

Pretreatment of iron for steel production in the Durgapur steel project

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INTRODUCTION

PRETREATMENT, as the term implies, is the treatment or conditioning of molten pig iron before it is charged into a steelmaking furnace with a view to improve the speed and quality of steel production. Steelmaking is fundamentally an oxidation process followed by varying degrees of reduction (deoxidation) of the over-oxidized metal. The metallurgical load during steelmaking in the open-hearth furnace can be appreciably reduced and hence the speed of production appreciably increased if some of the elements in the iron particularly Si and P, could be partially removed. The oxidation of a large part of Si and to some extent of P in the molten pig iron, before it is charged into a basic OH furnace, has therefore engaged the attention of many steelmakers.

HISTORICAL REVIEW

Campbell,¹ as early as 1890, conceived the idea of pretreatment in the form of the so-called 'washed metal' process in which the hearth of the washed metal open-hearth furnace consisted essentially of iron oxide and lime. The furnace was not allowed to reach a high temperature and the metal was tapped soon after a large part of the Si and part of P were oxidized. The process was abandoned owing to the frequent renewal of hearth and chilling of metal.

The Bertrand Thiel process² (1897) consisted of two OH furnaces; the one at the higher level was used as a pretreatment furnace to remove Si and P.

The Hoesch process in Germany used the same furnace, first for pretreatment of Si and P and then recharging the pretreated metal from the ladle from which the siliceous and phosphorus-bearing slags are allowed to overflow. This process had also to be abandoned in favour of the much superior Talbot process.

In all these processes, oxidation was effected primarily by iron ore, air, and furnace gases but with the availability of large quantities of almost pure O₂, the situation became different. In 1948 oxygen was used at Brymbo,³ in conjunction with BISRA, when it was found that about 10–12 m³ of oxygen only was required per ton of metal to reduce the Si from 1.2 to as low as 0.4%. This rapid method of desiliconizing became a standard practice at Brymbo^{4,5} and was later adopted in many steelworks in the UK and abroad.

Pretreatment of metal by O₂ has also been practised:

- (i) in the blast-furnace runner or channel suitably prepared from porous bricks through which oxygen is bubbled^{6,7}
- (ii) in transfer ladles or mixing ladles⁸ in which oxygen under different conditions⁹ is lanced or jetted either during filling of the ladle or otherwise
- (iii) in rotary vessels^{10,11} with oxygen, thereby minimizing the composition and temperature gradient in the volume of the metal and promoting early slag formation and better slag-metal contact

SYNOPSIS

For the first time in India, the Durgapur steel project has adopted the practice of pretreatment of 80 tons of mixer metal in a 120 ton ladle—the largest of its kind in the world. For such a large volume of metal, however, there are certain inherent difficulties in achieving a very low silicon content as well as a homogeneous metal when using a submerged oxygen lance at the top. In the present series of investigations the silicon content of the blown metal has not only been brought down to about 0.46%, starting from an initial silicon of about 1.5%, but the so-called stratification has been effectively reduced by lancing at a higher pressure (10 kg/cm²), lancing at variable angles 70° to 80° (the less steep angle helping circulation and the steeper angle helping penetration), lancing with pipes of different diameters (25 mm and 18 mm), immersion of the lance frequently but momentarily to a greater depth, and use of limestone at the bottom of the ladle. The difference between the silicon content of the bottom and top layers has been reduced on an average to only 0.1%. Oxygen efficiency has been increased from an average of 45% to 65%. Rate of lance consumption has been decreased from 16 cm/ton to about 9.8 cm/ton by comparatively earlier formation of slag, higher pressure of lancing, and the use of thick-walled pipe of smaller diameter.

The following advantages in the open-hearth practice have been established: (a) saving of limestone or lime per ton of steel, (b) better control of metal and slag, (c) greater speed of working.

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- (iv) in active mixers¹² by lancing and jetting O₂
- (v) in a basic OH furnace functioning as a pretreatment furnace.¹³

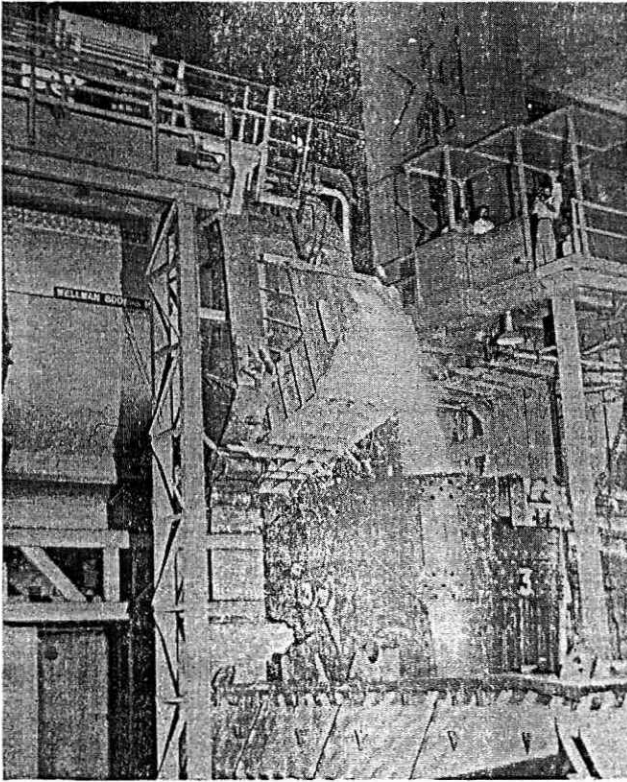
Although the reactions are fundamentally similar in the above cases, the speed of operation and also the nature of the results may be significantly different depending on:

- (i) the efficiency of mixing
- (ii) early formation of fluid slag
- (iii) intimacy of slag/metal contact
- (iv) variation of the extent of heat conservation and utilization
- (v) initial and final temperatures of the metal, etc.

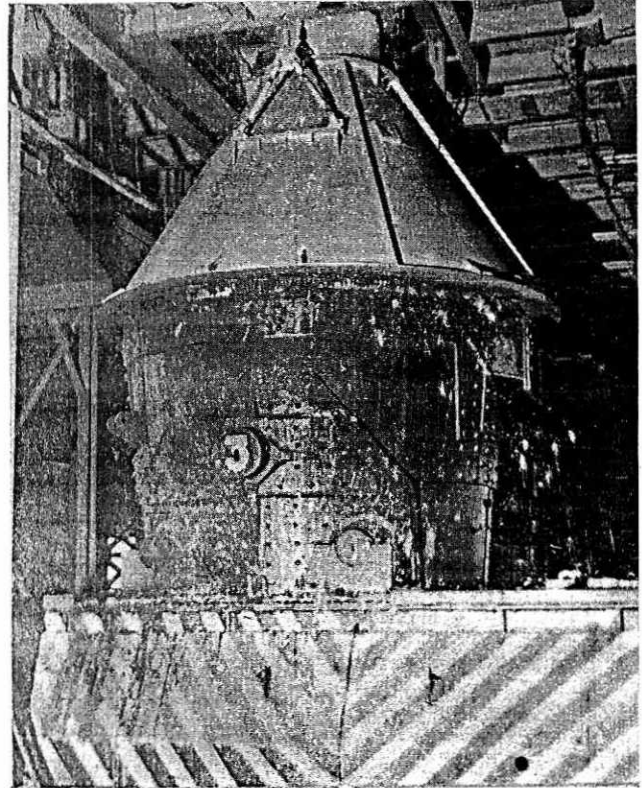
OBJECT OF THIS PAPER

An attempt has been made in this paper to indicate briefly the many advantages of pretreatment of iron with particular reference to Indian conditions and to describe briefly the process of pretreatment, as practised for the first time in India at the Durgapur steel project, together with the results of investigations on oxygen lancing in ladles under different conditions with the primary object of getting as low a silicon as economically feasible and to get as homogenous a metal as possible with the facilities available under Indian conditions with 80–90 tons of metal, i.e. the largest bulk of metal ever handled in a single desiliconizing ladle for oxygen lancing.

