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IRON REDUCTION WITH CONCURRENT PRODUCTION
OF FUEL GAS IN SHAFT REACTORS

by

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In this paper, the co-production of iron and fuel gases from composites of iron oxide and carbon in metallurgical-type counter-current reactors, such as cupolas or low shaft furnaces, is examined. For the purposes of thermochemical calculations, the reference case is considered of a no-loss reactor charged with pure iron oxide and carbon and blown with preheated air to produce iron at $1600^{\circ}C$ and top-gas at $327^{\circ}C$. For this case, the nominal calorific value of the top-gas ($CO:N_2$, 46:54) is calculated to be 158 BTU/ft^3 (59% of energy of carbon in net top-gas). If coal is used in the reactor, for a high volatile coal (70% fixed carbon) the top-gas calorific value becomes 206 BTU/ft^3 whereas for a charred low-rank coal (70% fixed carbon, 20% ash) the top-gas calorific value is 168 BTU/ft^3. If CO_2 is produced in the reactor tuyère zone (as in the case of a cupola), the energy balance calculation indicates a top-gas of nominal calorific value 140 BTU/ft^3 (51% of energy of carbon in net top-gas). Pre-reduction of the iron oxide without consumption of fixed carbon is calculated to provide a top-gas with nominal calorific value of 156 BTU/ft^3 (59% of energy of carbon in net top-gas). For the special case of a "coke-less" cupola oxidizing the fuel carbon to carbon dioxide with an agglomerate carbon stoichiometry to manufacture iron from prereduced FeO, the nominal top-gas calorific value is only 82 BTU/ft^3, or 102 BTU/ft^3 if a high volatile coal is used with 70% fixed carbon (35 per cent of energy of coal in net top-gas). Finally, an ideal process using a "sliding block" furnace to produce iron and fuel gas is outlined.

Introduction

This paper sets out the reasons for re-examining the co-production of iron and fuel gases in metallurgical-type reactors. Nearly all current studies of the gasification of solid fuels, in contrast, are being conducted under process conditions that may be described as chemical engineering, typically in fluid beds often operated at elevated pressure. Processes now being developed which are exceptions to this general pattern of development are however, noteworthy: gasification of coal in the presence of liquid iron and slag at elevated temperature ($\sim1500^{\circ}$C) with air or oxygen and steam, gasification of coal in the presence of a liquid salt and gasification of municipal and other low-grade hydrocarbon wastes in shaft furnaces generally similar to cupolas or small iron blast furnaces. In the latter group of processes the object is only to produce the gas although melted down inorganic material may be recovered.

For the case under consideration here - the co-production of gas and iron - the process may be simply regarded as the substitution of iron oxide for steam as the endothermic energy consumer to balance the energy released by the oxidation of the carbon to carbon monoxide. The reasons for re-examining this possibility at this time can be summarized as:

- iron ores and concentrates would be used in their available fine states to end the necessity for sintering or pelletizing processes, although an agglomeration stage to bind both the ore and the coal together is needed in the projected process which itself has serious developmental problems.

- low and high rank coals could be used (although in different ways) so that the classical high-cost coking process would no longer be needed. Moreover it is not likely that the same rigid limits on coal ash and impurities such as sodium and potassium would be necessary as for convential blast furnace requirements. However, charring or special briquette heat-processing stages may be required.

- the process would produce a liquid iron directly usable in conventional basic oxygen steelmaking processes, possibly with lower silicon content which would lead to less scrap additions in steelmaking to improve steel plant balance. Sulphur control in the iron may, however, require an intermediate external desulphurization stage at an extra cost of perhaps $2 or more per ton of iron, or alternatively, special methods of making the composite pellets to control sulphur by means of lime additions, etc.(1) may be required.

