# ON SOME FUNDAMENTAL ASPECTS OF OPERATIONAL PARAMETERS OF DIRECT REDUCTION IN A ROTARY KILN

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*Abstract*

*A rotary kiln for the reduction of iron oxides in solid state is essentially a continuous gas/solid reactor operating on either counter-current, or co-current flow of solids and gases. The factors affecting isothermal condition in the reaction zone and heat transfer are indicated. Limited rate of heat release, poor heat transfer and lengthy reduction time account for low output of a kiln. With a chosen retention time depending on the length and rotation, the output can be increased by increasing the diameter. The degradation due to self grinding increases with diameter, while exhaust gas velocity is decreased lowering entrainment of solids. For reasonable reaction rate, an appropriate temperature profile has to be maintained. The reaction temperature is dependant on softening temperature of solids. The reactivity of fuel and reducibility of the ore are the rate determining factors. The degree of metallization depends on the particle size and reducibility of the ore, temperature profile and reactivity of the fuel. All these factors should be considered in designing a rotary kiln pilot plant and particularly for evolving a commercial prototype.*

## Introduction

Principally a rotary kiln for the reduction of iron oxides in solid state is a continuous gas/solid reactor consisting of a refractory lined sylinder rotating on its axis, which is slightly inclined to the horizontal. The raw materials fed into the charging end of the rotary kiln at a higher level gravitate slowly to the lower or discharge end due to the inclination and rotation of the kiln, the time of residence for preheating the charge and the chemical reactions essentially depend on the inclination speed of rotation, and granulometry of the raw materials. The feeding of the raw materials and discharge of reduced iron oxide proceed continuously. Due to the rotation of the kiln, the solid charge is carried up the side of the kiln which on attaining a certain height from the charge lying at the bottom falls back freely through an atmosphere of kiln gas. Although the time taken by the solids to return to the bed of the charge is small, reasonably good gas/solid contact occurs during the free fall of solid particles along the entire length of kiln.

Consequently, longer length of the kiln affords better gas/solid contact.

The rotary kiln operates on either counter-current or co-current system. In a counter-current reactor the charge and the fuel are fed at opposite ends and, therefore, the raw materials travel in opposite direction to the flow of the kiln gases, while in co-current kiln the charge and the fuel fed at the same end and consequently the solids and the kiln gases move in the same direction. Almost all direct reduction kilns operate on counter-current principle excepting the four 60 m long x 4 m diameter kilns of Highveld steel and Vanadium Corporation Witbank, South Africa. It has been mentioned that co-current heating is associated with heat loss but the kiln can be of shorter length or alternatively the output can be higher[1,5]. It has been mentioned that heating of the kiln at the discharge end interferes with cooling of the sponge iron.

## TABLE I - Dimensional Relation in Several Rotary Kilns for Reduction of Iron Ore

| S.No. | Process | Kiln characteristics | | | Incli-nation to he-rizontal | R.P.M. | Time of residence |
|-------|---------|-------|-------|-------|-------|-------|-------|
| | | Length, m | Diameter, m | L.D. ratio | | | |
| 1. | Krupp-Renn (Six-Kilns) | 110 | 4.6 | 20 | | | |
| 2. | Do. (Two) | 90 | 4.2 | 21.4 | | | |
| 3. | Do. | 90 | 5.2 | 17.3 | | | |
| 4. | Do. (B'ham) | 60 | 3.6 | 16.7 | 2 % | 0.85 | |
| 5. | R.N(Albama) | 46 | 2.3 | 20 | | | 50 tpd |
| 6A | Krupp-Sponge (Rheinhausen) | 13 | 1.2 | 18.3 | | | |
| 6. | Krupp-Sponge (Dunswart Iron & Steel Works) | 74 | 4.6 | 16 | | | 500 tpd |
| 7. | SL/RN(New Zealand) Steel | 75 | 3.5 | 20 | 3 % | 0.60 | |
| 8. | SL/RN (Lurgi Pilot Plant) | 12 | 0.8 | 15 | 4 % | 0-1.2 | |
| 9. | SL(Steel Co.of Canada) | 35 | 2.3 | 15 | 2 % | Wide range | 100 tpd |
| 10. | Pre-reduction (Electrokemisk Norway) | 8.75 | 0.65 | 13 | | | |
| 11. | Pre-reduction (Nisse Steel, Japan) | 25.4 | 1.3 | 18 | 2.5% | 0.6-1.5 | 10 tpd (65% $O_2$ removal) |
| 12. | Do. (U.S.Bureau of Mines -Exptl) | 11 | 0.865 | 12.7 | 3.2% | 0.75 | About 2.4 tpd |
| 13. | Sponge-iron (NML-Exptl) | 10.7 | 0.9 | 12 | | 0.5-2.0 | 3.5 tpd |
| 14. | Spojpe (Yugoslavia) a)Pilot plant | 12 | 0.75 | 16 | 2.4% | 1.0-3.0 | - |
| | b)Commercial Plant | 95 | 4.35 | | - | - | 1500 tpd (37% $O_2$ removal) |
| 15. | SL/RN (Proposed Cartwright) | 150 | 6 | 25 | - | - | 2400 tpd |

