2.6.5 Restructuring the furnace lining

(1) Aggregate furnace output and furnace life in Japan

In Japan, the installed capacity of blast furnaces has been increased steadily for years. In keeping with this, major technical innovations have also been achieved in both tooling and operation of equipment in a sweeping range, including high-pressure high-temperature blasting, beneficiation, compounded blasting, charging methods, analysis on physical and chemical behavior in the furnace, instrumentation and computerized control to name a few.

At present, it is possible to turn out 5,000 tons of pig iron per m^3 of inner volume per campaign.

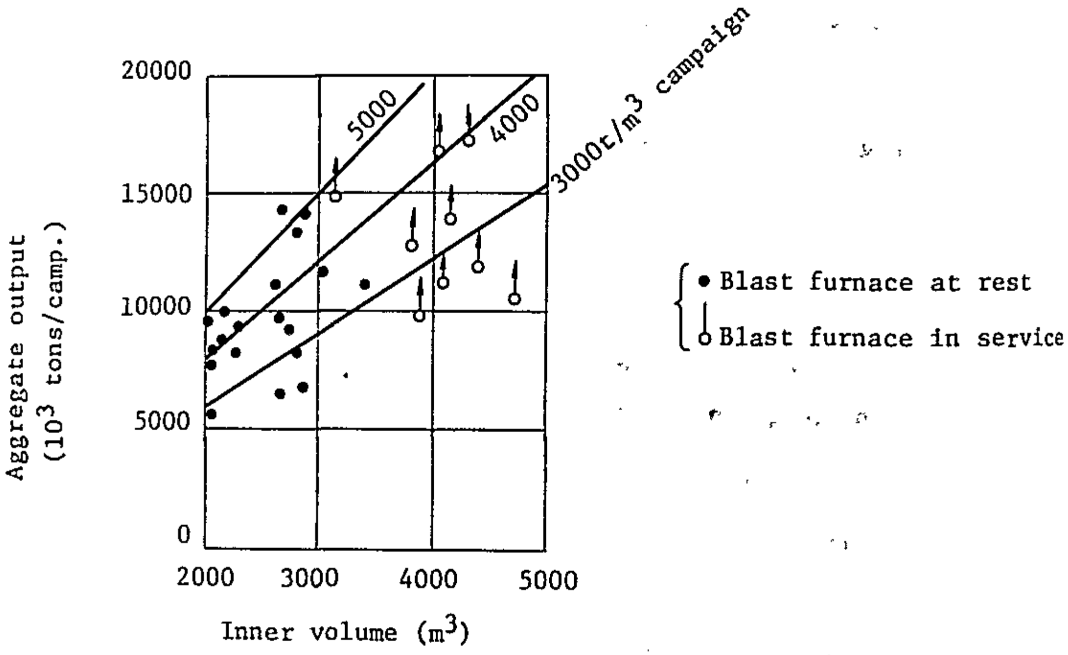


Fig. 2.6-19 Inner volume vs. pig iron output in Japan
(as of September 1976)

Total 2.6-9 Practice of the service life of small blast furnaces in Kobe Steel

Works	F'ce No.	Inner volume	Kind of iron to be smeltered	Blow-out date	Total time worked	Aggregate output	t/m^3.camp
Amagasaki	1	$721m^3$	Foundry pig iron	Nov. 5, 1976	8 years and a half	3,495,000	4.847
Amagasaki	2	$904m^3$	Pig iron for steel use	Mar.20, 1975	8 years and 10 months	5,226,680	5.782
Kobe	1	$904m^3$	"	Nov.16, 1975	7 years	4,523,400	5.004
Kobe	2	$1243m^3$	"	Oct. 8, 1970	9 years and one month	6,013,000	4.837

(2) Basic requirements for extending the blast furnace service life

What are the mechanisms of fretting the blast furnace refractories has already been expatiated in para. 2.6.1. Discussions here are made over the bottom and hearth bricks are of controlling importance for the extension of blast furnace service life.

In recent years, the service life of the blast furnace has been extended amazingly. This is greatly indebted to carbon bricks. Chamotte bricks are inferior in corrosion resistance to molten metal and slag to carbon bricks. This is because the former admits the penetration of molten metal or slag and are prone to gets the joints slackened to make the bricks themselves shaky. Shown in Table 2.6-10 is the corrosion resistivity to molten iron and slag of chamotte bricks and carbon bricks. The data were obtained by exposing the 65 mm by 200 mm surfaces of brick specimens (55 mm x 65 mm x 200 mm) to 1.2 kg of molten iron or slag arc-heated at 1,650°C in a rotary drum test crucible for 2 hrs. to examine their corrosion.

Table 2.6-10 Corrosion of bricks by molten iron and slag

	Chamotte brick		Carbon brick	
	Molten slag	Molten iron	Molten slag	Molten iron
Corrosion (%)	54.7	39.0	0.0	7.1
Max. depth of corrosion (mm)	46.0	33.0	0.0	7.5

From the data in Table 2.6-10, it is evident that the chamotte brick is very vulnerable to corrosion by molten slag and molten iron as well. On the other hand, the carbon brick is a standout, particularly against molten slag, though it yields to molten iron to a little extent. All these facts justify the carbon brick as a lining for the basin.

Namely, the carbon brick is preferred in the hearth and and furnace bottom which come in contact with molten slag and iron. The carbon brick, though excellent, cannot be a cure-all, and can be damaged when the following happen.

i) Dossolution of carbon into unsaturated molten iron.

ii) Oxidation by oxidizing gases such as H_2O, CO_2 and O_2.

iii) Breakdown due to thermal stress.

iv) Corrosion by alkali, etc.

The carbon brick is therefore required to be resistant against corrosion by molten iron and alkali, stable against thermal expansion and contraction and have a high thermal conductivity. For reasons above, the carbon bricks of proven quality available from reliable manufacturers should be picked up for blast furnace use.

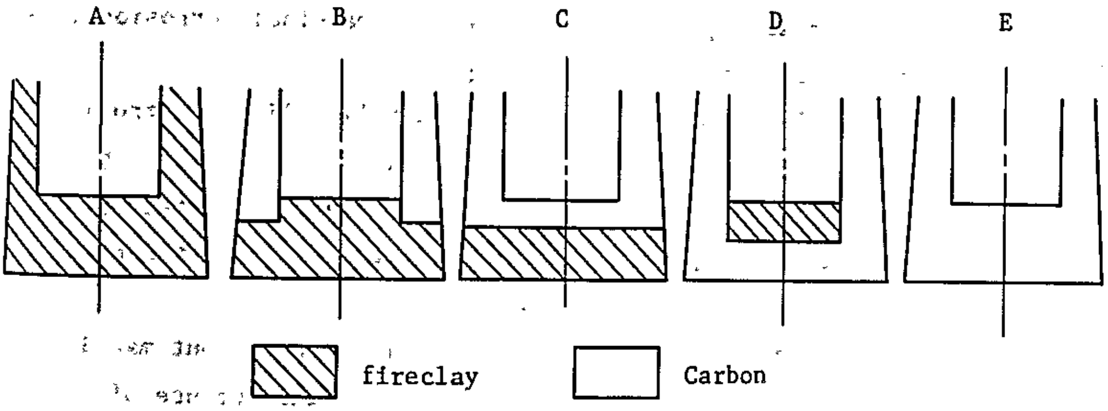


Fig. 2.6-20 Furnace bottom brick masonry

The furnace bottom brick masory has changed from all-fireclay structure to carbon-in-the-top and fireclay-in-the-bottom arrangement, fireclay-in-the-top and carbon-in-the-bottom arrangement and then to all-carbon structure in keeping with the increase in furnace capacity and upgrading of brick materials.

While the various schemes, including these, have been tried, there still is needed to establish which scheme is the best for the furnace bottom masonry.

According to W.G. Cowling, the marginal corrosion line of the bricks in the furnace bottom is represented by a line of iron solidifying temperatures, i.e., an isothermal line of 1,150°C. In the case of carbon-in-the-top and fireclay-in-the-bottom arrangement, the carbon bricks in the top are bound to be fretted away, and the corrosion may reach the fireclay bricks in the bottom depending on the thickness of brick layer. It is believed that the corrosion will progress more the larger the hearth diameter; namely, the refractories will be washed out in a concave form.

On the other hand, the fireclay-in-the-top and carbon-in-the-bottom arrangement has its marginal corrosion line in the upper fireclay brick layer, and the corrosion will take place uniformly to a limited extent.

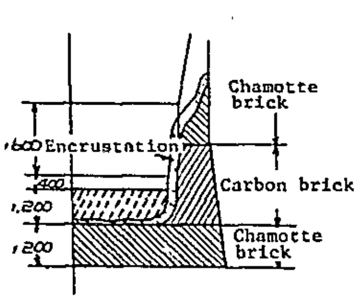
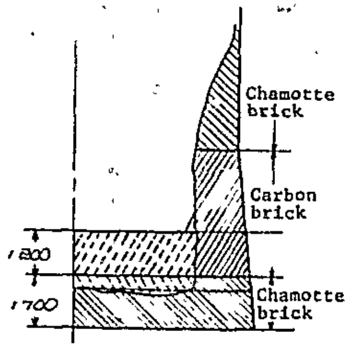
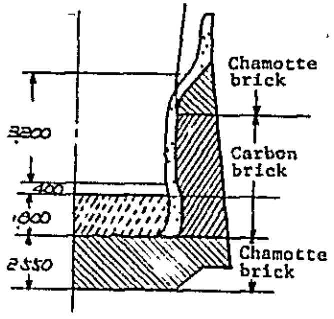
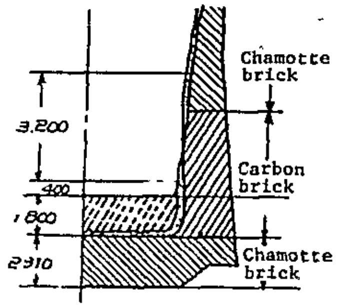
In the case of all-carbon scheme, the marginal corrosion line will be limited to a shallow depth.

As for the carbon bricks in the sidewalls, little corrosion will take place as demonstrated in Fig. 2.6-21 with respect to Amagasaki furnaces. They are in good shape and retain almost their integrity, affording a clear proof of the efficacy of the carbon brick.

In this case, however, it is necessary to carry out mantle cooling with water more carefully while avoiding the use of water-mixed clay dough for blocking the tap hole.

For the COLAR, the scheme C, D or E specified in Fig. 2.6-20 is recommended from the structural viewpoint, but the scheme C may be the best so far as the economics are concerned. If the scheme C is employed, the thickness of the carbon brick in the furnace bottom should be at least 1,000 mm. Also it is needed to design the brick shapes so as to prevent the bricks coming up loose.

Fig. 2.6-21 Corrosion of hearth and bottom bricks in the blast furnaces at Amagasaki Works

	Amagasaki No.1 BF (3rd campaign)	Amagasaki No.1 (4th campaign)	Amagasaki No.2 BF (1st campaign)	Amagasaki No.2 BF (2nd campaign)
Blowing-in	March 31, 1960	May 4, 1968	May 25, 1957	May 25, 1966
Blowing-out	March 1, 1968	November 5, 1976	March 1, 1966	March 20, 1975
Campaign	7 years and 11 months	8 years and 6 months	8 years and 9 months	8 years and 10 months
Total output, tons	2,485,000	3,495,000	3,022,000	5,226,760
Total output, tons/m³	3,750	4,847	4,013	5,782
Sketch of furnace bottom corrosion				
	The bosh bricks were washed away totally. The furnace bottom carbon bricks of 1,200 mm thick were completely lost. The chamotte bricks in the bottom remained in shape. No corrosion on the hearth bricks.	Serious damage on the bosh upper bricks. The furnace bottom carbon bricks of 1,200 mm thick were completely lost. The chamotte bricks in the furnace bottom were partly washed away. No corrosion on the hearth sidewalls.	Serious corrosion on the bosh bricks. The furnace bottom carbon bricks of 1,800 mm thick were completely lost. No corrosion on the chamotte bricks in the furnace bottom. A slight corrosion on the lower part of the hearth sidewalls.	Slight loss of bosh bricks. The furnace bottom carbon bricks 1,800 mm thick were completely lost. No corrosion on the furnace bottom chamotte bricks. A slight degree of corrosion on the lower part of the hearth sidewalls.

⬚ Deposition ▨ Corroded part of chamotte brick ▧ Corroded part of carbon brick ▨ Carbon brick ▧ Chamotte brick

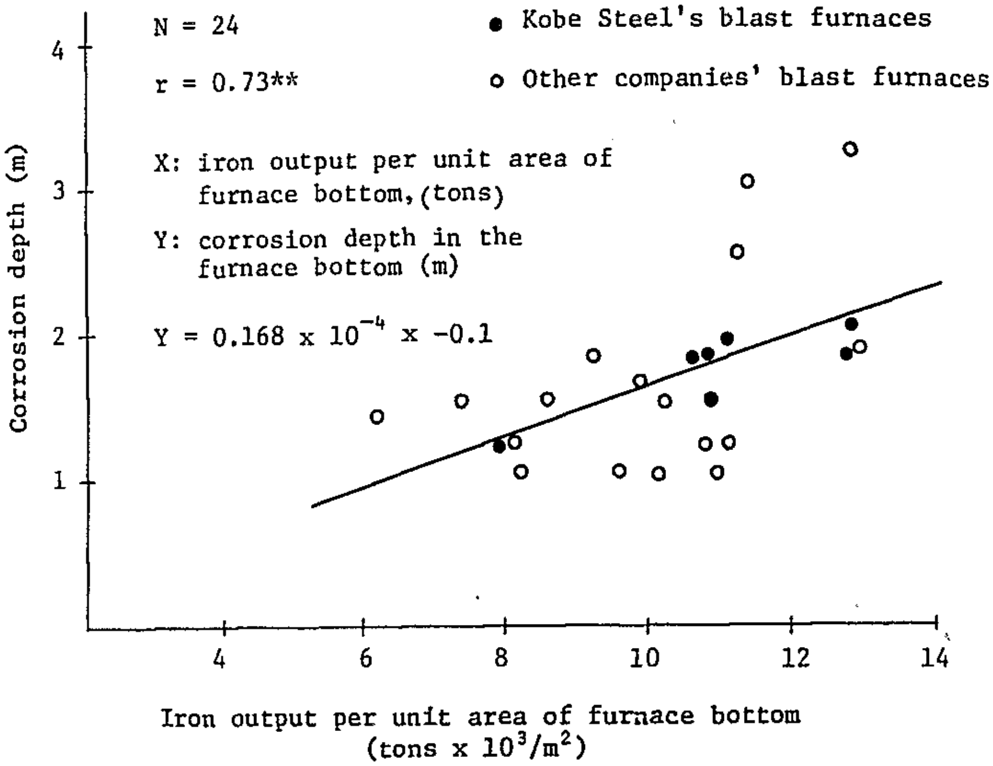


Fig. 2.6-22 Iron output per unit area of furnace bottom and corrosion depth

Fig. 2.6-22 shows the relationship between the iron output per unit area of furnace bottom and the corrosion depth in the furnace bottom bricks. From the regression formula in Fig. 2.6-22, it is suggested that a ton of pig iron output per m^2 of furnace bottom area will be accompanied by a loss of about 0.017 mm in the thickness of bricks. In the case of the Nelly, if carbon bricks are used 1.0 m thick and if the iron output is 166.6 tons/day, then the service life of the carbon bricks is estimated as follows.

$(((1.0 - 0.1)/(0.168 \times 10^{-4})) \times (3.8/2)^2\pi/(166.6 \times 365)$

$= 10$ years

The Nelly is operating at a low iron temperature and is small in size. In addition, the iron is of the high silicon type. Thus, a service life of about 12 years will be warranted if the carbon bricks are laid no less than 1.0 m thick.

(3) Recommendations for furnace brick masonry

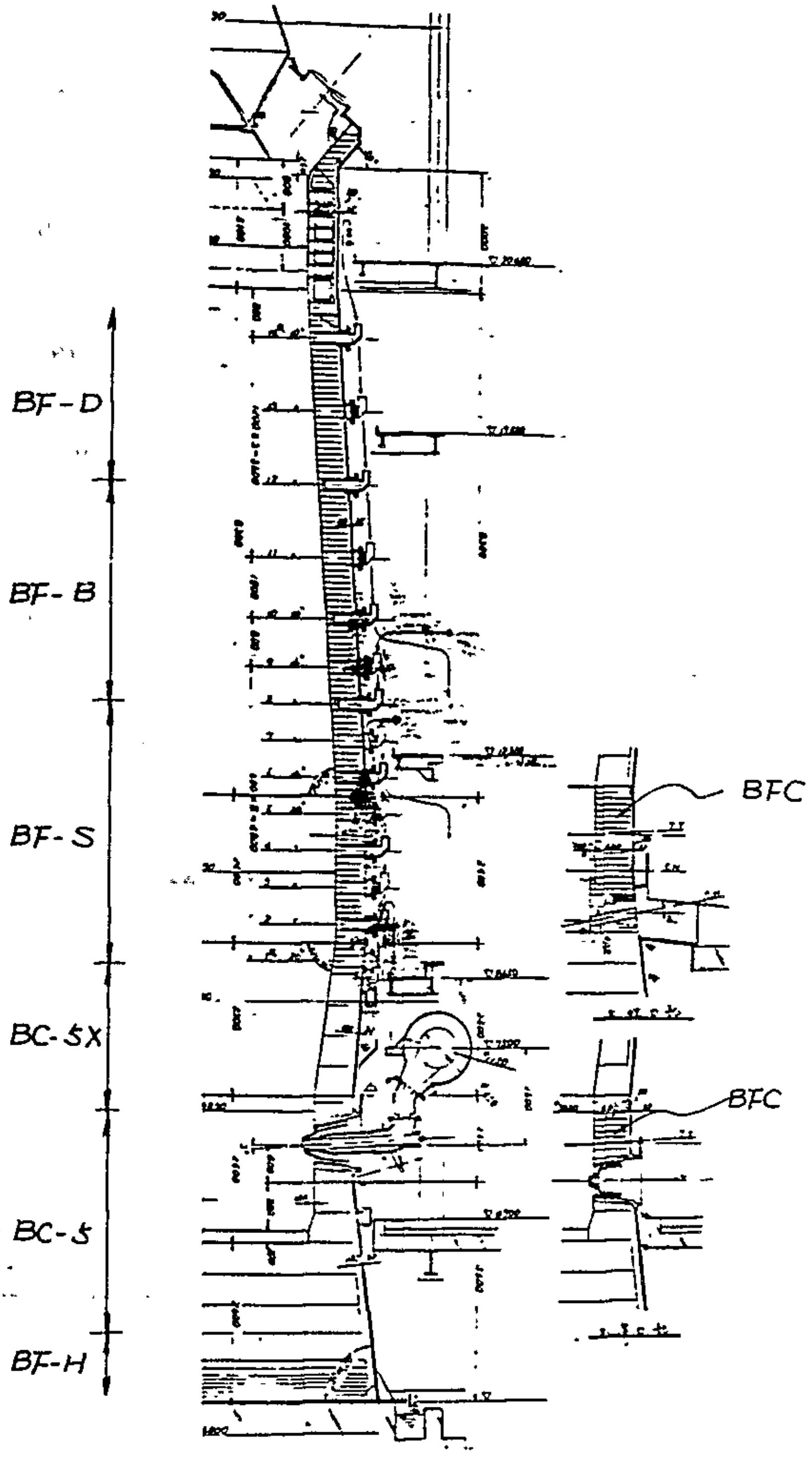


Fig. 2.6-23 Types of bricks and their locations in the furnace

Table 2.6-11 Properties of fireclay refractories for blast furnace

Brand Name Mark Item		BF-D	BF-B	BF-S	BF-C	BF-H
Refractoriness (SK)		32	33	35	34	35
Apparent Porosity (%)		14.0	14.0	12.5	14.0	12.5
Bulk Density		2.20	2.25	2.30	2.30	2.35
Cold Crushing Strength (kg/cm^2)		760	660	790	670	780
Refractoriness Under Load T_2 (°C) (Load: $2kg/cm^2$)		1,445	1,470	1,510	1,485	1,515
Modulus of Rupture (kg/cm^2)	at Room Temperature	-	-	-	-	-
	at 1,400°C	-	-	-	-	-
Permanent Linear Change (%)		1,400°C -2hrs -0.14	1,500°C -2hrs -0.15	1,500°C -2hrs 0	1,500°C -2hrs 0	1,500°C -2hrs 0
Thermal Expansion (%) (at 1,000°C)		0.55	0.56	0.64	0.62	0.66
Spalling Test (frequency) 1,000°C-Water-Cooling		above 6	above 6	above 7	above 7	above 7
Creep Test (%)		-	-	1,350°C $5kg/cm^2$ -5hrs -0.18	-	1,350°C $5kg/cm^2$ -5hrs -0.15
Chemical composition (%)						
Al_2O_3		38.6	40.6	43.1	43.4	44.1
Fe_2O_3		1.82	1.73	1.41	1.48	1.42
Application		Top	Middle inwall	Lower inwall	Tap hole Tuyere	Hearth
Maker		SHINAGAWA				

Table 2.6-12 Properties of carbon brick for blast furnace (Nihon Denkyoku)

Item \ Brand Name		BC-5X	BC-5
True density	(g/cc)	1.93	1.92
Bulk density	(g/cc)	1.62	1.59
Porosity	(%)	16	18
Compression strength	(kg/cm^2)	460	420
Bending strength	(kg/cm^2)	120	100
Contraction at 1,500°C	(%)	0	0
Ash content	(%)	7	4
Resistibility for alkali	(ASTM)	U	LC
Thermal conductivity 400°C	(Kcal/mH°C)	12	12
Thermal elongation coefficient	(10^{-6}/°C)	3.5	3.3
Gas permiability	(milli Darcy)	30	150
Reaction loss by CO_2 gas 1,000°C	(mg/cm^2H)		
Resistibility for molten iron	(%)	very good	very good
Location		Bosh	Hearth, Bottom

2.7 Blast Furnace Operations

2.7.1 Evaluation of the Nelly operating conditions until emergency repairs

The turnover the Nelly showed during the first campaign till the emergency repairs was very poor. Here, the problems involved in the present operating conditions dug up for the purpose of obtaining something of a basis upon which to improve the furnace operations in the future. Regrettably enough, the blast furnace was at rest when the survey mission inspected it, and proper data were not available for the mission to analyze what the operating conditions had been. Although these unavailabilities deny the mission necessary information for in-depth study of the blast furnace conditions, but as well the following may be the most crucial matters to be solved for the COLAR to achieve a higher productivity and a lower fuel ratio.

a) Furnace itself

i) Improper furnace profile

This has already been discussed in 2.5, and is omitted here.

ii) Slumping of shaft bricks

b) Furnace charges and their qualities

i) Use of coarse sizes of coke, ore and limestone

ii) Definiency in the coke strength

iii) Definiency in the technology for stabilizing the quality of charges (coke and ore).

iv) Defective characteristics of iron ore under hot conditions

c) Low blast temperature

(1) Effects of shaft brick slumping on the furnace operations

There are uncertainties about the how and when of the slumping of bricks from the upper zone of the shaft.

