BLAST FURNACE EFFICIENCY AND SUPPLY CHAINS

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SUMMARY

On the long march to the effective control of iron blast furnace what have to be done in the last mile, i.e., the investigations of deadman/hearth, are outlined from the point of view of the author.

Experimental work through dissections, tuyere level probing and sampling, radioactive tracers study of the deadman, etc. are reviewed. The heterogeneity of coke bed in deadman and physical barriers to fluid flow, and mechanisms of its formation are discussed. The DCI index and its applications at Port Kembla for monitoring the state of deadman are assessed. In conclusion, research topics in three areas are recommended: (1) computations of mass and heat balances for deadman/hearth under assumed conditions to establish the relative importance of tuyere practice, raw materials quality, burden distribution, chemical reactions, tapping practice, etc. for the state of this region, (2) continuous monitoring of hot metal temperature and frequent sampling during a cast to investigate the state of deadman/hearth and other operating conditions along the same line of DCI index, (3) New tests of iron ore and coke for its performance in deadman/hearth which is at the top of the supply chains of materials inside the furnace.

KEYWORDS: blast furnace, deadman, hearth

1. INTRODUCTION

The progress in the development of blast furnace ironmaking have been marked by the market forces and personal convictions. The invention of making Metallurgical coke from coals was necessary because of the shortage of charcoal in the market. On the other hand, the use of pre-heated blast was due to the personal vision of a Scottish ironmaker, James Neilson. It was contrary to popular belief at that time (1828) because blast furnace was more productive in the winter than in the summer.

Good raw materials are the necessary conditions for a good manufacturing operation such as blast furnace ironmaking, but not sufficient condition. Coke and sinter in a larger blast furnace which are more intensively operated may encounter increasingly varying situations at different localities. Furthermore, with a larger cross-section and ever increasing gas flow, the management of proper gas flow pattern to result in efficient and stable operation became more challenging. After the dissection of several experimental furnaces, the scene was set for Japanese steel companies to dissect commercial furnaces and to report the existence of cohesive zone and its role in the distribution of gas and in melting[1,2, 3].

After seeing the partially reacted iron ore and coke in the dissected blast furnace, Japanese steel companies demonstrated that new assessment of raw materials properties were needed. Tests of softening and melting of iron ore agglomerates and that for strength of damaged coke, CSR were developed with beneficial impact all over the world, for North America particularly in the 70's and 80's.

The switching from oil injection, widely practiced by North American steel companies in 1960's, to coal injection to lower the coke rate took place over a long period of time. Amco among several American Companies started coal injection and Chinese companies kept the hope alive until European and Japanese companies developed the technology to its maturity. The crisis of shortage of coking capacity in Western Europe and North American was forecasted and prevented largely by high levels of coal injection. With the establishment of Jewell-Thompson non-recovery (of coke oven gas) coking technology which eliminates most pollutants in carbonization, it is very difficult to see that a shortage of coke supply or an environmental issue that was threatening the future of blast furnace ironmaking could develop to a crisis level in the foreseeable future[4].

2. REGIONS AND THEIR FUNCTIONS IN A BLAST FURNACE

Physically a blast furnace may be divided into at least five regions or reactors. Each has certain function in the overall ironmaking operations, see Fig. 1, the hearth is at the top of the supply chain.

A. Raceways

The coke wall divides the blast furnace into two separate chemical reactors:

- The oxidizing reactor - Raceways
- The reducing reactor - The rest of the blast furnace

B. The Lumpy Zone

A blast furnace, minus the raceways, may be divided by the cohesive zone into two separate parts.

- The lumpy zone - above the cohesive zone and free of liquid slag or liquid metal
- The rest of the blast furnace

C. The Cohesive Zone

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Below the cohesive zone, there are three fluid phases (i.e., gas, liquid slag and liquid metal) and one solid phase (coke). Irregular operation, which leads to the presence of a significant amount of solid and partially reduced iron ore below the cohesive zone, will be ignored in this time. The portion of the blast furnace below the cohesive zone may be divided into two regions based on the movement of coke, i.e., active (relatively fast moving) or deadman (stationary).

D. The Active Coke Zone

Into this zone enters gas streams from the raceways below and coke from the collapsing layer above (as the result of melting of slag and iron in the layer below). Coke pieces are loosely packed and may be kicked around by gas flow at high velocity.

E. The Hearth

It is below the level of the tuyere and has two liquid phases (liquid slag and liquid iron) and solid coke. The deadman which is the three-phase mass, sits in liquid iron similar to the iceberg at sea. The deadman occupies the most space in the hearth and moves up and down in a casting cycle. The deadman/hearth is the last reactor to complete the process of ironmaking. Things happening in the whole supply chain have impact on the operation of the deadman/hearth.

3. THE INVESTIGATION OF THE LUMPY ZONE

The discovery of the relationship between the shape (e.g., inverse V and W shape) and position of cohesive zone and gas flow patterns (eg. Central and wall working) was a technological breakthrough[1,2]. It was understood that characteristics of cohesive zone has implications in productivity, fuel efficiency and refractory wear (particularly in the bosh area). Consequently, engineers all over the world have been working very hard and extensively towards the goal of controlling the cohesive zone - the most important feature of the inner state of the blast furnace.

In order to control gas flow, many ways of measuring the properties of gas (e.g., temperature and chemical composition) at locations above the burden and below the stockline, both as functions of distance in the radial directions. These data were analysed with the aid of mathematical models and assumptions to obtain gas flows in different artificially divided regions[1].

The most sophisticated system in terms of instrumentation and materials sampling has been and still is Oita #2 blast furnace[3]. The results of direct probing of the details of cohesive zone have been leading to the development of better sinter.

The stack which is defined as the region between the stockline and the cohesive zone, is the reactor under consideration. It is essentially a cylindrical reactor containing solids packed in certain ways with two boundaries for the investigation of gas flows, i.e., the top of the furnace and the region just bellow the cohesive zone. In this two boundary regions gas pressure is essentially uniform. The lower boundary of the reactor is the cohesive zone, i.e., the entrance of gas to the system under consideration.

Both over-burden and in-burden gas probes are very important. This fact must be emphasized here. The former provides data continuously from messengers, top gas, that have been in different regions of the interior of blast furnace a few seconds ago. However, it has all limitations of measured values at the boundary of a reactor. On the other hand, the in-burden probes have the advantage of being in the interior and measuring the gas properties at precise locations. It has the drawbacks that data are only available intermittently and there is certain error introduced due to the presence of the probe itself because of its large size. These two sets of independent data enhance the predictive power, of course, the usefulness of mathematical models which are validated with data from in-burden probes. But, it must be pointed out that so far it is only half of the story.

The important features of the cohesive zone are the 3-dimensional shape and the configurations of gas passages which include location and size of each coke slit (i.e., permeability of each coke layer) and location and size of each cohesive layer (i.e., permeability of each softened and compressed partially reduced iron ore layer). It is very obvious that characteristics of the cohesive zone would influence heavily the gas distribution in the stack. On the other hand characteristics of cohesive zone are also the consequence of gas-solid contacts in the stack. For example, the degree of metallization of iron ore and the extent of solution loss reaction suffered by coke in different regions would be different when it enters the cohesive zone, depending on the distribution of gas flow. It is a sort of chicken-and-egg problem. However, the solution was found by starting with a better known boundary conditions by studying behavior of coke and ore under programmed conditions. It led to more permeable cohesive zone. With the use of bell-less top, probes for gas temperature and compositions, and mathematical models, effective control of processing in the stack of modern blast furnace have been in practice in many countries. These advancements in technology have prepared operators for very low coke rate practice due to very high level of PCI injection in which there are higher flow resistance in stack and higher input of fines to the system. It is likely that similar success may be repeated in the investigation of the hearth region.

