Impact of PCI Coal Quality on Blast Furnace Operations

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ABSTRACT

Pulverized coal injection has assisted the steel industry to lower operating costs, extend coke oven life and lower greenhouse emissions. As the understanding of the impact of quality of the injected coal has increased, there has been a shift from high volatile thermal coals to low volatile semi-anthracites. A heat and mass model was used to investigate the impact of the injected coal properties on coke replacement ratio and operating costs under two sets of operating conditions corresponding to European and Japanese practices. The model was also used to investigate the impact of the injected coal ash content on the likely operating costs of a blast furnace.

INTRODUCTION

Blast furnace technology is central to the crude steel industry and is continually undergoing refinements to improve productivity and reduce operating costs. In the next two decades the blast furnace route for iron production will continue to contribute 50 to 60 % of world requirements. It will be the preferred route wherever the demand is large, scrap is not available, iron ore and coal are available and electric power is expensive. Continuous improvements in productivity, coke consumption and fuel use within the steelworks have been driven by competition in world steel markets.

One such process refinement has been the injection of auxiliary fuels. Prior to the 1980's the preferred injection fuel was oil, but sharply increasing oil prices led to other fuels being used, such as natural gas in USA and Australia and coal in most other countries. Pulverized Coal Injection (PCI) has now been implemented in most steelworks around the world.

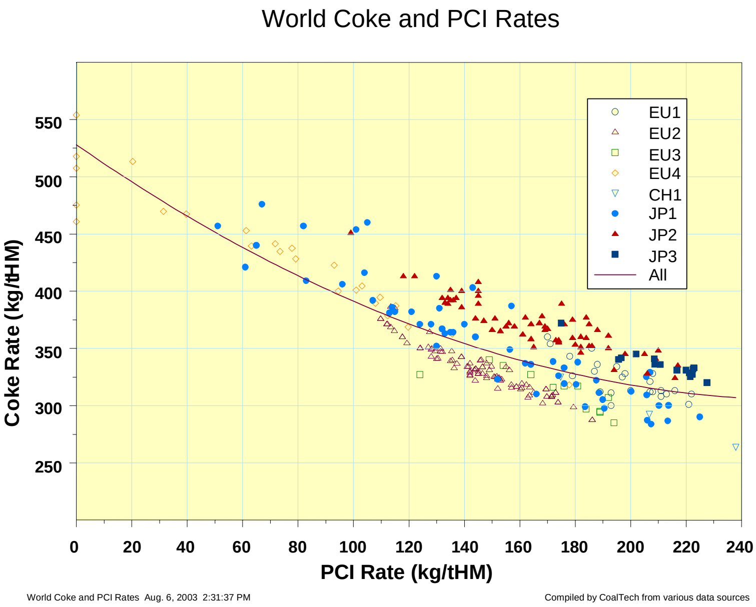
Increased injection of coal was initially driven by high oil prices but now increased use of PCI is driven by the need to reduce raw material costs, pollution and also by the need to extend the life of ageing coke ovens. The injection of coal into the blast furnace has been shown to:

1) Increase the productivity of the blast furnace, i.e. the amount of hot metal produced per day by the blast furnace;
2) Reduce the consumption of the more expensive coking coals by replacing coke with cheaper soft coking or thermal coals;
3) Assist in maintaining furnace stability;
4) Improve the consistency of the quality of the hot metal and reduce the silicon content of the pig iron.
5) Reduce greenhouse gas emissions, Life Cycle Analysis by Tata Steel showed a 6.7% reduction in CO2 emissions when the PCI rate increased from 16 kg/tHM to 116 kg/tHM (Sripriya and others, 2000).

In addition to the benefits mentioned above, coal injection has proved to be a powerful tool in the hands of the furnace operator to adjust the thermal condition of the furnace much faster than would be possible by adjusting the burden charge from the top.

Figure 1 shows how the coke rate varies with pulverized coal injection rates. The large scatter in this plot is due to the data being taken from the monthly average figures from a range of blast furnaces in various countries injecting a wide range of coals. The best fit curve to this data does indicate that there is a reduction in the incremental replacement ratio at high injection rates resulting in reduced coke savings at injections rates over 200 kg/tHM. The data for the European BF's (EU), Japanese (JP) and China (CH) reflect the different operating philosophy of these operators. Generally, the Europeans aim for lower fuel rates with high productivity while the Japanese aim for higher fuel ratio to meet the gas demand of integrated steel works.

