Selection of Coals for Coke Making - The Economic Worth Approach

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Introduction

More buyers and sellers today are relying on economic worth models to discriminate between the multitude of coal products that are available in the marketplace. A variety of terms have been used to describe economic worth such as comparative value ratings, equitable product costing, etc.. The economic worth approach to coal selection requires a working knowledge of coal quality and a clear understanding of the use for which the coal is intended. Computer models orchestrated by engineers help establish the relationships between product acceptability, cost and value within the context of operational constraints and process variables. Assessment of coal value must be carried through to some intermediate or final product by determining the impact that quality has up through that stage in the finishing process where the impact of coal quality on process economics ends. In this regard, the best interests of both buyer and seller are served when the delivered price of a seller's product, that has already been screened for acceptability, falls within a buyers budgetary constraints after its price has been adjusted for predicted performance in the process for which it is intended. Of course the higher a coal's value in a given process and the lower its delivered cost the greater the savings or economic worth to the customer (Figure 1).

Economic worth of coking coal as it pertains to the steel industry is the price that can be paid for an alternative metallurgical coal product while maintaining hot metal production and cost constant. Since it is coal that is being economically evaluated, constant hot metal production and cost also covers the requirements of maintaining coke production and cost constant. It follows then, that the economic worth evaluation of different coking coal sources is a two step process. First the relative value of the candidate coals must be evaluated within the context of the coal blending and coke operating conditions being employed and secondly the amount and type of coke produced under these conditions must be evaluated for their fuel value, reducing capabilities, and contribution to burden support within specified blast furnace raw material burdening and operating practice. In this regard, the economic worth of a metallurgical coal is more often than not site specific with its value changing in accordance with consumption setting because of the different cokemaking and blast furnace practices employed and raw materials available at each location, i.e. North America vs Far East vs Europe vs South America. Although the magnitude of the economic worth advantage or disadvantage of one coal versus another will change for different consumption settings, generally the relative rankings do not drastically change; and herein lies the justification for taking such an approach to discriminate between competing sources. It should also be noted that the economic worth selection of coking coals can change with time for a given consumption setting such that a coal which is not cost effective today may become more competitive tomorrow as the coke-making and blast furnace operations and/or raw materials supply situation changes for that particular consumer.

Economic Worth Considerations in Cokemaking and Hot Metal Production

Economic worth models for evaluating coking coals should predict the changes that coal blend chemistry will have on coke yield and by-product credits, inclusive of underfiring requirements, and how changes in chemical rheological and petrographic properties of the different coals in the blend influence resultant coke purity, strength (including breeze generation) and reactivity for the pulverization level, bulk density and heating practice being employed on the coke battery (Figures 2, 3, 4). Subsequently, an estimate of the cost impact resulting from these coal quality changes should be based on the coke rate and hot metal production expected from the use of these different predicted coke qualities in the blast furnace.

Typical quality specifications and standard deviations should be known not only for the coals being economically evaluated for purchase but also for each and every coal used in the carbonization blends (Figure 5). In this way, coal quality uniformity can be factored into coal quality changes and its predicted effect on coke ovens and blast furnace operations without under or over estimating the cost impact associated with these changes. If possible the delivered cost of all the coals being used should be known to conduct an accurate economic worth assessment. For instance, Australian metallurgical coals being consumed in the Far East have distinct transportation advantages over their American counterparts. The reverse has been true up to recently for delivery of Australian coals into Europe and South America. Coal conversion practice can also differ so substantially for different consumption settings that it sometimes is necessary to know conversion cost components such as labor and energy charges, and by-product credits in order to give an accurate assessment of cost impacts related to coal quality changes.

Special situations do exist where coal selection transcends the economic worth approach. In such cases, a candidate coal which may be indicated to have a high economic worth because of the improvements in coke strength and chemistry it offers the user must be disqualified from consideration because it cannot be carbonized safely with the coals which are currently being used in that consumption setting. This is a particularly sensitive issue in the States right now where the excessive age of the remaining coke oven batteries has made it necessary to select more contracting high vols and lower rank, and/or lower expanding or pressure prone low vols. In addition, the interchangeability of coals in a blend may be important because of logistics, prior commitments, or for other reasons.

Sometimes, the stockpiling and blending capabilities that exist or the ability to achieve certain pulverization and bulk density levels or even sustain certain heating practice may also eliminate the highest economic worth metallurgical coals from consideration. Finally, certain consumers which have captive and/or long-term raw material commitments may make their selection of outside coals unduly restrictive. In fact, in some cases the restrictions on coal selection due to captive raw material supply may have only to do with the ore and flux being used and reconciled against the hot metal quality desired for the operating limitations of the blast furnace.

Assessing the impact of coal blend changes on coke quality and cokemaking economics is easy compared to measuring their effect on blast furnace production and cost. This is simply due to the fewer number of interrelated variables that are involved in cokemaking versus hot metal production. The blast furnace evaluation portion of the model should possess the capability of assessing the cost impact that resultant coke size, shape and chemistry (ash, sulfur, phosphorous, alkali) and reactivity and strength have on coke rate and hot metal production within the context of the type and quality of ores and fluxes being used and the furnace operating conditions being employed (Figure 6). In this regard, the hot metal quality objectives, i.e., silicon, sulfur, phosphorous, and manganese targets as well as the furnace size and capabilities including but not limited to fuel injection rate, pressurization level and flame temperature capabilities, and the extent to which external desulfurization, continuous tapping or ladle metallurgy exist may all need to be considered in order to conduct a truly meaningful economic worth evaluation.

Assessing a coal's impact on blast furnace economics is further complicated by the evolution of change that has taken place in the areas of raw materials availability and preparation and blast furnace equipment selection and capability (Figure 7). The most important of these are:

1- Preference for larger diameter blast furnaces in which CSR and coke strength have taken on added significance;

2- A reduction of blast furnace slag volume through improved burden chemistry, in particular, the use of iron ore concentrates and lower ash and sulfur cokes and more recently a move away from acid to flux sinter and pellets;

3- Introduction of more uniform and closely sized burdens;

4- Achievement of higher hot blast and tuyere flame temperatures with the use of less coke through a combination of stove redesign and oxygen enrichment coupled with hydrocarbon tuyere injections;

5- Achievement of higher wind rates through a higher pressure operation increased coke stability and controlled reactivity;

6- Adoption of external desulfurization and novel laddle metallurgy techniques to make higher quality steel products.[1,2,3]

The gradual adoption of these changes over the past 30 years has given rise to various blast furnace burdening and operating practices throughout the world which makes computer programs being used to assess economic worth of coking coals more difficult to compare, particularly if they are written for a specific raw material supply and operating practice. Few programs, if any, are conceived to be flexible enough to handle all the different cost impacts relative to performance of different quality cokes in different consumption settings.