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1 Pig iron being poured from the mixer into the ladle before desiliconizing



2 Desiliconizing in progress inside the ladle covered with hood (sparks visible)

ADVANTAGES OF PRETREATMENT

A high speed and quality of steel production by the basic OH process depend to a large extent on the steady supply of hot metal of suitable and fairly constant composition.

The objects of pretreatment are thus two-fold :

- (i) to remove economically as many of the impurities in the pig iron as possible
- (ii) to keep the composition of the treated metal within narrow limits of variation.

The advantages of such pretreatment are cumulative. Not only are the amounts of impurities to be removed in the furnaces less but also the quantities of lime and ore to be added are less, the amounts of slag formed are less, the rate of heat transfer is better, the fuel consumption is lower, and the average life of the refractory lining is greater.

In addition to the above, another important advantage is that control of composition and temperature of the bath (including slag control methods) become very much simpler because with a treated metal of fairly constant composition the bath is more likely to melt and 'open' satisfactorily, and it becomes much easier to judge and shape the working and finishing slags.

Another advantage is that with treated metal it is possible to take a comparatively higher proportion of hot-metal charge in the open-hearth and thereby reduce the strain of procurement of suitable steel scrap from outside market.

In India, with comparatively higher alumina content in the iron ore, with higher 'insolubles' in the limestone, and with high ash in the coke and particularly with wide variations in the physical and chemical characteristics of these raw materials, it often becomes increasingly difficult to produce basic iron of satisfactory and constant composition for the basic OH process. To be able to

accommodate a higher silicon content in the blast-furnace metal and also a higher percentage of hot-metal in the OH furnace, a large desiliconizing plant has been established at the Durgapur steel project for ladle pretreatment of the mixer metal with industrially pure oxygen manufactured within the plant.

DESILICONIZING PLANT AND PROCESS AT DURGAPUR

Description of the plant

The desiliconizing plant at Durgapur is the first of its kind in India and is the largest in the world with regard to the single ladle capacity of 120 tons using about 80-90 tons of metal in a single blow.

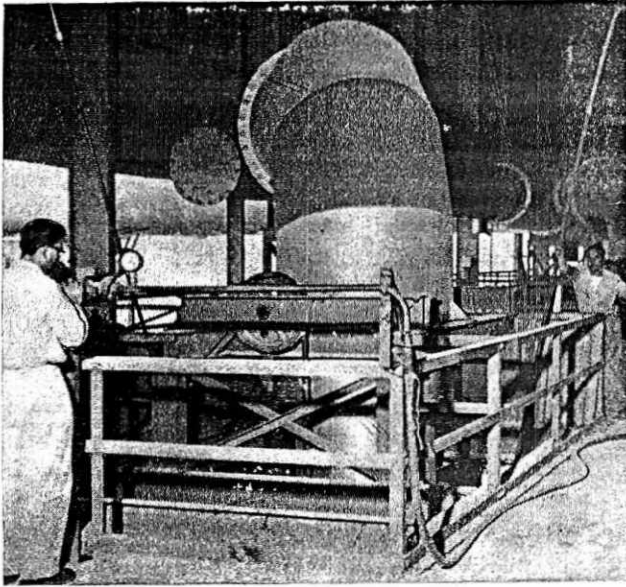
The mixer and the desiliconizing plant are housed separately in the north of the melting shop and are connected by a platform and a rail track for transfer of hot metal to the furnaces. Four 150-ton ladle cranes with 25-ton auxiliary hoists are provided in the mixer charging bay and the tapping bay.

Hot metal from the blast-furnace is brought in 85-ton ladles and stored in two 800-ton inactive mixers. The mixer is tilted by means of a 85 hp motor, driving a vertical rack through spur gear reductions.

About 80-90 tons of hot metal from the mixer is poured into a 120-ton ladle for transfer to the two desiliconizing stations. This ladle is placed on an electrically driven self-propelled carriage, one opposite each mixer (Fig. 1).

The desiliconizing station consists of a fume hood (Fig. 2) with an electrically operated lifting gear. The hood can be lowered into position 1 ft above the ladle so as to allow a liberal air circulation. Each fume hood is connected by a common exhaust main to the fume exhaust and dust extraction system.

The hood has openings to allow insertion of oxygen



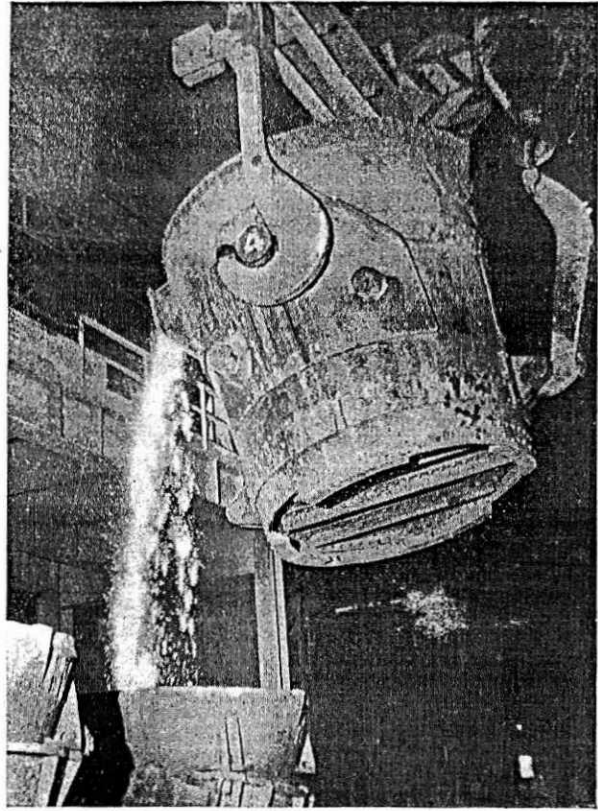
3 Desiliconizing stage showing both lances in position

lances into the metal for desiliconization. The oxygen lances are provided with flexible hose connection and control valves for regulating the pressure and the rate of oxygen input into the metal (Fig. 3).

Fans are provided to draw away the dense brown fume of iron oxide through the top of the hood to a dry dust cleaning plant consisting of a number of cyclones into which are deposited comparatively larger particles leaving the lighter ones to be discharged into the atmosphere by



4 Chimney emitting dense brown fume during desiliconizing



5 Deslagging in progress after desiliconizing

means of a chimney nearly 70 m high (Fig. 4).

A ladle carriage is provided to transfer the desiliconized metal to the melting shop.

Description of the process

A weighed amount (about 80–85 tons) of mixer metal of known composition is poured from the mixer into a 120 ton ladle which, by means of a self-propelled transfer car, is moved across the bay to the desiliconizing station below the limestone bunker from which weighed quantities of limestone are added through a cubimeter. If necessary, limestone, ore and scale may be added in the ladle before pouring the mixer metal, and scrap can be added by overhead crane. A rotary drier is also provided to deliver dry materials into the bunkers by a conveyor system.

After necessary additions the ladle is moved below the hood, which is lowered in position, and oxygen is blown through two steel lances (24 mm dia.) entering through two apertures in the refractory lined hood. About 30 m³ of oxygen can be blown per minute at a pressure of about 10–12 kgm/cm². The rate of blowing is controlled by valves connected to the oxygen pipe.

After desiliconizing, the hood is raised and the ladle is moved out and hoisted. A large part of the acid slag is removed by tilting the ladle over a slag pot (Fig. 5) and also manually by a wooden scraper. After a sample is taken, the ladle is placed on the carriage and transferred to the OH stage where the ladle is hoisted and desiliconized metal is poured through a spout into the furnace.

