BLAST FURNACE OPTIMISATION BY LINEAR PROGRAMMING

BY

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CERTIFICATION

I certify that this work was carried out by ABOGINIJE Peter Apata of the Department of Metallurgical and Materials Engineering, Federal University of Technology, Akure, and that the work has not been submitted elsewhere for the award of a degree.

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DEDICATION

This work is dedicated to God Almighty who teaches my hands to war and fingers to battle

ACKNOWLEDGMENT

I foremost, give thanks to almighty God whose enabling grace has seen me through, frustrate every plan of the enemy during this work, and made his peace which passes all human understanding multiplied unto me.

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THE LORD IS MY ROCK.

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ABSTRACT

The model used for optimizing the blast furnace input parameters is described. It is based on the mathematical description of the stoichiometric and enthalpy balances of blast furnace process, and quantifies the amount of fuels required for producing a specific amount of pig iron and the effects of varying these inputs. The models were communicated into a linear optimisation Computer program written in MATLAB.

The designed operating data obtained from the Nigerian blast furnace at Ajaokuta steel complex, and the parameters of various fuels used were input into the program. The outputs generated were analysed.

1.0 INTRODUCTION

Over the years, the steel industry has played a major role in the development of our industrialized society and still remains an important factor for the industrial growth of both the developed and developing nations. The Blast furnace has been the link in the chain processing of iron ores into a finished steel product (Poos 1986). It is an economic and reliable mass producer of liquid iron. During the last century, productivity, efficiency, and reliability of Blast furnace process have attained levels no iron makers would have dreamed of a few years earlier. From the point of view of energy requirement, this process has shown a very great flexibility and accepts a great variety of fuels. The type of fuel used varies from country to country and depend mainly on the relative abundance and cost of the different types of fuel.

The blast furnace (Fig 1) makes use of mainly coke for the production of the reducing gas necessary for iron ore reduction, and production of heat for the melting, and provision of support for the burden inside the furnace. The recent economic upheavals, double energy crisis, persistent recession of the economy in general, and the steel industry in particular, sky-rocketing costs, interest rates, and financial shortcomings in many steel industries have slashed the steel industry into a mood of uncertainty and pessimism (Leone and Meyer 1980, and Luersseen 1981). Of all the Blast furnace charge, Metallurgical Coke has the highest cost, and the possibility of the price of blast furnace coke declining is ruled out (Nashan 1996).

Obviously, there is a decline rate of coke production yearly. In Africa, most of the coal are not coking, especially the Nigeria coal.

Improvements being made in the blast furnace operations so far are aimed at the following;

(1) Better and smoother operation of the furnace.

(2) Increase in productivity to reduce production cost and meet increasing demands

(3) Reduction in coke consumption, which is very expensive due to diminishing reserves of coking coal.

In other to achieve the above objectives, the following steps are to be adopted.

(i) Injection of hydrocarbon liquids, gases or solids through the tuyeres, which has led to lowering of furnace requirement for coke.

(ii) Injection of these alternative fuels with the use of hotter blast.

(iii) Enrichment of blast with pure O_2 leading to increased flame temperature in front of the tuyeres thus permitting increased injection of hydrocarbon and increased rate of CO production.

(iv) Higher top pressure, which increase the residence time of reducing gases within the furnace.

(v) Better burden distribution in the furnace by the production of novel top charging devices such as the Paul Wurth Top and movable armor. The Paul

Wruth top in addition to better burden distribution permits the use of higher top pressures.

(vi) Better process control through the use of computerized instrumentation and installation of process control computers.

The use of computers in the optimization of the furnace permits the prediction of the total raw material combination to be used in the production of liquid steel at the minimum cost, and the thermal effect of such combination. Several optimization work have been used extensively for controlling blast furnace performance, deciding the composition of furnace charge, and neural network application to blast furnace burden. top gas, and heat distribution control (Inkala et al 1995, Iida 1995, Augstenberger 1996, Deitz 1997, and Zuo et al 1998).

This work shows that the flexibility of the blast furnace process is such that it can be adapted to a wide fuel combination and consumption, and the different aspect of the optimisation procedure are discussed.

2.0 LITERATURE REVIEW

2.1 THE IRON BLAST FURNACE

The iron blast furnace has developed from the earliest production of liquid iron in shaft furnace in 14th Century (Cottrel 1975), to the replacement later of charcoal by coke, which has led since to the blast furnace over increasing in size. Figure 1 depicts steel-making process in a modern blast furnace. The iron blast (Fig.2) furnace is a tall, vertical shaft furnace, which employs, mainly in form of coke to reduce iron form its oxides.

The foundation of a blast furnace carries a heavy load. It constitutes piles driven to the bedrock, over which a huge reinforced concrete structure is constructed. The steel column mounted on the concrete ring support the mantle ring. The blast furnace shell and the inside brickwork are supported by the mantle ring.

The hearth bottom consisting of courses of fireclay bricks and carbon blocks is laid out within the concrete ring. The hearth is a cylindrical portion where the Iron notch, slag notch and tuyeres are located. The bosh is the section that slopes outward just above the hearth. The body is again a cylindrical portion above the bosh. The shaft, which is in the form of a cone, comprises the portion above the body. The throat, cylindrical in form is at the top of the shaft.

There are box type coolers within the refractory lining of the throat and shaft through which water circulates. The coolers are mounted to the shell of the Blast furnace. The bottom of the hearth and sidewalls are having plate type coolers.

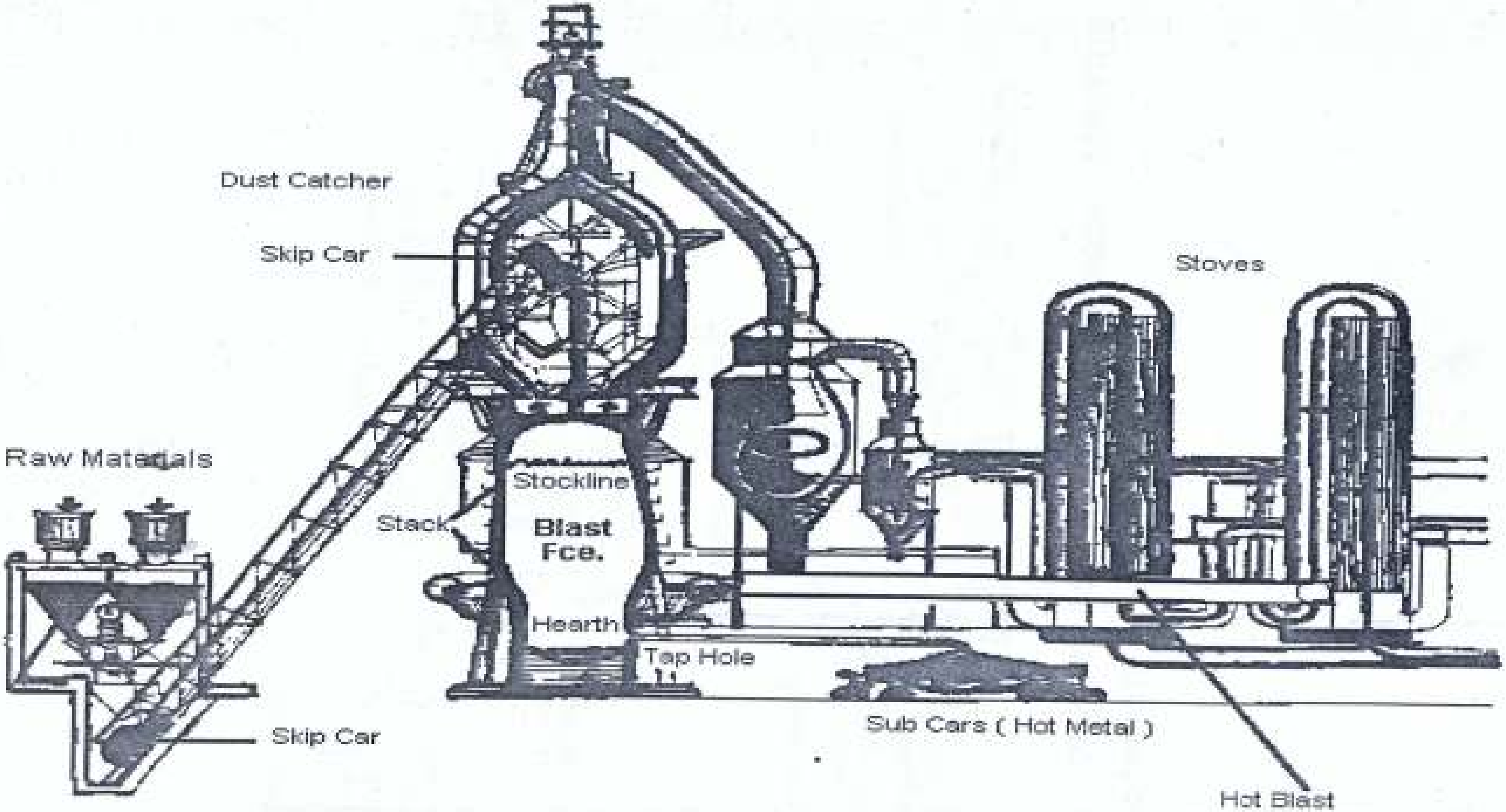


Figure 1 – The Modern Blast Furnace*

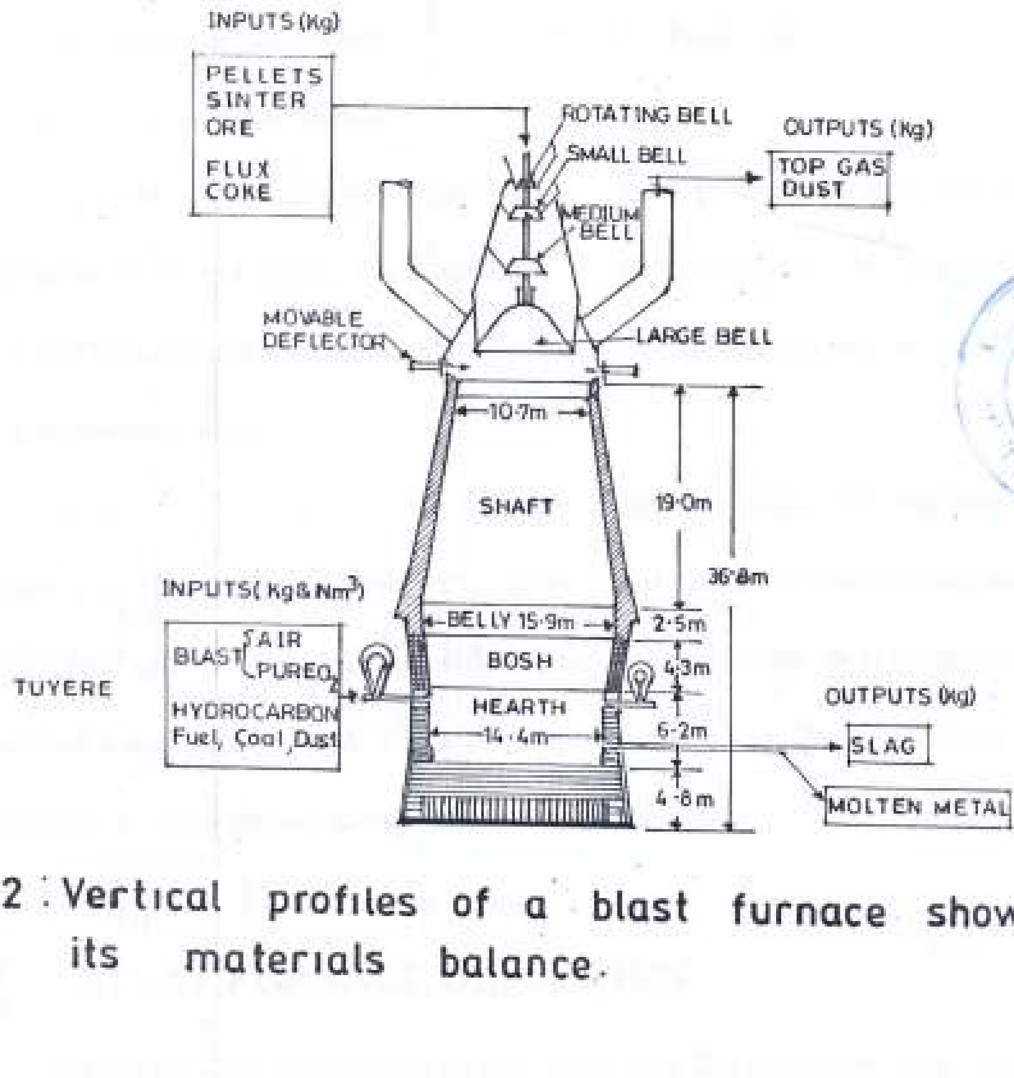


Fig.2 : Vertical profiles of a blast furnace showing its materials balance.

In a typical blast furnace, the Iron notch is situated at a height of 1.1m above the hearth bottom. The slag notch is located at a height of 1.8m above the Iron notch while the tuyeres is located at a height of 3.4m above Iron notch. Hot blast from stoves passes through the bustle pipe situated at bosh level. The bustle pipe is however located at a height of 5.5m above Iron notch.

The principal objective of the furnace is to produce molten iron of constant composition at a high rate. The furnace is of self supporting, free standing design in which the furnace shell form the hearth base to the furnace top ring is carried on a base ring at foundation level.

Many efforts were made in the 20th century towards the improvement of the operations of the furnace which were aimed at; Better and smoother operation of the furnace; Increase in productivity to reduce production cost and meet increasing demands; Reduction coke consumption which is very expensive due to diminishing reserves of cooking coal. These improvements are discussed in section.

2.2 BLAST FURNACE OPERATION

In modern blast furnace, the charge; coke form the coke over plant, flux, and sinter ore form the sintering plant, are conveyed through conveyor belts, and discharged into the receiving hopper of the blast furnace. In the conveyor system, one belt conveys sinter and flux, and the other conveys coke.

The charge is received by the hopper, and falls into the small bell. After each feed, the hopper revolves through an angle and the small bell opens, the charge is evenly distributed over the by bell. As the small bell closes, the by bell lowered, and the charge falls into the throat of the furnace.

Hot blast is supplied form the hot stones to the bustle pipe, and is blown through the tuyeres at the bottom of the furnace. It enters at a velocity of between 200 to 300mws-1 and a pressure of 2 to 4 atmosphere, so as to push the reducing gasses through the solid burden and to overcome the top pressure of the furnace.

According to Peacey (1979), the high velocity of the blast clears a raceway of gas and rapidly hurtling coke in front of each tuyere (Fig. 3). The bottom-most of this zone periodically fall into the raceways to be consumed by the incoming air, and hence the whole bed is always gradually moving down to be re-supplied at the top with coke from above. The hot blast reacts with the coke and the injectant in the belly and bosh of the furnace to form a mixture of carbon monoxide and nitrogen. The combustion of coke at the tuyere level raises the temperature to between 1800 and 2100^{0}C (Coudrier 1985).

This mixture ascends in the furnace while exchanging heat and reacting with the raw materials descending from the furnace top. The gas is eventually discharged from the furnace top. The gas is eventually discharged from the furnace top materials and recovered for use as fuel in work. During this process, the layer-thickness ratio of iron-bearing materials to coke charged from the furnace top and their redial distributions are controlled so that the hot blast can pass with appropriate radial distribution. During the descent of the burden in the furnace, the iron-bearing materials are indirectly reduced by

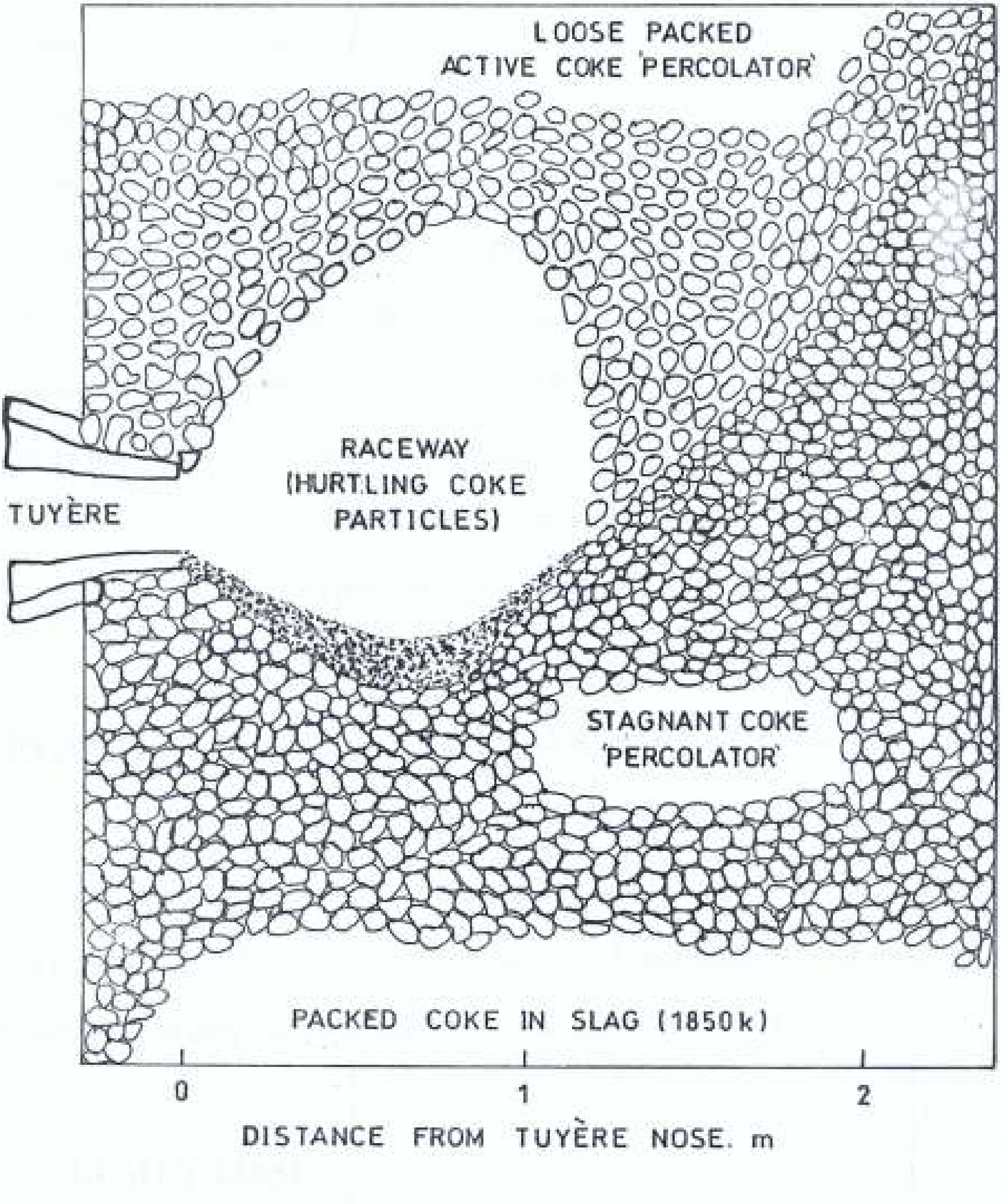


Fig.3 : Schematic view of tuyère region of the blast furnace.

carbon monoxide gas in the low-temperature zone of the upper furnace. In the lower part of the furnace, carbon dioxide, produced by the reduction of the remaining iron ore by carbon monoxide is instantaneously by coke (C) into carbon monoxide, which again reduces the iron oxide. According to Ghosh and Ray (1991), the CO becomes more stable at higher temperatures whereas all metal oxides generally less stable.

The overall sequence can be regarded as direct reduction of iron ore by solid carbon in the high-temperature zone of the lower furnace. The reduced iron simultaneously melts, drips and collects as hot metal at the hearth. The hot metal goes downward to the bottom of the hearth and the slag produced floats on top of the molten metal. The hot molten metal is tapped at regular intervals (usually 2-3 hours) from the iron notch while the slag is tapped from the slag notch.

2.3 REACTION ZONES IN THE BLAST FURNACE

The blast furnace is a packed bed reactor in which there is a counter current flow of solid materials from top and gases from bottom. The results the dissection of quenched blast furnace (Kanbara 1977, Yasuto 1977, Minoru 1977, and Kojiro 1977), show that, the blast furnace is divided into five reaction zones as shown in Figure 4.

2.3.1 LUMPY ZONE

The materials here are solid and gases. The solid are sinter, fluxes, and coke, while the gas is a mixture of CO, CO_2, N_2, and H_2, which have taken part in reduction reactions

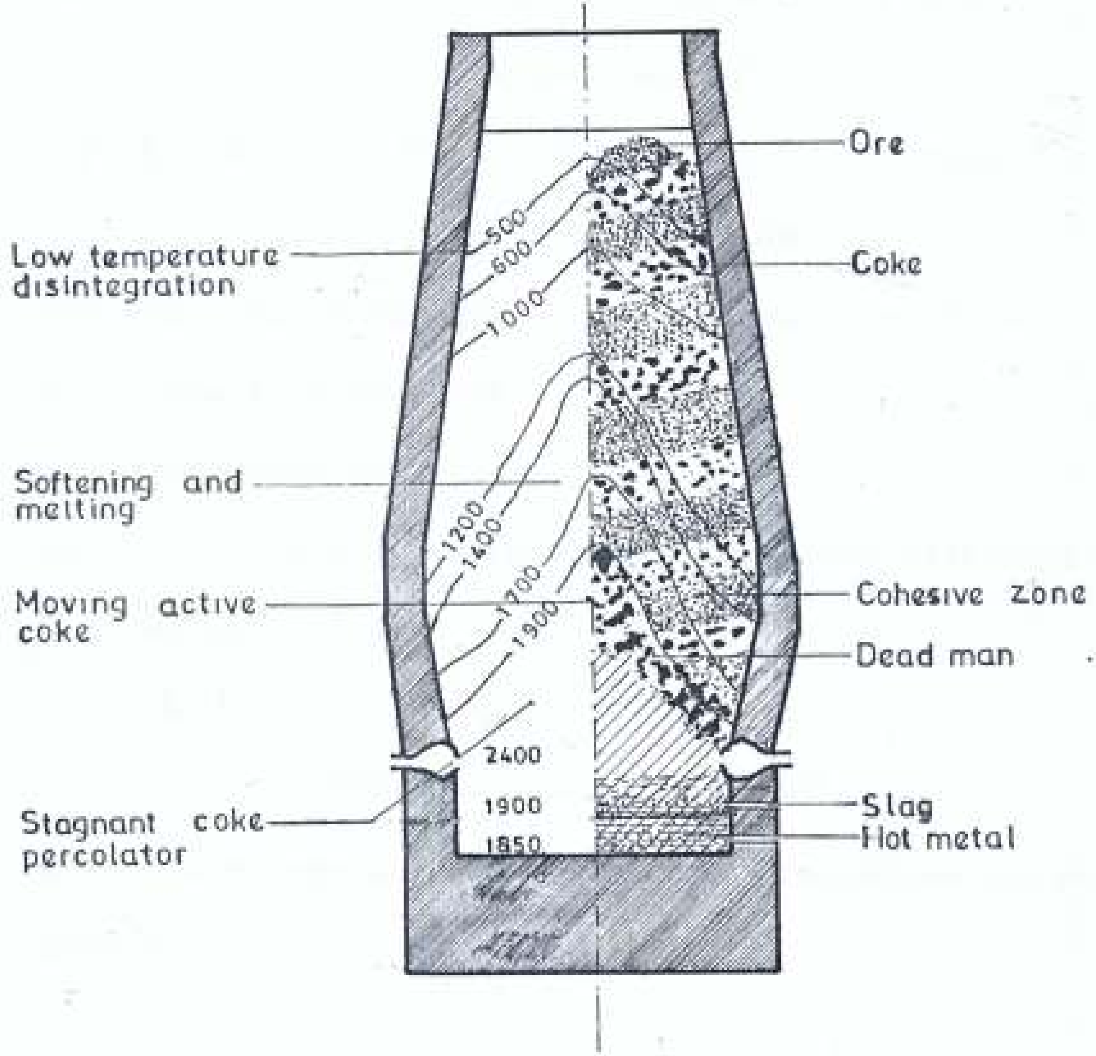


Fig.4 : Schematic drawing of the inside of a blast furnace.

further down in the furnace. Here the indirect reduction of iron oxides take place, some of which are;

$$3Fe_2O_3 + CO \text{-------}> 2Fe_3O_4 + CO_2 \text{ .... } (2.1)$$

$$\Delta H_{298} = -4800kj(kg\ mole\ CO)^{-1}$$

$$1.2Fe_3O_4 + CO \text{-------}> 3.8Fe_{0.947}{}^{0} + CO_2 \text{ .... } (2.2)$$

$$\Delta H^{0}_{298} = +50{,}000kj(kg\ mole\ CO)^{-1}$$

Temperature of the gas falls rapidly as it passes through this zone due to

(i) Cooling by incoming solids

(ii) Evaporation of moisture and

(iii) Net endothermic nature of reducing higher oxides to FeO according to the reaction.

$$1.12Fe_2O_3 + CO \text{-------}> 2.36Fe_{0.947}{}^{0} + CO_2 \text{ .... } (2.3)$$

$$\Delta H^{0}_{298} = +13{,}000kj(kg\ mole\ CO)^{-1}$$

It is also in this zone that reduction accompanied by degradation takes place as shown in.