## Length—Diameter ratio of a kiln

The factors influencing the residence time of the raw materials in a kiln have been enumerated. Having decided the residence time for a chosen degree of reduction of iron oxide depending on the characteristics of the raw materials treated, an increase in the output can be achieved by increasing the diameter. The velocity of the waste gases inside the kiln largely depends on the length/diameter ratio and therefore, the diameter can be altered within certain limits. In this context, the length/diameter ratio of some kilns for metallurgical processing of iron ore may be of interest, which are given in Table 1. From the assembled data, it can be observed that the length/diameter ratio varies from 12 to 25 and in commercial kilns the ratio is higher than experimental kilns. The entrainment of fine particles of the charge in the exit gas depends on its velocity, higher is the gas velocity larger will be the amount of fine particles carried away from the kiln. For identical quantity of gas leaving the kiln, the gas velocity decreases with the increase in the diameter of the kiln, which explains the higher length/diameter ratio of the commercial kilns. For gaseous reduction of iron oxide, the reaction rate depends on the flow rate of the gas to sweep away the product gas. Therefore, the rate controlling step of reduction depends on the gas velocity and it cannot be decreased below a definite limit. The velocity of exit gas of 20 m/sec. from a commercial kiln is sufficiently high to sweep the product gas.
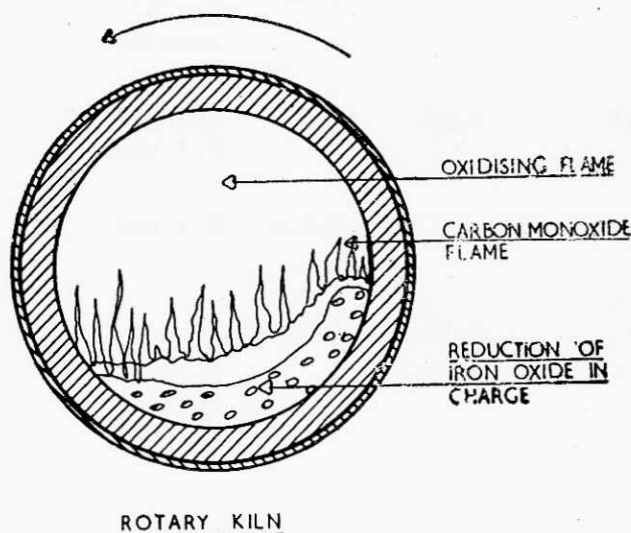
The height through which the solid charge is raised depends on the diameter of the kiln, larger diameter carries the charge to a higher height in relation to the bottom of the charge bed before the "flooding" occurs and this quantity of charge falls freely, as shown in Fig. 1. This process is occurring continuously and therefore, the generation of fines increases with the length and diameter of the kiln. Apart from the decrepitation of the iron ore lumps or pellets, and development of fissures in the particles of fuel employed due to progressive rise in temperature, the extent of mechanical degradation of the charge due to the constant tumbling action and failing freely are of considerable significance in relation to the physical and chemical characteristics of iron ore and fuel employed. As generation of fines partly contributes to the major operational problems of agglomeration and 'ring' formation in a rotary kiln, the necessity of adequate assessment of such properties of the raw materials needs no emphasis.

## Heat transfer in a rotary kiln :

In order to assure reasonable reaction rate commensurate with the time of residence of the charge in the kiln, heat has to be transferred to raise its temperature and to compensate for the endothermal reactions involved in the chemistry of the process. The thermo-chemistry of the main reactions occurring in a rotary kiln are given in Table II.

The net heat effect obviously depends on the extent of the exothermal and endothermal reactions, but the process needs supply of heat. The mechanism heat transfer in a rotary kiln is complicated and several paths need consideraion[3], such as

1. Convection between the gas and the solid,
2. Convection between the gas and the kiln wall,
3. Radiation between the gas and the solid.
4. Radiation between the gas and the kiln wall,
5. Radiation between the solid and the kiln wall, and
6. Conduction between the solid and the kiln wall.

It has been mentioned that heat transfer in rotary kilns occurs in two ways. As particles fall continuously through the gas phase, the exchange of heat in "dilute transfer regime" occurs, the "dense or emulsion regime" occurs in the solid charge lying on the refractory wall, as shown in Fig. 2. It has been opined that data on heat transfer in rotary kiln is not available.



Fig. I. Vertical Section through a sponge iron rotary kiln showing different zones.