According to the notes dated April 20 released by Dr. R. Torres to Mr. Kamatani, the operations during the last 18 months before shutdown were at a low with coke rate at 1,500 kg and output at 60 tons/day. Probably, the bricks in the upper part of the shaft may have already been absent in that period.

Normally, coke and ore in the solid zone should sink layer by layer in an orderly way. Overhaul surveys of normal blast furnaces show that although the thickness of each layer reduces with sinking down to the melting zone, alternate layers of ore and coke exist definetely.

The formation of mixed burden of ore and coke and extraordinary variations in the layer thickness in the radial direction will make the gas passages circuitous and biased. As a result, there will be developed nonuniform reduction of iron ore by gas. Fig. 2.7-1 shows the gas flow patterns and the shapes of melting zone depending on whether the mixed burden is present or not. As illustrated, when there is no mixed burden, the gas from the coke in the furnace center passes through the slits of coke layers circumscribing the semi-fused dome, runs into the solid zone and up through the ore layers right above.

If a mixed burden exists, the gas will take its own course through the mixed burden rather than ore layers because the permeability is higher in the mixed burden.

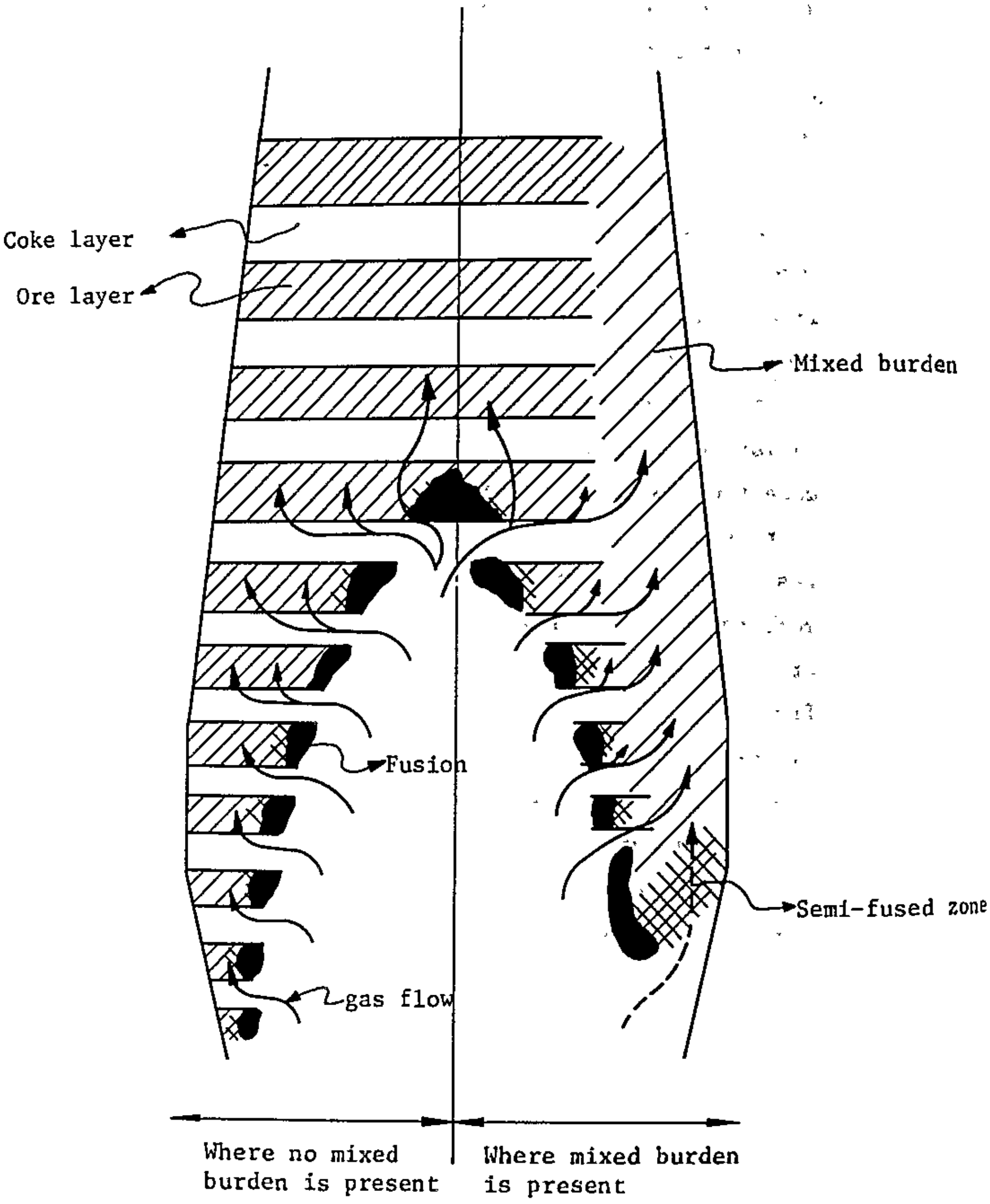


Fig.2.7-1 Schematic view of gas flow and fused zone in relation to charges

As a result, the semi-fused dome will assume an W-letter form when it must be of the inverted V type when in order. In the W form, the height of the dead core usually becomes low, reducing the volume of high-temperature zone and in most cases degrading the results of furnace operations.

The inner walls of the stack lining must be kept smooth. If they are made uneven by slumping of bricks or encrustation of foreign objects, he former will lead to the formation of mixed burden and the latter to the centralization of iron ore at the upper level of the encrustations.

Fig. 2.7-2 shows an analogy of the formation of mixed burden in the Nelly.

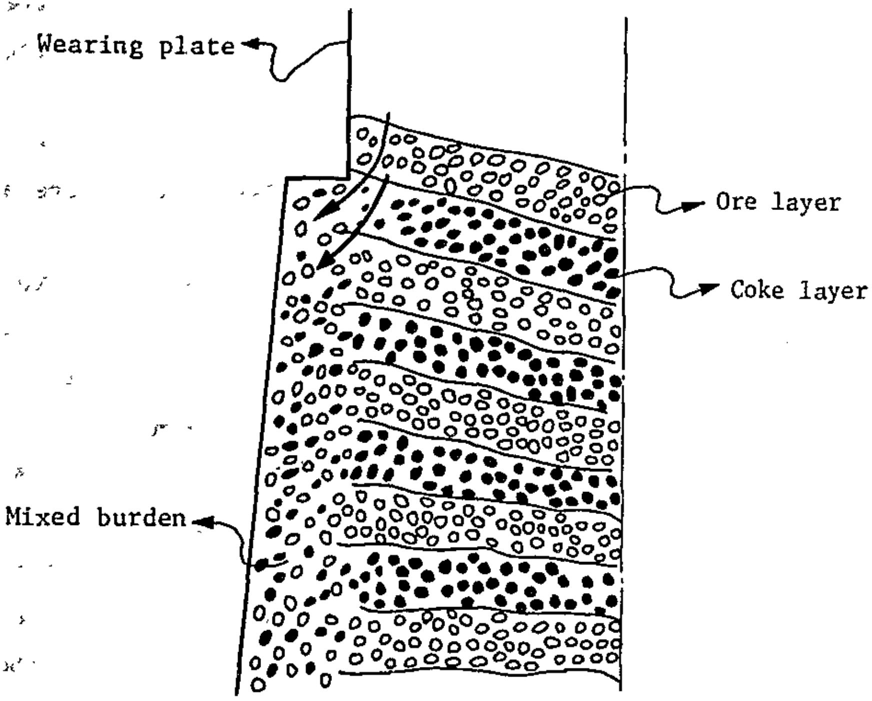


Fig. 2.7-2 Estimated pattern of mixed burden formed by the slumping of shaft bricks

The total slumping of shaft bricks from right under the wearing plate forms a recessed part, which is then filled up with the fallings of charges to form a mixed burden. The gas escapes through the mixed burden because of low draft resistance. Thus, under the influence of skin flow effect, the reduction of the ore layers by gas is lowered, which in turn reduce η_{co} of furnace gas, increases coke rate and reduces the iron output ratio.

(2) Effects of grain size of iron ore and coke

For the purpose of maintaining the gas flow in good condition, the furnace charges are usually subjected to screening out -5 mm dust. An upper limit is also controlled tight for the purpose of ensuring the heating time and reduction time of iron ore, heating time and combustibility of coke, the dissociation end point of limestone and after all the required furnace efficiency.

Discussed here is the significance of the grain size distribution of furnace charges upon the blast furnace operation and economy.

Segawa dedicated his efforts to thermodynamic and hydrodynamic analyses of reactions in the blast furnace, and established the relationship as illustrated in Fig. 2.7-3 in which the mean size of furnace charges necessary for a blast furnace of 20 m high and having a fuel ratio of 0.5 is shown. As is clear from the figure, coarse sizes lead to a deficiency in furnace heat input, that is, to an increase in fuel ratio for the purpose of thermal compensation. Segawa also proposed the following formula to show the relationship between the reduction and grain size of iron ore.

$$250 > (100 + 5d_0)\ (\!(\text{(wind volume)}/\text{(hearth dia.)}^2)\!)\ /H$$

Where, d_0 : iron ore size, mm
H : furnace height, m

In the case of the COLAR, for example, the critical size may be calculated from reduction reaction as follows.

Wind volume = 200 m^3/min.
Hearth diameter = 3.2 mϕ
H [illegible] = 17.8 m

This size should therefore be smaller than 25.56 mm.

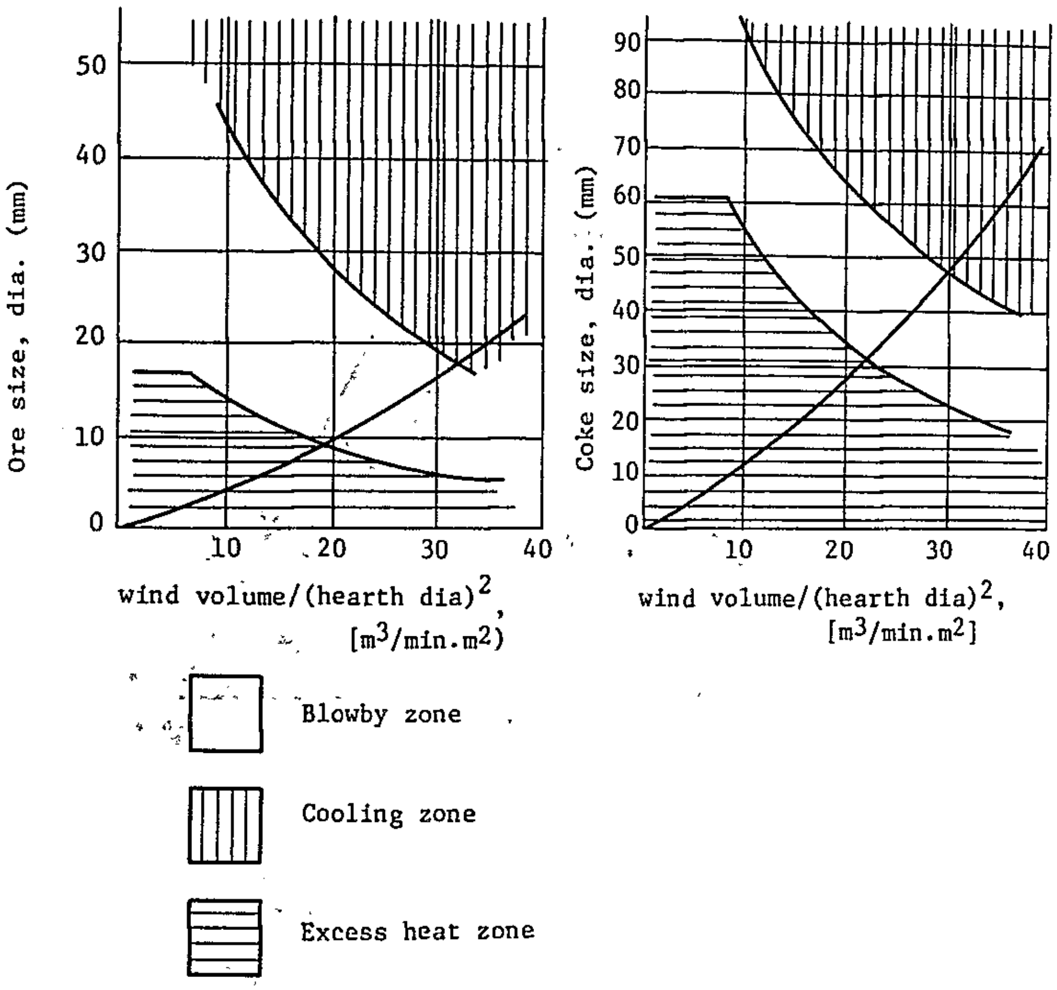


Fig. 2.7-3 Critical sizes of furnace charges in relation to heat transfer and blowby
(Furnace height: 20 m, Fuel ratio: 0.5)

This, along with the results of Fig. 2.7-3, contends that the proper charge size for the COLAR should be 10 to 30 mm for the iron ore and 35 to 60 mm for the coke, and hence that allowing for the costs for crushing and sizing, the control specification should be 5 to 50 mm for the iron ore and 15 to 75 mm for the coke.

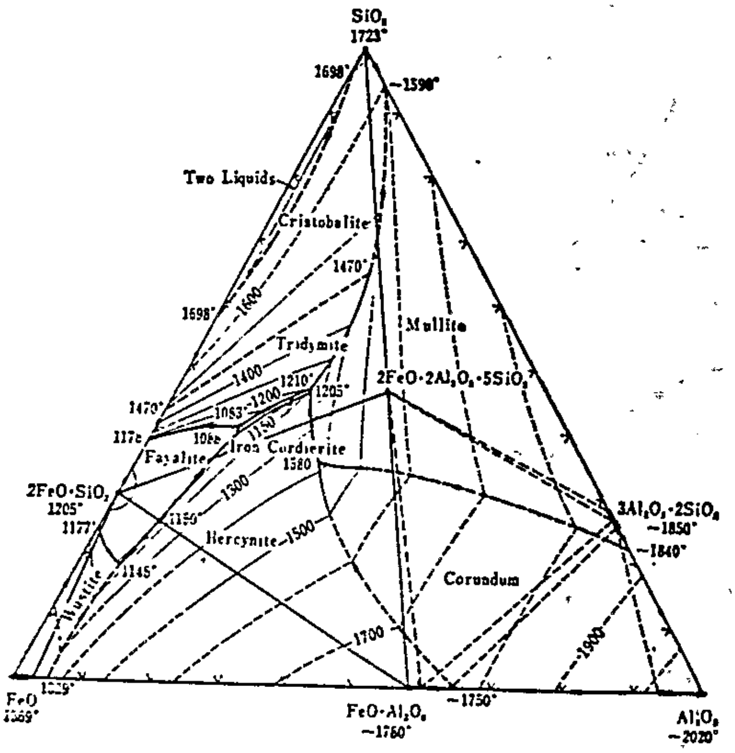


Fig. 2.7-4 SiO_2-Al_2O_3-FeO system

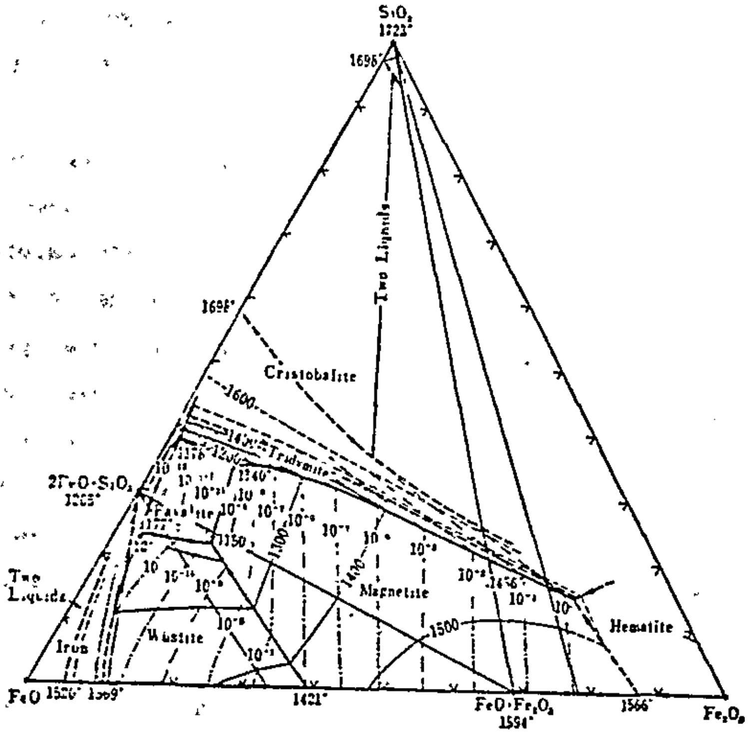


Fig. 2.7-5 SiO_2-iron oxide system

The behavior of iron ore in the processes of reduction, softening and melting is studied here from the metallurgical viewpoint to consolidate the understanding of grain size problem. As already discussed, coarse pieces of iron ore fall to the softening and melting zones without being heated up or reduced fully. In the zones whose temperature is lower than that of the melting zone, that is, in the solid packed zones, the less reduced ore will get its pores - vital to reducive reaction - blocked up on its way of travel from above down as a high component of FeO and a low component of Fe_2O_3 as well as gangue remaining in the ore will develop eutectoids having the minimum melting temperature as shown in Figs. 2.7-4 and -5 or similar substances, which soften and fuse away partially in the ore. As a result, the reducive reaction is stymied, and the ore will fall while keeping unreduced part in its core. With the advancement of heating, the entire ore particle will start melting at lower temperatures than the melting zone's, and will run away while maintaining a high degree of oxidation.

After melting, the reducing effect of CO gas will fall flat on such a melt, which instead will chiefly be reduced by solid carbon under endothermic reaction.
For this reason, great quantities of heat will be necessitated in the high-temperature zone of the blast furnace. Considering the heat transfer mechanism in the high-temperature zone of the blast furnace, it is of great importance to keep the ore in a solid state up to as high a temperature as possible and to melt it down in as short a time as possible when it is due. So far as the liquids are obtained by fusion at a low temperature, it is hardly possible to expect a high temperature of moten iron. For the reasons above, it will be well understood that the sizing of the charges to a proper value is the clincher in the blast furnace operation.

(3) Grain size and charge of limestone, and their effects

The control of the grain size of limestone is no less important than that of the coke and iron ore.
In the modern iron-making technology, there is a tendency that the mix proportion of self fluxing sintered ore and pellet gets increased more and more. As a result, it has become quite rare that the limestone is charged into the blast furnace. At the COLAR, however, raw iron ore along is used. Besides, the iron ore is highly siliceous. Consequently, the limestone ratio is sent up high. To make the matter worse, the sizing control is not enforced vigorously. All these have combined to increase the fuel ratio.
In order to reduce the fuel ratio, the sizing control of limestone should be tightened for the reasons explained below. According to an overhaul survey of a 1,150 m^3 blast furnace which has operated with much quantity of pellets not containing limestone and with limestone ratio a little higher than normal, it is found that maldistribution of limestone is developed in the radial direction, that the slagging is retarded considerably, and that part of limestone is plunged into the dead core (whose upper end lies on the upper bosh in the furnace under discussion) to block up the gas passage.