Economic Worth Calculations - Moisture, Volatile, Ash, and Sulfur

Changes in coal moisture and volatile matter content impact coke production costs exclusively while changes in coal ash, sulfur, and alkali content and coke strength and reactivity primarily influence hot metal production (Figure 8). Higher volatile matter reduces coke yield and increases by-product recovery. The effect of volatile matter on coke yield is predictable. At a \$100 per ton coke production cost a one percent reduction in coal volatile matter increases coke yield approximately 0.75% and is worth \$0.75 per ton of coking coal. On the other side of the ledger, the by-product credits, which increase as coal volatile matter increases, must be accounted for. The amount and type of coke by-products resulting from coal carbonization are also predictable from volatile matter content and coke oven practice. The value of gas, tar, light oils and other coal chemicals prevailing at the time of production will determine the magnitude of the credit received. In the past, the magnitude of the credit received by U.S. coke producers has been geographic sensitive. Recently the inability to fully consume the coke oven gas and upgrade other by-products produced at certain Steel Works has reduced by-product values and made the magnitude of the credit received even more geographic sensitive.

Increased moisture has a comparable impact on coke yield as that of volatile matter. However, higher moisture content also creates handling and bulk density control problems and increases the underfiring requirements in the coke ovens. The combined negative impact of all these factors can easily account for over a \$1.00 per ton penalty on the low side per 1% increase in moisture content to several dollars per ton if bulk density is severely impacted and cannot be corrected with oil additions. Changes in volatile matter also impact on heat of carbonization and coking time and thus underfiring requirements but its effect is not as easily measured and incorporated into an economic worth evaluation.

As early as the 1950's, Flint,[4] MacFetters,[5] and others performed multiple correlation studies to identify the independent variables that were believed to effect blast furnace performance. Flint was especially successful in determining the effect that 18 independent variables had on the consumption of carbon per ton of hot metal tapped. The importance of the Flint approach is that over 300 independent variables were examined and reduced to 18 with their effect on carbon rate inclusive for all the variables studied. Flint used the effective carbon rate as the common denominator among cokes of different specifications to compute how non-coke independent variables effect coke rate. It follows that cokes having the same production cost but with different effective carbons produced from different coal blends must contain coals of different economic worth providing the same burdening, hot metal analysis and furnace conditions are achieved. The effective carbon value of coke charged to the blast furnace is the contained carbon in the coke (100 - % ash - % sulfur - 2.5% moisture - 2.0% to account for non-carbon elements contained in volatile matter and fixed carbon of the coke) reduced for the pounds of carbon consumed in smelting its ash, eliminating its contained sulfur and disassociating the moisture in the blast required to burn the carbon (Figure 9). A simple estimate of the percent effective carbon in coke can be made as follows:

Percent Carbon in Coke

Minus

.55 x Percent Ash in Coke

Minus

3.00 x percent Sulfur in Coke

Minus

.15* x Percent Bases (CaO + MgO) required** to flux the Ash and Sulfur

*Use .15 coefficient if burden flux sinter or pellets is the source of the bases; use .45 coefficient if bases are provided by raw fluxes (Limestone and/or Dolomite)

**Each unit of ash requires approximately .65 units of bases; each unit of sulfur requires 5.0 units of bases.[6]

The effect of ash on carbon rate reflects the amount of carbon that will be consumed in smelting its ash content. A unit of coke ash requires 0.65 units of bases, produces 1.8 units of slag and requires 0.6 units of carbon per unit of coke ash slag or in essence has a carbon coefficient of 1.0 for coke ash if the bases are provided by raw fluxes (limestone or dolomite). If flux sinter is the source of the bases, a lower carbon coefficient for coke ash of 0.7 units is applied. The Japanese have been operating with flux sinter burdens for quite some time. More recently American steel producers have experimented with 100% flux pellet burdens and have reported dramatic improvements in coke and hot metal production rates of 50 lbs per ton of hot metal (NTHM) and 5%, respectively.[7] Improved lining wear also results from switching from acid to flux pellet burdens.[8] For North American blast furnace practice where raw fluxes are more commonly used a 1.0 percent change in ash has been equated to a 20 pound change in coke rate (The effect that ash has on coke ash slag formation and carbon rate plus the coke required to provide to the blast furnace an equivalent effective carbon at the higher coke ash level.). The Flint formula was later expanded to account for associated losses in hot metal production due to effective carbon and related slag volume changes resulting from increased coke ash.[9] The effect of ash on hot metal production reflects the use of more coke per ton of hot metal as a result of less effective carbon and more slag volume produced in the blast furnace and the associated volume displacement of iron units. In this regard, a 1% increase in coke ash has been associated with a 1% production rate decline.[10] The combined effect on coke rate and hot metal production for a 1% change in coke ash is roughly equivalent to $1.50 to $2.00 per ton of coking coal at coke production costs of $100 per ton +/- 10% and $125 per ton +/- 10% respectively. These production costs have been on the decline for the past several years and this trend is likely to continue in the future.[6, 11, 12]

The magnitude of the coke rate adjustment due to increased coke sulfur where an increase in sulfur content in the hot metal can still be tolerated is influenced by the amount of carbon required to smelt the contained sulfur. Each unit of sulfur requires 3 units of carbon. If coke sulfur increases and hot metal sulfur must be held constant the basicity of the slag will have to be increased to capture the increased sulfur load in the slag. The volume and chemistry of the slag at normal blast furnace operating conditions will determine at what coke sulfur level the basicity of the slag has to be adjusted to in order for the slag to capture additional sulfur. As a general rule each unit of sulfur requires 5 units of bases. For typical North American blast furnace practice each 0.1% change in coke sulfur will require approximately 8 lbs of additional coke and result in moderate hot metal production losses of approximately 0.5% - 0.6%.[9] These combined changes are roughly equal to a cost differential of $0.75 - $1.00 per ton of coking coal at the aforementioned coke and hot metal production costs. Where it becomes necessary to increase slag volume to achieve the desired level of iron desulfurization, the increase in coke rate and losses in hot metal production become serious. In addition, hot metal production is adversely affected for the same reasons stated for ash. A 0.1% increase in coke sulfur content has been associated with as much as a 30 lb increase in coke rate and a 3% decline in productivity where slag volume must be increased to maintain a constant sulfur slag.[6] If sulfur content in the hot metal is increased beyond acceptable levels for conversion into steel products, external desulfurization can be deployed and the capital, operating, and reagent costs for the system must be computed to determine their impact on blast furnace economics. Operating costs of $1.50/NTHM have been reported per 0.01% reduction in hot metal sulfur in sulfur critical situations where external desulfurization has been employed.[13] However, coke rate savings of 31 lbs/NTHM have been reported for each .01% permitted increase in hot metal sulfur content with corresponding improvements in productivity of as much as 5%.