4. CHEMICAL REACTIONS AND RAW MATERIALS PROPERTIES

Blast furnace is a chemical reactor which requires certain physical conditions such as permeability for fluid flows in order to produce liquid iron efficiently. From the tuyere level and above (lower part of the furnace will be discussed later), it is a counter-current reactor. The descending solids, are processed by the ascending gas which carries heat and reducing agents, H_2 and CO.

The behavior of iron ore inside a blast furnace depends on the properties of the ore or its agglomerates as charged and the rates of heating up and that of being reduced to metallic iron. It is very important to use different ore in different ways to realize its full potential.

Above tuyere level, excluding the raceways, coke behaves differently at lower temperatures (chemically inert with respect to blast furnace gas) and at high temperatures (active in solution loss reactions). The critical temperature which divides these two regions depends on the chemical reactivity of the coke and the amount of alkalies in blast furnace gas. Metallurgical coke plays a dominant role in controlling both the permeability of gas flow from raceways and up and that of liquid slag and hot metal in the hearth. Coke pieces that reach either the deadman or the raceway, are the damaged goods[2]. The damage is done by the combined oxygen in iron oxides in the ore.

It is true that iron oxides in the ore are always reduced by going through a blast furnace because of stepwise reduction as outlined in Fig. 1. The last step takes place in the hearth where there is excessive amount of coke and sufficient residence time to finish the job. Even though iron ore always gets reduced, the relative amounts of oxygen removal in different regions are of extreme importance in the productivity and fuel rate of the operation. The critical temperature which defines the indirect and direct reduction regions, depends only on coke reactivity and alkalies cycling and not on iron ore properties. This temperature is at the high end of thermal reserve zone, at which the solution loss reactions, as written below, become kinetically significant.

$$C\ (coke) + CO_2 \rightarrow 2\ CO$$

$$C\ (coke) + H_2O \rightarrow H_2 + CO$$

Both reactions restore the reducing power of the gas at expense of coke and heat.

By indirect reductions in which coke is chemically inext, hematite and magnetite, in general, are reduced to wustite and that with better contact with gas flow to metallic iron. Gaseous reaction products, CO_2 and H_2O, are carried away in the top gas. The extent of indirect reduction is often limited by the amount of reducing gases produce in raceways, reductability of iron ore and slow heating rate of solids below the stockline. At the risk of over-simplification, a high level of fuel injection and drier burden materials will promote indirect reduction for a given iron ore used.

When the descending ore layer across the isotherm of the critical temperature, solution loss reactions start to restore the reducing power of the local gas and the rate of the removal of the combined oxygen in solid wustite by H_2 and CO intensifies. Even though the reduction of wustite under these conditions (for example, at 1100°C with gas free of CO_2 and H_2O) is fast but the reaction is hardly ever completed by this mechanism. It is due to the fact that the rate of heating up of solids is also fast. At a certain temperature, liquid forms at the core of iron ore agglomerates from the remaining wustite and the gauge to fill up the pores in sponge iron layer by capillarity force to result in cutting off the reduction reaction and softening of the partially reduced agglomerates. Furthermore, the ore layer will be compressed to become denser and thinner cohesive layer with a drastically lowered permeability. Across the cohesive zone, one may assume that the kinetics of iron oxide reduction is insignificantly slow.

The primary slag forms at the melting of cohesive layer and drops across the active coke zone to reach the top of the stagnant coke bed, i.e., the deadman. Iron oxide in liquid slag meets the gas again on its way down to the hearth, therefore, the reduction resumes in the following way:

$$(FeO)_{slag} + CO \rightarrow Fe\ (s, l) + CO_2$$

$$CO_2 + C\ (coke) \rightarrow 2\ CO$$

In the above equations, CO and CO_2 may be replaced by H_2 and H_2O.

As we can see that for every atom of combined oxygen in iron oxide is removed by direct reduction mechanism, above or below the cohesive zone, there is one atom of carbon in coke gasified. The gasification of carbon in coke will make the remaining coke lump more porous or smaller, in general, or both. The properties of the damaged coke depends on how it was damaged by iron oxide, i.e., when iron oxides are reduced resulting in oxidizing gases CO_2 and H_2O.

What happens to coke or blast furnace should be briefly outlined first before various mechanisms of gasification of carbon in coke will be discussed. In the indirect reduction zone coke lumps are dried and heated. The possible chemical reactions are the absorption of alkalies from gaseous phase to form intercalation compounds which are more stable at lower temperatures.

The main chemical reactions which mechanically weaken coke lumps are the solution loss reactions involving both CO_2 and H_2O. It is the same mechanism in the direct reduction of solid wustite above cohesive zone, the reduction of iron oxide, manganese oxide, alkalies oxides, etc. in the slag by coke in the active coke zone, deadman and hearth. However, there are significant difference of the same reaction at different locations inside a blast furnace, depending on temperature and relative amounts of CO_2 and H_2O. When molecules of CO_2 and H_2O in a gas consisting mainly of N_2 and CO at a location very close to the outer surface of the coke lump, their next move may be striking a carbon atom on the surface or flying into the interior of the lump through pores. At a relatively lower temperature, e.g., 1000°C, CO_2 molecules may strike at carbon atoms many many times before the condition is right to gasify a carbon atom to form two CO molecules. Therefore, the probability of a CO_2 molecule to reach the interior and eventually to complete the reaction there is very high, at least in comparison with the case at 1600°C. Since the internal carbon surface area is much much larger than that on the surface of the lump, consequently, the solution loss reaction at low temperatures (above cohesive zone) will make coke lump having a thick layer (in millimeters) of increased porosity, (i.e., mechanically weaker) but not smaller in lump size or shape. In the reduction of iron oxide in slag in regions below cohesive zone, it takes place at much higher temperature, thus, the affected or mechanically weakened layer should be much thinner and resulted in a smaller lump. Furthermore, the contact of coke and slag may result in non-uniform generation of CO_2 and H_2O to change the shape of lump, i.e., much more carbon reacted near the contact spot with slag.

The ash-carbon reaction at high temperature, such as silica reduction

$$SiO_2\ (ash) + C \rightarrow SiO\ (g) + CO$$

At high temperature will weaken the structure throughout the whole lump.

There are other three factors, mechanical in nature, will weaken and break the coke lump without the involvement of any chemical reactions, the thermal stress due to heating, compression stress from shrinkage due to graphitization, and impact force in collisions between lumps in coke active zone and in raceways.

There are two destinations for coke charged into a blast furnace, the hearth and the raceways. It is generally accepted that solids descend in a plug flow pattern, therefore coke charged to the center of the furnace is more likely ending up at the center of the top of deadman to become part of hearth content. The extent of weakening of the coke lumps above cohesive zone by solution loss reactions depends on local situations such as the ore/coke ratio, rate of temperature rise, reactivity (alkalies absorption) of coke and reducibility of ore, etc. For those lumps that survived the passage of the cohesive zone and landed at the central region of the top part of deadman or in between raceway, their fate will be discussed in the next section.

