

A STUDY OF RING FORMATION OF SPONGE IRON IN THE ROTARY KILN

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Abstract

Ring formation and heavy build-up in an experimental rotary kiln for production of sponge iron using hematite pellets, bituminous coal and nut coke have been described. The build-up from different parts of the kiln was visually examined and its mineral composition was studied in detail by microscopical and X-ray methods. Besides some metallic iron, the minerals identified were magnetite, fayalite, wustite, iron cordierite, hercynite, anorthite and traces of haematite in different combinations. Relevant binary, ternary and quaternary phase diagrams concerning the observed mineral assemblages were examined in detail. The occurrence of the observed minerals was explained in the light of known phase diagrams. The actual chemical analysis of a sample from the zone of heavy build-up was composed of mainly of FeO , Fe_2O_3 , Al_2O_3 and SiO_2 (besides some metallic iron) and this composition was located in relevant phase diagram. The minimum temperature at which liquid would form was indicated from a study of these diagrams. The factors responsible for the build-up were examined.

Introduction

In recent years the production of sponge iron by direct reduction of iron ores has received considerable attention by metallurgists. Experiments for the production of sponge iron in a 34 feet long rotary kiln were successfully conducted at the National Metallurgical Laboratory using pellets made from Donimalai haematite ore and bituminous coal from Maharashtra also nut coke. The iron ore was of high grade with 65-66% Fe, 1.6-2.05% SiO_2 and 3.0-3.8 per cent Al_2O_3 . The bituminous coal had 9.7 per cent moisture, 34.4% volatile matter, 42.8 per cent fixed carbon, with caking index of (BS) of 2 and an ash content of 13.1%. The nut coke contained 3 per cent moisture, 1.8 per cent volatiles, with a fixed carbon of 75.1 per cent and ash content of 20.1 per cent. The coke ash contained SiO_2 57.8 per cent, Al_2O_3 35.0 per cent, CaO 3.7 per cent, MgO 2.8 per cent and Fe 0.59 per cent. At the end of one of the

campaigns lasting for four days a heavy build-up of ring formation was observed inside the kiln. In the present study, a detailed examination has been made on the constitution of the build up at different zones of the kiln and the phase equilibria involved are discussed in relation to the observed constitution.

Description of the kiln build-up

The build up on the rotary kiln lining was observed from the burner and upto a distance of 25 feet. It was not thick towards the burner end. Proceeding towards the charging end, it became progressively thicker and thicker attaining a maximum at about 14 feet and then tapering off.

The build up was in the form of irregular waves and ridges forming rings, and growing inwards to central axis of the kiln. Two rings at about 9 feet and 14 feet from the hot end were significant. These are shown as A and B respec-



Fig. 1 The Kiln build up as seen from the discharge end. At 'A' the internal diameter is 11 inches and at 'B' it is only 7 inches.

tively in Fig. 1. Fig. 2. shows the appearance of the kiln build up from the charging end. The approximate internal diameters of the kiln after the build up at different distances from the hot zone are given in Table 1.

TABLE I

Internal diameter of the kiln after ring formation

Distance from hot end				Approx. Int. kiln diameter			
4	feet	8	inches	1	foot	8	inches
5	„	6	„	1	„	4	„
6½	„	to	7½	1	„	2	„
7½	„	to	8½	1	„	0	„
8½	„	to	9½	0	„	11	„
13½	„	to	10½	0	„	7	„
25	„	to	34	2	feet	2	inches

The kiln build up was removed carefully so as not to damage the lining, and the typical appearance of build-up chunks from different distances is shown in Fig. 3.

Visual study of the build-up

A visual examination of these built up chunks removed from the kiln revealed the following:

From the burner end to a distance of 25 feet, the build-up portion exposed to the flame formed a black to grey vitrified or sintered skin embedding some pellets and mottled with coal or coke ash and cinder. The surface was somewhat reddish towards the burner end either possibly due to reoxidation or due to the unreached hematite. Below the skin, upto a distance of about

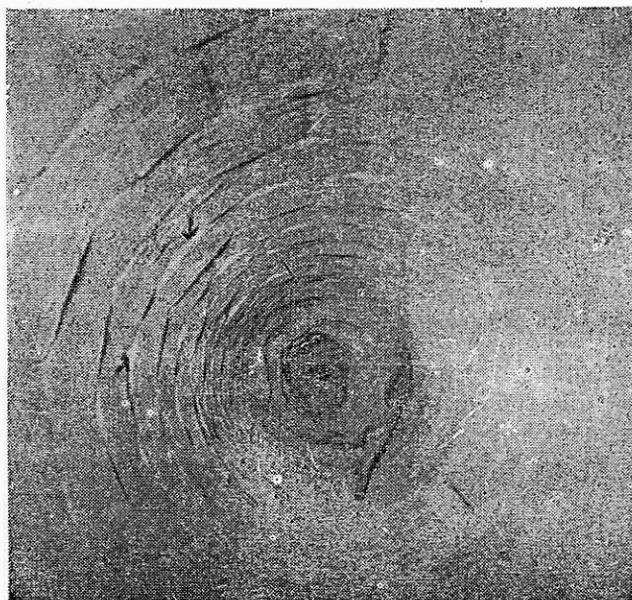


Fig. 2 The kiln build up as seen from the charging end. (note uneven brick laying)

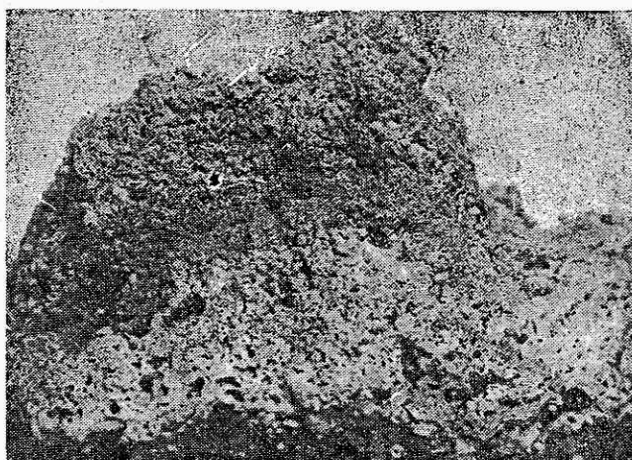


Fig. 3 A View of build-up chunks taken from the Kiln.

8 feet, grey to black pellets of coarser size were seen embedded in matrix of grey fused mass. Some of the pellets appeared recrystallised and glistening. At 8 to 9 feet from the burner end of the portion below the skin was generally finer in size with assorted globules of pellets, forming a conglomerate. This was possibly due to dust and finer ash being caught up early travel upto 9' from the burner end beyond which the clean coarser pellets were discharged. Some pitch like patches were also observed, but these were not pitch or organic matter as revealed by later examination. Some caked coal or pitch and unburnt and partly burnt coke together with ash and cinder were seen in the zone 25 to 28 feet.

