AN ANALYSIS OF THE EFFECT OF COKE CHARACTERISTICS AND OTHER OPERATING VARIABLES UPON BLAST FURNACE PERFORMANCE

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INTRODUCTION

The recognition of the importance of the physical and chemical properties of raw materials has contributed greatly to the improvement in blast furnace production and coke rate during the last two decades. Furnace outputs have doubled while coke rates have been reduced to half the values of yesterday.[1]

Advances in technology such as auxiliary fuel injection, higher hot blast temperatures, moisture injection, and oxygen enrichment have been major factors in increasing the efficiency of the blast furnace process. In today's economy, with the almost insatiable hot metal needs of the basic oxygen process, soaring scrap prices, and an energy crisis, even greater requirements are placed upon the blast furnace operator.

In order to meet these requirements, the operator needs more knowledge concerning the factors affecting blast furnace performance.

The purpose of this study was to investigate certain relationships between blast furnace operating parameters and production and coke usage so as to develop statistical models for evaluating present and future furnace performance. The scope of this study is limited to the following sets of operating parameters:

1) coke characteristics (physical and chemical)
2) hot metal chemistry
3) slag characteristics (physical and chemical)
4) metallic burden (% coarse, % pellets, % sinter)
5) wind rate (CFM)
6) oil rate (Lbs/NTHM)

The Study

The method of study involved the use of statistical analysis techniques to determine the character and extent of the relationship between certain operating parameters. The studies were essentially based on empirical relationships derived from operating experience such as the effect of coke quality on production.

The statistical aspects of the study involved the use of regression analysis techniques where the objective was to quantify the relationships between operating variables discussed above. For this purpose, a Step-Wise Multiple-Regression procedure was used. This procedure provided for the calculation of regression coefficients - quantitative estimates of the relationship between dependent operating variables and independent operating variables. Several other statistics were calculated for analysis including:

1) the multiple correlation coefficient (R) - a measure of the association between operating variables and,

2) the coefficient of determination (R^2) - the square of R, the proportion of the total variation in one operating variable explained by a set of operating variables under consideration.

Earlier sections of the paper deal with a study of the more significant bivariate relationships including the effect of stability, coke ash, and wind rate on performance. Later sections of the paper are concerned with a study of the multivariate relationships which result from the expansion of the bivariate relationships to include more operating variables.

The Data Base

Ideally, a study of this kind would be based on data collected from designed experiments in which the production level and coke usage could be observed for predetermined settings of some of the operating parameters such as wind rate and blast temperature. It is assumed in this procedure that the general relationship is known, and one is interested in studying the character of that relationship. The data generated from this experiment would then reflect changes in production and coke usage as a function of the operating parameters in question. However, the costs associated with the allocation of Inland's blast furnaces to an experiment prohibit the use of this procedure.

The data base that was used in this study consists of data collected from existing blast furnace operating data. The sources of this data included monthly operating reports prepared by blast furnace and coke plant personnel. The use of existing data may have affected the results of the study in the following ways:

1) The set of variables that was represented in the data base was limited to variables that were included in the monthly reports. Because no information was available, certain important variables may have been excluded which could introduce bias into the estimates of the coefficients.

2) The results of the study are appropriate for the specific set of conditions that the data represent. These conditions are reflected in the range of the observations of the variables and the sets of values that the variables take on simultaneously. This limits, somewhat, the application of the results of the study to new conditions.

3) The estimates and statistics derived from the data may reflect several distinct relationships and interrelationships between variables. This factor could affect the study results because the variables do not change independently.

A criterion was established for data selection so as to minimize the potentially detrimental effects of the use of the existing data. The criterion established was to only include data which represented efficient blast furnace operations, based on the assumption that with efficient operations the general relationships are move evident. The problem areas outlined above were considered when the study results were analyzed.