Coke lumps that dropped from the cohesive zone into the main stream of raceway gas flows, will have rough-and-tumble experience, intimate contacts with liquid slag and iron, and sharp temperature rise. All mechanisms of degradation of coke, chemically and physically, takes place in this coke active zone. The surviving lumps, move towards raceways, by gravity, to be combusted by blast. The linear velocity of gas stream in the raceway is very high which causes coke lumps to strike at the more stationary wall of coke and collisions among fast moving lumps. Fines of coke are created by such impact force and a portion of fines are carried by gas stream out of raceways into the coke active zone. A portion of the gas penetrates the stagnant coke bed at the top of the deadman. The resistance to gas flow provided by the coke bed will slow down the gas velocity and leave most fines in the stagnant coke bed. This is one of the major points of discussion in the next suction.

5. THE DEADMAN/HEARTH REGION

The deadman/hearth is the region where the job of ironmaking, particularly for quality control of hot metal, finishes and the remaining new frontier for more pioneering investigations. The collective effort of past generations of ironmakers makes the process in blast furnace that takes place at tuyere level and up essentially transparent for raw materials selection and operational control. On the contrary, our knowledge of the process below the tuyere level is still spotty, for example, the results of dissection of commercial furnaces are reproduced in Figs. 2-4. The schematic diagrams of the vertical cross-section, including tuyeres, of hearth and horizontal cross-section, including tuyeres of different diameter and oil injection are shown in Fig. 2. Nakamura et al. reported that coarse coke was found in the cavity and a distance away from the raceways. Immediately beyond the cavity where it was filled with coarse coke during shutdown, is the region of small coke, then, followed a dense layer containing a mixture of graphite, metal, slag and small coke. Takeda et al.[5] reported the existence of massive low permeability zone which hinders flows and made the effective space of hearth smaller, Fig. 3. In Fig. 4 they explained that the campaign life of twenty years for Chiba No. 6 had the benefit of low permeability zone.

The variations of coke bed around a raceway, and beyond, including the effect of high levels of coal injection, have been investigated during shutdown by tuyere probing and sampling by many authors. Beppler et al.[6] characterized the coke bed by reporting the amount of fines of coke (<6.3 mm) in the core samples as a function of distance from the tip of tuyere, see Fig. 5. They confirmed what was suggested by the results of Nakamura et al. that there is an envelope around each raceway, except the roof, which is made of smaller coke, more coke fines, more metallic iron drops and slag, see Figs. 6 and 7. They call the layer containing maximum amount of coke fines, metal and slag, located between 1.0 and 2.0 meters from the tip of tuyere, the edge or the outer shell of the deadman. The existence a layer of "outer shell" of the deadman can be generally accepted by those who has done tuyere level probing and sampling. Negro et al.[7] did similar sampling and found similar results.

Nakamura et al. did not offer any explanation of significance of finding metallic iron droplets and slag of higher amounts than that in the regions packed with coarser coke, however Beppler et al. did. It should be noted that results from dissection and tuyere probe represent the inner state of the hearth after shutdown, i.e., not the situation during operation. In the process of shutting down a furnace, the production of iron stops and the drainage of liquids in coke bed near the top essentially completed. In case iron droplets and slag can be found, it should be in the area of low permeability so that liquids were trapped. Beppler et al. suggested[6] that the hot metal flow is maximum in the vicinity of the outer shell of deadman is contrary to what Engan's equation of flow of fluids through a packed bed. In the vicinity of the outer shell of the deadman the permeability would be the minimum simply due to the presence of more fines if other factors are assumed to be the same. Takeda et al. and Negro et al. suggested that more metal and slag were trapped in the layer of low permeability. Furthermore, it is the relationship between flow rate, permeability and reaction time based on which Nightingale et al.[8] developed a new approach of the investigation of hearth reactions and coke bed properties.

5.1 The Speculation of a Healthy Deadman

We accept the common description of a deadman that it is the stagnant coke bed in the hearth and shaped by hearth wall, the outer shell near raceways and the top on which coke and liquids fall and through which raceways gas flows upwards. From the literature[2,6,7] one may conclude that the space of the hearth, excluding raceways as defined by the outer shell of the deadman is filled by coarse coke, i.e., permeable to fluids.

The mass flows in and out deadman/hearth may be listed as follows:

(i) liquid iron and slag originated from cohesive zone which covered the whole cross-section of the furnace, enters the region from top.

(ii) Raceway gas blows inwards and upwards mainly through the active coke zone, but a part of it passes the top portion of the stagnant coke bed, the deadman.

(iii) Liquid iron and slag are tapped out through tap holes

(iv) Gaseous product, i.e., carbon monoxide, of carbon reduction of reducible oxides (FeO, MnO, K_2O, etc.) in slag leaves this region to active coke zone

The heat balance of this region is very important because the temperature is a very important quality of hot metal and slag/metal reactions are very temperature sensitive. Heat input to the region are sensible heats of liquid iron and slag and gas enters the deadman across its outer shell. On the output side there are endothermic reactions, sensible heats of tapped iron and slag and gases originated in raceways and that from slag-metal-carbon reaction within the region. Direct temperature measurement by acoustic CT method at tuyere level during shutdown has been reported by Okada et al.[9]. Their results which are shown in Fig. 8, suggests that raceway gas are important sources of heat from temperature gradient remaining and endothermic reactions take place in the interior of the furnace for the cooling effect at this level.

From the point of view of operators, the third balance would be as important as that of heat and mass, the balance of fines generation and consumption in this region. Nightingale et al.[8] generalized the definition of fines which impair the permeability of a coke bed. In addition to coke fines, they included solid oxides, such as limonite ore, that would decrease the voidage of the bed as coke fines do, as long as remains in solid state. Coke fines are constantly being generated in raceways, and as the result of reduction of metal oxides in the coke active zone and the deadman, and likely from carburization of iron in the hearth. Based on the Laser-Raman method to identify the likely source of coke fines sampled at tuyere level, Fukada et al.[10] proposed the movement of coke fines for stable and unstable operations, see Fig. 9. Sunahara et al.[11] demonstrated in laboratory studies that when FeO-containing slag percolating through a coke bed most of the damage is done on coke lumps near the top of the bed, see Fig. 10. One could extend their results to imagine that for a less permeable bed the reaction would be more limited to the top of the bed. More work is needed to confirm that slag-coke reaction is the major reaction for the creation as well as the elimination of fines as Nightingale et al.[8] assumed it to be. Kasai et al.[12] compared coke degradation by CO_2 and by iron oxide in slag, their results are reproduced here in Figs.11 and 12. The combined effect of corrosive gas CO_2 and cracking could be the very powerful mechanism of localized coke degradation and fines elimination.

5.2 The Steady State and De-stabilization

Blast furnace is nominally considered as a continuous reactor which has advantages of steady state operation and relative easiness for process control. However, its deviations from a true continuous operation are the intermittent charging of solids at top and intermittent casting of hot metal and slag at the bottom and the layer structure of ore and coke in the stack. It is rather reasonable to ignore two of three disturbances because the discontinuity of charging operation happened at relatively far away from the intensive processing regions and that the thickness of ore and coke layers are small in comparison with the size of furnace. The disturbance due to casting deserves further discussion.

During the period between castings, liquid iron and slag are being made and collected in the hearth. Since the deadman which is made mainly of coke, much lighter than liquid iron, it will gradually move up as iron accumulates. The top of the deadman is also the bottom of active coke zone. The position of tuyeres are fixed but the direction of gas flow may change. As the bottom of active coke zone rises, the forces on the roof of this zone will cause it to change in shape and even in position. The roof of active coke zone is the bottom of the cohesive zone. As a consequence of changes in cohesive zone the distribution of gas in the stack will change. It is clear to accept that the rising of deadman between casting and its movement in the opposite direction during casing causes the inner state of a blast furnace oscillating between two extremes. In an operation with every thing under control, the movement of the deadman will remain as the fundamental cause for the de-stabilization of a steady state.