Methods of study

Microscopic examination and identification of the phases.

Microscopic examination of the constituent portions of the built up rings and the discharged pellets was conducted in powder mounts, using oils of different refractive indices as immersion media for examination under a petrographic microscope. Since most of the material was opaque, petrographic examination gave useful information for the identification of transparent phases but was useless for the study of opaque materials. Study of the specimens in reflected light was not only helpful in the identification of the crystalline phases, but the textural relationships also were clearly brought out. While the colour and other optical properties of transparent phases cannot be studied under incident petrographically, these properties of the transparent phases cannot be studied under incident light. However, the reflectivity of the transparent phases is directly proportional to their refractive indices the minerals having higher refractive indices appearing brighter than those having lower refractive indices. Therefore, from a combination of transmitted and reflected studies and with a previous knowledge of possible phases that would form as a result of consideration of phase equilibria, it was possible to identify all the phases present in polished sections. However, some X-ray powder diffraction patterns of some specimens, were also taken using 5.73 cm camera and Co K radiation for confirmation of the optical findings. The photomicrographs were taken on a Zeiss Neophot Microscope at a magnification of 500, with a Lieca Camera.

For studies in reflected light the specimens were mounted in "Leucite" and ground and polished using emery powders initially on a rotat-

ing lap, and then on successively finer emery papers. The final polishing was done on "Selvyt Cloth" on a lap rotating at 900 RPM using chromic oxide as polishing agent. Some of the porous specimens which were friable were impregnated and mounted in "Araldite", an epoxy resin made by M/s Ciba Ltd.

The known properties of the crystalline oxide and silicate phases identified in this study are given below:

- (1) Wustite, (FeO): M. P. 1370°C . R. I. 2.32 Colour black, nearly opaque; forms complete solid solutions with periclase (MgO): cubic
- (2) Magnetite ($\text{FeO}\cdot\text{Fe}_2\text{O}_3$): Black, Cubic Octohedra. R. I. 2.42 M. P. 1590°C .
- (3) Hematite (Fe_2O_3): M.P. 1595°C . Colour red hexagonal, R.I. 2.95-3.0.
- (4) Fayalite ($\text{FeO}\cdot\text{SiO}_2$): M.P. 1205°C . pale yellow to greenish yellow; orthorhombic; strong birefringence; R.I. 1.835-1.886.
- (5) Iron Cordierite ($\text{FeO}\cdot 2\text{Al}_2\text{O}_3\cdot 5\text{SiO}_2$): Metals in congruently to mullite and liquid at 1560°C ; orthorhombic, feak birefringence; R.I 1.539-1.55.
- (6) Hercynite ($\text{Fe}\cdot\text{Al}_2\text{O}_3$): M.P. 1750°C , Cubic; colour black, green. lilac or colourless; R.I. 1.83.
- (7) Anorthite ($\text{CaO}\cdot\text{Al}_2\text{O}_3\cdot 2\text{SiO}_2$): M. P. 1553°C , colourless, triclinic; R. I 1.576-1.589. Twinning common in the natural species, but not usually seen in artificial ones.

Results and discussion

At $3\frac{1}{2}$ feet away from the hot end, a 3 mm slag layer sticking to the brick, showed mostly magnetite with iron cordierite, fayalite and a small amount of glass (Fig. 4-7). At the periphery, magnetite showed slight oxidation to hematite (not seen in micrographs). At $0.4\frac{1}{2}$ feet from the hot zone, a globular pellet $\frac{1}{2}$ " below the skin was composed of magnetite oxidising to hematite, with fayalite and iron cordierite in the matrix and traces of anorthite. (Fig. 8). In the zone $4\frac{1}{2}$ to 14 feet, the top fused layer showed magnetite oxidising to hematite as the main phase with occasional streaks and droplets of metallic iron. The binding matrix was composed of fayalite and iron cordierite with minor amounts of anorthite and glass. The globular assorted pellets below the fused layer were mostly composed of magnetite with fayalite, iron cordierite with traces of anorthite. The mineral composition in the zone 14 to 25 feet was also similar to that of $4\frac{1}{2}$ to 14 feet zone. In the zone 14 to 19 feet, a pitch like

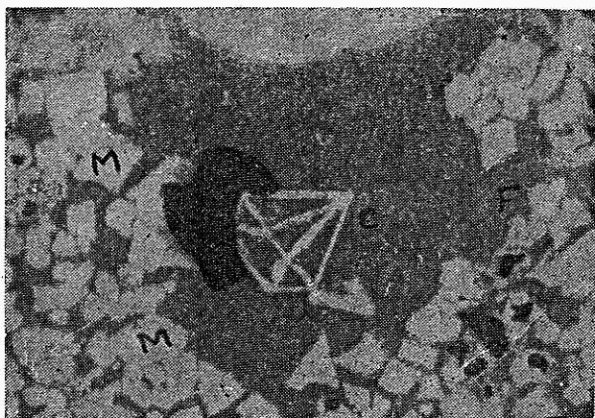


Fig. 4 Slag layer near brick. Shows hemihedral skeletal development of an octohedral magnetite in a pool of matrix consisting of fayalite and iron cordierite. M = Magnetite. F = Fayalite. C = Iron cordierite, and black areas = pores.

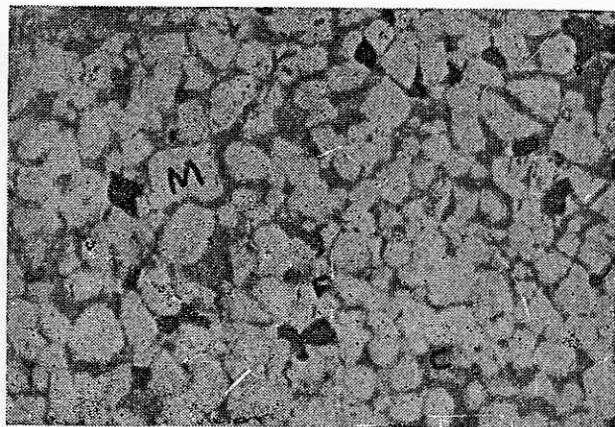


Fig. 7 Slag layer near brick, showing Magnetite (M) with a matrix of fayalite (F) and iron cordierite (C) Notation as in Fig. 4.

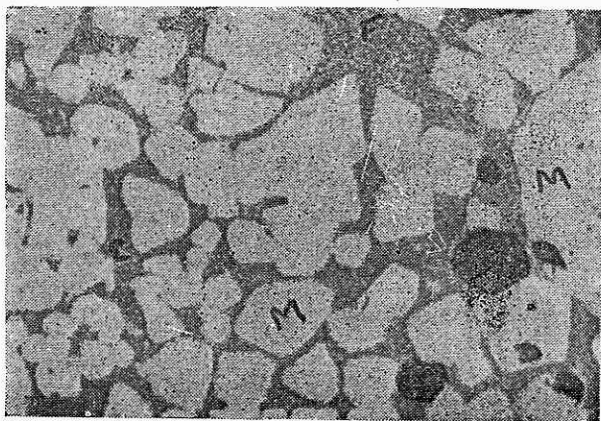


Fig. 5 Slag layer near brick showing magnetite, fayalite and iron cordierite. Notation as in No. 4.