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- the gas produced from the shaft would be cool ($\sim 300^\circ C$), amenable to known de-dusting techniques such as have been developed for the iron blast furnace and have a calorific value in the range 80 to 300 BTU/ft^3. This gas would be a useful fuel in both gas turbines and for underfiring boilers and other heating furnaces, particularly as NO_x formation on combustion would be expected to be less than for rich gaseous fuels such as natural gas. Difficulties may be encountered, however, when raw high volatile coals are used to form the composite agglomerate charge because of the evolution of tars and distillates to the off-gas.

- the forming or agglomerate production stage in effect combines two agglomerating processes now used in the steel industry - pelletizing (or sintering) and coking (or formed coking). Moreover, less strength is required of these agglomerates since it is unlikely that the shaft height would need to exceed forty or fifty feet there being no need of a "solids-gas" reaction zone as in the iron blast furnace. The agglomeration stage can also be regarded as a method of charging vertical shaft reactors directly with coal regardless of type. For the important case of the direct use of the raw swelling high volatile coals, the presence of the admixed iron ore prevents undue size distortion and sticking of the individual briquettes. Shaft coal gasifiers of the Lurgi-type have pronounced difficulties in using coal fines and swelling coals directly.

In Europe, a low-shaft furnace process was developed by the Demag-Humboldt Group(2) for the production of liquid iron from composite briquettes of fine iron ores and non-coking coals. Interest in Australia in iron ore-coal composite pellets started in an attempt to develop a continuous coking process utilizing high volatile fluid coals. As an extension of these studies, a method has been patented(3) for the smelting of ore-coal pellets in a shaft furnace, carbonization of the coal occurring in the upper part of the shaft by heat developed from combustion of volatiles lower down the shaft. Very recently, Obenchain in Pittsburgh(4) has patented a process for producing metal from metal oxide pellets using carbon containing pellets in alternate layers with coke in a cupola-type vessel. Control of carbon content in the molten metal is effected by oxygen enrichment of the air blast.

Thermochemical Base of Gas and Iron Co-Production in Shaft Furnaces

Reference Case

The simplest basis of calculation has been chosen to represent the thermochemical possibilities of this process. The reference

case for calculating the theoretical heat and mass balance will be assumed for simplicity to be a reactor charged with an agglomerate of sufficient strength made up entirely of pure iron oxide and pure carbon, blown with preheated air producing iron at $1600^{\circ}C$ and top-gas at $327^{\circ}C$, with negligible process and slag heat losses. Furthermore in the reference case it will be assumed that the tuyère zone of the shaft operates in blast furnace fashion, that is, only CO (and hydrogen if H_2O were to be present) leaves the combustion zone. Carbon deposition could occur and this reaction would lead to the presence of CO_2 in the top-gas but this secondary reaction will be assumed negligible here. However, this aspect of the process requires careful study perhaps in the first instance in a moving non-isothermal laboratory reactor such as the "Rist" apparatus. No net gas-solids type reduction will be assumed - this reaction also would cause CO_2 to be present in the top-gas.

Heat Supply to Process: - sensible heat in air blast
                         - combustion of C to CO

Heat Extraction from Process: - endothermic reduction of Fe_2O_3 to Fe with C (no gaseous reduction assumed)
                              - sensible heat of iron leaving at $1600^{\circ}C$
                              - sensible heat of gases $(CO + N_2$ only) leaving at $327^{\circ}C$

Heat and Mass Balance: 1 mole of Fe, room temperature basis
                       y = moles of O_2 in air blast/mole of Fe

IN	Quantity	Heat Unit kcal	Content kcal
Air:	y moles of O_2 at $1027^{\circ}C$	7.97	7.97y
	4y moles of N_2 at $1027^{\circ}C$	7.53	30.12y
Iron:	1 mole of $FeO_{1.5}$ at room temp	–	–
Carbon:	2y+1.5 moles C at room temp	–	–
Chemical Energy:	$C + \frac{1}{2} O_2 = CO : \Delta H = -26.4$	26.4x2y	52.80y
		Total	90.89y