Other Hot Metal Chemistry Requirements - Silicon, Alkali

Because silica, like sulfur, is the only slag making constituent that does not totally end up in the slag it has a decidedly strong impact on blast furnace economics. Part of the silica reacts with carbon to form silicon which ends up in the hot metal. The partitioning of silica in the slag and hot metal affects slag chemistry and volume. For this reason furnaces should operate at consistent hot metal silicon levels. Flint and others have estimated that an increase of 0.1 percent silicon in the hot metal will increase carbon consumption 11 - 13 lbs.[14] This increase in fuel consumption is necessary to achieve the higher hot metal temperature of 35 F, required to reduce and incorporate each 0.1% silicon in the hot metal. With hot metal silicon contents ranging from 0.3% to 1.3% for different furnace operations its importance in assessing carbon rate consumption for a particular furnace operation cannot be overstated.

The ability to produce lower silicon hot metal is partly related to the alkali load in the furnace which in turn affects the hot blast and flame temperature that a furnace can aspire to as cooler, leaner more acidic slags promote alkali removal.[15] Over 80 percent of a slag's alkali removal capability is associated with lower basicity while the remaining 20 percent comes from added slag volume.[16] Conversely, the sulfur removal demands placed on a furnace are more effectively achieved through the production of hotter more basic slags. The more basic the slag the higher the formation rate of lime and magnesia silicates at the expense of alkali silicates. Since it is general practice to remove at least 70 percent of the alkalies in the slag the operating route of lower flame temperatures and lower basicity slags is preferred when high alkali coals and ores are employed in ironmaking.

For most steel producers the largest contributor of alkalies to the blast furnace is from that present in coke ash, although some ores can contain higher concentrations than the coke itself. Preoccupation with the reduction of alkalies goes beyond their interrelationship with hot metal silicon levels as the other operating problems that have been associated with their presence are formidable. These include

1- Formation of scaffolds large enough to cause erratic burden movements and disrupt normal gas flow patterns through the furnace which in turn reduces available working volume;

2- Premature failure of refractory linings and stove refractories;

3- Increased rate of reaction of coke to CO2 which consumes additional heat and lowers the thermal efficiency of the furnace;

4- Increased swelling and decrepitation of iron-ore pellets containing low silica content.[17, 18, 19]

The impact that alkalies have on North American blast furnace operations has been quantified. Carbon rate increases of 10 lbs/ton of hot metal, and changes in hot metal production of 1.0% have been equated to a 0.10% increase in the alkali content of coke.[20, 21, 22]

Phosphorous and Manganese

Besides silicon and sulfur control in the hot metal, phosphorous is often maintained below 0.11% and preferably below 0.05% and manganese below 0.50% and preferably below 0.30%.[23, 24, 25] The final reduction of manganese oxide also takes place at high temperatures and its content in the hot metal is generally proportional to the hot metal temperature. Lime fluxes the non-reduced manganese oxide forming a slag while any phosphorous entering the furnace is completely reduced and dissolved in the hot metal. Some of the unwanted phosphorous is oxidized out in the BOF, however, in cases where phosphorous levels are excessively high dephosphorization of the hot metal prior to its introduction into the BOF has proven successful. Carbon consumption increases of 2.0 lbs per ton of hot metal have been correlated to phosphorous and manganese increases in the hot metal of 0.10% at moderate concentration levels for these oxides. Rarely does the phosphorous content contained in American coking coals material impact blast furnace economics, as the amount present is relatively small compared with that contained in the ores being used. This is not the case for coking coals from other parts of the world, especially those produced in Russia, Poland, and South Africa where the phosphorous content can be twenty times greater than the level present in American coals.

Coke, Ore, and Flux Physical Properties

The blast furnace is a continuous counter-current process for producing metallic iron from iron-ore coke and limestone. Fluctuations in the size and strength of these raw materials determine furnace efficiency through their influence on heat transfer, chemical reduction and melting. Coke makes up the bulk of the blast furnace burden by volume and has the greatest impact on gas distribution in the blast furnace which is the single most important factor controlling hot metal production rate. Close control of its size distribution has become increasingly important as blast furnace diameters increased and these large throat diameters created strong size segregation. As the burden size consist varies there is a significant loss of void volume and a resultant increase in pressure drop through the furnace. To prevent this occurrence moveable armor plates and the Paul Wurth charging chute have been implemented. Still it is necessary to charge raw materials with optimal size distribution if low coke rates and high productivity are to be achieved. Close study of different burden material and their relation to furnace performance has revealed the following desired operating ranges

Lump Ore	3 - 1 1/2 x 3/8 - 3/16
Sinter	1 x 1/8
Pellets	5/8 x 3/8
Coke Small BF	2 x 3/4
Coke Large BF	3 x 3/4
Flux	1/4 x 3/8

As already mentioned, if certain burden materials are too fine the pressure drop accelerates whereas adequate chemical reaction and heat transfer are adversely affected if certain raw materials are charged too coarse to the furnace.[14] Burden raw materials and their more critical upper and/or lower sizes are as follows:

Normal Lump Ore - plus 3/16
Sinter - plus 1/8
Pellet - plus 3/8
Coke - minus 2" for smaller BF
- minus 3" for larger BF
Flux - minus 1 1/4"

Over the years Flint's carbon rate formula has been expanded to reflect how a change in the following size consist categories of blast furnace raw materials entering the furnace (after stockhouse screening) can impact on carbon rates

Pellet and Sinter Variable	Carbon Coefficient Change Per 1 lb/NTHM
Minus 20 Mesh	+.12
Plus 20 Mesh, Minus 1/8"	+.08
Plus 1/8", Minus 3/8"	+.04
Plus 3/8", Minus 1"	0
Plus 1", Minus 2"	+.03
Plus 2", Minus 4"	+.05
Plus 4"	+.10

Coke Variable	Carbon Coefficient Change Per 1%
Minus 1/4"	+.045
Plus 1/4", Minus 3/4"	-.045
Plus 3/4", Minus 1-1/2"	-.075
Plus 1-1/2", Minus 2"	-.055
Plus 2", Minus 3"	-.025
Plus 3", Minus 4"	+.025
Plus 4"	+.075

Additional carbon is also required if the limestone diameter is greater than 1.3 inches because it is not completely calcined when it reaches the high temperatures zone of the furnace. For instance, almost 5 lbs of carbon per 100 lbs of limestone used can be saved if the limestone diameter is reduced from 3 to 2 inches.