Theoretically speaking, to minimize the drifting of high temperature processing due to the accumulation of liquids in the hearth is to minimize such accumulation by continuous casting. It can be done, in principle, in a furnace of multiple tap holes.

5.3 Irregularities in the Operation

Other than the hearth, blast furnace operators manage the gas flow in the furnace through tuyere practice, selection of raw materials and burden distribution to control the process. The state of deadman/hearth is mainly dependent on the whole supply chain to provide properties of incoming streams: liquids (iron and slag), solids (coke and unfluxed solid oxides) and a portion of raceway gas. Whenever the incoming streams become irregular the processing in the hearth would be adversely affected.

Radioactive tracers have been used to test the permeability between the point it was placed and the tap hole. By comparing the actual response and that for a uniform system, the extent of irregularity may be assessed. Takeda et al.[5] placed tracers for both iron and slag through tuyeres using pulverized coal injection line at 45°, 90°, 135° an 180° from the tap hole. Measured tracer residence time was far below that for the reference condition, particularly for the tuyere opposite to the tap hole. The compartmentalization and restricted flows in the hearth due to the presence of massive low permeability zone was confirmed. Negro et al.[7] introduced the tracer using the tuyere probe at different locations along the radius of the furnace, see Fig. 13. They concluded that the hearth may be divided into three zones based on liquid permeability, as marked on this figure. They also reported that the area of low permeability zone the center has been growing from 17% of hearth area in 1996, to 34% in 1998.

There are two fundamental causes for irregular operation in the hearth: inadequately prepared iron ore and impaired coke bed. Low reducibility and low softening temperature, alkalies cycling, improper gas distribution and ore to coke ratios, etc. can all lead to inadequate metallization when the ore layer reaches cohesive zone, thus, the primary slag enters the deadman. The excessive amount of iron oxide reduction which is very strongly endothermic, will chill the hearth with well known consequences. The most important properties of the coke bed in deadman and hearth is its permeability for liquid flows. The most common cause for the impairment of coke bed is using weak coke. It leads to erratic casting practice, see Fig. 14, and conceivably erratic flow of hot metal to damage the lining. Excessive generation of fines in raceways and alkalies cycling for example, can also lead to an impaired coke bed.

5.4 Physical and Chemical Reactions and DCI Index

Thermodynamic equilibrium states will be briefly outlined so that kinetic consideration could be discussed. In deadman/hearth there is excessive amount of carbon in coke for all possible physical and chemical reactions. It is perfectly acceptable to chemists that the thermodynamic activity of carbon is taken to be unity and as the reference point for equilibrium computations. It is written in most text books that the slag-metal (assumed to be carbon-saturated iron) reactions do not reach respective equilibrium state[13]. A simple example is the reduction of FeO in slag by carbon in iron. In its equilibrium state we should not find any detectable amount of iron oxide in the slag. The other important reactions which usually do not reach their equilibrium states include the transfer of silicon and sulfur between slag and metal phases. Recently, Nightingale et al. [8] reported, based on data collected in commercial operation, that even the simple physical reaction, the dissolution of carbon in iron, does not reach its completion. The hot metal tapped from blast furnace is not carbon-saturated, in view of the extensive contacts between coke and iron.

In order to discuss kinetics of heterogeneous reactions in coke bed, we should recognize that there are four different types of subsystems in deadman/hearth region. From the top to the bottom of the region, the first sub-system is an irrigated bed with counter-current flows of liquids and gas through the coke bed and gaseous phase is the continuous phase. The dominant reactions are likely to be the reduction of iron oxide in the primary slag and carburization of iron by coke and the gas. Reactions may be intensive, violent and far from respective equilibrium states.

In the second sub-system from the top, liquid slag is the continuous phase with dipped-in coke packing. Through the slag layer and around coke particles, there are falling iron droplets and rising CO bubbles which are generated in oxide reduction by carbon. This is the most important place in determining the final composition of hot metal because of two reasons, longer contacting time and larger interfacial area between phases. Both factors are very sensitive to the structure of coke bed. A fines laden coke bed will provide larger carbon surface area for reactions and longer time to complete them. The most sensitive way to measure the kinetics of reactions near its completion is to measure its deviation from the final equilibrium state. This is hypothesis based on which Nightingale et al.[8] developed the Deadman Cleanliness Index (DCI).

In the third sub-system from the top, liquid iron is the continuous phase with dipped-in coke packing, no slag and no gas. The only reaction in this part of hearth is carbon dissolution in liquid iron. In the case of a floating deadman, there is a sub-system at the bottom of hearth, a region of liquid iron only. It is obvious that reactions we have considered so far will not take place here.

Nightingale et al.[8] have been trying to monitor or to estimate the inner state of the deadman/hearth by examining the exit streams (hot metal and slag), the same idea of monitoring the stack by measuring temperature and composition of top gas. It is well understood that the health of the deadman is critical for smooth and stable operation. Furthermore, the key criterion for the health of a deadman is that it should be permeable for liquid flows. They considered that a relatively larger deviation from the theoretical equilibrium state reflects a more permeable bed. The reaction of carburization of iron by coke is chosen because it is independent of slag and directly related to coke bed. The yardstick to measure the kinetics of carburization is,

$$\Delta C = \%\,C_{sat} - \%C$$

where $\%C_{sat} = 1.3 + 2.57 \times 10^{-3}\,T - 0.31\,\%\,\underline{Si} - 0.33\%\,\underline{P} - 0.4\%\,\underline{S} + 0.028\%\,\underline{Mn}$

The ΔC values of 0.2% or greater have been observed by Nightingale et al.

The most effective parameter as a measurement of the risk of having unmelted oxides or of the deposition of solidified slag in the deadman is the liquidus temperature of the slag in comparison with the actual temperature.

$$\Delta T = \text{HMT (Hot Metal Temperature)} - \text{Liquidus temperature of the slag}$$

$$= \text{HMT} - T_{Liquidus}$$

For the practice at Port Kembla

$$T_{Liquidus} = 1430 - \text{correction term}$$

The DCI (Deadman Cleanliness Index) developed at the Port Kembla operation is the linear combination of ΔC and ΔT to give DCI in the unit of degree Celsius as follows.

$$DCI = HMT + \frac{1}{2.57 * 10^{-3}} \cdot \Delta C - (1430 - 190 * (1.23 - C/S))$$

where HMT = hot metal temperature, and
C/S = the CaO/SO_2 ratio of the tapped slag.

Examples of their application of DCI monitoring are shown in Figs. 15 and 16.

At Port Kembla, DCI has been very successfully used in reflecting direct changes in coke bed due to change in coke quality, gas velocity at tuyere and addition of ilmenite ore, etc. In Fig. 15, the co-relation with the chemical state of the system qualitatively in terms of distribution ratio of manganese and titanium is certainly discernible. In Fig. 16, comparing DCI and standard deviation of silicon in hot metal, which has been accepted a useful criterion for the stability of the operation, is almost like mirror images.

5.5 Spatial Variation of Top Gas Properties and Temporal Variations of Tapped Streams

Top gas leaving the stack always carries the same type of information about the inner state of the stack for decades in the past, regardless if we use it or not. A long time ago, it was found that the average temperature of top gas may be used to judge the extent of moisture condensation and operational safety. As the chemical composition of top gas became available the computation of mass and heat balances led to more precise burdening. At present time the information of profiles of top gas temperature and composition in the radial direction are necessary for effective process control. It took many years for us to be aware of the availability of useful information and even longer to establish that it is worth to spend the money to get it.

