A REPORT ON

"DATA DRIVEN ANALYSIS AND OPTIMIZATION OF FUEL RATE USING BLAST FURNACE PARAMETERS"

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FROM - 05/05/2025 TO 31/05/2025

REPORT SUBMITTED ON - 02/09/2025

CERTIFICATE

This is to certify that Piyush Narayan Rai has worked under my guidance for completion of his project on "DATA DRIVEN ANALYSIS AND OPTIMIZATION OF FUEL RATE USING BLAST FURNACE PARAMETERS " in Blast furnace division, Bhilai Steel Plant (BSP) from 05 May 2024 to 31st May 2024. Apart from suggestions made by me, the credit for all experimental work goes to him. I appreciate their hard working, involvement and tenacity to complete their project well in time.

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ACKNOWLEDGEMENT

We would like to express our sincere gratitude and appreciation to all those who have contributed us to the completion of this project.

First and foremost, we are deeply thankful to Shri. Satyabrata Sutar for their guidance, support, and invaluable insights throughout this endeavour. Their expertise and dedication have been instrumental in shaping the direction of our work and enhancing its quality. Their valuable feedback and constructive criticism, have immensely contributed to the refinement of this project.

We wish to thank and acknowledge all the help rendered by Shri. H K Verma . He encouraged us at difficult moment of study and instilled a lot of confidence.

Last but certainly not least, we want to acknowledge our family for their unwavering love, encouragement and understanding. Their constant support and belief in ourselves have been the driving force behind our achievements.

Thank you all for your invaluable support, guidance and encouragement.

HBT vs. Fuel Rate (Faceted by PCI Rate)

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ABSTRACT

Bhilai Steel Plant is the flagship of SAIL. The production capacity of Hot Metal, Crude Steel & Saleable Steel after completion of Modernisation & Expansion Programme (MEP Plant/unit wise) is as under:

Hot Metal – 7.5 MT (Million Tonnes)

Crude Steel – 7 MT

Saleable Steel – 6.56 MT

BSP being an integrated steel plant, where the role of Blast furnace is very important & performance of Blast furnace is judged by two very important factors, its coke rate and productivity.

This project report presents a comprehensive, data-driven analysis of key operational parameters influencing fuel rate optimization in Blast Furnace 8 at SAIL Bhilai Steel Plant (BSP).

The report begins with an overview of the Bhilai Steel Plant and its major departments, followed by a detailed examination of vital blast furnace parameters, including hot blast temperature, moisture content, CO utilization efficiency, slag rate, flame temperature, and top pressure. The interrelation among these parameters is also analyzed to understand their collective influence on furnace performance.

Using real-time industrial data from Blast Furnace 8, a variety of machine learning models were developed and evaluated to predict fuel rate. Tools and technologies such as Python, Pandas and Scikit-learn were employed for data preprocessing, model training, and result visualization. After comparing multiple models, the best-performing model was selected based on accuracy and robustness.

The latter sections of the report delve into the interpretation of code, visual output plots, and a parameter-wise analysis of how each variable affects fuel rate. Finally, the report concludes with a summary of findings and practical recommendations for optimizing fuel consumption in blast furnace operations, potentially leading to improved energy efficiency and reduced operational costs.

OVERVIEW

The Bhilai Steel Plant (BSP), located in Bhilai, in the Indian state of Chhattisgarh, is India's First and main producer of steel rails, as well as a major producer of wide steel plates and othersteel products.

Eleven times winner of Prime Minister's Trophy for Best Integrated Steel Plant in the Country,Bhilai Steel Plant (BSP) has been India's sole producer and supplier of world class Rails for Indian Railways including 260 metre long rails, and a major proudcer of large variety of wideand heavy steel plates and structural steel. With an annual production capacity of 5 MT of saleable steel, the plant also specializes in other products such as wire rods and merchant products. The entire range of TMT products (Bars and Rods) produced by the plant is of earthquake resistant grade and superior quality. The plant also produces heavy structural including channels and beans.

Bhilai Steel Plant functions as a unit of SAIL, with corporate offices in New Delhi. The chief Executive officer controls operations of the plant, township and iron mines. The CEO is assisted by his D.R.O.s(Direct Reporting Officers), i.e. the functional heads, Executive Directors, general Manager concept of zonal heads, and HODs who integrate functions with Clear accountability for achieving corporate vision, company goals and objectives.

Since BSP is accredited with ISO 9001:2000 Quality Management System Standard, all salteable products of Plant come under the ISO umbrella. The Plant's HR Dept. is also Certifiedwith ISO 9001:2000 QMS Standard. ISO: 141001 has been awarded for environment Management System in the Plant, Township and Dalli Mines. The Plant is accredited with SA:8000 certification for social accountability and the OHSAS-18001 Certification for Occupational Health and Safety.

BSP has receive Integrated Management System (IMS) Certificate by a single certifiying agency (M/s DNV), Integrating QMS, EMS, and OHSAS & SAMS- becoming the first SAIL unit and among few corporate houses in India to achieve this unique distinction.

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Sources of Raw materials in BSP –
Presently, the total requirement of iron ore of Bhilai Steel Plant is met from Dalli Rajhara IronOre Complex (IOC). In view of IOC’s rapidly depleting reserves, BSP is opening an iron ore mine at Rowghat, about 80 kilometres (50 mi) from Dalli Rajhara in Narayanpur District of Chhattisgarh. Accordingly, Bhilai Steel Plant will develop the mine in Block-A of deposit-F of Rowghat with a production capacity of 14.0 MT per year during 2011-12.

S.No.	Raw materials	Sources
1	Iron Ore Fines	Dalli Rajhra
2	Iron ore lumps	Dalli Rajhra
3	High Silica Limestone	Nandini
4	High Silica Dolomite	Hirri Mines
5	Low Silica Limestone	Jaiselmer, katni, kuteshwar
6	High Silica Mn Ore	Rantake Tirodi
7	Coal (Indegenous)	Bhojudh, Nandan,Rajarappa
8	Coal (Imported)	Australia, New Zealand

BLAST FURNACE PARAMETERS

In blast furnace ironmaking, fuel rate (typically the coke and injectant consumption per ton of hot metal) is a key performance indicator. Fuel costs often comprise 40–60% of hot metal production costs, so minimizing the fuel rate is essential for economic and environmental reasons. The fuel rate is influenced by many operational parameters, including the blast air temperature, burden moisture, gas utilization, slag volume, flame (raceway) temperature, and furnace top pressure. Each of these parameters affects the furnace's thermal balance and reduction efficiency, and thus the required fuel input. Below we examine the role of each parameter, its effect on fuel consumption, and how it interrelates with overall furnace performance.

➢ Hot Blast Temperature

Pre-heated air, or 'hot blast' is blown into the blast furnace via the tuyeres at a temperature of up to 1200°C. The hot blast burns the fuel that is in front of the tuyere, which is either coke or another fuel that has been injected into the furnace through the tuyeres. This burning generates a very hot flame and at the same time the oxygen in the blast is transformed into gaseous carbon monoxide (CO). The resulting gas has a flame temperature of between 2000 and 2300°C. Since the gas flow is very high, the residence time of the gas is very short, typically 6-10 seconds. In the 6-10 seconds, the heat generated at the tuyeres is transferred to the burden: the gas leaves the furnace with an average temperature of 100-150°C. However, in the centre of the furnace the coke chimney will allow much higher temperatures to be observed, up to 600 880°C or even higher. In the same 6-10 seconds the gas carries out a number of chemical reactions that go along way to make the furnace such an efficient process for the production of iron. Hot blast temperature is normally at or close to its maximum. The cheapest fuel used in the BF is the BF gas itself and this reduces the coke rate requirement.

Raising the blast air temperature reduces the coke required to reach the same internal temperatures. Studies report that when maintaining hot blast between about 1000 °C and 1200 °C, each 100 °C increase cuts the coke rate by roughly 2.8%. In practice, higher stove or stove bank performance (raising blast above nominal levels) has been shown to save significant fuel, on the order of 80–85 MJ per ton of hot metal. Optimizing blast temperature is thus crucial: too low a temperature forces extra coke firing, while too high a temperature can overheat equipment and risk damage. In summary, maintaining an elevated, stable hot blast temperature maximizes heat transfer to the burden and lowers the fuel rate.

➢ Moisture injection

A uniform and steady RAFT is on the basic prerequisite for smooth BF operation. RAFT is sensitive to moisture content of the blast, and moisture varies from season to season. Pre-heating of blast not only adds heat energy in the furnace, but also increases the RAFT. There is a limit to which RAFT can be allowed to increase, depending upon the burden characteristics and furnace profile, and beyond which it is detrimental to furnace operation. Blast temperature can be increased still further without increase in RAFT if equivalent coolants are added along with the blast. Steam is one such additive because of its endothermic reaction with carbon. The presence of moisture in the blast generates double the volume of reducing gas per mol of carbon burnt. for every carbon burnt one mol of CO and an additional mol of H2 will be available. More moisture the more will be this additional hydrogen available. Kinetically, hydrogen reduction of iron ore is faster than by CO. The presence of moisture helps to burn coke at a faster rate. Some of the endothermic heat of moisture disintegration is compensated by exothermic reduction of iron oxide by hydrogen. For an increase of 20 g/N m3 moisture in blast, endothermi heat can be compensated by a rise of 200 °C in the blast pre-heat.The endothermic nature of reaction between carbon and moisture is utilized with the following objectives:

(i) To decrease the erratic movement of the furnace when the flame temperature increases beyond a limit,
(ii) To use higher blast temperature while maintaining the RAFT constant,
(iii) To maintain uniformity in level of moisture in the blast which fluctuates seasonally, thus disrupting thermal regime of the furnace,
(iv) With increase in blast humidity, hydrogen in the bosh gas increases which in turn decreases the coke rate.

Most of the world’s highly productive BFs operate with blast humidity ranging between 15 and 20 g/N m3 mainly due to superior raw materials which are capable of accepting higher RAFT (2100–2300 °C).
Although increase in blast humidity decreases the RAFT, the simultaneous decrease in coke rate,Si, S content in hot metal could be attributed to the better efficiency of gas utilization. Japanese have also gone in for higher steam injection to produce low Si hot metal

➢ Carbon Monoxide (CO) Utilization Efficiency / Gas utilization Efficiency

Firstly, the heat with a temperature in excess of 1400°C is heating up the coke and the melting materials flowing over the coke. In the temperature range from 1200-1350°C the burden will soften and stick together rather than melt. In the cohesive zone the remaining oxygen in the ore burden is removed, which generates additional carbon monoxide gas. This is referred to as the direct reduction reaction or solution loss. At the high local temperature, the remaining oxygen of the melting burden reacts with coke and generates extra carbon monoxide gas. In general, the ore burden which is charged into the furnace has close to 3 atoms of oxygen for every 2 atoms of iron. About 2 of the 3 oxygen atoms are removed by reaction with gas and about 1 of the 3 oxygen atoms is removed by this direct reduction reaction Since the direct reduction reaction needs a lot of energy, the efficiency of the furnace is largely dependent on the amount of oxygen removed from the burden materials before reaching the 1200°C critical temperature. When the gas is cooling down further, below 1200°C, the gas contains a high amount of carbon monoxide and hydrogen. These components are effective in removing oxygen from the iron units and they form carbon dioxide and water, which leave the furnace out from the top. This is called 'gas reduction'. The oxygen content of the ore burden is reduced with gas. As soon as the gas emperature is below 500°C, the chemical reactions stop and the gas uses only its heat for heating up the burden and expelling moisture from the burden and coke.