2.3.2 SOFTENING - MELTING ZONE

This zone consists of solids, gases and small amount of liquids. The boundaries of this zone are characterised by the beginning of softening of iron-bearing burden materials as defined by 10 percent contraction under load (Lu 1979) and the commencement of melting of sponge iron into liquid metal and slag. The location and shape of this zone depends on relative total heat capacity of gaseous and solid streams. Factors such as higher fuel rates, less limestone addition or lower melting temperature for sponge iron will cause the melting front to move further up or further away from the tuyere level.

In this zone, both direct and indirect reduction reactions take place as well as coke gasification (solution loss). Not all the FeO produced can be completely reduced because of the reversing action of CO present (Nat 1992), thus the carbon accomplishes the reduction.

Direction reduction

$$2FeO + C \text{ -------> } 2Fe_{(s)} + CO_2 \quad \text{...} \quad (2.4)$$

Indirect reduction

$$Fe_{0.947}O + CO \text{ -------> } 0.947Fe_{(s)} + CO_2 \quad \text{.............................} \quad (2.5)$$

$$\Delta H^0_{298} = -1700kj(kg\ mole\ CO)^{-1}$$

Coke gasification

$$CO_2 + C \text{ -------> } 2CO \quad \text{...} \quad (2.6)$$

$$\Delta H^0_{298} = 172000\ Kj(kg\ mole\ CO)^{-1}$$

Other events in this zone are the absorption of silicon and sulphur by liquid metal and slag via the following reactions.

$$SiO_{(gas)} + C_{iron} \text{ -------------> } Si_{iron} + CO \quad \text{..............................} (2.7)$$

$$CaS_{(in\ coke\ ash)} + Si_{(gas)} \text{ ----------> } SiS + CaO \quad \text{.........................} \quad (2.8)$$

2.3.3 DRIPPING ZONE

The only solid material left here is coke, and the rest are gases and uids. Here direct reduction and solution loss reactions start. Generation of silicon monoxide from coke ash takes place according to the reaction.

$SiO_{2(ash)} + C_{Coke}$ -------------> SiO + CO ... .(2.9)

When droplets of liquid metal and slag tuckle down through the coke bed, silicon, sulphur, and heat are being transferred from gas to liquids. The large gas/liquid contact area and high temperature makes the dripping zone a very important region for reactions. The longer the dripping distance or time (i.e. the higher the location of the melting front). The more the silicon and sulphur, the more heat will be transferred within the coke bed.

2.3.4 RACEWAY ZONE

This zone consists of coke and gas. The raceway extends 1-2 meters into the furnace and are bound in front at the sides and below by rather firm regions of lump coke which have bypassed oxidation during its descent through the furnace. The raceways are also bounded above by lump coke but loosely packed due to the rapid ascent of raceway gas between the pieces.

The main activity in this zone is CO generation. This is a two step reaction; oxygine first reacts with coke to form CO_2.

$C_{(s)} + O_2$ -------------> CO_2 .... (2.10)

$$\Delta H^0_{298} = - 394,000 kj(kg\ mole\ CO_2)^{-1}$$

The net result of these two reactions is generation of heat, which is carried upwards into the furnace by the ascending gases, which also contains sulphur. Some SiO is generated in the peripheral region of the furnace.

In a furnace operation, where hydrocarbon is injected, the cracking of the hydrocarbon with the attendant loss of heat takes place in this zone and additional CO and H_2 generation

2.3.5 HEARTH ZONE

The hearth contains only coke and liquids (slag through the stagnant coke in bosh and hearth to be periodically or continuously (only in big furnaces) tapped from the furnance. The hearth region determines the quality of the hot metal (Williams 1983).

The high temperature reached in this zone lead to the reduction of the stable oxides MnO, SiO_2 and the phosphates. Silicon and manganese are dissolved in the iron and slag is formed from the ore gaugue. As the hot metal iron passes through the slay layer, there is the oxidation of silicon by iron and maganese oxide in the slay, and also the desulphunisation of metal.

The reactions take place are; (Tukdogan 1978 and 1980)

$SiO_2 + 2\underline{C}$ -------------> Si + 2CO .... (2.11)

MnO + $\underline{C}$ -------------> Mn + CO .... (2.12)

CaO + S + $\underline{C}$ ---------> CaS + CO .... (2.13)

The underscore indicates elements dissolved in iron.

TABLE 1

Summary of Reactions and Thermal Behaviour in Various Regiouns of the Iron Blast Furnace (steady-state conditions)

Zone	Chemical Behaviour	Thermal Behaviour
Hearth (below tuyeres)	Saturation of iron with carbon and final reduction of (CaO), P_2O_5, MnO and SiO_2. Impurities reach their final concentrations.	Falling drops of metal and slag bring heat down into the hearth.
Tuyere raceways	Coke and hydrocarbons are oxidized to CO_2 then CO	Large evolution of heat from combustion of incandescent coke with hot air
Active coke zone (bosh and belly)	Impurity oxides are reduced and iron absorbs carbon during percolation of metal and slag droplets. Coke bed acts as a reserve to guarantee complete reduction of iron oxides	Transfer of heat from ascending gas to descending coke and droplets of metal and slag. Gas supplies enthalpy for superheating of liquid metal and slag and for reduction of impurity metals
Fusion zone	Formation and melting of slag, final reduction of $Fe_{0.947}O$, melting of Fe	Transfer of heat from ascending gas to melting solids
Cyclic	Wustite reduction and coke	Temperature of ascending gas

reduction zone	gasification	falls rapidly due to absorption of enthalpy.
Middle of Shaft	Very little coke gasification occurs. Reduction of $Fe_{0.947}O$ by CO over much of the zone. Little or no reaction in higher portions due to depletion of CO (chemical reserve zone). Wustite is the iron oxide throughout this region	Steady temperature (1200K) throughout, (thermal reserve zone). Wustite reduction of Fe requires no enthalpy.
Upper quarter of Shaft	Reduction of Fe_2O_3 and Fe_3O_4 to wustite	Temperature of gases decreases rapidly due to transfer of heat to cold incoming solids. Reduction reactions and evaporation of moisture also require enthalpy.

2.4 IMPROVEMENTS IN BLAST FURNACE OPERATION.

The severe competition into which the blast furnace has entered with alternative processes during the past years has not modified its predominant position as a reducing unit, but on the contrary, it had quite a simulative effect (Poos 1981). Several efforts have been made towards improving the operations of the furnace to enhance high productivity, efficiency, and reliability. These are achieved by the following factors.

(i) Burden type

(ii) Gas permeability

(iii) Blast enrichment

(iv) Coke quality

(v) Blast injectants

(vi) Blast velocity

(vii) Burden arrangement and uniformity

(viii) Operating temperature

(ix) Operating pressure

(x) Furnace capacity

(xi) Cooling system

2.4.1 BURDEN TYPE

For the production of iron at minimum cost and efficient operation of the iron blast furnace, a burden of optimum properties is necessary (Egundebi 1986). Compare to a lump ore practice, pellets provided for increased permeability, more uniform reducing gas distribution, improved reducibility of the burden, and a smoother stock (Holditch and Eikidysz 1986). Lumps and pellets melt earlier than sinter. Sinter proves to be the more favourable on account of its higher temperature softening and melting point (Walter

1996). Burden that melts easily have a negative effect on the reducing action of the process reduce gas permeability (Panigraphy and Rigand 1986) concluded that Ca-ferrite provide good physical strength and reduction properties, and posses high softening and melt - down properties.

2.4.2 BURDEN ARRANGEMENT AND UNIFORMITY

Up to the fusion zone, the burden is made up of alternate layers of ore and flux usually 0.5 - 1m thick. Burden distribution at the stock-line is one of the most important factors governing furnace operation (Standish 1986). Uniform gas-flow especially in the stack is die to proper distribution of burden right from the receiving hopper. Uniform burden permits furnace gases to rise rapidly through the charge without channeling and allow the furnace to be operated at high blast rates.

Proper separation of coke and sinter from fines is usually maintained. Coke and sinter both tend to abrasion, which affects the blast furnace (Benhard 1992). Arrangement of the conveyor system, and the bell top charging system helps in proper layering of the charge inside the furnace, thereby improving the gas flow.

2.4.3 GAS PERMEABILITY

The productivity of blast furnace is defined as the quotient between the possible gas throughput per unit of time and the specific gas generation for one tone of hot metal (Walter 1996). The gas throughput is a function of the furnace permeability (Beppler 2000), through high quality charge materials. The quality and behaviour of charge in the blast furnace determines the permeability. Good permeability can be achieved by having the different components of the charge in their correct sizes range. Non-uniform sizing of materials results in non-uniform gas flow and thereby reduced furnace permeability. Fines results in coke penalty and reduction of productivity.

Flow equation for packed beds have been developed by many workers (Furnas 1929 and Ergun 1952), and the relationship between pressure and gas flow rate in a packed bed is given by the Ergun equation.

$$\frac{P}{L} = 1.75 \quad \frac{1 - \Sigma}{\Sigma\phi De} \quad \frac{G^2}{Pg}$$

P = Pressure drop

L = Length or height of packed column

Σ = Void fraction

φ = Shape fraction

Pg = Density of the gas

De = Equivalent particle diameter

G = Mass flow rate (Gas velocity)

The equation shows that an increased top pressure increases gas density and decreases resistance to flow. The equation is rearranged to define the burden permeability 'K' as:

$$K = \frac{G^2/Pg}{P/L} = 0.57 \quad \frac{\Sigma^3\phi De}{1 - \Sigma}$$

Permeability 'k' is proportional to the equivalent particle diameter De, the shape factor i.e. approach to sphericity and the quantity

$$\frac{\Sigma^3}{1 - \Sigma} \cdot \qquad \frac{1-2}{\Sigma^3} \quad = \text{Resistance to flow.}$$

The permeability increased as particle diameter and void fraction increases.

2.4.4 COKE QUALITY

Coke does not change in state of aggregation down to the tap hole level. Therefore, the properties of coke in the cohesive zone are of special importance. Coke functions as;

(1) The supplier of the reducing gas and heat.

(2) Supporting structure for the burden.

(3) Gas distributor

(4) The direct reduction of iron oxides.

Since efforts are being made to minimize coke consumption by using alternative fuel injectants, the quality of coke charged and the charging techniques is paramount importance. The quality of coke influences the blast furnace performance especially if high rates of additional reducing agents are injected (Beppler 1999). To achieve a uniform furnace working, and good operating results, the process must take place evenly around the furnace centre line (Peter and Poth, 1986). Tuyere flame temperature and blast velocity have a great influence on the degredation of coke (Iwanaga, Takatani, and

Aminaga 1986), leading of the system. For this reason, a greater quantity of coke must be charged into the furnace centre as the injection rate increases (Beppler 1999).

The quality of coke needed for a good operation of the blast furnace are based on:

(1) High hot coke strength (CSR), and lower coke reactivity (CRI) (Beppler 1996).

(2) Coarse coke to ensure high voidage gas permeability (Beppler 2000)

(3) Low ash to increase the rate of burden yield and to reduce coke disintegration (Beppler 1994). Low sulphur content so as to get an acid slag. Low phosphorus and volatile matters.

Hearth disturbances in the blast furnace can be avoided y maintaining a suitably high CSR (Kerkkoven 1997). As the CSR value increases, alternative fuel injection can be move, thereby lowers the level of coke consumption, and increasing gas permeability.

2.4.5 BLAST INJECTANTS

The goal of alternative fuels injection through the tuyere is to demonstrate the economic, environmental, and energy savings benefits by minimising the amount of coke consumption and the reduction of the harmful emissions from the coke oven plants.

The choice of these fuels depends on many factors of which relative abundance and cost are paramount. For example, Canada, India, and UK use pulverized coal. Nigeria and part of USA use natural gas, and according to Tsukasa (1998), presently researches in Japan are being carried out on the use of plastic. The success of these injectants is dependent on their combustion rate as well as the control of the gas distribution. Their choice is dependent on the following.

(i) Their effect on bosh slag basicity.

(ii) Flame temperature

(iii) Utilization of hydrogen in indirect reduction of iron oxide.

(iv) Productivity

(v) Fuel requirement

(vi) Coke replacement ratio

Alternative fuel injection requires additional blast heat, thus a combined blast i.e. simultaneous injection of atmospheric blast, process oxygen and injectants is adopted (Ulianor 1986). Thus a working relationship is established to maintain a thermal balance, since injectants reduced the flame temperature. In iron making process in the blast furnace, the injectants' carbon combines with the ore's Oxygen to form Carbon monoxide and Hydrogen gas leading high quality molten iron with a lower Oxygen contents (Tsukasa 1998).

Various work have been carried out on different injectants and results have shown that they have different effects (Guili 1986, Tavorovskii 1980, Gudenau 1986, Ulianor 1986, Watanable 1986, and Athapan 1996). High slag basicity has an adverse effect on the permeability of the furnace, thus reducing productivity. Low ash basicity leads to better liquidus temperature, fluidity, and permeability (Athapan 1996).

High injection rate increases the residence time (Antonie 1994 and Gudenan 1986). High residence time increase combustion degree, and affects coke degradation.

Tovarovskii (1980) gives the coke Replacement Ratio (RR) for various injectants.

For Natural gas

$RR = (3.2T/2000 + 2.3)\,\Delta r$

$\Delta r = 0.2 - 2.5 \times 10^{-4} Vng$

Coke oven gas

$RR = (2.3T/2000 + 2.3)\Delta r$

$\Delta r = 0.10 - 10^{-4} Vcg$

Fuel oil

$RR = 1 + 0.4T/2000$

Δr = Constant

Δr = increase in the degree of indirect reduction per unit blast addition.

T = Flame temperature

Vng = Consumption of natural gas NG, m^3/t pig iron

Vcg = Consumption of coke oven gas CG, m^3/t pig iron

2.4.6 BLAST TEMPERATURE AND VELOCITY

The overall heat required for the blast furnace is obtained from the heat of coke gasification, which is dependent on the temperature of the blast. The introduction of injectant lowers the operating temperature of the furnace. Oxygen enrichment, and increasing the blast temperature compensate for such. The blast temperature is usually 1200°C or up to 1400°C, but the flame temperature must be within the range of 2200K and 2600K (Peacey 1978, Tovarovskii 1980).

To obtain sufficient kinetic energy of the blast, the velocity must be high enough, even up to 250m/s (Jose 1998). When there is fuel injection, the velocity of the blast must be increased, because some gases like N_2, H_2, and O_2 are gasified before the tuyere tip. The velocity therefore needs to be increase by 15m/s in view of the composition of the injectant (Beppler 1994).

2.5 OPTIMIZATION CONCEPTS AND ITS APPLICATION IN STEEL INDUSTRY

2.5.1 CONCEPT OF OPTIMIZATION

Optimization means to select the best course of action from the available alternatives (Ray W.H. and Szekely Y. 1973). It involves finding the best solution to a problem. Mathematically, this means finding the minimum or maximum of a function of n variables, $f(x_1 ----, x_n)$, say, where n may be any integer greater than zero (Beale 1988). The function may be unconstrained or it may be, subject to certain constraints on the variables of the function.

The Linear Programming (LP) is one of the most widely used optimization techniques, and one of the most effective (Edgar and Himmelblan 1989). The term linear Programming was coined be George Dantzing in 1947 to refer to the procedure of optimization in problems in which objective function and the contraints are linear (Dantzig 1963). Once the mathematical programming model has been formulated, we communicated it to the computer programme. The LP has a wide range of application especially in Engineering, Agriculture and Manufacturing.

2.5.2 APPLICATION OF OPTIMIZATION IN THE STEEL INDUSTRY

Mathematical programming techniques were used in the steel industry as early as 1958, and many application of optimization in steel production have been reported since then. Duttal and Fourer (2001). A survey of published applications of optimization are summarised below.

2.5.2.1 PRODUCTION PLANNING

Tsao and Day (1971) developed a process analysis model of production in the United States on a national level. A technology matrix is estimated using engineering and metallurgical information. This matrix together with the detailed cost, sales and revenue figures is then used in LP model of short run allocations of the steel industry as a reliable. The study of Mexican steel modeled, by Kendrick, Meeraus, and Alatoire (1984) developed two static models for production planning and one dynamic model for investment analysis. The two static models, formulated as linear programming models, are mixed production and transportation problems. The dynamic model, formulated as a mixed integer programme. Their inputs were similar, and the outputs were, optimal product distribution, and investment decisions.

In the production planning in Zambia, sashidhar and Achray (1991a) deal with the problem of planning in a steel mill with the objective of maximizing capacity utilization. The model is formulated as a maximum flow problem in a multiple activity network formulation for production planning with the priorities in a steel will. In another paper, Sashidhar and Achray (1991b) discussed the problem of allocating the major components of process costs to various quantities of products produced in a smelting shop of an alloy and special steel manufacturing unit. Quadratic programming techniques was used to estimate the consumption pattern of important operational materials.

Also, in the production planning in Algeria, Sarma (1995) describe an application of lexicographical goal programming at the only steel manufacturing plant; Societe Nationale de Siderurgie. The lexicographical approach has helped the management to spell out aspiration level of several principal objectives such as profitability, capacity utilization of some key plants, and production quantity of some key products.

Bielefeld et al (1986) describe an L-P based supply chain planning model which plans purchasing, production, and distribution for many products in many plants on an annual basis for Hoesch, a German Steel-maker.

2.5.2.2 PRODUCT - MIX OPTIMIZATION

Fourer (1997) presents a model which grew out of a project to design an optimization package for steel mill planning for American iron and steel institute. This was based on generic model, which could be customized by any steel plant to its own operation, simply by supplying its own data, which has been proved sucessful. In United Kingdom, Lawrence and Flowerdew (1963) develop an economic model for steel production that focussed on the application to the individual process. Bandyopadhy (1969) also proposed a linear programming model that allocates different capacities between two processes for production planning, namely basic oxygen furnace and the open hearth furnace. The model is a cost minimization model with all technological and financial constraints. The model can also predict the required operation level of blast furnace and lime burning plant at different level of total steel production.

In the Indian steel plant, Dutta, Sinha, and Roy (1990), Dutta et al (1994), and Sinha et al (1995) deal with the development and implementation of a mathematical model for optimal allocation of electrical energy of Tata steel. The guiding principle of the model is that in the case of a power shortage, power is allocated to those non-essential loads which have a higher profitability (based on a mixed integer linear programming model). Hunneault and Galiana (1991) Mc Cutcheon (1988), later reported the use of power plants, such studies have addressed the issue with a cost minimization modeling approach for power generating and distributing plants. Fabian (1958), Bielfield, Walter and Wartman (1986), Baker et al (1987) studied the most profitable use of an integrated steel plant, where the problem has been addressed as a cost minimization or profit maximization linear programming model. In the steel authority of India limited, Shama and Sinha (1991), describe an optimization model for determining the optimal product mix in which various issues relevant to the choice of an optimum product mix in a steel making operation.

2.5.2.3 BLENDING MODELS

Generally, the problems are formulated as cost minimization linear programming models.

In the United State blast furnace/cupola blending, the results obtained from Fabian (1967) enable producers to determine among others, the least cost raw material, blending, optimal furnace scheduling and optimal raw material inventory level. Metzger and Schwarxreck (1961), describe an application of linear programming for the determination of least cost cupola charging in an iron foundry. Actual data, evolution of the solution, and cost saving were obtained from the work.

In United Kingdom, Beale, Coen, and Flowerdew (1965), proposed a model in which the variables are usages, in a given time period of ore and other materials, outputs of gi iron, and levels of certain factors that depend on the mix of materials.

In Belgium, Hernandez and Proth (1982) approached the problem of selecting the charge materials from available stock in order to produce alloy as cheaply as possible which extremely important to foundaries producing micro components alloys, such as bronze and special steels, through the use of a new algorithm. The system has been implemented to give an improvement in profit.

In Sweden, Westerberg, Bjorkland and Hultan (1977) carried out work on Fagersta AB, and the contact Research Group Applied Mathematics, Royal Institue of Technology in stock-holum. The problem was modeled as a traditional blending model with the additional constraint that some of the variables should be integer valued. The company produce stainless steels in high frequency furnaces, and used up to fifteen different types of scrap and alloys which are melted together. The linear programming model is a cost minimization model with constraints given by weight restrictions and metallurgical composition restriction. The implementation of the model has decreased the cost raw material by 5%.

In East European countries, Muteana and Rado (1960) solved a blending problem in a Rumanian Steel Plant that deal with the raw material loading of an iron-smelting furnace in such a way as to obtain an optimal production at minimum cost of pig iron, taking into account definite prescribed production. Tarabar (1963) developed a model in Yugoslaria, which has a objective of profit maximization. It provides an elementay example of the use of the linear programming and in deciding the composition of furnace charge for blast furnace.