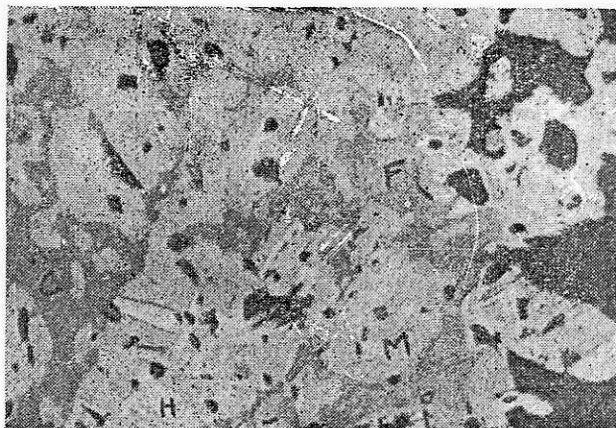


Fig. 8 A pellet $\frac{1}{2}'$ below the skin at 0-4 $\frac{1}{2}$ feet M = Magnetite H = Hematite F = Fayalite. Dark areas are pores

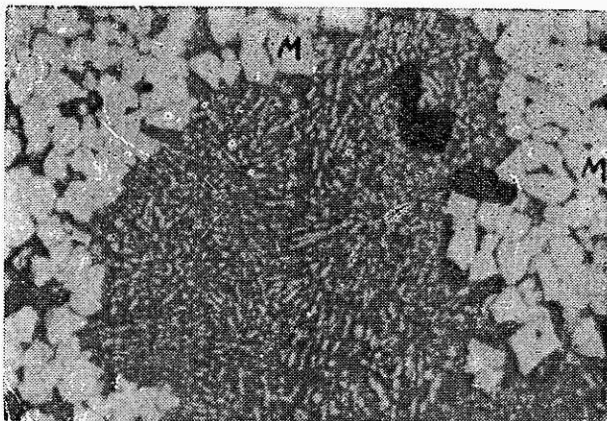


Fig. 6 Slag layer near brick showing magnetite (M) and inter-growth of iron cordierite and magnetite crystallising from liquid (Central area)



Fig. 9 Top fused layer in the zone 12 $\frac{1}{2}$ to 14 $\frac{1}{2}$ feet. F = fayalite H = hercynite; W = wustite. Dark areas are pores

Figs. 10-14 show sections of glistening pellet caught up in the build-up showing different stages of reduction.

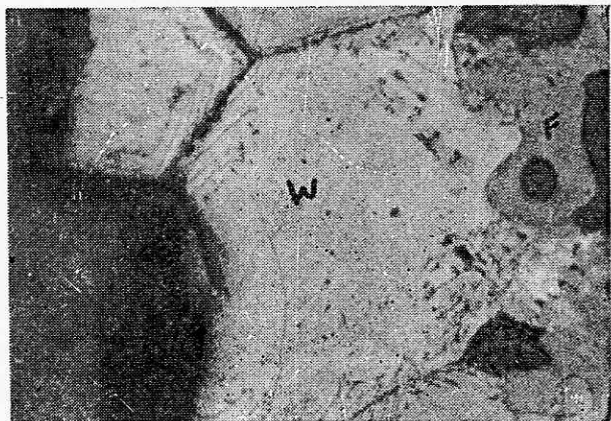


Fig. 10 Showing skin of the glistening pellet
W = wustite oxidising to magnetite! F = fayalite
I = Iron, black areas are pores.



Fig. 11 Showing iron (I) Wustite (W) oxidising to magnetite and fayalite (F)



Fig 12 I = iron; W = wustite; F = fayalite
C = iron cordierite

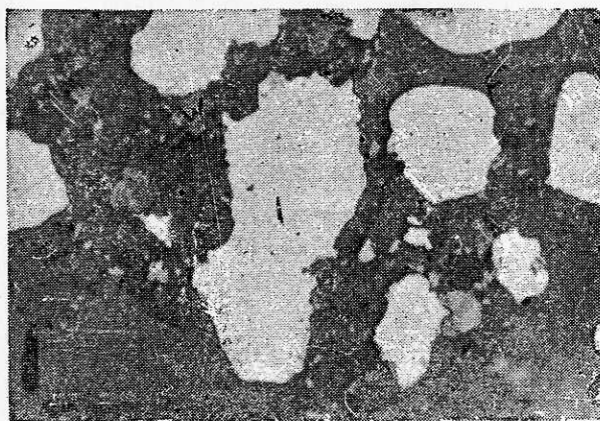


Fig. 13 Notation as in Fig. 12

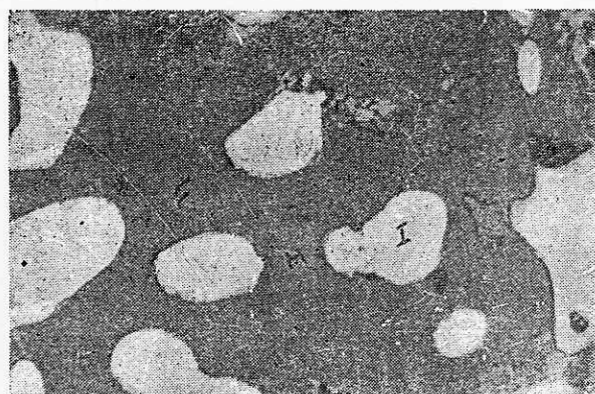


Fig. 14 I = iron F = fayalite H = hercynite in glass W = wustite.

Figs. 15-18 are sections of pellets discharged from hot end of the kiln, showing progressive reduction

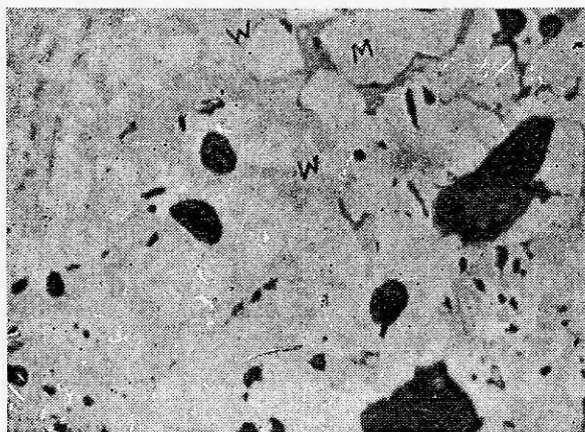


Fig. 15 M = magnetite, F = fayalite; W = wustite

iron-magnetite portion below the glistening pellets caught up in the conglomerate was composed mostly of fayalite and wustite with traces of metallic iron. The fused layer at a distance of 12½-14½ feet which visually showed some metallic iron on rough grinding was composed of fayalite, hercynite and wustite (Fig. 9). This assemblage indicated considerable reducing conditions in this zone.