To a great extent the top size and size distribution of coke can be controlled by the coal blend charged and the coal preparation and coke oven operation conditions employed in the carbonization process. Proper coal selection up front can help control heat of carbonization, and coking time in the required ranges necessary to achieve the starting coke size desired on the wharf for the charge preparation and coke operating conditions being employed.

Coke Stability

High coke strength with good reactivity is required to operate at maximum hot metal production levels.[26] An increase in coke stability of one point between 50 and 60 can result in a 2% increase in wind rate and a comparable increase in hot metal production (1.5 - 1.7%) until maximum blower wind is attained.[27] Once blower wind reaches a maximum the production increase due to further increases in stability is reduced to 0.7 - 1.0% per point increase. This is caused purely by the lower carbon rate achieved with the higher strength coke. A decrease in coke rate of 5 - 10 lbs per ton of hot metal is also associated with a 1 point increase in stability with no blower wind restrictions. The coke rate changes are on the high side of the range when blower wind restricts production. A beneficial reduction in coke breeze generation of 0.5 - 0.75% per point of stability is also associated with coke strength improvements. Consequently, a one point improvement in coke strength can translate into an economic benefit of as much as $1.50 - $2.00 per ton of coking coal.

Coke Reactivity

Investigations into the influence that coke reactivity has on blast furnace performance has shown that an increase in the reactivity and a decrease in after reaction strength of coke charged to the blast furnace results in increased coke fines in the raceway, expansion of the deadman, and a contraction of the raceway depth and active coke zones. With coke degradation, pulverized fines accumulate above and in front of the combustion zone causing a peripheral gas flow in the shaft. This causes channeling of gases in the shaft of the blast furnace and deterioration of liquid permeability in the hearth due to a compacted coke zone below the tuyeres. Ishikawa[28] summarized these changes in terms of coke rate as follows:

+1.45 Kg coke/THM/-1% CSR when CSR < 57.5

+0.30 Kg coke/THM/-1% CSR when CSR > 57.5

Adverse effects on hot metal production have also been implied when using high reactive coke. More recently one U.S. Steel producer has reported coke rate and hot metal production improvements of 10 lbs and 0.7% per point of CSR while maintaining coke strength and chemistry constant.[29, 30] Lining deterioration was also reported to have ceased.

Operating Conditions in the Blast Furnace

Operating conditions in the blast furnace can impact on carbon rates and thus the magnitude of the economic worth value assigned to different coal attributes. In order to lower the carbon rate in the blast furnace the proper balance between indirect and direct reduction must be achieved and maintained. Indirect reduction takes place in the upper portion of the furnace generally at temperatures of around 1700 - 1800 F according to the following reaction, $CO + FeO = Fe + CO_2$.[31] Direct reduction by the reaction $C + FeO = Fe + CO$ takes place in the lower portion of the furnace at temperatures generally above 2000 F, absorbing large quantities of heat. In actual practice, a balance of 55 percent indirect to 45 percent direct results in the most economic blast furnace practice. The key to lowering coke rates lies in maintaining this balance by increasing the amount of heat in the lower portion of the furnace while providing enough heat and carbon monoxide for indirect reduction in the stack.[32] This is generally accomplished by controlling flame temperature through hot blast and oxygen enrichment while at the same time introducing injection fuels and moisture in the blast. Each of these changes has a different effect on flame temperature.

Increasing hot blast increases the flame temperature because the sensible heat in the air increases. Increasing oxygen enrichment by 1% increases flame temperature about 80 F because the amount of N_2 in the total blast decreases therefore decreasing the amount of combustion gas formed per pound of carbon and thus the amount of combustion gas that must be heated.[33] For every 100 F increase in the hot blast temperature direct reduction increases by two percent. Increasing the moisture in the blast decreases blast temperature 22 F per grain of moisture per standard cubic foot because of the increased heat consumed by moisture when it reacts with carbon. However, the H_2 and CO that is formed in the lower portion of the furnace increases the amount of reducing gas in the stack and thus, the relative percentage of indirect reduction occurring in the furnace.

Fuel injection decreases flame temperature because fuels burned with O2 release less heat per pound of C than does the burning of coke with CO2.[34, 35] Injected fuels consume O2 that would otherwise consume coke C so cold fuel is replacing hot preheated coke. Injected fuels also contain H2 which is released in the tuyere zone thus increasing the amount of combustion products produced per pound of C consumed that must be heated.

By injecting oil, gas or coal and other hydrocarbon fuels in combination with oxygen enrichment of the blast the coke rates can be reduced and the hot blast and flame temperatures can be increased without upsetting the optimum heat balance in the various zones of the blast furnace.[36, 37] The following savings in carbon rate have been established through the years for different hydrocarbon injectants

Variable	Carbon Coefficient Change Per 1 lb/NTHM
Natural Gas	-1.05
Coke Oven Gas	- .80
Fuel Oil	- .90
Tar	- .90
Coal - High Volatile	- .80
Coal - Low Volatile	- .75

Finally, increasing the top pressure increases productivity and decreases carbon rates by preventing the burden from lifting and upsetting its normal decent in the furnace at higher operating wind rates. Increasing the temperature of the hot blast, as already mentioned, can also increase productivity and decrease coke rates while the moisture in the hot blast or in the injected coal or from other burden materials results in an increase in effective carbon rate. The following relationships with carbon rates for these blast furnace operating conditions have been established.[6]

Variable	Carbon Coefficient Change	Per Measurement Unit
Top Pressure	-1	+1 PSIG
Temperature of Hot Blast	-.25	+10 F
Moisture in Hot Blast	+.40	+lb/ton of hot metal tapped
Moisture in Injected Coal	+.55	+lb/ton of hot metal tapped

Base Formulas Required for Economic Worth Evaluations

From the foregoing discussions it is clear that any economic worth comparison of coking coals cannot be conducted until formulas for measuring the effect that changes in coke breeze generation, coke yield, and coke by-products have on coke production costs have been established (Figure 10). To compute these effects, it is necessary to know coke cost, coke yield, and furnace coke yield but also, for calculating coke breeze effect:

1 Average coke breeze generation;

2 Change in the average generation per point change in stability;

3 Coke breeze value;

for calculating coke yield effect:

1 An accurate estimate of coke yield differences for different volatile content coals and coal blends.

and for calculating by-product credit:

1 An accurate estimate of by-product yields for different volatile matter content coals and coal blends;

2 Current value of different by-products such as gas, tar, light oil.

Formulas for predicting coke ash, sulfur, alkali, and phosphorous content and stability and reactivity are also required as are applicable coke rate and hot metal production effect formulas for the blast furnace in the consumption setting being studied. The coke rate effect formula at the very least will be influenced by coke cost, coke yield, furnace coke yield, and coke rate for the consumption setting being studied. The hot metal effect formula will also be influenced by coke yield, furnace coke yield and average coke rate but most importantly by some measure of blast furnace efficiency that relates to a profitability standard for the conversion of iron ore to hot metal and hot metal to steel.