It appears to be that we are about to repeat the story of top gas in the monitoring of the hearth. The knowledge of flow patterns of iron and slag inside deadman/hearth is important for smooth operation, long lining life and the design of a better hearth for a given practice. From physical modeling, it has been suggested that whether the deadman is sitting or floating has dominant influence on the flow patterns.

However, at the present time, in general, we have no way of knowing when the deadman is standing up and floating or by how much. If the properties of coke bed can be better characterized by DCI index, basic rules of thumb of flow in coke bed have been figured out, the temporal variations in iron and slag streams during a cast may be able to be converted to special variations inside the hearth. Gaining such detailed knowledge about the inner state of deadman/hearth will be the last mile in the long march to the total and effective control of iron blast furnace.

In North America there are several steel companies that are practicing continuous measurement of hot metal temperature during every cast. It is a very encouraging development. Combined with frequent sampling of hot metal for chemical analysis, this time-dependent information could be as exciting as measuring the profiles by over-burden probes. At the very least, there will be refined measurements of DCI indices. The state of oxygen potential of deadman/hearth, i.e., the amount of iron oxide entering the system, may be measured by ΔSi or ΔS (deviation from final equilibrium state for silicon and sulfur transfer) or distribution ratios as used by Nightingale. With strategic selection of blast furnaces for this type of investigation, for example, significantly different in raw materials properties, operating conditions and hearth design, etc., it will be just a matter of time and effort that the messages carried out by hot metal and slag will be de-coded.

5.6 The Mystery of Coke Renewal in Deadman, Raw Materials Quality and Burden Distribution

It is well known that the recovery from a hearth problem may take days or weeks because operators have no tools to reach deadman/hearth. The usual tools we have are the "forced gas flow" which cannot reach the bulk of deadman and burdening which is faraway. Once the deadman is impaired, i.e., impermeable to liquid flows, it floats like an iceberg in liquid pool or worse anchored at bottom. Hot metal and slag from coke active zone can only digest it slowly at the iceberg. The more aggressive slag cannot reach the bottom.

A healthy deadman receives coke lumps and fines, liquids and heat from raceway gas oscillating between two extreme values of its height due to casting. In order to operate the furnace continuously, there must be a reliable mechanism to consume coke, lumps and fines, to maintain the region in a more-or-less steady state. During the period of liquid accumulation the deadman is rising in relation to tuyere position. The rising top of the coke bed enters the coke active zone, therefore, these lumps and fines will find its way into one of raceways and to be burned there. The shaved top portion of coke bed will be re-built with fresh coke during casting. This scenario described above is certainly acceptable, but it can not be the whole story. What would happen to coke trapped in the pools of slag and of metal? We will come back to this topic after some discussion on raw materials quality.

The generally accepted practice of charging good coke, in size and in strength, to the center of the furnace to improve the coke bed in deadman indicates that it serves its intended purpose. The centrally charged coke which will suffer less damage before entering the deadman, go through the stack along a path of low ore-to-coke ratio, far away from raceways and in shorter time. We all accept the fact that in the central region of the hearth, the permeability of liquid is low. The question is why? From dissection and deep probing through tuyeres, fines in this area are not excessively high. The cause of the difficulty for liquid to flow through may not be solid packing, at least initially. If the local temperature is too low, the slag would be viscous or would even solidify. In their management of the hearth, Chung et al.[14], in addition to these measurements reviewed in this article, they monitored slag composition and viscosity very carefully. The cause of their concern is shown in Fig. 17. As we cannot provide much heat from raceway gas to the central area because the outer shell of the deadman, the corresponding measure should be to lighten its thermal load, i.e., less direct reduction of oxides by carbon. Therefore, the success of the central charging of coke could be due to less ore rather than more coke.

What would happen to a coke lump after being part of the deadman depends very much on the quality of iron ore used and operating conditions. From cohesive layers liquid iron with certain amount of carbon and primary slag of various amounts of reducible oxides will react with carbon in coke and causes it to degrade. Iron with less carbon and slag with more iron oxide will do more damage to the coke at higher temperature. In laboratory tests of softening and melting properties of iron ore similar reactions take place. Due to our appreciation of the formation and the functions of cohesive zone, data on temperature range of softening were used in the development of fluxed agglomerates. On the other hand, properties of molten phases (temperature and chemical composition) and the damage done on the coke layer below did not receive much attention at the time when these tests were frequently conducted.

The mechanisms of reactions with of carbon in coke by liquid iron and by liquid primary slag are very different. The reaction with liquid iron does not involve any gas species and the surface tension of iron is very large so that the reaction zone is restricted to the external surface. In the reaction with FeO-containing slag, carbon monoxide takes part in the reduction of iron oxide to produce carbon dioxide and simultaneously CO_2 reacts with carbon in coke to regenerate CO. The reaction zone in the gasification of carbon in coke would certainly go beyond the external surface of the coke. Even though slag does not wet a carbon surface, the ash layer on coke would make the penetration of slag into fissures and larger pores easier. With a gas as the intermediate in slag attack on coke, the gasification of carbon would be selective. Comparing of these two mechanisms, one would conclude that slag attack is more likely leading to the disintegration of the lump.

The spot where the attack on coke is most intensive, is at the top of stagnant coke bed, i.e., the entrance to the deadman. The fresh liquid iron and slag have a very large capacity to remove carbon in coke. The gas flow from raceways provide the force to mix the reacting phases and to cause coke lumps to crack, to disintegrate and to be consumed very quickly on the spot. In the discussion of the renewal of coke bed in deadman, we are talking about the surviving lumps that move further down below the entrance to the deadman.

It is the time to come back to the question of why the recovery of hearth problem takes days and weeks. There are possibly several kinds of hearth problems, for example, three are given below:

(i) A chilled or frozen hearth

It is likely due to excessive energy consumption, assuming no mistakes in burdening, by excessive endothermic reactions sustained for a period of time. The common situation is the arrival of primary slag low in temperature and high in iron oxide content. The endothermic reduction of iron oxide continues and cools the materials on site because there is no other source of heat. The solidification of slag in the irrigated bed and the pool will stop the reaction and fill up the voidage of coke bed. Even after the cause of the problem, inadequately metallized iron ore, has been corrected, it would take a long time for incoming liquids to digest the impermeable core from its boundary. After metallization of iron oxide, the melting temperature of the remainder will increase.

(ii) A dirty hearth

It is the opposite case to (i). The incoming liquids have inadequate capacity to consume coke, particularly coke fines. It is due to the accumulation of fines in deadman coke bed as the result of excessive creation of fines in the furnace or the incoming liquid iron containing too much carbon and too little iron oxide in the primary slag. It takes long time to recover because the core became impermeable.

(iii) Segregation in fines and liquids

It is a little bit of both case (i) and case (ii). Such imbalance may be created by some unbalanced operation around the furnace, for example, burden distribution, tuyere practice and off-schedule tapping for a multiple tap holes furnace. In principle, the size of impermeable mass would be smaller and shorter recovery time.

Finally, we have to consider the possible mechanism of the renewal of coke lumps which are already dipped in the slag and metal pool. The obvious problem is that we see the entrance but not an exit of coke lumps. A gradual shrinking of lumps as the result of carbon removal will lower the average size of coke and the permeability of the bed. It is the opinion of this author that a relatively simple mechanism may be proposed provided coke lumps behave in certain ways. It requires that as the result of reaction with slag and/or iron, coke lumps shrink in size gradually only down to certain size, then, it disintegrates into fines. The mechanism of coke renewal in slag and metal pools may be proposed as follows:

The surviving coke lumps at the top of the deadman are pushed downwards by gravity of materials falling from above gradually to liquid pools. The lumps in pools react, shrink in size and eventually disintegrates into fines. Coke fines float up in pools through interstices between lumps eventually to the surface of slag pool to be consumed by the very reactive incoming liquids.