OXIDISING FLAME

CARBON MONOXIDE FLAME

REDUCTION OF IRON OXIDE IN CHARGE

ROTARY KILN

| Sl.No: | Reactions | Heat formation $\Delta H^o_{25}$ |
|---|---|---|
| 1. | $3Fe_2O_3 + CO = 2 Fe_3O_4 + CO_2$ | – 12.64 Kcal/mole of CO |
| 2. | $Fe_3O_4 + CO = 3FeO + CO_2$ | + 8.7 Kcal/mole of CO |
| 3. | $FeO + CO = Fe + CO_2$ | – 4.14 Kcal/mole CO |
| 4. | $3Fe_2O_3 + H_2 = 2Fe_3O_4 + H_2O$ | – 2.8 Kcal/mole $H_2$ |
| 5. | $Fe_3O_4 + H_2 + 3FeO + H_2O$ | + 15.5 Kcal/mole $H_2$ |
| 6. | $FeO + H_2 + Fe + H_2O$ | + 5.7 Kcal/mole $H_2$ |
| 7. | $FeO + C = Fe + CO$ | + 37 Kcal/mole CO |
| 8. | $CaCO_3 \longrightarrow CaO + CO_2$ | + 42.4 Kcal/mole |
| 9. | $C + O_2 \longrightarrow CO_2$ | – 94 Kcal/mole |
| 10. | $C + \tfrac{1}{2} O_2 \longrightarrow CO$ | – 26.4 Kcal/mole |
| 11. | $C + CO_2 \longrightarrow 2CO$ | + 41.2 Kcal/mole of $CO_2$ |
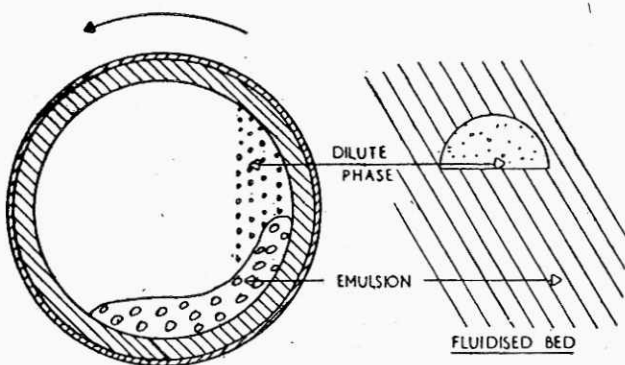


ROTARY KILN

**Fig. 2 Mechanism of heat transfer in a Rotary Kiln**

In a rotary kiln, the charge normally occupies a small area and a large area of refractory wall is exposed to the flame or hot gases (Fig. 1). Due to the rotation of the kiln, the heated refractory lining gets covered with the charge leading to substantial heat transfer by conduction, besides which occurs by radiation and convection. Even for counter-current operation, the exchange of heat between the gas and solid is not very efficient. The transfer of heat from the combustion zone to the reduction zone can be promoted by sacrificing the reducing atmosphere of the reaction zone and obviously cannot be adapted in practice. In co-current kiln, rapid heat transfer occurs. Complete combustion of CO evolved during reduction[2].

It has been mentioned that at low temperatures, the heat transfer depends on conduction, but at high temperatures radiation becomes the predominant heat transfer path[4].

The extent of the pre-heating zone chiefly depends on the exhaust gas temperature, its

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volume and the exposed area of the charge. The temperature varies from 800 to 1050°C, while the gas volume varies from 3000 to 5000 Nm³ / ton sponge iron. Higher exhaust gas temperature decreases the thermal efficiency of the kiln and the temperature has to be lowered by admission of air, before it can be treated in a gas cleaning plant.

In the semi-commercial plant of the Steel Company of Canada, the temperature of the exhaust gas increases from about 600°C at the charging end to 1100°C at a distance of about 14 m. Assuming identical temperature of the exhaust gas and the solid charge, the preheating zone was 40% of the kiln length. A higher exhaust gas temperature will reduce the extent of the preheating zone and will consequently increase the output.

The time taken to heat the charge to the reaction temperature and to compensate for the endothermal reactions in the reduction zone depend on the availability of heat. It has been mentioned that the optimum rate of heat release in rotary kilns is 6000 Btu/h/ft³ (53250 Kcal/h/m³) and the intensity of combustion inside a kiln is low[1].

For controlling the metallurgical reactions in the reduction zone, a fairly even isothermal condition at a high temperature has to be maintained, which in a rotary kiln with an axial burner is difficult. It was assured in the R-N Kiln by the provision or airports placed at regular intervals along the length of kiln, through which the admission of secondary air lengthened the combustion zone. The same objective has been attained by providing air ports, air nozzles with shell mounted blowers, shell burners with individual fuel and air supplies. The provision of shell burners with separate fuel and air supply system is complicated[8]. In a system comprising of air nozzles spaced at regular intervals, the residual volatile matter in the solid fuel fed with the charge may not be sufficient to generate heat, as a large part of it is liberated in the neighbourhood of charging end. A schematic diagram of counter-current rotary kiln and the temperature profiles of solid and gas phases are shown in Fig 3. This has been achieved by axially located coal blowers at the discharge end, throwing coal to reducing zone, where limited quantity of air is supplied and consequently the coal volatiles burn along the kiln length. In the rotary kiln at the New Zealand Steel Ltd., the
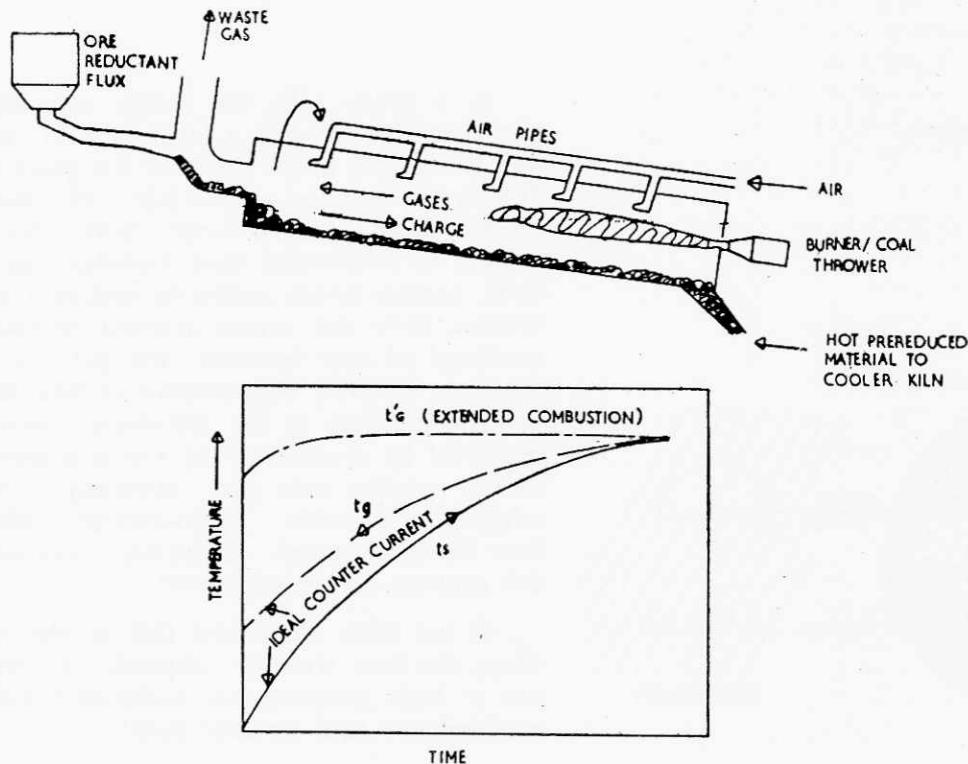