The size of limestone used in the furnace has been in the range of about 10 to 30 mm. Kobe Steel has studied according to a theory of reaction rate where the limestone of crude sizes used in COLAR furnace will take place, and at the same time has tried the following calculations for the purpose of understanding the importance of the limestone sizing control. Upon assumptions of axial distribution of temperatures, gas compositions and pressure, etc., the calculations were made according to the following limestone cracking reaction kinetic formula using Muchi model.

$$R^* = \frac{\pi d_p{}^2 \phi^{-1} N . 273 (P_{co2}{}^* - yP') \;/\; 22.4t}{1/k_f + d_p\{(1-f_\ell)^{-1/3} - 1\}/2D_s + \{(1-f_\ell)^{2/3} k . R' . t/k\}^{-1}}$$

Where, R^* : overall reaction rate, kg.mol/m^3(bed).hr.

d_p : grain size of limestone, m

ϕ : from coefficient of limestone, -

N : number of particles of limestone per volume, 1/m^3 (bed)

$P_{co_2}{}^*$: partial pressure of CO_2 under equlibrium state, atm.

k_f : laminar film substance mobility, m/hr.

f : reactivity of limestone, -

Ds : diffusion factor of CO_2 in the particles of limestone in the CaO phase, m^2/hr.

R' : gas constant, m^3.atm./kg.mol.°C

y : mol fraction of CO_2, -

t : temperature of particles of limestone, °K

P' : intra-bed pressure, atm.

K : long $K = 7.0099 - 8{,}202.5/t$

k : $5.47 \times 10^6 \exp(-40{,}000/RT)$

T : gas temperature, °K

Operating conditions of COLAR blast furnace

Coke rate : 1,000 kg/T
Ore ratio : 1,840 kg/T
Limestone ratio : 500 kg/T
Blast rate : 200 m^3/min.
Blast temperature : 600°C
Blase pressure : 0.3 kg/cm^2
Furnace gas temperature : 150°C
Furnace gas composition : $28\%CO + 13\%CO_2 + 59\%N_2$
Iron output : 100 tons/day
Tapping temperature : 1,450°C
[Si] : 2.5%

Premises

i) The distribution of temperatures, gas compositons and pressure in the axial direction in the furnace is assumed as shown in Fig. 2.7-6.

ii) For the purpose of simplicity, the blast furnace is regarded as cylindrical.
Mean cross-sectional area ≒ 12.13 m^2

iii) Increase in the furnace gas due to cracking of limestone is neglected.

iv) dfe/dz = AzR*/Fs.Co is numerically calculated according to Euler's method.

Where, Z : axial distance from stock line, m
Az : Cross-sectional area of furnace, m^2
Fs : volumetric charging rate, m^3/hr.
Co : initial concentration of limestone, kg.mol/m^3.bed

$$Co = 500\ (kg/T) \times 100\ (T/day) \times 1/24\ (D/H) \times \frac{1}{100}\ (kg.mol/kg) \times 1/Fs\ (hr./m^3)$$

$$Co = 1.51\ kg.mol/m^3(bed)$$

Table 2.7-1 Calculation of volumetric charging rate in the furnace

	Consumption ratio (kg/T)	Bulk density (kg/m^3)	Volumetric charging rate (m^3/hr)
Coke	1000	500	8.33
Ore	1840	1800	4.26
Limestone	500	1670	1.25
Fs			13.84

With reference to the conditions specified in Fig. 2.7-6, the axial distribution of reactivity and reaction rate of limestone in the furnace was calculated using a computer. The results are as shown in Fig. 2.7-7.

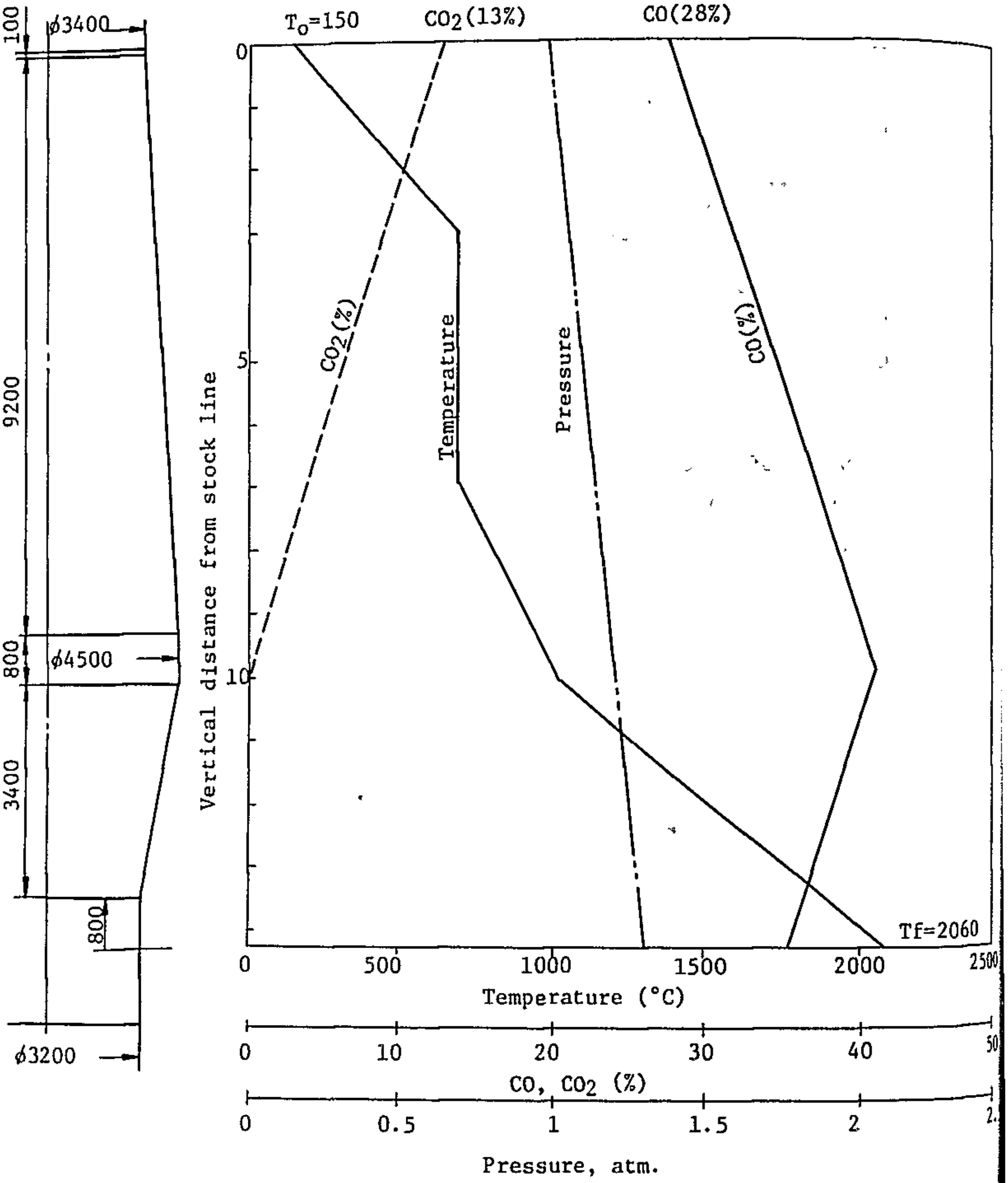


Fig. 2.7-6 Assumed distribution of temperatures, gas compositions and pressures in the axial direction of COLAR blast furnace

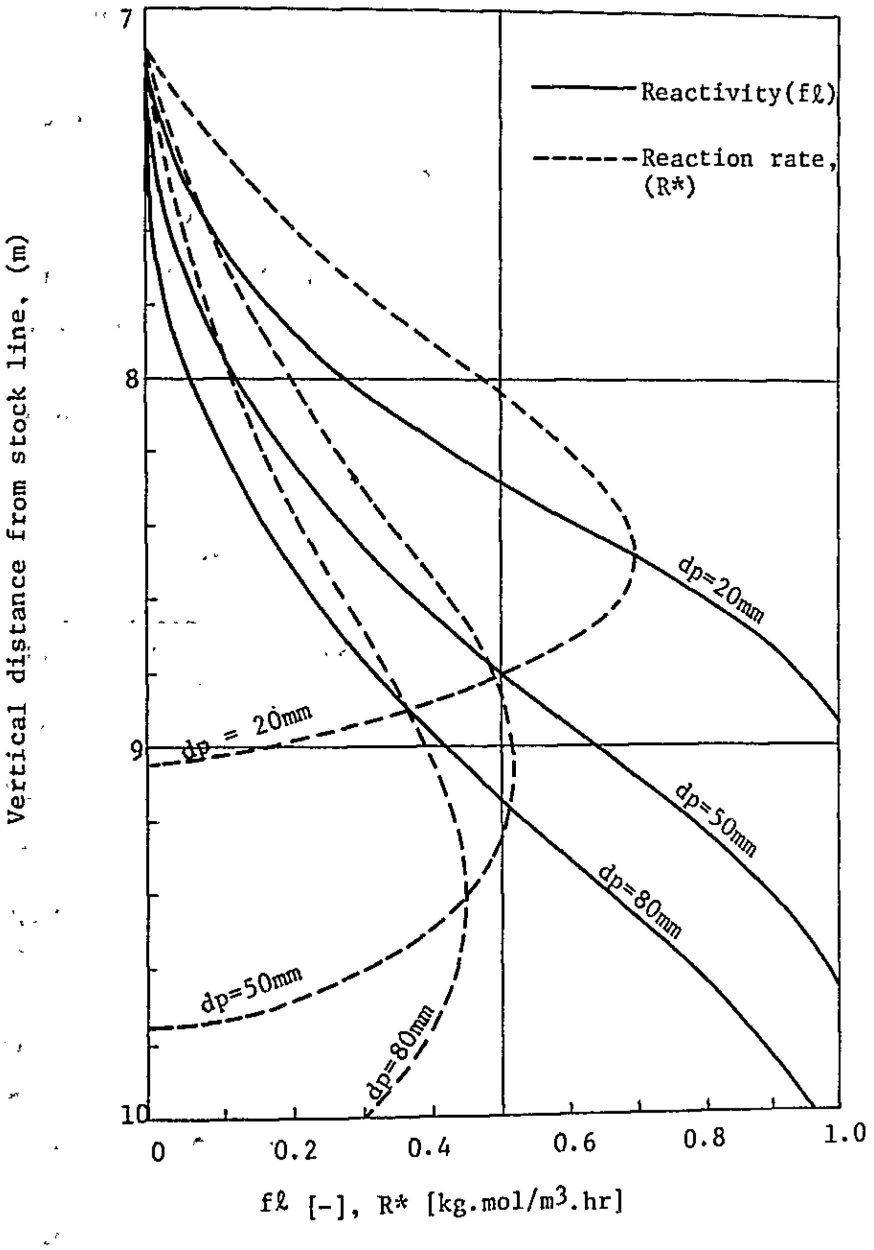


Fig. 2.7-7 Axial distribution of reactivities and reaction rates of limestone in COLAR blast furnace

From Fig. 2.7-7, the following will be found.

i) The dissociation of limestone starts at around 710°C.

ii) The reaction rate increases with increase in temperature as represented by a dotted line in the figure, after culmination, starts declining as what is left of reaction decreases.

iii) The maximum value of reaction rate decreases with increase in the grain size of limestone, and the degree of extent of reaction is also lowered.

iv) The reactivity on a same level basis (i.e., with the location and temperature fixed) becomes smaller the larger the size of limestone is, and the range of reaction from the start to end becomes as shown in the following table.

Table 2.7-2 Grain size vs. dissociative reaction of limestone

Location / Grain size	Start point		Max. reaction rate			End point	
	Location	Temperature	Max. value	Location	Temperature	Location	Temperature
20 mm	7.1m	710°C	0.692	8.5m	850°C	9.0m	900°C
50	7.2	720	0.523	9.1	910	9.7	970
80	2.2	720	0.451	9.5	950	10.2	1050

v) The effects of the grain size of limestone is represented by dp and N in R* formula already discussed. dp and N correspond, so to speak, to the area of reaction boundary surface per unit volume.
The larger the grain size of limestone becomes, the larger becomes dp, but the smaller becomes N to offset dp. Taken altogether, the increase in the grain size leads to the decline in the reaction boundary surface and hence in the reaction rate.

The discussions above are made with emphasis on the vertical distribution of gas temperatures, etc. as in Fig. 2.7-6.
In actuality, however, the temperature variations in the radial direction are quite large.
Even such places that are adjacent to the melting zone sometimes show a low temperature. For example, the reactivity of 80 mmϕ limestone pieces is less than 50% even when they are 9 m below the stock line or in the lower part of the belly.
As in the case of 1,150 m^3 blast furnace, it may happen that a great quantity of limestone falls into the melting zone to consume precious heat in the melting zone by dissociative reaction.
According to a close stocktaking analysis of blast furnace operations by Kobe Steel, it is found that, when using limestone sized not to exceed 40 mm, a 1 kg increase of limestone consumption results in an increase of 0.2 kg-coke/ton-iron.
The COLAR is forced to use much quantity of limestone, and it is well understood that the crushing and sizing of limestone is very important to the reduction of blast furnace fuel ratio.

(4) Effects of coke strength

The coke is one of the major heat sources in the blast furnace.
It also plays a role of reducing agent and spacer to run gas and liquid smooth through the furnace.
The coke should therefore be strong enough to stand physical and chemical conditions as well as high temperatures in the furnace.
If coke of low strength is charged into the blast furnace, the following evil phenomena will take place.

i) Increase in gas flow resistance and pressure variation.

ii) Increase in the volume of dust resulting from the fluidization of coke pulverized in the furnace.

iii) High-frequency occurrence of uneven sinking of furnace charges.

iv) Skin flow of furnace gas in the high-temperature zone.

v) Frequency burnout of tuyeres owing to poor passage of liquids at the level of buyeres.

vi) Difficulties in tapping and slag flushing because of poor liquid passage through the hearth.

For the purpose of stabilizing the furnace operations by coping with these evil phenomena, the following measure are required.

vii) To increase the fuel ratio while decreasing wind volume for the purpose of improving gas flow.
This, however, results in increased fuel ratio, decreased output and reduced wind temperature.

viii) On the other hand, since the variation in the reduction ratio of ore due to uneven sinking of furnace charges and heterogeneity of gas flow, the chemical composition of pig iron is changeable.

Such being the case, the coke strength is a vital control item in the blast furnace operation.
In Japan, efforts are being made to clarify the characteristics and behavior of coke under high-temperature conditions, and substantive results have already been raised in some aspects. Here, however, the characteristics of coke under room temperature conditions are discussed as they are fundamental to furnace operations.

Table 2.7-3 Coke strength testing methods practised in various countries

Country	Measuring method	Drum speed	Size of sample (mm)	Sample weight (kg)	Shape of screen mesh	Screen size (mm)	Indication of coke strength	Required strength range of metal-lurgical coke (%)
Japan	JIS method (crushing strength)	15rpmx2min =30 Rev	> 50	10	Square	15	>15mm(%) Crushing strength	Crushing strength > 90
U.S.A.	ASTM method (tumbler strength)	24rpmx58min =1400 Rev	"	"	ditto	25	>25mm(%) Stability	Stability > 40
						6	> 6mm(%) Hardness	Hardness > 65
West Germany and France	DIM method (micum strength)	25rpmx4min =100 Rev	"	50	Circular	40	>40mm Festigkeit	Festigkeit > 67
						10	<10mm Abrieb	Abrieb < 10

Table 2.7-3 lists the coke strength testing methods practised in various countries. They all use a drum, but are different in the screen mesh and running speed.

The measurements by these methods are bound to each other by the following formula obtained by multiple regression analysis.

$$x = 61 + 0.66y - 0.32Z$$

Where, x: JIS method, 15 mm index of crushing strength, DI^{30}_{15}

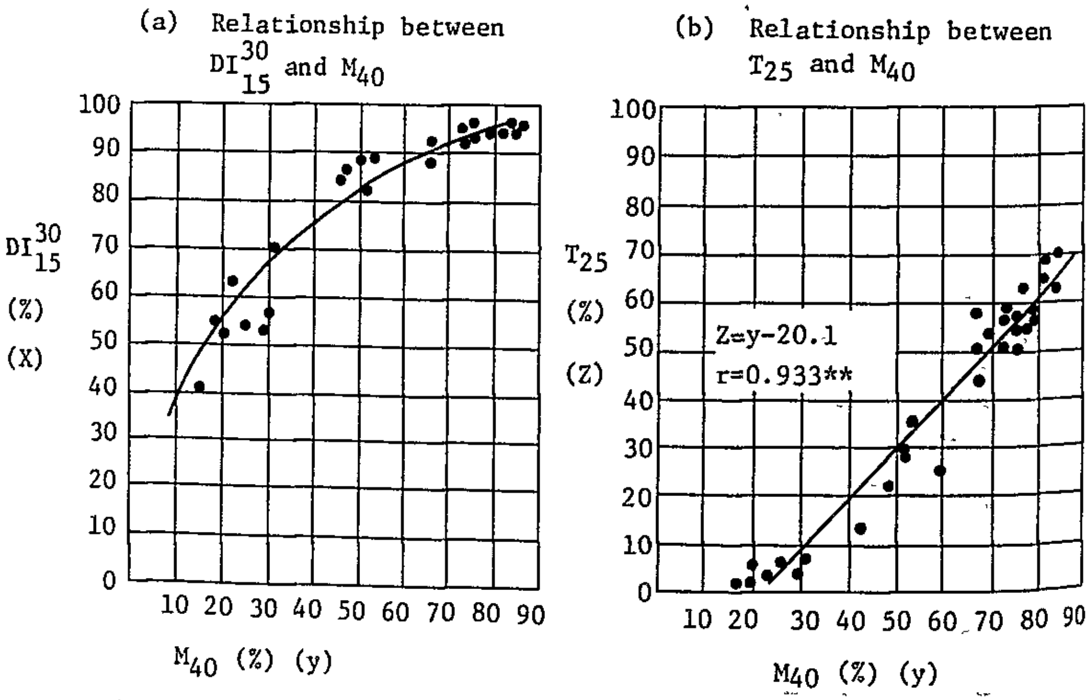
y: DIN method, 40 mm index of micum strength, M_{40}

z: ASTM method, 25 mm index of tumbler strength, T_{25}

Namely, if the coke strength is known in two different methods, its measurement in the remaining method can be estimated to a high degree of accuracy.

Fig. 2.7-8 shows the relationships between measurements by various methods; (a) shows the relationship between DI^{30}_{15} and M_{40}, and (b) the relationship between T_{25} and M_{40}.

By combining the regression formula given above with Fig. 2.7-8, the relationships between testing methods can be determined, accordingly.


(a) Relationship between DI^{30}_{15} and M_{40}

(b) Relationship between T_{25} and M_{40}

Fig. 2.7-8 Relationships between the measurements of coke strength by various methods

It is reported that the strength of COLAR coke is 30 to 40% in tumbler 25 mm index. This value can be evaluated in DIN and JIS methods as follows.

$$(T_{25} = 30\%) = (M_{40} = 50\%) = (DI^{30}_{15} = 84.4\%)$$

$$(T_{25} = 40\%) = (M_{40} = 60\%) = (DI^{30}_{15} = 87.8\%)$$

In Japan, it is rarely the case that the coke strength for small blast furnaces is below 90.5% in terms of DI^{30}_{15}.
Even in case the demand-supply conditions of material coal are tight, the coke strength is controlled to be at least 90.0%. Considering the fact that the coke serves as a spacer in the furnace, increasing the coke rate may be one way to keep a required gas flow state against the reduction in coke strength. But it is far from a genuine answer. So far as the COLAR is determined to reduce the fuel rate and stabilize the furnace operation, it should make every effort to achieve the coke strength of more than 45% in T_{25} to begin with.
The significance of the coke strength will be more clearly understood from the following explanation given in relation to the excerpts from Kobe Steel's technical data "Effects of coke strength on the blast furnace operations."
Figs. 2.7-9 and -10 show the relationships between coke strengthm wind temperature and fuel rate of Kobe Steel's smallest blast furnaces Amagasaki No. 1 BF (inner volume, 721 m^3; foundry pig iron) and No. 2 BF (inner volume, 904 m^3; pig iron for steel use) on the various coke strength.