The wide spread development of PCI systems has resulted in the maturing of milling, storage and distribution technologies. The critical factor in the distribution system design is to ensure uniform feed of coal to each tuyere without fluctuations in the coal delivery rate. Further development is continuing to improve combustion of the coal through lance design and oxygen injection.



World Coke and PCI Rates Aug. 6, 2003 2:31:37 PM

Compiled by CoalTech from various data sources

Figure 1: Selected world coke and PCI rates

British Steel has developed an alternative method of injecting coal, Granulated Coal Injection (GCI). GCI and PCI technology were evaluated at Bethlehem Steel Corporation's Burns Harbor steel plant in a US DOE funded project. Hill and others (2001) reported that the only operational difference between PCI and GCI at injection rates up to 140 kg/tHM was that GCI had lower milling requirements giving savings in both capital and operating costs.

PCI COALS

The world coal market is divided into Coking, Semi-Soft Coking and Thermal sectors according to the properties of the coal. Hard coking coals demand a premium price due to their unique plastic properties required for strong coke and their limited supply. Semi-Soft coking coals have some plastic properties and can be used in coke oven blends. Thermal coals are generally regarded as have good combustibility in conventional coal-fired power plant and have Fuel Ratio (Fixed Carbon / Volatile Matter) around 2 or lower. Low volatile coals can also be regarded as thermal coals as they are used to fire cement kilns and fluidised bed boilers.

The relative importance of different aspects of PCI coal quality has varied, as the technology for injection has improved and the rate of injection increased. In the late 1970's, triggered by the oil crisis, interest in PCI was renewed and coal was considered as an economic replacement fuel for oil. As combustibility was considered to be of importance, the coals used for PCI were thermal coals. At that time, thermal coals were readily available and had a much lower cost than hard coking and semi-soft coking coals. As understanding of the impact of coal quality on BF performance increased the demand for lower volatile coals has increased over the last 5 years.

Today, there are many criteria used to measure the performance of coal injection, both economic and technical, such as the following:

> **Economic Benefit.** The main cost benefit is the replacement of high cost coking coal, though other benefits such as improved productivity have also been observed. The replacement ratio is kilograms of coke replaced per kilogram of coal injected and is reported as the “actual” or the “corrected” replacement ratio. The "corrected"

replacement ratio is calculated by taking account of other changes in the energy and mass balance of the blast furnace that influence coke rate, for example, blast temperature.

Milling & Handleability. The main operating costs, other than coal costs, are related to the milling and distribution of the coal to the blast furnace. The Hardgrove Grindability Index (HGI) is a good indicator for the expected milling behaviour of a coal. The high HGI of a soft coal allows a mill to be operated at a higher mill throughput with the same or lower mill power requirement. The size distribution of the coal can impact on combustibility and coal handleability in bins and transfer lines.

Blast Furnace Operation. The injected coal quality can influence the quality of the hot metal, stability of the blast furnace and top gas composition. The ash from the injected can act as an inhibitor for the oxidising process, is the main deliverer of undesirable alkalies and consumes melting energy.

BLAST FURNACE MODELING

An implementation of Rist and Meysson (1967) blast furnace process model was used to investigate the impact of PCI coal quality on the operation of a blast furnace. This model examines:

- The fuel rate which closely relates to the heat balance in the lower part of the furnace and gas (indirect) reduction rate at the shaft.
- The influence of PCI on the heat balance in the lower zone by its partial combustion heat in the raceway, and on gas reduction rate in the shaft by CO + H_2 from PCI coal.

The model was used to investigate the impact of the injected coal properties (see Table 1) on coke replacement ratio, operating costs and top gas composition under two sets of operating conditions corresponding to European and Japanese practices (see Table 2).

Replacement Ratio

For one coal, J01, the coke rate was determined for 3 injections rates of 100, 150 and 200 kg/tHM. This allowed the calculation of a hypothetical coke rate at zero coal injection, as shown in Figure 2 for the high fuel rate operation. This maximum coke rate was checked for two other coals using two PCI rates and then used to calculate the replacement ratio that could be expected from the other coals.

Comparing the calculated replacement ratios for the Japanese high fuel operation with those predicted by the relationship given by Ishii (2000) showed good agreement. Whereas, the model gave slightly lower replacement ratios for European low fuel operations than those estimated by the relationship of Brouwer and Toxopeus (1991), which was based on data from Hoogoven's blast furnaces.