2.5.2.4 BLAST FURNACE OPERATION

Many researchers have carried out work, and the development of models for the operation of blast furnace. Peacey and Davenport (1979) development models for the blast furnace operation, focussing on the use of alternative fuel injectants. The modelts can be used to determine cost of materials, raw materials balances, and the thermal requirement and implication on the furnace.

Deitz (1997), describes a system developed by Voest Alphma Stahl, an Austrian firm, for controlling blast furnace performance. The system consist of a series of computer models for various phases of blast furnace operation. It includes a burden optimization model for determining the optimal mix of inputs, while other models determine control settings and hot metal qualities. Zuo et al (1998) report on the design of three models base on neutral network for recognition of top gas distribution, distribution of the heat fluxes through the furnace wall, and the prediction of slips in the blast furnace. Inkala et al (1995), describes the application of an expert system, at the finish firm Rautaruukki Oy, to blast furnace control. Iida et al (1995) describes several AI applications at Kawasaki steel including fuzzy inference applied to store heat control and a neutral network application to blast furnace burden distribution control. Angstenberger (1996) describes the application of fuzzy clustering and neutral network to blast furnace modeling and control at a German steel producer.

2.6 THE MATLAB

MATLAB is a mathematical programming language built for solving the tedious and the resulting interface slow problem, in interfacing in an environment where complex mathematical calculations are involved. MATLAB stands for Matrix Laboratory. It was originally written to provide easy access to matrix developed by LINPACK and ELSPACK projects, which together represent the state-of-the-art in software for matrix computation. In industry, MATLAB is the tool of choice for high productivity research, development, and analysis, in university environments, it is the standard instructional tool for introductory and advanced courses in mathematics, engineering , and science.

MATLAB is a high – performance language for technical computing. It integrates computation, visualisation, and programming in an easy-to-use environment where problems and solutions are expressed in familiar Mathematical notation. Typical uses include;

(1) Math and Computation

(2) Algorithm development

(3) Modelling, simulation and prototyping

(4) Data analysis, exploration, and visualisation

(5) Scientific and engineering graphics

(6) Application development including graphical user interface building

MATLAB is an interactive system whose basic data element is an array that does not require dimensioning.

This allows solving many technical – computing problems, especially those with matrix and vector formulations, ion a fraction of the time it would take to write a program in a scalar non – interactive language such as C or Fortran.

MATLAB features a family of application – specific solutions called toolboxes. Very important to most users of MATLAB, toolboxes allow you to leaf and apply specialised technology. Toolboxes are comprehensive collections of MATLAB functions (M-files) that extend the MATLAB environment to salve particular classes of problems. Areas in which tool boxes are available include signal processing, control systems, neutral networks, fuzzy logic, warless, simulation, and many others.

2.6.1 THE MATLAB SYSTEM

The MATLAB system consists of five main parts:

1. The MATLAB language. This is a high-level matrix/array language with control flow statements, functions, data structures, input/output, and object-oriented programming features. It allows both "programming in the small" to rapidly create quick and dirty throwaway programs, and "programming in the large" to create complete large and complex application programs.
2. The MATLAB Working Environment. This is the set of tools and facilities that you work with as the MATLAB user or programmer. It includes facilities for managing the variables in your workspace and importing and exporting data. It also includes tools for developing, managing, debugging, and profiling M-files, MATLAB's applications.

3. Handle Graphics ®. This is the MATLAB graphics system. It includes high-level commands for two-dimensional and three-dimensional data visualisation, image processing, animation, and presentation graphics. It also includes low-level commands that allow you to fully customise the appearance of graphics as well as to build complete graphical user interfaces (GUIs) for your ops Operators and special characters.
4. The MATLAB Mathematical Function Library. This is a vast collection of computational algorithms ranging form elementary functions like sum, sine, cosine, and complex arithmetic, to more sophisticated functions like matrix inverse, matrix eigenvalues, Bessel functions and fast Fourier transforms.
5. The MATLAB Application Program Interface (API). This is a library that allows you to write C and Fortran programs that interact with MATLAB. It includes facilities for calling routines form MATLAB (dynamic linking), calling MATLAB as a computational engine and for reading and writing MAT-files.

2.6.1.1 PORTABILITY

It's sometimes necessary to work with MATLAB implementations on different computer systems, or to transmit MATLAB applications to users on other systems. MATLAB applications consist of M-files, containing functions and scripts, and MAT-files, containing binary data. Both types of files can be transported directly between different computers:

1. M-files consist of ordinary text. They are machine independent. While different platforms terminate lines with various combinations of CR (carriage return) and LF (line feed) characters, the MATLAB interpreter tolerates all possible combinations. (However, text editors and other tools may not work correctly with M-files form other platforms.)
2. MAT-files are binary and machine dependent, but they can be transported between machines because they contain a machine signature in the file header. MATLAB checks the signature when it loads a file and, if a signature indicates that a file is foreign, performs the necessary conversion.

To us MATLAB across different platforms, you need a program for exchanging both binary and text data between the machines. When using these programs, be sure to transmit MAT-files in binary file mode and M-files in ASCII file mode. Failure to set these modes correctly usually corrupts the data.

2.6.1.2 M-FILES

Files that contain MATLAB language code are called M-files. M-files can be functions that accept arguments and produce output, or they can be scripts that execute a seize of MATLAB statements. For MATLAB to recognize a file as an M-file, its name must end in .m. You create M-files using a text editor, then use them as you would any other MATLAB function or command.

2.6.1.3 SCRIPTS

Scripts are the simplest kind of M-file – they have no input arguments. They're useful for automating series of MATLAB commands, such as computations that you have to perform repeatedly from the command line.

Scripts operate on existing data in the workspace, or they can create new data on which to operate. Any variables that scripts create remain in the workspace after the script finishes so you cans use them for further computations.

2.6.1.4 FUNCTIONS

Functions are M-files that accept input arguments and return output arguments. They operate on variables within their own workspace. This is separate form the workspace you access at the MATLAB command prompt.

2.6.1.4.1 BASIC PARTS OF A FUNCTION M-FILE

A function M-file consists of:

1. A function definition line
2. A H1 line
3. Help text
4. The function body
5. Comment

2.6.1.4.2 FUNCTION DEFINITION LINE

The function definition line informs MATLAB that the M-file contains a function, and specifies the argument calling sequence of the function.

ALL MATLAB functions have a function definition line that follows this pattern. If the function has multiple output values, enclose the output argument list in square brackets. Input arguments, if present, are enclosed in parentheses. Use commas to separate multiple input or output arguments.

2.6.1.4.3 H1 LINE

The H1 line, so named because it is the first help text line, is a comment line immediately following the function definition line. Because it consists of comment text, the HI line begins with a percent sign "%".

This is the first line of text that appears when a user types help function name at the MATLAB prompt. Further, the **lookfor** command searches on and displays only the H1 line. Because this line provides important summary information about the M-file, it is important to make it as descriptive as possible.

2.6.1.4.4 HELP TEXT

You can create online help for your M-files by entering text on one or more comment lines, beginning with the line immediately following the H1 line. When you type help function name, MATLAB displays the comment lines that appear between the function definition line and the first non-comment (executable or blank) line. The help system ignores any comment lines that appear after this help block.

2.6.1.4.5 FUNCTION BODY

The function body contains all the MATLAB code that performs computations and assigns values to output arguments. The statements in the function body can consist of function calls, programming constructs like flow control and interactive input/output, calculations, assignments, comments, and blank lines.

2.6.1.4.6 COMMENTS

As mentioned earlier, comment lines begin with a percent sign (%). Comment lines can appear anywhere in an M-file, and you can append comments to the end of a line of code. The first comment line immediately following the function definition line is considered the H1 line for the function. The H1 line and any comment lines immediately following it constitute the online help entry for the file. In addition to comment lines, you can insert blank lines anywhere in an M-file.

Blank lines are ignored. However, a blank line can indicate the end of the help text entry for an M-file.

2.6.1.4.7 FUNCTION NAMES

MATLAB function names have the same constraints as variable names. MATLAB uses the first 31 characters of names. Function names must begin with a letter; the remaining characters can be any combination of letters, numbers, and underscores. Some operating systems may restrict function names to shorter lengths. The name of the text file that contains a MATLAB function consists of the function name with the extension .m. appended.

If the filename and the function definition line name are different, the internal name is ignored. Thus, while the function name specified on the function definition line does not have to be the same as the filename.

2.6.1.4.8 SUBFUNCTIONS

Function M-files can contain code for more than one function. The first function in the file is the primary function, the function invoked with the M-file name. Additional functions within the file are Subfunctions that are only visible to the primary function or other Subfunctions in the same file.

Each subfuntion begins with its own function definition line. The functions, immediately follow each other. The various Subfunctions can occur in any order, as long as the primary function appears first.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 MATERIALS

For the purpose of this project work the data collected for the programming are obtained from the Nigerian blast furnace at Ajaokuta Steel Complex. The auxiliary fuels used are:

1.	Natural gas	75% Carbon	25% Hydrogen
2.	Bunker C Oil	86% Hydrogen	14% Hydrogen
3.	Coal dust	79.2% Carbon	5.4% Hydrogen
		12.4% Oxygen	

3.2 MODEL FORMULATION

Model can be described to be a simplified representation of a certain aspect of a real system. Mathematical model is a representation of the essential part of an existing system (or a system to be constructed), which presents knowledge of that in a usable form and is created using mathematical concepts such as functions and equations.

The main aim of formulating models in this work is to provide a basis to; calculate the quantities of coke, injectants, and blast air require for the production of a given quantity of hot metal, and to predict their effects on the thermodynamics and kinetics of the system.

3.2.1 STOICHIOMETRIC DEVELOPMENT

The three basic elemental balance equations is which the blast furnace must obey under a steady state conditions are;

$n^{I}Fe = n^{0}Fe$ .... (3.1)

$n^{I}C = n^{0}C$ .... (3.2)

$n^{I}O = n^{0}O$ .... (3.3)

n^{I} and n^{0} are the number of moles of each component entering and leaving the furnace respectively.

$(O/C)^{g}$ = moles of O_2 leaving the top gas per mole of carbon leaving the top gas.

$(O/Fe)^{x}$ = moles of O_2 entering in iron oxides per mole of Fe entering in iron oxide.

$(C/Fe)^{m}$ = moles of C leaving in the molten metal per mole of product Fe.

$X^{g}\ CO_2 = (O/C)^{g} = -1$ .... (3.4)

$X^{g}\ CO = 2 - (O/C)^{g}$ .... (3.5)

$X^{g}\ CO_2$ and $X^{g}\ CO$ are the mole fractions of CO and CO_2 in the top gas.

$(O/Fe)^{x}$ - for hematite = $^{3}/_{2}$

- for magnetite = ¾

Iron Balance;

The only outlet for Fe is the molten metal, thus

$n^{I}Fe = n^{0}Fe = 1$ .... (3.6)

Carbon Balance;

Carbon leaves in the top gas and in the molten iron.

$$n^{0}C = n^{g}C + (O/Fe)^{m} \qquad (3.7)$$

Oxygen Balance;

Oxygen enters in the blast air and iron oxides, and leaves in the top gas.

$$n^{I}O = n^{B}O + (O/Fe)^{x} \qquad (3.8)$$

$$n^{0}O = n^{g}O \ . (O/Fe)^{g} \qquad (3.9)$$

Therefore,

$$n^{B}C + (O/Fe)^{x} = n^{g}C \ . (O/C)^{g} \qquad (3.10)$$

$n^{B}O$ = moles of O_2 through the blast air per kg mole product Fe.

$n^{g}C$ = moles of C leaving in the top gas as either CO_2 or CO.

The actual carbon, which actually reacts in the reduction production is $n^{A}C$; which ends up as either CO or CO_2.

Therefore,

$$n^{A}C = n^{g}C \qquad (3.11)$$

Substitute eqn. (3.11) in eqn. (3.10)

$$n^{B}O + (O/Fe)^{x} = n^{A}C \ . (O/C)^{g} \qquad (3.12)$$

If coke is the only source of carbon; $n^{I}C = n^{coke}C$ and $n^{I}C = n^{0}C$.

From eqn. 3. 7 & 3.11,

$$n^{coke}C = n^{g}C + (O/Fe)^{x} \qquad (3.13)$$

3.2.2 ENTHALPY BALANCE

Under steady state condition,

Enthalpy into the furnace = Enthalpy out of the furnace.

Thus,

$$nFe_2O_3.\underset{Fe_2O_3}{H^0_{298}} = \underset{Fe_l}{H^0_{1800}} + n^gCO.\underset{CO}{H^0_{298}} + n^gCO_2.\underset{CO_2}{H^0_{298}} \ldots\ldots\ldots\ldots\ldots (3.14)$$

Rearanging to give a positive value,

$$nFe_2O_3(-\underset{Fe_2O_3}{H^0_{298}}) + \underset{Fe_l}{H^0_{1800}} = n^gCO(-\underset{CO}{H^0_{298}}) + n^gCO_2(\underset{CO_2}{H^0_{298}}) \ldots\ldots\ldots (3.15)$$

Heat Supplied = Heat Demand

$$S \quad = \quad D$$

$$D = nFe_2O_3(-\underset{Fe_2O_3}{H^0_{298}}) + \underset{Fe_l}{H^0_{1800}}$$

$$S = n^gCO(-\underset{CO}{H^0_{298}}) + n^gCO_2(\underset{CO_2}{H^0_{298}})$$

Numerically, (from appendices IV & V)

$$\underset{Fe_2O_3}{H^0_{298}} = \underset{Fe_2O_3}{H^f_{298}} = -826000 \text{ KJ(kg mole of } Fe_2O_3)^{-1}$$

$$\underset{CO}{H^0_{298}} = \underset{CO}{H^f_{298}} = -111000 \text{ KJ(kg mole of CO)}^{-1}$$

$$\underset{CO_2}{H^0_{298}} = \underset{CO_2}{H^f_{298}} = -394000 \text{ KJ(kg mole of } CO_2)^{-1}$$

$$H^0_{1800} = (H^0_{1800} - H^0_{298}) = -73000 \text{ KJ(kg mole of Fe)}^{-1}$$

Fe_l Fe_l Fe_s

Eqn. 3.14 becomes

$$nFe_2O_3.\ 826000 + 73000 = n^BCO.\ 111000 + n^BCO_2.394000 \ldots\ldots (3.16)$$

One mole product Fe requires ½ mole input Fe_2O_3, thus, nFe_2O_3 = ½

Substituting eqn.3. 4 &3.5 into eqn.3. 15

$$½\ 826000 + 73000 = n^AC\ \{(2 - (O/C)^B - 1)\ .\ 394000\} \ldots\ldots (3.17)$$

$$½\ 826000 + 73000 = n^AC\ \{283000.\ (O/C)^B - 172000\} \ldots\ldots (3.18)$$

D S

Eqn. 18 can be rearranged to give

$$\frac{D}{283000} = n^AC\ (O/C)^B - n^AC\ \frac{172000}{283000} \ldots\ldots (3.19)$$

Subtract eqn. 3.19 from eqn. 3.12

$$n^BO + (O/Fe)^x - \frac{D}{283000} = n^AC\ \frac{172000}{283000} \ldots\ldots (3.20)$$

Eqn. 3.12 and 3.20 are the basis for the "Rist Diagram" (Rist 1977). The diagram can be used to obtain a graphical view of the efficiency of the furnace, and the effects of changes in operating parameters.

3.2.3 THE WUSTITE REDUCTION ZONE.

Eqn. 12 can be rewritten as

$$n^BO + (O/Fe)^{x\ wrz} = n^AC\ (O/C)^{B\ wrz} \ldots\ldots (3.21)$$

wrz = wustite reduction zone.

The only iron-bearing material in this zone is $Fe_{0.947}O$.

$(O/Fe)^{x\ wrz} = 1.056$

Also, $CO + Fe_{0.947}O$. $0.947Fe + CO_2$

According to Stull (1970), at 1200k, the equilibrium composition is

$XCO = 0.694 \approx 0.7$

$X\ CO_2 = 0.306 \approx 0.3$

Therefore,

$(O/fe)^{x\ wrz} = 1.3$

Substitution these numerical values into eqn. 3.20,

$N^{B}O + 1.06 = 1.3.\ N^{\wedge}C$ .... (3.22)

The enthalpy eqn. for the Wustite reduction zone can be summarises as,

$$1.06.\underset{Fe_{0.947}0}{H^{0}_{1200}} + \{n^{\wedge}C + (O/Fe)^{m}\}.\underset{C}{H^{0}_{1200}} + n^{B}O.(\tfrac{1}{2}\underset{O_2}{H^{0}TB} + \frac{0.79}{0.21} + \tfrac{1}{2}\underset{N_2}{H^{0}TB}) =$$

$$\underset{Fe_l}{H^{0}_{1800}} + (C/Fe)^{m}\ .\ \underset{(C)}{H^{0}_{1800}} + = n^{\wedge}C\ \{(2 - (O/C)^{gwrz})\ .\ \underset{CO}{H^{0}_{1200}} + \{(O/Fe)^{gwrz} - 1)\ .\ \underset{CO_2}{H^{0}_{1200}}\}$$

$$+\ n^{B}O.\ \frac{079}{0.21}\tfrac{1}{2}.\ \underset{N_2}{H^{0}_{1200}}\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (3.23)$$

upon simplifcation, eqn 3. 23 becomes

$D^{wrz} = S^{wrz}$

$$= n^{\wedge}C\ \{(2 - (O/C)^{gwrz})\ .\ \underset{CO}{H^{f}_{1200}} + \{(O/Fe)^{gwrz} - 1)\ .\ \underset{CO_2}{H^{f}_{1200}}\}$$

$$+\ E^{B}.E^{B}_{O}.\ \tfrac{1}{2}.\underset{O_2}{H^{0}_{1200}}\ \{n^{\wedge}C\ .\ (O/C)^{gwrz} - n^{B}_{O} - 1.06\}\ldots\ldots\ldots\ldots\ (3.24)$$

$$E^B = (\tfrac{1}{2}H^0_{TB,O_2} - \tfrac{1}{2}H^0_{1200,O_2}) + \frac{0.79}{0.21} . (\tfrac{1}{2}H^0_{TB,N_2} - H^0_{1200,N_2}) \quad \ldots\ldots (3.25)$$

T_B = blast temperature

E^B = blast Enthalpy

Numerically

$H^f_{1200,CO}$ = - 113000 KJ(kg mole of CO)$^{-1}$

H^f_{1200,CO_2} = - 395000 KJ(kg mole of CO_2)$^{-1}$

$(O/C)^{gwrz}$ = 1.3

eqn. 3.24 becomes

$D^{wrz} = S^{wrz}$

$$= n^AC\ (198000) + E^B.n^BO. - \tfrac{1}{2}.H^0_{1200,O_2}(1.3n^AC - n^BO - 1.06\} \quad \ldots\ldots (3.26)$$

The last term of eqn.3. 26 is always zero, therefore eqn. 26 becomes.

$D^{wrz} = S^{wrz}$

$$= n^AC\ .\ 198000 + E^B.n^BO \quad \ldots\ldots (3.27)$$

Recall eqn. 3.22,

$$n^BO + 1.06 = 1.3\ n^AC$$

$$n^{B}O = 1.3\, n^{A}C - 1.06$$

Substituting into eqn. 3.27

$$D^{wrz} = S^{wrz}$$

$$= n^{A}C\,(198000) + E^{B}(1.3n^{A}C - 1.06\}$$

$$= n^{A}C\,(198000 + 1.3E^{B}) - 1.06 \quad \text{.......................................} \quad (3.28)$$

3.2.4 TUYERE INJECTION EFFECT

Injectant is generally represented as

$C_xH_2)_y O_2$

N^1 is termed the mole of injectant per mole of product Fe.

Stoichiametrically, the elements present in injectants are;

Carbon: xN^1 (mole of C per mole of product Fe)

Hydrogen: $y N^1$ (mole of H_2 per mole of product Fe)

Oxygen: zN^1 (mole of O per mole of product Fe)

Carbon balance;

This is altered as

$n^lC = n^{coke}C + N^1$

$n^0C = n^AC + (C/Fe)^m$

Therefore

$n^AC + n^{coke}C + XN^1 - (C/Fe)^m$ .... (3.29)

Oxygen Balance;

$n^1O = n^BO + (O/Fe)^x + ZN^1$ .... (3.30)

$n^0O = n^BCO . + 2n^BCO_2 + n^BH_2O$ .... (3.31)

The Stoichiometric equation is given as

$$n^{B}C + (O/Fe)^{xwrz} + ZN^{I} = n^{\wedge}C\ (X^{gwrz}CO + 2X^{gwrz}CO_2) + y.N^{I}\ X^{gwrz}H_2O$$

.........................(3.32)

where $(O/Fe)^{xwrz} = 1.06$

$X^{gwrz}CO = 0.7$

$X^{gwrz}CO_2 = 0.3$

The value of XH_2^{gwrz} and XH_2O^{gwrz} are;

$XH_2^{gwrz} = 0.62$

$XH_2O^{gwrz} = 0.38$

Inserting these values into eqn 3.32.

$n^{B}O + zN^{I} + 1.06 = n^{\wedge}C\,(1.3) + y.N^{I}\,(0.38)$ ....(3.33)

In the Enthalpy form,

$D^{wrz} = S^{wrz}$

Recall eqn 3.27

$= n^{\wedge}C\,(198000) + E^{B}n^{B}O$

The total heat demand is altered as

heat demand = $D^{wrz} + N^{I}D^{I}$

D^{I} = injectant heat demand, KJ (kg mole of injectant)$^{-1}$ from eqn. 3.33 the heat demand can be simplified as

$D^{wrz} + N^I D^I = S^{wrz}$

$$= n^{\wedge}C\,(0.7H^{f}_{1200\,CO} + 0.3H^{f}_{1200\,CO_2}) - 0.38.\,y.N^I\,H^{f}_{1200\,H_2O} + E^{B}.n^{B}O \quad \text{........(3.34}$$

$$H^{f}_{1200\,CO} = -113000\ \text{KJ(kg mole of gas)}^{-1}$$

$$H^{f}_{1200\,CO_2} = -395000\ \text{KJ(kg mole of gas)}^{-1}$$

$$H^{f}_{1200\,H_2O} = -249000\ \text{KJ(kg mole of gas)}^{-1}$$

Substitute into eqn. (3.34)

$D^{wrz} + N^I D^I = S^{wrz}$

$$= n^{\wedge}C\,(0.7(-113000) + 0.3(-395000) - 0.38(-249000 + y.N^I + E^{B}.n^{B}O$$

$$D^{wrz} + N^I D^I = n^{\wedge}C\,(198000) + y.N^I\,(95000) + E^{B}.n^{B}O \quad \text{......... (3.35)}$$

D^I is given as

$$D^I_T = -H^f_T \quad + x\,(H^0_{1200} - H^0_T)_C + y\,(H^0_{1200} - H^0_T)H_2 + Z$$

$$.½(\,(H^0_{1200} - H^0_T)O_2 \quad \text{.......................(3.36)}$$

$$C_X(H_2)yO_Z$$

T = injection temperature.

