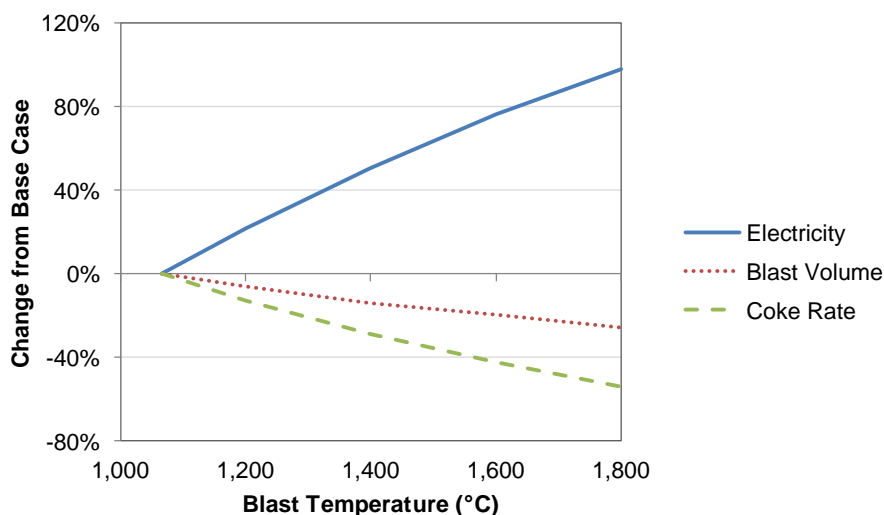


Figure 2. Impact of increasing blast temperature using plasma torches.

A summary of the different coke replacement strategies is provided in the Table 4 below:

Table 4. Impact of increasing blast temperature as a coke replacement strategy

Parameter	Units	Case 1	Case 2	Case 3	Case 4	Case 5
Blast temperature	°C	1,065	1,200	1,400	1,600	1,800
Coke	kg/t HM	387	338	276	223	178
PCI	kg/t HM	128	157	196	233	259
Fuel Rate*	kg/t HM	502	480	452	433	411
Blast volume	Nm ³ /t HM	990	930	855	800	738
Blast oxygen	%	26	26	26	26	26
Flame temperature	°C	2,220	2,220	2,220	2,220	2,220
Top gas temperature	°C	127	125	125	128	121
Electricity	kWh/t HM	150	183	226	265	297
Electrical demand for a 6,000 t/d BF	MW	38	46	56	66	74
Number of MARC 11H units required at 2,400 kW each and 85% efficiency		-	4	8	12	16

*Fuel rate = Coke rate + (0.9×PCI rate)

Fuel usage between the various cases is compared in Figure 3. The PCI rate increases with blast temperature to reduce the flame temperature back to the base case value of 2,220°C. The blast oxygen enrichment is fixed for all cases presented.

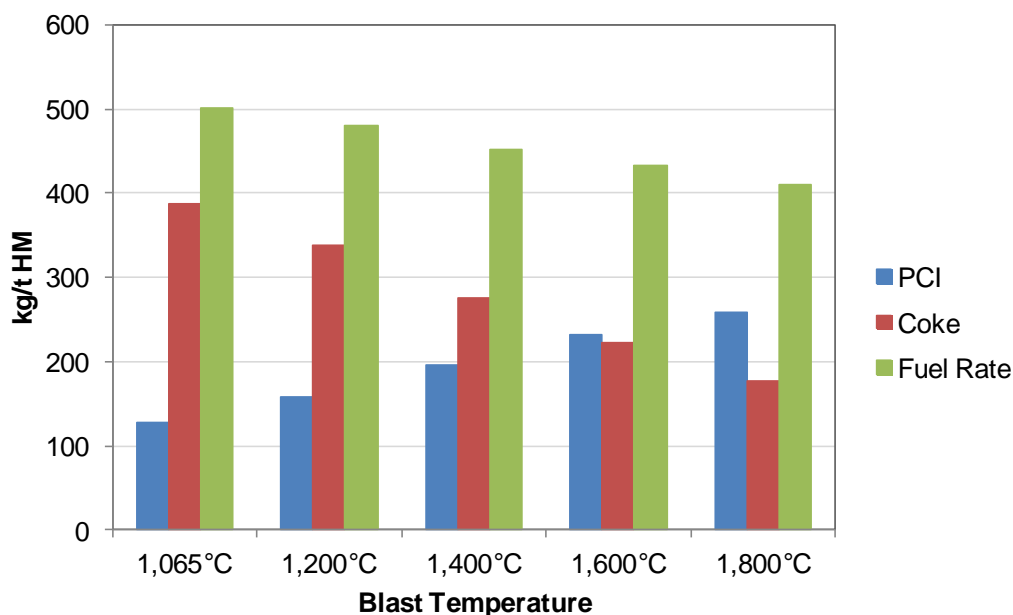


Figure 3. Fuel rate comparison across the cases.