➢ ETA CO / Gas Utilization Efficiency

ETA CO / Gas Utilization Efficiency ***= (sCO_2 / (CO + CO_2)) × 100***

- 3Fe203 + CO- 2Fe304 + CO2
  Hematite + Carbon Monoxide- Magnetite + Carbon Dioxide
- Fe304 + CO- 3FeO +C02
  Magnetite + Carbon Monoxide- Wustite + Carbon Dioxide
- FeO + CO- Fe +C02
  Wustite + Carbon Monoxide- Iron metal (solid) + Carbon Dioxide

CO utilization efficiency in blast furnace top gas, shows how well CO is used for ore reduction. A **low ratio** means more CO is converted to CO_2, indicating efficient fuel use. A **high ratio** signals wasted CO and higher coke demand. Improving CO efficiency—through better gas-solid contact or longer gas residence time—lowers coke consumption. Furnace controls monitor this ratio to optimize fuel use, adjusting factors like oxygen enrichment and coke injection to ensure CO is effectively consumed.

- **Slag Rate**

The blast furnace process results in liquid iron and slag being produced. These two liquids drip down into the coke-filled hearth of the blast furnace where they wait to be tapped, or cast from the furnace. The densities of the two liquids are quite different; with iron (7.2 t/m3) being three times that of slag (2.4 t/m3). This difference leads to very good separation between the iron and the slag once it is outside the furnace. If the slag level is so high that it reaches the tuyeres then the gas flow will be severely affected. This can result in poor reduction of the burden and therefore a chilling furnace. The slag can be blown high up in the dead man coke, impeding normal gas distribution.

A higher slag rate increases fuel consumption because more flux and impurities must be melted, requiring additional heat. This raises the furnace's endothermic thm and coke use. While slag is necessary to capture impurities, minimizing excess slag improves fuel efficiency by reducing heat losses. Optimal slag rates balance impurity removal with lower thermal and fuel demands.

- **Flame Temperature**

The flame temperature in the raceway is the temperature that the raceway gas reaches as soon as all oxygen and water have been converted to CO and H2. The flame temperature is a theoretical concept, since not all reactions are completed in the raceway. From a theoretical point of view, it should be calculated from a heat balance calculation over the raceway. For practical purposes linear formulas have been derived, basically all steel plants use their own formula, but the standard calculation as defined by AISI is

Metric Units

RAFT = 1489 + 0.82xBT – 5.705xBM + 52.778x(OE) – 18.1xCoal/WCx100 – 43.01xOil/WCx100 – 27.9xTar/WCx100 – 50.66xNG/WCx100

Where:	BT	= Blast Temperature in °C
	BM	= Blast Moisture in grams/Nm^3 dry blast
	OE	= Oxygen enrichment, %02 – 21%
	Oil	= Dry oil injection rate in kg/tHM
	Tar	= Dry tar injection rate in kg/tHM
	Coal	= Dry coal injection rate in kg/tHM
	NG	= Natural gas injection rate in kg/tHM
	WC	= Wind Consumption m^3/tHM

Flame temperatures are normally in the range of 2000-2300°C. The flame temperature is influenced by the raceway conditions. Qualitatively: the flame temperature increases, if: Hot blast temperature increases, Oxygen percentage in blast increases. The flame temperature decreases, if: Moisture increases in the blast, Fuel injection rate increases, since cold fuels are burned instead of hot coke. The precise effect depends also on auxiliary fuel composition. Some companies tend to keep flame temperature constant. In itself this is a good strategy, since a blast furnace runs best if you keep everything constant. However, we have experienced that furnaces can operate well in a wide range of flame temperatures.

Higher flame temperatures improve combustion efficiency by converting more fuel energy into heat, reducing coke use. Methods like oxygen enrichment and hot blast increase this temperature, enhancing heat transfer to the burden. However, too low a flame temperature causes incomplete combustion, while too high can damage furnace materials. Optimizing flame temperature boosts thermal efficiency and lowers the fuel rate.

- **Top Pressure**

For the BF operator, one of the main raw material concerns is that of the fines thming. This is the proportion of undersize material that is in the furnace. The direct effect of a high fines thming is that it will affect the permeability of the furnace. Whether it is ferrous or carbon fines, the result is that the gaps through which the gasses pass will be blocked. The first effect of this is that the blast pressure will increase, increasing the difference between the top pressure and the blast pressure, known as delta-P. As the top pressure is usually kept constant, in the case where the blast pressure is limited by the structural integrity of the stoves, the wind rate must be reduced whenever the blast pressure increases.
The delta-P, ΔP, or pressure differential is a number calculated by subtracting the top pressure from the blast pressure.

$$\boxed{\Delta P = \text{Blast Pressure} - \text{Top Pressure}}$$

As the blast pressure increases it will increase the upward force on the descending burden, causing it to 'hang'. If nothing is done to relieve the pressure, then the gas will find an escape route, often against the wall, resulting in high heat losses, or through the burden, known as channeling. The sudden pressure relief then allows the burden to descend in an uncontrolled way, known as a 'slip'. There are of course other causes if the delta-P increasing, and for hanging and slipping to occur, but an increase in fines thming, without any actions taken to compensate for it, is likely to cause problems with the furnace operation.

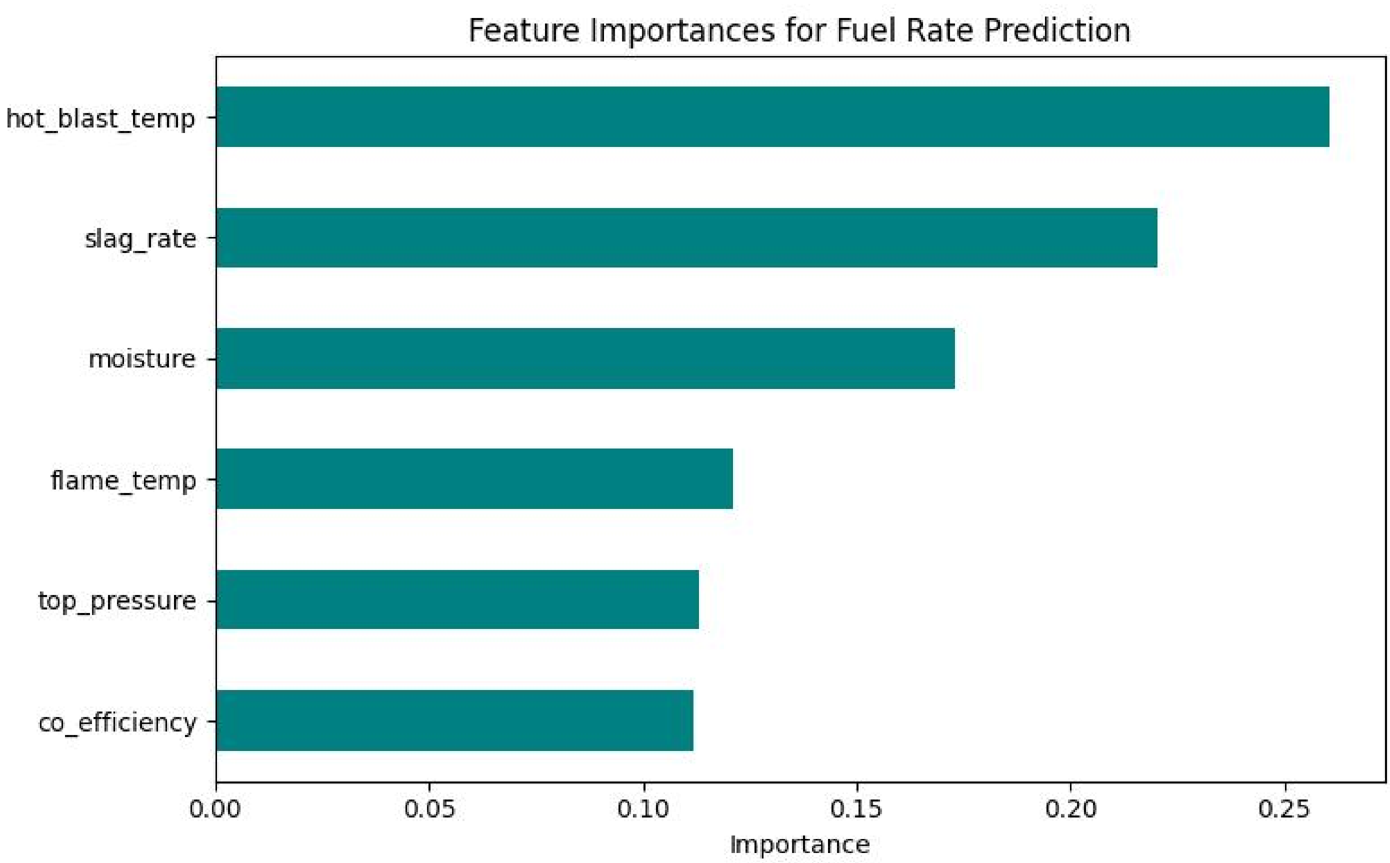
Blast furnace top pressure (gauge pressure at the furnace throat) influences gas flow and retention time. Typically, it's slightly negative or low positive; increasing it (e.g., above 0.5 bar) improves gas-solid reactions. Higher pressure slows gas up flow, increasing contact time between reducing gases and descending ore, which enhances reduction and reduces coke usage. This results in lower fuel rates and more efficient operation. Higher pressure also stabilizes furnace performance and can enable power generation from off-gases, offsetting plant energy needs. Optimizing top pressure reduces coke and injectant requirements while improving heat utilization.

Tech Stack / Tools used-

- **Languages & Environments:** Python, VS Code, Jupyter Notebook
- **Data Handling:** pandas, numpy
- **Machine_Learning:** scikit-learn(RandomForestRegressor, GradientBoostingRegressor, LinearRegression, DecisionTreeRegressor)
- **Data Visualization:** plotly, matplotlib, seaborn
- **Model Evaluation & Metrics:** r2_score, mean_squared_error, train_test_split
- **Model Deployment & Persistence:** joblib

BEST MODEL FOR FUEL RATE PREDICTION

- The Random Forest(Tuned) model was selected as the best performer because it achieved the highest R² score among all tested models,
- The model performance comparision is attached below



Fuel Rate Prediction Model

We also made a prediction model to study the changes in fuel rate while changing the blast furnace parameters.