Fig. 3 Temperature profiles of solid and gas phases in a counter current rotary kiln

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desired temperature profile is maintained by controlling the secondary air through the peripherially mounted air nozzles provided with air blowers. As coal thrown by the coal thrower can reach a limited distance from the discharge end of a counter-current kiln, side feeders for feeding raw coal were provided in a 25.4 m long x 1.3 m diameter semi-industrial kiln in Japan, where nine secondary air ports were also provided to maintain the desired temperature profile[6]. Exclusive dependence on the solid fuel for meeting the heat requirements depends on the amount of volatile matter in it. The evolution of volatile matter starts at about 550°C and a portion of it escapes in a counter-current kiln. In a co-current kiln, significant amount of the coal volatiles cannot escape, which are burnt inside the kiln with the supply of secondary air through the air nozzles. The volatile matter produces flame with high luminosity which aids to transfer heat by radiation to the charge. A schematic diagram of co-current rotary kiln and the temperature profiles of solid and gas phases are shown in Fig. 4. In the 35 m long x 2.3 in dia SL/RN rotary kiln of the Steel Company of Canada, ten evenly spaced burners with 72° offset are mounted on the shell[7]. The material of construction of either air nozzles of burners need consideration to ensure long life.

The optimum temperature of operation inside the kiln mainly depends on the softening temperature of the ash of the reductant. As the output of the kiln increases steeply with increase in reaction temperature, the kiln should be operated at the maximum permissible temperature, which should preferably be about 100°C below the ash softening temperature. The softening of fusion of any constituent of the raw material and presence of fines lead to the major problems of balling up of the ingredients and "ring" formation or deposition of accretions on the kiln wall, progressive of operation. In fact if the "ring" formation can be totally eliminated, a rotary kiln will be an ideal reactor for reduction of iron oxide. The ash softening temperature of the Indian non-coking coals is not very high, thereby limiting the maximum operational kiln temperature.
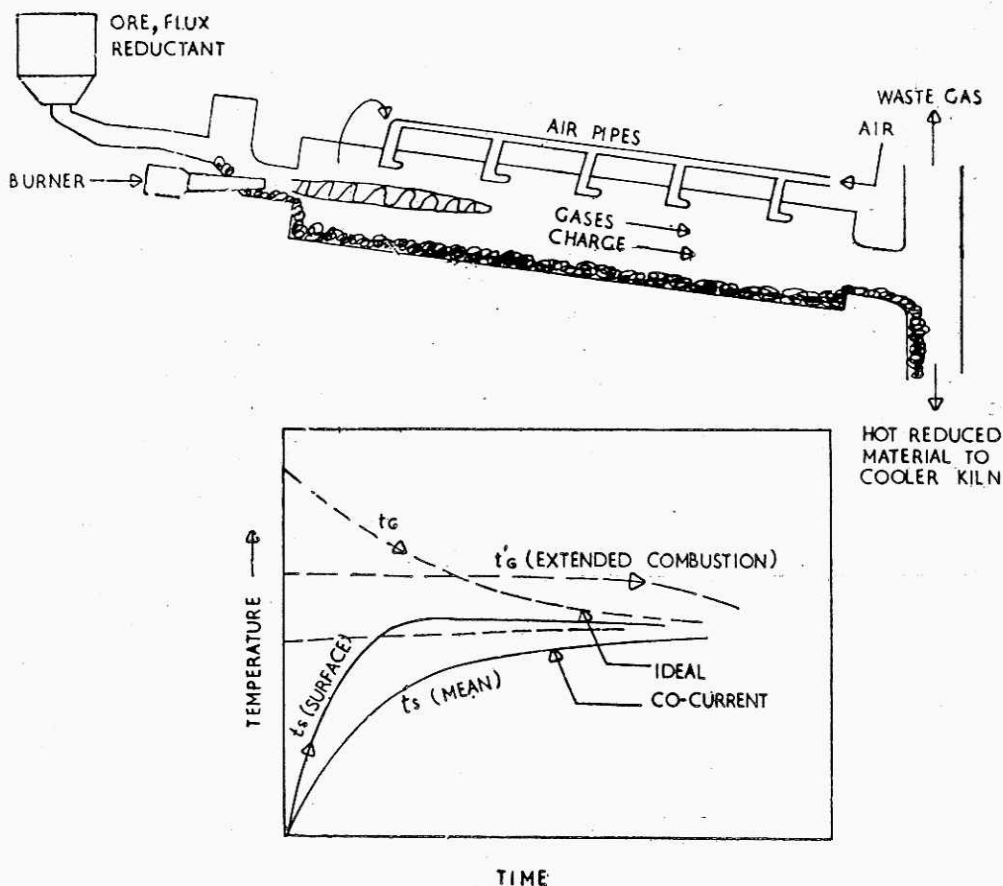