Figs. 10-14 show the micrographs typical of glistening pellets caught up in the conglomerate of the build up. The periphery of the pellet was mostly wustite oxidising to magnetite. (Fig. 1). The oxidation of wustite to magnetite is beautifully illustrated in the Fig. 11. Figs 12 and 13 show a further stage of reduction where only metallic iron, fayalite, wustite and hercynite in glass were seen.

Fig. 15 to 19 show sections of pellets discharged from the kiln; they depict progressive stages of reduction. Fig. 15 shows magnetite, fayalite and the pellet is least reduced. In Fig. 16 magnetite is absent. Prominent globular wustite and interstitial fayalite with droplets of metallic iron could be seen. This represents a further advances in reduction. Fig. 17 also shows same phases but the metallic iron content is more, with decreased amount of wustite Fig. 18 shows further reduction with more metallic iron, in a matrix of fayalite with some wustite.

Fig. 19 is micrograph of a discharged pellet which was further reduced by hydrogen in the laboratory. Besides metallic iron which is present in larger amounts some fayalite and possible some hercynite still persist.

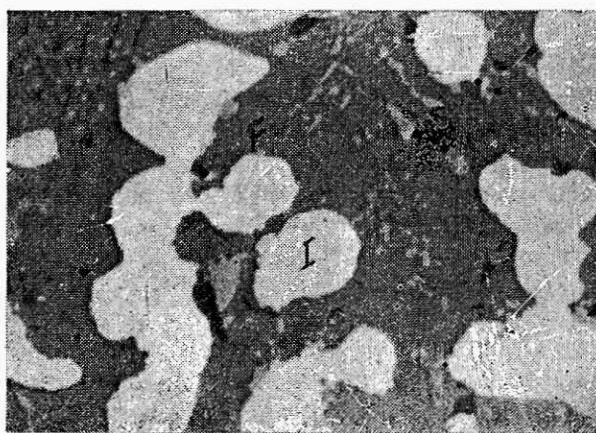


Fig 17 I = iron; F = fayalite; W = wustite

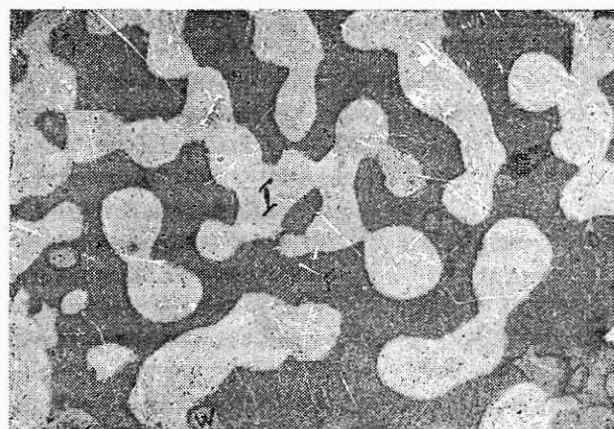


Fig. 18 I = iron, F = fayalite; W = wustite.



Fig. 16 W = wustite; F = fayalite; I = iron

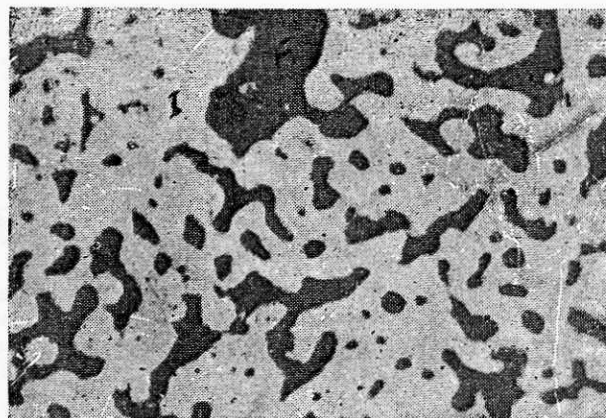


Fig. 19 Pellets further reduced by hydrogen
I = iron (with same wustite); F = fayalite

Phase equilibrium consideration of the observed situation.

The phase equilibria involved in the reduction of hematite to sponge iron by using coal and/or coke are rather complicated. In view of large number of components involved and presence of oxygen as a gas phase in the Gibb's equation, $P + F = C + 2$. However, from the present knowledge of phase diagrams it is possible to explain the occurrence of different mineral phases observed and the fusion phenomenon obtained during operation of the kiln. The system is a complex one involving metallic iron, iron oxides in different states of oxidation (FeO , Fe_3O_4 and Fe_2O_3) alumina, silica and small amounts of lime and very small amounts of magnesia. Ignoring traces of alkalis and magnesia, which forms complete solid solution with wustite, the system may be considered as: $\text{FeO}-\text{Al}_2\text{O}_3-\text{CO}-\text{SO}_2$.

Since the pellets are in contact with the ash from coal or coke during their travel in the kiln, contamination of pellets or their admixture with the ash cannot be ignored especially with regard to kiln build up. Assuming a complete admixture of the ore pellets with ash derived from coal, (when charge ratio is 1:1 pellets to coal) the overall chemical composition works out to: 83.52 per cent FeO , 8.41 per cent SiO_2 , 7.35 per cent Al_2O_3 , 0.42 per cent CaO and 0.30 MgO , when all the iron is present as FeO . If it is present in ferric state the relative proportions of other constituents will decrease and if it is reduced to Fe , the relative proportions of other oxides would increase.

The core of the pellets may be considered as having the least or no contamination, and, therefore, having the original composition, while the outer portions and the skin of the pellets could be admixed with ash to varying degrees. The initial ring formation may be visualised as due to the sticking of this contaminated admixture of ash and fines from the pellets. The surface of the ring which is subject to constant "ash attack" would be enriched in silica, alumina, lime and magnesia lowering the refractoriness at operating temperatures.

With the considerations above an examination is of the relevant phase diagrams applicable to this study in relation to the constitution and liquid formation.

Fig. 20 shows the system Fe and O depicting the equilibrium relationships between the metallic iron and its oxides as a function of partial

Fe-O

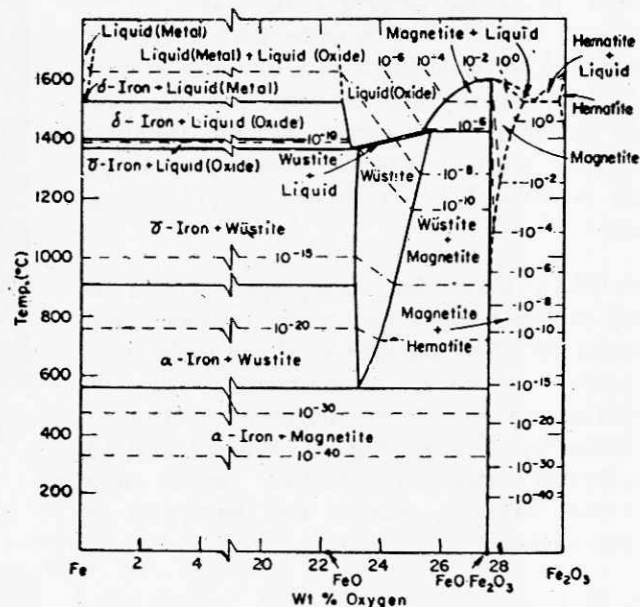


Fig. 20 The System Fe-O Arnulf Muan. Bull. Amer. Ceram. Soc. 37(2) 81 (1958)

The dash not lines are oxygen isobars (Data mainly based on Darken & Gurry) J. Am Chem. Soc. 67, 1378-1412 (1945); 68, 798-816, (1946).