PRESENT WORK AT DURGAPUR

As indicated before, the Durgapur steel project is using for the first time in India, a ladle desiliconizing process (by oxygen lancing in ladle) on a scale not so far practised in any part of the world. The process, which was started

TABLE I Average data of a campaign of 500 routine blows (with limestone only)

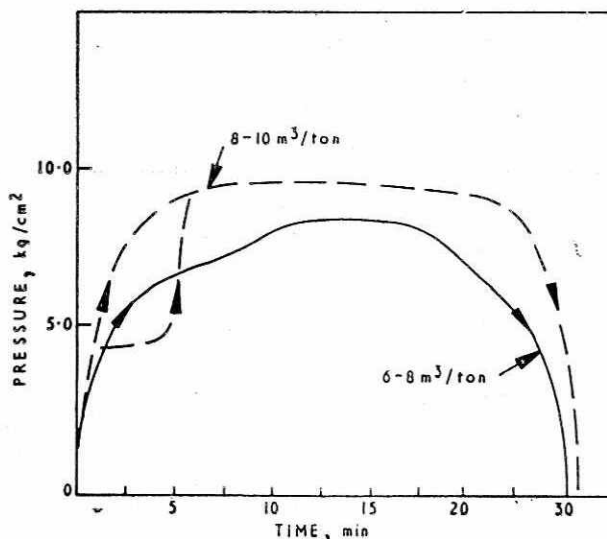
	Mixer metal	Limestone	Total charge	Blown metal	O ₂ -consumed	Lance consumed	
Total	37 400 tons	240 tons	37 640 tons	36 600 tons	250 000 m ³	6 000 m	
% or rate	99.36	0.64	100	98.0	6.7 m ³ /ton	16 cm/ton	
Average per blow	75 tons	0.5 ton	75.5 tons	73.2 tons	500 m ³	12 m	
Material	Si	high	Manganese	high	C	P	S
	low		low				
Metal before blow	1.1%	1.7%	0.75%	1.2%	3.8	0.23	0.04
Metal after blow*	0.55%	1.1%	0.52%	0.65%	3.7	0.22	0.04
	SiO ₂	Total iron	MnO	CaO	MgO	P ₂ O ₅	
Slag	42.0%	20.0%	18.5%	8.0%	0.95%	0.10%	
Fume	3.8%	60.5%	0.1	0.1		Tr	

* Analysis of several bottom samples revealed an average increase of silicon by 0.25%. Average 'silicon-oxygen' efficiency = 45%; average hood life = 165 blows; average ladle life = 85 blows

over two years ago (5 August 1960), was based on the experience of oxygen lancing in the UK in ladles containing 20-60 tons of metal. After overcoming a few initial difficulties, the process settled down to lancing about 70-85 tons of blast-furnace metal (varying from 1.1 to 1.7%Si) for about 25-30 min through two pipes (nearly 25 mm dia.) under a pressure varying from 5 to 7 kg/cm² and thereby bringing down the silicon in the blown metal. Based on the analyses of samples of metal collected from the top of the ladle, the silicon of the desiliconized metal varied from 0.55 to 1.1%. It was soon discovered that there was considerable variation in the silicon content between the top and bottom layers of the blown metal, and samples collected from the bottom showed silicon content varying between 0.7 and 1.3%. As there was considerable scope for improvement a series of investigations was started with a view to:

- bringing down the average silicon content of the metal to a lower level
- effecting a better homogenization of the blown metal
- increasing the oxygen efficiency.

With these objects in view, two sets of experiments were planned, one on a comparatively smaller scale in the foundry to study the process under more closely controlled conditions, and the other on a full scale at the desiliconizing plant. The present paper incorporates the results of the full scale investigations.



6 Pressure of lancing in kg/cm² as a function of lancing time, min. Full line curve is typical for routine lancing, dotted line for controlled lancing. Figures within the area of the plot show average total oxygen lanced per ton of metal

RESULTS AND DISCUSSION

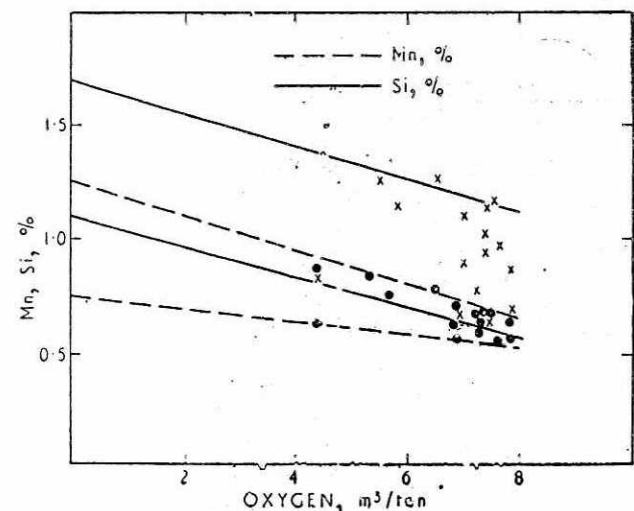
The results are shown in Tables I-V and Figs. 1-14.

Campaign of 500 heats

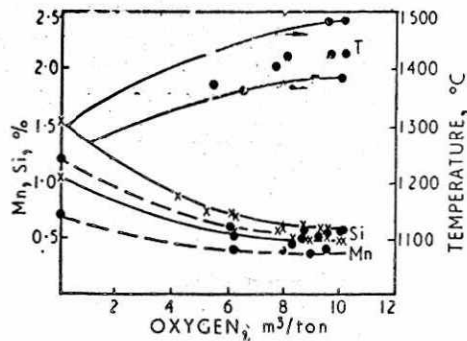
Table I shows the data of a campaign of 500 heats by using about 0.5 tons of limestone on the top of 70-80 tons of metal and lancing oxygen first at a somewhat lower pressure of 4-5 kg/cm² during the initial slag-forming period and then at an increased pressure of 7-8 kg/cm² and finally again at a somewhat lower pressure to avoid spilling large quantities of slag. The full line curve in Fig. 6 shows a typical plot of pressure as a function of lancing time. On an average, about 6-8 m³ of oxygen/ton was used to get blown metal of different silicon contents depending on the composition of the mixer metal, the amount of oxygen lanced and the mode of lancing. These data are plotted in Fig. 7 which shows two typical bands for the ranges of silicon and manganese contents in the blown metal as a function of oxygen in m³/ton. The wide scatter of points is indicative of the presence of several variable factors which affect the end results.

Investigations under controlled conditions

To be able to control some of the variables (such as pressure and rate of oxygen flow in relation to the silicon level of the mixer metal, depth and angle of lancing, quicker slag formation, etc.) as well as to get a more homogeneous metal with a lower silicon content, about



7 Si and Mn%, in the blown metal as function of oxygen in m³/ton (for uncontrolled blows)

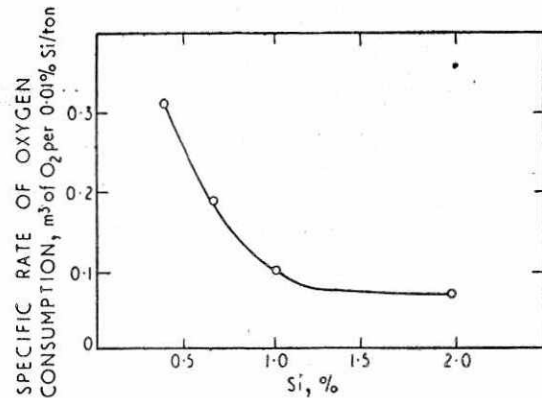


8 Si and Mn%, and temperature °C of blown metal as a function of oxygen in m³/ton (for controlled blows)

twice the quantity of limestone (about 1 ton) together with about 1 ton of ore and variable quantities of scale, were used under controlled conditions. These materials were taken at the bottom of the ladle and the mixer metal poured comparatively slowly to afford good reaction and mixing, leading to earlier formation of slag during lancing, which not only helps to minimize the rate of lance consumption but increases the oxygen efficiency. This practice, however, had to be somewhat modified later by adding limestone only at the bottom and charging ore and scale at the top to avoid the risk of explosive splashing of slag which presumably occurs owing to pieces of ore getting stuck at the bottom where they subsequently create intense localized reactions not only with Si and Mn but with C, suddenly releasing large quantities of CO gas which, accelerating towards the top under the action of buoyant forces, belches out slag and metal in tiny eruptions, particularly towards the latter portion of the blow and also during manual scraping of the slag. It was noticed, however, that such phenomena seldom occur on careful and continued lancing of oxygen under a high pressure, because the metal then gets sufficiently hot to dissolve out any residual ore at the bottom and the slag becomes fluid enough to release easily all gas bubbles.