D^{wrz} is the sum of the heat demand of the elements in the furnace. Therefore;

$$D^{wrz} = D^{fe} + (C/Fe)^m\,.\,D^c + D^{loss} + (Si/Fe)^m\,.\,D^{si} + (Mn/Fe)^m\,.\,D^{mn} + (P/Fe)^m\,.\,D^P + Wtslag.\,D^{slag} + nCaCO_3.\,D^{caco3} \quad \text{.................................. (3.37)}$$

D^{si}, D^{fe}, D^c, D^{mn}, D^P, D^{slag}, D^{caco3} are the heat demand of such element and product.

The calculated values of the heat demands are given as (Peacey 1979).

D^{si} = 873000 KJ(kg mole of dissolved Si)$^{-1}$

D^{fe} = 435000 KJ(kg mole of dissolved Mn)$^{-1}$

D^{c} = 44000 KJ(kg mole of dissolved C)$^{-1}$

D^{fe} = 319000 KJ(kg mole of dissolved Fe)$^{-1}$

D^{caco3} = 561000 KJ(kg mole of dissolved $CaCO_3$)$^{-1}$

$(C/Fe)^m$, $(Si/Fe)^m$, $(Mn/Fe)^m$, $(P/Fe)^m$, are the moles of such element per mole of product Fe. They are specified from data collected about a particular furnace.

The slag heat demand is calculated from the data given by (Foerster 1967) to be,

D^{slag} = 250 KJ(kg of Slag))$^{-1}$

According to Peacey 1979, D^{loss} is given to be,

$D^{loss} = 6.4 \times 10^6 m^{-1} hr^{-1}$ x hearth diameter (m)

$$\frac{\text{Pig iron Production rate } (Kghr^{-1})}{55.85} \times \frac{\%Fe \text{ in Pig Iron}}{100}$$

When using injectants with known weight percentages of its composition and known Heat of combustion,

Equation 3.12 becomes,

$$n^B{}_O = n^{coke}{}_C + 1 + \frac{0}{100} . W1 - (C/Fe)m \qquad \text{.............................3.39}$$

W^1 = injectant

Equation 3.22 also becomes,

$$n^{B}_{O} + 1 . B . W^{1} + 1.06 = 1.3. n^{\wedge}c + 0.38.½. \frac{\lambda}{100} . W^{1} \text{ ....} 3.40$$

likewise equation 3.35 becomes

$$D^{WTZ} + W^{1} . D^{1}W . n^{\wedge}c . (198000) + .½. \frac{\lambda}{100} . W^{1} . (95000) + E^{B} . n^{B}_{O} \text{ ....} (3.41)$$

The injectant heat demand $D^{1}w$ is given as;

$$D^{1}w = \left(H^{c}_{w} - \frac{1}{12} . \frac{0}{100} . \underset{CO_2}{H^{f}_{298}} - ½ . \frac{\lambda}{100} . \underset{H_2O}{H^{f}_{298}} \right)$$

$$+ \quad \frac{1}{12} . \frac{0}{100} . \left[H^{0}_{1200} - H^{0}_{298}\right]_{c} + \frac{1}{12} . \frac{\lambda}{100} . \left[H^{0}_{1200} - H^{0}_{298}\right] H_2$$

$$+ \quad \left(\frac{1}{28} . \frac{0}{100}\right) . . ½ \left[H^{0}_{1200} - H^{0}_{298}\right] N_2 \text{ ....} (3.42)$$

H^{c}_{w} is the heat of combustion of the injectant, given as;

$$H^{c}_{w} - \frac{1}{2} . \frac{0}{100} . \underset{CO_2}{H^{f}_{298}} - ½ . \frac{\lambda}{100} . \underset{H_2O}{H^{f}_{298}} - H^{f}_{w} \text{ ....} (3.43)$$

- H^{f}_{w} is the of dissociation of the injectant

Θ = wt % C $\quad\quad$ φ = wt % N

λ= wt % H $\quad\quad$ β = wt % O

3.3 THE DATA PROPOSED FOR THE FURNACE ;

TABLE 2.1 CHARGE MATERIAL

DESCRIPTION	UNIT	VALUE
Sinter Analysis		
Fe (Total)S	%	52.70
Fe_2O_3	%	60.29
Fe_2	%	13.55
Mn	%	1.03
P	%	0.036
S	%	0.011
MnO	%	1.33
SiO_2	%	9.03
Al_2O_3	%	1.00
CaO	%	12.09
MgO	%	2.12
TiO_2	%	0.05
P_2O_5	%	0.026
Coke Analysis		
Ash	%	13.0
Sulphur	%	1.2
Volatiles	%	2.0
Humidity	%	1.0
Carbon	%	83.8
Organic Mass of Coke		
N_2	%	0.33
H_2	%	0.25
O_2	%	0.25
C	%	86.21
H_2O	%	2.7

TABLE 2.2 FURNACE PRODUCT

DESCRIPTION	UNIT	VALUE
Hot Metal Analysis		
Si	%	0.8
Mn	%	1.1
S	%	0.025
P	%	0.067
C	%	4.4
Slag Analysis		
SiO_2	%	28.59
Al_2O_3	%	6.07
TiO_2	%	0.19
CaO	%	44.10
MgO	%	8.0
MnO	%	1.94
FeO	%	0.25
Alkalis	%	0.25
S	%	0.50
B/f Gas Analysis		
CO	%	29.08
CO_2	%	17.68
H_2	%	11.26
N_2	%	41.98

TABLE 2.3 DIMENSION OF THE FURNACE

PARAMETER		UNIT	VALUE
Diameter	Hearth	Mm	9750
	Belly	Mm	10900
	Top	Mm	7300
	Large bell	Mm	5400
Height	Hearth	Mm	4300
	Bosh	Mm	3000
	Belly	Mm	1700
	Stack	Mm	18200
	Top	Mm	2900
	"Dead Space"	Mm	1103
Distance from slag notch centre-line		Mm	1800
Effective height of furnace		Mm	30100
Hearth Area		m^2	74.67

TABLE 2.4 CONSUMPTION AND OUTPUT

DESCRIPTION	UNIT	VALUE
Natural gas consumption	N.m/ton of Fe	115
Skip coke consumption	Kg/ton of Fe	475
Consumption of gas for blast heating:		
Blast furnace gas	N.m/ton of Fe	400
Natural gas	N.m/ton of Fe	10
Dry top gas recovery	N.m/ton of Fe	1660
Oxygen enrichment	%	30
Flue dust yield	Kg/ton of Fe	15
Output of furnace:		
Daily output	Tons/day	3860
Annual output	Thou. Tons/year	1350
Slag basicity:		
In term of CaO/SiO_2 ratio	Unit	1.14
In term of $\frac{CaO/MgO}{Al_2O_3+SiO_2}$ ratio	Unit	1.17
Relative weight of slag	Kg/ton of fe	500

3.4 OPTIMIZATION METHOD

The objective of the optimization is to minimize the total cost of fuel required for producing a given quantity of liquid iron.

This objective function i.e. the cost equation is given as;

Total fuel cost (₦) = Cost (₦) of coke Per kg of product Fe + Cost (₦) of injectant per kg of product Fe

This can also be written as:

Total Cost (₦) = n^{coke}C (₦) + N^{I} (₦

This objective function is evaluated by the linearly related operating equations (eqn. 3.29, 3.33, 3.35, 3.39, 3.40, 3.41),which describe the process.

3.5 CONSTRAINTS

The constrains entered into the program are:

1. Those provided by the physical requirement of the furnace. According to Peacey and Davenport (1978), the amount of coke that must be left inside the furnace for proper burden support must not be less than 320kg (100%C). In the model form,

   $nc \geq 1.5$

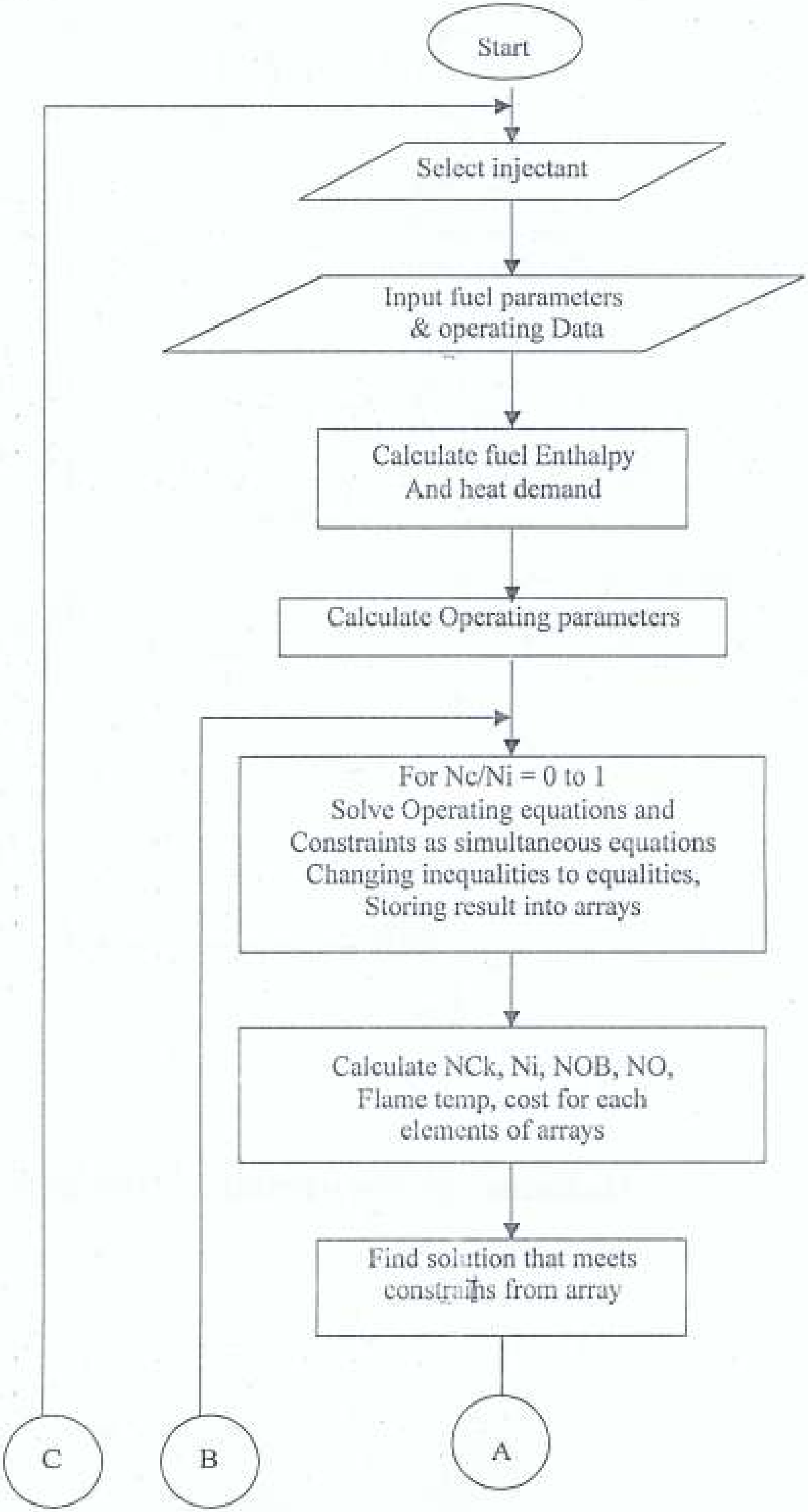
2. The thermal requirements of the process. According to Tovarovskii et al (1980) the flame temperature must be between 2200k and 2600k.

   $2200k \leq T_f \leq 2600k.$

3.6 THE PROGRAM

The operating equation, constrains, fuel parameters, and the furnace operating data are input into the linear optimization computer program

The coke/injectant ratio is varied. The operating equations and constrains were solved as simultaneous equations changing inequalities to equalities. The results were stored into arrays. The algorithm is as shown.


Start
Select injectant
Input fuel parameters & operating Data
Calculate fuel Enthalpy And heat demand
Calculate Operating parameters
For Nc/Ni = 0 to 1 Solve Operating equations and Constraints as simultaneous equations Changing inequalities to equalities, Storing result into arrays
Calculate NCk, Ni, NOB, NO, Flame temp, cost for each elements of arrays
Find solution that meets constrains from array
C
B
A

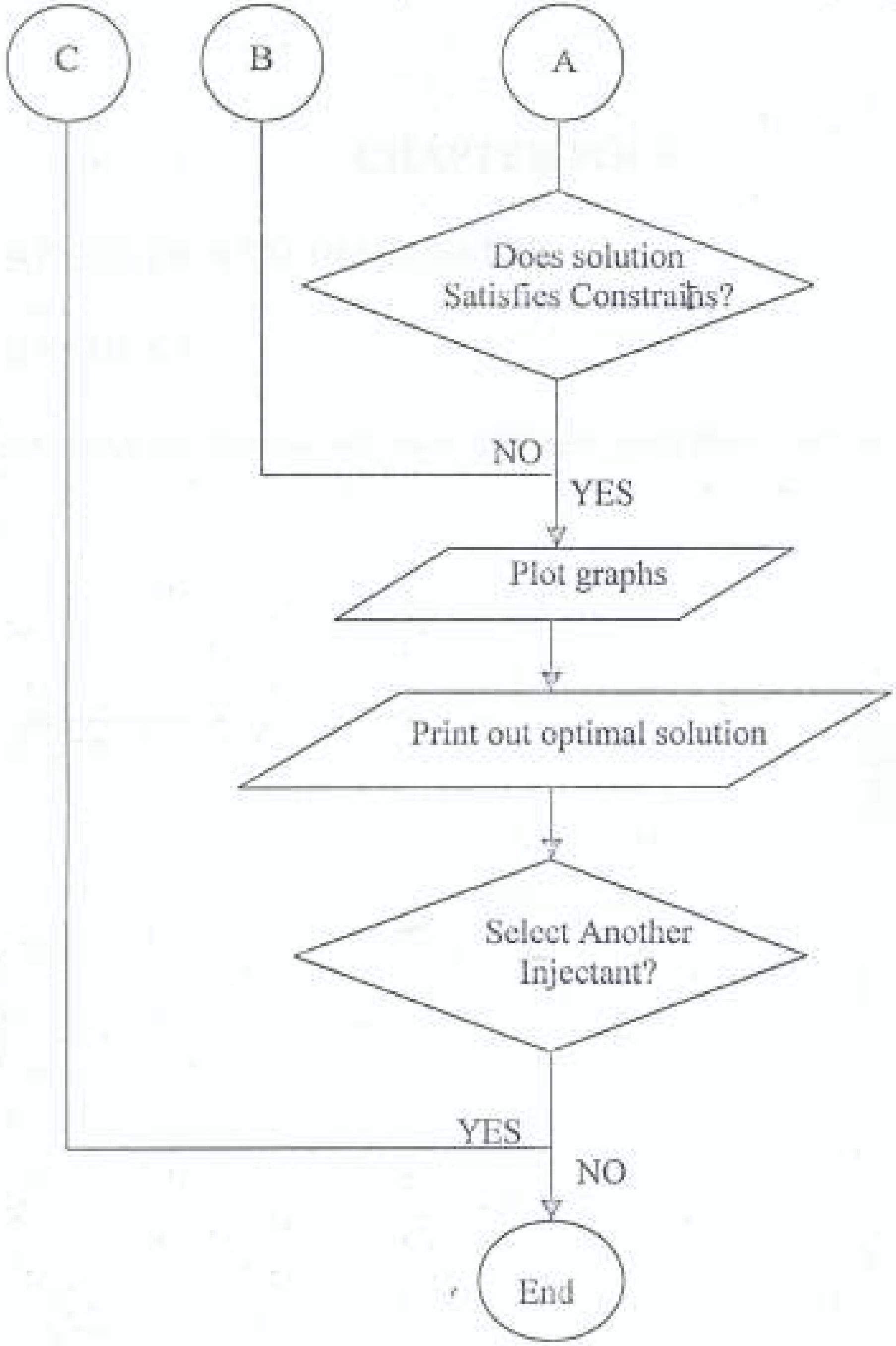


FIG5: THE ALGORITHM FOR THE PROGRAM

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 RESULTS

The results obtained after running the program are in appendix 2,and as shown in Figures 6 to 16.

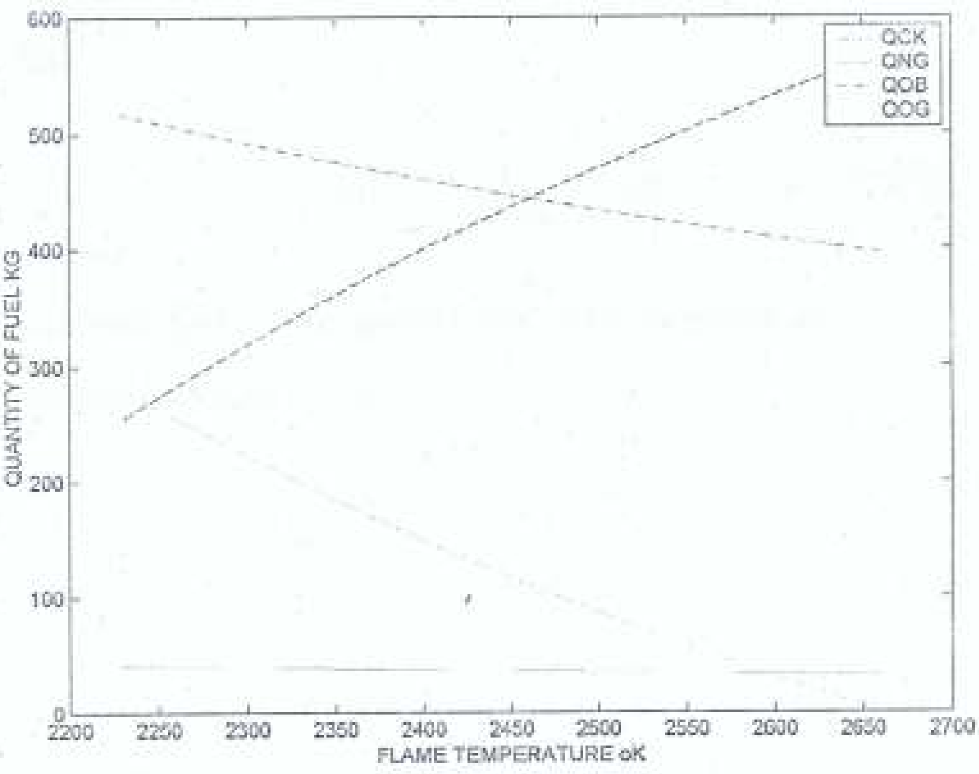


Fig 6: Plot of total Quantity of fuel against flame temperature at blast temperature of 1200k for natural gas injection.

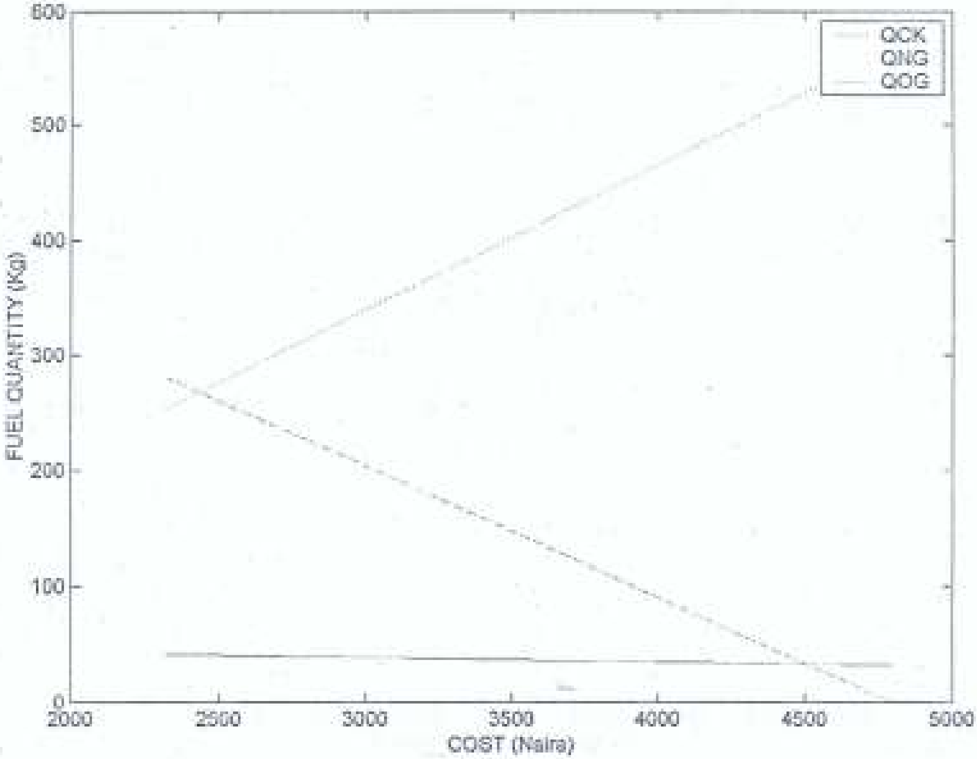


Fig 7: Plot of total Quality of fuel against cost at a Blast temperature of

1200k for natural gas injection.

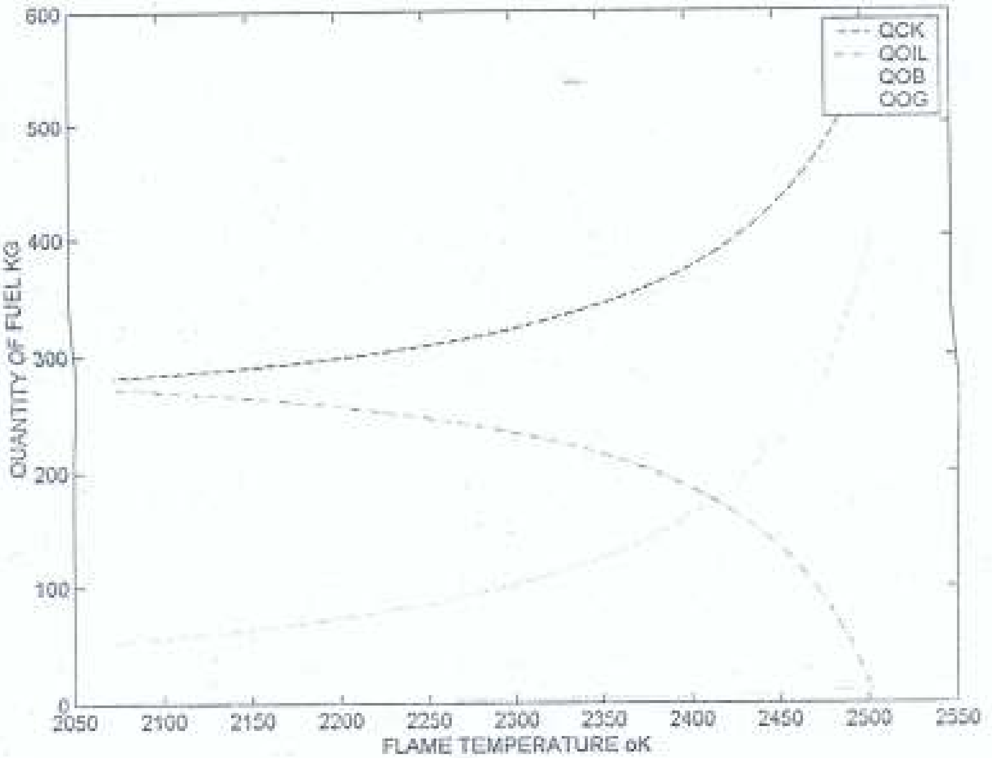


Fig 8: Plot of total Quality of fuel against flame temperature at blast temperature of 1200k for oil injection.