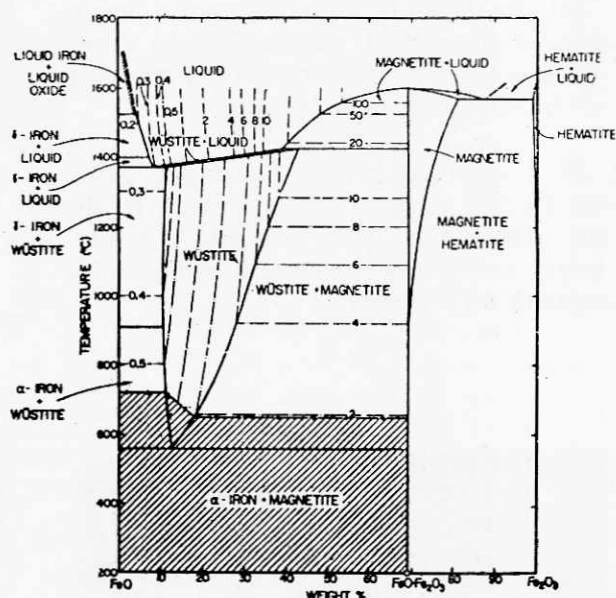


Fig. 21 Phase relations among metallic iron and oxides as function of temperature and CO_2/CO ratios of atmosphere at a total pressure of one atmosphere. Dash not curves are CO_2/CO ratios of gas phase; dash-cross line is the carbon deposition curve. The cross hatched area represents metal stable conditions which cannot be experimentally realised if equilibrium prevails.

Arnulf Muan and E.F Osborn : Phase equilibria among oxides in steel making. p. 52. Addison Wesley Publishing Co. Mass (1964)

pressure of oxygen. The system Fe-O-C (Fig. 21) shows the existence of iron and its oxides with reference to CO_2/CO ratio of the atmosphere. In the system Fe-O, iron and magnetite, iron and wustite, iron and wustite, wustite and magnetite and magnetite and hematite could exist in equilibrium at different temperatures below the solidus and at different partial pressures of oxygen. The same phase assemblages are also obtained when the system is considered as Fe-O-C where the partial pressure of oxy-

gen is expressed in terms of CO_2/CO ratio. The reported occurrences of wustite at room temperatures could only be considered as metastable as evident from the above two systems.

The system FeO-Fe₂O₃-SiO₂ shows (Fig. 22 and 23) two binary compounds, magnetite and fayalite, but no ternary compound. The following phase assemblages co-exist as solids at the solidus within the composition triangle magnetite-FeO-SiO₂. (Fig. 24).

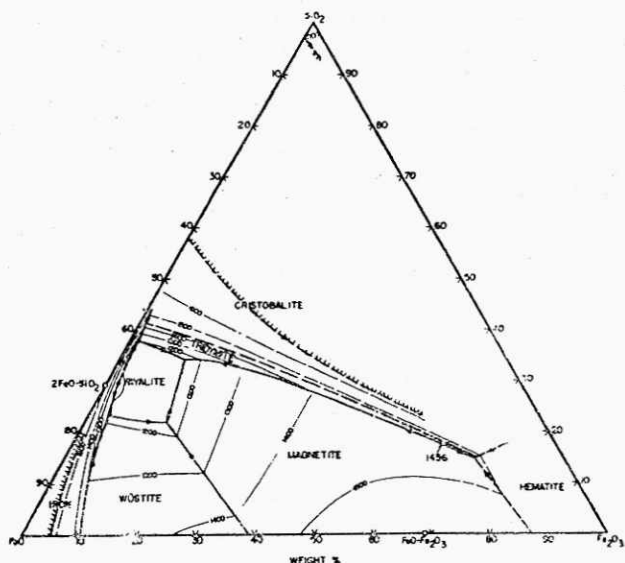


Fig. 22 The system FeO-Fe₂O₃-SiO₂ Arnulf Muan. Trans. A.I.M.E., 203, 965-66, 1955

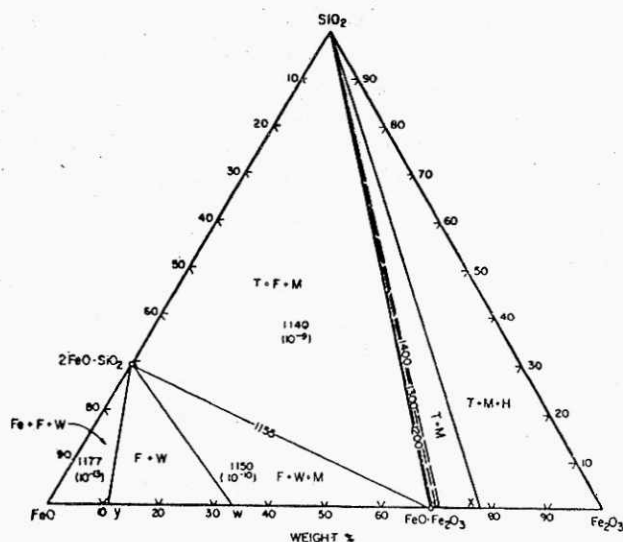


Fig. 24 The solidus surface of the system FeO-Fe₂O₃-SiO₂ Arnulf Muan. & E.F. Osborn : Phase equilibria among oxides in steel making. Addition-Wesly Publishing Co. Mass (1964)

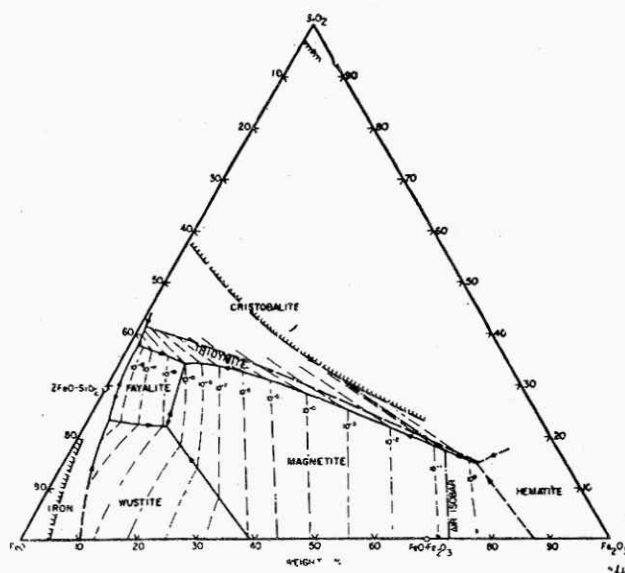


Fig. 23 The system FeO-Fe₂O₃-SiO₂ Arnulf Muan. Trans. A.I.M.E., 203, 965-66, 1955