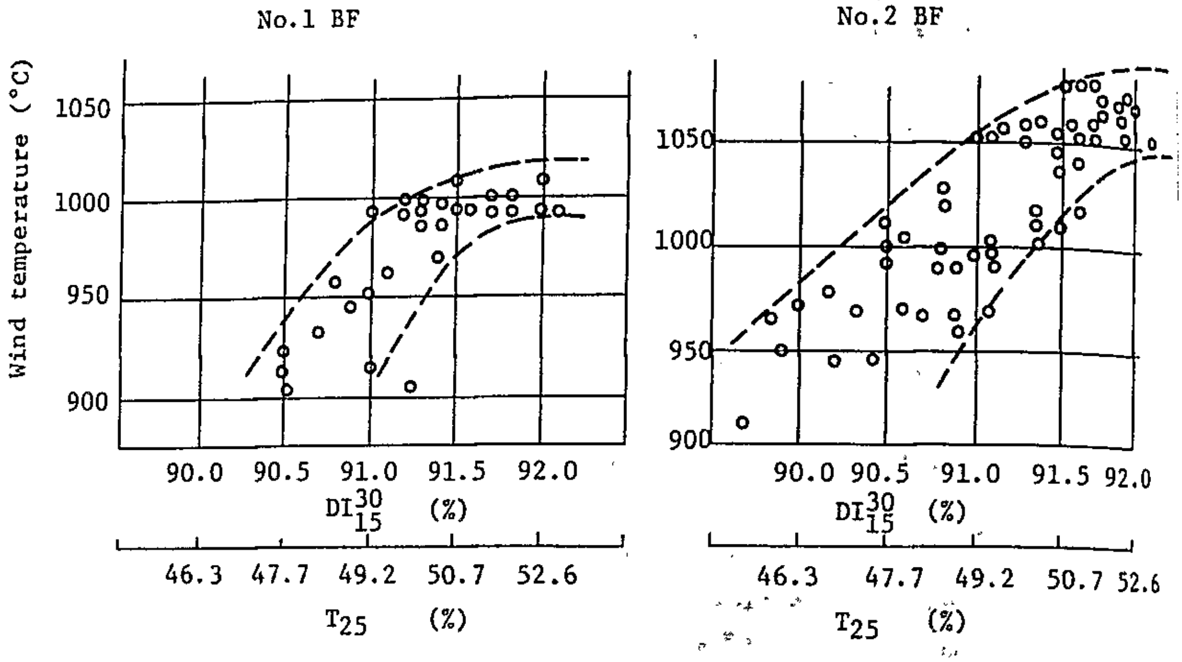


Fig. 2.7-9 Relationship between coke strength and wind temperature of Amagasaki furnaces

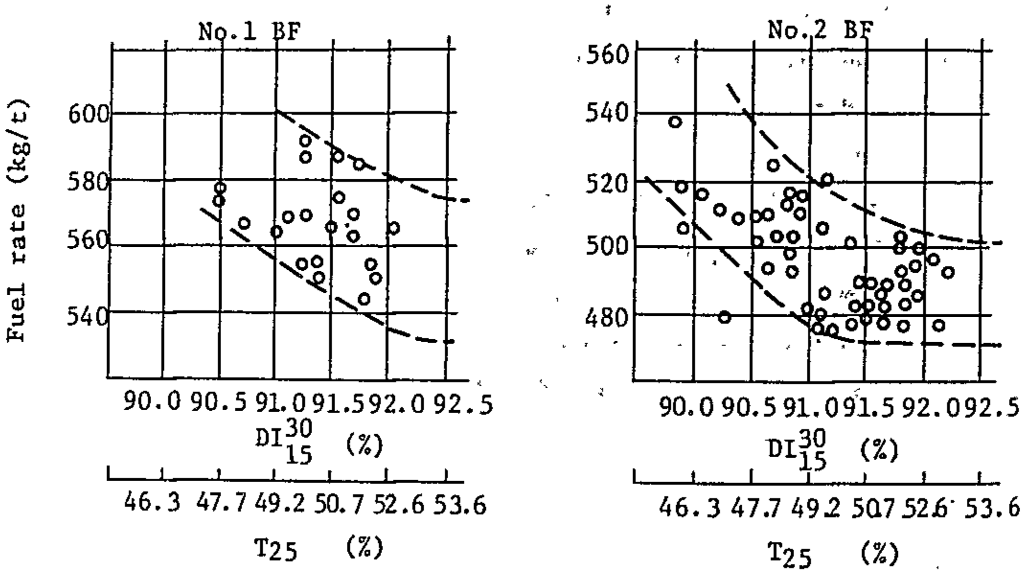


Fig. 2.7-10 Relationship between coke strength and fuel rate of Amagasaki furnaces

As is clear from these figures, the blast furnaces were almost impossible to maintain stable operations when DI$^{30}_{15}$ was reduced to 91.5% (50.7% in T_{25}).

Thus, the furnace operator had to increase the fuel rate, that is, coke rate, while decreasing the wind temperature, in order to recoup the stability.
But his efforts had no effect on the improvement in furnace conditions; the gas flow took a bad turn, and the hanging frequency increased, as seen in Figs. 2.7-11 and -12.

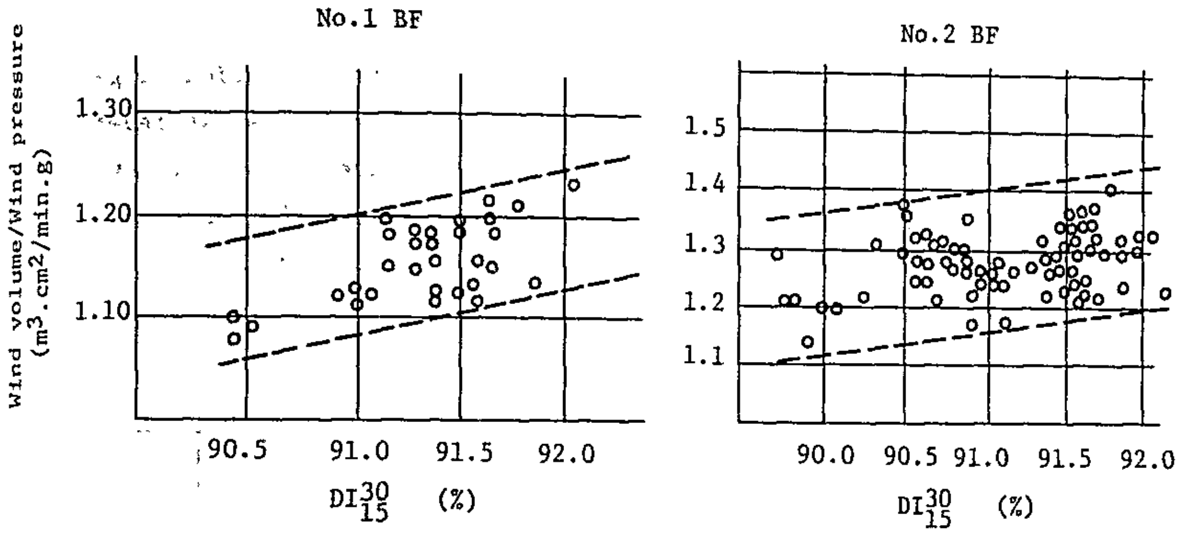


Fig. 2.7-11 Coke strength vs. gas permeability

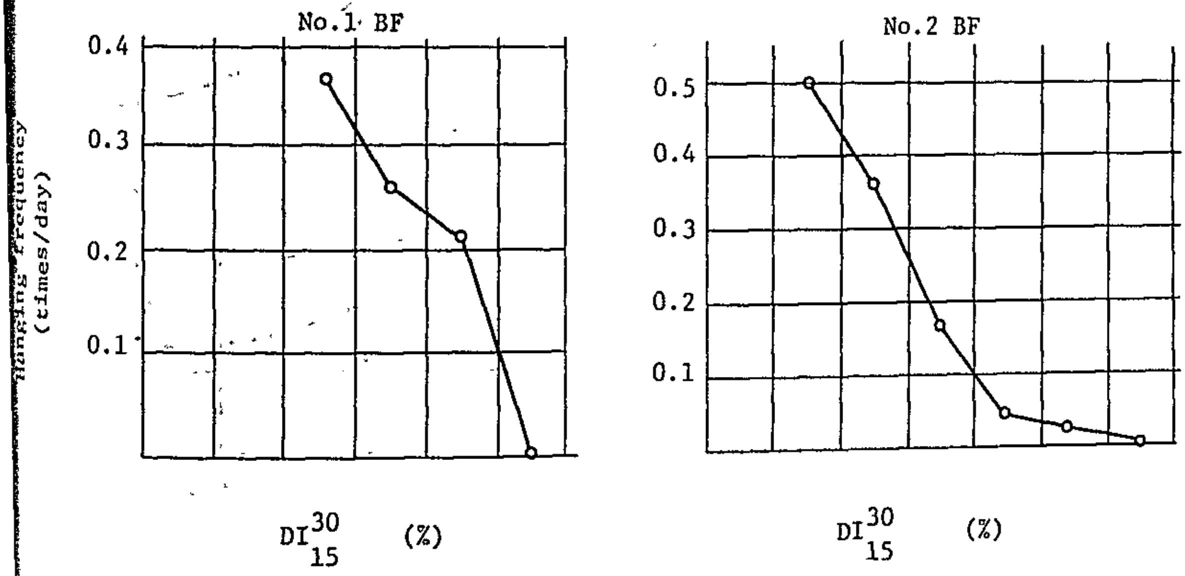


Fig. 2.7-12 Coke strength vs. handing frequency

When the coke of a low strength is used, an increase in coke rate may a thought of a compensatory measure for keeping a proper percentage of voids in the furnace charges in the upper low-temperature zone. However, the coke of low strength generally shows poor characteristics under hot conditions, is sure to break up into fine pieces in the high temperature zones including softening and melting zone, deadman, raceway and hearth.

Once these extremities have happened, the situation of gas flow and liquid passage is hard to improve in any way whatever.

The hard realities can just show a reduced output of low grade.

Fig. 2.7-13 gives the relationship between the coke strength and the width of variations in pig iron silicon content ($Rsi = Si_{max.} - Si_{min.}$, %/day).

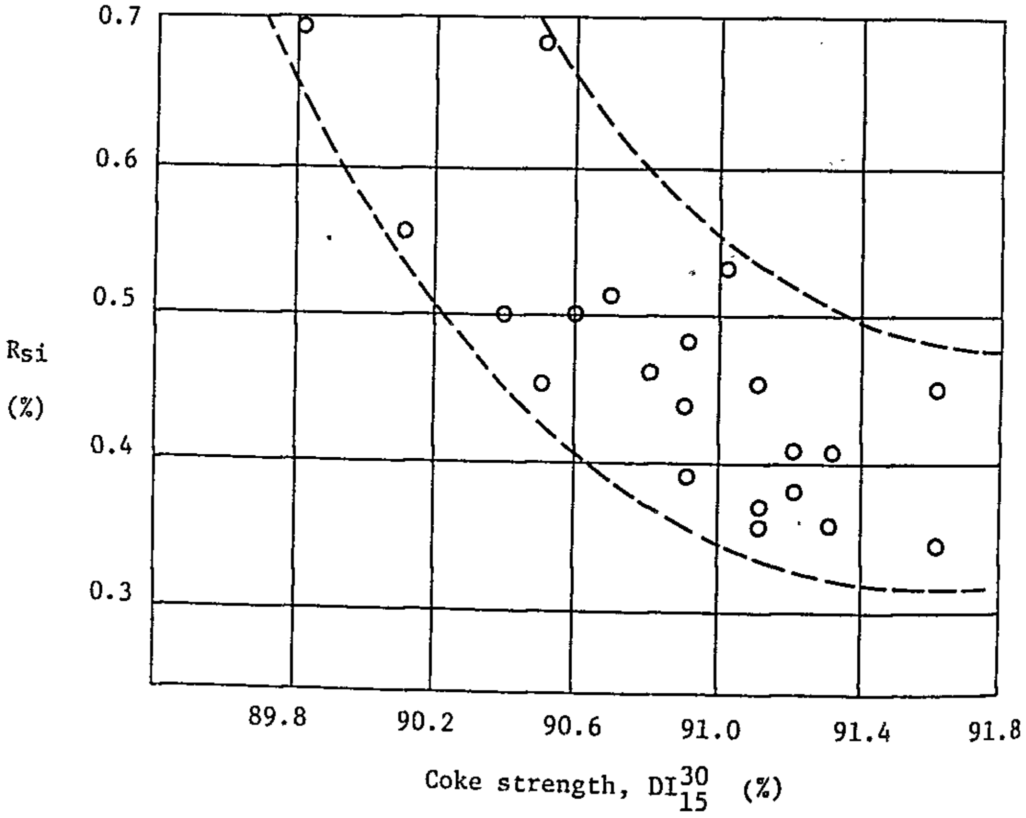


Fig. 2.7-13 Coke strength vs. range of Si content in pig iron

Kobe Steel has no experience in such a small furnace as COLAR's in relation to the target value of coke strength set by COLAR. But, the results of survey about blast furnace capacity and coke strength in Japan and Kobe Steel's target value of coke strength will provide something of a basis. Figs. 2.7-14 shows the changes in gas flow characteristics in the blast furnace in relation to the improvement in the furnace capacity and coke strength level. The value on the ordinate shows the gas permeability improvement factor (η) determined from the K-value in the following formula representing the gas flow conditions, and the value on the abscissa the furnace capacity.

$$K = (P_B{}^2 - P_T{}^2) / V^{1.7}$$

Where, V : wind volume

P_B : wind pressure

P_T : furnace gas pressure at the top

Permeability improvement factor,

$$\eta = \{1 - (\text{K-value at } DI^{30}_{15}(A))/(\text{K-value at } DI^{30}_{15}(B)\} \times 100\%$$

Provided, A < B

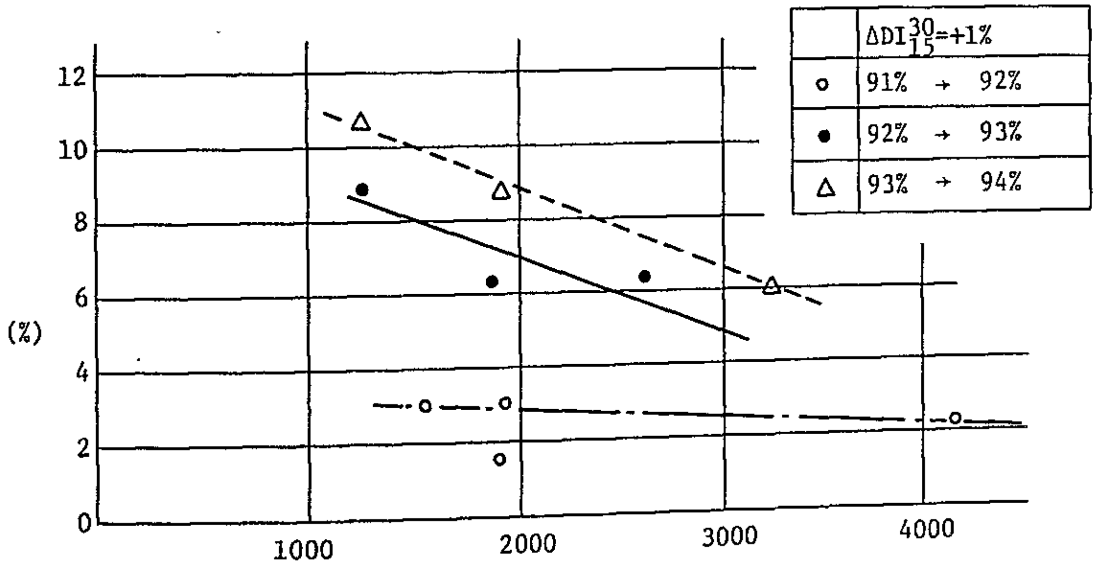


Fig. 2.7-14 Furnace capacity vs. permeability improvement factor

Generally speaking, if the furnace capacity is small, its height is low, and inside temperature low. Thus, the coke of low strength is applicable. Namely, even a 1% increase in the coke strength will tell more effectively on the permeability improvement in a smaller furnace than in a larger furnace if it is made at a high level of coke strength (e.g., from DI^{30}_{15} 93% to 94% or 92% to 93%). But if it is made at a low level (e.g., DI^{30}_{15} 91% to 92%), the improvement factor will remain almost constant irrespective of the size of furnace, and its absolute value will also be reduced sharply. In other words, the coke strength tells hard upon the gas permeability regardless of furnace capacity if it falls around 90.5%. Kobe Steel conducted a sweeping survey about the relationship between the coke strength and furnace capacity, and could find the critical coke strength as shown in Fig. 2.7-15 which is prerequisite to the stabilized blast furnace operation, using a high blast air temperature, as represented by smooth sinking of furnace charges, minimized occurrence of slipping, hanging, and tuyere burnout failure.

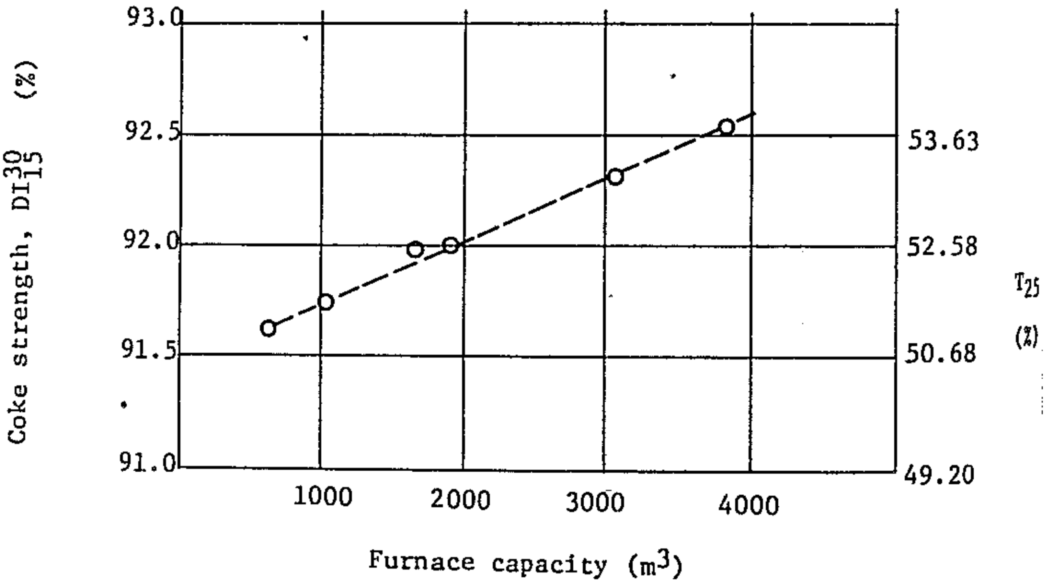


Fig. 2.7-15 Furnace capacity vs. critical coke strength necessary for ensuring high-level production in Kobe Steel

The results shown in Fig. 2.7-15 refer to a high-production case as represented by a wind temperature of 1,050°C to 1,250°C, fuel ratio of 490 to 460 kg/ton, voids concomitant of high ore/coke ratio, and iron output ratio of as high as 1.7 to 2.3. Because of their significant departure from the current COLAR operating conditions, they may not offer first-hand information about what COLAR's setting of coke strength should be. Notwithstanding, Kobe Steel deems it necessary for the COLAR to set an ultimate target of T_{25} above 50% for the purpose of improving the blast furnace operations.

(5) Effects of heterogeneity of materials properties

If the blast furnace is operated under conditions that the properties of feedstocks are always changing, the furnace operator must strain to keep the furnace heat always in reserve in order to let the furnace temperature fall below a limit. On the other hand, he must lower the wind temperature if a sharp temperature rise has happened as the control of ore/coke ratio is not effective in such an event. Under these conditions, the expectation of reduced fuel ratio and increased output is a far cry from possibilities.

On the other hand, if the blast furnace can be operated under fully controlled conditions of physical and chemical properties of feedstocks, it is possible to set the best wind conditions (wind volume and wind temperature) and also adjust the ore/coke ratio to control the furnace heat input with a good response.

The chemical composition of pig iron producted by the COLAR is changing over a wider range than normal.

This phenomenon cannot be brushed away as a matter of change in chemical composition of iron ore.

Data that will help analyze the thermal variations in the blast furnace owing to the changes in the properties of materials were denied the survey mission.

Accordingly, no definite thing cannot be said about this point.

Explained here are the factors relating to the changes in the chemical composition of pig iron, which will be of some help to improving the COLAR's furnace operating conditions in future. The factors that seem likely to have caused variations in the chemical composition of pig iron produced by the COLAR will include the following.

i) Factors relating to furnace inner volume and Si control command

Generally, the smaller the furnace size becomes, the larger will become the change in heat input and hence in Si content. The higher the content of Si in the pig iron, the larger the change in Si content. This problem is unavoidable from the viewpoint of furnace operation, and should be solved through improvements in the factors dealt with below.

ii) Furnace equipment

The slumping of shaft bricks, poor profile of the furnace, etc. may have caused disturbances in the sinking process of furnace charges and resultant changes in furnace heat. Refer to 2.5.2 and 2.7.1 etc.

iii) Coke properties

As has been discussed in 2.7.1-(3) with respect to Fig. 2.7-13, there is a close relationship between the coke strength and Si content variation. The COLAR coke is weak and shows a wide range of variations in Si content. In addition, the coke held in the yard shows a high moisture content. The higher the moisture content, the wider the range of changes in moisture content. The change in ash content is also large. All these are closely concerned with the change in the content of solid carbon or with the change in the ore/carbon ratio which governs the furnace heat input.

iv) Change in chemical composition of iron ore

The chemical composition of COLAR iron ore shows a wide range of changes. As a result, a large change is developed in the iron/coke ratio.

In addition the resultant change in mineralogical and chemical composition leads to change in reduction.characteristics and high-temperature characteristics of furnace charges to vary the furnace heat.

(6) Effects of hot characteristics of iron ore

The staple materials for the blast furnace are required to have been beneficiated to an optimum condition beforehand and at the same time to be excellent in high-temperature characteristics. So that the iron ore is reduced, softened, and molten down to pig iron in a smooth way while being heated up in the blast furnace, it is required to exhibit the properties to meet the atmospheric conditions it has to undergo in each specific reaction stage.