Figure 8 shows a typical plot of Si and Mn and temperature as function of O₂ in m³/ton for the controlled blows. In spite of the wide variations in the composition of the mixer metal, the gradual decrease in the widths of the bands for blown metal may be compared with those of Fig. 7 for uncontrolled blows. The non-linear trend of the band in Fig. 8 (unlike Fig. 7) is also understandable from reference to Fig. 9 which shows that the specific rate of consumption of O₂ progressively increases with decrease in the silicon level. Further discussions in this connexion follow later in this paper.

Since the depth (h) a bubble can penetrate into a liquid is proportional to the square of the component of velocity perpendicular to the surface, (equation 5a) the lancing angle was made somewhat more vertical (about 75°–80°) and the oxygen pressure was increased to about 10 kg/cm². Since the tip of the lance has to be kept just a little below the slag metal interfacial layer (a few cm only below the surface of the metal to minimize lance consumption) and as oxygen is intensely reactive with molten pig iron, it was calculated that the oxygen bubbles from a lance with 25 mm dia. at 10 kg/cm² cannot penetrate deep enough to stir up the metal at the bottom. As the solubility of oxygen in pig iron is quite low it is helpful at this stage to compute theoretically the possible limit of penetration of the stream of oxygen bubbles under a given set of conditions and discuss some factors and mathematical relations involved in the theoretical mass transfer of oxygen from the bubbles to the bath.



9 Specific rate of oxygen consumption in m³ per 0.01% Si/ton of metal at different level of Si in hot metal. (Data from Harrison et al.)

Considerations on mass diffusivity of gas from bubble to liquid bath during lancing

For diffusion of atoms in solid metals and alloys^{14–20} it is well known that the rate of transfer mass of dm/dt of some particle (atoms or ions) is proportional to the area A and the activity gradient da/dx of that particle along some arbitrary direction x normal to A .

$$\frac{dm}{dt} = -DA \frac{da}{dx} \quad \dots \quad (1)$$

where D is the diffusion coefficient. In the case of fluids (gases and liquid) it is necessary to introduce the concept of molecular mass diffusivity D_m which is related to D as indicated in 4a and 4b. Although the fundamental equation (1) is rather difficult to apply for diffusion in fluids, values of a physical quantity similar to D have been computed from D_m by Holden and Hogg.²¹ Representing for the present the rate of oxygen input as dO/dt and assuming that a fraction η of this rate is actually transferred into the liquid mass, one gets

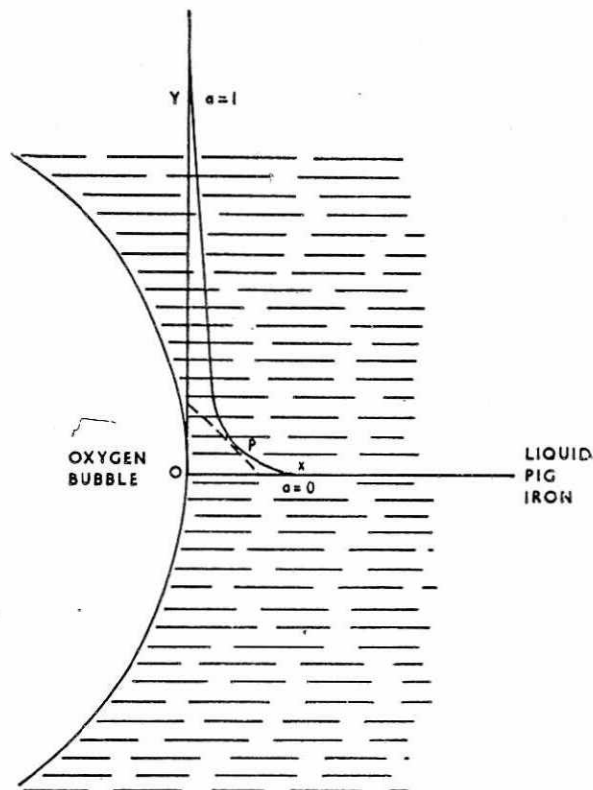
$$\frac{dm}{dt} = -DA \frac{da}{dx} = \eta \frac{dO}{dt} \quad \dots \quad (1a)$$

Being the ratio of dm/dt to dO/dt , η is the oxygen efficiency. Assuming that no oxygen escapes in elemental form but is all utilized in oxidizing Fe and other elements particularly in the case of submerged lancing in direct contact with the metal below the slag, η may be reasonably assumed to be unity. One may therefore write

$$\frac{dO}{dt} = -DA \frac{da}{dx} \quad \dots \quad (1b)$$

Reaction of O₂ with C in pig iron generates CO and may change the concentration and therefore the activity of the gas within the bubble. But reaction of oxygen with other elements in pig iron merely changes the size of the bubble but does not change the concentration of O₂ within the bubble. Neglecting the small amounts of reactions with C, one may assume the activity of nearly pure O₂ to be unity. However, the activity gradient normal to the interfacial layer of the bubble is unknown, the activity changing rapidly from unity near the interface O to nearly zero at x (Fig. 10). The slopes of the curve XPY at different points represent the different variable values of da/dx , starting from a fairly high value at the interface O and decreasing very rapidly to nearly unity at P and zero at x .

Assuming the gas bubbles to be spherical, the value of A in equation (1b) at some instant depends on the number ν and radii r of the bubbles. For the so-called



10 Sharp drop of activity a in the interface of oxygen-bubble and liquid pig iron as function of distance x within the metal

'chain-bubbling', v may be expressed²¹ approximately by the relation

$$v = \frac{v}{2r} \quad \dots \quad (2)$$

where v is the terminal velocity.

One may get some idea about the radii r from Calderbank's observation²² that d , the maximum bubble diameter, depends on the nature of the forces present in the system. For example, when viscous forces are predominant,

$$d^3 = \beta \mu^2 (\rho_1/\rho_2) \frac{1}{\Delta \rho} \quad \dots \quad (3a)$$

and when surface tension σ is predominant

$$d^2 = \sigma / \Delta \rho \quad \dots \quad (3b)$$

where ρ_1, ρ_2 are the densities of the continuous and dispersed phases, $\Delta \rho$ is the difference between their densities, μ is the viscosity of the dispersed phase and β is a suitable constant.

The diffusion coefficient D in equation (1b) is proportional to D_m^n where D_m is the so-called molecular mass diffusivity which, for sparingly soluble gas bubbles, is a function of viscosity μ and the density ρ of the gas bubble in the liquid. From Higbie's relation²³ between Reynold's number and Schmidt and Sherwood numbers for large gas bubbles in a liquid phase and assuming for the sake of mathematical simplicity, the slightly lower value of 0.83 (instead of 0.86 as suggested by Calderbank²⁴ for the value of n , the exponent of D_m in Sherwood number), it may be easily shown that

$$D_m = K(\mu/\rho)^{\frac{1}{2}} v' \quad \dots \quad (4a)$$

$$= CD^{1/n} \quad \dots \quad (4b)$$

where K and C are appropriate dimensional constants and v' is the relative velocity of bubble and liquid.