The characteristics of the data that result from this selection process include high wind rates, high production rates, and preferential burdening. It should be noted, however, that these characteristics are incidental to the selection process rather than an integral part of it.

Data representing Inland's large and small furnaces was collected during the time period of November, 1967 through October, 1973. Some characteristics of the eight blast furnaces included in the study are given in Table I. When the production level is considered, two distinct sets of data are formed. This occurs because of the difference in production capacity for the large and small furnace groups. Where a production level of 1900 NTHM/Day would be considered a high level for the small furnace group, 1900 NTHM/Day would be considered a low level for the large furnace group. The time period for data selection for the large furnaces was influenced by a desire to include observations from a blast furnace practice with high oil usage, and to show the effect of technological advances. Table II includes the expected values and standard deviations of the operating variables considered in this study.

The data for the small furnaces reflect the wind rate and blast temperature limitations found on the smaller furnaces. Further, several of the small furnaces have been operated to produce mold foundry grade iron. These aspects of the operation of the small furnace group are also represented in the data.

The next section of the paper addresses itself to an analysis of the effect of the blast furnace operating parameters on hot metal production and coke rate from two perspectives:

1) Where certain operating parameters are compared with production and coke usage on an individual variable basis.

2) Where a set of operating variables is compared with production and coke usage in the multivariate sense.

For the most part, the equations and statistics that will be presented in the following sections refer to the large furnace set. The reason for this is to avoid redundancy and because the above mentioned operating restrictions make the results very specific to Inland Steel's operation.

Coke Stability and Production

Increases in unit production and efficiency place even greater demands on the most important blast furnace raw material of all — coke. While the increase in the use of auxiliary fuels has decreased somewhat the importance of coke as a source of reducing gas, the corresponding increase in burden ratio due to improved raw materials and fuel injection has greatly increased the need for coke of sufficient strength to provide the permeability so vital to efficient blast furnace operation. The measure of coke strength used by most blast furnace operators is stability. While the correlation between stability and furnace performance has not always been obvious, the blast furnace operator has always considered good coke stability a necessity. Inland Steel Company is no exception in this regard and has taken steps to improve the stability of its coke.

Early in 1972, several changes were made which resulted in increased coke stability. Table III shows the type of change made and the approximate data. As you can see, the coal grind was improved, the coke time lengthened, and the bulk density increased. Figure 1 depicts the effect of increasing the percentage of -1/8" material upon stability.

The effect of increases in coke stability upon blast furnace production is shown in Figure 2. The months selected were representative of more efficient furnace operation, and thus, more closely reflect the relationship between stability and production.

The correlation coefficient for production with stability is 0.800 which indicates that stability is positively associated with production. R^2, the coefficient of determination, is 0.64, which indicates that approximately 64% of the change in production is attributable to changes in stability. Further, the regression coefficient implies that a 1% improvement in stability is equivalent to almost a 2% increase in production. A separate analysis of our better small furnace operation indicated a similar relationship between stability and production.

It should be noted that the validity of data is dependent upon its accuracy. Since coke stability has often been given only cursory consideration, it is possible that the technique used in obtaining stability values may have become somewhat slipshod, thus, resulting in inaccurate information which can only serve to cloud any results. It would be worthwhile for any operator who wishes to study his coke stability, to make sure that the techniques and equipment used adhere to ASTM standards.

Coke Ash and Furnace Coke

The chemistry of coke is also of paramount importance in the production of quality hot metal. Coke contains approximately 90% carbon with the remainder consisting of undesirable, although unavoidable, ash and volatile matter. Chemical uniformity is a must in coke because the method of production and handling at Inland precludes any chance of blending the coke before charging it into the furnace. A change in coke chemistry is especially harmful because it causes a change in slag chemistry and subsequent hearth temperature.