To sum up, the iron ore must satisfy the following requirements.

i) High insusceptibility to disintegration into powder under reducing or physical conditions.

ii) High insusceptibility to deformation under solidstate conditions.

iii) High reducibility at both low and high temperatures.

iv) Sufficiently high softening and melting temperatures with as little a difference in between as possible.

v) High liquatability between slag and iron in the melting process; etc.

At the COLAR, crude ore along is used which is of the limonite family containing a high percentage of the water crystallization. As already discussed in 2.2, it leaves much to be desired so far as high-temperature characteristics are concerned, and serves as a major minus factor in improving the furnace operating performance.

If quantities of dust is developed owing to disintegration by low-temperature reduction, thermal cracking, and reduction in mechanical strength in the reducing process, etc., the overall reducing reactivity gets impaired seriously however excellent the reducibility of the ore itself may be, because the gas flow in the blast furnace is hampered bitterly. Also, the ore shrunk up after liberation of the water of crystallization becomes poor in high-temperature reducibility. Cangue, especially of large grain sizes with high siliceous component, will delay slagging, increase the melting temperature excessively and eventually enervate the furnace heat.

In order to solve these problems, it will be imperative to carry out crushing and sizing strictly for the purpose of improving the reducibility and promoting softening and melting reactions if the crude ore is to be used.

For a drastic reform of the situation, however, the COLAR may have to buckle themselves to studying the production and use of sinters with excellent hot characteristics instead of natural ore.

(7) Effects of wind temperature

Increase in wind temperature leads to an increase in the furnace heat input, saves coke consumption, increases bosh gas temperature, increases reactive atmosphere gas temperature in the lower high-temperature zone in the blast furnace, and thus increases the reaction rate and efficiency. Since the heat content per unit weight of bosh gas is increased, the melting rate per unit volume of wind can be increased.

Namely, the increased wind temperature goes a long way toward reducing coke rate and increasing tapping rate.

It should be noted however that the reduction in coke rate with increase in wind temperature varies largely depending on the operating conditions.

Fig. 2.7-16 shows a projection of fuel rate reduction due to increased wind temperature.

<The chart below refers to a fuel rate reduction expected when the wind temperature is increased by 100°C from a reference value shown on the abscissa>

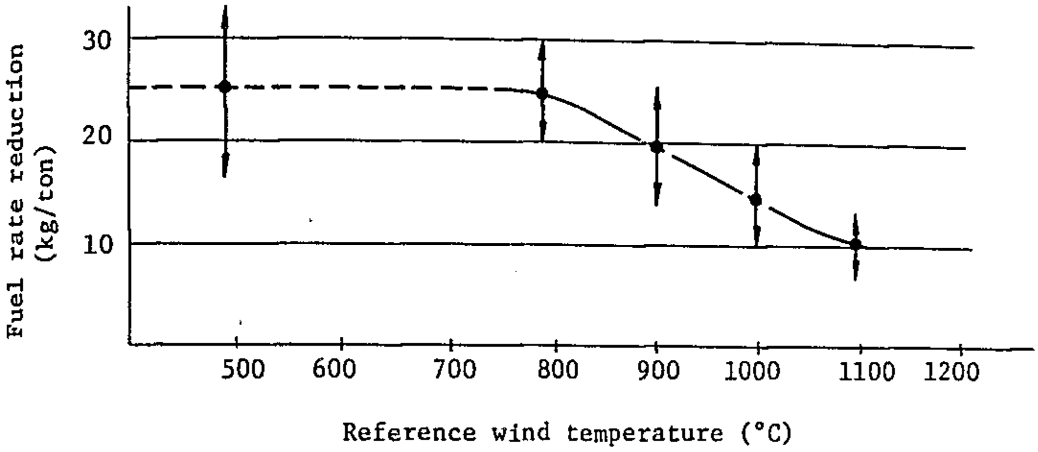


Fig. 2.7-16 An estimated reduction in fuel rate due to increase in wind temperature
(in the case of pig iron for steel-making use)

As discussed above, the increase in wind temperature brings about an increase in ore/coke rate and also in melting zone temperature. This means that the wind temperature cannot be increased unlimitedly unless the flow of gas and liquid in the furnace is improved.

It is therefore evident that the improvement of furnace charges in properties is of paramount importance.

At the COLAR, the wind temperature is as low as about 500°C, and should be increased by a large margin for the purpose of reducing the fuel rate and for efficient smelting of foundry pig iron.

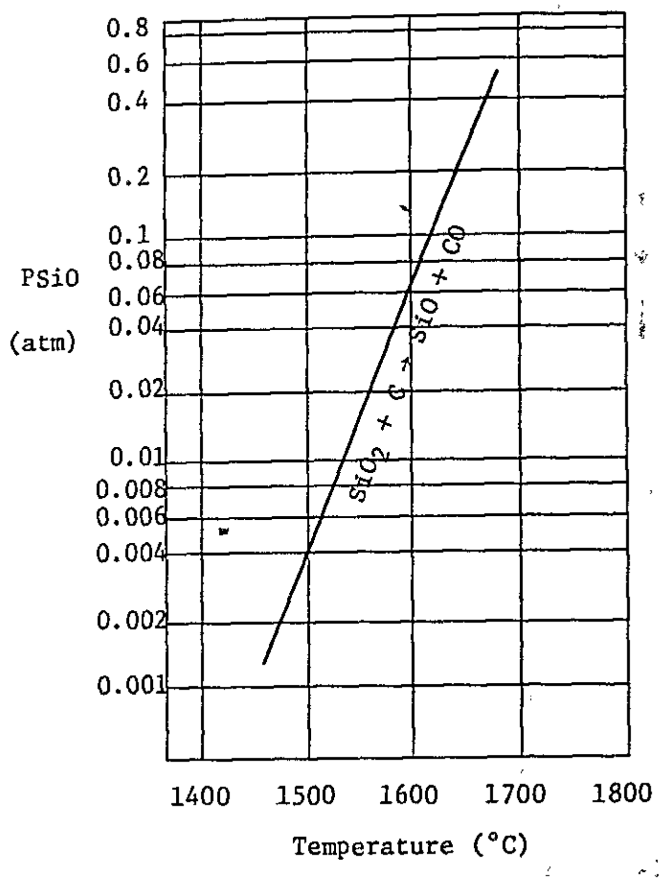


Fig. 2.7-17 SiO equilibrium gas pressure in the Si-O-C system having a total pressure of 1 atm.

As regards the reduction of Si in the blast furnace, it is believed that a process in which SiO gas produced from SiO_2 in the coke ash by the following reaction is reduced by the carbon in the molten metal plays a major role, and that the production of Si through the slag-metal reaction is of little importance.

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

$$SiO(g) + C \rightarrow Si + CO(g)$$

Judging from the fact that the coke temperature in the burning zone is 75% of the combustion temperature at the tuyere, it is easily understood that the coke temperature can be increased by increasing the wind temperature.

Accordingly, the equilibrium pressure of SiO gas (P_{SiO}) produced by the reduction of SiO_2 in coke ash increases at a sharp rate with increase in the temperature as shown in Fig. 2.7-17, sending up the concentration of SiO gas. The SiO gas generated from high-temperature coke is partly oxidized into SiO_2 by molten iron drippings having a lower temperature than coke or in the zones of high oxygen potential, reducing P_{SiO}. It should be added by the way that a higher P_{SiO} can remain higher than a lower P_{SiO} even after reaction with molten iron. As shown in Fig. 2.7-18, a higher P_{SiO} is more effective in sending up Si content in the molten iron than a lower P_{SiO} on a same carbon content basis.

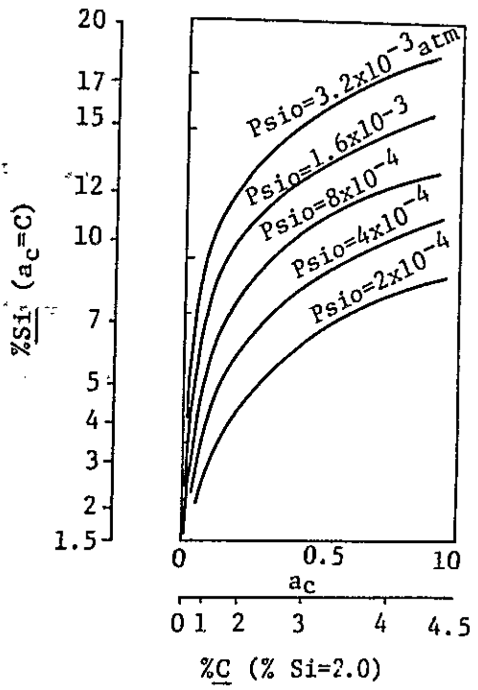


Fig. 2.7-18 The relation between a_{Si} and a_c at 1,500°C

From the above, it is recommended to use a wind temperature of more than 900°C, though there is a fear that in the foundry pig iron smelting an extremely high wind temperature may cause a trouble in furnace operation.

2.7.2 Targets for blast furnace operation in the future

(1) Establishment of feedstock conditions

As discussed in 2.7.1, strict control of crushing and sizing of blast furnace raw materials is of prime importance for improving the blast furnace operational performance. But, vigorous enforcement of crushing and sizing control will aggravate the situation as the resulting smalls and fines will add to volumes of 10 mm screenings left in dead stock (approx. 13,000 tons of coke breeze) for which there is little demand and which is now telling hard upon the financial position of the COLAR.

To cope with this problem, the COLAR has decided upon the production and use of sinter as a furnace charge for the purpose of disposing of dust and improving the characteristics of furnace charges as a whole.

Table 2.7-4 shows target values to achieve in the grain size control of various raw materials.

Table 2.7-4 Recommended target values for various raw materials

Material	1st phase target	2nd phase target
Iron ore	5 ∿ 50 mm	5 ∿ 30 mm
Sinter	–	5 ∿ 50 mm
Limestone	5 ∿ 50 mm	5 ∿ 30 mm
Coke	15 ∿ 75 mm	15 ∿ 75 mm

The COLAR should make efforts to achieve at least 45% of T_{25} to begin with, and then more than 50% in the ultimate stage. The mix proportion of sinter should be determined to meet the development the under size particle.

(2) Target fuel rate

The COLAR iron ore is low in grade in terms of iron content and is highly siliceous. The coke is also high in ash content. All these run to the disadvantage of COLAR's efforts to reduce the fuel rate.

However, these have the following advantages in smelting foundry pig iron of high silicon content.

i) There is no need of charging SiO_2 source like silica.

ii) High ash content increases P_{SiO} and increases Si reduction.

iii) The high slag rate reduces S, V, Ti, etc. in molten iron according to slag-metal partition distribution.

From the viewpoint of installation conditions, the following merits are also offered.

iv) Reduction in the intra-furnace pressure leads to an increase in P_{SiO} and hence in the reduction efficiency of Si. The low wind pressure and low atmospheric pressure employed by the COLAR are favorable for the smelting of foundry pig iron.

v) The smaller blast furnace shows a higher Si reduction efficiency than the larger blast furnace because of gas flow conditions in the high-temperature zone.

With reference to the second phase target values shown in Table 2.7-4, let us now forecast to what value the fuel ratio of the COLAR blast furnace can be reduced. It should be noted that the forecast is made based on a limited few of the various factors that are necessary for reflecting the complexicities of physico-chemical behavior in the furnace, and that its justifiability leaves some doubt from the viewpoint of practicality.

Preconditions for correction of coke rate

i) Correction for furnace capacity

With Amagasaki No. 1 blast furnace (inner volume: 721 m^3) taken as a reference, the intra-furnace temperature, pressure, A_c, reduction time and laminar film diffusion, etc. were examined to obtain the following relationship between the furnace capacity and Si reduction coefficient (ηsi).

$$\mu si = 0.93^{(V - 721)/100}$$

Where, V : inner volume of blast furnace (m^3)

ii) Correction for other factors

Wind temperature	: ∓ (0.2 ∿ 0.25) kg/±1°C
Coke and content	: ± 10 kg/± 1%
Sinter	: ∓ 0.9 kg/± 1%
Slag rate	: ± 0.2 kg/± 1 kg
Wind moisture	: ± 0.9 kg/± 1 g
Limestone	: ± 0.2 kg/± 1 kg
Heavy oil	: ∓ 1.0 kg/± 1 kg
Si	: ± 65 kg/± 1%
Mix proportion of pellets not containing limestone	: ∓ 0.5 kg/± 1%

iii) Intra-furnace reaction characteristics of iron ore, sinter and coke have a great bearing on the fuel rate. Here, however, they are handled as constant.

Under the conditions above, Amagasaki No. 1 blast furnace smelting foundry pig iron and a blast furnace (184 m^3) owned by "A" company are compared to estimate the COLAR coke rate. Table 2.7-5 lists the furnace operating conditions practised by the companies concerned, and Table 2.7-6 shows the corrected coke ratios with Amagasaki No. 1 blast furnace taken as a reference.

Table 2.7-5 Standard operating conditions practised by the companies concerned

Factors		Operating data		Improvements for 2nd phase target values
		Amagasaki No. 1 BF	"A" company BF	COLAR
Furnace inner volume	(m^3)	721	184	188
Wind temperature	(°C)	1000	950	600
Wind moisture content	(g/m^3)	7	20	7
Pig iron Si content	(%)	2.1	2.5	2.5
Coke ash content	(%)	11.0	11.0	15.0
Sinter mix proportion	(%)	70	0	x
Mix proportion of pellets not containing limestone	(%)	0	8	0
Limestone,	(kg/t)	15	220	y
Slag rate	(kg/t)	320	310	z
Pig iron output	(t/d)	1100	270	-
Coke rate	(kg/t)	515	610	-
Heavy oil rate	(kg/t)	45	0	0
Fuel rate	(kg/t)	560	625	-

Table 2.7-6 Calculation for corrected fuel rate

Item	Amagasaki No. 1 BF	"A" company	COLAR	Remarks
Wind temperature	kg-coke/t 0	kg-coke/t +0.2(950-1,000)=-10	kg-coke/t +0.25(600-1,000)=-100	The correction factor is set at 0.25 because the COLAR uses a low temperature.
Wind moisture content	0	-0.9(20-7)=-11.7	±0.9(7-7)=±0	The same value as Amagasaki is employed because the COLAR's moisture content is unknown.
Pig iron Si content	+65(2.5-2.1)=+26	0	0	Amagasaki's value is corrected.
Si reduction efficiency as determined by furnace capacity	0	$-2.5(1-0.93^{(184-721)/100})\times 65=+77.4$	$-2.5(1-0.93^{(188-721)/100})=+76.7$	
Coke ash content	0	0	-10(15-11)=-40	Both ash and coke values of COLAR show a significant departure from empirical data available in Japan, and the correction factor leaves some question.
Sinter mix proportion	0	+0.9(0-70)=-63	+0.9(x-70)	
Limestone-free pellets	0	+0.5(8-0)=+4	+0.5(0-0)=0	
Limestone rate	0	-0.2(220-15)=-41	-0.2(y-15)	
Slag rate	0	-0.2(310-320)=+2	-0.2(z-320)	
Actual fuel rate	560	625	FR	
Corrected fuel rate under the same conditions with Amagasaki set at 2.5% Si	586	583	590=FR-100+76.7-40+0.9(x-70) -0.2(y-15)-0.2(z-320) *FR=650-0.9x+0.2y+0.2z+Σα	The corrected fuel ratios of Amagasaki and "A" company are rounded up to 590 kg, which is taken for COLAR's. Σα: other correction factors

Here, the fuel ratio (FR) is forecast with respect to a case where the sinter is not mixed.

$$x = 0$$

$$FR = 650 + 0.2(y + z) + \Sigma\alpha$$

$$FR' = FR - \Sigma\alpha = 650 + 0.2(y + z)$$

Chemical composition of furnace charges

	Fe	SiO_2	CaO	Al_2O_3	ash
Iron ore	50.0	10.0	0.06	3.0	
Coke					15
Coke ash		62.8	0.04	27.3	
Limestone		4.25	52.2		

Accordingly, ore rate = 930/0.5 = 1,860 kg-ore/ton

			SiO_2	CaO	Al_2O_3
(i)	Contribution by iron ore,	(kg)	186	1.1	55.8
(ii)	Quantity of SiO_2 corresponding to 2.5% Si	(kg)	53.6		
(iii)	(i) - (ii)	(kg)	132.4	1.1	55.8
(iv)	Contribution by limestone (335 kg) necessary for adjusting (iii) to have a CaO/SiO_2 ratio of 1.2	(kg)	14.24	174.87	
(v)	(iii) + (iv)	(kg)	146.64	175.97	55.8
(vi)	Sum of the components in (v)	(kg)		378.4	
(vii)	Slag volume corresponding to (vi) = (vi)/0.94			402.3	

Assuming y = y' + 35 and z = z' + 402.3

$$FR' = 797.5 + 0.2(y' + z') \quad \ldots\ldots\ldots\ldots \quad (a)$$

		SiO_2	CaO	Al_2O_3
(viii)	Contribution by FR' (kg)	0.094FR'		0.0409FR'
	The limestone (y') necessary for adjusting the slag from FR' to attain a CaO/SiO_2 ratio of 1.2 is given by the following formula. $y' = 0.2395FR'$ .... (b)			
(ix)	Components corresponding to y' (kg)	0.0102FR'	0.12502FR'	
(x)	(viii) + (ix) (kg)	0.1042FR'	0.12502FR'	0.0409FR'
(xi)	Slag volume corresponding to (x) = (x)/0.95 (kg)	$Z' = 0.2873FR'$ ...... (c)		
	By substituting (b) and (c) into (a), FR' = 891 kg-coke/ton			

From the calculation above, the coke rate may roughly be 890 kg if $\Sigma\alpha = 0$ and if sized crude ore is used.

As already explained, the forecast here is predicated on a limited few out of the various factors representing complex furnace behavior. Accordingly, it cannot be declared that the estimated value can immediately be achieved. The estimated value, however, is not a critical one, but leaves some room for further reduction.

2.7.3 Control of slag basicity, etc.

The blast furnace slag is required to satisfy the following characteristic requirements.

a) The slag must melt down at a comparatively low temperature, run well, and separate easily from iron. It must also run smooth through the coke beds, and can be discharged from the slag notch with ease.

b) The slag must show a high smelting reaction efficiency.

   i) Desulfurizing reaction

   ii) Si reduction reaction at the time of foundry pig iron smelting

   iii) Reaction for removal of impurities, such as Ti and V

For the purpose of blast furnace operations control, the basicity of slag is often employed as a control index. The basicity is given by CaO/SiO_2, $(CaO + MgO)/SiO_2$, $(CaO + MgO)/(SiO_2 + Al_2O_3)$, etc. If a plural number of basic oxides and acid oxides are summed and compared in ratio, it happens that each of basic or acid oxides is weighed on a par. Thus, the following problems are invited.

i) Whether or not a given oxide touches direct upon the chemical reactions

For example, CaO performs desulfurization as given by the following formula. But, MgO which comes under a group of basic oxides does not produce sulfides in the blast furnace.

$$FeS + CaO + C \rightarrow Fe + CaS + CO$$

SiO_2 performs Si reducing reaction as given by the following formula. But Al_2O_3, which belongs among acid oxides, does not serve as a Si source.

$$SiO_2 + 2C \rightarrow Si + 2CO$$

ii) The oxides, whether basic or acid, show different physical properties (melting temperature, viscosity, etc.) depending on their chemical composition.

iii) The degree of basicity or acidity varies oxide by oxide.

Table 2.7-7 shows the ion-oxygen attraction parameters of various oxides.

The basic oxide has a small value of I (see Table 2.7-7 below), and serves as a network modifier.

The acid oxide has a large value of I, and the order of I falls in with the descending order of basicity.

Namely, basic and acid oxides are different in intensity from each other.

Table 2.7-7 Ion radius and intensity of I of oxides

Oxides	Cation M^{2+}	O^{2-} ion coordinating	Ion radius (Å)		$I = \frac{2Z^+}{a^2}$
			M^{2+}	O^{2-}	
Na_2O	Na^+	6	0.95	1.40	0.36
Li_2O	Li^+	6	0.60	"	0.50
CaO	Ca^{2+}	6	0.99	"	0.70
MnO	Mn^{2+}	6	0.80	"	0.83
FeO	Fe^{2+}	6	0.75	"	0.87
NiO	Ni^{2+}	6	0.70	"	0.91
MgO	Mg^{2+}	6	0.65	"	0.93
ZnO	Zn^{2+}	4	0.70	1.30	1.00
ThO_2	Th^{4+}	6	1.02	1.40	1.38
Cr_2O_3	Cr^{3+}	6	0.64	"	1.43
Fe_2O_3	Fe^{3+}	6	0.60	"	1.50
BeO	Be^{2+}	4	0.30	1.30	1.59
ZrO_2	Zr^{4+}	6	0.79	1.40	1.67
TiO_2	Ti^{4+}	6	0.68	"	1.85
Al_2O_3	Al^{3+}	{6 4	{0.50 0.47	{" 1.30	{1.66 1.90
SiO_2	Si^{4+}	4	0.39	"	2.81

Legend: I: ion-oxygen attraction parameter
a: interionic distance (sum of the ion radii of M^{2+} and O^{2-})

Accordingly, the basicity given by (sum of basic components)/ sum of acid components) cannot always reflect the correct picture of slag characteristics; namely, the same value of basicity may be assigned to slags which are quite different in characteristics from each other. In the present state of the art, there has not yet been any tool which can represent the furnace slag characteristics simply and which can be applied to the furnace operations.