It will be evident that in the fundamental diffusion equation (1b) there are three factors $D, A,$ and da/dx . Keeping in view the very high activity and also the very high value of the activity gradient da/dx for oxygen bubble in liquid pig iron, it is understandable that the factor (DA) is a fraction of the rate of oxygen transfer dO/dt . Assuming da/dx to remain more or less constant, independent of the bubble size or velocity, it is understandable that the value of (DA) increases with increased rate of oxygen input.

Rate of oxygen input and depth of penetration

Rate of oxygen input can be increased by increasing the pressure of gas supply which also helps to increase the delivery speed of the oxygen stream and therefore its deeper penetration into the bath. The diameter of the lancing pipe is important because as the diameter decreases, the delivery speed of oxygen increases and bubble diameter decreases. Bubble size is important because the residence time for smaller bubbles of insoluble gas is longer and these have greater dispersed trajectory²¹ within the metal and therefore have greater chances to traverse a larger volume of metal. However, owing to a greater surface area for a larger number of smaller bubbles, the speed of oxygen reaction is also greater and hence residence time and also chances to cover a larger bulk of metal are, on this account, smaller. Lancing with pipes of different diameters therefore offers a suitable balance: the pipe of larger diameter helping circulation and the pipe of smaller diameter helping greater depth of penetration.

Under certain simplifying assumptions, one may get an idea of the apparent depth of penetration (h') by the oxygen bubbles into the bath from the following relation

$$h' = \frac{8 (\rho_1/\rho_2) (dv/dt)^2 \sin^2 \theta}{\pi d^4 (1+\lambda)g} \quad \dots \quad (5a)$$

where d is the diameter of the lance, ρ_1 and ρ_2 are the densities of gas and liquid respectively, dv/dt is the volume rate of input of oxygen through the lance, λ is a suitable coefficient to express the effects of the so-called drag and viscous forces of the metal, θ is the angle of lancing, and g the acceleration due to gravity. Assuming a suitable value for λ , equation (5) helps to indicate that at 10 m³/min and lance diameter of 25 mm, the value of h' is of the order of one meter. Actually the true value of h is smaller, because although sparingly soluble in pig iron, oxygen is highly reactive with it and a suitable coefficient γ as a correction factor has to be incorporated in relation 5(a) leading to the true depth of penetration h expressed as

$$h = \gamma h' \quad \dots \quad (5b)$$

These mathematical relations and discussions are important because they are helpful to indicate and predict often in a semi-quantitative way, (and sometimes quantitatively when sufficient data are available), the effects of different essential factors as (a) the rate of oxygen input both in m³/ton and m³/s, (b) the mode of lancing both with regard to angle and depth of lancing, (c) the selection of the most suitable diameter of the lancing pipe both with regard to pressure, volume and speed of delivery of oxygen, as well as (d) lance consumption, and (e) oxygen efficiencies.

These discussions are also important because the rate of flow of oxygen in a given oxidizing region should as far as practicable be matched by the rate of diffusion of fresh masses of molten metal, otherwise large quantities of iron burn out unnecessarily, particularly because of

TABLE II Average data of 10 controlled blows with limestone, ore and scale

	Mixer metal	Limestone	Ore	Scale	Total charges	Blown metal about	Oxygen consumed	Lance consumed	
Total	716 tons	9.5 tons	9.5 tons	2.9 tons	737.9	700 tons	5 433 m ³		
% or rate	97.2	1.2	1.2	0.4	100	96.5	7.6 m ³ /ton		
Average per blow	71.6 tons	0.95 ton	0.95 ton	0.29 ton	73.8	70 tons	543.3 m ³		
Material		Silicon low	high	Manganese low	high	C	P	S	
Metal before blow		1.26%	1.54%	0.78%	1.16%	4.0%	0.22%	0.04%	
Metal after blow (top sample)*		0.46	0.93	0.36	0.84	3.9	0.21	0.04	
Slag 40 kg/ton		SiO ₂	Total Fe	MnO	CaO	MgO	P ₂ O ₅	FeO	Fe ₂ O ₃
Fume 10 kg/ton		40%	23%	14%	12%	0.8%	0.3%	8.7	85.5
		3.8%	60.5%	0.1%	0.1%	...	Tr.

* The bottom samples showed an increase of silicon by about 0.1%
Average 'silicon-oxygen' efficiency = 60%.

the large concentration of iron atoms compared to those of other elements (for each atom of Mn there are about 3 atoms of Si, 25 atoms of C and at least about 125 atoms of Fe in a given volume of the mixer metal).

From these discussions and available data it becomes increasingly evident that with the pressure available, the oxygen bubble, in spite of its low solubility in pig iron, is seldom able to reach the bottom of a mass of 80 tons of metal. Although sparingly soluble in pig iron, the latter is highly reactive to oxygen and acts as a 'reactant-absorbent' much like a solvent acts as a 'solution-absorbent' to a soluble gas. As far as oxygen is concerned the entire mass of hot molten metal behaves as though it were a solvent or absorbent (much as water behaves with ammonia) and therefore, before the gas bubble could dive through the molten metal to any depth, it just disappears, leaving the bottom layers more or less undisturbed and causing what is known as stratification.

Minimizing stratification of the metal

The primary reason for the differences in composition of the top and bottom layers of the metal is the inability of the oxygen stream to reach the colder and heavier layers at the bottom. To stir up the metal from the bottom, the following procedures were adopted:

- to lance at as high a pressure as practicable
- to lance at variable angles (70°–80°), the steeper angle helping penetration
- lancing with pipes of different diameters (25–15 mm)
- immersing the lance frequently but momentarily to a greater depth, the object being to stir up the bottom metal yet not permit the lance temperature to rise to ignition temperature (900°C) (every 5 min the lance was plunged 1–1½ m deeper, held not more than 5 s at that depth and then quickly raised to the initial level). A coated lance is very helpful for this purpose
- agitation of bath by limestone and/or ore.

A suitable combination of the above was adopted with considerable success as will be seen from Table II: Not only was the metal systematically lower in Si but the stratification was considerably less, the bottom sample analysis varied from the top by only 0.1% on the average.

Lancing to a lower silicon

Figure 8 shows ranges of Si and Mn as a function of volume of oxygen in m³/ton. This reveals certain interesting features not detectable in the more or less linear band of Fig. 7. It is evident from Fig. 8 that the band is non-linear and tends to flatten with increased volume of oxygen lanced. This is understandable because the specific

rate of oxygen consumption increases progressively at lower silicon levels.

This will be evident from Fig. 9 which shows that to remove one point (0.01%) of Si/ton from a metal containing 0.4% Si, the volume of O₂ required is nearly 3 times more (namely 0.3 m³ oxygen per 0.01% Si per ton) than that required (namely 0.1 m³) to remove the same one point of Si from the metal containing 1.4% Si (or higher). Moreover with higher initial silicon content (greater than 1.4% Si) it becomes essential to control the temperature by the addition of scrap and ore to bring down the silicon effectively and economically to 0.1% and lower. Iron losses by oxidation increase progressively on continuous blowing. At higher temperatures, the thermal losses also increase. For all these reasons no attempt was made to reduce the average silicon content of the blown metal to a level lower than 0.4% in the present series of investigations. It was observed that with 70 tons of metal containing about 1.4% Si, Si could be effectively reduced to about 0.4–0.5% by lancing oxygen at the rate of about 20 m³/min for 35 min. The pressure of lancing had to be kept steadily higher than the conventional lancing as indicated by the upper dotted curve compared to the full line curve in Fig. 6.

Table III shows a typical log sheet indicating some details of the operation including the amounts and composition of the mixer metal, blown metal, slag and flue dust together with the rates of oxygen and lance consumption, the temperature of the metal before and after lancing and also when it reaches the OH furnace.