Once the base formulas have been established, it is necessary to have some feel for the impact that changes in coke stability, reactivity, ash, sulfur and alkali content have on coke rate and hot metal production in the blast furnace. As already mentioned, these relationships are site specific and must be established over a long operating period and be constantly updated as changes in blast furnace burdening and operating conditions change. Some typical values that have been used over the past years for estimating cost impacts due to changes in the aforementioned coke quality parameters in the context of North American blast furnace practice are as follows:

Coke Rate Change/Pt. of Stability = 10 lbs
Hot Metal Change/Pt. of Stability = 1.50%
Coke Rate Change/Pt. of CSR
Coke After Reaction < 58 = 3.0 lbs
Coke After Reaction > = 58 = 1.5 lbs
Hot Metal Rate Change/Pt. of CSR 0.5%
Coke Rate Change/% Coke Ash = 20 lbs
Hot Metal Change/% Coke Ash = 1.25%
Coke Rate Change/.01% Coke Sulfur = 10 lbs
Hot Metal Change/.01% Coke Sulfur = 1.00%
Coke Rate Change/.1% Coke K2O = 12 lbs
Hot Metal Change/.1% Coke K2O = 1.10%

Output of Economic Worth Model

The final output of economic worth models in which real coal costs reflect the cost of producing coke and the performance of that coke in the production of hot metal is most conveniently equated back to a cost per ton of coal charged whether for a single coal or a blend (Figure 11). Since rank is the most controlling factor with regard to utilization, only coals or blends of coals of similar rank can be effectively compared. If individual coals of comparable rank are being compared,the proportions of the other coals in the blend are held constant and the entire cost advantage or disadvantage of one blend versus another is expressed in terms of the cost per net ton of substituted coal used in the blend. If different rank coals are being substituted, it is often necessary to change the participation of the other blend coals in order to compensate for this rank difference. In this way, the substitution of different rank coals can be fairly evaluated with regard to their overall affect on resultant coke quality and subsequent blast furnace performance. In this case, it is not only the individual substituting coals that are credited with the resultant change in economic worth but the entire blend and the cost advantage or disadvantage must be expressed on the basis of cost per ton of all coal charged (not just the substituting coal).

Statistical Process Control

With the recent adoption of Statistical Process Control (SPC) techniques to maintain metallurgical shipments made to U.S. steel producers, the economic worth evaluation techniques have taken on added significance (Figure 12). One steel producer is actually using the economic worth approach to report back to coal producers on their monthly performance in terms of the dollar impact their shipments have had on the production of coke and hot metal. This novel approach applies statistical process control techniques to monitor the average and ranges in chemical quality of shipments made by each supplier for comparison with the typical and min/max specifications that the products were sold on (Figure 13, 14). The impact on coke and hot metal production costs attributed to differences between the mean quality of the shipments made and the typical specifications agreed to along with the impact associated with the differences between the range in chemical quality for the shipments made and the min/max specifications agreed to, or in essence a measure of variability, are computed and expressed on a cost per ton of coking coal charged to the ovens. These calculations are distributed to each supplier on a monthly basis and will be used as the basis for future purchases.

Future Work

With the advent of sophisticated computer control equipment and our growing knowledge of what takes place in the blast furnace the concepts of economic worth are taking on added significance. Instead of having to infer performance in the blast furnace, systems like the Koverhar Blast Furnace Supervising System are being used to actually measure slag bascisity, fuel consumption, blast furnace production rate, and process efficiency on a continuous basis along with pertinent temperature and pressure data. With more developments of this kind hot metal production costs will continue to decline and the steel industry's future will be assured.

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Ecoworth Concept

- Price vs Quality vs Value
- Delivered Cost Plus Quality Effects on Process Variables = Value
- Price that can be Paid for Alternative Supply While Coke and Hot Metal Production Costs are Held Constant

FIGURE 1

Coal Variables

- Handling Capabilities
  - Moisture
  - Size Consist
- Chemical
  - Volatile Matter
  - Ash
  - Sulfur
  - Ash Chemistry
- Rheological
  - FSI
  - Fluidity
  - Dilation
  - Sole Heated Oven Contraction/Expansion Pressure
- Petrographic
  - Reflectance
  - Inert Content
  - Non-Maceral Microtexture

FIGURE 2

Coke Production Variables

- Coal Blending
- Coke Operating Conditions
  Pulverization
  Bulk Density Control
  Charging Practice
  Heat Rate
  Underfiring Requirments
  Byproduct Credits

FIGURE 3

Coke Variables

- Yield
- Fuel Value
- Purity
- Stability (Burden Support)
- Reactivity (Reducing Capacity)

FIGURE 4

Demographic Variables

- Historical Perspective
- Operational Constraints
- Captive/Purchase
- Contract/Spot
- Railroad/Port of Loading Preference
- Quantity Required Matched to Shipping Ability

FIGURE 5

Hot Metal Production Variables.

- Raw Materials Supply
- Blast Furnace Operating Conditions
- Desired Hot Metal Quality

FIGURE 6

North American vs Japanese
Blast Furnace Practice

- American vs Australian/Canadian Coals
- Lower Ash and Higher Sulfur Cokes
- Higher Alkali Coke
- More Pellets and Less Sinter in Burden
- Less Flux Pellets or Sinter in Burden
- Lower Slag Viscosity
- Higher Hot Metal Silicon Content
- Higher Blast Moistures
- Lower Hot Blast and Flame Temperatures
- Lower Top Pressures
- Less Frequent Casting
- Less Deployment of External Desulfurization