The theoretical relationship between coke ash, furnace flux, and coke requirements is presented in Table IV. As you can see, a 1% increase in coke ash requires an 11% increase in flux and causes a 2.8% increase in coke rate. The relationshp in actual operation has been quite vividly proven to our operators when an unsuspected increase in coke ash of approximately 1.5% occurred and resulted in over 50% off-quality iron over a two day period. One can imagine the havoc caused in steelmaking by such a large quantity of high sulphur hot metal.

Production and Wind

Wind serves several functions in the blast furnace process. It provides the environment for fuel combustion by supplying the needed oxygen and also serves as a heat transfer medium. The oxygen combines with fuel carbon to supply reducing gases for process reactions. Changes in the wind level bring about changes in the process reaction rate, which affects the production level.

The relationship between wind rate and production is shown in Figure 3. It has been our practice to use a factor of a 7% increase in production for every 10% increase in wind rate, and this factor was essentially confirmed by the statistical analysis which indicated a relationship of the same magnitude. The correlation coefficient for production and wind is 0.781, which is indicative of a positive association between production and wind. The coefficient of determination (R^2) is 0.610.

In summary, this section of the study supports the hypothesis that strong relationships exist between the operating variables under consideration (production, coke usage, coke stability, coke ash, and wind). The equations that result from this analysis can be useful in predicting furnace performance, production and coke usage, as a function of the other operating variables. For example, production may be predicted as a function of stability by using the production/stability relationship discussed above.

MULTIVARIATE MODELS

The subject of this section is the expansion of the bivariate relationships discussed above to include other operating variables.

Using the regression analysis techniques described above, predictive equations were developed for production and coke usage and are shown in Figures 4 and 6. These equations are represented functionally as follows:

Production = f (coke stability, % coke ash, % SiO_2 in slag, slag production, % coarse ore, % pellets, oil usage, wind)

Coke Usage = f (coke stability, slag production, oil usage, average coke size, % Mn in hot metal, wind, % S in slag, % CaO in slag, % MgO in slag)

From these equations, a theoretical coke rate may be calculated. The equations appear to be good predictors of coke usage and production with R^2, the coefficient of determination, approximating 0.90. The following paragraphs contain a more detailed discussion of the equations.

Production

With reference to Figure 4, the coefficient of determination for the production equation is 0.913. The major amount of variation explained by the equation is attributable to coke stability, slag production, and wind rate. In fact, these variables account for 84.4% of the variation, which is certainly consistent with the strong relationship between stability, wind rate, and production noted in the earlier discussions.

The slag production variable included in the equation represents total slag production rather than the more conventional (Lbs/NTHM) units. The reason for this change in units was to minimize the effect of the use of precalcined steelmaking slag on furnace operation and the resulting slag volumes, since the use of steelmaking slag as a charge material is a relatively new practice at Inland, and is reflected in part, but not all, of the data. A regression model was developed to investigate the effects of this material on production, using limited data. The resulting equation indicated a positive relationship between production and steelmaking slag, but it should be noted that, because of data limitations, due to limited operating experience with this material, these results were interpreted cautiously.

The remaining variables, including % pellets in the burden, % coarse ore in the burden, % SiO_2 in slag, % coke ash, and oil usage account for 6.9% of the variation, given that stability, slag production, and wind have been considered. An examination of the regression coefficients indicates that the pellet, SiO_2, coke ash, and oil variables appear to reflect the beneficial chemical and physical characteristics of pellets in the burden, the effect of a leaner slag operation on production, and the relationship of carbon and fluxes to coke ash. However, the regression coefficients could reflect the influence of other operating variables which are not included in the equation. These coefficients may be influenced by the data used for this study as discussed earlier.

The effect or the influence of the variables which are not included in the data is apparent when one considers the coarse ore variable.