The theoretical and actual rise of temperature and their differences ΔT as function of volume of oxygen per ton of metal

The theoretical rise of temperature has been computed in the usual way from the relation

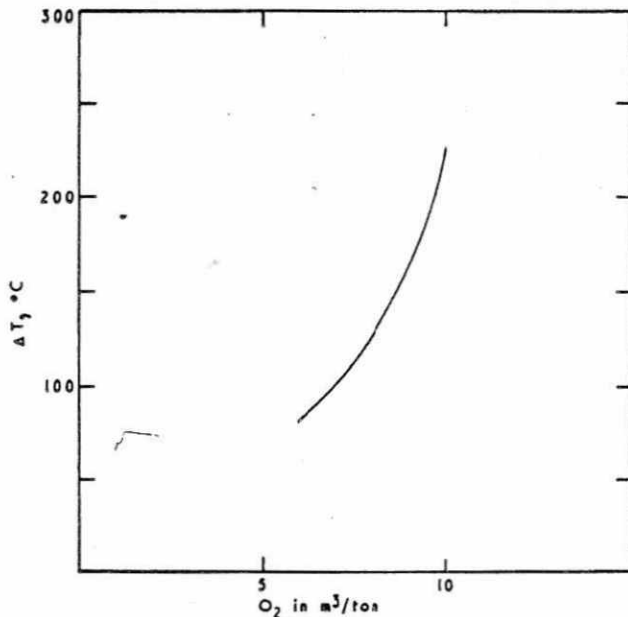
$$\Delta T = \frac{\Sigma \Delta Q}{m C_p} \quad \dots \quad (6)$$

where ΔT is the rise of temperature, $\Sigma \Delta Q/m$ is the sum of the heat evolved per unit mass of metal owing to oxidation of the different elements including iron and C_p is the average specific heat of pig iron (0.194 cal/g °C between 1250 and 1450°C) obtained by plotting values²⁵ of enthalpy H as function of temperature T and then plotting the slopes $(dH/dT)_p = C_p$ as function of T .

For quicker computation without much loss of accuracy the following relation²⁶ has been used in computing the theoretical rise of temperature ΔT_1

$$\Delta T_1 = (3.1\text{Si} + 1.3\text{C} + 0.8(\text{Mn} + \text{S}) + 2.0\text{P} + 0.5\text{Fe})^\circ\text{C} \quad (7)$$

where Si, C, Mn, S, etc. represent the so-called number of points, that is, 100 × % decrease of the respective elements, (e.g. if the %Si before and after lancing be 1.46%



11 ΔT , the difference of temperature between the theoretical and actual rise of temperature of blown metal as function of oxygen in m^3/ton

and 0.56% respectively, $Si = 100 \times 0.90 = 90$).

The data on actual rise of temperature ΔT_2 were obtained by taking temperatures before and after lancing by an optical pyrometer. A special immersion thermoelectric pyrometer was devised to take the temperature of the metal. A graphical plot of simultaneous readings of the optical pyrometer and the immersion pyrometer indicated the average correction to be applied to the optical pyrometer readings.

The average variations between the ranges of theoretical and actual rise of temperatures for a number of cases as function of volume of oxygen blown per ton of metal are plotted in Fig. 11. The non-linear relation and also the very large differences on continued blowing are due to greater thermal losses at higher temperature. Open ladle desiliconization has this inherent disadvantage and the data of Fig. 11, for a given plant practice, are necessary to evaluate the optimum economic level of desiliconization in open ladles particularly in view of the progressively lower oxygen efficiencies on desiliconization to progressively lower silicon levels.

The theoretical and actual volumes of oxygen consumed: different oxygen efficiencies

The theoretical volume V of oxygen required per ton of metal has been computed from the following relation

$V = (0.08Si + 0.093C + 0.02Mn + 0.09P + 0.07S)m^3/ton$ (8) where Si, C, Mn, etc. represent, as before, the number of points, that is $100 \times \%$ decrease of the elements concerned. The numerical coefficients in equation (3) represent the volume of oxygen in m^3 required to oxidize 0.01% of the element per ton of metal. If the actual volume consumed be V_a , the overall oxygen efficiency is given by

$$\text{Overall oxygen efficiency} = \frac{V}{V_a} \times 100 \quad \dots (9)$$

If the volume of oxygen required for the removal of the silicon be V_{si} , oxygen efficiency for the removal of silicon is given by

$$\text{Silicon oxygen efficiency} = \frac{V_{si}}{V_a} \times 100 \quad \dots (10)$$

For example from the data in Table III one gets the

TABLE III Typical desiliconizing log sheet

		Si	Mn	P	S	C			
Date _____									
Cast _____									
Mixer metal	75 tons	1.46	0.92	0.22	0.04	4.1			
Blown metal	72.8 tons	0.56	0.46	0.20	0.038	3.9			
		SiO ₂	CaO	P ₂ O ₅	Fe	MgO	MnO	FeO	Fe ₂ O ₃
Slag		42.0	8.0	0.12	19.8	0.94	18.4
Flue dust		3.8	0.1	0.06	0.1	...	0.1	8.7	85.5
Time									
0 h	00 min	Added 1 000 kg limestone at the bottom of the ladle							
"	01 "	Started pouring mixer metal							
"	03 "	Metal sample taken							
"	05 "	Finished pouring mixer metal							
"	06 "	500 kg scale and 1 000 kg ore added on top of metal							
"	07 "	Ladle arrived below hood and hood placed in position							
"	08 "	Lancing started							
"	41 "	Lancing stopped							
"	43 "	Ladle hoisted by crane							
"	45 "	Deslagging started.							
"	50 "	Deslagging finished							
"	51 "	Blown metal sample taken							
"	54 "	Ladle placed in transfer car							
"	58 "	Blown metal arrived at OH furnace							
Average O ₂ flow rate		= 21 m ³ /min							
O ₂ consumed		= 680 m ³							
Actual rate of O ₂ consumed		= 9.1 m ³ /ton							
Theoretical rate of O ₂ consumption		= 10.2 m ³ /ton							
Lance consumed		= 7.4 meters							
Rate of lance consumption		= 9.8 cm/ton							
		= 22.4 cm/min							
Overall oxygen efficiency		= 100%							
Silicon oxygen efficiency		= 79%							
Temperature before lancing		= 1230°C							
Temperature after lancing		= 1380°C							
Actual rise of temperature		150 deg C (theoretical rise=340 deg C)							
Temperature during pouring in OH		= 1330°C							
Loss of temperature during transit		= 50 deg C							

$$\text{overall oxygen efficiency} = \frac{10.2}{9.1} \times 100 = 112\%$$

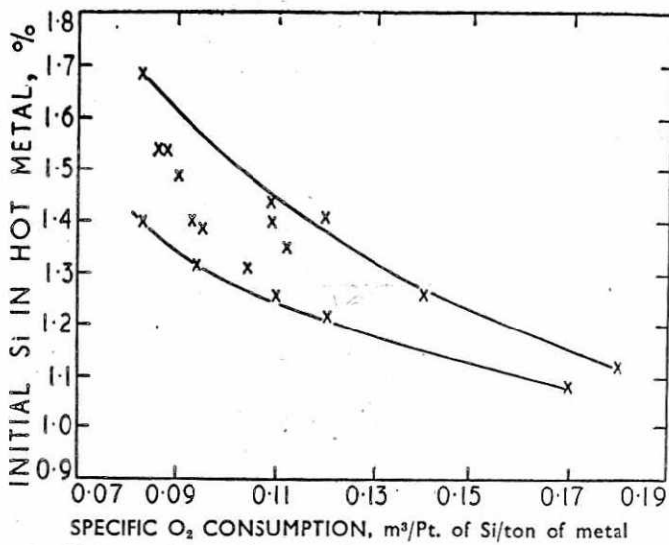
$$\text{Since } V_{si} = 100 (1.46 - 0.56) \times 0.08 = 7.2 \text{ m}^3$$

$$\text{the 'silicon-oxygen' efficiency} = \frac{7.2}{9.1} \times 100 = 79\%$$

If, due to the effect of stratification, one takes into account the comparatively higher silicon content at the bottom of the ladle, the actual 'silicon-oxygen' efficiency is lower. Bottom samples of blown metal, collected after pouring the metal into the OH furnaces, showed variations of silicon between 0.1 and 0.3% from those of the corresponding top samples in normal lancing. Under controlled conditions, however, this difference was much smaller. For example, for the typical case in Table III, the Si of the bottom sample, being 0.72%, the average Si of the blown metal may be taken as the arithmetical average, namely $\frac{1}{2}(0.56 + 0.72)$ or 0.64%, and then the net silicon-oxygen efficiency = 72%.