The following gives a Kobe Steel's concept for slag control by way of reference, but cannot be recommended as best.

(1) Determination of basicity

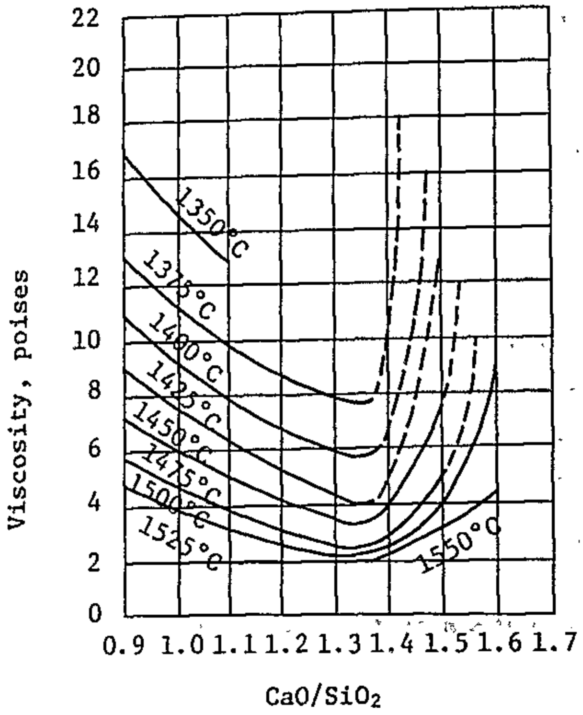
First, pick up representative basic and acid oxides (such as CaO and SiO_2 as shown in Table 2.7-7) prevailing among the slag components, and determine their gravimetric ratio (CaO/SiO_2) as basicity.

Then, the basicity is adjusted with account taken of the following factors.

i) Fluidity

As is clear from Fig. 2.7-19 in which slag viscosity closely relating to the slag fluidity is shown, the slag viscosity increases sharply irrespective of temperature if CaO/SiO_2 goes in excess of 1.35.

Since the increase in the viscosity decreases the chemical reactivity (for example, the desulfurizing efficiency decreases because of poor fluidity even when the basicity is increased), the CaO/SiO_2 ratio should be made lower than 1.35 (approx. 10 poises) from the viewpoint of viscosity.



other components:
MgO_2: 3 to 4%
Al_2O_3: 12 to 13%

Fig. 2.7-19 CaO/SiO_2 vs. slag viscosity relationships with temperature as a parameter

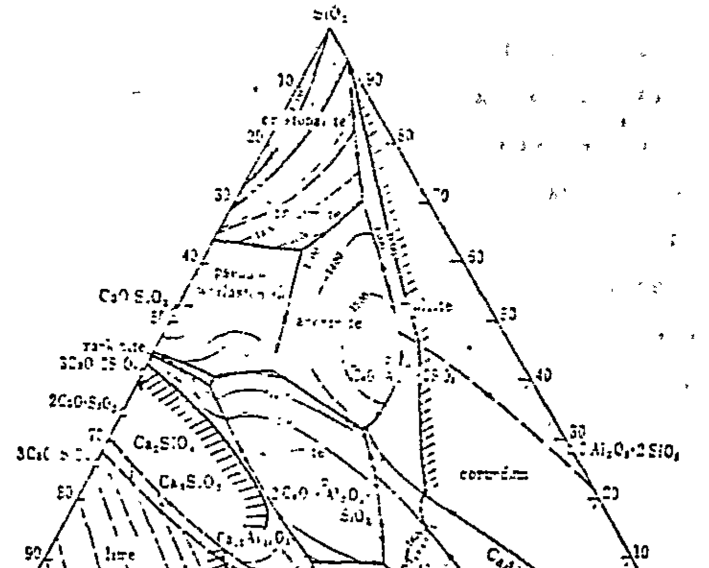


Fig. 2.7-20 $CaO-SiO_2-Al_2O_3$ ternary system

ii) Melting temperature

In actual operation, the slag must be dead molten in a place below the softening and melting zone where violent temperature changes take place.

Namely, the slag melting temperature should be a little lower than the temperature in the melting zone. Fig. 2.7-20 shows a ternary diagram of CaO, SiO_2 and Al_2O_3 which are the main constituents of the slag. In the diagram, a circular hatched field shows the range in which slag components lie.

If the melting temperature is set at below 1,400°C, a straight line drawn $CaO/SiO_2 = 1.35$ (i.e., 57.4% CaO point) on the $CaO-SiO_2$ line to 100% Al_2O_3 point nearly runs through the zone showing a melting temperature of below 1,400°C.

Just as with i), the basicity can be raised up to 1.35.

iii) Desulfurizing reaction

The desulfurizing reaction in the blast furnace is given by the following formula.

$$[FeS] + (CaO) + C \rightarrow [Fe] + (CaS) + CO$$

The formula above can be rewritten as follows.

$$O^{2-} + S = S^{2-} + O$$

$$\log Ks = (a_S{}^{2-} . a_O)/(a_O{}^{2-} . a_S) = -6{,}500/T + 2.63$$

From the above, it is evident that the desulfurizing power can be increased by increasing $a_O{}^{2-}$ and decreasing a_O.

a_O can be reduced by reducing FeO in slag through improvement of reducive reaction in the furnace and increasing the carbon saturation. On the other hand, $a_O{}^{2-}$ can be increased by increasing the basicity.

While the increase in basicity is desirable as demonstrated above, it runs counter to the requirement described in i) because the slag fluidity decreases to reduce the desulfurizing factor. Fig. 2.7-21 shows the slag basicity vs. S distribution coeff. (Ls = (S)/[S]). Fig. 2.7-22 shows the actual operating data of Kobe Works, Kobe Steel.

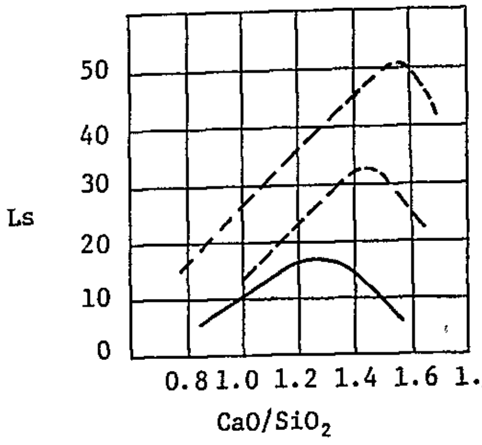


Fig. 2.7-21 Slag basicity vs. S partition ratio
(V.G. Voskoboinikov)

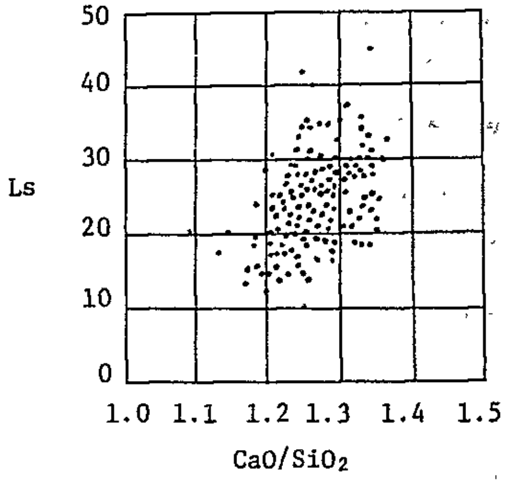


Fig. 2.7-22 Slag basicity vs. Ls relationship
at Kobe Works, Kobe Steel

In the case of Kobe Works, the tapping temperature is in the range of 1,400°C to 1,500°C, and Fig. 2.7-22 shows a good agreement with V.G. Voskobonikov's data.
When the basicity is to be determined for the purpose of desulfurization while allowing for tapping temperature drop, the CaO/SiO_2 ratio is normally limited to around 1.35.

iv) Si reducing reaction

With reference to the hearth reaction, the Si distribution equilibrium between the saturated molten iron and $CaO-SiO_2-Al_2O_3$ ternary system slag shows that the Si concentration in iron increases with decline in the CaO/SiO_2 ratio as illustrated in Fig. 2.7-23.

So far as the chemical kinetics is concerned, the phenomena in a real furnace cannot be explained by the slag-metal boundary surface reaction alone, but the transitional reaction by SiO gas explained in 2.7.1-(6) is prevalent.

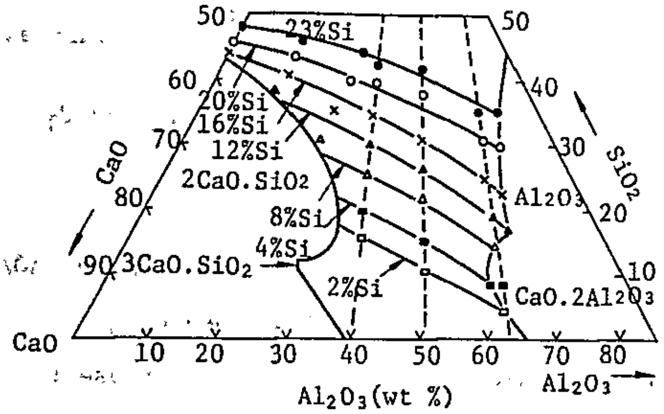


Fig. 2.7-23 Si concentration in equilibrium with $CaO-SiO_2-Al_2O_3$ ternary slag system

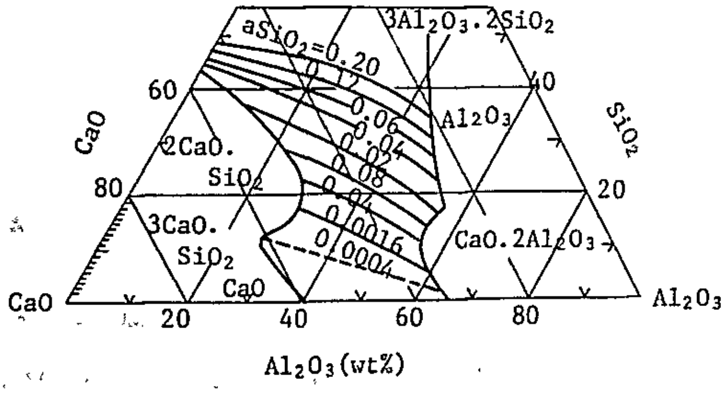


Fig. 2.7-24 a_{SiO_2} on the $CaO-SiO_2-Al_2O_3$ ternary system (1,600°C)

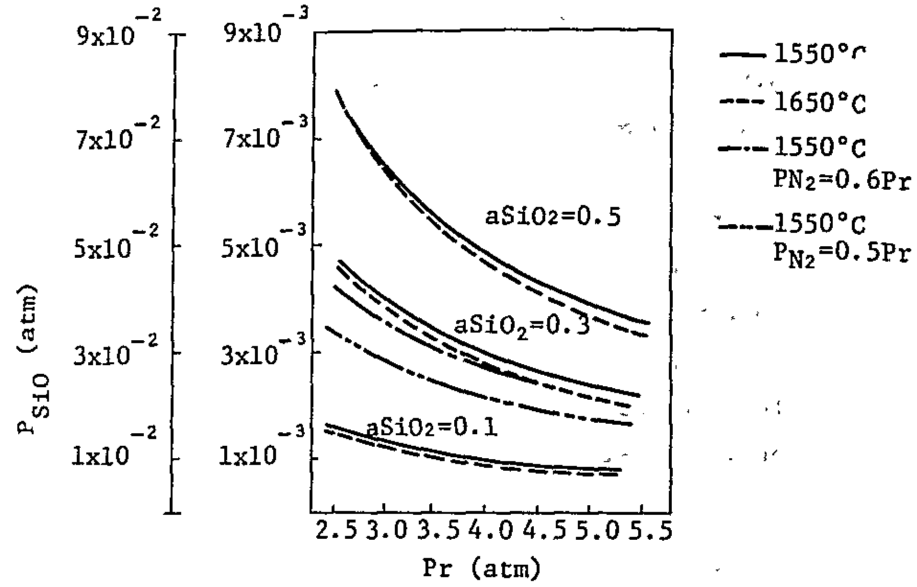


Fig. 2.7-25 The relation between Psio and P_T

As is clear from Fig. 2.7-24, the reduction in CaO/SiO_2 Sends up SiO_2, which in turn increases P_{SiO}.
This suggests that it is desirable to decrease the basicity for the purpose of increasing the concentration of Si in the molten iron.
In Kobe Steel, the slag basicity is set within the following ranges for the smeltering of foundry pig iron and steel-use pig iron in consideration of slag fluidity, desulfurizability, Si reduction factor, etc.

Foundry pig iron : 1.00 ∿ 1.20

Steel-use pig iron : 1.10 ∿ 1.35

The reduced basicity of foundry pig iron goes a long way toward decreasing the reduction factor of Ti, V, etc.
For example, $[Ti]/(TiO_2)$ is given by the following formula.

$$[Ti]/[TiO_2] = -4.00 + 0.105\ (CaO/SiO_2) + 0.00272\ (\text{tapping temperature, °C})$$

(2) Determination of Al_2O_3

(See Table 2.7-7) Usually, the oxides having a large iron radius and a small ion-oxygen attraction parameter show a strong basicity. Characteristically, these oxides decrease their viscosity with decline in melting point. However, Al_2O_3, having the second stronger acidic oxide to SiO_2, increases viscosity as it forms an anionic bond. Fig. 2.7-26 shows the relationship between the concentration of Al_2O_3 and viscosity at various temperatures under CaO/SiO_2 = 1.15 to 1.24 and MgO = 3 to 4%.

As illustrated, the viscosity increases with increase in the concentration of Al_2O_3, which tendency is even more amplified when the temperature is low.

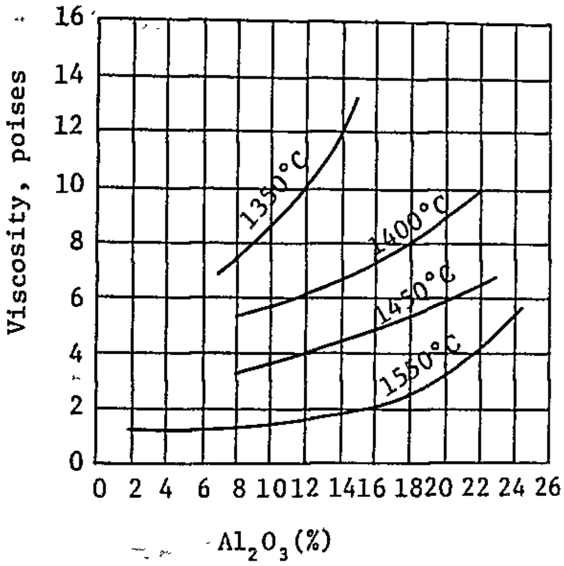


Fig. 2.7-26 Al_2O_3 concentration vs. viscosity relationship at various temperatures

The increase in the viscosity decreases the slag-metal boundary surface reactivity. Also, the increase in Al_2O_3 concentration reduces the basicity to reduce the desulfurizing efficiency. Accordingly, Al_2O_3 concentration should preferably be lower than 15 to 16%.

(3) Determination of MgO

Although MgO is an effective slag component, it is not taken as so serious a control item as CaO/SiO_2 and Al_2O_3 explained in the foregoing.

Rather is emphasis placed on improving the high-temperature characteristics by adding MgO source to sinter and pellet while benefiting from the resultant increase in MgO in the slag.

MgO is weaker in basicity than CaO, and is expected to play a role of improving slag viscosity rather than intensifying basicity. In many cases, the $CaO-Al_2O_3-SiO_2$ system shows a sharp change in slag viscosity with a little change in chemical composition, but if up to 5% of MgO is dosed, this sharp change can be checked, and the viscosity can be held to a low value. Fig. 2.7-27 shows the MgO concentration vs. viscosity relationship at various temperatures under CaO/SiO_2 = 1 and Al_2O_3 = 12 to 15%.

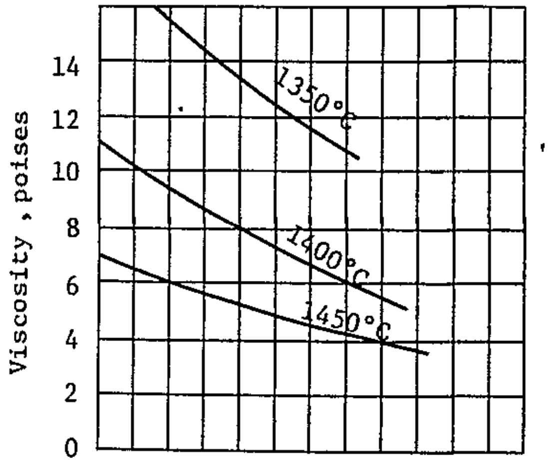


Fig. 2.7-27 MgO concentration vs. viscosity relationship at various temperature

As illustrated, the increase in MgO concentration improves the slag viscosity remarkably. As a result, the desulfurization efficiency of molten iron can be enhanced as shown in Fig. 2.7-28.

It is therefore concluded that MgO as a slag component should preferably be a high value.

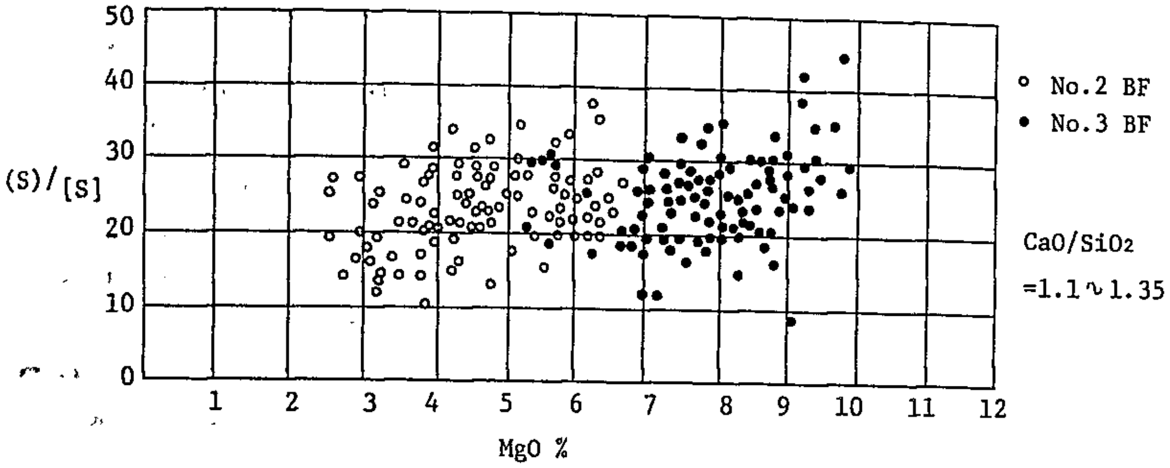


Fig. 2.7-28 Relationship between MgO concentration in slag and (S)/[S]
(Kobe Steel, Kobe Works, No.2 and No.3 BF)

[Reference]

If water-granulated slag is delivered as a blast furnace cement material, its chemical composition is recommended to be as follows for the purpose of increasing pressure resistance.

i) $(CaO + Al_2O_3 + MgO)/SiO_2$: the higher, the better 1.8 ∿ 2.1

ii) SiO_2/Al_2O_3 : the lower, the better 1.8 ∿ 2.1

iii) MgO and MnO: the lower, the better

iv) High vitriceousness and high whiteness

2.7.4 Alkali in the blast furnace operations

(1) Effects of alkali on blast furnace operations

Alkali is found mainly in the form of silicates in the furnace charges. The majority of it is discharged out of the blast furnace together with slag. But part of it remains in the form of metallic gas in the high temperature zone, is oxidized and circulated through the furnace. As already discussed in 2.6.1, potassium (K) is thermodynamically more astable, easier to be gasified and more liable to be converted into a recirculating alkali than sodium (Na). For this reason, the intra-furnace alkalies are mostly accounted for by potassium.

K_2SiO_3 in the charges is converted into potassium gas (boiling point, 760°C) through the following reducive reaction when it is sinking through the furnace.

K_2SiO_3 which has remained unreduced is trapped as a slag component and discharged out of the furnace.

In and around the thermal reserve zone:-

$$K_2SiO_3 + Fe \rightarrow 2K(g) + SiO_2 + FeO$$

Below bosh:-

$$K_2SiO_3 + C \rightarrow 2K(g) + SiO_2 + CO(g)$$

The potassium gas produced by reduction goes up, and when it has reached a low-temperature high oxygen-potential zone, is subjected to oxidation shown by the following formulas. In this way, potassium recycles itself through the blast furnace.