FIGURE 7

ECOWORTH CONCEPT

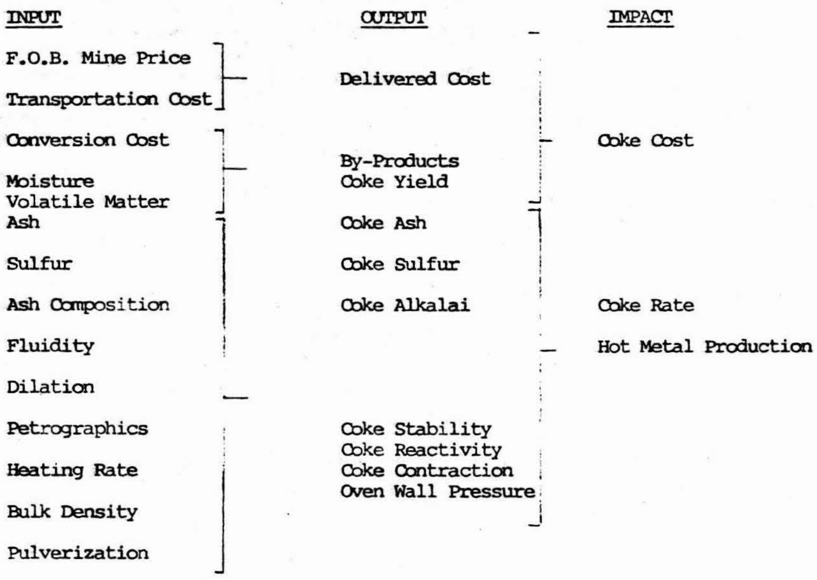


FIGURE 8

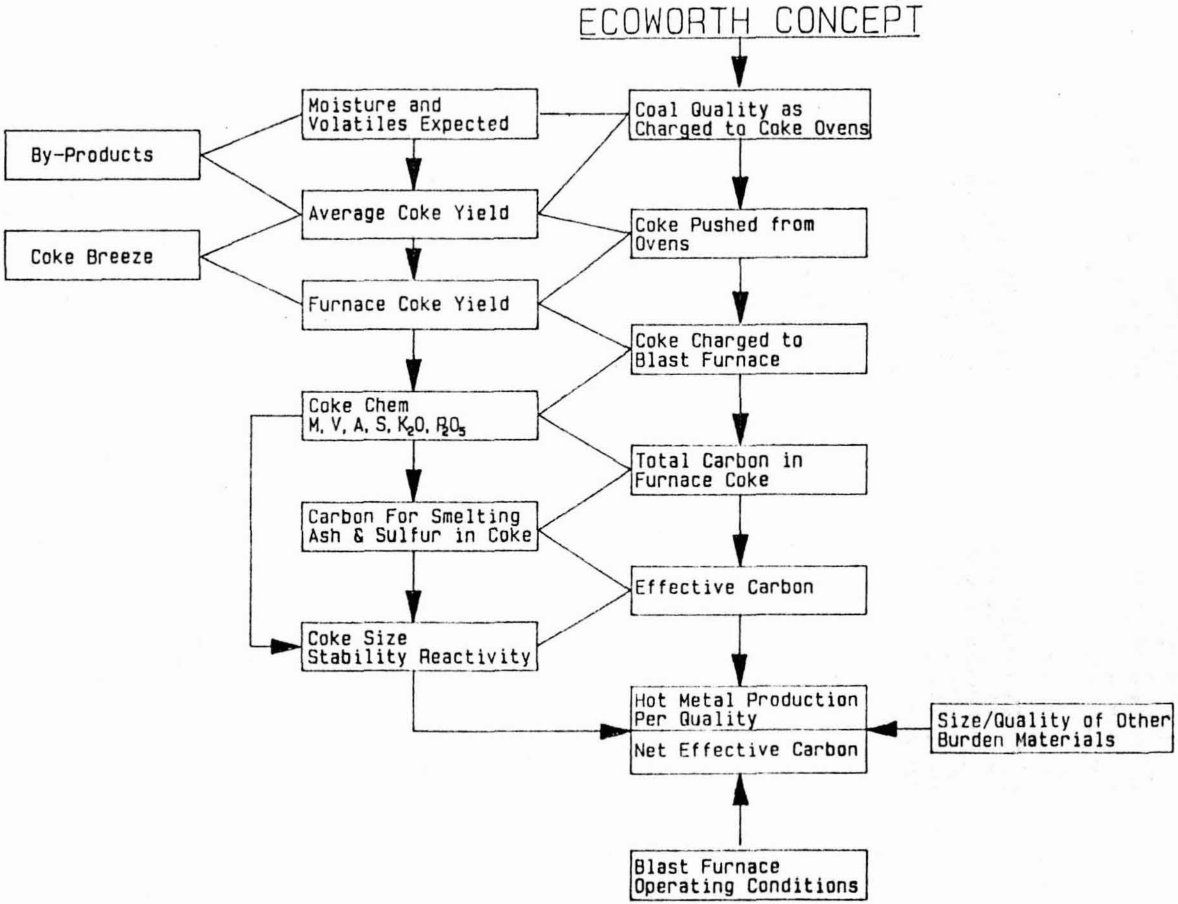

ECOWORTH CONCEPT
By-Products
Coke Breeze
Moisture and Volatiles Expected
Average Coke Yield
Furnace Coke Yield
Coke Chem M, V, A, S, K_2O, P_2O_5
Carbon For Smelting Ash & Sulfur in Coke
Coke Size Stability Reactivity
Coal Quality as Charged to Coke Ovens
Coke Pushed from Ovens
Coke Charged to Blast Furnace
Total Carbon in Furnace Coke
Effective Carbon
Hot Metal Production Per Quality
Net Effective Carbon
Size/Quality of Other Burden Materials
Blast Furnace Operating Conditions

FIGURE 9

COKE RATE EFFECT
Avg Coke Yield
Avg Furnace Coke Yield
Avg Coke Rate
Avg Coke Cost