The fuel rate prediction model gives approximately accurate figures
For example according to the given inputs the actual fuel rate is 573.3
The predicted fuel rate is 573.5

```
PS C:\Users\piyus\.vscode\CODES> python -u "c:\Users\piyus\.vscode\CODES\finalexp.py"

Data shape after outlier removal: (209, 7)

Tuning Random Forest...
Best RF Params: {'max_depth': None, 'min_samples_split': 5, 'n_estimators': 100}

Tuning Gradient Boosting...
Best GB Params: {'learning_rate': 0.05, 'max_depth': 3, 'n_estimators': 100}
Linear Regression - MSE: 207.47, R2: 0.27
Decision Tree - MSE: 297.89, R2: -0.05
Random Forest (Tuned) - MSE: 165.81, R2: 0.42
Gradient Boosting (Tuned) - MSE: 198.09, R2: 0.30

Model Evaluation Results:
                        Model         MSE  R2 Score
0           Linear Regression  207.469673  0.270912
1               Decision Tree  297.893016 -0.046853
2       Random Forest (Tuned)  165.814301  0.417297
3   Gradient Boosting (Tuned)  198.086702  0.303886
Enter moisture: 5.5
Enter co efficiency: 46.65
Enter hot blast temp: 1181.71
Enter slag rate: 507
Enter flame temp: 2208.6
Enter top pressure: 2.26

Predicted Fuel Rate for New Data: 573.525401190476

Model saved as 'fuel_rate_rf_model.pkl'
Cleaned data saved as 'cleaned_blast_furnace_data.csv'
PS C:\Users\piyus\.vscode\CODES>
```

OUTPUT DATA

The operational data from the blast furnace, recorded as daily averages, is not a record of a controlled scientific experiment where single variables are changed in isolation. Instead, each day's data point is a reflection of a complex system being constantly adjusted over 24 hours to remain within a narrow, optimal "operating window.

This fundamental distinction is the primary reason why simple scatter plots can yield results that appear to contradict established metallurgical theory.

The primary goal of the blast furnace operator throughout each day is to maintain process stability and achieve consistent product quality. Operators work to keep the furnace within a stable operating window, which is defined by critical constraints.

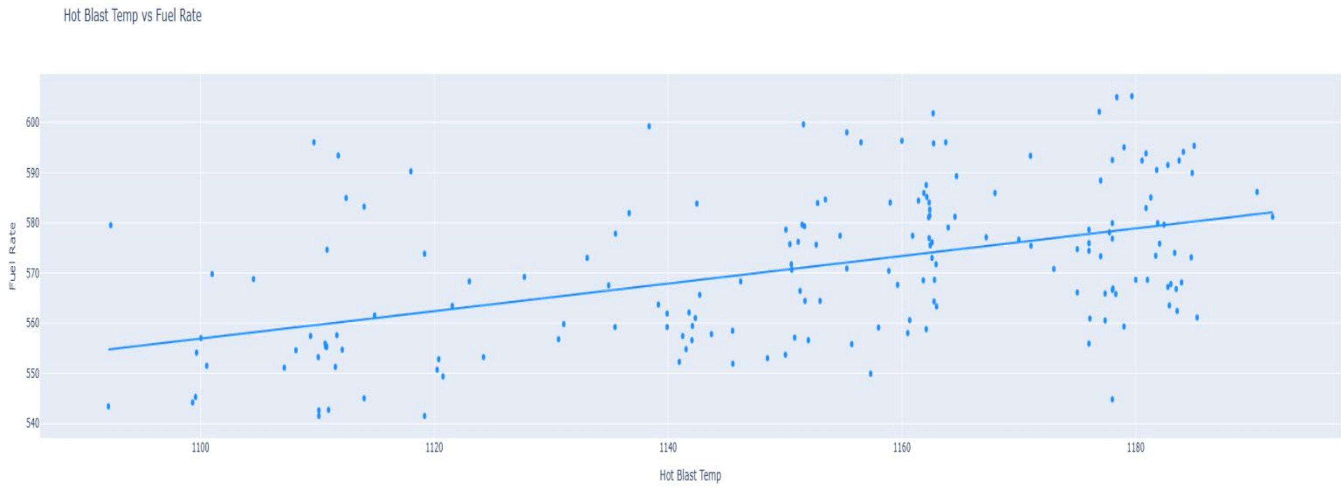
For instance, the top gas temperature must remain above approximately 100°C to prevent water condensation, while the flame temperature (RAFT) must be high enough (e.g., above 1800°C) to supply the necessary thermal energy.

The data points in plots, representing the average for an entire day, capture the net result of all the continuous adjustments operators made during that period to stay within this window.

Table 1: Summary of Theoretical vs. Observed Relationships

Parameter	Theoretical Relationship with Fuel Rate	Observed Trend in Provided Graph	Primary Reason for Discrepancy
Hot Blast Temperature	Negative (Higher temp = less fuel)	Positive	Compensatory Control for Thermal Stability/ Control
Moisture Injection	Positive (Moisture cools = more fuel)	Negative	Use as a Fast-Acting Coolant for an Overheated Furnace
Slag Rate	Positive (More slag = more energy = more fuel)	Positive	Direct Energy Penalty (Matches Theory)
Top Pressure	Negative (Better reduction = less fuel)	Slightly Positive	High-Productivity Operating Regimes
Flame Temperature	Negative (Hotter flame = less fuel)	Positive	Compensatory Control & High-Throughput Operation
CO Efficiency (Eta CO)	Negative (Higher efficiency = less fuel)	Flat / No Trend	Successful Process Control (Kept in a Stable Range)

➢ Hot Blast Temperature



Analysis of Graph: The scatter plot of daily averages shows a clear, albeit noisy, positive trendline. On days when the average hot blast temperature was higher, increasing from approximately 1090°C to 1190°C, the corresponding average fuel rate for that day also trended upward from around 555 kg/thm to over 580 kg/thm. This is in direct opposition to the fundamental principle.

Reconciliation: This counterintuitive positive correlation is a classic artifact of confounding variables and the compensatory control strategies employed over a 24-hour period. The daily data point doesn't show an isolated action but rather the net result of a day's worth of balancing thermal conditions.

Control of Hot Metal Silicon: The silicon content in the hot metal is the primary indicator of the hearth's thermal condition. If the furnace shows signs of running cold (indicated by lower hot metal temperature and silicon), the day's operational strategy must involve adding heat to restore balance. The operators will run with a higher average hot blast temperature to provide more sensible heat and a higher average coke rate (fuel rate) to provide more chemical heat. The daily average data captures the result of these concerted, day-long actions to combat a cooling furnace. Consequently, it records days of high average hot blast temperature co-occurring with days of high average fuel rate, creating a positive correlation.·

Compensation for High Injectant Rates: PCI has a cooling effect on the raceway. To enable these high PCI rates, operators must raise the hot blast temperature to compensate for the cooling effect and maintain the overall heat balance and RAFT. Therefore, operational periods characterized by high total fuel injection rates (coke + high PCI) are also the periods that necessitate a high hot blast temperature.

The Significance and Effect of Oxygen Enrichment in Blast Furnace Operation

Massive Increase in Flame Temperature (RAFT): This is the most immediate and powerful effect. By replacing inert nitrogen (N_2) with reactive oxygen (O_2), the combustion of coke and injectants at the tuyeres becomes far more intense, significantly raising the RAFT.

A higher oxygen level allows for the combustion of more fuel in the same amount of time. This increases the production rate of hot metal (tons per day).

By increasing the flame temperature, oxygen enrichment improves the thermal efficiency of the furnace. This allows for a higher replacement ratio of cheaper injectants (like PCI) for expensive metallurgical coke, leading to a lower overall fuel rate. A common rule of thumb is that a 1% increase in oxygen enrichment can decrease the coke rate by 10-15 kg/thm.

The primary limitation is the flame temperature itself. If the RAFT becomes too high (e.g., >2300°C), it can cause severe operational problems, including damage to the tuyeres and poor permeability. Therefore, oxygen enrichment is almost never used in isolation.

The Challenge: High rates of Pulverized Coal Injection (PCI) are economically desirable but have a strong cooling effect on the raceway.

The Operator's Toolkit: To counteract this cooling, the operator has two primary tools: increasing Hot Blast Temperature and increasing Oxygen Enrichment.

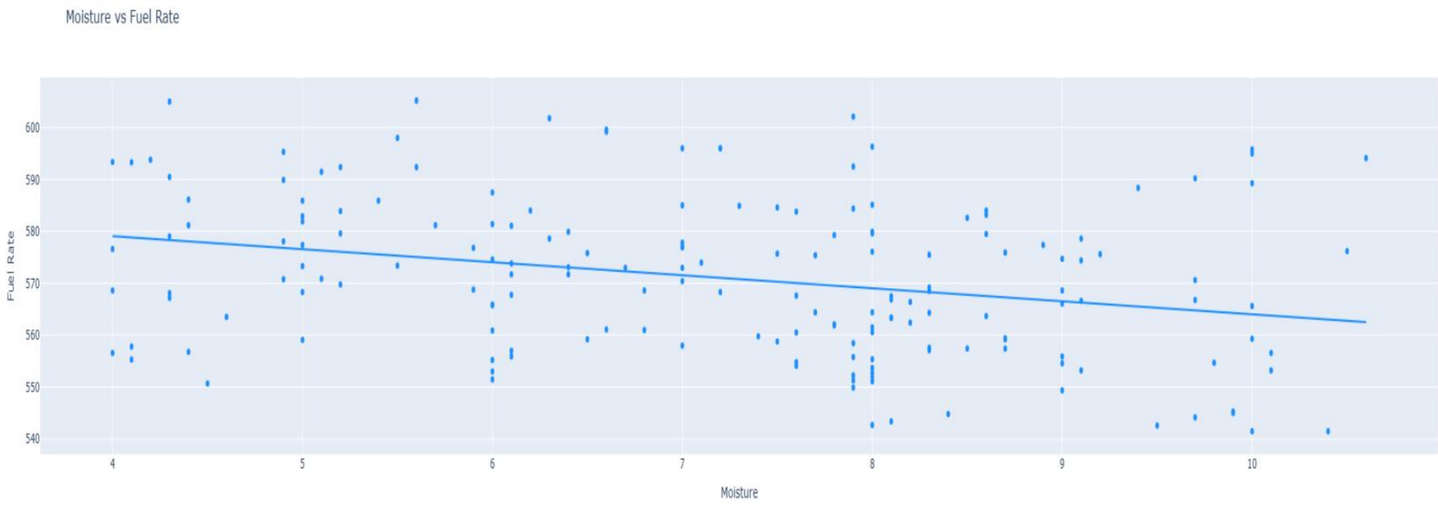
The Synergy: Increasing blast temperature alone is often insufficient to compensate for very high PCI rates. Therefore, on days with the highest PCI injection, operators use a three-part strategy:

High PCI Rate: To replace expensive coke (contributes to a high total fuel rate).

High Oxygen Enrichment: To significantly boost the flame temperature and provide the intense heat needed to combust the coal efficiently.

High Hot Blast Temperature: To provide additional sensible heat and further support the high injection strategy.