$2K + 3CO \rightarrow K_2CO_3 + 2C$ (K_2CO_3 : stable at temperatures below 900°C)

$2K + CO_2 \rightarrow K_2O + CO$ (K_2O : stable at temperatures below 750°C)

$2K + 2SiO_2 + CO \rightarrow K_2SiO_3 + C$ (K_2SiO_3 : stable at temperatures below 1,100°C)

K_2O fixed in the coke is changed into KCN(g) as it reacts with C and N in the high-temperature zone near the burning zone of the blast furnace according to the formula given below.

$$K_2O + 3C + N_2 \rightarrow 2KCN + CO$$

KCN thus produced ascends together with furnace gas, and part of it reacts with the furnace gas to form K_2CO_3 according to the following formula.

$$4CO_2 + 2KCN \rightarrow K_2CO_3 + N_2 + 5CO$$

Table 2.7-8 Melting and sublimation points of alkalis and alkali compounds

	K	Na	K_2O	Na_2O	K_2SiO_3	K_2CO_3	Na_2CO_3	KCN	NaCN	Na_2SiO_3
m.p(°C)	63.7	97.8		1132	997	901	850	622	562	1089
b.p(°C)	760	892	881					1625	1530	

The recycling of alkali in the furnace has been explained above. It is reported however that according to an dissection survey, about 2.3 kg of alkali (= $K_2O + Na_2O$)/ton-iron) produced about 6 to 7 times as much alkali being recycled. The circulation of much alkali like this causes the following troubles in the blast furnace operations.

a) The furnace wall refractories are damaged.
As per explanation in 2.6.

b) Deposition of low-melting point alkali compounds causes hanging and encrustations on the furnace walls.

Figs. 2.7-29 and -30 show the equilibrium diagrams of SiO_2-Al_2O_3-K_2O ternary system and SiO_2-Al_2O_3-Na_2O ternary system, respectively. As illustrated, the compounds having as low a melting point as below 800°C exist. These-melting point substances lodge in between particles of furnace wall bricks or furnace charges, developing hanging or forming furnace wall encrustations.

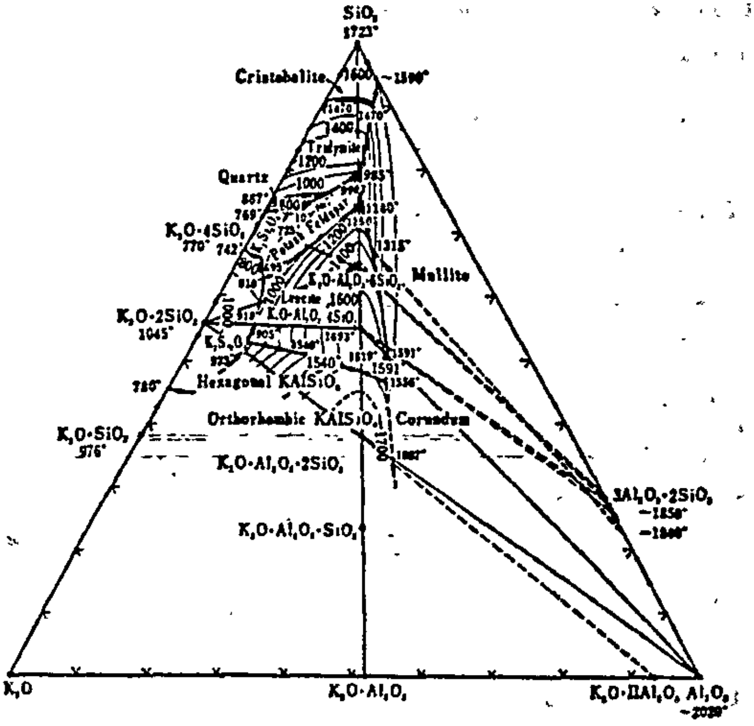


Fig. 2.7-29 SiO_2-Al_2O_3-K_2O ternary system diagram

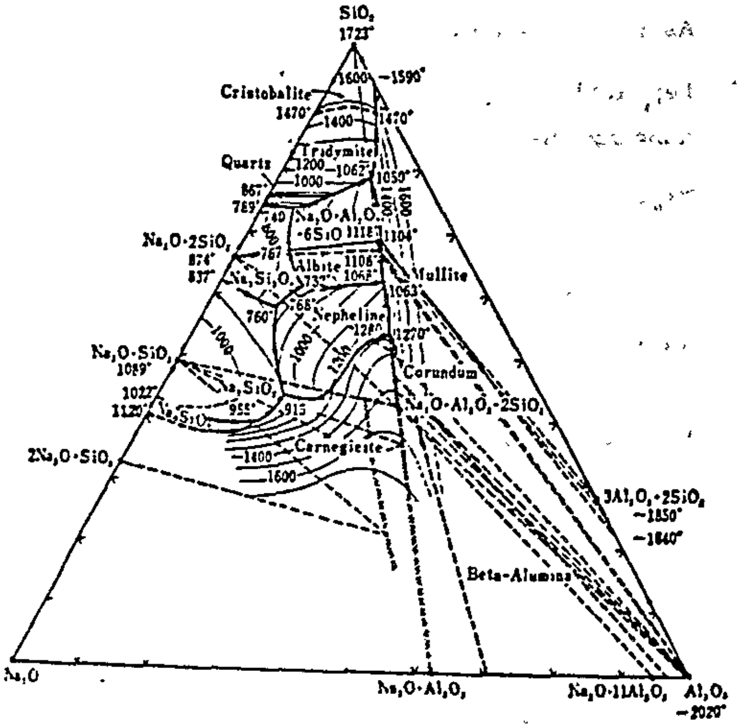


Fig. 2.7-30 SiO_2-Al_2O_3-Na_2O ternary system diagram

c) The alkali reduces the coke strength and aggravates the carbon solution loss reaction.

The rate of carbon being gasified according to the reducing behavior in the blast furnace is given by the following formula.

Carbon gasifying rate,

$$C_{gas} = \frac{3}{4} M(1 - R)(1 + CO/CO_2)$$

where, R: direct reduction ratio (%/100)

M: reduced oxygen per ton of iron (kg-O/ton-iron)

CO, CO_2: composition of furnace gas exclusive of dissociated gases of carbonates

According to the formula above which has been established stoichiometrically, it is found that the fuel ratio can be decreased by increasing the direct reduction ratio and decreasing the CO/CO_2 ratio.

However, an extraordinary increase in direct reduction ratio will increase CO/CO_2 ratio as much or more, sending up Cgas. It is when the furnace heat leaves an ample margin in the high-temperature zones of above 1,000°C and when the CO/CO_2 ratio which represents the reaction efficiency in the lower temperature zones is lying close to 1 that the direct reduction ratio must be increased.

In such a case it is desirable to increase the solution loss (direct reduction) in order to increase the reducing capacity and volume of shaft gas.

As regards the COLAR furnace, it is not recommended to increase the solution loss because CO/CO_2 is high.

Namely, it is necessary that the coke reactivity should not be so high. As already discussed, the alkalis are circulating within the blast furnace. According to an overhaul inspection of Amagasaki No. 1 blast furnace, it was found that some coke ash in the high-temperature zone registered no less than 30% of ($K_2O + Na_2O$). According to JIS reactivity test, such coke showed more than 70% of reactivity.

Fig. 2.7-31 shows the relationship between alkali content in coke before charge and JIS reactivity according to JIS method.

As shown in Fig. 2.7-31, the increase in alkali increases the reactivity.

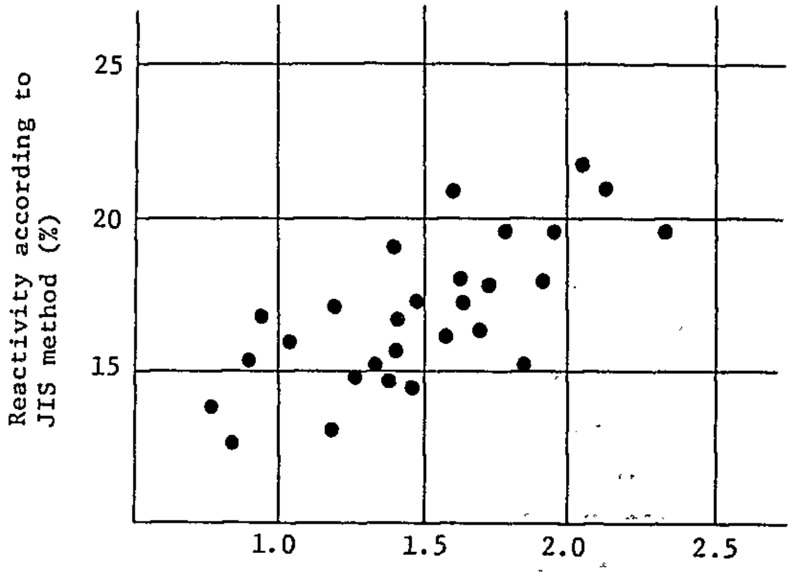


Fig. 2.7-31 Alkali content in coke before charge and JIS reactivity

The high-reactivity coke shows a low mechanical strength in the high-temperature zone, and is liable to be disintegrated into dust to choke up the passages of gases and liquids. For reasons above, it is necessary to control the alkali content in the coke to within a tolerable limit.

(2) Alkali charges in COLAR

a) Alkali in coke

Fig. 2.7-32 shows an alkali analysis of ashes of coke and coal and its relations with COLAR data checked by the survey mission.

According to Kobe Steel's experience, the alkali content in the ashes of coal and coke shows little or no change; namely, it is recognized that the alkali is not lost in the dry distillation process.

There are singularities in alkali content between ashes of COLAR coal and caking coal, which may result from brand differences. It should be noted however that the alkali content in the COLAR coke ashes is generally so low that it will not cause any problem.

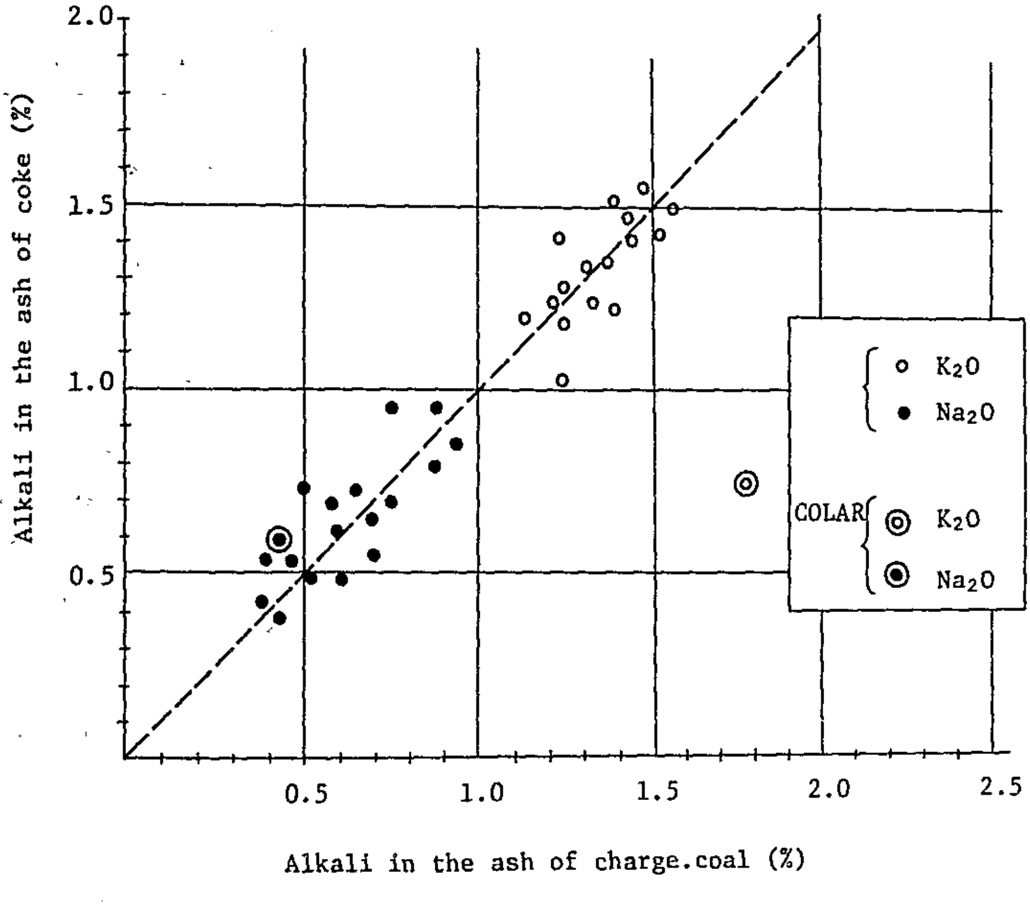


Fig. 2.7-32 Alkali in the ash part of coke and charge coal, and its relations with alkali in COLAR coke

b) Alkali in the iron ore

Table 2.7-9 shows an alkali analysis of COLAR iron ores and Kobe Steel sinters.

Table 2.7-9 Alkali in ores and sinters

	COLAR			K S L				
				Sinter		Pellet		
	Pericos cocopan	Pericos adit	CYF mineros	Kakogawa	Kobe	Amagasaki	Kobe	Kakogawa
K_2O,%	0.048	0.024	0.012	0.06	0.07	0.08	0.07	0.07
Na_2O,%	0.013	0.013	0.013	0.04	0.07	0.10	0.10	0.04

As shown in the table, COLAR iron ores show low alkali contents. Kobe Steel has matched sinters against COLAR ores. This is because Kobe Steel uses a high charge rate of sinter.

c) Alkali charges into the blast furnace

As already discussed in a) and b) above, COLAR coke and ore show not so large an alkali content as to cause a problem. On the other hand, COLAR uses iron ores of low grade, which in turn sends up the ore ratio and coke rate. Accordingly, the alkali charge per ton of iron is far from small.
Namely, from coke comes 2.97 kg of alkali per ton of iron
(= 1,500 kg-coke/ton-iron x 0.15 x (0.0058 + 0.0074),
provided that coke ash contains 0.58% of Na_2O and 0.74%
of K_2O, and
from ore comes 0.864 kg of alkali per ton of iron
(= 1,800 kg-ore/ton-iron z (0.00035 + 0.00013).
These make up a total 3.8 kg of alkali per ton of iron.
In Japan, the alkali charge is 2.0 to 3.0 kg or so of alkali per ton of iron. As compared with this, COLAR's alkali charge is a little higher. This value, however, will be reduced when the coke rate is reduced.

The reduction of coke rate solves many problems in an effective way, and it is therefore none too emphasized that the beneficiation is a very important project worth promoting.

As mentioned above, the alkali content in COLAR coke is none too high. Although it cannot be said decisively that the embrittlement of coke in the COLAR furnace is larger than in other furnaces, the attack by recirculating alkali is another problem.

Kobe Steel has not yet made close studies about the relationships between the alkali entrained together with furnace charges and the recirculating alkali.

It may well be quite logical to think that there will be some relation between the amounts of recirculating and charged alkalis. But, it is also believed that the physicochemical reactions in the furnace will be more significant in the production of recirculating alkali than the charged alkali is.

The COLAR furnace is low in temperature, high in slag ratio and low in CaO/SiO_2. Under these operating conditions, it cannot always be said that the recirculating alkali will be high.

For the purpose of providing against alkali problems, it is necessary not only to reduce the coke rate, but to control the slag basicity to a low value ($CaO/SiO_2 < 1.1$)

2.7.5 Wind velocity at the tip of tuyere

There will be arguments over whether the physical quantity of wind governing the depth of raceway should be represented vectorially (momentum) or in a scaler value (kinetic energy). Here, the kinetic energy is taken up for the purpose of discussion, however.

Z.I. Nekrasov surveyed a good number of blast furnaces in good operating conditions, and proposed the following formula concerning the kinetic energy of wind befitted to the hearth diameter.

$$E = 86.5D^2 - 313D + 1{,}160 \quad \dots\dots\dots\dots (1)$$

Where, E : kinetic energy of wind, kg.m/sec./tuyere
D : hearth diameter, mϕ

The kinetic energy of the wind is also given by the following formula.

$$E = \frac{1}{2} \cdot \frac{1.293 \times Q}{0.8 \times N} \left(\frac{Q}{N.S} \times \frac{T + 273}{273} \times \frac{1{,}034}{P_1 + P_2} \right)^2 \quad \dots\dots\dots\dots (2)$$

Where, Q : wind rate, m^3 in NPT/sec.
N : number of tuyeres
S : area of the tip of tuyere, m^2/tuyere
T : wind temperature, °C
P_1: atmospheric pressure, g/cm^2
P_2: wind pressure, g/cm^2 in gauge
E : kinetic energy of wind, kg.m/sec./tuyere

There are many researches who have reported the relationships between kinetic energy and raceway depth (L_R (m)).
Here, the formula (3) below, proposed by Bardin, et al, is used.

$$L_R(m) = 0.118 \times 10^{-3} E + 0.77 \quad \dots\dots\dots\dots (3)$$

From Eqs. (1) and (3), the raceway depth best matched with a given hearth diameter is obtained as given by the formula (4) below.

$$L_R = 0.0102D^2 - 0.037D + 0.907 \quad \dots\dots\dots\dots (4)$$

Table 2.7-10 Hearth diameter vs. best raceway depth and wind energy

Hearth diameter (mϕ)	3	4	5	6	7	8	9	10
Kinetic energy (kg.m/sec.tuyere)	1000	1300	1800	2750	3200	4200	5350	6700
Raceway depth (m)	0.888	0.922	0.977	1.052	1.148	1.264	1.400	1.560

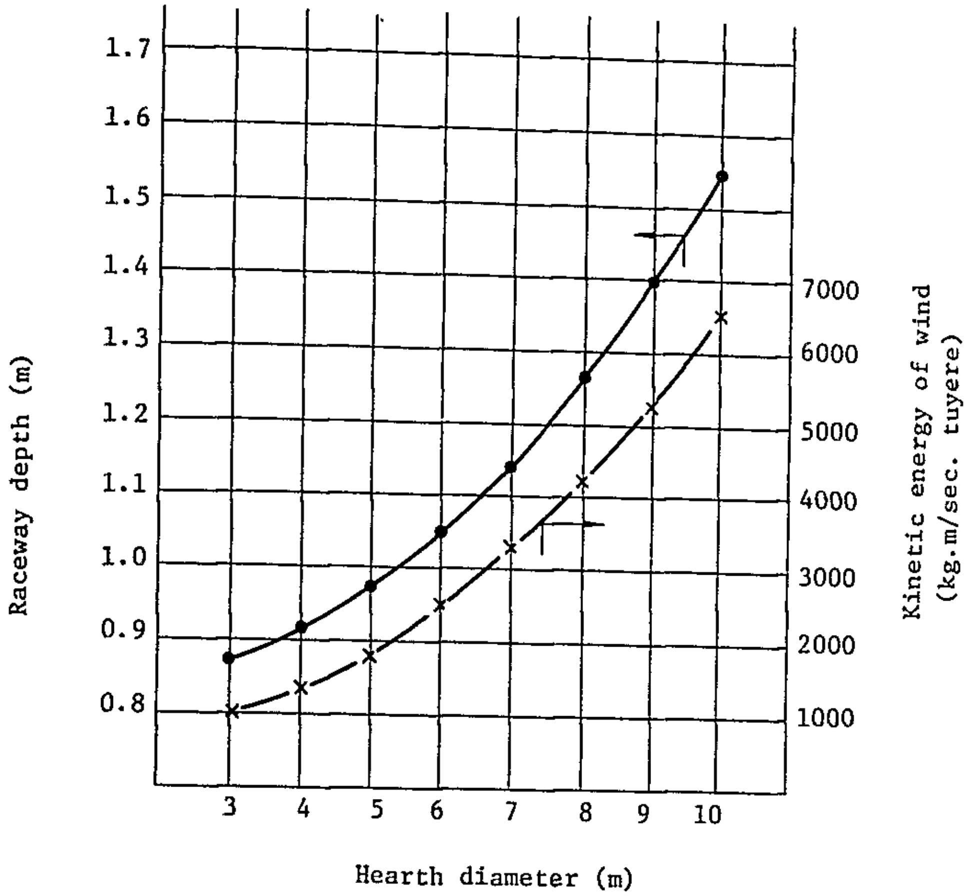


Fig. 2.7-33 Hearth diameter vs. best raceway depth and kinetic energy of wind

Fig. 2.7-33 is prepared according to Z.I. Nekrasov's formula. According to Kobe Steel's experience, however, the values for small furnaces measuring 5 mϕ or smaller seem to be rather too small.

In the case of 3 to 4 mϕ furnaces, the kinetic energy of wind should be at least 1,300 kg.m/sec.

In the case of a 3.8 mϕ furnace owned by "A" company in Japan, good operating results have been achieved with kinetic energy of nearly 2,000 kg.m/sec.

In Japan, the wind velocity at the tip of tuyere lies in the range of 180 to 270 m/sec. irrespective of the furnace inner volume.

In the extreme cases, the wind velocity is as high as 300 m/sec.

Now let us calculate the tuyere diameter and wind velocity on assumption that COLAR wind has 1,300 kg.m/sec. of kinetic energy.

Preconditions

i) Wind rate : 200 m^3/min. = 3.333 m^3/sec.

ii) Atmospheric pressure : 1,034 x 580/760 = 789 g/cm^2

iii) Wind temperature : 600°C

iv) Number of tuyeres : 6

v) Wind pressure : 250 g/cm^2

vi) Area of tuyere : S m^2/tuyere

By applying Eq. (2),

$$1{,}300 = \frac{1}{2} \cdot \frac{1.293 \times 3.333}{9.8 \times 6} \left(\frac{3.333}{6 \times S} \times \frac{600 + 273}{273} \times \frac{1{,}034}{789 + 250}\right)^2$$

Hence, S = 0.009486 m^2

Thus, the tuyere diameter is calculated at 110 mmϕ, and the wind velocity at 188 m/sec.