The calculated replacement ratio for both high and low fuel operations are shown in Figure 3 against the Volatile Matter of the respective coals. As seen in this figure there is considerable variation if Volatile Matter is used as the ranking parameter for replacement ratio.

It was found that the partial heat of combustion was a better parameter to estimate the replacement ratio, as there was a near linear fit between the two. The partial heat of combustion is the heat released when coal is gasified to CO and H_2.

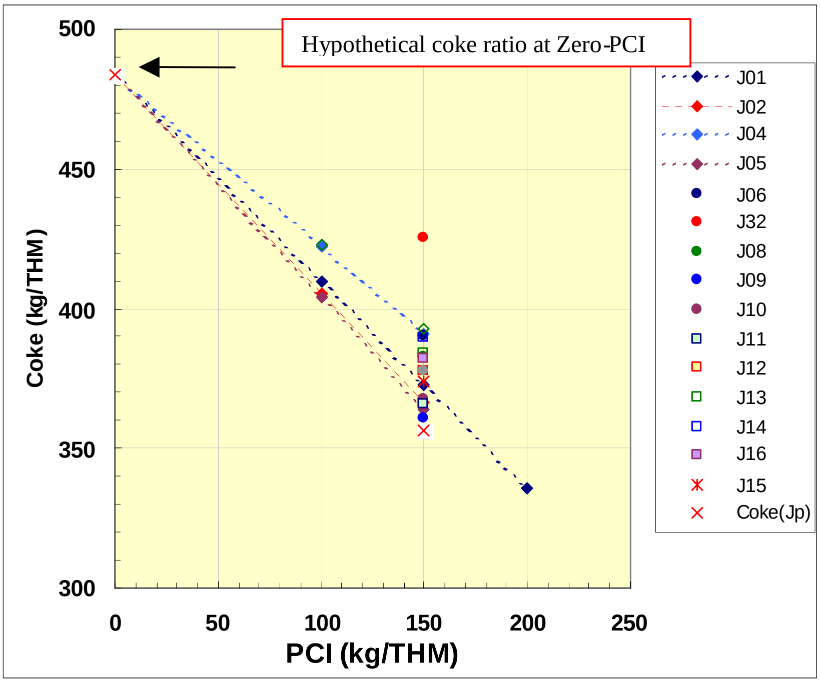


Figure 2: Calculated coke rate at different PCI rates for the High Fuel Rate Operation

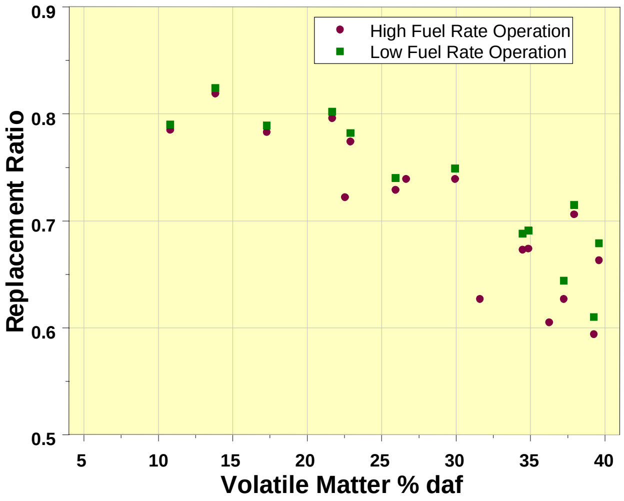


Figure 3: Calculated replacement ratios versus Volatile Matter

Combustibility of Injected Coal

Goto and others (2002) investigated the maximum rate for pulverized coal from a carbon balance in the blast furnace using a material and heat balance model. The rising lines in Figure 4 present the generation rate of unburnt char as a function of the combustion efficiency of pulverized coal and the falling line represents the carbon consumed by the solution loss (gasification) reaction within the blast furnace. Unburnt char not consumed by solution loss reaction will be trapped in the blast furnace or exit as dust. Shen and others (2002) estimated the maximum rate of 230 kg/tHM at a combustion efficiency of 75%, which is in agreement with Figure 4.