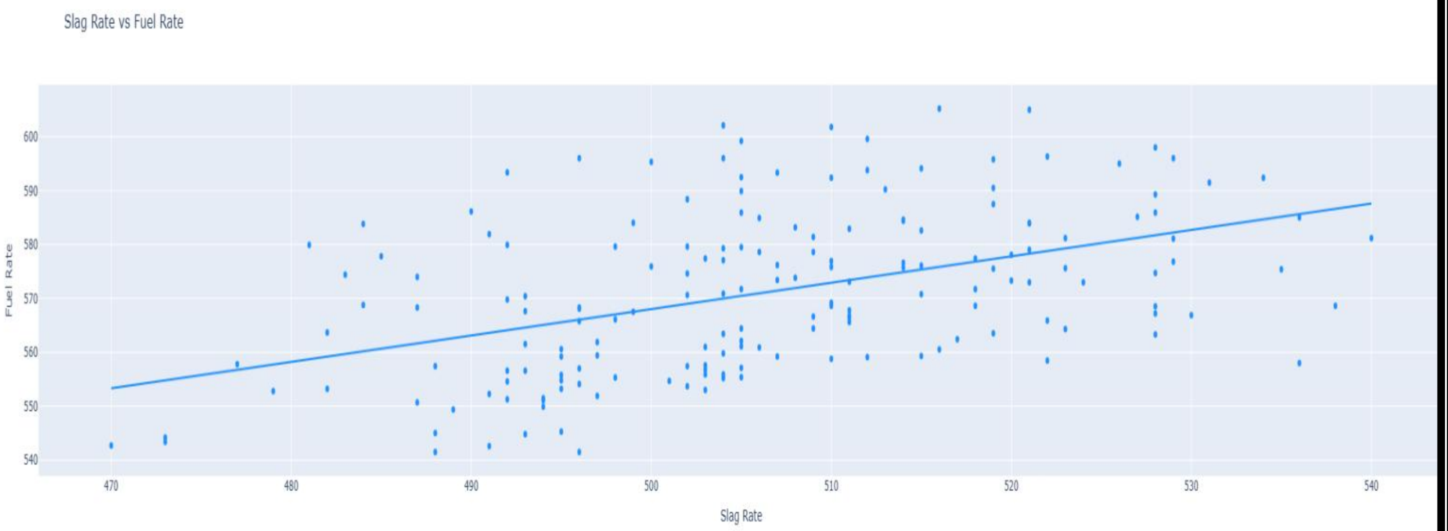
➢ Moisture Injection



- **Analysis of Graph:** A distinct negative trendline. As the moisture content in the blast increases from approximately 4 g/Nm³ to over 10 g/Nm³, the fuel rate trends downward from roughly 580 kg/thm to 565 kg/thm.
- **Reconciliation:** This complete reversal of the expected trend is a prime example of how a parameter's use as a control tool can invert its apparent correlation with an outcome.
- **Moisture as a Fast-Acting Coolant**: Operators use moisture injection not to heat the furnace, but as a primary, fast-acting lever to cool the raceway. An excessively high flame temperature (e.g., above 2400-2450 K) can lead to severe operational problems, including premature melting of the burden high in the furnace, which degrades permeability, and accelerated wear of the refractory lining.
- **Correlation with an Efficient State:** A blast furnace that is running hot is, by definition, in a highly efficient thermal state. This efficiency means it can produce hot metal with a lower specific fuel consumption. It is precisely under these hot, efficient, low-fuel-rate conditions that the RAFT is most likely to approach its upper operational limit. To prevent overheating, the operator will inject moisture to absorb excess heat and moderate the flame temperature. The

operational data therefore captures a correlation between the symptom of an efficient furnace (the need for cooling via moisture injection) and the result of an efficient furnace (a low fuel rate). The moisture injection does not cause the fuel rate to decrease; it is a response to the same underlying high-temperature condition that allows for a lower fuel rate in the first place.

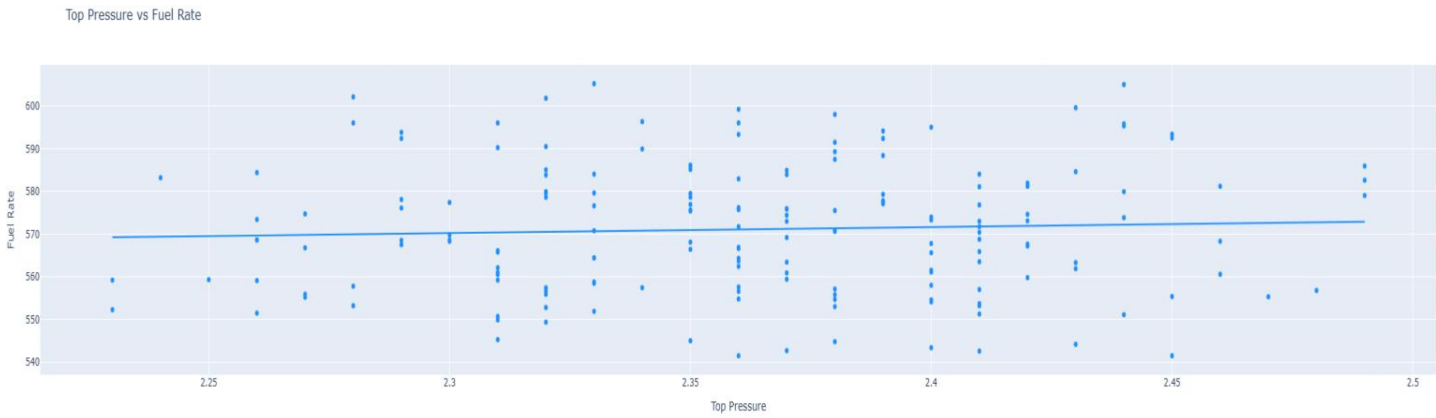
➢ Slag Rate



- **Analysis of Graph:** A clear and relatively strong positive trendline. As the slag rate increases from approximately 470 kg/thm to 540 kg/thm, the fuel rate trends upward from about 555 kg/thm to 585 kg/thm.

- **Reconciliation:** In this case, the observed operational data perfectly aligns with the established metallurgical principle. The relationship between slag rate and fuel rate is less susceptible to being inverted by control logic because a high slag rate is almost universally detrimental to energy efficiency and productivity. There is no operational scenario where an operator would intentionally increase the slag rate to achieve a different process goal. The slag rate is primarily determined by the quality of the raw materials (iron ore and coke) being charged. This graph is a direct reflection of the energy penalty associated with processing lower-quality inputs that contain higher levels of gangue and ash.

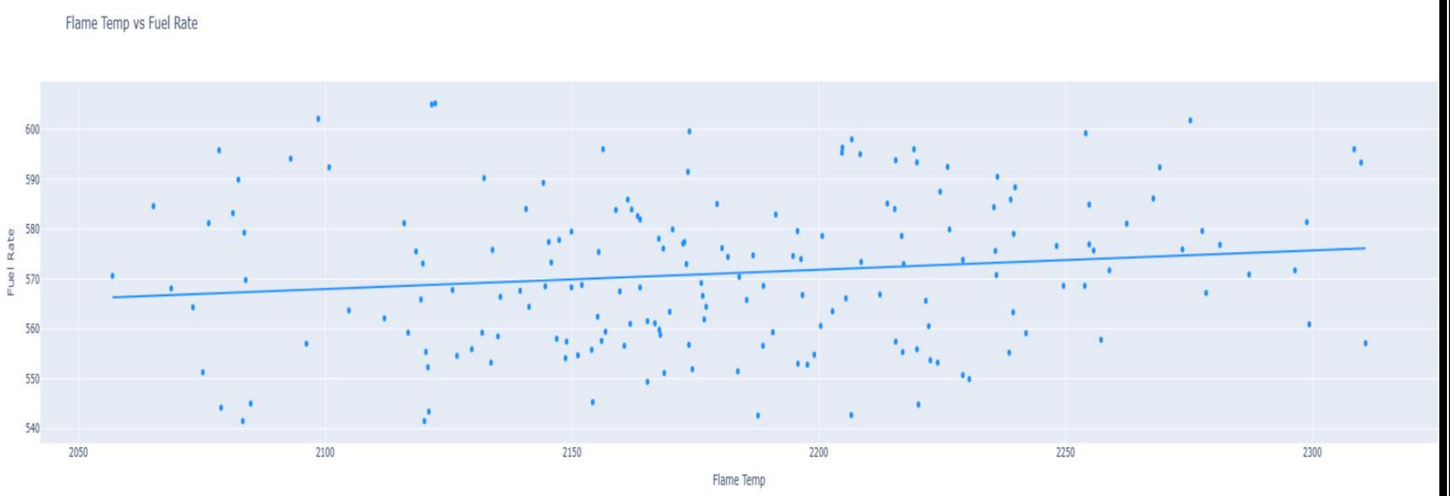
➢ Top Pressure



- Analysis of Graph: a very weak, nearly flat, but slightly positive trendline. There is no evidence of the expected negative correlation.
- Reconciliation: The strong theoretical benefit of high top pressure is being masked by its direct link to high-productivity operating regimes.
- Enabling High Productivity: High top pressure is a prerequisite for achieving high productivity. It provides a greater pressure differential between the tuyeres and the top, allowing operators to blow a larger volume of wind (blast volume) into the furnace without reaching excessive gas velocities that would fluidize the bed, disrupt the smooth descent of the burden, and increase flue dust losses.
- Confounding by Production Rate: The data points with the highest top pressure likely correspond to operational periods where the primary goal was to maximize hot metal output. During these high-throughput campaigns, operators push all inputs to their limits: blast volume, oxygen enrichment, and total fuel injection rates are all increased. While the specific fuel rate (kg/thm) might be lower in these periods due to the efficiency gains of high pressure,

the absolute fuel consumption per hour is higher simply because the furnace is processing more material. The y-axis of the plot is "Fuel Rate," which is typically measured in kg/thm. However, if the data points are aggregated over shifts or days with varying production targets, the plot can inadvertently correlate the conditions required for high throughput (high top pressure) with the higher fuel consumption associated with those periods.