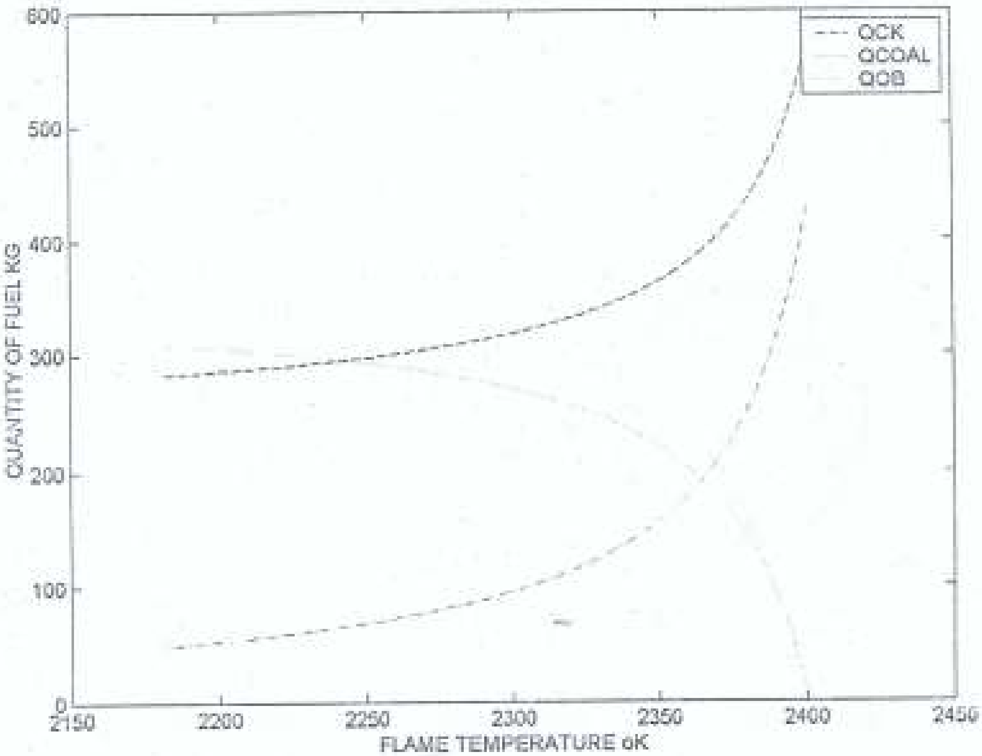


Fig 9: Plot of total Quantity of fuel against flame temperature at blast temperature of 1200k coal injection.

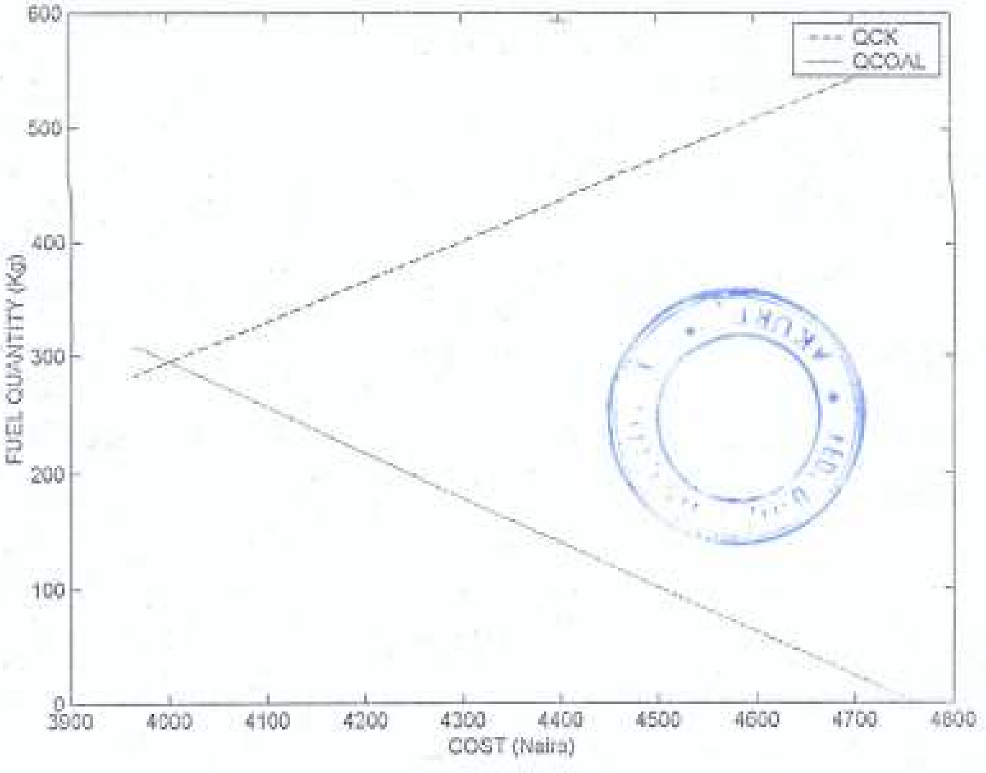


Fig 10: Plot of total Quality of fuel against cost temperature at blast temperature of 1200k coal injection.

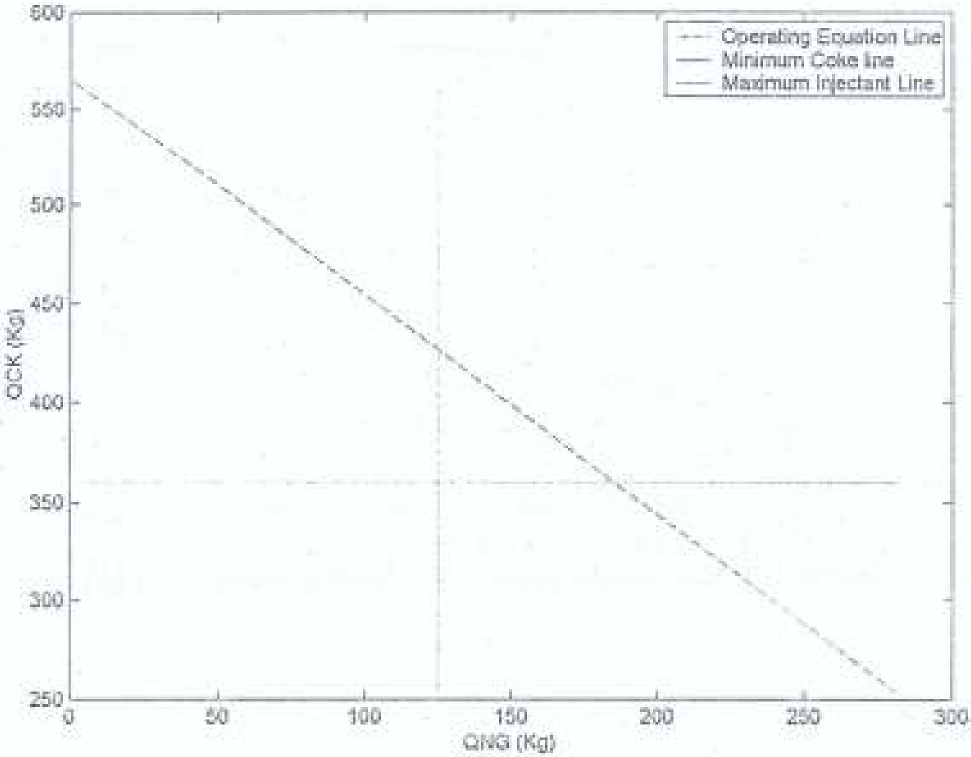


Fig 11: Optimisation graph for natural gas injection at blast temperature of 1200k

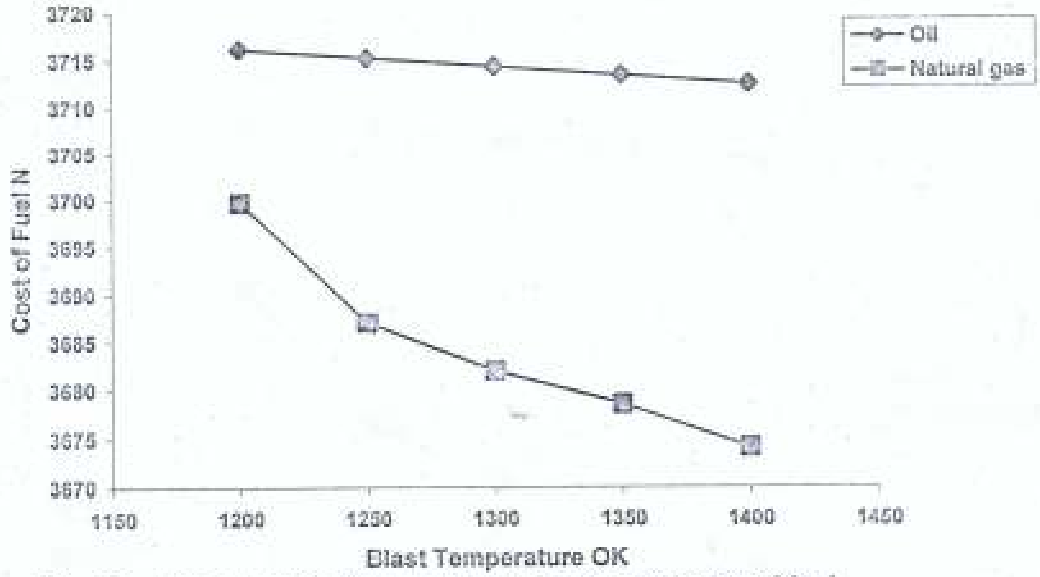


Fig 12: **Effect of Blast temperature on the total cost of fuel**

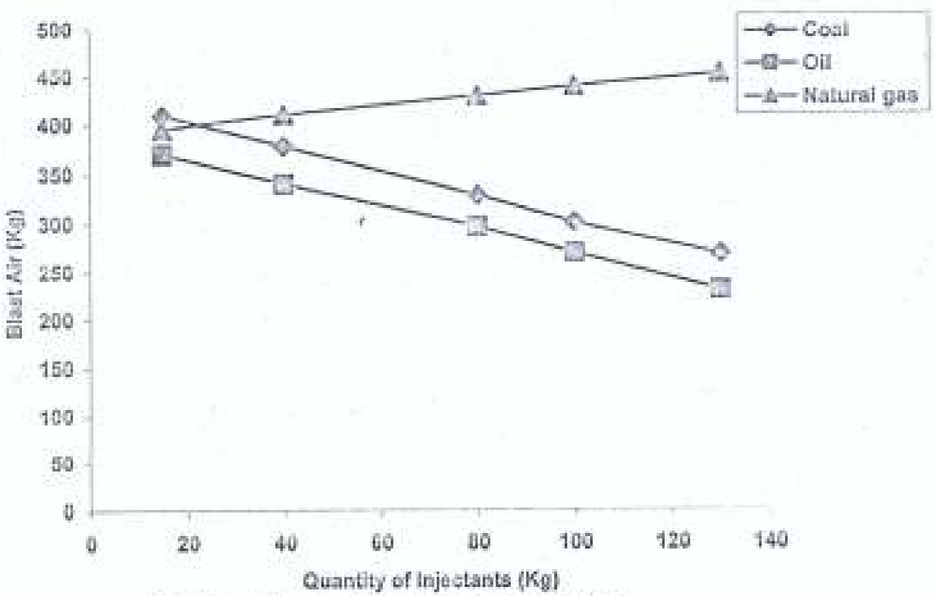


Fig 13: **Effect of injectant on Blast air**

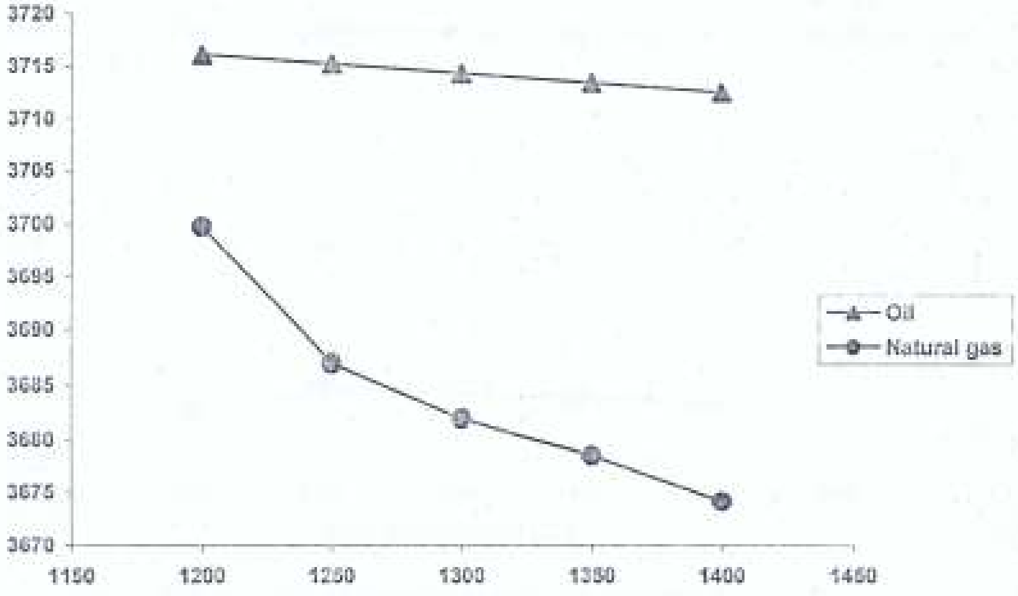


Fig 14: **Effect of Blast temperature on the total cost of fuel**

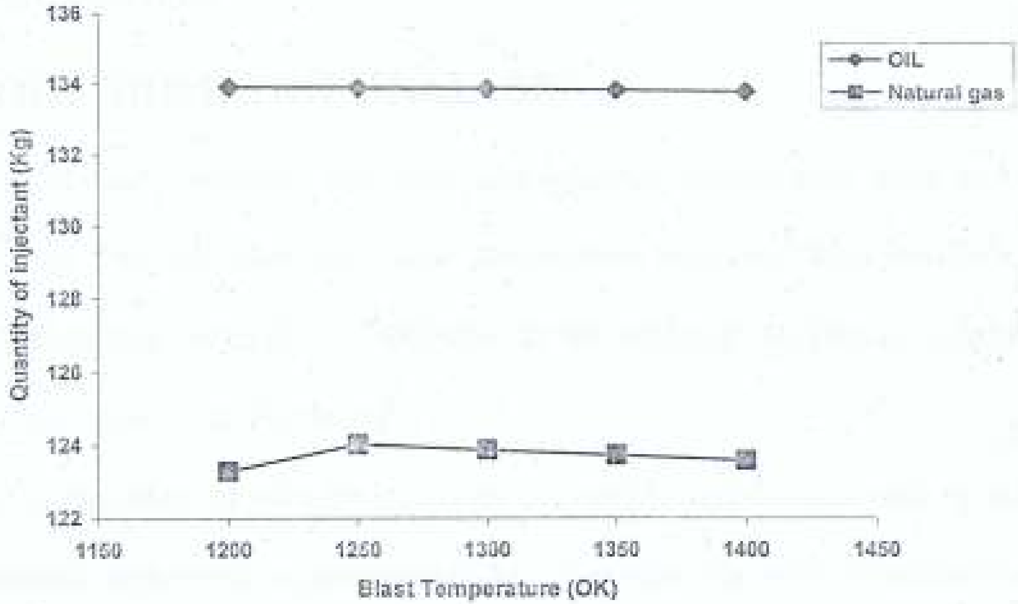


Fig 15: **Effect of Blast temperature on injectant**

4.2 DISCUSSION

4.2.1 STOICHIOMETRIC ANALYSIS

It is generally observed that coke and injectant consumption have an inverse relationship as both the blast and flame temperature increases; thus confirming that injectants substitutes coke. This is attributed to the reducing components (carbon and hydrogen) contained in the injectants.

The replacement of coke by injectants (the weight replacement ratio of coke per kg of injectants) varies with temperature and injectant type. The coke replacement ratio is made up of two components; coke saving from the decrease in the degree of direct reduction, and lowering (rise) of coke consumption because of the change in the amount of heat introduced into the furnace and carried out. Hence replacement ratio increases with rise in blast temperature. The replacement ratio of coke by heavy oil with increasing heaving oil consumption falls less significantly than with increasing natural gas consumption.

The blast air required for the various injectants varies. Table 6, Fig 6, 8, 9, 13 and Appendix II. It is observed that Natural gas injection has the highest requirement. This higher blast requirements and Oxygen enrichment of natural gas injection compared with Coal and Oil can be attributed to lack of Oxygen content as in Coal and Oil. As a result, blast requirement to burn unit quantity of natural gas and subsequently the yield of tuyere gas is higher for Natural gas.

4.2.2 THERMAL ANALYSIS

Changing blast temperature affects the flame temperature and heat loss in production zone. Flame temperature increases with increase in blast temperature and so also is heat loss in production zone The flame temperature is also observed to fall as the amount of injectant increases and rises as the quantity of coke consumed increase. Table 3, 5, Fig 6, 8, 9, and Appendix II.

As fuel is injected, in effect hydrogen replaces Nitrogen in the tuyere gas. As hydrogen reduction replaces the solution loss reaction, the thermal requirements to make a tonne of iron decrease markedly. The endothermic reaction of injectant combustion maintains a thermal balance unaltered, the blast temperature is either increased, or oxygen enrichment increased.

The oxygen enrichment reduces the heat loss in production zone and reduces the nitrogen contents of top gas. The reduction in heat loss in production zone with increase in flame temperature is connected with decreases in N_2 content of the gas leaving production zone. N_2 has been decreased due to increase in 0_2. This establishes N_2 as the main heat transporters in the furnace. Top gas temperature also goes down reduction in N_2

The enrichment of the blast with oxygen raises the flame temperature in the tuyere zone thus permit some injectants to be added while still maintaining an acceptable hearth temperature. This enriched oxygen combust the incandescent coke and injectant to CO, producing heat for melting and CO for reduction.

Reducing the coke rate leads to reduction in flame temperature, blast consumption and slag volume and therefore increase in production rate but also a situation of thermal imbalance may arise.

4.2.3 COST ANALYSIS

In trying to assess the technological aspect of the use of fuel addition and Oxygen enrichment of the blast, the main criterion in assessing the promise of any auxiliary fuel injection in the final reckoning is the overall economic effectiveness.
The maximum economic effectiveness is therefore achieved at the optimum ratio of consumptions of fuel additions and Oxygen.

The results clearly show that at higher alternative fuel injection rate, the cost reduces. Table 3, 4, 5, Fig 7, 10, 14 and Appendix II. This confirms the main basis for which cheaper fuel is injected. There is just a little reduction in cost as the blast temperature increases at constant coke/injectant consumption rate. On the other hand, the cost reduction is obvious at constant blast temperature varying the coke/injectant consumption rate.

The furnace was designed to be operated at a coke rate of 475kg/Thm and natural gas rate of 81kg (115m^3)/Thm, amounting to ₦4,099.87 for the production of a tonne of hot pig iron which cost ₦11,135.00. Operating the furnace according to the programme, as much as ₦399.9 can be saved in every tonne of Fe produced.

Table 3: Effect of injectant on Blast Furnace Performance

Parameters	Unit	BLAST TEMPERATURE				
		1200k	1250k	1300k	1350k	1400k
Coke rate	Kg/Thm	428.46	426.96	426.45	425.94	425.43
Natural gas rate	Kg/Thm	124.28	124.03	123.88	123.73	123.58
Oxygen rate	Kg/Thm	35.93	35.87	35.79	35.71	35.64
Total fuel rate	Kg/Thm	368.67	586.86	586.12	585.38	584.65
Blast air	Kg/Thm	448.97	448.39	447.43	446.47	445.52
Cost of coke	₦ /Thm	3607.70	3595.02	3590.72	3586.43	3582.19
Cost of natural gas	₦ /Thm	44.73	44.63	44.59	44.54	44.49
Cost of oxygen	₦ /Thm	28.73	28.69	28.63	28.57	28.51
Total fuel cost	₦ /Thm	3672.79	3660.38	3655.98	3651.00	3647.23
Flame temp.	^{o}K	2439	2478	2518	2558	2588
Carbon from coke consumed	Kg/Tfe	355.62	354.37	353.95	353.53	353.1
Carbon from natural gas consumed	Kg/Tfe	93.21	93.02	92.91	92.79	92.68
Total carbon consumed	Kg/Tfe	448.83	447.39	446.86	446.32	445.78

Table 4: Optimum Cost Analysis And Comparism of Natural Gas Injection

Variant	Quantity of coke consumed Kg/Thm	Quantity of natural gas consumed Kg/Thm	Quantity of oxygen consumed Kg/Thm	Cost (₦)	Cost difference compared to the Optimum Value		
					Per tonne (₦)	Per day (₦)	Per year (₦)
High blast Temp.	565.15	-	-	4758.89	1086.09	4,192,307.4	1,530,192.201
High blast Temp + O_2 injection	560.08	-	31.08	4740.23	1067.43	4,120,279.8	1,503,902,127
Designed rate	475.50	81	30	4055.87	384.01	1,482,501.2	541.116.223
Optimum 1200^{0} K	428.46	123.3	35.92	367.280	-	-	-

Table 5: **Effect of Oil injection on blast furnace performance and cost**

Parameters	Unit	Blast Temp. ^0C	Blast Temperature ^0C	Blast Temperature ^0C	Blast Temperature ^0C	Blast Temperature ^0C
		1200	1250	1300	1350	1400
Coke rate	Kg/Thm	425.52	425.42	425.32	425.21	425.11
Oil rate	Kg/Thm	133.91	133.88	133.85	133.82	133.78
Oxygen rate	Kg/Thm	7.26	7.251	7.242	7.237	7.23
Total fuel rate	Kg/Thm	566.69	566.55	566.412	566.267	566.12
Blast air	Kg/Thm	226.88	226.73	226.59	226.45	226.31
Cost of coke	#/Thm	3582.96	3582.08	3581.21	3580.34	3579.47
Cost of oil	#/Thm	131.239	131.2075	131.1755	131.14	131.11
Cost of oxygen	#/Thm	5.8082	5.804	5.8	5.797	5.793
Total cost	#/Thm	3716.11	3715.21	3714.30	3713.40	3712.5
Flame temperature	Ok	2449.46	2488.67	2527.88	2567	2606
Carbon from coke consumed	Kg/kgFe	353.18	353.09	353.21	352.91	353.84
Carbon from oil consumed	Kg/kgFe	115.16	115.13	115.11	115.08	115.05
Total carbon consumed	Kg/kgFe	468.34	468.22	468.12	467.99	467.89

Table 6: Cooling & coke replacement characteristics and the effect on coke rate for Typical injectants

Variant	Blast temp. ok	Optimum cost Rate Kg/Thm	Optimum Injectant Rate Kg/Thm	Optimum oxygen Injection rate Kg/Thm	Optimum Blast air rate Kg/Thm	Flame Temp. OK	Replacement Ratio
High Blast Temp.	1200	565.18	-	-	427.62	2450	-
Natural gas	1200	428.46	123.28	28.92	448.94	2439	1.10
Oil	1200	425.52	133.91	7.26	226.88	2449	1.48
Coal	1200	428.99	148.75	-	244.63	2379	0.91

Optimum cost for coke only without injectant = ₦4758.89/Thm

Optimum cost for coal dust injection = ₦437348/Thm

Optimum cost for oil injection = ₦3716.11/Thm

Optimum cost for natural gas injection = ₦3699.72/Thm

4.2.4 OPTIMUM SOLUTION ANALYSIS

In a bit to reduce the consumption of coke, at the least, cost, it is proposed that the Blast furnace should use natural gas as blast additive due to its high coke saving. This should be accompanied by oxygen enrichment of the blast, which compensate to a desirable level for the cooling effect of natural gas on the flame temperature.