In fact the net silicon-oxygen efficiency is still lower, because considerable homogenization of the stratified layers takes place within the ladle during pouring and the sample collected at the end of pouring therefore does not represent the actual composition of the bottom layer.

To be able to get a better picture of the condition of stratification, a simple device was made to collect samples from different depths of the blown metal. It consists essentially of a long steel tube closed at one end (coated preferably with refractory material). Near the bottom of the tube (about 6 in from the enclosed end) a small hole is drilled and is plugged with aluminium. The tube is plugged quickly into the blown metal



12 Variation in specific rate of oxygen consumption with initial silicon content of the hot metal before lancing

at the desired depth. The aluminium plug melts and permits molten metal to flow into the tube. On lifting up, some extra metal flows out from the hole but enough is left at the bottom to form a good laboratory sample.

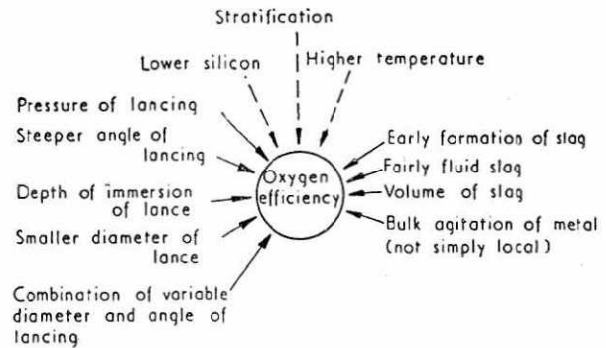
If a linear relationship be assumed between the composition and depth of metal in the ladle, one is justified in taking an arithmetic mean of the values of Si of the top and bottom samples in computing the average Si content of the whole metal. But, as later experiments proved, such a linear relationship seldom holds. To get the average Si content, one may of course pour back the blown metal into another ladle and thereby effect thorough homogenization of the stratified layers. But such a process involves loss of both metal and heat and also means delay. To avoid this, one may adopt the procedure of a simple integration. For this purpose it is only necessary to know the silicon content of three metal samples, from the top, bottom, and a third at some other known depth of the blown metal. Assuming the form of variation of silicon as function of height, and as the mass of metal as function of height for a given ladle may be easily computed, one may obtain the corrected average silicon content by straightforward integration.

In large-scale industrial practice it is not practicable to collect, as a matter of routine, samples of metal from different depths of the metal after lancing. However, for the sake of investigation and to get an approximate idea of the magnitude of correction, a typical computation was made and it was found that for the case in which the arithmetical average indicates 0.64%Si, the corrected average is 0.69% and on this basis the net silicon-oxygen efficiency=68%.

Thus, for a typical case, on the basis of only top sample analysis, the silicon-oxygen efficiency is 79% but on the basis of arithmetical average of the top and bottom samples, the efficiency is 72%, while on the basis of a more rigorous analysis as indicated above, the efficiency is only 68%. The corresponding figures for typical uncontrolled normal blows are 58%, 51% and 46% only.

Lancing for higher oxygen efficiency

The primary object of lancing at Durgapur has been to remove as much of the silicon as possible from the mixer



13 Factors affecting oxygen efficiency (full line arrows indicate increase, dotted line arrows, decrease)

metal. From thermodynamic considerations it is well known, however, that the efficiency of oxygen with regard to the silicon oxidation progressively decreases with rise in temperature as well as with the decrease in the silicon content (and therefore activity of the silicon) in the metal. Apart from these, however, a few other factors come into play to decrease or increase the oxygen efficiency. Fundamentally these factors are related to kinetic considerations affecting rates of reaction. For example a larger interfacial area between metal and gas bubbles (namely, larger number of smaller bubbles) and greater depth of penetration of the bubbles to effect better mixing as well as to afford better opportunities for the iron oxide molecules (almost simultaneously formed along with the oxidation of silicon) to part with their oxygen to the neighbouring silicon/manganese atoms—all these tend to increase the oxygen efficiency. Figure 13 indicates some of the important factors which affect the oxygen efficiency. To be able to put some of these scientific considerations into effective action within a large bulk of metal, it is necessary to adjust the pressure of lancing, the diameter of the lancing pipe, the angle and depth of lancing, the quantity as well as the physical and chemical characteristics of the slag (to facilitate its early formation, to minimize spillage, lance consumption, and corrosion of the refractories, and to arrest if possible at least a part of the rich iron oxide fume by bulk of the slag). A more or less steady pressure of about 10 kg/cm² and adoption of a few methods to minimize stratification, as indicated earlier in the section, 'Minimizing stratification of the metal' by agitating the metal and therefore bringing fresh metal into the active areas and thereby minimizing unnecessary oxidation of iron, help definitely to increase the oxygen efficiency. In India, rich iron ore being comparatively cheaper than oxygen, it is an advantage to obtain a part of the oxygen from this source. Iron ore also helps to control the temperature of the metal and thereby indirectly helps to increase the oxygen efficiency.

Although the amounts of consumed oxygen for the same amount of removed silicon varied from heat to heat, the general scatter of the points could easily be explained on the basis of the factors indicated before as well as on the basis of the initial silicon content of the metal before lancing. This is also evident from Fig. 12 which shows specific oxygen requirement per point of silicon per ton of metal as a function of the initial silicon level of the metal before lancing. The gradual decrease in the width of the band is particularly noteworthy. It indicates that at higher silicon levels, the rate of specific oxygen consumption is comparatively less affected by variation of the initial silicon content. For example, the specific rate of 0.08 to 0.09 m³/0.01%Si/ton of metal remains

TABLE IV Materials balance for pretreatment of iron, tonnes

a Incoming material

Material	Weight	Fe	C	Si	Mn	P	S	CaO	SiO ₂	MnO	MgO	FeO/Fe ₂ O ₃	CO	CO ₂	O ₂	Volatiles
Mixer metal	80.0	74.44	3.20	1.25	0.88	0.20	0.03									
Limestone	1.0								0.60					0.30	(0.08)	0.02
Ore	1.0	0.38							0.07			(0.32)			(0.20)	0.03
Scale	0.5	0.18										(0.20)			(0.12)	
Oxygen	1.0														1.0	
Total	83.50	75.00	3.2	1.25	0.88	0.20	0.03		0.67			5.2		0.30	1.40	

b Outgoing material

Material	Weight	Fe	C	Si	Mn	P	S	CaO	SiO ₂	Al ₂ O ₃	MgO	MnO	FeO/Fe ₂ O ₃	CO	CO ₂	O ₂	Volatiles
Blown metal	78.22	74.0	3.15	0.45	0.40	0.19	0.03										
Slag	4.16	0.50		0.80	0.48	0.01			0.65				0.52			1.2*	
Fume	0.65	0.50							0.02							0.14	
Gases	0.46		0.05											0.30		0.06	0.05
Total	83.50	75.0	3.20	1.25	0.88	0.20	0.03		0.67				0.52	0.30		1.40	0.05

* 1.2 tonnes of oxygen is distributed in slag as 0.91 t (or 65% of total O₂) in SiO₂, as 0.14 t (or 10%) in FeO, 0.14 t (or 10%) in MnO, and 0.01 t (less than 1%) as P₂O₅; 0.14 t of O₂ in fume account for 10% of the total O₂. The balance 0.06 t (4%) goes to gases

about constant irrespective of whether the initial silicon level varies from 1.4 to 1.7%. This is not so, however, when the initial level of silicon is around 1.1% or lower. The specific rate of oxygen consumption from this level downwards tends to fluctuate widely. For example, for a variation of initial level of silicon from 1.2 to 1.1% only the specific rate of oxygen consumption may vary from 0.12 to as much as 0.18 m³ per 0.01%Si per ton of metal, i.e., an increase of 50% in the specific rate for a decrease of only about 10% in the initial silicon level. These considerations are important when one attempts to attain higher oxygen efficiencies starting with a metal of comparatively lower silicon content.