The effect of this variable on the production equation on the average is slight (approximately 0.77%). In the larger furnace data set, the average value of the % coarse is approximately 3.4%, which represents a practice where coarse ore is not significant. In fact, consideration of the probability distribution for % coarse (Figure 5) reveals that in a significant number of observations there was no coarse ore at all. A similar model was developed for the small furnace group where coarse ore makes up a significant part of the burden — approximately 17.8%. The resulting equation is presented in part as follows:

$$\text{Production (T/D)} = -514.91 - 44.746 \times (1/\text{Slag Production}^2) * 10^6 \text{ (T/D)}$$
$$+ 714.302 \times \text{Wind}^2 \times 10^6 \text{ (CFM)} - 6.218 \times \%\text{ Coarse Ore} \; . \; . \; . \; . \; . \; .$$

It is implied by this equation that an increase in the % coarse ore in the burden results in a decrease in production, which is consistent with operating experience.

COKE USAGE

An equation for coke usage comparable to the one developed for production is presented in Figure 6. The coefficient of determination for this equation is 0.887. As in the production equation, the stability variable appears to explain a good deal of the variation in coke usage.

Several factors appear to be dominant. Slag production, stability, and oil usage account for a large amount of the variance — approximately 78.2%, which is consistent with the relationships developed earlier. Given that the slag, stability, and oil variables have been considered, the remaining variables-coke size, Mn in hot metal, and wind and slag chemistry-account for 10.5% of the variance.

The coke stability and % Mn in hot metal variables include higher order terms in the equation. This is apparently indicative of curvilinear relationships that exist between coke stability, hot metal Mn, and coke usage. The product term, calcium oxide in slag and sulphur in slag represents interactions between these variables.

With reference to the Table II variables, it should be noted that some variables which are included in the table and were considered in analysis do not appear in the coke and production equations. The reason for exclusion is related to the relative contribution of the variable to explaining variation, the relative significance of the variables being considered in the model, and the range of values that the variables take. As an example, consider the case of the % hot metal sulphur. Hot metal sulphur is known to have an effect upon furnace productivity and coke rate, but it was not included in the equation because its range was so narrow in the data set that most changes in hot metal sulphur fell within the expected range of error in chemical analysis. The quantitative effect of hot metal sulphur upon furnace performance was described quite well by the excellent experiment conducted at another steel company recently.

The regression equations for production and coke consumption have been used to develop graphs describing the relationships between coke rate, stability, and oil. Figure 7 is a plot of the effect of stability upon coke rate. The graph indicates an almost linear relationship at higher values of stability which deteriorates as poorer levels of stability are approached. Figure 8 indicates that, in the data set studied, a replacement ratio of 1:1 exists between oil and coke at high levels of oil injection. This relationship is consistent with our experience and the reports of others.[2]

Thus far, bivariate and multivariate models have been presented which compare certain operating variables to production and coke usage. Each of the equations explains a substantial amount of the variation in the response variable. However, certain limitations must be placed on the application of these equations to specific operating conditions.

The equations represent the operation of Inland's blast furnaces under a specific set of conditions as defined by the assumed models and the study data. If the process were to change and the operating parameters were to take on a set of values that was not included in the data, then the equations might not be appropriate. Therefore, applications of these equations should be handled cautiously.

It is interesting to note that an application of these equations to data concerning a competitor's operation with similar operating characteristics resulted in predicted values of production and coke rate which were very close to the actual values. While a great deal of analysis would be required before one could determine whether this is, in fact, an appropriate application, the results appear to be consistent with Inland's operating experience.

CONCLUSIONS

In summary, the study supports the hypothesis that a definite relationship exists between coke quality and furnace performance. This was reflected in study results in both the bivariate and multivariate cases.

The quantitative relationship between production and coke stability has provided a basis for the justification of programs designed to improve coke stability. The relationship between production and wind rate can be used as a tool for projecting furnace outputs as a function of wind. It is expected that the multivariate models will be used to predict and analyze furnace performance by considering the behavior of certain significant variables. Although the range of the operating variables included in the data is somewhat limited, it is felt that the equations are useful in understanding blast furnace operations.