From the experience of blast furnace operators, and this work, Oxygen enrichment permits the use of more tuyere injectant. This work had provided the operational choice with their corresponding cost and thermal implication. As revealed by the results, it is quite obvious that the furnace can be operated at a much minimised coke consumption rate, compared with the design. Based on the operational and physical restrictions, the best optimum solution is natural gas injection at 1200k (Table 4 and Figure 11). Higher blast temperature will attract higher cost for heating which are not included in the programme, and may require the use of expensive higher heat resistance equipment.

At the optimal solution, it can be seen that;

(1) 123.2847kg of Natural gas per tonne of Fe lowers the coke requirement of the process by approximately 136.4kg i.e. the weight replacement ratio is of the order of 1.1kg of coke per kg of Natural gas. This lowered coke requirement produces the desired effect of providing more gaseous space at the shaft of the furnace for iron ore, thus permitting higher permeability.

(2) ₦3,699.9 will be spent in producing a tonne of pig iron. If the furnace is to be operated at no injectant, ₦4,768.71 will be spent and if to be operated at the designed

fuel combination, ₦4,099.87 will be spent. A cost saving of ₦1,064.97 is obtained when compared with no injectant, and ₦399.97 when compared with the designed.

(3) The total carbon requirement of the process is decreased by injecting natural gas i.e. from 565.1891kg of carbon (from coke only) to 520.6176 of carbon (from both coke and natural gas) per tonne of product Fe. This is due to the contribution made by hydrogen towards reducing wustite in the wustite reduction zone.

(4) The blast oxygen requirement is slightly increased with natural gas injection. This extra oxygen is necessary to compensate (by combusting extra oxygen) for the heat demand of the injectant.

(5) With oxygen enrichment of up to 30% the total gas volume is kept not too high, thereby decreasing the amount of Nitrogen entering the furnace per kg mole of product Fe. Thus, the enriched oxygen compensates for the cooling effect from the injectant, and the nitrogen.

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

When a blast furnace is being operated in the era of high cost of metallurgical coke, it is important to carefully analyse and evaluate the performances of other cheap alternative fuels available at such locality, which will meet both the Stoichiometric and thermal requirement of the process.

This work has clearly shown the flexibility of the blast furnace process, and how the input parameters can be optimized in order to minimize the consumption rate of Metallurgical coke, still maintaining a good process controllability. Alternative fuel injection with increased blast temperature enables optimum raceway flame temperature and burden support to achieved and controlled.

Reliance on cheap Natural gas saves diminishing supplies of expensive Metallurgical coking coal requiring high-cost coke ovens. By this prediction procedure, the total inputs can be evaluated in the absence of costly experiments. More so, the value of auxiliary fuel injection will increase as the availability of metallurgical grade coke decreases, as coke-oven production deteriorates, and as coke-oven environmental emission standards becomes more stringent.

This optimization work meets both the operating equation and the furnace physical restrictions. It has been found to be both technically acceptable and economically justified.

For optimum, from the techno-economic analysis of the □ptimization programme, using the data from the Nigerian blast furnace at Ajaokuta Steel Complex, the following conclusions can be drawn;

The coke consumption rate should be 428.4686kg/Thm. while the natural gas consumption be 123.2847kg/Thm. Since the coke charge are to function more as support, they should have a high hot coke strength (CSR), and lower coke reactivity (CRI).

The blast temperature should be maintained at 1200k, because higher blast temperature is always cost demanding.

In order to increase the flame temperature at such fuel combination, the blast air should be enriched with oxygen, up to 30%.

The coke, should be charged at the centre of the furnace for proper burden support, while the natural gas being blown through the tuyere at the wall produces much of the heat needed, and the reducing gas.

5.2 RECOMMENDATIONS

In order to obtain a better furnace performance and operating the furnace at the optimum fuel combination, further research work should be centered on obtaining a coke with high hot coke strength (CSR), and lower coke reactivity (CRI). Also, effort should be made on improving the charge distribution system to ensure changing coke at the centre of the furnace to give enough burden support.

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APPENDIX I

THE PROGRAM

```
%program to optimise the fuel cost of blast furnance
% written by Aboginije Peter Apata

injectant=input('Enter the injectant number, CH4=1,
Oil=2, Coaldust=3  ');
teta=input ('input the percentage composition of carbon
in injectant, teta  ');
beta=input('input the percentage composition of
hydrogen in injectant, beta  ');
phi=input('input the percentage composition of oxygen
in injectant, phi  ');

switch injectant
     case 1
       x=1;
       y=2;
       z=0;
       HOTBNI=-75000;
       Di= 145000;
       material='Natural gas';
       inj=0.49;%cost
       case 2
       x=1/12*(teta/100);
       y=1/2*(beta/100);
       z=0;
       HOTBNI=-1660;
       Di=4700;
       material='Oil';
       inj=0.98;%cost
         case 3
       x=1/12*(teta/100);
       y=1/2*(beta/100);
       z=1/16*(phi/100);
       HOTBNI=0;
       Di=2400;
       material='Coal Dust';
       inj=5.4;%cost
 end
 temp=input ('input the operating temperature');
t=num2str(temp);
wtC=input('input weight percent of carbon in
injectant');
```

```
wtH=input('input weight percent of hydrogen in
injectant');

%CFe('carbon content of the molten iron')
CFe=0.22;
% Eb=input('blast enthalpy')
Dwrz=388857;
%operating parameters
    HOTBO2=36.2*temp-13500;
    HOTBH2O=47.4*temp-22200-242000;
    H1800C=30500;
    HOTBN2=34.4*temp-13000;
    HTFCO=36.6*temp-16400;
    HTFH2=35.2*temp-17200;
    HTFN2=36.4*temp-16500;
    HOTBC=15.3*temp-46000;
    HOTBH2=32.5*temp-12200;
    HO1200O2=36.2*1200-13500;
%print heading for result NI/NC=injectant/coke ratio
%initialise the output file for results of calculation
%if ran without change, it overwrites the named file
%to change output filename, change the filename below
or
%add another path
% calculate eb
Eb=1/2*((HOTBO2-29940)+3.762*(HOTBN2-28280));
filenam=num2str(temp);
filename=strcat('a:',filenam,'.txt');
% rest=fopen(filename,'w');
i=1;
No=0;
for c=0:.0025:1;
   a=198000+95000*y-Di;
     b=Dwrz+198000*CFe-No*Eb;
   %equation is entered as a matrix [m1][d]=[m2]
   %where [d] is [NI NC]
   m1=[a 198000;-1 c];
     m2=[b;0];
     %solve for d
     d=inv(m1)*m2;
     N(i)=d(1);
   NC(i)=d(2);
     NAC(i)=NC(i)+x*N(i)-CFe;
     NB(i)=NAC(i)*1.3+y*N(i)*0.38-z*N(i)-1.06;
switch injectant
     case 1
       NOB(i)=NB(i)/1.08;
```

```
        NO(i)= NB(i)-NOB(i);
        QNG=286.4*N;
        INJ=QNG;
      case 2
        NOB(i)=NB(i)/1.08;
        NO(i)= .4*(NB(i)-NOB(i));
        QOIL=14*17.9*N;
        INJ=QOIL;
    case 3
        NOB(i)=NB(i);
        NO(i)=0;
        QCOAL=N*214.8/0.76;
        INJ=QCOAL;
    otherwise
        NOB(i)=NB(i);
        NO(i)=0;
    end
    NH2o(i)=0.024*NOB(i);

flame=NOB(i)*1/2*HOTBO2+NH2o(i)*HOTBH2O+NO(i)*HOTBO2+N(
i)*HOTBNI+...
         ((NOB(i)+NH2o(i)+2*NO(i))-
wtC/1200*N(i))*H1800C+...

1.88*NOB(i)*HOTBN2+(NOB(i)+NH2o(i)+2*NO(i))*127400+(NH2
o(i)+wtH/200*N(i))*17200+1.88*NOB(i)*16500;

flame1=(NOB(i)+NH2o(i))*36.6+(NH2o(i)+wtH/200*N(i))*35.
2+1.88*NOB(i)*36.4;
     flamet(i)=flame/flame1;
No=NO(i);
   i=i+1;
end
       QCK=(214.8/0.83)*NC;
       QOG=286.4*NO;
       QOB=286.4*NOB;
switch injectant;
case 1
   g=1;
   while (QNG(g)<=125)
      g=g+1;
   end
   h=1;
   while(QCK(h)>=385)
      h=h+1;
   end
g=min([g-1 h-1]);
```

```
    cost=8.42*QCK+0.49*QNG+1.1*QOG;
    h1=figure;
    plot(QNG,QCK,'--', QNG,360,'-',125,QCK,'-.');
legend('Operating Equation Line', 'Minimum Coke
line','Maximum Injectant Line')
xlabel('QNG (Kg)');
ylabel('QCK (Kg)');
tit=strcat('OPTIMISATION GRAPH FOR NATURAL GAS AT BLAST
TEMPERATURE',t);
title(tit);
h2=figure;
plot(flamet,QCK,'--',flamet,QNG',':',flamet,QOB,'-
.',flamet,QOG,'-');
xlabel('FLAME TEMPERATURE oK')'
ylabel('QUANTITY OF FUEL KG')
legend('QCK', 'QNG', 'QOB','QOG');
tit=strcat('GRAPH OF QUANTITY OF FUEL VS FLAME
TEMPERATURE AT ',t,'oK');
title(tit);
h3=figure;
plot(cost,QCK,':',cost,QNG,'--',cost,QOG,'-');
xlabel('COST (Naira)');
ylabel('FUEL QUANTITY (Kg)');
legend('QCK','QNG','QOG');
tit=strcat('GRAPH OF QUANTITY OF FUEL VS COST
AT',t,'oK');
title(tit);
case 2
    h=1;
    while(QCK(h)>=385)
        h=h+1;
    end
    g=1;
    while(QOIL(g)<135)
        g=g+1;
    end
    g=min([g-1 h-1]);
    cost=8.42*QCK+0.98*QOIL+1.1*QOG;
    h1=figure;
    plot(QOIL,QCK,':', QOIL,360,'--',135,QCK,'-');
legend('Operating Equation Line', 'Minimum Coke
line','Maximum Injectant Line')
xlabel('QOIL (Kg)');
ylabel('QCK (Kg)');
tit=strcat('OPTIMISATION GRAPH FOR OIL AT BLAST
TEMPERATURE',t);
title(tit);
```

```
h2=figure;
plot(flamet,QCK,'--',flamet,QOIL,'-
.',flamet,QOB,':',flamet,QOG,'-');
xlabel('FLAME TEMPERATURE oK')'
ylabel('QUANTITY OF FUEL KG');
legend('QCK', 'QOIL', 'QOB','QOG');
tit=strcat('GRAPH OF QUANTITY OF FUEL VS FLAME
TEMPERATURE AT ',t,'oK');
title(tit);
h3=figure;
plot(cost,QCK,'-',cost,QOIL,'--',cost,QOG,':');
xlabel('COST (Naira)');
ylabel('FUEL QUANTITY (Kg)');
legend('QCK','QOIL','QOG');
tit=strcat('GRAPH OF QUANTITY OF FUEL VS COST
AT',t,'oK');
title(tit);
case 3
    h=1;
   while(QCK(h)>=385)
      h=h+1;
   end
   g=1;
   while(QCOAL(g)<=150)
      g=g+1;
   end
   g=min([g-1 h-1]);
      cost=8.42*QCK+5.14*QCOAL;
         h1=figure;
   plot(QCOAL,QCK,':', QCOAL,360,'-.',150,QCK);
legend('Operating Equation Line', 'Minimum Coke
line','Maximum Injectant Line')
xlabel('QCOAL (Kg)');
ylabel('QCOAL (Kg)');
tit=strcat('OPTIMISATION GRAPH FOR COAL DUST AT BLAST
TEMPERATURE',t);
title(tit);
h2=figure;
plot(flamet,QCK,'--',flamet,QCOAL,':',flamet,QOB,'-.');
xlabel('FLAME TEMPERATURE oK')'
ylabel('QUANTITY OF FUEL KG')
legend('QCK', 'QCOAL', 'QOB');
tit=strcat('GRAPH OF QUANTITY OF FUEL VS FLAME
TEMPERATURE AT ',t,'oK');
title(tit);
h3=figure;
plot(cost,QCK,'--',cost,QCOAL,'-');
```

```
xlabel('COST (Naira)');
ylabel('FUEL QUANTITY (Kg)');
legend('QCK','QCOAL');
tit=strcat('GRAPH OF QUANTITY OF FUEL VS COST
AT',t,'oK');
title(tit);
 end
format compact;
format long G;
material;
OperatingTemperature=temp;
f=min([g-1 h-1]);
     fname1= strcat(t,material,'optim.jpg');
   fname2= strcat(t,material,'QTY.jpg');
   saveas(h1,fname1);
   saveas(h1,fname2);
   fname=strcat(material,t,'.txt');
   fid= fopen(fname,'w');
   fprintf(fid,'result computed for %s at temperature
%4f \n',material, temp);
  fprintf(fid,' QCK        QINJECT  QOB      QOG
     COST     FLAME TEMP \n');
  for j=1:10:length(QNG);

fprintf(fid,'%8.4f\t%8.4f\t%8.4f\t%8.4f\t%8.4f\t%8.4f\n
',...
        QCK(j),INJ(j),QOB(j),QOG(j),cost(j),flamet(j));
  end
  fprintf(fid,'OPTIMUM Coke= %8.4f Kg\n',QCK(f));
 fprintf(fid,'OPTIMUM injectant= %8.4f Kg\n',INJ(f));
 fprintf(fid,'OPTIMUN Blast Oxygen= %8.4f
Kg\n',QOB(f));
 fprintf(fid,'OPTIMUM Injected Oxygen= %8.4f
Kg\n',QOG(f));
 fprintf(fid,'OPTIMUM TEMP=%8.4f oK\n',flamet(f));
 fprintf(fid,'OPTIMALCOST= %8.4f  Naira\n', cost(g));
 fprintf(fid,'OPTIMALCOST of coke= %8.4f  Naira\n',
8.42*QCK(f));
 fprintf(fid,'OPTIMALCOST of injectant = %8.4f
Naira\n', inj*INJ(f));
 fprintf(fid,'OPTIMALCOST of oxygen = %8.4f  Naira\n',
0.8*QOG(f));
 fclose(fid);
 close all;
```

APPENDIX II

RESULTS

Result computed for Natural gas at temperature 1200.000000

QCK	QINJECT	QOB	QOG	COST	FLAME TEMP
565.1891	0.0000	395.9484	31.6759	4793.7354	2659.7517
548.3643	15.1714	402.4742	32.1979	4660.0788	2629.2702
532.5122	29.4657	408.6226	32.6898	4534.1496	2601.5243
517.5509	42.9567	414.4256	33.1540	4415.2965	2576.1615
503.4073	55.7104	419.9114	33.5929	4302.9395	2552.8874
490.0161	67.7856	425.1053	34.0084	4196.5601	2531.4543
477.3190	79.2350	430.0301	34.4024	4095.6936	2511.6519
465.2632	90.1060	434.7061	34.7765	3999.9224	2493.3011
453.8014	100.4414	439.1517	35.1321	3908.8698	2476.2478
442.8908	110.2798	443.3836	35.4707	3822.1955	2460.3591
432.4925	119.6563	447.4167	35.7933	3739.5911	2445.5197
422.5713	128.6025	451.2648	36.1012	3660.7766	2431.6289
413.0950	137.1475	454.9403	36.3952	3585.4969	2418.5986
404.0344	145.3177	458.4546	36.6764	3513.5196	2406.3513
395.3628	153.1372	461.8180	36.9454	3444.6318	2394.8184
387.0555	160.6281	465.0401	37.2032	3378.6390	2383.9392
379.0902	167.8106	468.1296	37.4504	3315.3623	2373.6597
371.4461	174.7035	471.0944	37.6876	3254.6375	2363.9315
364.1042	181.3239	473.9421	37.9154	3196.3133	2354.7115
357.0469	187.6877	476.6794	38.1344	3140.2499	2345.9610
350.2580	193.8094	479.3126	38.3450	3086.3186	2337.6448
343.7224	199.7027	481.8475	38.5478	3034.3999	2329.7315
337.4263	205.3801	484.2895	38.7432	2984.3833	2322.1925
331.3567	210.8533	486.6437	38.9315	2936.1660	2315.0018
325.5016	216.1330	488.9147	39.1132	2889.6528	2308.1359
319.8498	221.2294	491.1068	39.2885	2844.7548	2301.5732
314.3909	226.1518	493.2242	39.4579	2801.3894	2295.2941
309.1152	230.9091	495.2704	39.6216	2759.4793	2289.2805
304.0137	235.5093	497.2491	39.7799	2718.9526	2283.5161
299.0778	239.9601	499.1636	39.9331	2679.7419	2277.9855
294.2996	244.2687	501.0168	40.0813	2641.7841	2272.6750
289.6717	248.4418	502.8118	40.2249	2605.0200	2267.5715
285.1871	252.4857	504.5513	40.3641	2569.3943	2262.6632
280.8393	256.4063	506.2376	40.4990	2534.8548	2257.9392
276.6220	260.2091	507.8734	40.6299	2501.3527	2253.3892
272.5295	263.8994	509.4607	40.7569	2468.8418	2249.0038
268.5564	267.4821	511.0017	40.8801	2437.2790	2244.7743
264.6974	270.9619	512.4985	40.9999	2406.6231	2240.6924
260.9477	274.3431	513.9529	41.1162	2376.8359	2236.7506
257.3028	277.6298	515.3666	41.2293	2347.8807	2232.9417
253.7584	280.8259	516.7414	41.3393	2319.7233	2229.2592

OPTIMUM Coke= 428.4686 Kg
OPTIMUM injectant= 123.2847 Kg
OPTIMUN Blast Oxygen= 448.9774 Kg
OPTIMUM Injected Oxygen= 35.9182 Kg
OPTIMUM TEMP=2439.8547 oK
OPTIMALCOST= 3699.7266 Naira
OPTIMALCOST of coke= 3607.7058 Naira
OPTIMALCOST of injectant = 60.4095 Naira
OPTIMALCOST of oxygen = 28.7346 Naira

Result computed for Natural gas at temperature 1250.000000

QCK	QINJECT	QOB	QOG	COST	FLAME TEMP
565.1891	0.0000	395.9484	31.6759	4793.7354	2700.4080
547.7761	15.1551	401.6596	32.1328	4655.0469	2669.8344
531.9323	29.4336	407.7889	32.6231	4529.1774	2642.0047
516.9792	42.9093	413.5735	33.0859	4410.3847	2616.5654
502.8438	55.6480	419.0418	33.5233	4298.0880	2593.2212
489.4608	67.7087	424.2191	33.9375	4191.7688	2571.7234
476.7718	79.1441	429.1279	34.3302	4090.9622	2551.8614
464.7240	90.0015	433.7886	34.7031	[illegible]	2533.4554
453.2701	100.3238	438.2196	35.0576	3904.2562	2516.3507
442.3672	110.1494	442.4374	35.3950	3817.6397	2500.4143
431.9765	119.5135	446.4571	35.7166	3735.0923	2485.5303
422.0628	128.4478	450.2923	36.0234	3656.3337	2471.5978
412.5939	136.9812	453.9554	36.3164	3581.1091	2458.5284
403.5405	145.1401	457.4577	36.5966	3509.1856	2446.2443
394.8759	152.9486	460.8097	36.8648	3440.3508	2434.6768
386.5755	160.4288	464.0207	37.1217	3374.4099	2423.7650
378.6169	167.6011	467.0995	37.3680	3311.1840	2413.4546
370.9795	174.4840	470.0541	37.6043	3250.5089	2403.6973
363.6440	181.0947	472.8919	37.8313	3192.2333	2394.4497
356.5930	187.4491	475.6196	38.0496	3136.2177	2385.6729
349.8102	193.5617	478.2435	38.2595	3082.3329	2377.3318
343.2807	199.4461	480.7695	38.4616	3030.4598	2369.3948
336.9905	205.1149	483.2029	38.6562	2980.4878	2361.8333
330.9266	210.5796	485.5487	38.8439	2932.3141	2354.6211
325.0771	215.8512	487.8117	39.0249	2885.8435	2347.7346
319.4308	220.9396	489.9960	39.1997	2840.9872	2341.1523
313.9773	225.8543	492.1057	39.3685	[illegible]	[illegible]
308.7069	230.6040	494.1446	39.5316	2755.7924	2328.8228
303.6104	235.1969	496.1161	39.6893	2715.3047	2323.0411
298.6796	239.6406	498.0237	39.8419	2676.1321	2317.4941
293.9063	243.9422	499.8702	39.9896	2638.2115	2312.1676
289.2832	248.1086	501.6587	40.1327	2601.4839	2307.0489
284.8033	252.1459	503.3918	40.2713	2565.8939	2302.1260
280.4600	256.0600	505.0720	40.4058	2531.3893	2297.3878
276.2473	259.8566	506.7017	40.5361	2497.9214	2292.8243
272.1592	263.5408	508.2833	40.6627	2465.4440	[illegible]
268.1903	267.1175	509.8186	40.7855	2433.9138	2284.1836
264.3355	270.5914	511.3099	40.9048	2403.2901	2280.0895
260.5900	273.9669	512.7589	41.0207	2373.5341	2276.1359
256.9491	277.2481	514.1674	41.1334	2344.6097	2272.3157
253.4086	280.4388	515.5370	41.2430	2316.4824	2268.6222