To achieve the maximum temperature of 1800°C on a 6,000 t/d blast furnace, 16 Westinghouse MARC 11H units would be needed based on a torch thermal efficiency of 85%.⁵ Torch requirements for the complete range of blast temperatures considered can be seen in Table 4.

4.3 Considerations for installing plasma torches at the blast furnace

In a blast furnace plant, potential locations for installation of the plasma torches for blast superheating include the hot blast main, bustle pipe and penstocks immediately

above each tuyere, or combinations of these locations. The larger MARC 11 plasma torches ideally require a strong mounting point and good access for planned maintenance. Location of plasma torches in the hot blast main, mounted in a ring, could allow for initial hot blast heating with 3-6 torches between the stove discharge and the junction between the bustle pipe and hot blast main. Locating additional torches in the bustle pipe close to the entrance would be an additional opportunity to superheat the blast air. The plasma torches should be mounted symmetrically on either side of the bustle pipe entrance to ensure even heating of the blast air delivered to each tuyere. Potentially 4-5 torches could be installed on either side of the bustle pipe for a total of 8-10 torches. Combining both approaches, the potential to implement 12 torches is worth further engineering investigations.

Installing a smaller plasma torch at each tuyere was deemed too challenging due to the demanding environment and to reduce the number of torches employed. Regardless of the location chosen, appropriate protective measures must be taken to account for potential fire hazard issues and hot blast system integrity due to the high temperature gas flows involved. For instance, at higher blast temperatures, the refractory lining of the hot blast main, bustle pipe and penstocks would need to be replaced with higher temperature brick (more expensive), or a redesigned bustle pipe with cooling technology would need to be implemented to keep the refractory intact and from glazing over. This would increase the implementation cost and requires further engineering and development.

In addition to the power supply, air, and water systems for the plasma torches, the plant electrical infrastructure, such as the substation and transformer may require upgrades to handle the power load from the plasma torches. In many older plants redundant electrical distribution equipment may be available, reducing the investment costs.

5. FINANCIAL ANALYSIS

The cost of producing hot metal (HM) was calculated based on the assumed costs shown in Table 5 that reflect the early 2016 time period.

Table 5. Cost inputs

Material	Units	Cost (\$/unit)
Sinter	tonne	50
Pellets	tonne	60
Coke	tonne	150
PCI	tonne	70
Oxygen	Nm ³	0.03
Nitrogen	Nm ³	0.02
Air	Nm ³	0.01
Electricity	kWh	0.11

A breakout of the operating cost differences from the base case are provided in Figure 4 below as waterfall diagrams. For each case, the left-most bar represents the operating cost of the base case, with subsequent bars (values shown in \$/t HM) representing the incremental step change for coke, blast air, oxygen, power and PCI costs, in that order. Subtracting and adding these bars to the base case cost results in the right-most bar showing the new operating cost for the case presented.