Our plans include the expansion of the data base to include observations of furnace performance at a wider range of operating levels and to consider the contributions of additional operating variables in explaining variance. Such an expansion could result in a set of equations which are appropriate throughout a wider range of furnace operating levels. A study of the effects of different types of pellets upon furnace operation is also planned for the future if operating conditions permit.

REFERENCES

1. Charles M. Squarcy and Richard J. Wilson, "More Iron Without More Furnaces" Chicago Regional Technical Meeting of American Iron and Steel Institute, Oct. 17, 1956.

2. Blast Furnace Injection Symposium Proceedings, Wollongong University Australia, February, 1972.

Table I - General Description of Eight Small and Larger Furnaces Studied.

	SMALL FURNACES (4)	LARGER FURNACES (4)
HEARTH DIAMETER, FT.	19' 9" TO 20' 9"	26' 6"
WORKING VOLUME, FT.^{3}	24,000 TO 31,000	46,000 TO 47,000
MAXIMUM WIND RATE, CFM	70,000	125,000
HOT BLAST TEMPERATURE RANGE, °F	1500 - 1800	1700 - 2000
OXYGEN ENRICHMENT SYSTEM	ON 3 OF 4	ON 2 OF 4
BEST MONTHLY PRODUCTION NT/DAY	1914	2861

Table II - Data Summary (Larger Furnaces).

	MEAN	STANDARD DEVIATION
PRODUCTION - NT/DAY	2642.415	154.232
COKE - NT/DAY	1200.223	91.829
OIL - NT/DAY	256.199	46.524
WIND - CFM	103975.650	5907.438
COARSE ORE - %	3.385	5.787
PELLETS - %	84.920	9.779
MgO IN SLAG - %	13.785	.776
CaO IN SLAG - %	38.846	1.110
S IN SLAG - %	2.070	.300
SiO_2 IN SLAG - %	36.198	.498
SLAG PRODUCTION - NT/DAY	615.238	61.320
COKE STABILITY - %	56.727	2.610
COKE ASH - %	8.097	.375
AVERAGE COKE SIZE (INCHES)	1.981	.093
Mn IN HOT METAL - %	.801	.155
S IN HOT METAL - %	.032	.003

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Table III - Coke Stability Improvement Due to Operational Changes.

DATE 1973	STARTING CONDITIONS AND OPERATIONAL CHANGES		STABILITY
APRIL 1	COKING TIME COAL GRIND, -1/8" BULK DENSITY, LB/FT^3	15:07 75% 44.5	47.1
APRIL 17	IMPROVED COAL GRIND (-1/8") TO	79%	51.4
MAY 1	INCREASED BULK DENSITY (LB/FT.^{3}) TO	45.5	56.8
MAY 5	LENGTHENED COKING TIME TO	18:33	59.2
MAY 10	INCREASED BULK DENSITY (LB/FT.^{3}) TO	46.0	60.1

Table IV - Analysis of Blast Furnace Coke and Flux Requirements with Increased Amounts of Coke Ash*

	BASE CASE	+1% COKE ASH		+1.5% COKE ASH	
		NEW	DIFF.	NEW	DIFF.
COKE RATE - LBS/NTHM	979	1007	+28	1021	+42
FLUX REQUIREMENT - LBS/NTHM	223	247	+24	259	+36
FLUX REQUIREMENT PER CHARGE	3791	4199	+408	4403	+612
INCREASE IN DAILY COKE USE (NT/DAY AT 15,000 NTHM/DAY	–	–	+210	–	+315
COKE REQUIRED FOR COKE ASH SLAG	48	57	+8	60	+12
COKE REQUIRED FOR UNCALCINED FLUX	76	85	+9	89	+13
ADDITIONAL COKE REQUIRED FOR LOSS OF CARBON	–	–	+11	–	–17
% INCREASE IN COKE RATE	–	2.8		4.2	