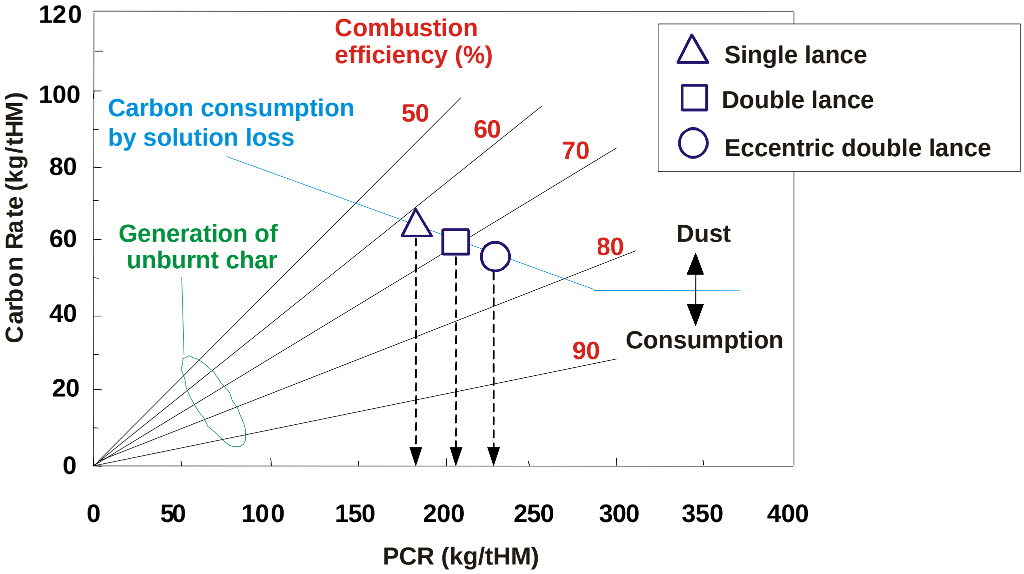


Figure 4: Estimation of maximum injection rate (after Goto and others, 2002)

To estimate the likely economic impact on blast furnace operations Fukushima's model was used to determine the differences in coke requirements for two combustion efficiencies (>80% and <60%) for a low and high volatile coal injected at 150 kg/tHM. For the high volatile coal, there was no difference in coke requirements. For the low volatile coal at the lower combustion efficiency, the coke requirements did increase by only 1%. The coke requirements for the low volatile coal at a low combustion efficiency were still less than those for the high volatile coal case.

Babich et el (2002) and Kochura et el (2002) summarised the measures that intensify coal combustion in the raceway as:

- Enriching the blast with process oxygen. However, the non-linear effect of blast oxygen on the degree of combustion should be taken into account: the increase in the combustion rate becomes smaller as oxygen content increases.
- Preliminary mixing of PC with process oxygen before introduction into the tuyere cavity.
- Use of coal blends (usually coals with high and low content of volatile matter) and fuel mixtures to maintain both high combustion degree and high coke/coal replacement ratio.
- Coal injection with iron oxides (fine iron ore, iron-containing waste, etc.), carbonates and other oxygen-rich additives.
- Use of chemical and physical phenomena, e.g. catalytic, polarising and other effects.
- Optimisation of coal grinding, depending on operating conditions and coal properties.

Impact of Ash of Injected Coal on Operating Costs

The model was used for a quantitative study on the influence of ash content of the PCI-coal on blast furnace operation, particularly focusing on the impact on operating costs.

For this study the blast furnace process parameters shaft efficiency, reserve zone temperature, heat losses of upper shaft and lower shaft and theoretical flame temperature at raceway were constant for all calculations of this study. One coal (J02) was used in all calculations with different amounts of ash – 10, 9, and 8 % ad.

Two approaches were used to determine the influence of ash on blast furnace operations, these were:

1. Three PCI rates (100, 150 & 200 kg/tHM) were modelled with constant blast temperature and moisture allowing coke rate and blast volume to change.
2. Coke rate and raceway flame temperature held to similar values with PCI rate and oxygen enrichment changing for three cases, which were
   Case I - Blast temperature and moisture held constant,
   Case II - Blast temperature held constant,
   Case III - Blast moisture held constant.