Simple experiments were carried out with plastic beads of different sizes and a pool of water in a glass container. There is no surprise that the floating of fines can easily be seen. However, fines also drift towards the wall of pool where the wall effect also creates interstices for fines to stay rather than to pass by. In case the space between raceways is a significant portion of the deadman/hearth for the processing of liquids, for small furnaces or large furnaces with less permeable center, the segregation of fines near the wall could be beneficial. If the immediate layer next to lining is of low permeability, then, low velocity of liquid flow will be beneficial for the protection of the lining in several ways.

6. CONCLUDING REMARKS

In ending this article it would be more appropriate to recommend a few research topics than to conclude with some encouraging statements. For basic science, there is more than adequate thermodynamic data of chemical reactions to satisfy our need at present time. For the advance in our understanding of physical and chemical phenomena in deadman/hearth region and to complete the last mile in the long march to control the blast furnace ironmaking effectively, research topics in following three areas are recommended:

6.1 Raw Materials Characterization and Development

(a) Melting test of iron ore under various programmed reducing conditions, including various heating rates and reducing power of the gas, corresponding to the cases with and without high level of fuel injections.

(b) Degradation of coke, up to disintegration, as the result of reactions in slag pool and iron pool of various initial compositions and temperatures.

6.2 Computations of Basic Relations in the System Under Assumed Conditions to Establish Sensitivity of Each Independent Variables

(a) Mass balance
(b) Heat balance
(c) Space Occupancy by various phases
(d) Fines balance for selected periods.

6.3 Investigation of the Inner State of Deadman/Hearth by Continuous Monitoring of Hot Metal (and slag) during a cast and regularity of casting practice

(a) Correlates the refined DCI values with coke bed characteristics, raw materials, operating conditions and cast practice.
(b) In addition to DCI, oxygen potential of deadman/hearth be monitored by the continuous measurement of the deviation from final equilibrium state of silicon transfer or sulfur transfer.
(c) Physical modeling of deadman/hearth.
(d) Mathematical modeling of deadman/hearth.

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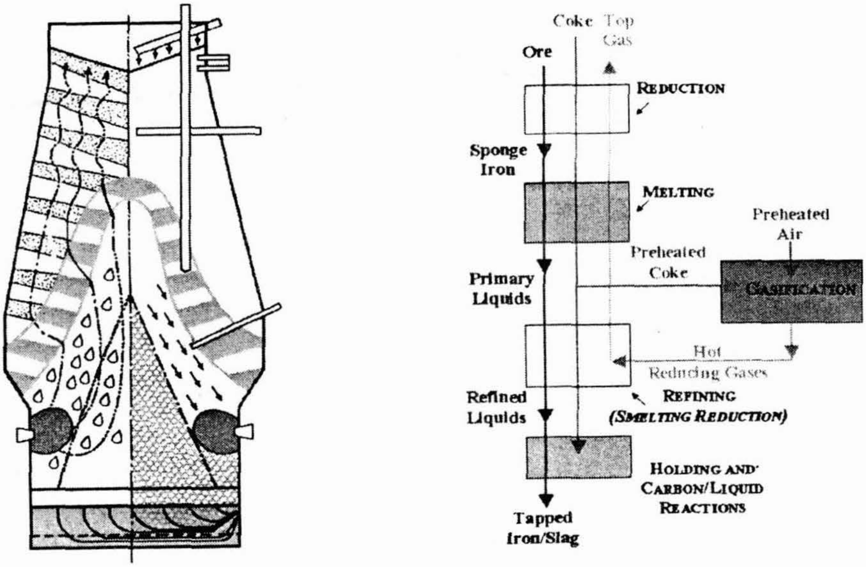
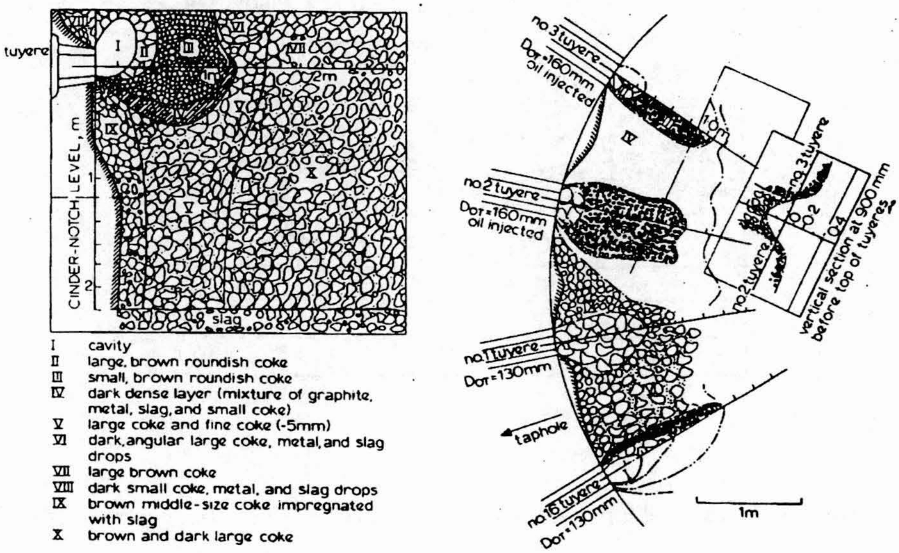


(a) (b)

Fig. 1 Artificial division of a blast furnace.
(a) physical structure
(b) chemical processing and material flows



(a) (b)

Fig. 2 Sections of Kukioka No. 4 Blast Furnace at tuyere level[2].
(a) vertical
(b) horizontal

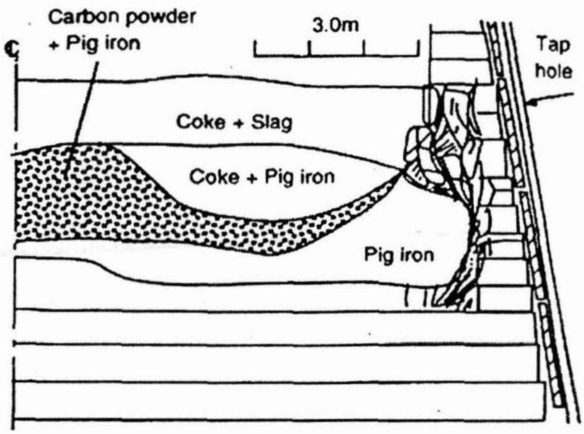
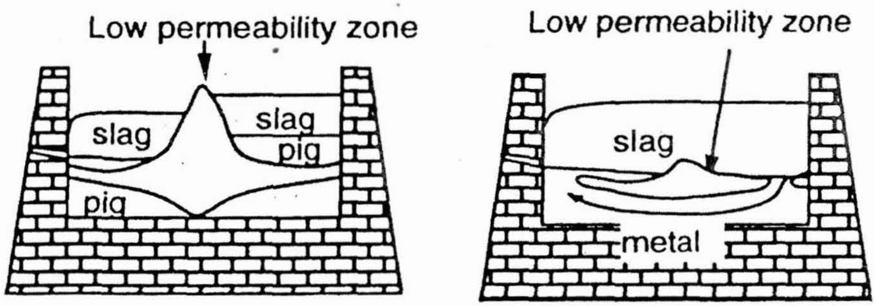


Fig. 3 Inner profile of blast furnace hearth at dissection survey (Mizushima No. 4 F)[5].