OUT

Iron:	1 mole at $1600^{\circ}C$	18.4 kcal	18.4
Top-Gas:	4y moles of N_2 at $327^{\circ}C$	2.1x4y	8.4y
	2y+1.5 moles of CO at $327^{\circ}C$	2.1(2y+1.5)	4.2y+3.2
Chemical Energy:	$1.5C + FeO_{1.5} = Fe + 1.5CO$	58.8	58.8
		Total	12.6y+80.4

Solving y = 1.03 moles of oxygen/mole of iron
Thus per 2000 lb of Fe

<u>Air</u> requirement is: $\dfrac{5 \times 1.03 \times 359 \times 2000}{56}$ = 66,000 scf

<u>Carbon</u> requirement is: $\dfrac{(2 \times 1.03 + 1.5) \times 12 \times 2000}{56}$ = 1,530 lb

<u>Gross Top-Gas:</u> quantity = $\dfrac{(4.12 + 3.56) \times 359 \times 2000}{56}$ = 98,400 scf

Composition = CO 46.4%
N_2 53.6%

Nominal calorific value: 158 BTU/ft^3 (taking CO at
340 BTU/ft^3)

<u>Net Top-Gas</u> (assume 60% stove efficiency of theoretical
requirement):

Underfiring heat requirement: 4,200,000 BTU/2000 lb Fe
Net gas production: 71,800 scf
Proportion of energy of <u>carbon</u> in net top-gas: 59%

The general characteristics of this type of process are clear
from these calculations:

(1) high carbon consumption per unit of iron produced. Note
that the energy not consumed in producing iron appears
in the top-gas.
(2) high air requirement per unit of iron. Note that pre-
heating is needed to achieve the temperature needs of
the tuyère zone to produce iron at 1600°C. An important
fraction of the top-gas produced is thus needed to under-
fire the hot blast stoves where capacity must be greater
per ton of iron than in the iron blast furnace case.

<u>First Variant from the Standard Case</u>

<u>Volatile Matter of Coal</u> - There are essentially two alternative
types of coal that should be considered for use in this
process. When a high volatile coal is to be the reductant, one
possibility is to charge the process with agglomerates made up of
the coal not previously reduced in volatile matter content. If it
is assumed that the fixed carbon requirement for the reduction
stays the same as for the reference case and little extra energy
is needed for the release of the volatile matter in the furnace
shaft, we can augment the top-gas with the volatile content of the
coal. For simplicity we can convert the carbon requirement into
the coal requirement of this case by assuming a fixed carbon
content of 70%. We thus obtain 1,530/0.7 = 2190 lbs of coal/ton
of iron. For each 2000 lb of coal approximately 10,000 ft^3 of gas

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of calorific value 525 BTU/ft^3 will be added to the top-gas. Thus the net top-gas becomes 71,800 + 10,950 or 82,750 ft^3/ton of iron of calculated calorific value 206 BTU/ft^3, or 54% of the energy of the coal appears in the gas.

This estimate ignores the energy required to heat the additional gas to the top-gas temperature of 327°C because in compensation it is assumed that all distillates report to the gas. Interactions between the gases produced in the tuyère zone and the coal volatile matter released in the shaft are not taken into consideration. Moreover, it is unlikely that agglomerates produced from cold mixes of high volatile coal and iron ore could be heated to any degree without the volatile matter of the coal at least partially reducing the iron oxide; this case is dealt with below.