OPTIMUM Coke= 426.9621 Kg
OPTIMUM injectant= 124.0325 Kg
OPTIMUN Blast Oxygen= 448.3970 Kg
OPTIMUM Injected Oxygen= 35.8718 Kg
OPTIMUM TEMP 2478.4509 oK
OPTIMALCOST= 3687.3993 Naira
OPTIMALCOST of coke= 3595.0210 Naira
OPTIMALCOST of injectant = 60.7759 Naira
OPTIMALCOST of oxygen = 28.6974 Naira

Result computed for Natural gas at temperature 1300.000000

QCK	QINJECT	QOB	QOG	COST	FLAME TEMP
565.1891	0.0000	395.9484	31.6759	4793.7354	2741.0644
547.1903	15.1389	400.8484	32.0679	4650.0353	2710.3986
531.3547	29.4016	406.9585	32.5567	4524.2256	[illegible]
516.4098	42.8620	412.7250	33.0180	4405.4929	2656.9690
502.2827	55.5859	418.1759	33.4541	4293.2565	2633.5545
488.9078	67.6323	423.3365	33.8669	4186.9974	2611.9921
476.2268	79.0537	428.2295	34.2584	4086.2505	2592.0704
464.1870	89.8976	432.8750	34.6300	3990.5977	2573.6090
452.7410	100.2067	437.2914	34.9833	3899.6622	2556.4530
441.8459	110.0196	441.4953	35.3196	3813.1033	2540.4687
431.4628	119.3714	445.5016	35.6401	3730.6127	2525.5401
421.5565	128.2937	449.3239	35.9459	3651.9100	2511.5658
412.0949	136.8155	452.9747	36.2380	3576.7401	2498.4572
403.0487	144.9632	456.4652	36.5172	3504.8705	2486.1363
394.3911	152.7608	459.8057	36.7845	3436.0885	2474.5342
386.0976	160.2305	463.0057	37.0405	3370.1992	2463.5897
378.1457	167.3925	466.0739	37.2859	3307.0240	2453.2484
370.5148	174.2655	469.0183	37.5215	3246.3985	2443.4619
363.1858	180.8665	471.8462	37.7477	3188.1715	2434.1866
356.1411	187.2115	474.5644	37.9652	3132.2033	2425.3836
349.3645	193.3150	477.1792	38.1743	3078.3650	2417.0176
342.8409	199.1906	479.6963	38.3757	3026.5373	2409.0566
336.5566	204.8508	482.1212	38.5697	2976.6097	2401.4727
330.4984	210.3072	484.4587	38.7567	2928.4795	2394.2390
324.6545	215.5706	486.7136	38.9371	2882.0514	2387.3319
319.0137	220.6511	488.8901	39.1112	2837.2366	2380.7299
313.5655	225.5581	490.9923	39.2794	2793.9526	2374.4132
308.3003	230.3004	493.0238	39.4419	2752.1221	2368.3637
303.2090	234.8859	494.9883	39.5991	2711.6733	2362.5647
298.2832	239.3225	496.8890	39.7511	2672.5387	2357.0011
293.5148	243.6173	498.7289	39.8983	2634.6553	2351.6588
288.8965	247.7769	500.5109	40.0409	2597.9640	2346.5248
284.4212	251.8076	502.2376	40.1790	2562.4096	2341.5872
280.0825	255.7154	503.9117	40.3129	2527.9398	2336.8349
275.8742	259.5057	505.5355	40.4428	2494.5059	2332.2577
271.7905	263.1838	507.1112	40.5689	2462.0618	2327.8461
267.8259	266.7546	508.6410	40.6913	2430.5643	2323.5913
263.9753	270.2227	510.1268	40.8101	2399.9724	2319.4850
260.2339	273.5925	511.5704	40.9256	2370.2477	2315.5196
256.5970	276.8682	512.9737	41.0379	2341.3539	2311.6880
253.0604	280.0535	514.3383	41.1471	[illegible]	[illegible]

OPTIMUM Coke= 426.4521 Kg
OPTIMUM injectant= 123.8843 Kg
OPTIMUN Blast Oxygen= 447.4350 Kg
OPTIMUM Injected Oxygen= 35.7948 Kg
OPTIMUM TEMP=2518.4394 oK
OPTIMALCOST= 3682.9533 Naira
OPTIMALCOST of coke= 3590.7267 Naira
OPTIMALCOST of injectant = 60.7033 Naira
OPTIMALCOST of oxygen = 28.6358 Naira

Result computed for Natural gas at temperature 1350.000000

QCK	QINJECT	QOB	QOG	COST	FLAME TEMP
565.1891	0.0000	395.9484	31.6759	4793.7354	2781.7208
546.6069	15.1228	400.0404	32.0032	4645.0439	2750.9626
530.7795	29.3698	406.1316	32.4905	4519.2938	2722.9650
515.8428	42.8150	411.8799	32.9504	4400.6212	2697.3723
501.7238	55.5241	417.3135	33.3851	4288.4450	2673.8874
488.3571	67.5561	422.4576	33.7966	4182.2458	2652.2602
475.6842	78.9636	427.3348	34.1868	4081.5585	2632.2787
463.6523	89.7940	431.9652	34.5572	3985.9647	2613.7619
452.2141	100.0901	436.3672	34.9094	3895.0875	2596.5545
441.3267	109.8904	440.5572	35.2446	3808.5862	2580.5224
430.9512	119.2298	444.5502	35.5640	3726.1522	2565.5490
421.0523	128.1403	448.3597	35.8688	3647.5052	2551.5329
411.5980	136.6505	451.9982	36.1599	3572.3900	2538.3851
402.5590	144.7870	455.4769	36.4382	3500.5741	2526.0273
393.9084	152.5738	458.8061	36.7045	3431.8447	2514.3905
385.6218	160.0330	461.9952	36.9596	3366.0070	2503.4133
377.6766	167.1848	[illegible]	[illegible]	[illegible]	[illegible]
370.0522	174.0479	467.9871	37.4390	3242.3062	2483.2254
362.7296	180.6393	470.8052	37.6644	3184.1275	2473.9224
355.6912	186.9750	473.5140	37.8811	3128.2067	2465.0931
348.9207	193.0694	476.1196	38.0896	3074.4147	2456.7021
342.4031	198.9362	478.6279	38.2902	3022.6323	2448.7177
336.1246	204.5878	481.0442	38.4835	2972.7489	2441.1109
330.0722	210.0359	483.3735	38.6699	2924.6621	2433.8555
324.2338	215.2913	485.6204	38.8496	2878.2763	2426.9279
318.5985	220.3639	487.7892	39.0231	2833.5029	2420.3062
313.1557	225.2633	489.8839	39.1907	2790.2594	2413.9707
307.8957	229.9981	491.9082	39.3527	2748.4685	2407.9031
302.8095	234.5764	493.8656	39.5093	2708.0584	2402.0869
297.8886	239.0059	495.7595	39.6608	2668.9616	2396.5067
293.1251	243.2938	497.5927	39.8074	2631.1152	2391.1485
288.5115	247.4467	499.3682	39.9495	2594.4602	2385.9992
284.0409	251.4709	501.0888	40.0871	2558.9412	2381.0469
279.7068	255.3723	502.7568	40.2205	2524.5061	2376.2805
275.5029	259.1564	504.3747	40.3500	2491.1061	2371.6897
271.4235	262.8285	505.9446	40.4756	2458.6952	2367.2649
267.4632	266.3933	507.4688	40.5975	2427.2301	2362.9974
263.6168	269.8557	508.9491	40.7159	2396.6700	2358.8789
259.8794	273.2199	510.3874	40.8310	2366.9765	2354.9018
256.2465	276.4900	511.7856	40.9428	2338.1131	2351.0588
252.7138	279.6700	513.1451	41.0516	2310.0456	2347.3433

OPTIMUM Coke= 425.9443 Kg
OPTIMUM injectant= 123.7368 Kg
OPTIMUN Blast Oxygen= 446.4771 Kg
OPTIMUM Injected Oxygen= 35.7182 Kg
OPTIMUM TEMP=2558.4271 oK
OPTIMALCOST= 3678.5264 Naira
OPTIMALCOST of coke= 3586.4508 Naira
OPTIMALCOST of injectant = 60.6310 Naira
OPTIMALCOST of oxygen = 28.5745 Naira

Result computed for Natural gas at temperature 1400.000000

QCK	QINJECT	QOB	QOG	COST	FLAME TEMP
565.1891	0.0000	395.9484	31.6759	4793.7354	2822.3772
546.0258	15.1067	399.2357	31.9389	4640.0725	2791.5265
530.2066	29.3381	405.3079	32.4246	4514.3820	2763.4447
515.2781	42.7681	411.0382	32.8831	4395.7694	2737.7752
501.1671	55.4625	416.4547	33.3164	4283.6532	2714.2199
487.8087	67.4802	421.5824	33.7266	4177.5140	2692.5278
475.1438	78.8739	426.4438	34.1155	4076.8861	2672.4865
463.1199	89.6909	431.0592	34.4847	3981.3512	2653.9143
451.6895	99.9739	435.4468	34.8357	3890.5322	2636.6554
440.8098	109.7616	439.6230	35.1698	3804.0883	2620.5752
430.4418	119.0889	443.6028	35.4882	3721.7107	2605.5571
420.5504	127.9875	447.3997	35.7920	3643.1192	2591.4991
411.1033	136.4863	451.0260	36.0821	3568.0586	2578.3120
402.0714	144.6117	454.4929	36.3594	3496.2962	2565.9174
393.4278	152.3877	457.8108	36.6249	3427.6192	2554.2458
385.1480	159.8364	460.9891	36.8791	3361.8330	2543.2358
377.2095	166.9781	464.0363	37.1229	3298.7586	2532.8327
369.5917	173.8313	466.9604	37.3568	3238.2318	2522.9877
362.2754	180.4132	469.7688	37.5815	3180.1014	2513.6570
355.2432	186.7395	472.4682	37.7975	3124.2277	2504.8014
348.4789	192.8250	475.0648	38.0052	3070.4819	2496.3854
341.9673	198.6830	477.5643	38.2051	3018.4446	2488.[illegible]
335.6945	204.3261	479.9721	38.3978	2968.9054	2480.7477
329.6478	209.7659	482.2932	38.5835	2920.8617	2473.4708
323.8151	215.0132	484.5321	38.7626	2874.5181	2466.5225
318.1851	220.0780	486.6932	38.9355	2829.7860	2459.8811
312.7476	224.9698	488.7805	39.1024	2786.5828	2453.5268
307.4928	229.6971	490.7976	39.2638	2744.8314	2447.4411
302.4117	234.2683	492.7480	39.4198	2704.4598	2441.6076
297.4958	238.6908	494.6350	39.5708	2665.4008	2436.0108
292.7371	242.9718	496.4617	39.7169	2627.5913	2430.6367
288.1283	247.1180	498.2308	39.8585	2590.9724	2425.4721
283.6623	251.1357	499.9451	39.9956	2555.4886	2420.5050
279.3327	255.0308	501.6071	40.1286	2521.0880	2415.7245
275.1333	258.8087	503.2191	40.2575	2487.7218	2411.1200
271.0582	262.4747	504.7834	40.3827	2455.3440	2406.6821
267.1022	266.0338	506.3019	40.5042	2423.9113	2402.4020
263.2599	269.4904	507.7768	40.6221	2393.3829	2398.2712
259.5266	272.8490	509.2099	40.7368	2363.7204	2394.2822
255.8977	276.1136	510.6029	40.8482	2334.8873	2390.4278
252.3689	279.2882	511.9575	40.9566	2306.8495	2386.[illegible]

OPTIMUM Coke= 425.4386 Kg
OPTIMUM injectant= 123.5899 Kg
OPTIMUM Blast Oxygen 445.5211 Kg
OPTIMUM Injected Oxygen= 35.6419 Kg
OPTIMUM TEMP=2598.4139 oK
OPTIMALCOST= 3674.1183 Naira
OPTIMALCOST of coke= 3582.1931 Naira
OPTIMALCOST of injectant = 60.5591 Naira
OPTIMALCOST of oxygen = 28.5135 Naira

Result computed for Oil at temperature 1200.000000

QCK	QINJECT	QOB	QOG	COST	FLAME TEMP
565.1891	0.0000	395.9484	12.6703	4772.8293	2504.2977
551.2716	13.3454	379.1002	12.1312	4668.1292	2500.9797
538.0230	26.0493	363.0619	11.6180	4568.4616	2497.5416
525.3963	38.1569	347.7764	11.1288	4473.4721	2493.9768
513.3486	49.7093	333.1918	10.6621	4382.8389	2490.2781
501.8411	60.7437	319.2612	10.2164	4296.2691	2486.4378
490.8382	71.2943	305.9414	9.7901	4213.4954	2482.4476
480.3075	81.3921	293.1931	9.3822	4134.2735	2478.2986
470.2191	91.0658	280.9804	8.9914	4058.3795	2473.9811
460.5457	100.3414	269.2702	8.6166	3985.6081	2469.4846
451.2624	109.2431	258.0320	8.2570	3915.7704	2464.7978
442.3459	117.7930	247.2380	7.9116	3848.6926	2459.9083
433.7750	126.0116	236.8622	7.5796	3784.2142	2454.8027
425.5298	133.9178	226.8809	7.2602	3722.1870	2449.4664
417.5923	141.5290	217.2720	6.9527	3662.4738	2443.8832
409.9455	148.8615	208.0149	6.6565	3604.9475	2438.0357
402.5737	155.9302	199.0908	6.3709	3549.4901	2431.9047
395.4623	162.7492	190.4820	6.0954	3495.9920	2425.4691
388.5978	169.3315	182.1721	5.8295	3444.3512	2418.7055
381.9676	175.6892	174.1457	5.5727	3394.4725	2411.5882
375.5598	181.8335	166.3886	5.3244	3346.2674	2404.0887
369.3635	187.7752	158.8875	5.0844	3299.6529	2396.1755
363.3683	193.5239	151.6298	4.8522	3254.5516	2387.8133
357.5646	199.0890	144.6041	4.6273	3210.8911	2378.9627
351.9434	204.4791	137.7992	4.4096	3168.6033	2369.5797
346.4962	209.7024	131.2050	4.1986	3127.6245	2359.6148
341.2150	214.7664	124.8117	3.9940	3087.8949	2349.0121
336.0924	219.6784	118.6105	3.7955	3049.3582	2337.7084
331.1214	224.4451	112.5927	3.6030	3011.9614	2325.6316
326.2952	229.0728	106.7503	3.4160	2975.6548	2312.6999
321.6077	233.5676	101.0757	3.2344	2940.3914	2298.8189
317.0530	237.9351	95.5619	3.0580	2906.1267	2283.8802
312.6255	242.1806	90.2021	2.8865	2872.8191	2267.7582
308.3200	246.3091	84.9899	2.7197	2840.4288	2250.3064
304.1314	250.3255	79.9194	2.5574	2808.9187	2231.3532
300.0551	254.2342	74.9847	2.3995	2778.2532	2210.6962
296.0867	258.0395	70.1806	2.2458	2748.3988	2188.0948
292.2218	261.7455	65.5019	2.0961	2719.3239	2163.2609
288.4565	265.3560	60.9438	1.9502	2690.9981	2135.8466
284.7871	268.8746	56.5017	1.8081	2663.3931	2105.4277
281.2098	272.3048	52.1711	1.6695	2636.4816	2071.4814

OPTIMUM Coke= 425.5298 Kg
OPTIMUM injectant= 133.9178 Kg
OPTIMUN Blast Oxygen= 226.8809 Kg
OPTIMUM Injected Oxygen= 7.2602 Kg
OPTIMUM TEMP=2449.4664 oK
OPTIMALCOST= 3716.1137 Naira
OPTIMALCOST of coke= 3582.9613 Naira
OPTIMALCOST of injectant = 131.2394 Naira
OPTIMALCOST of oxygen = 5.8082 Naira

Result computed for Oil at temperature 1250.000000

QCK	QINJECT	QOB	QOG	COST	FLAME TEMP
565.1891	0.0000	395.9484	12.6703	4772.8293	2544.1402
551.0472	13.3399	378.8007	12.1216	4666.2242	2540.7840
537.8133	26.0391	362.7813	11.6090	4566.6760	2537.3063
525.2001	38.1427	347.5132	11.1204	4471.7971	2533.7004
513.1650	49.6915	332.9450	10.6542	4381.2666	2529.9590
501.6691	60.7229	319.0294	10.2089	4294.7922	2526.0745
490.6770	71.2708	305.7236	9.7832	4212.1073	2522.0383
480.1563	81.3665	292.9885	9.3756	4132.9681	2517.8415
470.0772	91.0383	280.7880	8.9852	4057.1514	2513.4743
460.4126	100.3124	269.0891	8.6109	3984.4522	2508.9260
451.1374	109.2128	257.8616	8.2516	3914.6821	2504.1852
442.2285	117.7618	247.0776	7.9065	3847.6676	[illegible]
433.6646	125.9796	236.7112	7.5748	3783.2486	2494.0750
425.4262	133.8852	226.7387	7.2556	3721.2771	2488.6771
417.4949	141.4960	217.1380	6.9484	3661.6164	2483.0297
409.8539	148.8282	207.8887	6.6524	3604.1394	2477.1149
402.4876	155.8969	198.9719	6.3671	3548.7285	2470.9133
395.3814	162.7159	190.3700	6.0918	3495.2743	2464.4036
388.5218	169.2984	182.0666	5.8261	3443.6748	2457.5621
381.8962	175.6563	174.0463	5.5695	3393.8353	2450.3629
375.4927	181.8010	166.2951	5.3214	3345.6671	2442.7772
369.3004	187.7431	158.7994	5.0816	3299.0876	2434.7729
363.3091	193.4924	151.5470	4.8495	3254.0195	2426.3145
357.5090	199.0581	144.5262	4.6248	3210.3903	2417.3621
351.8913	204.4488	137.7259	4.4072	3168.1323	2407.8712
346.4473	209.6728	131.1361	4.1964	3127.1818	2397.7917
341.1692	214.7376	124.7471	3.9919	3087.4790	2387.0671
336.0496	219.6504	118.5499	3.7936	3048.9678	2375.6334
331.0813	224.4179	112.5358	3.6011	3011.5954	2363.4179
326.2578	229.0466	106.6971	3.4143	2975.3119	2350.3376
321.5728	233.5422	101.0260	3.2328	2940.0704	[illegible]
317.0205	237.9106	95.5154	3.0565	2905.8268	2321.1670
312.5952	242.1571	90.1587	2.8851	2872.5391	2304.8799
308.2918	246.2866	84.9495	2.7184	2840.1680	2287.2278
304.1053	250.3040	79.8818	2.5562	2808.6760	2268.0572
300.0309	254.2137	74.9499	2.3984	2778.0279	2247.1633
296.0643	258.0200	70.1484	2.2447	2748.1902	2224.3028
292.2012	261.7270	65.4721	2.0951	2719.1312	2199.1843
288.4376	265.3386	60.9164	1.9493	2690.8207	2171.4560
284.7697	268.8582	56.4765	1.8072	2663.2302	2140.6888
281.1940	272.2895	52.1481	1.6687	2636.3326	2106.3542

OPTIMUM Coke= 425.4262 Kg
OPTIMUM injectant= 133.8852 Kg
OPTIMUN Blast Oxygen= 226.7387 Kg
OPTIMUM Injected Oxygen= 7.2556 Kg
OPTIMUM TEMP=2488.6771 oK
OPTIMALCOST= 3715.2092 Naira
OPTIMALCOST of coke= 3582.0885 Naira
OPTIMALCOST of injectant = 131.2075 Naira
OPTIMALCOST of oxygen = 5.8045 Naira

Result computed for Oil at temperature 1300.000000

QCK	QINJECT	QOB	QOG	COST	FLAME TEMP
565.1891	0.0000	395.9484	12.6703	4772.8293	2583.9828
550.8232	13.3345	378.5016	12.1121	4664.3221	2580.5883
537.6039	26.0290	362.5011	11.6000	4564.8931	2577.0709
525.0042	38.1284	347.2505	11.1120	4470.1247	2573.4239
512.9816	49.6737	332.6985	10.6464	4379.6967	2569.6399
501.4974	60.7021	318.7980	10.2015	4293.3175	2565.7110
490.5160	71.2475	305.5062	9.7762	4210.7212	2561.6289
480.0053	81.3409	292.7841	9.3691	4131.6646	2557.3842
469.9356	91.0109	280.5950	8.9791	4055.9250	2552.9672
460.2796	100.2834	268.9083	8.6051	3983.2979	2548.3671
451.0125	109.1826	257.6915	8.2461	3913.5952	2543.5722
442.1112	117.7305	246.9174	7.9014	3846.6439	2538.5701
433.5545	125.9476	236.5604	7.5699	3782.2842	2533.3468
425.3226	133.8526	226.5966	7.2511	3720.3684	2527.8875
417.3976	141.4630	217.0042	6.9441	3660.7600	2522.1757
409.7625	148.7950	207.7627	6.6484	3603.3323	2516.1935
402.4017	155.8636	198.8532	6.3633	3547.9679	2509.9211
395.3006	162.6827	190.2582	6.0883	3494.5574	2503.3374
388.4459	169.2653	181.9612	5.8228	3442.9993	2496.4180
381.8248	175.6235	173.9471	5.5663	3393.1987	2489.1369
375.4256	181.7686	166.2016	5.3185	3345.0675	2481.4648
369.2375	187.7111	158.7115	5.0788	3298.5229	2473.3694
363.2500	193.4609	151.4643	4.8469	3253.4879	2464.8147
357.4535	199.0272	144.4483	4.6223	3209.8901	2455.7604
351.8392	204.4186	137.6528	4.4049	3167.6618	2446.1616
346.3985	209.6433	131.0674	4.1942	3126.7395	2435.9674
341.1235	214.7088	124.6826	3.9898	3087.0636	2425.1209
336.0068	219.6224	118.4893	3.7917	3048.5779	2413.5572
331.0413	224.3908	112.4791	3.5993	3011.2297	2401.2028
326.2204	229.0203	106.6439	3.4126	2974.9693	2387.9738
321.5379	233.5169	100.9762	3.2312	2939.7498	2373.7738
316.9879	237.8862	95.4690	3.0550	2905.5271	2358.4920
312.5649	242.1336	90.1154	2.8837	2872.2595	2341.9997
308.2636	246.2641	84.9092	2.7171	2839.9074	2324.1472
304.0791	250.2825	79.8443	2.5550	2808.4336	2304.7590
300.0067	254.1932	74.9151	2.3973	2777.8029	2283.6280
296.0419	258.0006	70.1161	2.2437	2747.9818	2260.5083
292.1806	261.7086	65.4424	2.0942	2718.9386	2235.1051
288.4187	265.3212	60.8890	1.9484	2690.6433	2207.0626
284.7524	268.8419	56.4513	1.8064	2663.0674	2175.9470
281.1782	272.2742	52.1251	1.6680	2636.1837	2141.2237