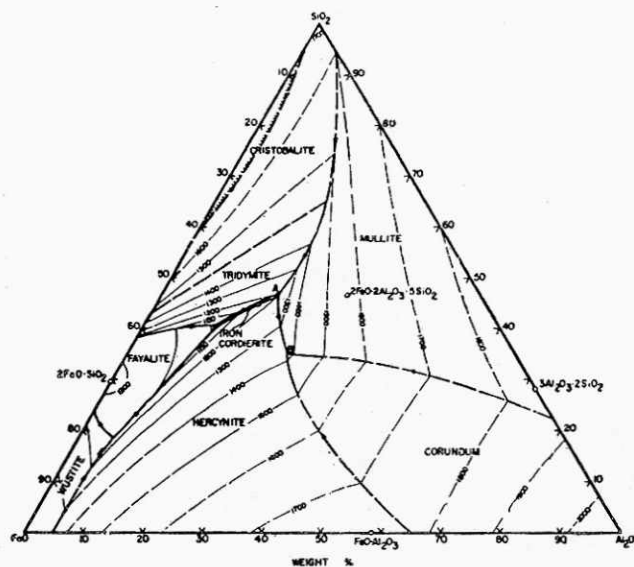


Fig. 25 the system FeO-Al₂O₃-SiO₂ in contact with Metallic iron (originally by Shairer J.F. & Yagi K) J. Am. Sci. Bowen Volume PP 47-512 (1952) (Diagram with later modification given by Muan & Osborn in ref. given in Fig. 24)

- Iron + Fayalite + Wustite at 1177°C (below 10^{12} O₂ partial pressure)
- Iron + Wustite (below 10^{12} O₂ partial pressure)
- Wustite + Fayalite + Magnetite at 1150°C (between 10^9 and 10^{12} O₂ partial pressure).
- Tridymite + Fayalite + Magnetite at 1140°C (at 10^9 O₂ partial pressure)

The system $\text{FeO}-\text{Al}_2\text{O}_3-\text{SiO}_2$ (Fig. 25), in contact with metallic iron at O₂ partial pressure 10^{13} atmosphere, shows three binary compounds (magnetite, fayalite and mullite) and a ternary compound, iron cordierite, incongruently melting at 1560°C, with a small primary field of crystallisation. This phase is important as it occurs in most of the specimens along with magnetite and silica. The following phase assemblages occur at solidus of this system at 10^{13} O₂ pressure: (Fig. 26).

- Metallic iron—FeO—Fayalite coexist at 1177°C and below
- Wustite—Hercynite—Fayalite coexist at 1148°C and below
- Hercynite—Fayalite—iron cordierite coexist at 1088°C and below

All the above phases were observed in the kiln build up indicating different stages of reduction of iron oxide; the minimum temperature of liquid formation in this system is 1088°C.

Fig. 27 shows the quarternary system $\text{FeO}-\text{Fe}_2\text{O}_3-\text{Al}_2\text{O}_3-\text{SiO}_2$ showing the univariant

curves quarternary invariant points and primary phase volumes. The composition of the mostly reduced pellets would lie in the primary phase volume of wustite, the phase assemblage being Fe-Wustite-Hercynite (SS). When the reduction is not fully complete, magnetite, iron cordierite, fayalite and silica are in equilibrium with liquid. The liquidus temperature at this quarternary invariant point is 1050°C.

The average chemical analysis of the fused top zone at a distance of 16-19 feet from the burner and showed: 80.88 per cent FeO, 16.89 per cent Fe_2O_3 , 7.9 per cent Al_2O_3 and 13.68 per cent silica. The location of this composition indicated by a cross in Fig. 27, lies in the primary volume of fayalite. Complete crystallisation liquid of this composition yields fayalite, magnetite, wustite and spinel (hercynite), which forms solid solutions with magnetite. Such mineral assemblage is indicated in Fig. 15, but when the composition shifts to FeO side, under highly reducing conditions, metallic iron appears as one of the constituents phase in equilibrium with fayalite (Fig. 14). The co-existence of fayalite wustite and iron cordierite indicates that equilibrium conditions were not fully attained.

Fig. 28 shows the composition tetrahedron $\text{CaO}-\text{FeO}-\text{Al}_2\text{O}_3-\text{SiO}_2$. This quarternary system becomes applicable to our study where $(\text{CaO}.\text{Al}_2\text{O}_3.2\text{SiO}_2)$ occurs. As the lime constant is very small, the compositions would lie very close to the triangle $\text{FeO}-\text{Al}_2\text{O}_3-\text{SiO}_2$ in the quar-

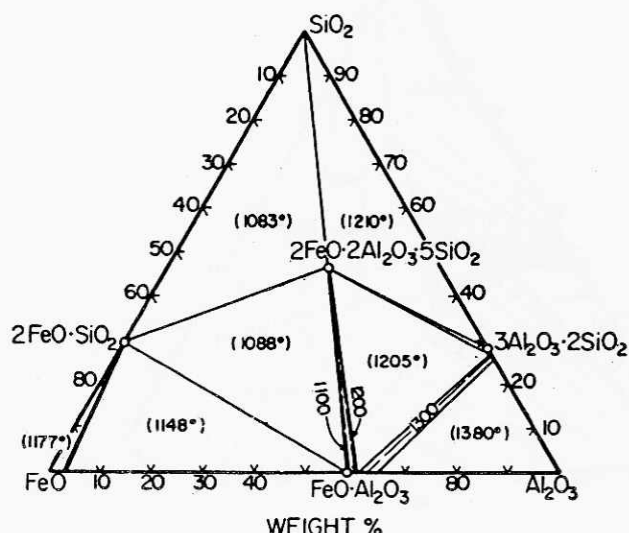


Fig. 26 Solidus surface in the system $\text{FeO}-\text{Al}_2\text{O}_3-\text{SiO}_2$
Arnulf Muan & Osborn E.F.: Phase equilibria
among oxides in steel making (1964)