Fig. 4. Temperature profiles of solid and gas phases in a co-current rotary kiln

A large number of thermo-couples is provided for the accurate measurement of temperature along the kiln length. But deposition of accretion on the tip of the thermo-couple which projects slightly inside the kiln, precludes maping of temperature profile. The attainment of a higher temperature or 'hot shot' in a particular zone initiates 'ring' formation. The provision of suction pyrometers may be helpful. Besides, for the measurement of temperature of the kiln gas and the solids, the thermo-couples for the measurement of kiln gas temperature must project well inside so that its tip does not get covered with solid when it passes through the bottom position during the rotation.

## Direct reduction of iron ore

The rate of removal of oxygen from iron ore depends on the temperature of reaction. The effect of temperature on gaseous reduction of an iron ore at identical gas flow rate is illustrated in Fig. 5. A study of the kinetics of removal of oxygen by gaseous reductants reveals that the reaction rate progressively increases from 700°C to 1000°C and the time of 90% reduction, for a particular ore decreases from 145 min. to 70 min. In other words the kinetics of iron ore reduction by gaseous reductants like $H_2$ or CO at temperature below 800°C is exceedingly slow even when the product of the reaction is swiftly swept away from the reaction front. Consequently, the raw materials in the kiln are to be preheated to an appropriate temperature to assure a reasonable reaction rate as in the presence of large amount of carbon in the charge a significant part of reduction occurs through the agency of solid reductant. Above the mass of the charge, the conditions are somewhat oxidising for complete combustion of the fuel values and therefore, the reducing potential of the gas in the kiln due to its composition is significantly less than either $H_2$ or CO or their mixture, which lengthens the time for reduction. The static bed reduction tests conducted with various combinations of

Fig. 5 Effect of temperature on gaseous reduction of iron ore

several iron ores and non-coking coals at 1000°C disclosed that 85-98% metallisation occurred in 90 minutes.

The rate of conversion of $CO_2$ liberated in reducing reactions $2FeO + C \rightarrow 2Fe + CO_2$, or $FeO + CO \rightarrow Fe + CO_2$, to CO by the Boudouard reaction $CO_2 + C \rightarrow 2CO$ depends on the reactivity of the fuel employed. The endothermal reaction of $CO_2$ with solid carbon, known as "solution-loss reaction", is not preferred in blast furnace, but in a rotary kiln, where reduction is primarily caused by carbon and CO. The extent of the Boudouard reaction regenerating CO largely determines the rate of reduction of iron oxide to metallic iron, and its acceleration increases the kiln output. Due to the presence of volatile matter, the reactivity of raw non-coking coals cannot be determined. The reactivity towards CO of some chars produced on low temperature carbonization of non-coking coals and metallurgical coke for comparison are given in Table III. It may be seen that the reactivity of any char is higher than that of blast furnace coke. For direct reduction of iron oxide at relatively lower temperature, the reactivity of the fuel is a major criteria[10]. It has been reported that for identical degree of reduction, the residence time decreases with the increase in the reactivity of the fuel[11, 12, 13]. The appropriate properties of fuel such as high volatile matter, high ash softening temperature are of primary importance to the success of iron oxide reduction in a rotary kiln. Besides, to prevent agglomeration with the fines generated from the raw materials, the coal should not have any caking property.

Due to the release of volatile constituents, the ash content in the char increases with progressive decrease of its fuel value. Recycling of char may, therefore, lead to complications.

The gas leaving the kiln has practically no chemical heat value and from this angle the fuel efficiency in a rotary kiln is superior to the blast furnace, where due to equilibrium between the oxide of iron and oxides of carbon, the top gas contains a substantial amount of CO.