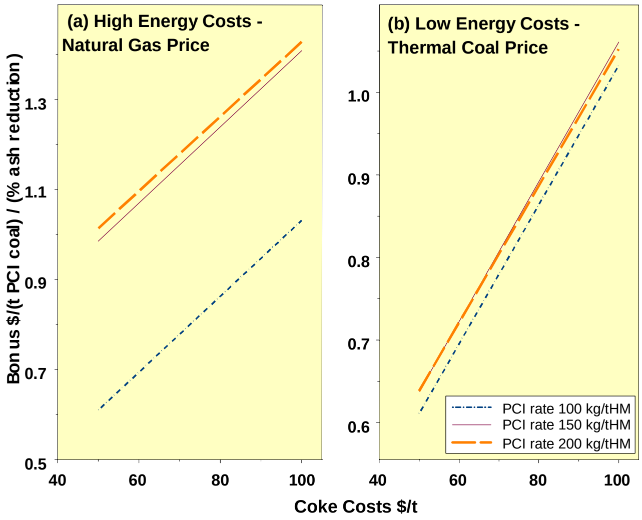


Figure 5: Bonus in PCI price for ash reduction – Approach 1

In Approach 2 the three cases correspond to the normal control strategies to maintain constant raceway flame temperature.

The major process variables that impact on hot metal costs are summarized as difference from the base ash content of 10% and are given in Tables 3 and 4.

For Approach 1, the likely impact on the price paid for PCI of varying ash due to changes in blast furnace operating costs was determined as a bonus US$/tonne for a 1% reduction in ash. These calculation where done using a high-energy cost (Natural Gas) and a low energy cost (Thermal Coal) for the energy consume within the steelworks. Figures 5(a) & 5(b) show how the bonus for a lower ash coal varies with coke cost. It is only at high injection rates (150 and 200 kg/tHM) with high-energy costs that a lower ash significantly lowers operating costs.

For Approach 2, the impact of ash on costs is calculated as a bonus (US$/ tonne PCI coal) from the base case of US$30/t for the 10% ash coal. Figures 6(a) & 6(b) show how this bonus is influenced by the ash content, also shown in these figures is the bonus calculated to a dry ash free basis. At low energy costs the cases evaluated do not depart significantly from the "daf" adjustment. Whereas, at high energy costs, the three different operating strategies differ significantly from the "daf" adjustment. Case III shows a negative bonus for a 1% decrease in ash, that is, ash seems to be beneficial. In all the cases at high energy cost, the control strategies to maintain constant coke rate at different PCI coal ash content are having a greater influence than the ash of the injected coal. In Case III the benefit of "control by oxygen" is the major influence.

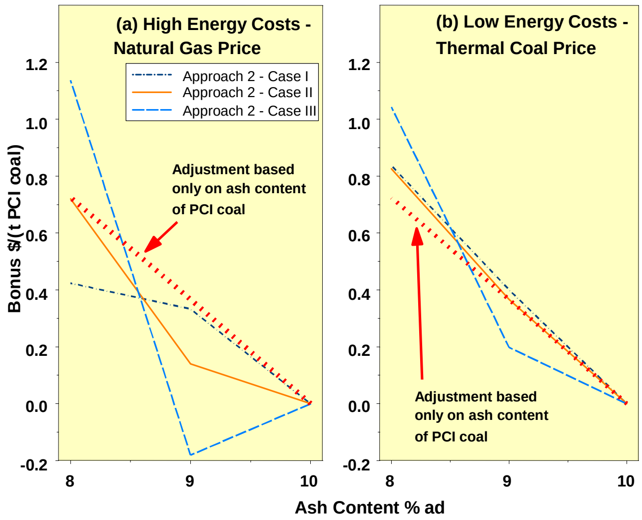


Figure 6: Bonus in PCI price versus ash content – Approach 2

Other PCI Influences on Blast Furnace Operation

These calculations do not take into account for the possible impact of ash on blast furnace operation, which could affect productivity and therefore costs. At injection rates, greater than 160 kg/tHM, it has been observed that changes were occurring in the operation of the blast furnace. Some of these changes included:

- The size of the raceway,
- Reduction of permeability of the coke surrounding the raceway,
- Changes in temperature distribution in the raceway,
- Mechanical degradation of coke in the raceway, and
- Decrease in deadman temperature.

All these changes are interdependent and are influenced by the properties and amount of the injected coal and blast conditions. At injection rates greater than 180 kg/tHM the permeability surrounding that raceway is of primary concern. Ichida and others (2002) discusses the principal causes of reduced permeability by injection of coal. These causes are related to unburnt char and slag chemistry.

CONCLUSIONS

The current and future needs of blast furnace operators are to maintain a stable, productive blast furnace, while reducing costs and minimising the environmental impact of steel production. Coal injection will continue to be a means for the steel industry to address these needs. The better replacement ratio of low volatile coals makes them the preferred PCI coals at current injection rates of around 170 kg/tHM. High combustion efficiency within the raceway is important to achieve injection rates greater than 190 kg/tHM. To determine the optimum coal or blend at high injection rates requires further research into the combustion kinetics of different coals and blends under the intense conditions of the raceway.