OPTIMUM Coke= 425.3226 Kg

OPTIMUM injectant= 133.8526 Kg

OPTIMUN Blast Oxygen= 226.5966 Kg

OPTIMUM Injected Oxygen= 7.2511 Kg

OPTIMUM TEMP=2527.8875 oK

OPTIMALCOST= 3714.3059 Naira

OPTIMALCOST of coke= 3581.2167 Naira

OPTIMALCOST of injectant = 131.1755 Naira

OPTIMALCOST of oxygen = 5.8009 Naira

Result computed for Oil at temperature 1350.000000

QCK	QINJECT	QOB	QOG	COST	FLAME TEMP
565.1891	0.0000	395.9484	12.6703	4772.8293	2623.8253
550.5995	13.3291	378.2029	12.1025	4662.4231	2620.3926
537.3948	26.0189	362.2213	11.5911	4563.1130	2616.8355
524.8087	38.1142	346.9882	11.1036	4468.4548	2613.1473
512.7986	49.6560	332.4523	10.6385	4378.1290	2609.3206
501.3258	60.6813	318.5669	10.1941	4291.8449	2605.3474
490.3553	71.2241	305.2891	9.7693	4209.3370	2601.2192
479.8545	81.3153	292.5800	9.3626	4130.3629	2596.9267
469.7941	90.9835	280.4039	8.9729	4054.7003	2592.4598
460.1468	100.2545	268.7278	8.5993	3982.1451	2587.8078
450.8878	109.1524	257.5216	8.2407	3912.5098	2582.9589
441.9941	117.6993	246.7574	7.8962	3845.6216	2577.9004
433.4444	125.9156	236.4097	7.5651	3781.3210	2572.6182
425.2192	133.8200	226.4547	7.2466	3719.4609	2567.0973
417.3004	141.4301	216.8705	6.9399	3659.9047	2561.3212
409.6711	148.7618	207.6368	6.6444	3602.5262	2555.2715
402.3158	155.8303	198.7346	6.3595	3547.2081	2548.9286
395.2199	162.6495	190.1464	6.0847	3493.8414	2542.2706
388.3700	169.2322	181.8560	5.8194	3442.3245	2535.2732
381.7535	175.5907	173.8480	5.5631	3392.5629	2527.9100
375.3587	181.7362	166.1083	5.3155	3344.4685	2520.1515
369.1746	187.6791	158.6236	5.0760	3297.9588	2511.9650
363.1909	193.4294	151.3816	4.8442	3252.9568	2503.3139
357.3981	198.9963	144.3706	4.6199	3209.3904	2494.1577
351.7872	204.3884	137.5797	4.4025	3167.1918	2484.4508
346.3498	209.6138	130.9987	4.1920	3126.2977	2474.1419
341.0779	214.6801	124.6181	3.9878	3086.6486	2463.1733
335.9640	219.5945	118.4288	3.7897	3048.1884	2451.4795
331.0013	224.3637	112.4224	3.5975	3010.8644	2438.9862
326.1830	228.9941	106.5908	3.4109	2974.6271	2425.6084
321.5030	233.4916	100.9266	3.2296	2939.4296	2411.2488
316.9554	237.8618	95.4226	3.0535	2905.2278	2395.7952
312.5346	242.1102	90.0721	2.8823	2871.9801	2379.1176
308.2355	246.2416	84.8688	2.7158	2839.6470	2361.0645
304.0530	250.2610	79.8068	2.5538	2808.1915	2341.4586
299.9825	254.1727	74.8803	2.3962	2777.5781	2320.0905
296.0196	257.9811	70.0839	2.2427	2747.7736	2296.7113
292.1600	261.6902	65.4126	2.0932	2718.7463	2271.0232
288.3998	265.3038	60.8616	1.9476	2690.4661	2242.6664
284.7351	268.8255	56.4262	1.8056	2662.9047	2211.2021
281.1624	272.2589	52.1021	1.6673	2636.0350	2176.0901

OPTIMUM Coke= 425.2192 Kg
OPTIMUM injectant= 133.8200 Kg
OPTIMUN Blast Oxygen= 226.4547 Kg
OPTIMUM Injected Oxygen= 7.2466 Kg
OPTIMUM TEMP=2567.0973 oK
OPTIMALCOST= 3713.4037 Naira
OPTIMALCOST of coke= 3580.3460 Naira
OPTIMALCOST of injectant = 131.1436 Naira
OPTIMALCOST of oxygen = 5.7972 Naira

Result computed for Oil at temperature 1400.000000

QCK	QINJECT	QOB	QOG	COST	FLAME TEMP
565.1891	0.0000	395.9484	12.6703	4772.8293	2663.6679
550.3762	13.3237	377.9048	12.0930	4660.5270	2660.1968
537.1861	26.0088	361.9419	11.5821	4561.3357	2656.6000
524.6134	38.1000	346.7263	11.0952	4466.7874	2652.8706
512.6157	49.6383	332.2065	10.6306	4376.5637	2649.0012
501.1546	60.6606	318.3361	10.1868	4290.3744	2644.9837
490.1947	71.2008	305.0723	9.7623	4207.9549	2640.8094
479.7040	81.2898	292.3762	9.3560	4129.0631	2636.4689
469.6528	90.9561	280.2122	8.9668	4053.4772	2631.9522
460.0142	100.2256	268.5475	8.5935	3980.9939	2627.2483
450.7633	109.1223	257.3519	8.2353	3911.4258	2622.3453
441.8771	117.6682	246.5977	7.8911	3844.6005	2617.2303
433.3345	125.8837	236.2593	7.5603	3780.3591	2611.8892
425.1160	133.7875	226.3131	7.2420	3718.5544	2606.3067
417.2033	141.3972	216.7371	6.9356	3659.0505	2600.4661
409.5799	148.7287	207.5111	6.6404	3601.7211	2594.3490
402.2300	155.7971	198.6162	6.3557	3546.4493	2587.9334
395.1393	162.6163	190.0349	6.0811	3493.1262	2581.2031
388.2943	169.1992	181.7509	5.8160	3441.6505	2574.1277
381.6823	175.5580	173.7490	5.5600	3391.9279	2566.6825
375.2918	181.7038	166.0151	5.3125	3343.8703	2558.8375
369.1117	187.6472	158.5359	5.0731	3297.3954	2550.5597
363.1319	193.3980	151.2990	4.8416	3252.4264	2541.8122
357.3427	198.9655	144.2929	4.6174	3208.8912	2532.5540
351.7353	204.3582	137.5067	4.4002	3166.7223	2522.7390
346.3011	209.5843	130.9301	4.1898	3125.8564	2512.3153
341.0322	214.6514	124.5537	3.9857	3086.2340	2501.2245
335.9213	219.5666	118.3684	3.7878	3047.7992	2489.4005
330.9613	224.3366	112.3657	3.5957	3010.4995	2476.7681
326.1457	228.9678	106.5377	3.4092	2974.2851	2463.2415
321.4681	233.4662	100.8769	3.2281	2939.1096	2448.7221
316.9229	237.8374	95.3762	3.0520	2904.[illegible]287	2433.0966
312.5044	242.0867	90.0288	2.8809	2871.7009	2416.2336
308.2074	246.2192	84.8285	2.7145	2839.3869	2397.9799
304.0269	250.2395	79.7693	2.5526	2807.9495	2378.1561
299.9584	254.1523	74.8455	2.3951	2777.3535	2356.5506
295.9973	257.9617	70.0517	2.2417	2747.5656	2332.9119
292.1395	261.6718	65.3829	2.0923	2718.5541	2306.9387
288.3809	265.2864	60.8342	1.9467	2690.2891	2278.2673
284.7178	268.8092	56.4011	1.8048	2662.7422	2246.4542
281.1466	272.2436	52.0792	1.6665	2635.8864	2210.9531

OPTIMUM Coke= 425.1160 Kg
OPTIMUM injectant= 133.7875 Kg
OPTIMUN Blast Oxygen= 226.3131 Kg
OPTIMUM Injected Oxygen= 7.2420 Kg
OPTIMUM TEMP=2606.3067 oK
OPTIMALCOST= 3712.5027 Naira
OPTIMALCOST of coke= 3579.4764 Naira
OPTIMALCOST of injectant = 131.1118 Naira
OPTIMALCOST of oxygen = 5.7936 Naira

Result computed for Coal Dust at temperature 1200.000000

QCK	QINJECT	QOB	QOG	COST	FLAME TEMP
565.1891	0.0000	427.6243	0.0000	4758.8920	2400.6617
551.3928	15.0545	409.1251	0.0000	4720.1071	2399.3243
538.2539	29.3915	391.5075	0.0000	4683.1705	2397.9342
525.7267	43.0612	374.7100	0.0000	4647.9533	2396.4880
513.7693	56.1090	358.6766	0.0000	4614.3380	2394.9823
502.3438	68.5765	343.3563	0.0000	4582.2179	2393.4135
491.4153	80.5016	328.7026	0.0000	4551.4954	2391.7773
480.9523	91.9188	314.6728	0.0000	4522.0810	2390.0695
470.9255	102.8600	301.2281	0.0000	4493.8932	2388.2852
461.3082	113.3544	288.3325	0.0000	4466.8566	2386.4191
452.0759	123.4286	275.9531	0.0000	4440.9023	2384.4654
443.2059	133.1076	264.0594	0.0000	4415.9664	2382.4180
434.6772	142.4140	252.6235	0.0000	4391.9902	2380.2697
426.4706	151.3690	241.6195	0.0000	4368.9193	2378.0131
418.5681	159.9922	231.0232	0.0000	4346.7034	2375.6397
410.9532	168.3016	220.8125	0.0000	4325.2959	2373.1402
403.6104	176.3140	210.9666	0.0000	4304.6534	2370.5043
396.5254	184.0452	201.4665	0.0000	4284.7356	2367.7204
389.6848	191.5096	192.2941	0.0000	4265.5050	2364.7758
383.0762	198.7208	183.4328	0.0000	4246.9267	2361.6562
376.6881	205.6915	174.8670	0.0000	4228.9680	2358.3454
370.5095	212.4336	166.5823	0.0000	4211.5984	2354.8254
364.5303	218.9580	158.5649	0.0000	4194.7895	2351.0755
358.7411	225.2752	150.8023	0.0000	4178.5144	2347.0727
353.1328	231.3949	143.2823	0.0000	4162.7482	2342.7904
347.6972	237.3262	135.9938	0.0000	4147.4674	2338.1982
342.4264	243.0777	128.9263	0.0000	4132.6498	2333.2613
337.3130	248.6574	122.0698	0.0000	4118.2748	2327.9393
332.3501	254.0729	115.4152	0.0000	4104.3228	2322.1854
327.5311	259.3314	108.9535	0.0000	4090.7754	2315.9447
322.8499	264.4395	102.6765	0.0000	4077.6152	2309.1527
318.3006	269.4037	96.5764	0.0000	4064.8259	2301.7330
313.8777	274.2300	90.6458	0.0000	4052.3921	2293.5945
309.5760	278.9239	84.8778	0.0000	4040.2990	2284.6272
305.3907	283.4909	79.2658	0.0000	4028.5330	2274.6978
301.3170	287.9361	73.8035	0.0000	4017.0808	2263.6428
297.3506	292.2643	68.4849	0.0000	4005.9302	2251.2591
293.4872	296.4800	63.3046	0.0000	3995.0693	2237.2921
289.7229	300.5875	58.2572	0.0000	3984.4870	2221.4171
286.0540	304.5911	53.3376	0.0000	3974.1727	2203.2147
282.4768	308.4944	48.5411	0.0000	3964.1164	2182.1325

OPTIMUM Coke= 428.8999 Kg
OPTIMUM injectant= 148.7182 Kg
OPTIMUN Blast Oxygen= 244.8768 Kg
OPTIMUM Injected Oxygen= 0.0000 Kg
OPTIMUM TEMP=2378.7020 oK
OPTIMALCOST= 4373.4635 Naira
OPTIMALCOST of coke= 3611.3370 Naira
OPTIMALCOST of injectant = 803.0783 Naira
OPTIMALCOST of oxygen = 0.0000 Naira

APPENDIX III

List of Symbols Appearing in Principal Equations

SYMBOL	MEANING	UNITS
$(C/Fe)^m$	Molecular ratio: C/Fe in product metal	$\left\{ \frac{\text{Kg moles of dissolved C}}{\text{Kg mole of product Fe}} \right\}$
D^c	For heating and sissolving carbon in product	KJ (kg mol,e of C in metal)$^{-1}$
D^{CaCO_3}	For decomposing charged $CaCO_3$ to CaO, C and O_2 at the thermal reserve temperature ()extra heat demand due to charging $CaCO_3$ rather than CaO)	KJ (kg mole of $CaCO_3$)$^{-1}$
D^{Fe}	For reducing $Fe_{0.947}O$ and for heating and melting Fe	KJ (kg mole of product in Fe)$^{-1}$
D^I	For decomposing 1 mole of tuyere injectant at its injection temperature to form its component elements at the thermal reserve temperature.	KJ (kg mole of injectant)$^{-1}$
D^I_w	As above for 1 kg of injectant	KJ (kg mole of injectant)$^{-1}$
D^{loss}	For convective and radiative heat loss per kg mole of product Fe	KJ (kg mol,e of product in Fe)$^{-1}$
D^{Mn}	For reducing MnO and for heating Mn and dissolving it in product metal	KJ (kg mol,e of Mn in metal)$^{-1}$
D^{Si}	For reducing SiO_2 and for heating Si and dissolving it in product metal	KJ (kg mol,e of Si in metal)$^{-1}$
D^{slag}	For heating slag oxides and forming 1 kg of liquid slag.	KJ (kg of slag)$^{-1}$

SYMBOL	MEANING	UNITS
D^{wrz}	Sum of wustite resduction zone heat demands (excluding injectant demands), per kg mole of product Fe	KJ (kg mole of product Fe)$^{-1}$
E^{B}	Enthalpy in blast air above that which it would have at the thermal reserve temperature.	KJ (kg mol,e of O in dry blast air)$^{-1}$
$(Mn/Fe)^{m}$	Molecular ratio: Mn/Fe in product metal	$\left\{ \frac{\text{Kg moles of dissolved C}}{\text{Kg mole of product Fe}} \right\}$
n^{A}_{c}	Carbon taking part in wustite reduction zone reduction reactions = carbon leaving wustite reduction zone in ascending gases	kg mole of C (kg mole of product in Fe)$^{-1}$
n^{coke}_{c}	Carbon entering furnace in coke	kg mole of C (kg mole of product in Fe)$^{-1}$
n^{B}_{O}	Oxygen entering furnace in dry blast air, i.e not including oxygen from humidity or tuyere injectants	kg mole of O (kg mole of product in Fe)$^{-1}$
$^{a}CaCO_3$	Limestone charged to the furnace	kg mole of $CaCO_3$ (kg mole of product Fe)$^{-1}$
N^{i}	Quantity of tuyere injectant	kg mole of injectant (kg mole of product in Fe)$^{-1}$
$(O/C)^{g}$	Molecular ratio: O/C in carbonaceous portion of top gas	
$(O/C)^{gwrz}$	Molecular ratio: O/C in carbonaceous portion of the gas in chemical reserve	
$(O/H_2)^{g}$	Molecular ratio: O/H_2 in hydrogenous portion of top gas	
$(O/H_2)^{gwrz}$	Molecular ratio: O/H_2 in hydrogenous portion of the gas in the chemical reserve.	

$(O/Fe)^x$	Molecular ratio: O/Fe in iron oxides charged to the furnace (=3/2 for Fe_2O_3; 4/3 for Fe_3O_4)	kg mole of O (kg mole of product in Fe
$(O/Fe)^{xwrz}$	Molecular ratio: O/Fe in iorn oxide in he chemical reserve (=1.06 for $Fe_{0.947}O$)	kg mole of O (kg mole of product in Fe
$(Si/Fe)^m$	Molecular ratio: Si/Fe in product metal	$\left\{ \frac{\text{Kg moles of dissolved C}}{\text{Kg mole of product Fe}} \right\}$
$T_B T_g$	Temperatures of blast and top gas	K
$Wt._{slag}$	Weight of product slag per mole of product Fe	kg mole of slag (kg mole of product Fe)$^{-1}$
W^I	Weight of tuyere injectant per mole of product Fe	kg mole of injectant (kg mole of prod in Fe)$^{-1}$
x,y,z	Moles of C, H_2 and O per mole of tuyere injectant	kg moles (kg mole of injectant)$^{-1}$

APPENDIX IV

Enthalpy Increment Equations for Elements and Compounds, $[H^\circ_T - H^\circ_{298}]$

Enthalpy values calculated with these equations are within ±500 kJ of their published numerical equivalents. Sources are noted at the end of Appendix VII

Substance	Units: kJ per kg mole of element or compound				
	Temperature range, K				
	298–800 Top gas	800–1100	1100–1300 Wustite reduction	1100–1900 Bosh & Hearth	1800–2800 Flame temperature
Al_2O_3	107T−32 000	124T−46 000	128T−50 000	132T−55 000	–
C	15.3T− 4600	20.7T− 8700	22.7T−11 000	23.5T−11 800	–
CO	30.2T− 9100	32.5T−10 800	34.2T−12 600	35.3T−14 000	36.6T−16 400
CO_2	45.6T−14 100	52.8T−19 200	56.3T−23 100	58.6T−26 000	61.0T−30 500
CaO	48.5T−14 500	51.6T−17 000	54.2T−19 800	55.5T−21 200	–
$CaCO_3$	106T−31 500	123T−45 100	129T−52 200	Decomposes above 1300 K	
$CaO\cdot SiO_2$	108T−32 300	122T−43 600	128T−49 500	128T−50 000	–
$(CaO)_2\cdot SiO_2$	158T−47 000	186T−69 000	189T−73 000	218T−105 000	–
$(CaO)_3\cdot P_2O_5$	284T−84 500	356T−142 000	402T−193 000	403T−194 000	–
Fe_s	30.8T− 9200	48.9T−23 700		38.4T−11 400	–
Fe_l[a] (M.P. ≈ 1800 K)	–	–	–	44.0T− 5800	–
$Fe_{0.947}O$	52.2T−15 600	56.4T−18 900	58.6T−21 400	61.1T−24 100	–
Fe_2O_3	135T−40 200	158T−58 800	142T−40 600	144T−43 000	–
Fe_3O_4	202T−60 000	227T−82 000	201T−53 200	201T−53 200	–
H_2	29.3T− 8800	29.9T− 9200	30.9T−10 300	32.5T−12 200	35.2T−17 200
$H_2O_{(g)}$	35.8T−10 800	40.0T−13 800	43.7T−17 900	47.4T−22 200	–
MgO	45.6T−13 600	50.9T−17 800	52.2T−19 300	55.0T−22 300	–
$MgCO_3$	102T−30 500	126T−49 500	Decomposes below 1100 K		
Mn_s	31.0T− 9200	44.3T−19 900	38.2T−13 200	48.6T−24 600	–
Mn_l[a] (M.P. = 1517 K)	–	–	–	48.6T−10 000	–
MnO	49.2T−14 700	53.7T−18 300	56.9T−21 800	57.1T−22 000	–
MnO_2	68.2T−20 300	77.3T−27 600	–	–	–
Mn_3O_4	167T−49 600	182T−61 900	199T−80 200	238T−123 000	–
N_2	30.0T− 9000	32.1T−10 500	–	34.4T−13 000	36.4T−16 500
O_2	31.6T− 9600	34.3T−11 500	–	36.2T−13 500	–
P_{2g}	34.9T−10 500	36.7T−11 900	37.1T−12 300	37.3T−12 600	
S_{2g}	35.2T−10 600	36.9T−11 900	37.2T−12 300	37.4T−12 500	
Si_s	23.6T− 7000	26.4T− 9300	27.2T−10 200	27.1T−10 100	–
Si_l[a] (M.P. = 1683 K)	–	–	–	27.2T+40 400	–
SiO_2	61.1T−18 200	71.0T−25 900	71.4T−24 300[b]	72.8T−26 200[b]	

[a] $[H^\circ_T - H^\circ_{298}]$ M_l M_s [b] $[H^\circ_T$ cristobalite $- H^\circ_{298}$ quartz$]$

APPENDIX V

Enthalpies of Formation at Temperature T *from Elements at Temperature* T (H_T^f)

Values for compounds central to the analyses of this text (i.e. CO, CO_2, H_2O, $Fe_{0.947}O$) are accurate to within ±500 kJ. Sources are noted at the end of the table.

Compound	Units: kJ per kg mole of compound			
	298 K	1100 K	1200 K	1300 K
CH_4	−75 000	−91 000	−91 000	−92 000
C_2H_6	−84 000	−102 000	−101 000	−100 000
C_3H_8	−105 000	−129 000	−128 000	−127 000
CO	−111 000	−113 000	−113 000	−114 000
CO_2	−394 000	−395 000	−395 000	−395 000
$CaCO_3$ (from CaO, C and O_2)	−572 000	−563 000	−561 000	−559 000
$CaCO_3 \cdot MgCO_3$ (from carbonates)	−12 000	decomposes below 1100 K		
$(CaO)_3 \cdot P_2O_5$ (from CaO, O_2 and P_{2g})	−2 400 000	−2 364 000	−2 353 000	−2 341 000
$CaO \cdot SiO_2$ (from oxides)	−89 000	−91 000	−91 000	−91 000
$(CaO)_2 \cdot SiO_2$ (from oxides)	−126 000	−125 000	−124 000	−123 000
$Fe_{0.947}O$	−266 000	−265 000	−265 000	−265 000
Fe_3O_4	−1 121 000	−1 096 000	−1 098 000	−1 095 000
Fe_2O_3	−826 000	−810 000	−811 000	−809 000
H_2O_l ($\Delta H_{298}^{vaporization}$ = +44 000)	−286 000			
H_2O_g	−242 000	−248 000	−249 000	−250 000 (also −250 000 at 1500 K)
$MgCO_3$ (from MgO, C and O_2)	−511 000	decomposes below 1100 K		
MnO	−385 000	−386 000	−386 000	−386 000
Mn_3O_4	−1 387 000	−1 387 000	−1 386 000	−1 384 000
MnO_2	−521 000	−516 000	decomposes at 1120 K	
SO_2 (from gaseous S_2)	−362 000	−362 000	−362 000	−362 000
SiO_2	−911 000	−902 000	−901 000	−901 000

The data are from:

Stull, D. R., Prophet, H. *et al.* (1970) ***JANAF Thermochemical Tables,*** 2nd edition, United States Department of Commerce, Document NSRDS-NBS 37, Washington, June 1971,

with the exception of:

(a) CaO, $CaCO_3$, $CaCO_3 \cdot MgCO_3$, $(CaO)_3 \cdot P_2O_5$, $CaO \cdot SiO_2$, $(CaO)_2 \cdot SiO_2$, MgO, $MgCO_3$ which are from:

Robie, R. A. and Waldbaum, D. R. (1968) *Thermodynamic Properties of Minerals,* United States Geological Survey Bulletin 1259, Washington.

(b) C_2H_6, C_3H_8 which are from:

Scott, D. W. (1974) *Chemical Thermodynamic Properties of Hydrocarbons,* United States Bureau of Mines Bulletin 666, Washington.