Another important criteria is the reducibility of the iron ore. The reducibility discloses the rate at which oxygen from the ore can be removed by gaseous reductants. Higher is the reducibility faster is the rate of removal of oxygen from the ore. Reducibility can be determined by several methods, but there is no unit in
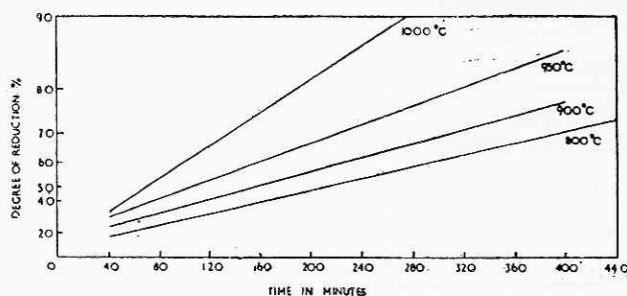
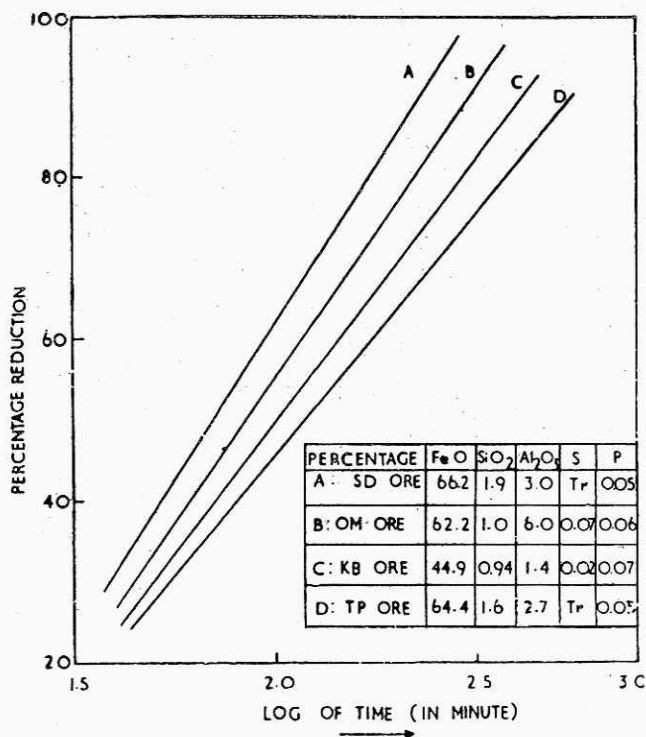| PERCENTAGE | $FeO$ | $SiO_2$ | $Al_2O_3$ | S | P |
|---|---|---|---|---|---|
| A: SD ORE | 66.2 | 1.9 | 3.0 | Tr | 0.05 |
| B: OM ORE | 62.2 | 1.0 | 6.0 | 0.07 | 0.06 |
| C: KB ORE | 44.9 | 0.94 | 1.4 | 0.02 | 0.07 |
| D: TP ORE | 64.4 | 1.6 | 2.7 | Tr | 0.05 |

**Fig. 6 Variation in the reducibility of several ores**

which reducibility can be measured, while it can be expressed relative to another ore, as shown in Fig. 6.

As the removal of last few percentages of oxygen is extraordinarily difficult and time consuming, and as complete reduction of iron oxide to metallic iron is rarely attained in any direct reduction technique, the time for 90% removal

of oxygen at any selected isothermal condition and gas flow is taken as a measure of the reducibility of the ore. The time of reduction is proportional to the diameter of the iron ore particles and therefore, small lumpy ore or pellets should be charged in a kiln. The effect of reducibility on degree of reduction has been reported and ore with better reducibility has resulted in higher degree of metallization, or lower retention time.

Based on the reactivity of fuel, reducibility of the ore and the reaction temperature, the production of sponge iron per unit kiln volume has been calculated[14]. Due to low rate of heat release, poor heat transfer and the oxygen potential of the gas in a rotary kiln causing slow rate of removal of $O_2$ from ore, the output rate is 0.30 to 0.40 tons of sponge iron/$m^3$ of the kiln volume/day[8]), which is significantly low in comparison with a modern blast furnace producing 2.8 tons of hot metal/m/day. Appropriate technique to improve the output/$m^3$/day will greatly enhance the possibilities of its adaptation.

## Quality of sponge iron

In order to clearly indicate the chemistry of sponge iron, a clarification of the various terms used is warranted. The percentage or degree of metallization is defined as:—

$$\frac{\text{Weight of the metalic iron in the final product}}{\text{Total weight of iron in the product}} \times 100$$

while the percentage removal of oxygen is :—

$$\frac{\text{Wt. of } O_2 \text{ in Ore} - \text{Wt. of } O_2 \text{ in Reduced Material}}{\text{Wt. of } O_2 \text{ in Ore}} \times 100$$

The degree of oxygen removal is always higher than the degree of metallization.

It has been mentioned that the removal of last few percentages of oxygen from the iron oxide is extremely slow and therefore costly. The percentage of metallic iron in the product is obviously the weight of metallic iron in the product divided by its weight and will be obviously less than percentage metallization, percentage of metallic iron and percentage of total iron are quite distinct and separate[17] and these should not be used synonimously.

Another factor of considerable importance is the analyses of the iron ore and the composition of sponge iron produced. The final analyses of sponge iron resulting from 90% and 95% metallization respectively of three different ores containing 55, 60 and 65% iron are given in Table IV, which clearly indicates the increase in $SiO_2$

TABLE III — Reactivity towards $CO_2$ of some chars produced on low temperature carbonization of non-coking coals and metallurgical coke.

FUELS

| | | |
|---|---|---|
| 1. | Nut coke (Bhilai) | 55.30 |
| 2. | Lodhna coke | 63.23 |
| 3. | Nut coke (Durgapur) | 67.70 |
| 4. | Nut coke (TISCO) | 69.03 |
| 5. | Ballarpur L.T.C | 71.70 |
| 6. | Chanda coal L.T.C. | 80.86 |
| 7. | Raniganj coal L.T.C. | 85.10 |
| 8. | Mazri coal L.T.C. (made at C.F.R.I.) | 89.50 |
| 9. | Singareni coal — L.T.C. | 92.10 |
| 10. | Ghugush L.T.C. (made at C.F.R.I.) | 98.70 |

and $Al_2O_3$ due to removal of oxygen from the ore. An interesting feature is increase in FeO in the sponge iron with the improvement in the grade of the ore.