The second general case involving the types of coal concerns the utilization of low-rank coals. It is difficult to use these coals in the standard blast furnace because of the necessity of achieving acceptably low ash contents with a coal of high volatile and inherent moisture contents (preferably the fixed carbon to ash ratio should be at least eleven)and because difficulties with high reactivity may be encountered. Also, to date, the only processes successfully able to convert these coals into a coke-like substitute have been studied only at the pilot scale. Invariably these processes call for pre-charring of the coal either in fluidized beds or shaft processes which themselves require major development. For the composite pellet route, these coals would either be pre-charred and subsequently the iron ore and the char would be agglomerated, or the raw coal and iron ore would be agglomerated and heat hardened. The first route has the advantage that binders useful for the agglomeration stage could be recovered. It is assumed here that available methods are used for processing low-rank coals with the resultant char containing 10% volatile matter. One ton of this char will be assumed to release 2500 ft^3 of gas in the furnace shaft with an energy content of 450 BTU/ft^3. On the same basis as the previous case, taking the fixed carbon content of the char at 70%, ash 20% and volatile matter 10%, 1530/0.7 or 2190 lbs of char are needed per ton of iron. Thus the net top gas becomes 71,800 + 2,740 or 74,500 ft^3/ton of iron of calculated calorific value 168 BTU/ft^3, or approximately 53% of the energy of the char appears in the gas depending upon the assumptions made concerning the char.

Cupola-Type Tuyère Zone

In this case, it will be assumed that it is possible to operate the shaft furnace in such a way that CO_2 (or H_2O were hydrogen present) could be produced in the tuyère zone. This could come about if insufficient hot exposed carbon were available on the surface of the agglomerates to reconvert completely the CO_2 produced initially in the zone back to CO following the generally accepted reaction route in shaft furnace combustion zones. For the

purposes of calculation, the product gas will be taken as 80% CO and 20% CO_2, with no subsequent reaction of the CO_2 higher in the shaft. The energy balance thus becomes:

Heat and Mass Balance - Cupola Tuyère Zone Case
- 1 mole of Fe, room temperature basis
- pure Fe_2O_3 reacts only with pure carbon
- sensible heat of iron leaving at 1600°C
- sensible heat of gases ($CO+CO_2+N_2$) leaving at 327°C
- tuyère zone gas product 80% CO, 20% CO_2
  y = moles of O_2 in air blast/mole Fe

IN	Quantity	Heat Unit kcal	Content kcal
Air:	y moles of O_2 at 1027°C	7.97	7.97y
	4y moles of N_2 at 1027°C	7.53	30.12y
Iron:	1 mole of $FeO_{1.5}$ at room temp	–	–
Carbon:	5/3y+1.5 moles C at room temp	–	–
Chemical Energy:	$C+\frac{1}{2}O_2$ = CO:		
	ΔH = -26.4x4/3y		35.20y
	$C+O_2$ = CO_2:		
	ΔH = -94.1x1/3y		31.40y
		Total	104.69y

OUT			
Iron:	1 mole at 1600°C	18.4 kcal	18.4
Top-Gas:	4y moles of N_2 at 327°C	2.1x4y	8.4y
	(4/3y+1.5) moles of CO at 327°C	2.1(4/3y+1.5)	2.8y+3.2
	1/3y moles of CO_2 at 327°C	1/3yx3.1	1.0y
Chemical Energy:	$1.5C+FeO_{1.5}$ = $Fe+1.5CO$	58.8	58.8
		Total	12.2y+80.4

Solving y = 0.869 moles of oxygen/mole of iron
Thus per 2000 lb of Fe

Air requirement is: $\dfrac{5 \times 0.869 \times 359 \times 2000}{56}$ = 55,700 scf

Carbon requirement is: $\dfrac{(5/3 \times 0.869 + 1.5) \times 12 \times 2000}{56}$ = 1,264 lb

Gross Top-Gas:	moles/mole Fe	%
N_2 = 4 x 0.869	3.48	54
CO = 4/3 x 0.869 + 1.5	2.66	41
CO_2 = 1/3 x 0.869	0.29	5
Total	6.43	100

quantity: $\dfrac{6.43 \times 359 \times 2000}{56}$ = 82,400 scf

nominal calorific value: 140 BTU/ft^3
(taking CO at 340 BTU/ft^3)

Net Top-Gas (assume 60% stove efficiency of theoretical requirement)