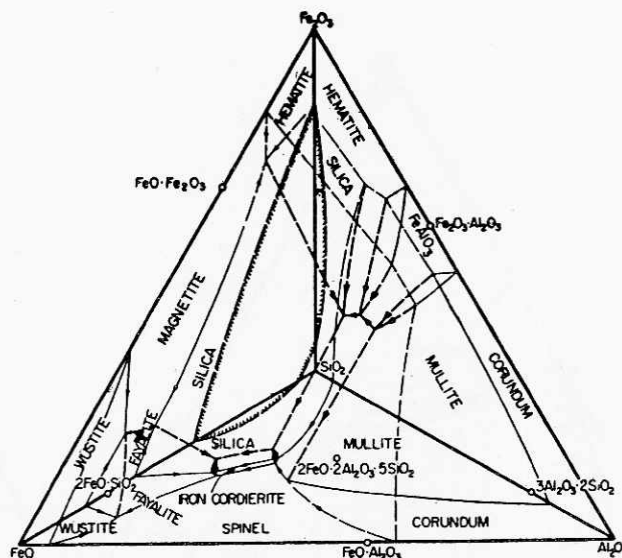


Fig. 27 Liquidus relationship in the system
 $\text{FeO}-\text{Fe}_2\text{O}_3-\text{SiO}_2$ Arnulf Muan: J. Am. Ceram. Soc.
40, (12), 425 (1957)

ternary subsystem FeO-Al₂O₃-SiO₂. Anorthite.

Fig. 29 shows the system Anorthite—Wustite—Silica. Two piercing points occur; one is at 1108°C where the phase volumes of anorthite, fayalite and hercynite meet and the other at 1120°C where the primary phase volumes of Wustite-fayalite and hercynite meet. In the present study the compositions containing small amounts of anorthite would lie away from the plane towards the $\text{Fe-Al}_2\text{O}_3\text{-SiO}_2$ base and the quaternary invariant point could be between 1088°C and 1108°C.

Fig. 30 shows the system $\text{FeO-Fe}_2\text{O}_3\text{-SiO}_2$ and anorthite. At low anorthite contents and low O_2 pressures the compositions lie in the primary phase volumes of wustite and fayalite which have apparently low liquidus temperatures.

As seen above, the phase assemblages observed in the pellet and in the build up could be explained on the basis of the phase diagrams described above. The minimum temperature at which liquid would initially form is 1050°C.

Possible causes of build up and ring formation in the kiln.

As the iron ore pellets and coal and or coke travel along the kiln from charging end, a small amounts of fine dust would be generated due to attrition during rotation. This dust along-with the moisture present in the raw materials would tend to stick at the cold end of kiln. As the charge travels through the kiln. the volatiles of the coal burn first and some caking would take place at about 450°—500°C. The fine dust

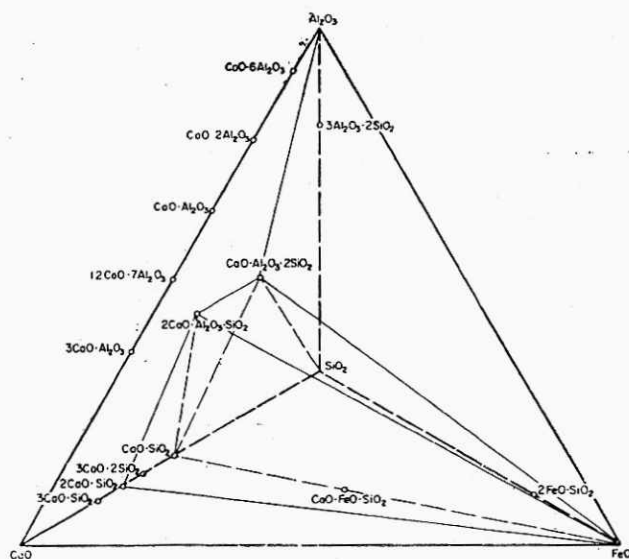


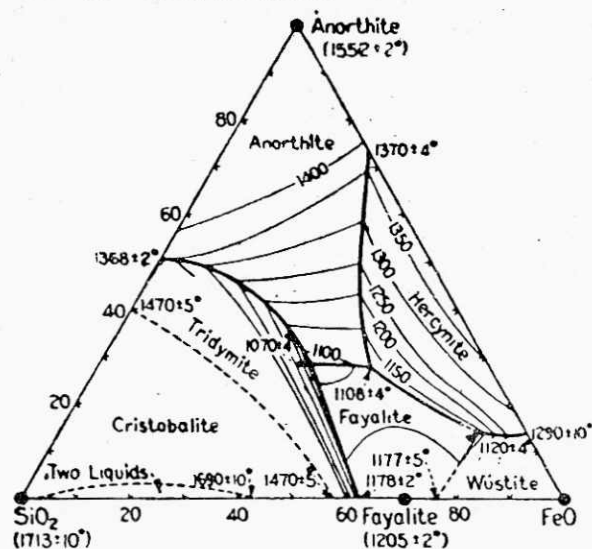
Fig. 28 The system $\text{CaO-FeO-Al}_2\text{O}_3\text{-SiO}_2$ showing Compatibility triangles and composition sub-tetrahedra. A. Muan & E.F. Osborn (p. 144 of ref in Fig. 24)

along with the some cake would tend to stick to brick profile (see arrows in Fig. 2).

As the charge travels further, when a temperature zone of 1000 C to 1100 C is reached. (about 14 to 22 feet from the discharge end) low melting liquids would form and a mass consisting of mostly of fines, some pellets and carbonaceous matter form a conglomerate sticking to the lining.

With the gradual build up, a damping action in kiln is achieved, and temperature tends to

CaO-FeO-Al₂O₃-SiO₂ (cont.)

—Join-plane $\text{FeO-SiO}_2\text{-CaO}\cdot\text{Al}_2\text{O}_3\cdot 2\text{SiO}_2$

Modified from J. F. Schairer, *J. Am. Ceram. Soc.*, 25 [10] 252 (June, 1942).

Fig. 29 The system Anorthite-FeO-SiO₂
Modified from J. F. Schairer, J. Am. Ceram. Soc. 25,
(10), 252, 1942

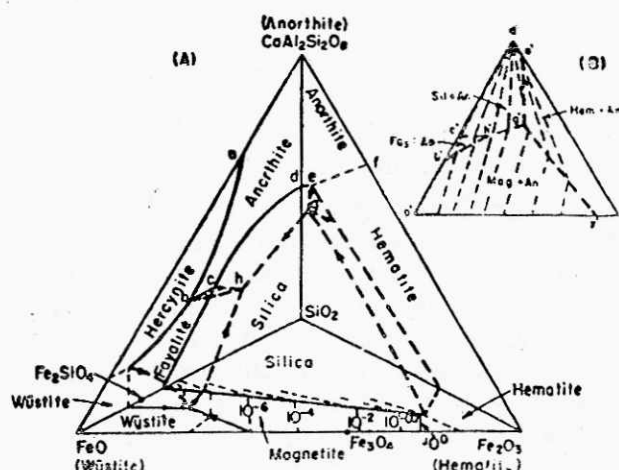


Fig 30 The System $\text{FeO-Fe}_2\text{O}_3\text{-Anorthite-Silica}$
P. L. Roedder & E. F. Osborn. *Am. J. Sci.* 264, 439, 1966.

rise. Between 8 and 19 feet from the discharge end highly reducing conditions must have prevailed resulting in the formation of low melting liquid. It is in this zone that most of the reduction appears to have taken place, as considerable amount of metallic iron could be seen in the skin of the build up as well as beneath it. This is also evident from the entrapping of large balls and cylindrical heavy agglomerates in the zone 14-19 feet. Somewhat oxidising conditions must have prevailed at times during kiln operation upto 8 feet from the discharge end as evidenced by the oxidation of magnetite to a larger extent in this zone. The O_2 pressure seems to have fluctuated, but it appeared to be least in the zone 8'-19' and above. The fusion of the skin of the built up rings shows that temperatures in the excess of $1050^\circ C$ where at times prevalent.