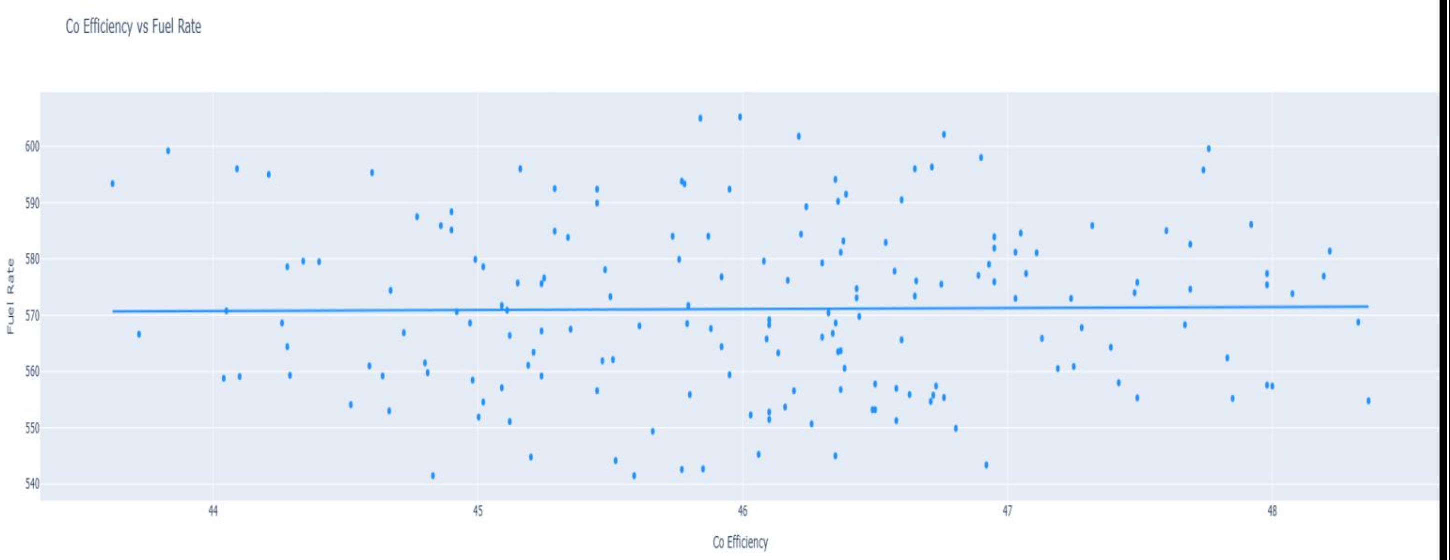
➢ Flame Temperature



- ➢ Analysis of Graph: Plotting Flame Temperature vs. Fuel Rate, shows a weak but positive trend. As flame temperature increases, the fuel rate also tends to increase slightly.
- ➢ Reconciliation: This paradox arises because RAFT is not an independent input variable but a calculated result of several other inputs that are manipulated in concert.
- ➢ RAFT as a Controlled Output: RAFT is a function of hot blast temperature, blast moisture, oxygen enrichment, and the type and amount of fuels. Operators do not set the RAFT directly; they adjust these other parameters to achieve a target RAFT to ensure stable operation.

➢ Compensatory Actions for Fuel Injection: As established, the injection of auxiliary fuels like PCI or natural gas has a cooling effect on the raceway. To operate at high injection rates (a strategy to reduce the consumption of expensive coke), operators must take compensatory actions to bring the RAFT back up into the optimal range. These actions include increasing the hot blast temperature and enriching the blast with oxygen. Therefore, the data points in the graph that show the highest flame temperatures are often the same data points that correspond to periods of high total fuel injection (coke + PCI) coupled with high levels of compensatory oxygen and blast heat. This complex interplay, driven by the goal of maintaining a stable RAFT while maximizing the use of cheaper injectants, creates the observed positive correlation.

➢ CO Efficiency (ETA CO)

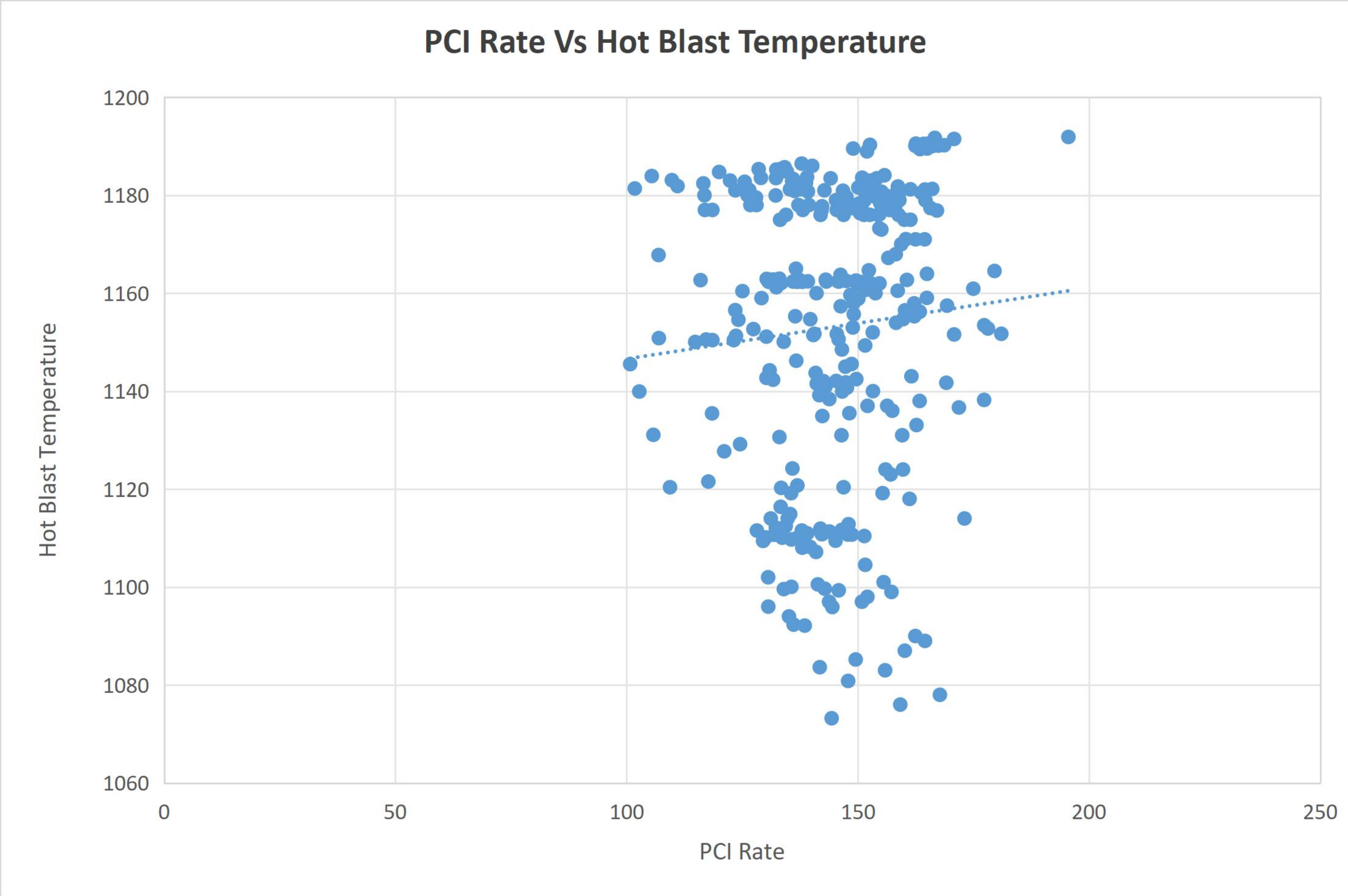


➢ Analysis of Graph: Plotting CO Efficiency vs. Fuel Rate, shows an almost perfectly flat trendline. The data points are scattered in a horizontal band, indicating no discernible correlation between the two variables.

➢ Reconciliation: This flat line is perhaps the most compelling evidence of a tightly and successfully controlled process.

- The Goal of Process Control: A primary objective of modern blast furnace operation is to maximize gas utilization efficiency. Operators and advanced control systems use sophisticated tools, such as bell-less charging systems, to precisely control the distribution of the burden materials at the furnace top. This control aims to create a stable and optimized gas flow pattern throughout the furnace cross-section, ensuring maximum contact between the reducing gases and the iron-bearing burden, thereby keeping ηCO in a narrow, high, and stable range.
- Success Masking Correlation: The furnace is not allowed to operate for extended periods with poor gas efficiency. Any significant deviation in the radial gas distribution, which would affect ηCO, is detected by sensors and quickly corrected by adjusting the charging pattern or other parameters. The flat trendline does not imply that ηCO is unimportant for fuel efficiency; on the contrary, it signifies that the control of ηCO is so successful that its value is held relatively constant. The scatter of points around this flat line simply represents the small, continuous fluctuations around the desired operational setpoint. The strong underlying relationship is masked because the furnace is always operated in a state of high efficiency.

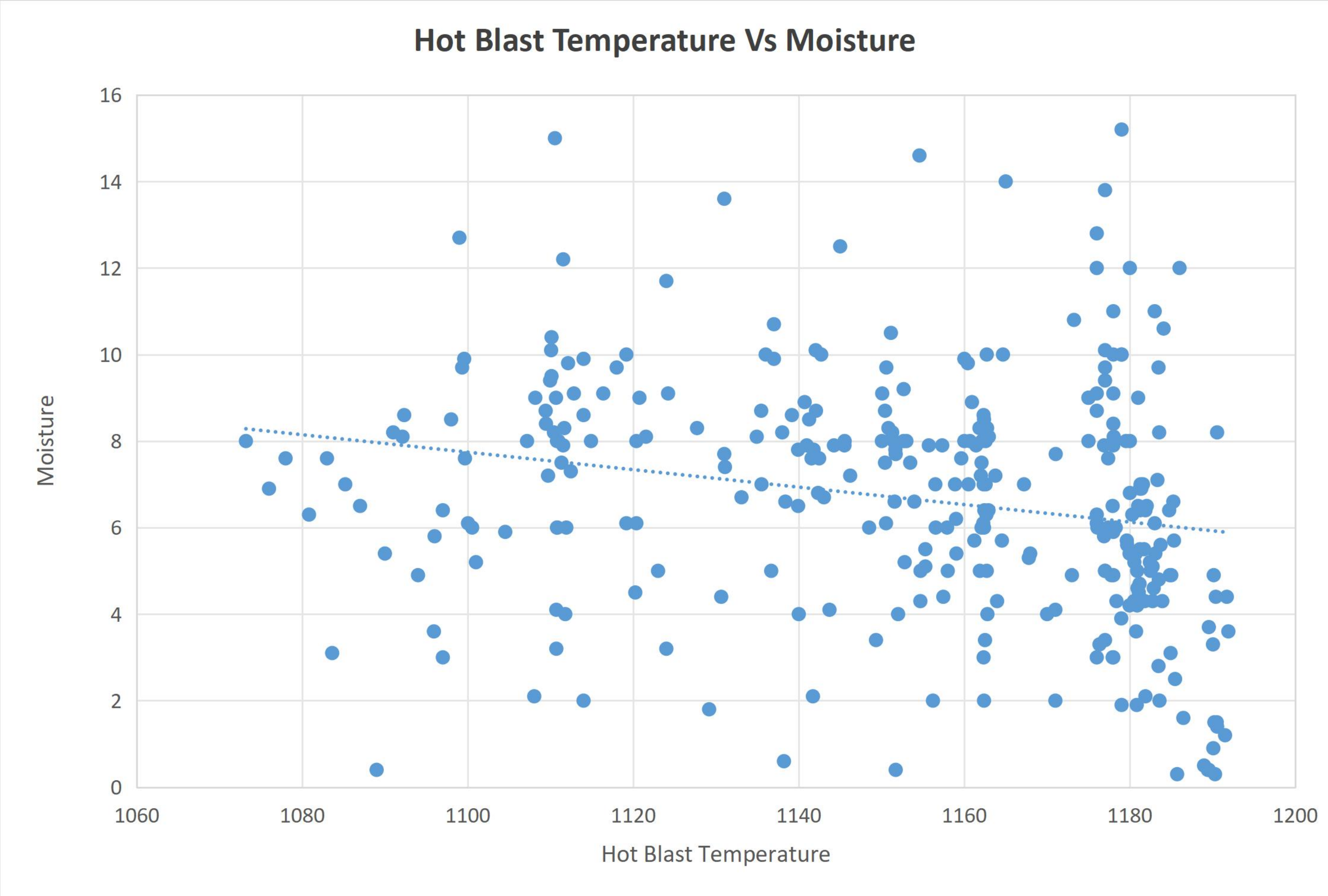
DATA SUPPORTING VISUALIZED DATA



PCI Rate vs. Hot Blast Temperature:

Observation: The plot shows a weak but clear positive correlation. As the rate of Pulverized Coal Injection (PCI) increases, the Hot Blast Temperature is also operated at a higher level.