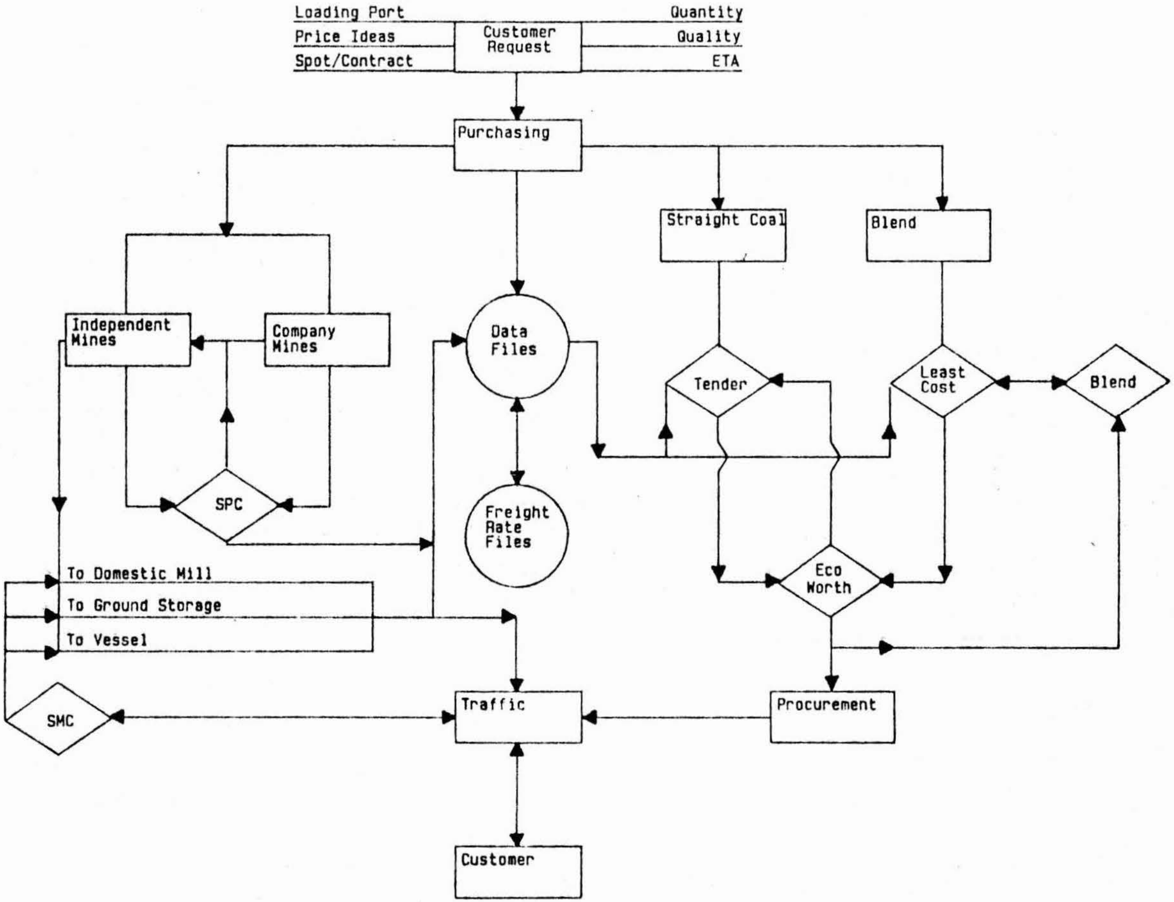
HOT METAL EFFECT
Avg Coke Yield
Avg Furnace Coke Yield
Avg Coke Rate
Ratio of Steel to Hot Metal

COKE BREEZE EFFECT
Coke Stability Difference
Avg Coke Breeze Generation
Avg Coke Yield
Avg Coke Cost
Avg Breeze Value

COKE YIELD EFFECT
Coke Yield Difference
Avg Furnace Coke Yield
Avg Coke Cost

COKE BY-PRODUCT EFFECT
By-Product Yield Difference
Avg By-Product Value

FIGURE 10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Price Ideas
Spot/Contract
Customer Request
Quantity
Quality
ETA
Purchasing
Straight Coal
Blend
Independent Mines
Company Mines
Data Files
Tender
Least Cost
Blend
SPC
Freight Rate Files
Eco Worth
To Domestic Mill
To Ground Storage
To Vessel
SMC
Traffic
Procurement
Customer

FIGURE 11

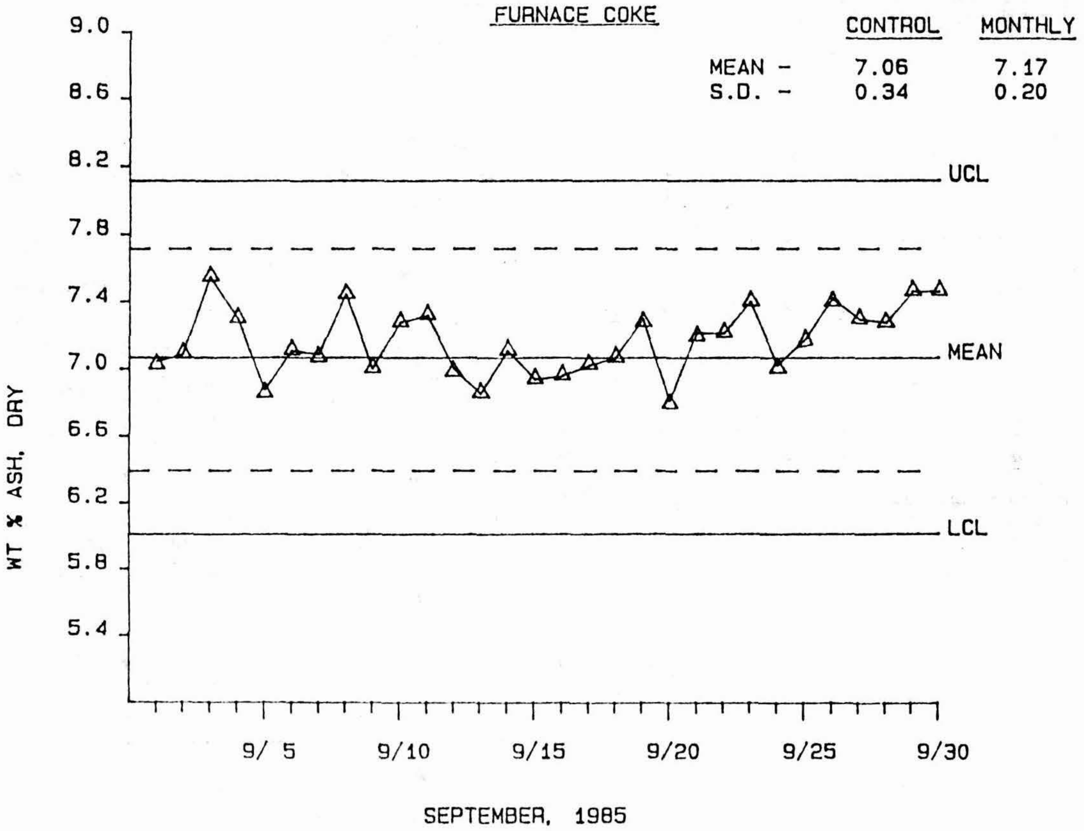

FURNACE COKE
CONTROL
MONTHLY
MEAN - 7.06 7.17
S.D. - 0.34 0.20
UCL
MEAN
LCL
9.0
8.6
8.2
7.8
7.4
7.0
6.6
6.2
5.8
5.4
WT % ASH, DRY
9/ 5
9/10
9/15
9/20
9/25
9/30
SEPTEMBER, 1985