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TABLE IV — Influence of the analysis of ore and degree of metallization on the composition of sponge iron.

| Analysis of the ores | Analysis of the sponge iron at | |
|---|---|---|
| | 90% Metallization | 95% metallization |
| Fe — 55% | 63.6 | 67.9 |
| $Fe_2O_3$ — 78.6% | | |
| FeO — Nil | 9.1 | 4.37 |
| $Al_2O_3$ — 9.05% | 11.5 | 11.7 |
| $SiO_2$ — 12.35% | 15.8 | 16.05 |
| S & P — 0.05% | 0.064 | 0.065 |
| Fe — 60% | 71.0 | 75.8 |
| $Fe_2O_3$ — 85.6% | | |
| FeO — Nil | 10.1 | 5.18 |
| $Al_2O_3$ — 6.50% | 8.54 | 8.63 |
| $SiO_2$ — 7.75% | 10.20 | 10.30 |
| S & P — 0.05% | 0.066 | 0.067 |
| Fe — 65% | 79.2 | 84.70 |
| $Fe_2O_3$ — 93% | | |
| FeO — Nil | 11.34 | 5.73 |
| $Al_2O_3$ — 3.00% | 4.06 | 4.11 |
| $SiO_2$ — 3.95% | 5.34 | 5.41 |
| S & P — 0.05% | 0.068 | 0.069 |

## Acknowledgement

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## Discussion

Dr. S. Jha Ajit (Regional Institute of Technology, Jamshedpur): (1) In the paper, the author has mentioned that the rate of production is slower because of the atmosphere present in the furnace. Was any gas analysis carried out to find out the oxygen potential of the gas phase? In my view this may be due to the low kinetics of reaction in the initial period when the temperature of the charge is low. (2) In view of the above, will it not be advantageous to utilise the sensible heat of the waste gas for pre-heating of the charge?

Dr. A. B. Chatterjea (Author): The oxygen potential of the gaseous phase in a rotary kiln above the bed of the charge cannot be identical with the conditions prevailing in the stack of the blast furnace or inside the reactor or furnace for direct reduction of iron oxide with a mixture of hydrogen and carbon monoxide. For optimising the combustion of either coal volatile or carbon monoxide generated in the reducing reaction, the conditions are somewhat oxidising and therefore, the oxygen potential is higher than the other processes. The analysis of the exhaust gas confirms that there is hardly any carbon monoxide or hydrogen in it. The composition of the gas above bed of the charge lengthens the time for reduction, as has been fully discussed in the paper.

The sensible heat of the exhaust gas can be utilised for pre-heating the charge as in Krupp Sponge Iron Process, provided its dust contents be not objectionable.

Mr. M. C. Abraham (Indian Institute of Technology, Kanpur): The author has mentioned that the gasification reaction (which produces CO for production of the oxide) controls the overall rate of reduction in the rotary kilns. In the recent times many efforts are being made to improve the gasification reaction by adding suitable catalysts. The work done by Walker[*] and that by Y. K. Rao[**] reveals that the activation energy for gasification reaction can be brought down from 85 K cal/mole to as low as 15 K Cal/mole. What are your comments on using such catalysers in the Rotary Kiln.?

* P. L. Walker, Jr., M. Shelef, and R. A. Anderson, 'Catalysis of Carbon gasification', Chemistry and Physics of Carbon (P. L. Walker Ed.), Marcel Dekker. Inc., New York 4 (1968) 287

** Y. K. Rao and B. P. Jalan, 'The use of catalysts to enhance the Rate of Boudouard's Reaction in Direct Reduction Metallurgical Processes', Blast Furnace Technology Science and Practice (Julian Szekely Ed.) Marcel Dekker, Inc., New York (1972).

Dr. A. B. Chatterjea (Author): The treatment of the fuel with sodium salts will make it unsuitable for use in rotary kiln as the refractory lining will be adversely affected. The overall reaction rate depends on the reducibility of iron ore and the reactivity of fuel. It is known that many chemical reactions can be accelerated in the presence of catalyst. For this objective catalyst has to be intimately mixed with the reactant. In a rotary kiln lumpy raw non-coking coal is used in large quantity and treatment with a catalyst may not be practicable. Besides, we have studied the effect of catalysts on reactivity by impregnation of solid fuels with sodium and barium salts but the reactivity was not significantly altered.

Mr. S. C. Koria (University of Roorkee, Roorkee): Dr. Chatterjea has stated that the reduction kinetics by $H_2$ or CO at temperature below 800°C is exceedingly slow even when the product of the reaction is swept away from the reaction site. This statement seems to be confusing because reference of the Fe-C-O and Fe-H-O equ. systems indicate that $H_2$ is particularly more effective reductant at temperatures below 800°C while CO is above 800 C.