Metallurgical Interpretation: This perfectly aligns with established theory. PCI has a significant cooling effect on the raceway. To counteract this and maintain the required thermal energy and flame temperature, operators must provide compensatory heat by increasing the temperature of the hot blast. This graph is a clear signature of this essential balancing act.



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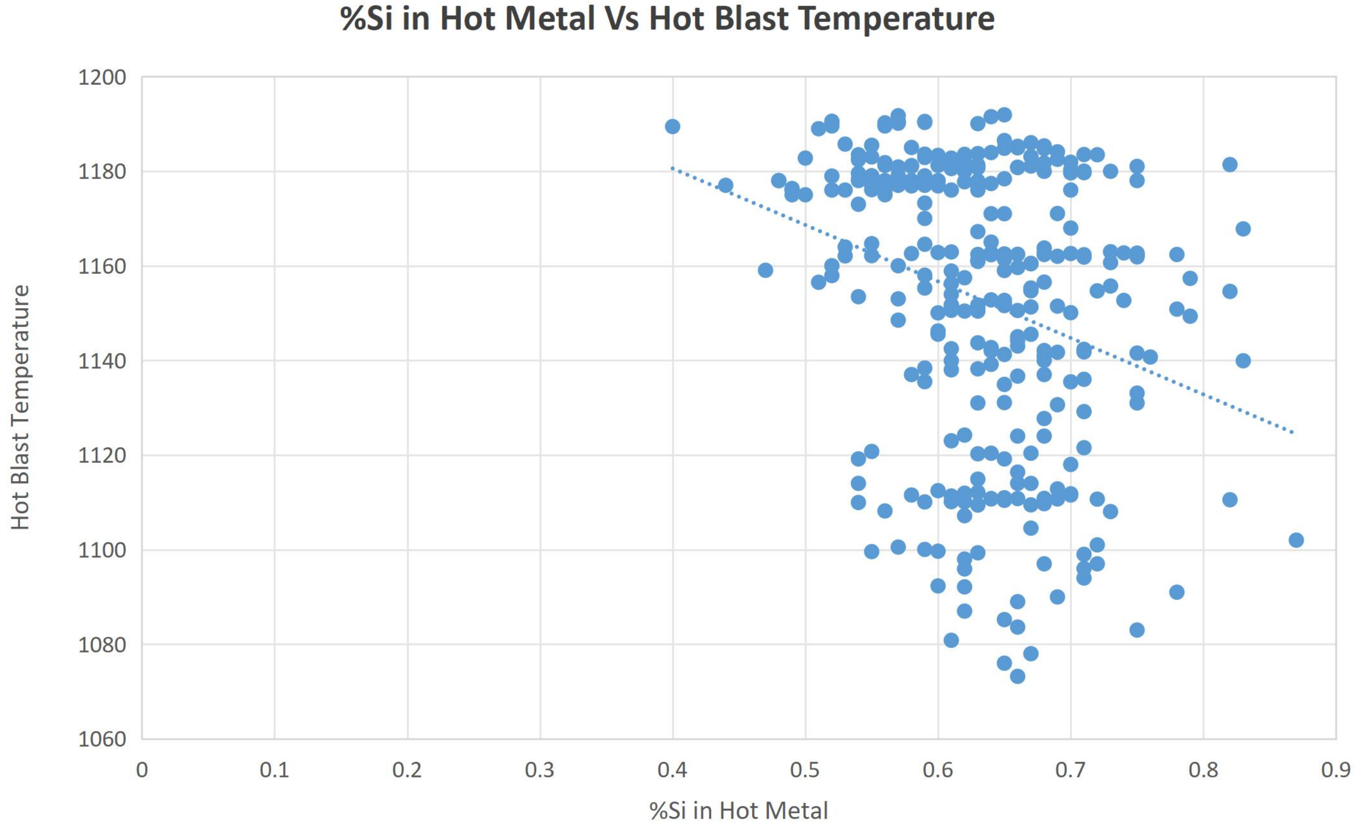
Hot Blast Temperature vs. Moisture:

Observation: The plot displays a weak negative correlation. Days with higher Hot Blast Temperatures tend to have lower Moisture injection, and vice-versa.

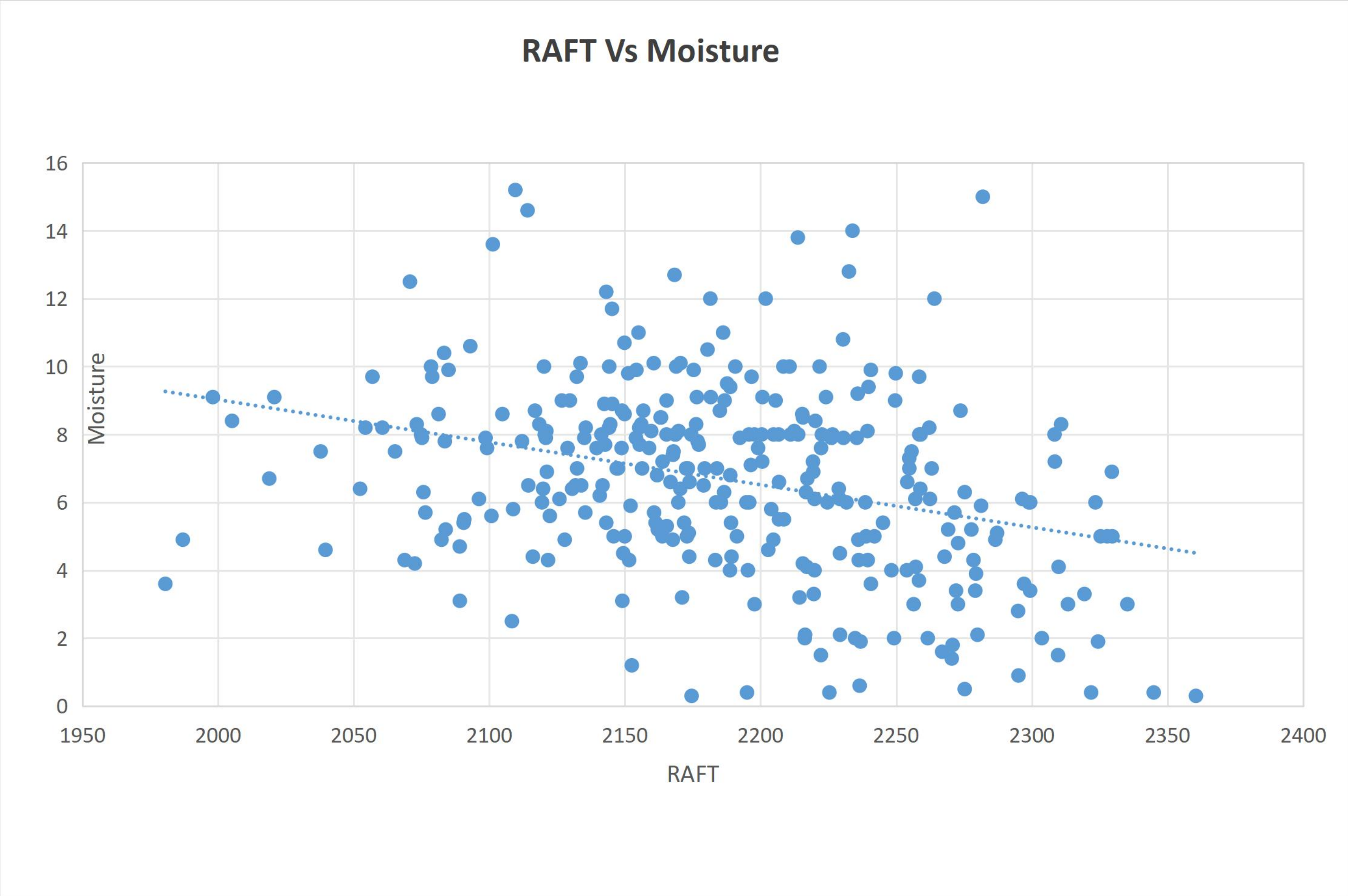
Metallurgical Interpretation: This demonstrates that Hot Blast Temperature and Moisture are used as opposing levers for thermal control. To add heat to the furnace, operators increase temperature and decrease moisture. To cool the furnace (often during periods of high efficiency to maintain stability), they may decrease temperature or add moisture. The graph captures this inverse relationship.



%Si in Hot Metal vs. Hot Blast Temperature:

Observation: This plot reveals a clear negative correlation. On days when higher Silicon (Si) percentages were produced in the hot metal, the furnace was operated with a lower Hot Blast Temperature.

Metallurgical Interpretation: This is a sophisticated finding. While producing high-silicon iron is an energy-intensive process, the primary tool to achieve it is by increasing the coke rate, which provides both the chemical energy and the carbon required. The Hot Blast Temperature is then used as a secondary control tool to balance the overall thermal state. To prevent the furnace from overheating due to the high coke rate, the operator may actually reduce the blast temperature. This plot is powerful evidence that the target product quality is a primary driver that dictates the entire operational strategy.



Raceway Adiabatic Flame Temperature (RAFT) vs. Moisture Injection

Observation: The plot shows a clear and distinct negative correlation. As the Flame Temperature increases from approximately 2000°C to 2350°C, the corresponding Moisture content trends downward. Conversely, on days with high moisture injection, the flame temperature is consistently in the lower range.

The negative correlation observed is not a contradictory finding; it is the expected outcome based on the fundamental chemistry of the blast furnace raceway.

The Role of RAFT: The Raceway Adiabatic Flame Temperature is a critical calculated value representing the maximum theoretical heat generated at the tuyeres. It is a primary indicator of the thermal energy available to drive the melting and reduction processes in the lower part of the furnace.