Underfiring heat requirement: 3,550,000 BTU/2000 lb Fe
Net gas production 57,000 scf
Proportion of energy of <u>carbon</u> in net top gas: 50.5%

This practice lowers the unit carbon requirement and thus the quantity of air that must be blown in the shaft. The tuyère adiabatic temperature is also increased and while the air blast temperature was left at 1027°C in this calculation, there may be no thermochemical reason for leaving the preheat temperature at this high level. Operating under these conditions makes small-scale trials in conventional cupolas and short shaft furnaces possible: the alternative (in the absence of adequate stove capacity for preheating) being the use of an oxygen enriched blast. On the other hand, the penalty for this practice is the production of a smaller quantity of top-gas of diminished calorific value. The proportion of the potential energy of the carbon appearing in the top-gas is reduced to 50.5%.

Experimentation is necessary to determine to what extent tuyère zone conditions can be controlled when composite pellets are charged. If it turned out that appreciable production of CO_2 was in fact possible with a standard type composite, then presumably the proportion of CO_2 produced from the tuyère zone could be varied by either admixing free carbon (perhaps in the form of coke as used by Obenchain(4)) with the charge of composites or by using fuel injectants through the tuyères. Special equipment already in existence designed to study blast-furnace raceways under high temperature conditions may be useful to assess the extent to which CO_2 and H_2O from the tuyère zone can be varied. This type of study should be undertaken as a matter of importance.

When volatile matter is present in the composite charge, its augmentation of the top-gas may be allowed for as in the previous calculations. However, in this case it seems highly probable that the CO_2 produced in the tuyère raceway would interact with the evolving hydrocarbon constituents in the shaft. This may have the perhaps useful effect of depressing the production of tars and distillates.

Pre-reduction Case

If heat is needed to prepare the agglomerates or as the

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agglomerates descend down the shaft, it seems highly probable that some degree of pre-reduction of the iron oxide would occur without the consumption of fixed carbon. In the following case it will be assumed that the agglomerate fed to the shaft consists of carbon plus "FeO".

<u>Heat and Mass Balance - Pre-reduction Case</u>
- 1 mole of Fe, room temperature basis
- pure "FeO" reacts only with pure carbon
- sensible heat of iron leaving at $1600^{\circ}C$
- sensible heat of gases ($CO+N_2$) leaving at $327^{\circ}C$
- tuyère zone gas $CO+N_2$ only
  y = moles of O_2 in air blast/mole Fe

IN	Quantity	Heat Unit kcal	Content kcal
Air:	y moles of O_2 at $1027^{\circ}C$	7.97	7.97y
	4y moles of N_2 at $1027^{\circ}C$	7.53	30.12y
Iron:	1 mole of FeO at room temp	-	-
Carbon:	2y+1.0 moles C at room temp	-	-
Chemical Energy:	$C+\frac{1}{2}O_2 = CO$:		
	$\Delta H = -26.4 \times 2y$	-	52.80y
		Total	90.89y

OUT			
Iron:	1 mole at $1600^{\circ}C$	18.4 kcal	18.4
Top-Gas:	4y moles of N_2 at $327^{\circ}C$	2.1x4y	8.4y
	(2y+1.0) moles of CO at $327^{\circ}C$	2.1(2y+1.0)	4.2y+2.1
Chemical Energy:	$C+FeO = Fe+CO$	37.4	37.4
	$\Delta H = +37.4$		
		Total	57.9+12.6y

Solving y = 0.74 moles of oxygen/mole of iron
Thus per 2000 lb of Fe
<u>Air</u> requirement is: $\dfrac{5 \times 0.74 \times 359 \times 2000}{56}$ = 47,400 scf

<u>Carbon</u> requirement is: $\dfrac{(2 \times 0.74 + 1.0) \times 12 \times 2000}{56}$ = 1060 lb