Material balance and distribution of oxygen

With a view to getting an approximately quantitative idea of the weights of slag, fumes and gases and the distribution of materials (particularly oxygen) an attempt has been made to compute the materials balance with the incoming and outgoing materials. A typical materials balance sheet is indicated in Table IV.

The weight of the slag has been computed on the basis of manganese balance and this may also be approximately checked from the sum of the different slag-forming materials. It has been assumed that about half of the oxygen from the CO₂ of the limestone and a major portion of the oxygen from ore and scale are available for oxidation to make a total of 1.4 ton of oxygen including 1 ton of gaseous oxygen. From the different analyses of the constituents it is then easy to compute the approximate average distribution of oxygen as shown in Table V.

One disadvantage of the addition of slightly increased quantities of limestone, ore and scale is the bulk of highly siliceous slag (about 50-60 kg/ton of metal) which need be carefully removed as much as possible before the metal is sent to open-hearth furnaces. Nevertheless the advantages gained fully justify such additions.

TABLE V Average distribution of oxygen

Materials used (70 tons mixer metal)	Average distribution of oxygen				
	For Si, %	For Mn, %	For Fe in slag, %	For Fe in fume, %	Gases etc., %
With 6 to 7 kg limestone/ton metal but without ore and scale	45	8	15	20	12
With 12-14 kg limestone/ton+12-14 kg ore/ton (without scale)	55	8	10	15	12
With 12-14 kg limestone/ton+12-14 kg ore/ton+6 to 7 kg scale/ton	65	10	10	10	5

Minimizing the rate of lance consumption

The average rate of lance consumption in the routine blows was about 12 m per blow, that is, about 16 cm per ton of metal. This figure is comparatively rather high.

In the present series of investigations the use of ore and scale along with limestone has been helpful to decrease the rate of lance consumption by early formation of slag.

Several attempts were also made to use lances coated with refractory materials and an actual trial with some of these lances (coated both inside and outside with a thick slurry of burnt magnesite) showed that the rate of lance consumption could be virtually reduced to half.

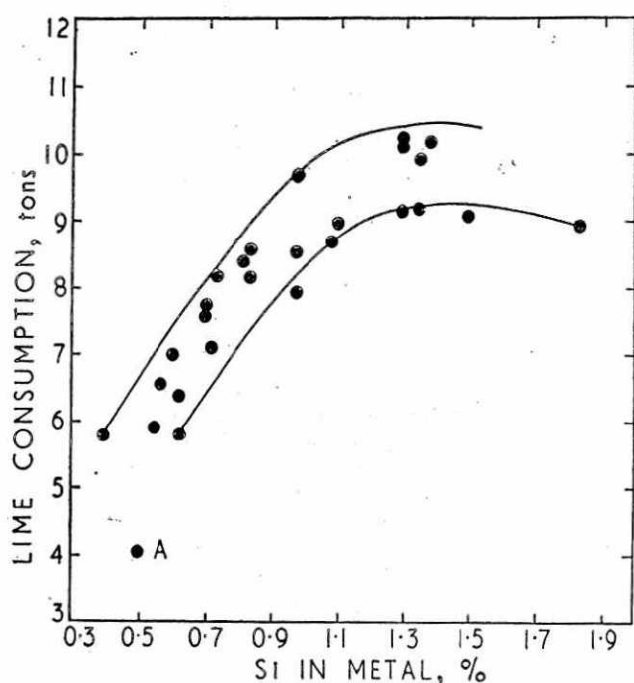
The use of a comparatively smaller dia. but thick walled pipe has also been helpful to minimize the rate of consumption.

Apart from the thicker wall, the rate of consumption of pipes of smaller dia. (18 mm instead of 25 mm) has been less due to greater velocity of emission of oxygen under a given pressure. The greater pressure of lancing used in this investigation has also been helpful to decrease the rate of lance consumption.

Thus a combination of the following factors has been helpful to minimize the rate of lance consumption:

- (i) use of scale and ore to help early formation of slag
- (ii) use of thicker-walled pipe
- (iii) use of smaller dia. pipes
- (iv) higher pressure of lancing
- (v) use of coated lance.

From the data indicated in Table III it may be noted that the rate of lance consumption is 9.8 cm per ton for the controlled blows compared to 16 cm per ton for the routine blows. Further work is in hand in this connexion with a view to minimize the rate of lance consumption still further.



14 Average lime consumption in OH furnace as function of Si% in blown metal

Some effects on open-hearth practice

The lower silicon content, the higher temperature and last but not least, a more homogeneous metal had quite a few advantages in the open-hearth practice at Durgapur, particularly in the rate of limestone/lime consumption per ton of iron. Figure 14 shows a typical plot of lime consumption as function of silicon content of the molten metal used. The band clearly indicates a sharp drop in the rate of lime consumption with decrease in the silicon content of the metal. Point A (Fig. 14) refers to the present investigation.

It was observed that for ordinary heats with routine blown metal, opening carbon in the bath is usually high and fluctuating. With the use of experimental blown metal under controlled conditions, it was observed that the bath opened more or less with the desired carbon. Owing to smaller quantities of limestone added, the slag was more fluid. No further lime additions were necessary during the working period and the rate of decrease of carbon was under better control. The actual period of working was also considerably lower (1½ h compared to an average of 2½ h for normal routine working).

Further work in this connexion is in hand with a view to increase the speed and quality of steel production.

CONCLUSION

Durgapur steel project for the first time in India has adopted the practice of pretreatment of 80 tons of mixer metal in a 120 ton ladle, the largest of its kind in the world. However, for such a large volume of metal there were certain inherent difficulties in achieving low silicon as well as a homogeneous metal by lancing oxygen from the top. Attempts have been made in the present series of investigations not only to reduce the silicon content of the metal but also to get as homogeneous a metal as possible. In this connexion the following conclusions may be drawn :

1. In spite of fluctuations in the silicon content of the mixer metal the silicon content of blown metal by oxygen lancing has been brought down to 0.46%.

2. The so-called stratification has effectively been reduced by a suitable combination of the following :
 - (a) lancing at a high pressure (10 kg/cm²)
 - (b) lancing at variable angles 70° to 80° (the less steep angle helping circulation and the steeper angle helping penetration)
 - (c) lancing with pipes of different diameters
 - (d) immersion of the lance frequently but momentarily to a greater depth
 - (e) use of limestone at bottom.
 The difference between the silicon content of the bottom and top layers has been reduced on an average to 0.1% only.
3. Oxygen efficiency has been increased from an average of 45% to 65% by a suitable combination of the following :
 - (a) use of 12-14 kg of limestone/ton, a similar amount of ore and about 6 to 7 kg of scale/ton (limestone preferably at the bottom)
 - (b) bulk agitation of metal by
 - (i) increased pressure of lancing (10 kg/cm²)
 - (ii) steeper angle of lancing
 - (iii) smaller dia. of lance (18 mm)
 - (c) earlier formation of fluid slag and somewhat increased volume of slag
 - (d) bring down the silicon to about 0.5%
 - (e) not raising the temperature beyond 1450°C.
4. Rate of lance consumption has been reduced from 16 cm/ton to about 9.8 cm/ton by comparatively earlier formation of slag, higher pressure of lancing, use of thick-walled pipe and use of pipe of smaller dia.
5. The following advantages in OH practice have been established :
 - (a) saving of limestone/lime per ton of steel ;
 - (b) better control of metal and slag ;
 - (c) greater speed of working period.

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