The factors responsible for the build seem to be:—

- (1) The generation fines during rotation, and their tendency to stick to the lining in the presence of moisture at the cold end.
- (2) Formation of cake from coal at 400 to $500^\circ C$ and agglomeration and sticking tendency of 1 & 2 to the brick surface as the charge travels.
- (3) Stabilisation of the sticking tendency at higher temperatures of the order of $1050^\circ C$ due to liquid formation resulting in the fusion of the exposed surface. This appears to be principal cause of the heavy build up.

The possible remedies to avoid the sticking are:

- (1) elimination of fines
- (2) use of coarse coal with low alumina and silica
- (3) operation of the kiln between $1000^\circ C$ and $1050^\circ C$ without any flash of temperature.
- (4) usage of smooth, even lining

Summary and Conclusions

The maximum build up and ring formation in the kiln were observed between 5½ and 19 feet from the discharge end. The initial build up at the cold end could be attributed to the presence of some fines and moisture and plastic carbonaceous matter. It results in further accretion on the surface of the kiln lining at higher temperature upto $500^\circ C$. As the temperature in the kiln rises from $500^\circ C$ to $1050^\circ C$ this sticking gets stabilised by liquid formation. the amount of which increases with increased

silica and alumina contents, derived from the ore and ash from coal or coke. The fusion of the build-up surface in contact with the flame and hot gases indicates that temperatures of the order of at least 1050° were prevalent during kiln operation.

The phase assemblage in the build up is mostly composed of magnetite, (some superficially oxidising to hematite) fayalite and iron cordierite with small amounts of anorthite and glass. At places where there was more reduction. fayalite, wustite and hercynite were observed along with metallic iron.

In the pellets discharged from the burner end, the following phase assemblages were observed with progressive reduction.

- a) Magnetite (SS)—fayalite—wustite
- b) Wustite—fayalite—hercynite (SS)
- c) Metallic iron—wustite—fayalite
- d) Metallic iron—fayalite—hercynite.

The initial liquid in this complex $FeO-Fe_2O_3-Al_2O_3-CaO-SiO_2$ is likely to form in the temperature range between $1050^\circ C$ and $1088^\circ C$. To avoid the liquid formation, the kiln should be fired below $1050^\circ C$. To avoid excess liquid formation above $1050^\circ C$, the amounts of silica and alumina, should be kept to minimum possible limits in the ore and low ash coal or coke should be preferred.

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Discussion

Mr. S. Dharanipalan (Bhilai Steel Plant, Bhilai): I am more interested in the practical aspects of the ring formation and to get rid of it once it has been formed. In all the three papers from the NML, something or other has been stated about ring formation. In the first paper, it has been said that ring formation has been avoided by control of operational parameters but unfortunately nothing has come out in black and white. What are these parameters which were actually controlled? Something has been talked about by Dr. Chatterjea about the counter or the co-current principles. Now the kiln you have mentioned works on counter current principle. I just want to know from you whether counter-current or co-current has got any effect on this ring formation. I personally believe that the rate of revolution of the kiln might play a dominant role on the ring formation. The first photograph shown by you there is layer formation. It is well known for practical reason that once the ring is formed ultimately the kiln has to be stopped. But it can be put the other way also. For some reason or other you stop the kiln say non-availability of raw materials or anything else and then you adjust the temperature zone inside the kiln which will definitely affect or facilitate the so called layer formation. I am just putting the cart before the horse in the sense that you have stopped kiln or you operate the kiln intermittently for a variety of reasons which would have facilitated the ring formation and vice-versa, the ring formation might have led to stoppage of kiln. Will the author please clarify my points?

Dr. A. B. Chatterjea (on behalf of Author): Mr. Dharanipalan is little wrong by saying that nothing has been said by NML as to the cause of ring formation. In fact, summary of my paper which I finished in two sentences at the end, I mentioned that if the generation of the dust can be avoided and a desired temperature profile can be maintained, the Rotary Kiln would be a finest piece of equipment for solid state reduction of iron ore. So the prime cause for ring formation is, the generation of dust and I have mentioned very categorically the reason for which dust is generated by referring to how the charge climbs up depending on the diameter of the rotary kiln. Secondly, the degradation characteristics of the raw materials have to be taken into consideration particularly under the conditions in which a rotary kiln is operated. Determination of degradation characteristics

in a laboratory at room temperature will not fully disclose the behaviour. Another factor of significance is the maintenance of the desired temperature profile along the length of the kiln, which was very elaborately discussed by Dr. Meyer. One has to maintain the temperature of the kiln below the ash fusion temperature or softening temperature of any constituent which may be formed during the process of reduction. Now how to measure the temperature of the kiln accurately? For measuring the temperature along the length, a large number of thermocouples are embedded but the trouble arises when the tip of the thermocouple gets buried due to the deposition of accretion on the kiln wall and then the thermo-couples fail to record correct temperature. Referring again to my recent visit to the Newzealand Steel Plant, I saw a large number of thermocouples which have been embedded in the rotary kiln of a length of about 75 metres and I have no hesitation to say that there were wide variations in these readings from the desired temperature of 1000-1050°C. Since then for the maintenance of the temperature profile, so far as the New Zealand rotary kiln is concerned, is not primarily based on the readings indicated by the thermocouples, but by what they call maintenance of appropriate 'air profile' in which a certain amount of air is injected through the secondary pipes located at regular intervals along with kiln length. By feeding a certain quantity of air and knowing of amount of fuel input, the temperature profile can be maintained far more accurately than by measuring through the thermocouples. Besides, as the thermocouples project little above the refractory lining, the temperature of the bed of the charge along with refractory lining can only be measured and these will not indicate the temperature at the top of the charge or of the gaseous phase above the charge, for which the thermocouple should project well inside the kiln and therefore gets damaged after a short period. So, summarising the factors which lead to ring formation, the dust generation has got to be kept at a minimum and the pre-determined temperature profile has to be maintained. At the NML, the ring formation took place during initial operation when several thermocouples were not inserted along with length of the kiln for continuous measurement of temperature and besides we have since learnt to avoid the dust generation by screening or by selecting suitable iron ore and by the maintenance of temperature profile inside the kiln and thereby the ring formation had been avoided.