* FROM R.V. FLINT FORMULA

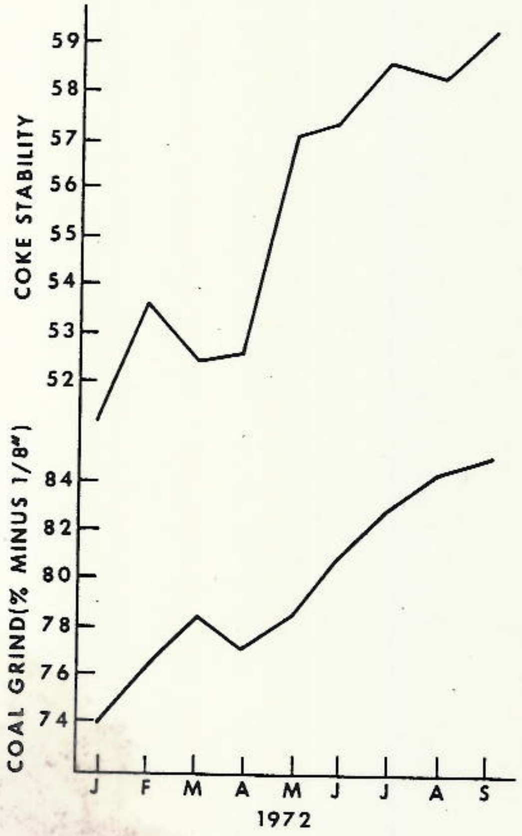

Figure 1 - Effect of Coal Grind on Coke Stability - 1972.

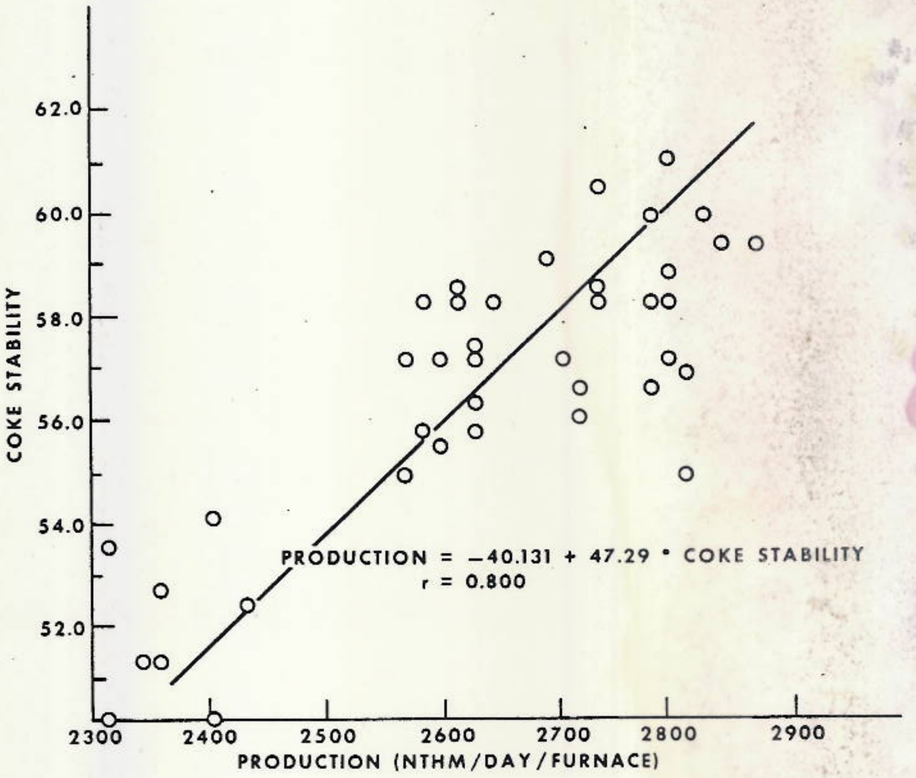

Figure 2 - Effect of Coke Stability upon Production for Large Furnaces.