The Role of Moisture: Moisture (H_2O) injected with the hot blast undergoes an endothermic dissociation reaction:

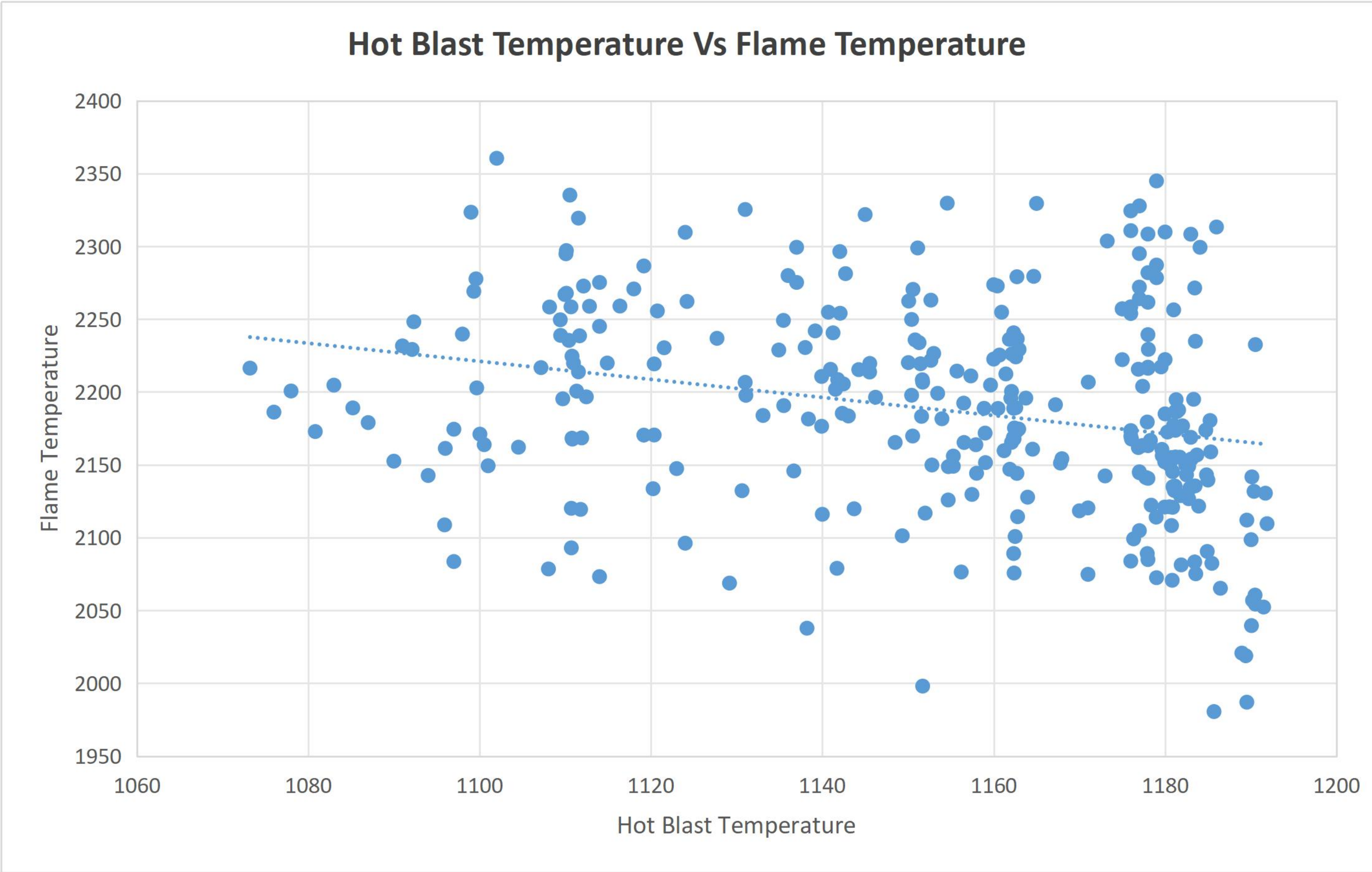
$$H_2O + C \rightarrow H_2 + CO$$

This reaction is highly endothermic, meaning it consumes a significant amount of heat from the raceway. In effect, moisture acts as a powerful coolant.

The Control Logic: Blast furnace operators use moisture injection as a fast-acting and precise lever to control the thermal state of the furnace.

When the furnace runs too hot: If other parameters (like high hot blast temperature, high oxygen enrichment, or low PCI rate) cause the RAFT to rise towards its upper operational limit (which can damage equipment), the operator's primary corrective action is to increase moisture injection. This deliberately consumes heat and brings the RAFT back down into the desired, stable range.

When the furnace needs more heat: If the furnace is running cold or the operator wants to maximize thermal energy, one of the first actions is to decrease or cut moisture injection. This stops the endothermic reaction, preserving heat and causing the RAFT to rise.



Hot Blast Temperature vs. Flame Temperature

Observation: The plot shows a clear and distinct positive correlation. As the Hot Blast Temperature increases from approximately 1075°C to 1190°C, the corresponding Flame Temperature also trends upward.

The positive correlation observed is not a contradictory finding; it is the expected outcome based on the fundamental chemistry of the blast furnace raceway.

The Role of Hot Blast Temperature: The Hot Blast Temperature is a measure of the sensible heat being introduced into the furnace. The hotter the blast, the more energy is available for combustion.

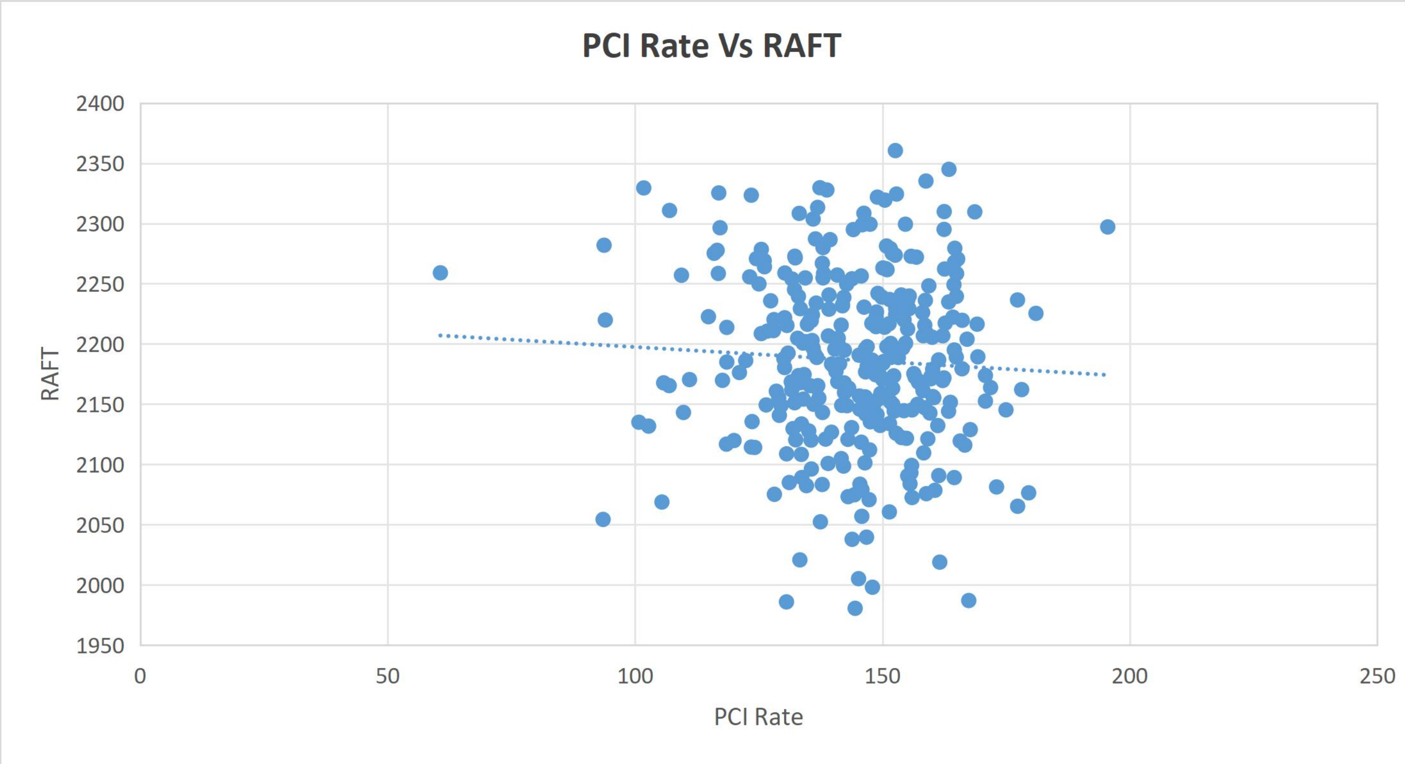
The Role of Flame Temperature: The Raceway Adiabatic Flame Temperature (RAFT) is a critical calculated value representing the maximum theoretical heat generated at the tuyeres. It is a primary indicator of the thermal energy available to drive the melting and reduction processes in the lower part of the furnace.

The Control Logic:
Blast furnace operators use Hot Blast Temperature as a primary lever to control the thermal state of the furnace.

When the furnace needs more heat: If the furnace is running cold or the operator wants to maximize thermal energy, one of the first actions is to increase the Hot Blast Temperature. This directly increases the flame temperature, providing more energy for the process.

When the furnace runs too hot: If other parameters (like high oxygen enrichment or low PCI rate) cause the RAFT to rise towards its upper operational limit (which can damage equipment), the operator may decrease the Hot Blast Temperature to bring the RAFT back down into the desired, stable range.

Operators actively increase the Hot Blast Temperature to increase the Flame Temperature, creating the data points in the top-right of the graph. They decrease the Hot Blast Temperature to decrease the Flame Temperature, creating the points in the bottom-left. This is a classic example of a direct, positive relationship where the operational data perfectly validates metallurgical theory.



<u>Pulverized Coal Injection (PCI) Rate vs. Raceway Adiabatic Flame Temperature</u>

Observation: The plot shows a very weak, nearly flat, but slightly negative trendline. The data points are scattered in a wide horizontal band, indicating that the Flame Temperature remains relatively stable across a broad range of PCI rates (from ~100 to ~190).

The Theoretical Effect of PCI: Pulverized Coal Injection involves blowing fine coal powder into the raceway. This coal is much colder than the coke already in the furnace and requires a significant amount of energy to combust. Therefore, PCI has a strong cooling effect on the raceway. In an uncontrolled system, increasing the PCI rate would cause a sharp decrease in the Flame Temperature.

RAFT as a Tightly Controlled Parameter: The Flame Temperature is one of the most critical parameters for stable furnace operation. If the RAFT is too low, combustion is incomplete, and the furnace runs cold.

If the RAFT is too high, it can damage the tuyeres and refractory lining.

Operators therefore work to keep the RAFT within a narrow, optimal operating window (e.g., 2100°C - 2300°C).

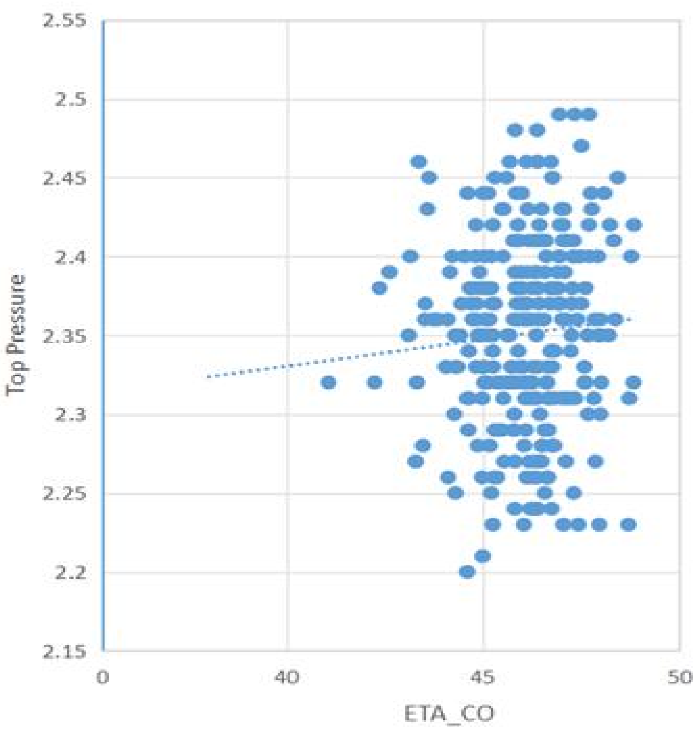
The Operator's Compensatory Strategy:

An operator never increases the PCI rate in isolation. To counteract the known cooling effect of the coal and keep the RAFT stable, they simultaneously take one or both of the following actions:

- Increase the Hot Blast Temperature: Adding more sensible heat to the blast.
- Increase Oxygen Enrichment: Making the combustion more intense to generate more heat.