Dr. A. B. Chatterjea (Author): I am afraid, I have not been able to get the question quite correctly. It seems that you are trying to say that the reduction of iron oxide with hydrogen is faster at low temperature and that with carbon monoxide is slower at lower temperature. I do not agree with your views. Considering a simplified view of the thermochemistry of the involved chemical reactions, it is known that reduction of iron oxide with hydrogen, is endothermal reaction. This reaction will be promoted at higher temperatures. Reaction with carbon monoxide is exothermal and will be favoured at low temperature. Mr. Koria referred to the iron-carbon — oxygen and iron-hydrogen-oxygen equilibrium diagram. The curves of Fe-O-$H_2$ and Fe-O-CO intersect at about 810°C, which signifies that above this temperature hydrogen is better reducing agent than carbon dioxide, but at lower temperature the conversion is true. However. the reaction kinetics is extremely complicated and various theories are proposed to ex-

plain the mechanism of reduction. The observation of the speed of reduction of iron oxide by $H_2$ at 800°C was based on experiments at different temperatures.

Mr. R. S. Rohidekar (Sandur Manganese and Iron Ores Ltd., Hospet): Dr. Chatterjea mentioned that because of the short length of the kiln at NML degree of mtallization obtained is limited to 92%. But the retention time and hence metallization can be increased by reducing inclination or speed of the kiln. Was this done? Secondly, there are various reasons like reducibility of iron ore, reactivity of coal, retention time which affect degree of metallization. So how much weightage do you give to each of these arguments?

Dr. A. B. Chatterjea (Author): As has been indicated in the paper, the retention time obviously depends on inclination as well as on the rotation. These are the two factors which control the retention time apart from the length. But if one has to optimise the production and to accept a certain degree of reduction, it would be a fair decision to sacrifice a little in the degree of metallization. It was certainly possible to increase the degree of metallisation either by reducing the rpm or by reducing the inclination, associated with decrease in daily output.

The second question refers to the individual effects of some operational parameters on the degree of metallisation. Amongst these, the reduciblity of the ore and reactivity of the fuel are dependant on the characteristics of the materials. Improvement of either of these two properties will accelerate removal of oxygen from the ore and therefore lower the retention time. However, it is impracticable to allocate their contribution on the totality of oxygen removal to attain a desired degree of metallisation. I definitely mentioned that if we increase the retention time by reducing rpm or by changing the inclination of the rotary kiln the degree of metallisation can be increased. But then production will decrease and the amount of sponge iron will be lower. The removal of last few percentage of oxygen from the ore is notoriously difficult. If you intend to have 95-98% degree of metallisation, it can be obtained, provided increase the retention time; if I may say, disproportionately affecting the output of a rotary kiln.

Dr. S. K. Gupta (Indian Institute of Technology, Bombay): The author has mentioned that since the rotary kiln's length was small it could not be possible to increase the degree of metallization of the sponge above 92 per cent. However, it is felt that the statement is little simplified since by controlling the retention time and temperature and atmospheric conditions inside the rotary kiln it may be possible to produce sponge with higher degree of metallization, though it may adversely affect the productivity of the unit and cost of production. Incidentally, Dr. Meyer's suggestion for production of sponge with 95 per cent metallization instead of 92 per cent, since the rest of the oxygen has to be removed in expense of electric power, connot be completely justifiable since the sponge is deposited with highly active carbon which will readily take care of this marginal amount of oxygen during melting.

Dr. A. B. Chatterjea (Author): The various process parameters controlling the degree of metallization has been explained very exhaustively and it was not mentioned that the length of the Kiln was the only criteria. But even after optimising the conditions in a particular rotary kiln by controlling the oxygen potential of the gas etc., the major consideration lies with the length of rotary kiln and consequently the retention time of charge. Let me discuss it hypothetically taking the NML experimental rotary kiln as an example. Now if its length is rduced from 10 m to 5 m what would happen? Could one get the same 92% degree of metallisation? The obvious answer is no. That is what I have mentioned that depending on the characteristics of the iron ore and fuel which are employed, the retention time has to be fixed bearing in mind the kiln output. The retention time depends on the revolution and length and after the retention time has been fixed, the only way to increase the production is by means of increasing the diameter.

I have also to add one or two words. Everybody knows that to remove last few percentage of oxygen from iron ore is notoriously difficult. If it takes a certain time to remove 2% oxygen from 90-92% it does not mean that it would take the same time to remove another 2 percentage oxygen from 92-94%. One has to seriously consider the economic throughput from a particular kiln in relation to the degree of metallization. Allowing sufficient time of retention, the degree of metallization can certainly be improved, but it will adversely affect the kiln throughput and here the length of kiln decides the issue.

In the later part of the question, Dr. Gupta advocates 92% metallisation instead of 95 per cent as he considers that presence of active car-

bon in the sponge will react with residual oxygen in it. If Dr. Gupta is of this view, the necessity of higher degree of metallization is not warranted.

Dr. A. K. Chakraborty (Alloy Steel Plant Durgapur): I wonder if any of the speakers this morning could enlighten me on what effect the porosity has on the degree of metallisation using pellets. Perhaps Dr. Chatterjea can enlighten me in this matter.

Dr. A. B. Chatterjea (Author): The porosity is intimately connected with the reducibility. So if the porosity is increased, the reducibility is increased and consequently the time required for a certain degree of reduction becomes less.

## Contribution

Prof. V. A. Altekar (National Metallurgical Laboratory, Jamshedpur): The degree of metallisation is comparatively low when green pellets are used instead of indurated pellets. The metallisation can be enhanced when the charge is preheated by the hot exit gases of the kiln by the use of a grate type or shaft type pre-heater preceding the rotary kiln. A preheating device is under contemplation at NML.