(a) stagnant metal flow at hearth bottom by the large low permeability zone

(b) metal flow through the low permeability zone

Fig. 4 Roles of a low permeable layer in hearth[5].
(a) Stagnant metal flow at hearth bottom by the large flow permeability zone
(b) Metal flow through the low permeability zone

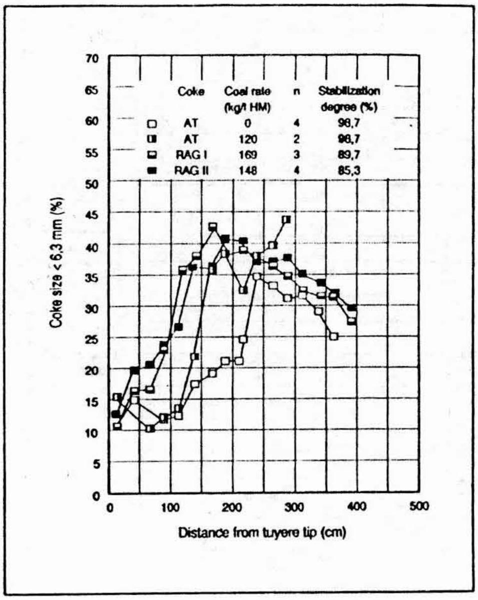


Fig. 5 Radial distribution of coke –6.3 mm with and without coal injection[6].

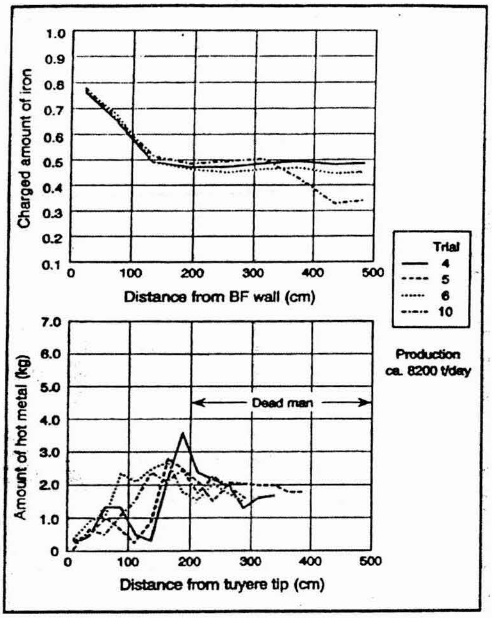


Fig. 6 Radial amount of charged iron and hot metal in tuyere level in all coke operations[6].

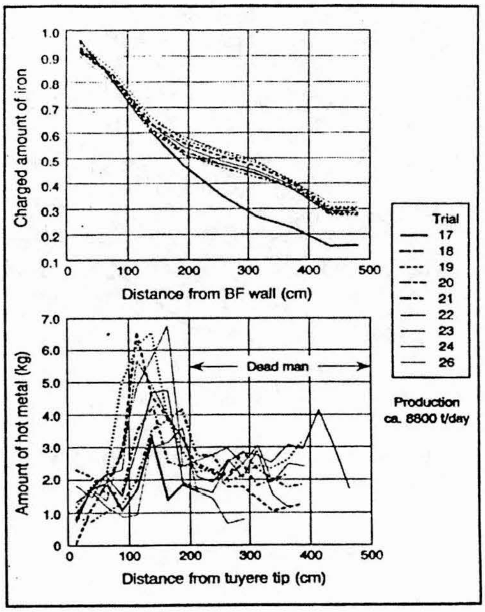


Fig. 7 Radial amount of charged iron and hot metal in tuyere level with coal injection[6].

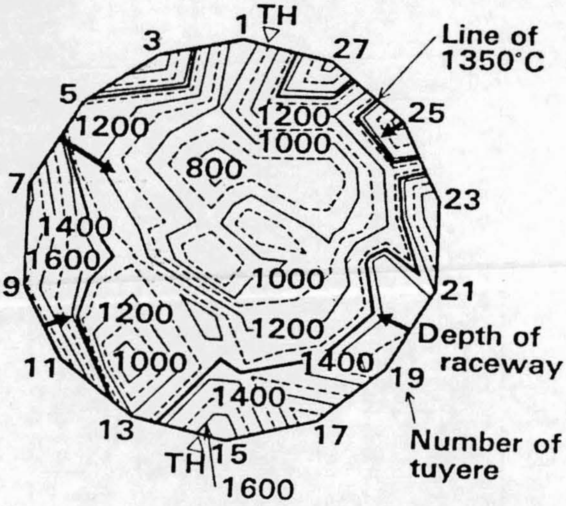


Fig. 8 Depth of raceway and temperature distribution on tuyere level at Hokkai No. 2 BF (unit: °C)[9].

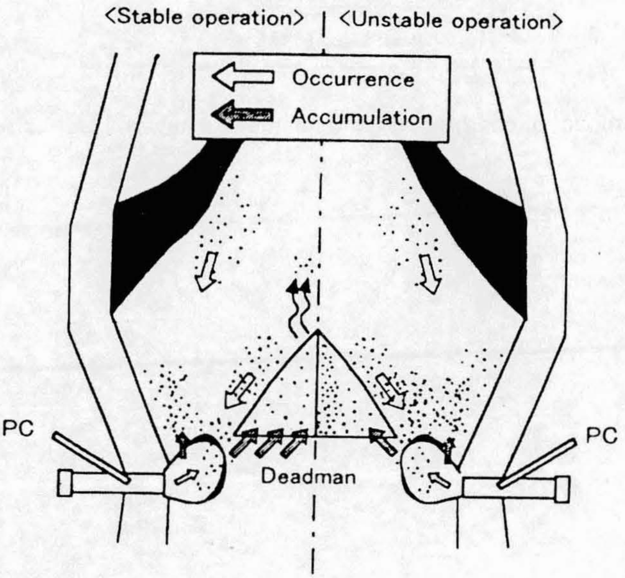
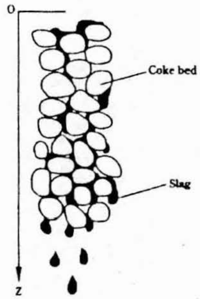
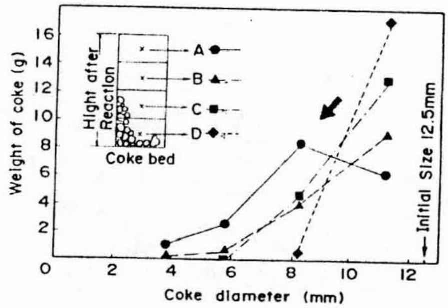


Fig. 9 Schematic illustration of the coke fines movement and accumulation in the lower part of the blast furnace[10].



(a)



(b)

Fig. 10 Laboratory study of coke degradation by FeO in liquid slag[11].
(a) Situation to be studied.
(b) Size degradation after reaction.

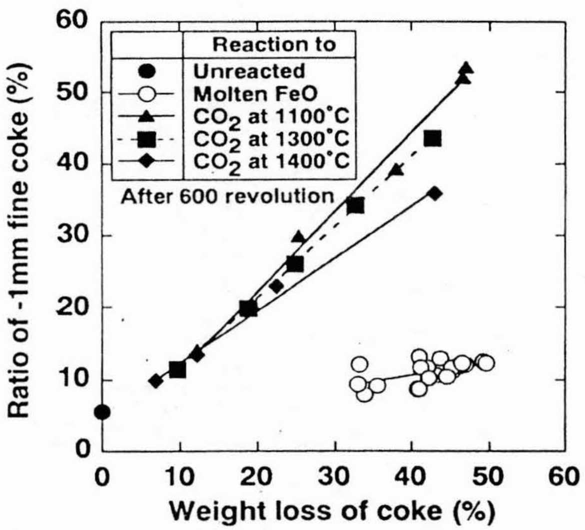


Fig. 11 Effect of reactant on fine coke ratio[12].