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Table 1: Coals Properties

Coal	Moisture %ad	Ash % ad	Volatiles % ad	Total Sulphur % ad	Gross Calorific Value kcal/kg	Net Calorific Value kcal/kg
J01	2.0	9.5	26.5	0.40	7450	7214
J02	1.5	10.0	15.3	0.65	7567	7363
J04	4.0	8.0	36.5	0.85	7030	6773
J05	1.8	7.8	19.6	0.19	7640	7437
J06	5.0	4.0	39.0	0.70	7138	6867
J08	3.5	8.0	30.5	0.40	7150	6911
J09	1.2	8.5	12.5	0.45	7800	7597
J10	1.5	9.0	20.5	0.50	7600	7380
J11	2.0	10.0	9.5	0.65	7450	7285
J12	2.5	10.5	33.0	0.50	7200	6955
J13	2.6	9.0	35.0	0.50	7096	6857
J14	3.5	10.3	32.1	0.57	6880	6642
J31	6.1	5.1	32.2	0.30	6844	6618
J32	5.2	8.1	27.4	0.31	6827	6613
J33*	2.1	9.6	23.6	0.50	7444	7219
J34*	3.2	8.3	20.0	0.38	7313	7104
* Blends						

Table 2: Blast furnace operating conditions

Operating Condition	High Fuel Rate Operation Typical of Japanese BF's	Low Fuel Rate Operation Typical of European BF's
Blast Temperature (°C)	1157	1178
Blast Moisture (g)	30.0	11.8
Oxygen enrichment (Nm^3/tHM)	40	34
Hot Blast Vol. (Nm^3/tHM)	980 - 1190	990 - 1150
Fuel Rate (kg/tHM)	510 - 570	470 - 530
Coke Rate (kg/tHM)	360 - 420	320 - 380
PCI-Rate (kg/tHM)	150	150
Raceway Adiabatic Flame Temperature RAFT (°C)	1920 - 2230	1980 - 2240
Slag volume (kg/tHM)	270 - 300	270 - 300
Shaft Efficiency (%)	74.4	82.7

Table 3: Impact of Ash content of PCI-Coal - Change from Base case for Approach- 1

Ash in PCI	% ad	10 (Base)	9	8	10 (Base)	9	8	10 (Base)	9	8
PCI Rate	kg/THM	100			150			200		
Coke Rate	kg/THM	405.27	-0.77	-1.83	366.64	-1.17	-2.75	326.92	-1.51	-3.61
Blast Rate	Nm^3/THM	1093.1	-2.46	-4.11	1017.0	-4.16	-6.21	950.2	-5.47	-8.84
Oxygen	Nm^3/THM	13.77	0.60	0.97	40.22	0.96	1.52	64.14	1.31	2.15
Slag Ratio	kg/THM	288.4	-1.7	-3.5	288.7	-2.39	-5.22	288.7	-3.3	-7.1
Top Gas Heat	kcal/THM	1263719	1578	2245	1317226	2438	3374	1363529	3527	4773
Blast Temp.	°C	1157			1157			1157		
Blast Moisture	gm/Nm^3	25			30			33		

Table 4: Impact of Ash content of PCI-Coal - Change from Base case for Approach- 2

		Case I			Case II			Case III		
Ash in PCI	%	10 (Base)	9	8	10 (Base)	9	8	10 (Base)	9	8
PCI Rate	kg/THM	150	-1.57	-3.69	150	-1.72	-3.48	150	-1.74	-3.45
Coke Rate	kg/THM	366.64			366.64			366.64		
Blast Rate	Nm^3/THM	1017.0	-0.91	0.74	1017.0	0.34	-0.49	1017.0	0.00	-0.04
Oxygen	Nm^3/THM	40.22	0.37	-0.41	40.22	0.01	-0.02	40.22	0.00	0.00
Slag Rate	kg/THM	288.7	-2.60	-5.15	288.7	-2.61	-5.07	288.7	-2.61	-5.13
Top Gas Heat	kcal/THM	1317246	259	-1812	1317246	-693	-444	1317246	-382	-816
Blast Temp.	°C	1157			1157			1157	1.10	-1.40
Blast Moisture	gm/Nm^3	30.0			30.0	-0.16	0.20	30.0		