FIGURE 12

COMBINED CHEMISTRY -- FEBRUARY 1987
VARIANCE FROM TYPICAL ANALYSIS

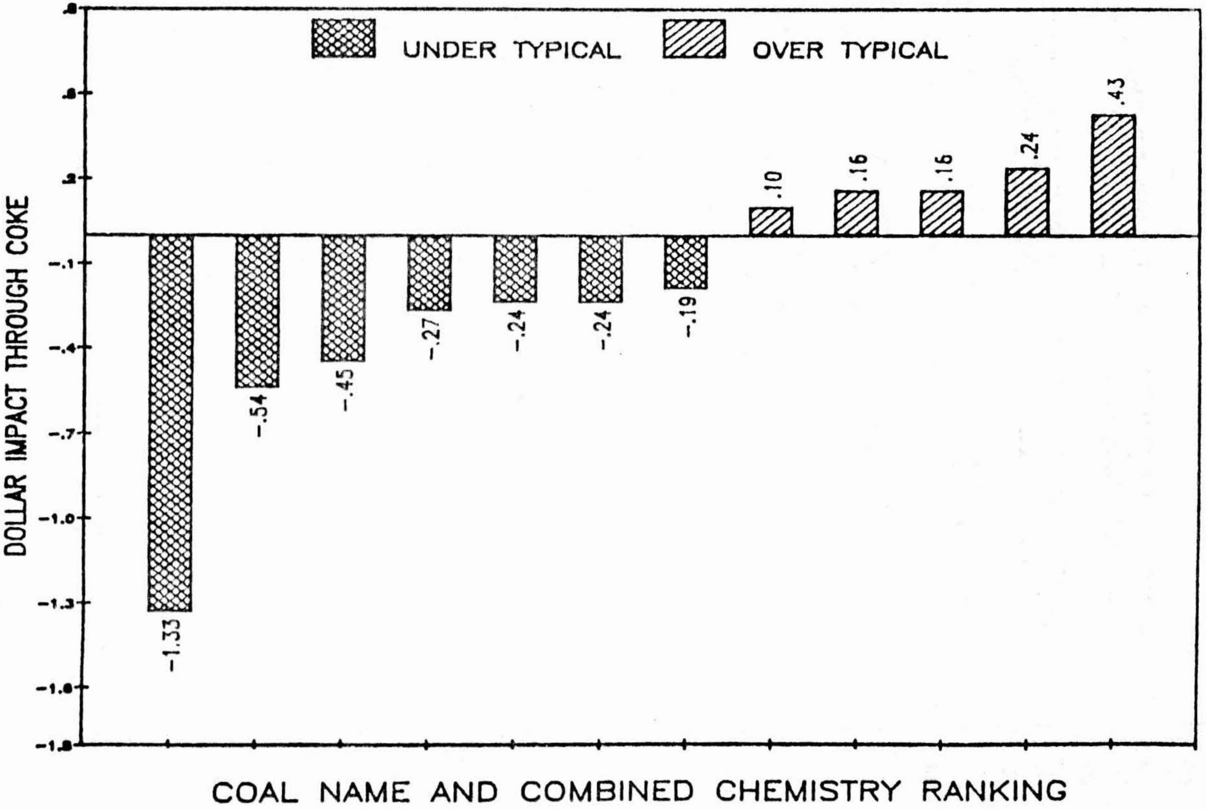
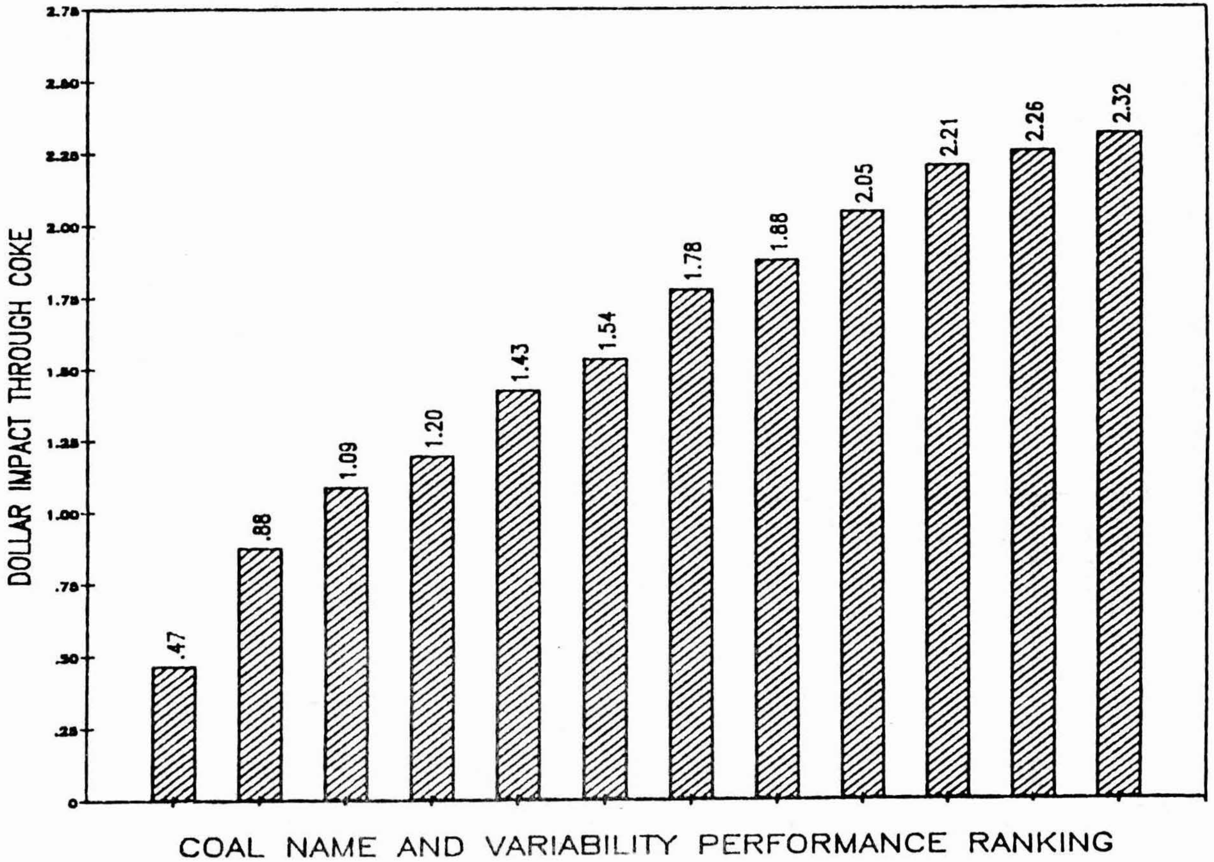


FIGURE 13



COMBINED CHEMISTRY VARIABILITY -- FEBRUARY 1987

FIGURE 14