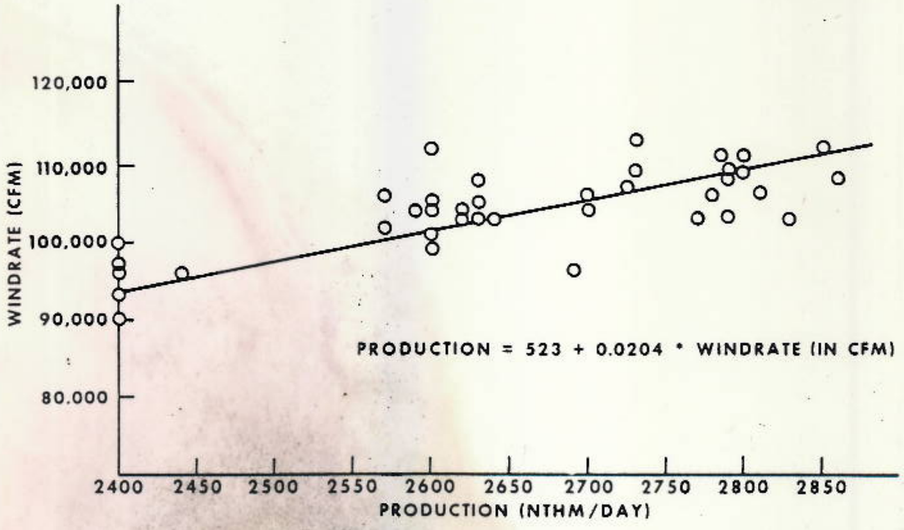

Figure 3 - Hot Metal Production vs. Wind Rate.

$$\begin{aligned}\text{PRODUCTION (NT/DAY)} = & -564.05 \\ & + 12.85 \cdot \text{COKE STABILITY} \\ & -141.94 \cdot \frac{10^6}{(\text{SLAG PRODUCTION})^2} (\text{NT/DAY}) \\ & + 0.91 \cdot \text{WIND} \cdot 10^{-2} (\text{CFM}) \\ & + 4.09 \cdot \text{PELLETS } (\%) \\ & + 5.32 \cdot \text{COARSE ORE } (\%) \\ & + 52.42 \cdot \text{SLAG SiO}_2 \ (\%) \\ & - 57.27 \cdot \text{COKE ASH } (\%) \\ & + 0.46 \cdot \text{OIL (NT/DAY)}\end{aligned}$$

$R^2 = 0.913$

Figure 4 - Multivariate Production Model.

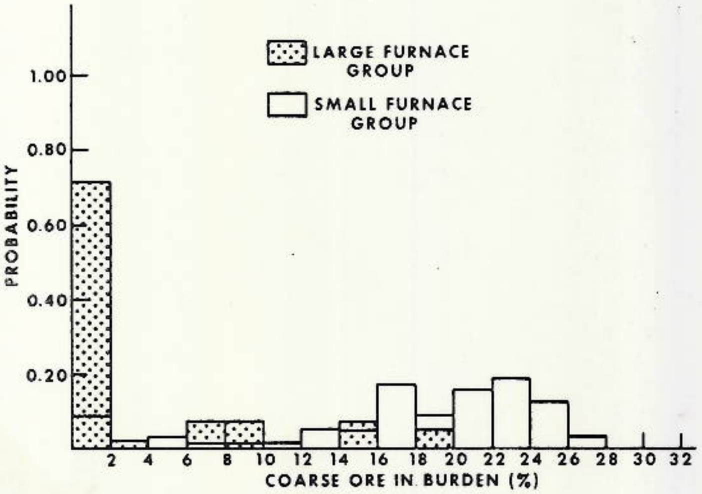

Figure 5 - Distribution of Coarse Ore in Large and Small Furnace Data Sets.