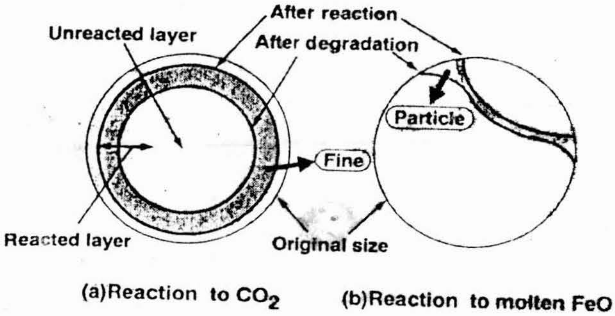


Fig. 12 Schematic diagram of reaction model[12].

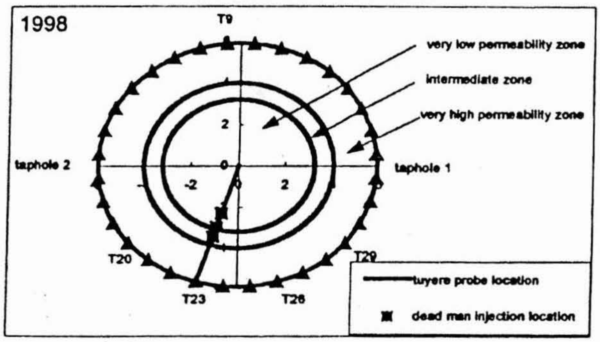


Fig. 13 Zones of different permeability for liquid flows[7].

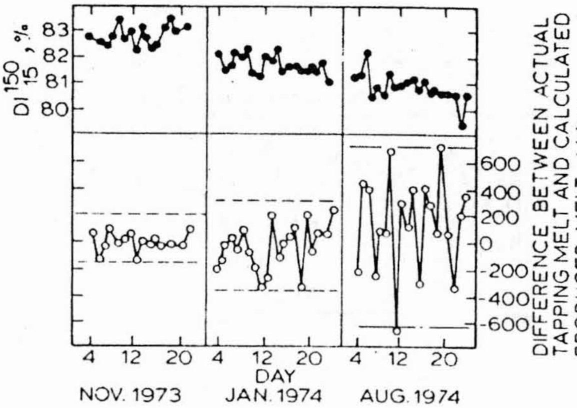


Fig 14 Effect of coke strength on stability of tapping (Kimitsu Works)[2].

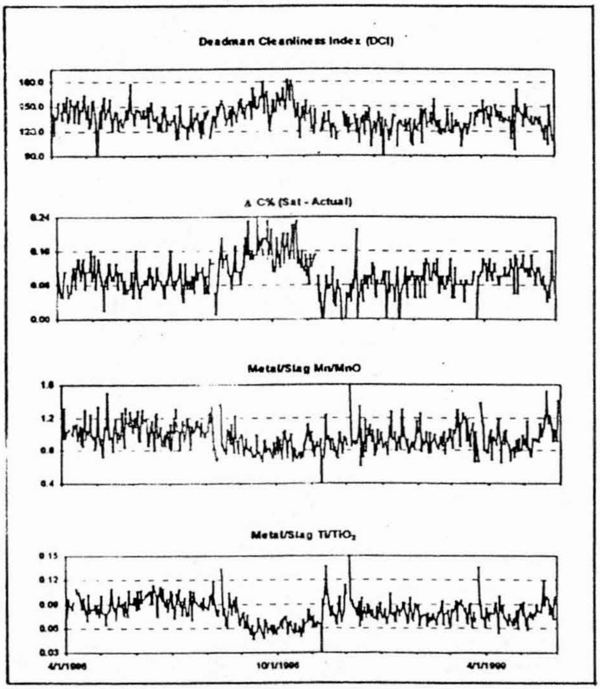


Fig. 15 Comparison between DCI and partition ratios for manganese and titanium. Port Kembla No. 5 Blast Furnace[8].

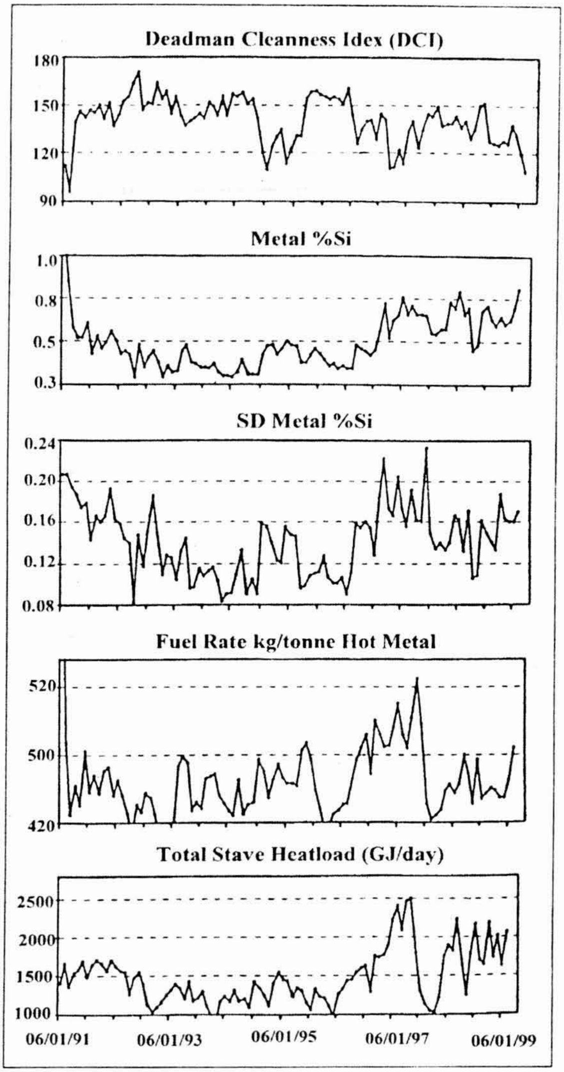


Fig. 16 Comparison between DCI and key operating indices. Current campaign of Port Kembla No. 5 Blast Furnace[8].

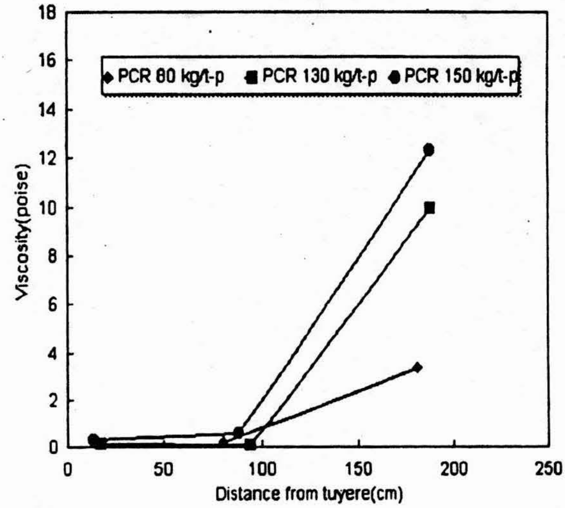


Fig. 17 Viscosity of the slag sampled at tuyere level with PCR.