Gross Top-Gas:

	moles/mole Fe	%
N_2 = 4 x 0.74	2.96	54
CO =2 x 0.74 + 1.0	2.48	46
Total	5.44	100

quantity: $\dfrac{5.44 \times 359 \times 2000}{56}$ = 69,700 scf

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nominal calorific value: 156 BTU/ft^3
(taking CO at 340 BTU/ft^3)

<u>Net Top-Gas</u> (assume 60% stove efficiency of theoretical requirement)

Underfiring heat requirement: 3,020,000 BTU/2000 lb Fe
Net gas production: 50,300 scf
Proportion of energy of <u>carbon</u> in net top gas: 59%

As before, any volatile matter entering with the composite can be added to the heating value of the top-gas, after adjustment for the energy consumed in the pre-reduction to FeO from Fe_2O_3. There is also no reason why cupola-type tuyère behaviour could not be possible in this case as well. Higher degrees of pre-reduction may be possible. The general effect of pre-reduction practice is to lessen the role of the shaft reduction furnace.

<u>Other Combustion Conditions</u>

The development of the "coke-less" cupola suggests other conditions under which composites could be smelted. Normally natural gas and air are introduced in or beneath a "support matrix" made up of unreactive carbon rods. The combustion gases pass up through the matrix and pass through the scrap. Molten scrap descends through the matrix to the cupola well. It would appear that substantially more highly oxidizing conditions can be obtained (if desired) in this type of process than in the conventional melting shafts discussed previously. Thus composites, particularly if surrounded by a reductant layer on the exterior of the individual agglomerates(5), could be reacted with gases richer in carbon dioxide and water vapour contents. The main advantage would be a further reduction in the air blast needed per unit of iron. Further there would no longer be the same need for high-temperature air blast preheat because of the adequate flame temperature that could be obtained from the more complete combustion conditions.

In the hypothetical case that follows, the composite will be assumed to contain only the carbon requirement to reduce FeO to Fe; the reductant will be taken to be a high volatile coal of 70% fixed carbon. Complete combustion of carbon in air to carbon dioxide will be assumed in the flame zone with no free oxygen.

<u>Heat and Mass Balance - "Coke-less" Cupola Case</u>
- 1 mole of Fe, room-temperature basis
- pure "FeO" reacts only with pure carbon
- sensible heat of iron leaving at $1600^{o}C$
- sensible heat of gases leaving at $327^{o}C$
- tuyère zone gas CO_2+N_2 only, air preheat $327^{o}C$
  y = moles of O_2 in air blast/mole Fe

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IN	Quantity	Heat Unit kcal	Content kcal

Air: y moles at O_2 at 327°C   2.2   2.2y
       4y moles of N_2 at 327°C   2.1   8.4y
Iron: 1 mole of FeO at room temp   -   -
Carbon: y+1.0 moles C at room temp   -   -
Chemical Energy: $C+O_2 = CO_2 : \Delta H = -94.1$ 94.1y

                               Total   104.7y

OUT

Iron: 1 mole at 1600°C   18.4 kcal   18.4
Top-Gas: 4y moles of N_2 at 327°C   2.1x4   8.4
         1.0 mole of CO at 327°C   2.1   2.1
         y moles of CO_2 at 327°C   3.1   3.1y
Chemical Energy: $C+FeO_2 = Fe+CO$ 37.4   37.4

                                Total   11.5y+57.9

Solving y = 0.62 moles of oxygen/mole of Fe
Thus per 2000 lb of Fe
Air requirement is: $\dfrac{5 \times 0.62 \times 359 \times 2000}{56}$ = 39,700 scf

Carbon requirement is: $\dfrac{(0.62 + 1.0) \times 12 \times 2000}{56}$ = 694 lb

Gross Top-Gas: (no volatiles included)

	moles/mole Fe	%
N_2 = 4 x 0.62	2.48	61
CO = 1.0	1.00	24
CO_2 = 0.62	0.62	15
Total	4.10	100

quantity: $\dfrac{4.10 \times 359 \times 2000}{56}$ = 52,600 scf

nominal calorific value: 82 BTU/ft^3
                  (taking CO at 340 BTU/ft^3)