$$\begin{aligned}\text{COKE (NT/DAY)} = & -18708.29 \\ & + 1072.06 \cdot \text{STABILITY} \\ & - 94.15 \cdot \text{STABILITY}^{3/2} \\ & - 147.64 \cdot \frac{10^6}{(\text{SLAG PRODUCTION})^2} (\text{NT/DAY}) \\ & - 0.75 \cdot \text{OIL (NT/DAY)} \\ & - 214.51 \cdot \text{AVERAGE COKE SIZE (INCHES)} \\ & + 367.87 \cdot \text{HOT METAL Mn } (\%) \\ & - 337.25 \cdot (\text{HOT METAL Mn})^2 \\ & + 0.35 \cdot \text{WIND} \cdot 10^{-2} (\text{CFM}) \\ & + 711.92 \cdot \text{SLAG SULFUR } (\%) \\ & - 14.54 \cdot \text{SLAG CaO} \cdot \text{SLAG SULFUR} \\ & - 26.81 \cdot \text{SLAG MgO } (\%)\end{aligned}$$

$R^2 = 0.887$

Figure 6 - Multivariate Coke Model.

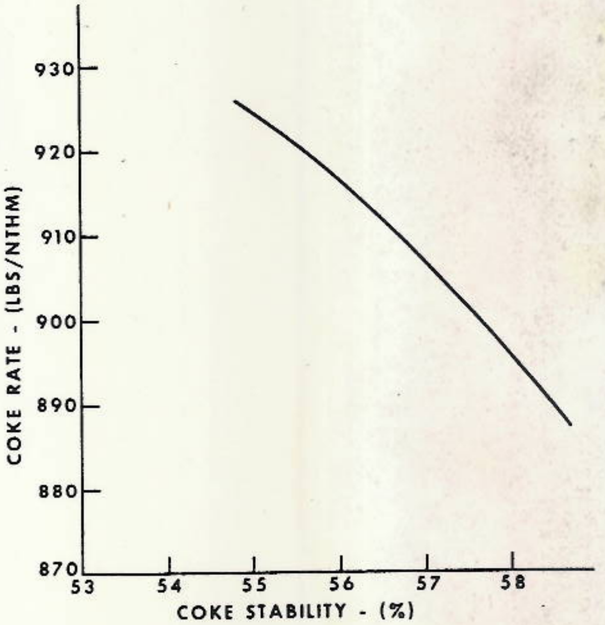

Figure 7 - Effect of Coke Stability upon Coke Rate.

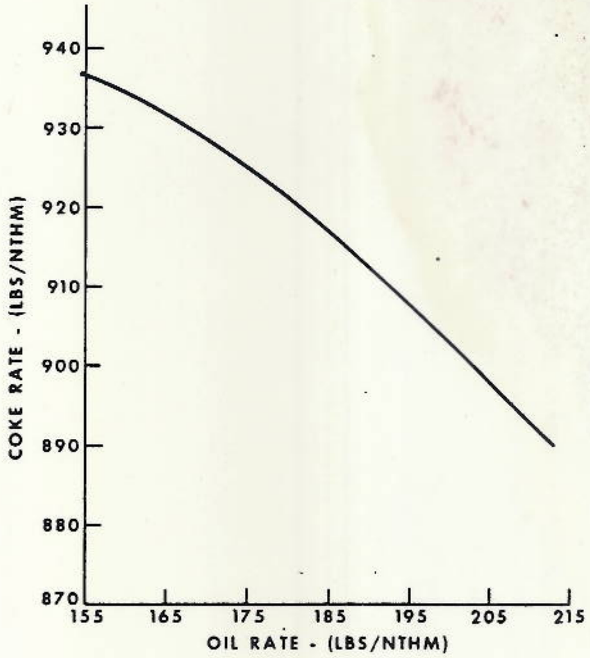

Figure 8 - Effect of Oil Injection Rate upon Coke Rate.