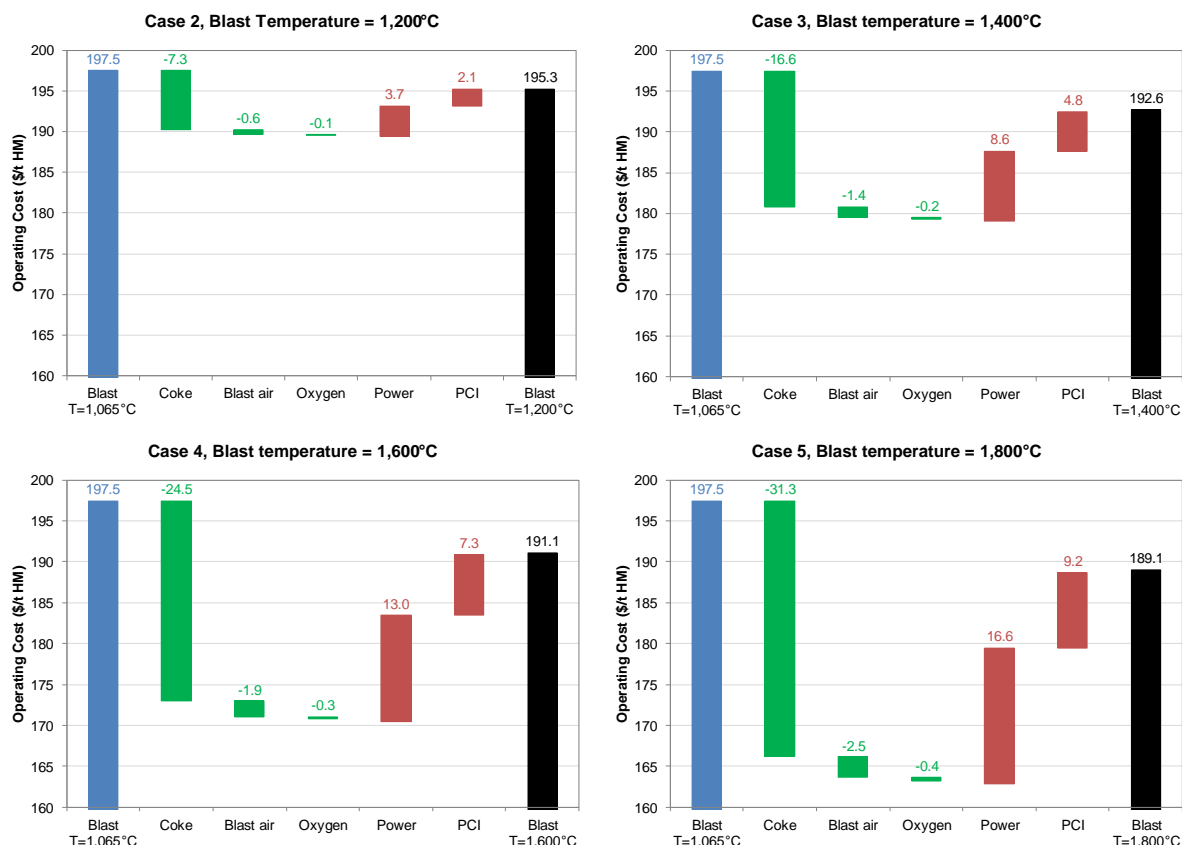


Figure 4. Operating cost differences from Case 1.

The rate of return was based on a 10-year project life, a 1-year implementation period, an installed capital cost of \$2.5 million for each plasma torch system, and electrical infrastructure upgrade costs at \$100k per MW for a new substation. A summary of each case is presented in Table 6.

Table 6. Financial analysis summary

Parameter	Units	Case 1	Case 2	Case 3	Case 4	Case 5
Blast Temperature	°C	1,065	1,200	1,400	1,600	1,800
Operating Cost	\$/t HM	197	195	193	191	189
Change in operating cost	\$/t HM	-	-2.2	-4.8	-6.3	-8.4
Change in operating cost	million \$/year	-	-2	-5	-6	-8
Capital cost	million \$	-	11	22	33	44
Simple payback	years	-	2.4	2.2	2.5	2.5
Pre-tax IRR	%	-	40	45	38	38

Using plasma torches to superheat the blast provides returns on investment in the order of 40%, with a simple payback under 2.5 years for capital costs of \$10-40 million. The key benefits from increasing the blast temperature are realized in the difference between coke rate savings and increased power requirements.

When planning to implement plasma torches in an existing steel plant, the plant may have available electrical infrastructure that could be used to reduce the investment costs significantly. Additionally, the implementation can be staged, especially if redundant power is available at the plant site.

7. CONCLUSION

Superheating the blast air using plasma torch technology offers an opportunity to reduce coke consumption below today's best practices with oxygen enriched blast and coal injection. The plasma technology can be introduced in a staged manner to allow for the required engineering developments to be completed and optimized. The financial payback is attractive, with payback of about 2.5 years, and this can be achieved for each stage of the technology implementation. Engineering design work is needed to develop the best way to implement the newer plasma torches available from Alter NRG, including an ultra high temperature hot blast system. With a focused development program, these engineering challenges can be overcome.

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