This is a deliberate, multi-variable control action. The goal is to maximize the use of cheaper PCI while using blast temperature and oxygen to "pay for" the thermal cost, ensuring the RAFT remains stable.

The graph is not showing the isolated effect of PCI; it is showing the net result of a complex, balanced action: (Cooling from PCI) + (Heating from Blast Temp/Oxygen) ≈ Stable RAFT.



CO Efficiency ETA_CO vs. Top Pressure

Observation: The plot shows a clear, albeit noisy, positive correlation. The data points form a distinct cluster where higher Top Pressures are consistently associated with higher levels of CO Efficiency. As the Top Pressure increases from ~2.20 to ~2.50 bar, the corresponding ETA_CO trends upward from ~43% to ~48%.

The Role of Top Pressure: In modern, high-productivity furnaces, operating at an elevated top pressure is a key strategy. Increasing the pressure inside the furnace stack effectively slows down the velocity of the ascending reducing gases (primarily CO).

The Effect of Gas Residence Time: This slowdown is crucial because it increases the gas residence time—the amount of time the CO gas is in contact with the iron ore burden as it descends.

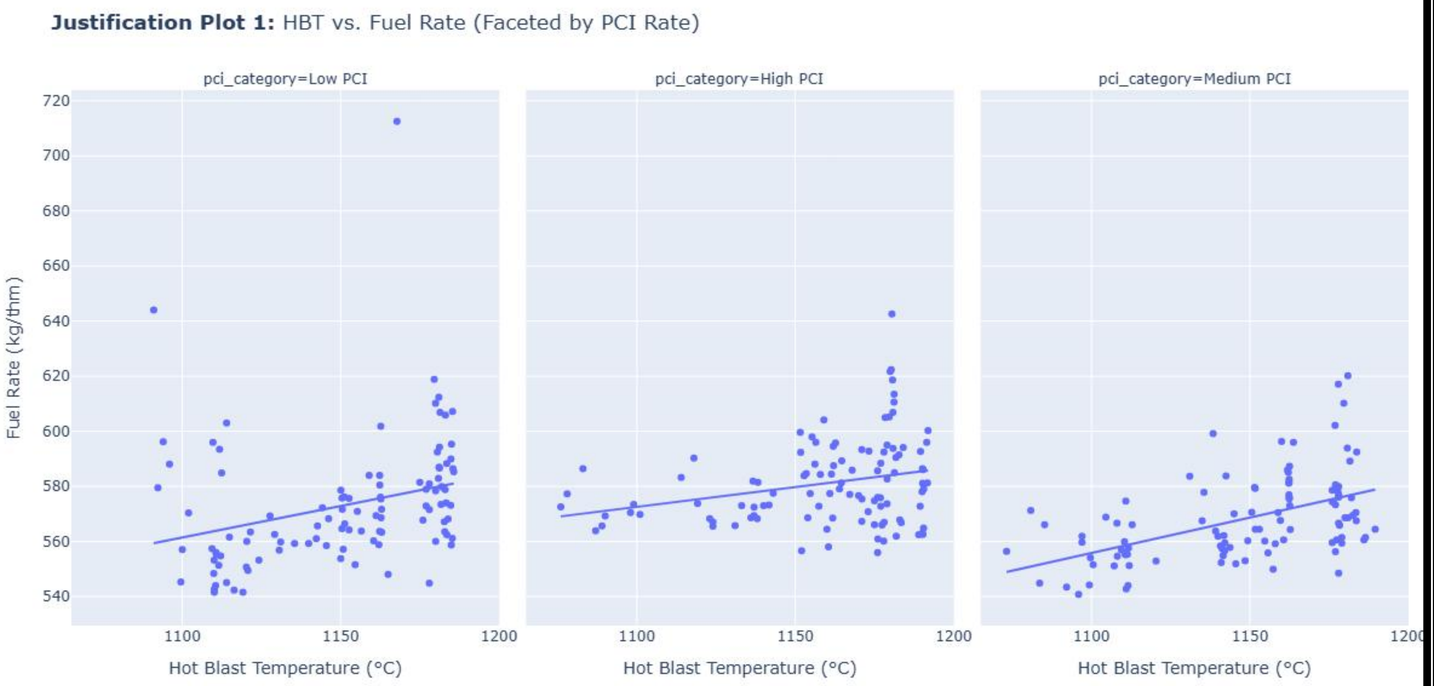
The Impact on CO Efficiency: The primary chemical work of the blast furnace is the reduction of iron oxides by CO gas. By increasing the contact time between the gas and the ore, the efficiency of these reduction reactions is significantly improved.

Increasing the top pressure suppresses the solution loss reaction or gasification reaction

$$\mathbf{C + CO_2 \rightarrow 2CO}$$

in the upper and middle parts of the furnace stack which prevents the

coke from getting converted into CO gas that will be unutiized by the furnace.



HBT vs. Fuel Rate (Faceted by PCI Rate)

Observation: This plot separates the relationship between Hot Blast Temperature (HBT) and Fuel Rate into three distinct operational regimes: Low, Medium, and High Pulverized Coal Injection (PCI) rates. While the positive trendline persists within each facet, there is a clear upward shift in the entire data cloud as the PCI rate increases. The fuel rates in the "High PCI" facet are, on average, significantly higher than those in the "Low PCI" facet.

Logical Justification: This is a direct visual confirmation of the compensatory control theory.PCI is a component of the total fuel rate. Therefore, a higher PCI rate naturally leads to a higher overall fuel rate.

More importantly, PCI has a strong cooling effect. To enable a high injection strategy, operators must provide extra heat by increasing the HBT.

The plot proves this: the "High PCI" regime not only has higher fuel rates but also operates at a higher average HBT. This justifies the original contradiction by showing that high HBT does not cause high fuel rates; rather, it is the necessary enabler for a high PCI strategy.

SUMMARY

The daily data from the blast furnace reflects a complex, real-world operation, not a controlled lab experiment. Operators constantly adjust multiple parameters to prioritize stability and quality. Therefore, simple scatter plots often contradict theory because each data point captures the combined result of all these simultaneous adjustments made throughout the day.

- **Hot Blast Temperature**

Theory: Higher temperature should decrease the fuel rate.

Observed Data: Higher temperature is linked to a higher fuel rate.

Reason: Operators use high blast temperature as a support tool to compensate for the cooling effect of high coal injection (PCI) or to fix a furnace that is running cold. The data captures these corrective actions, not a simple cause-and-effect.

- **Moisture Injection**

Theory: Adding moisture (a coolant) should increase the fuel rate.

Observed Data: Higher moisture is linked to a lower fuel rate.

Reason: Moisture is used when the furnace is already running very hot and efficiently (which means it's already in a low-fuel-rate state). The moisture is a response to the high efficiency, not the cause of it.

- **Slag Rate**

Theory: More slag (waste) to melt requires more energy, so it should increase the fuel rate.

Observed Data: This relationship matches the theory.

Reason: A high slag rate is always bad for efficiency. This parameter is directly linked to the quality of the raw materials and is not used as a control lever, so its relationship is straightforward.

- **Top Pressure**

Theory: Higher pressure improves gas efficiency and should decrease fuel rate.

Observed Data: A weak, slightly positive relationship.

Reason: High top pressure is used to achieve maximum production rates. These high-throughput periods also involve pushing all inputs (including fuel) to their limits, which masks the underlying efficiency gain.

- **Flame Temperature (RAFT)**

Theory: A hotter flame should be more efficient and decrease the fuel rate.

Observed Data: A weak, positive relationship.

Reason: Flame temperature is a result of other inputs. To compensate for the cooling effect of high fuel injection (like PCI), operators increase blast temperature and oxygen, which also increases the calculated flame temperature. The data links the high fuel input with the resulting high flame temperature.

- **CO Efficiency (ETA CO)**

Theory: Higher gas utilization efficiency should decrease the fuel rate.

Observed Data: A flat line, showing no correlation.

Reason: This is a sign of successful process control. The operators and control systems work hard to keep CO efficiency in a narrow, optimal range. The relationship is masked because the furnace is not allowed to operate with poor efficiency for long.

RECOMMENDATIONS

- **Prioritize Raw Material Quality and Burden Management.**Primary driver of high efficiency is the quality of the raw materials being charged. Efforts should be focused on securing and utilizing higher-grade iron ore and coke with fewer impurities (gangue and ash). A lower slag rate directly reduces the energy required for melting non-productive material, leading to substantial fuel savings. This finding is consistent with metallurgical theory and is the most reliable lever for optimization identified in this analysis.

- **Maintain a Higher top pressure and a stable CO efficiency**. Maintain focus on holistic process stability. This includes ensuring smooth material descent and optimal gas flow, which is facilitated by high top pressure for overall fuel efficiency.

- **High PCI Rate:** Push this as high as possible because powdered coal is much cheaper than metallurgical coke. This is the primary driver for cost savings.

- **High Hot Blast Temperature:** Because high PCI has a strong cooling effect, thus must be compensated by adding a massive amount of heat.

- **High Oxygen Enrichment:** To burn the large amount of coal effectively and further boost the temperature, enrich the blast with oxygen. This makes the combustion much more intense and allows to push the PCI rate even higher.

- **Low Moisture:** Since goal is to maximize heat, to keep any coolants (like moisture) as low as possible. In an perfect state it would have very less added moisture.

- The Silicon percentage is a primary driver of the furnace's thermal state and fuel consumption. By **quantifying the energy cost of producing different silicon levels**, the plant can make more informed decisions about production planning and fuel optimization.

- Treat **Oxygen Enrichment as a Strategic Enabler for High PCI Rates.** The primary strategic use of oxygen should be to enable the maximization of the Pulverized Coal Injection (PCI) rate. High PCI rates have a strong cooling effect. Oxygen enrichment is the most powerful tool to counteract this cooling, providing the intense heat required for the efficient and complete combustion of the injected coal. Therefore, the level of oxygen enrichment should be directly coupled with the target PCI rate.

- **Lower slag rate:** A key characteristic of a high-efficiency operation. Reducing the amount of non-productive material that needs to be melted is the most reliable way to achieve a direct and significant reduction in fuel consumption.

- **RAFT as a Stability Constraint, Not an Optimization Target.** The goal should not be to simply maximize RAFT. Instead, define an optimal operating window for RAFT that ensures process stability and equipment longevity. Pushing for the absolute maximum can lead to operational problems. The focus should be on consistency and stability within a proven range.