    Assuming that the composite was formed from a high volatile coal with a fixed carbon content of 70%, the coal requirement becomes:

$$\frac{694}{0.7} = 991 \text{ lb coal/2000 lb Fe}$$

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The distribution of the volatile matter will be arbitrarily assumed as one half available to the top-gas after pre-reduction of Fe_2O_3 to FeO, or 2480 ft^3 at 525 BTU/ft^3 using the same assumptions as previously regarding the coal volatile matter. Thus the augmented gross top-gas becomes:

    quantity: 55,100 scf
    nominal calorific value: 102 BTU/ft^3

Net Top-Gas: Because of the low temperature of air preheat assumed in this case, heat exchange can be used at 80% efficiency.

Heat exchange energy requirement: 528,000 BTU/2000 lb Fe
Net gas production: 49,990 scf
Proportion of energy of <u>coal</u> in net top-gas: 35%

This case represents what could be achieved with agglomerates containing only the carbon needed for the direct reduction reaction, and with no reaction (except heat exchange) between the combustion gases and the downward-moving agglomerates. The process equipment needs of this stage are much less as only air heat exchangers of modest temperature capability are needed and the wind volume requirements per unit of iron are reduced, assuming that coal and air can be burnt in the "support matrix" zone to produce carbon dioxide and water vapour.

The attractiveness of these figures perhaps explains the interest of several developers in pursuing work in this direction. Moreover if negligible reaction can, in fact, be achieved between the gases from the "support matrix" zone and the composite charge, it becomes possible to introduce other gases into the shaft, such as oxygen/steam mixtures, which would result in an enriched top-gas.

Outline of Ideal Process to Produce Iron and Fuel Gas

Consideration of the preceeding section, where the attractive possibilities of the "coke-less" cupola are evident, leads to development of the steps of an ideal process. It is clear that if it is desired to use the flame temperature resulting from the full oxidation of the "injected" fuel as the basis of the melting stage, the heating value of the top-gas will fall to a level that makes its application doubtful unless the volatile matter of the coal were incorporated to as great an extent as possible in the off-gases. Unfortunately, all the available experimental evidence[6] suggests that composites made containing raw coal are weak, no matter what the technique or binder used in their preparation. Consequently a process is needed that can utilize weak composites satisfactorily. The process should also provide a reasonably efficient gas-solids

counter-current heat exchange system and a mechanism for transfer of the reacted composites, after heating and reduction, to the liquid bath without undue contact with the oxidizing gases.

The use of an inclined furnace may help meet these requirements especially now as the "sliding block" type of inclined furnace is available commercially to facilitate the downwards motion of the charge. In such a device, the composites are not required to support any great height of charge merely their bed thickness on the incline. While gas-solids heat exchange will be less efficient than in the shaft configuration, the exchange to a relatively thin layer of discrete agglomerates should be sufficient. Although the heat loss in the top-gas will not be negligible, its temperature would be low enough to permit heat exchange with the incoming air in low-cost recuperators. The "sliding block" device would also allow a positive action feed to the melting zone. The coal-air flame could be directed downwards into the slag to minimize refractory damage provided oxidation loss was not excessive. Bench-scale measurements of the reduction of coal-ore composites extended to studies under oxidizing conditions suggest that carbon levels of over two per cent could be obtained(6); this level of carbon should allow the melting of the composites without any great iron loss.

The advantages of such a process can be summarized as:

(1) ability to use many types of coals and iron ores and concentrates in their available fine states without stringent impurity limits
(2) no need for extensive air preheating apparatus
(3) composites of only moderate agglomerate strength needed
(4) low-sulphur fuel gas of readily usable but low energy content produced
(5) liquid iron of usable composition produced but in common with other variants of this process low in silicon and high in sulphur contents

It would seem desirable to place some effort on the evaluation of such a process.

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