Little though the COLAR furnace is, the tuyere wind velocity should be at least 180 m/sec. The reasons are as follows. First, smalls of coke are liable to stay on the dead core walls in the deepest section of the raceway because the coke strength is weak.

Secondly, this chokes up the gas flow through the furnace center to develop skin flow of furnace gas.

Bardin, et al, showed the raceway depth as simply a function of kinetic energy of wind.

In actuality, however, the raceway depth is largely governed by the coke grain size. If the tuyere is covered up with smalls of coke, the depth will become shallow; thus, the raceway will be enlarged upwards.

If the wind rate exceeds a certain limit, the particles in and over the raceway will slug up continuously or intermittently along the furnace walls, making the raceway astable.

In such an event, the tuyere diameter should be reduced to increase the raceway depth.

2.8 Quality of Pig Iron

2.8.1 Behavior of impurities in the intra-furnace reactions

When smelting foundry pig iron, the impurities should be controlled for reasons explained below.

a) For the purpose of ensuring high-quality products, tramp elements must be minimized.

b) The smelting of foundry pig iron is carried out at higher temperatures and in more reducing atmosphere than that of pig iron for steel-making use, and the amount of tramp elements trapped in the pig iron is increased more.

In the production of foundry pig iron, these two contradictory conditions must be solved. This asks the smelter to be well conversant with the behavior of tramp elements (impurities) in the pig iron.

The requirements of alloying elements for the pig iron are as follows.

a) To stem from furnace charges.

b) To become metallic elements when reduced in the furnace.

c) Not to evaporate after being reduced.

d) To dissolve in the pig iron.

The reducibility of metal oxides can be judged from the free energy for standard formation. Here it is discussed according to Table 2.8-1 showing a modified periodic chart of elements.

Table 2.8-1 Modified periodic chart of elements

H	He	Li	Be	B	C											N	O	F
	Ne	Na	Mg	Al	Si											P	S	Cl
	A	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br
	Kr	Rb	Sr	Y	Zr	Nb	Mo		Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I
	Xe	Cs	Ba	La	Ce													
				Yb		Ta	W		Os	Ir	Pt	Au	Hg	Tl	Pb	Bi		
					Th		U											

Table 2.8-2 Boiling temperatures of the metallic elements

element	V	Cr	Mn	Mo	Fe	Co	Ni	Cu	Zn
b.p.(°C)	3,400	2,500	2,150	4,800	2,740	2,900	2,730	2,600	906
element	As	Se	Cd	Sn	Sb	Te	Pb	Bi	
b.p.(°C)	610	680	765	2,270	1,440	1,390	1,740	1,420	

element	Ca	Zr	Al	Mg	Mn	V	Si	Ti	Sb	As	Zn	P	Sn	Ni	Cu	Cr	Pb	Co	Bi	S
reduced elements	●	●	●	●	◒	◒	◒	◒	○	○	○	○	○	○	○	○	○	○	○	○
vaporizing elements	○	○	○	●	○	○	○	○	◒	◒	◒	○	○	○	○	○	○	○	◒	○
alloying elements	●	●	○	●	○	○	○	○	○	○	○	○	○	○	○	○	●	○	○	○
elements contained in iron	●	●	●	●	◒	◒	◒	◒	◒	◒	◒	○	○	○	○	○	●	○	◒	◒
yield (%)	0	0	0	0	50 70	50 60	20 65	35 45	50 65	50 70	0 30	100	100	100	100	100	0	100	-	5 15

Fig. 2.8-1 Yield of the elements into the pig iron through the various process in the blast furnace

With reference to Table 2.8-1, Fe is in the middle row of the chart. Since the principal objective of the blast furnace operations is the reduction of iron oxides, the table offers a pungent statement. In the table, the elements are arranged according to the ionization potential period and atomic number.

The elements show lower ionization potential the more they go leftwards, and vice versa. The elements lying on the lefthand side of Fe are hard to be reduced in the furnace. Those on the righthand side of Fe are easy to reduce, however. This goes well with the relationship of free energy of oxide, with the exception of Cr and other special elements.

Table 2.8-2 shows the boiling points of metallic elements. Although the metallic oxides show a high boiling point, their boiling point goes down when reduced into pure metals. Zn, As, Se, Cd, Sb, Bi, etc. in their pure metallic state is vaporized in the furnace and vented out together with furnace gas. Some of them, however, solidify in the low temperature zones in the furnace and fly down in the furnace together with furnace charges. In this way, these metals recycle themselves in the furnace. A very little part of these metals is also dissolved in the pig iron as determined by vapor pressure.

The following shows the elements classified by the dissolution for iron.

Alloying elements : Al, As, Co, Cr, Mn, Ni, P, Pt, S, Si, Sn, W, Mo, Ti, V, Bi, C, Cu

Non-alloying elements : Pb, Hg

In short, the elements in the furnace charges are trapped into pig iron after going through reduction, partial evaporation and alloying. Fig. 2.8-1 is a summary of the processes above, and shows a yield of each element taken into pig iron as an alloying substance.

In the blast furnace operations, the furnace charges should be selected to eliminate tramp elements, that is that group of elements which shows a higher ionization tendency that Fe.

As regards the elements whose ionization potential is extremely lower than Fe, no particular consideration is needed as they can be removed in the form of slag. It should be borne in mind that those elements, the ionization potential of which is just short of that of Fe, May be trapped into the pig iron in varying degrees depending on the operating conditions. Of the transition elements, carbide-forming ones whose ionization potential is a little lower than that of Fe should be controlled carefully in furnace operation. All these are governed by the general laws of chemistry given below.

i) The elements whose ionization potential is low become susceptible to reduction at an increased level of temperature.

ii) The basic oxides which are liable to liberate oxide ions get reducible when CaO is increased.

These are summarized in Table 2.8-3 below.

Table 2.8-3 Effects of tapping temperature and basicity of slag upon [M]/[MO]

element	tapping temp	basicity of slag
Si	Positive correlation	Negative correlation
Mn	"	Positive correlation
Ti	"	"
V	"	"
Cr	"	"

The behavior of trace elements to be seen in the smelting of pig iron has been discussed, and may be summarized as follows.

(1) Elements lacking affinity with Fe

1) Ca, Zr, Al, Mg

2) Pb

(2) Elements whose yield is changeable depending on furnace operating conditions.

1) Mn, Ti, Si, V, (Cr)

2) As, Zn, Sb, Bi

(3) Elements showing a high solubility in Fe

P, Sn, Ni, Cu, Co, (Cr)

The classification above is nothing but a rough measure, and may change more or less depending on specific furnace operating conditions. For example, Al shows a high affinity for oxygen, and is considered to be turned into slag without being reduced.
According to close surveys conducted by Kobe Steel, it is found that a very little quantity of aluminum is reduced and trapped into pig iron as represented by the following regression formula.

$$[Al,\%]/(Al_2O_3,\%) \times 10^{-4} = -13.16 + 0.011x_1 + 0.127x_2$$

Where, x_1 : moten iron temperature, °C

x_2 : slag basicity = CaO/SiO_2

It is therefore necessary to fully understand the behavior of trace elements in the blast furnace and prepare data concerning the yield of elements in the pig iron and daily operating conditions. In the blast furnace operations, the batching of feedstocks should be made by brand according to the following formula in order to attain a target chemical composition.

B element in pig iron,

$$\% = ((\text{Sigma } (Mi.Bi) + Mo.b)) . \mu B/((1/(0.94 \text{ Sigma } (Mi.Ai))$$

Where, $\mu B, \mu C$: yield of alloying element, %

Mi : ore rate by brand, kg/ton-iron

Mo : coke rate, kg/ton-iron

Ai : Fe component by ore brand, %

Bi, Ci : component of alloying element in ore, %

b, c : component of alloying element in coke, %

2.8.2 Control of impurities in the foundry pig iron

The products turned out of a foundry pig iron smelting blast furnace are supplied to various users of different needs; some require soft, machinable products, and some others ask for wear-resistant hard products.

In order to answer these different needs, the supplier must produce homegeneous products of uniformly grown graphitized structure. Namely, it is necessary to improve reducing conditions in the blast furnace for the purpose of minimizing oxides and P, S and trace impurities.

In Japan, the total of trace impurities is represented symbolically by ΣA, and the composition control is carried out to minimize ΣA on assumption that all the impurities are equally detrimental to the pig iron.

This method is significant in its own way considering the synergy of trace impurities. Fig. 2.8-2 shows the significance of the relationship between ΣA and graphitizing ratio. It will be understood that the reduction in ΣA is quite effective in increasing the graphitizing ratio.

Table 2.8-4 Effects of trace elements in ordinary pig iron on the structure, and their relationships with gaseous elements

Element	Graphitizing		Relations with gaseous elements		Others
	Promoted	Hampered	Deoxidizing	Denitriding	
Al	o		o		Impairs castability.
Zr	o		o		Forms eutectic graphite.
Ti	o		o	o	ditto
Cu	o				Synergizes with Cr, Mr and V.
Ni	o				Consolidates the texture.
Cr		o			Impairs castability.
Sn		o			Checks the segregation of ferrite and embrittles the iron.
Ce		o	o		Desulfurizes.
Pb		o			Works to develop cracks.
V		o	o	o	Synergizes with Mo, Ni, Cu, and Ti.
B		o			Consolidates the texture.
Mg		o	o		Desulfurizes
Mo		o			Fines down the matrix.
Te		o			Tends to supercool.
Se					Forms eutectic graphite.
Bi					Forms eutectic graphite.
Zn					Tends to supercool.
Sb		o			Stabilizes pearlite.
As		o			

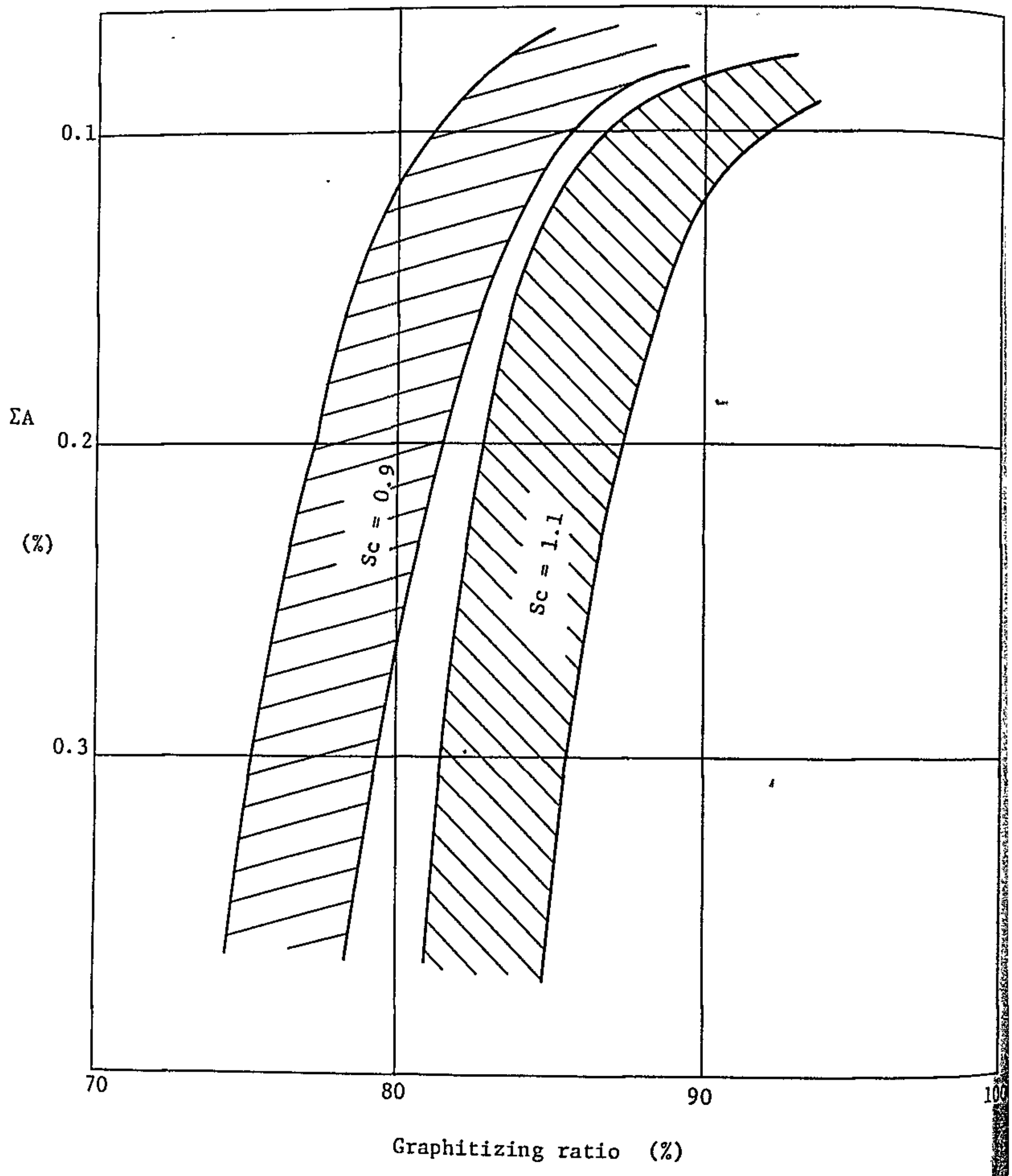


Fig. 2.8-2 ΣA and graphitizing ratio relationship with respect to Sc = 0.9 and 1.1

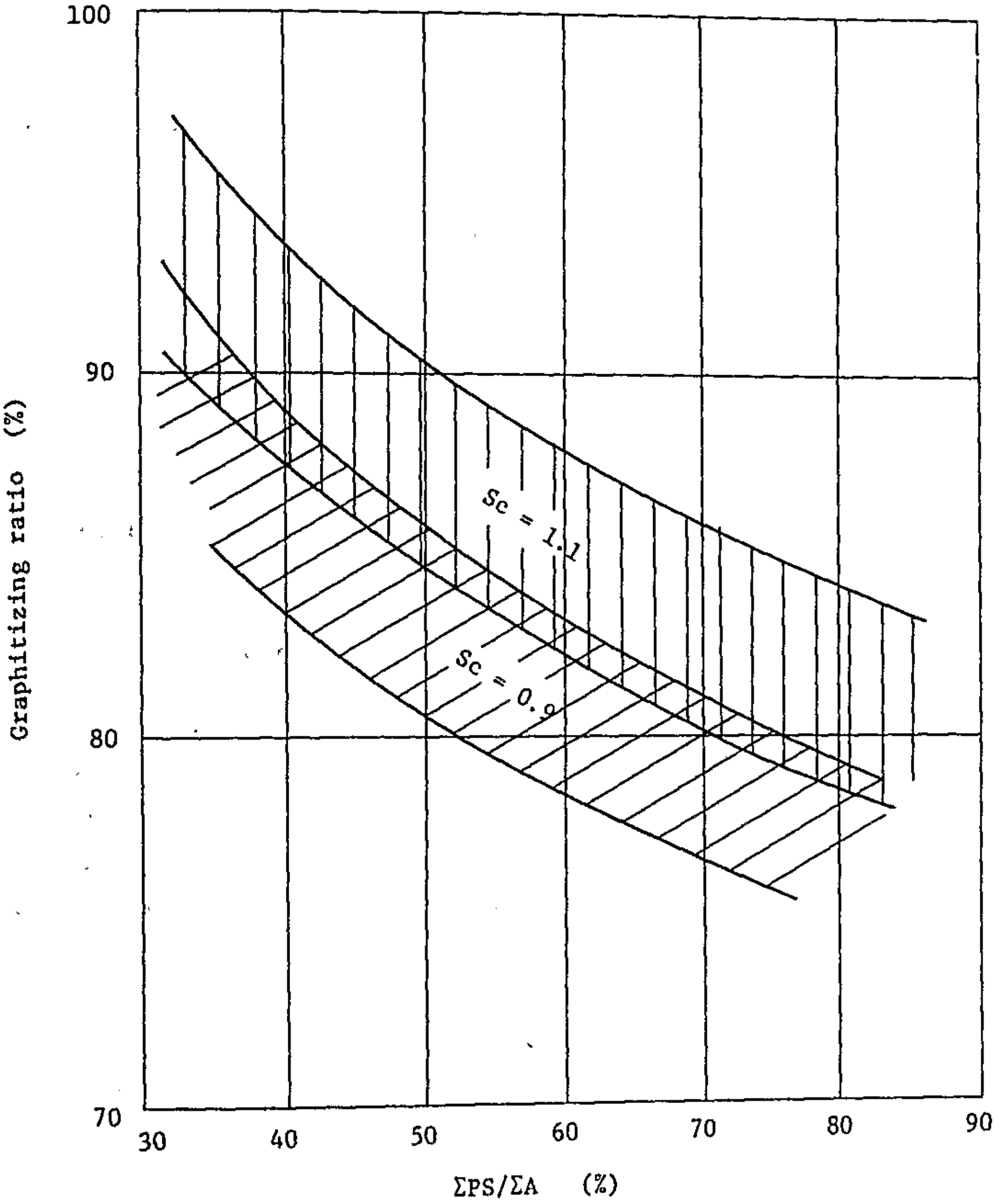


Fig. 2.8-3 ΣPS/ΣA vs. graphitizing ratio relationship with respect to Sc = 0.9 and 1.1

In Figs. 2.8-2 and -3, Sc means the carbon saturation degree given by the following formula.

$$Sc = [c,\%]/((4.23 - [Si.\%]/3.2 - 0.275[P,\%]))$$

Table 2.8-4 shows the effects of tramp elements in ordinary pig iron on the graphitization and their relationship with gaseous elements.

The elements are classified according to their effects on the graphitized structure as follows.

Total of elements promoting graphitization,

$$\Sigma G = Cu + Ti + Ni + Al + Co$$

Total of elements impeding graphitization,

$$\Sigma AG = Cr + Mo + V + Sn + Pb + As$$

Total of elements promoting to fine graphite,

$$\Sigma EG = Cu + Cr + Ni + V + Sn + Sb + Al + Ti + Bi + Co$$

Total of elements stabilizing pearlite,

$$\Sigma PS = Cu + Cr + As + Ni + Mo + V + Sn + Sb$$

As already explained, the microstructure of the foundry pig iron is required to show uniformly developed graphite flakes. Accordingly, ΣAG, ΣEG and ΣPS should be minimized. Fig. 2.8-3 shows the ΣPS/ΣA vs. graphitizing ratio relationship. As is clear from Fig. 2.8-3, it is necessary to reduce the total of those elements stabilizing pearlite which come under ΣA for the purpose of increasing the graphitizing ratio.

For the purpose of promoting the sale of foundry pig iron, the COLAR cannot but turn its eyes to the producers of high-quality castings. Namely, the pig iron products to be furnished to them must be high-quality ones containing little impurities. According to Kobe Steel's experience, the chemical composition of the pig iron products meeting the user's needs is as shown in Table 2.8-5.

The pig irons shown are excellent as a raw material for high-quality machine castings.

Table 2.8-5 Practice of the impurities analyses of pig iron for foundry in Amagasaki Works, Kobe Steel.

	Pig iron for grey cast iron	Pig iron for nodular graphite cast iron	Pig iron for malleable cast iron
Mn	0.45 ∿ 0.70 %	0.20 max. %	0.50 ∿ 0.90%
S	0.040 max.	0.030 max.	0.035 max.
P	0.060 ∿ 0.080	0.060 ∿ 0.070	0.060 ∿ 0.080

Trace impurities

Cu	0.005 ∿ 0.010	0.003 ∿ 0.010	0.005 ∿ 0.010
Cr	0.002 ∿ 0.010	0.002 ∿ 0.010	0.002 ∿ 0.010
Ti	0.050 ∿ 0.080	0.050 ∿ 0.070	0.050 ∿ 0.080
As	tr. ∿ 0.004	tr. ∿ 0.003	tr. ∿ 0.004
Al	0.005 ∿ 0.025	0.002 ∿ 0.010	0.005 ∿ 0.025
V	0.005 ∿ 0.015	0.005 ∿ 0.015	0.005 ∿ 0.015
Ni	0.001 ∿ 0.005	0.001 ∿ 0.005	0.001 ∿ 0.005
Mo	0.001 ∿ 0.003	0.001 ∿ 0.003	0.001 ∿ 0.003
Sn	0.001 ∿ 0.005	0.001 ∿ 0.005	0.001 ∿ 0.005
Sb	0.0002 ∿ 0.0010	0.0002 ∿ 0.0010	0.0002 ∿ 0.0010
Pb	tr. ∿ 0.0005	tr. ∿ 0.0005	tr. ∿ 0.0005
Zn	tr. ∿ 0.001	tr. ∿ 0.001	tr. ∿ 0.001
Bi	tr. ∿ 0.0005	tr. ∿ 0.0005	tr. ∿ 0.0005
Co	tr. ∿ 0.005	tr. ∿ 0.005	tr. ∿ 0.005
ΣA	0.0702 ∿ 0.1650	0.0652 ∿ 0.1390	0.0702 ∿ 0.1650

Reference: Japanese Industrial Standard

FOUNDRY PIG IRON[*]

1. Scope

This Japanese Industrial Standard specifies foundry pig iron, hereinafter referred to as the "pig iron".

2. Classification

The classification of pig iron shall conform to Table A.

Table A. Class

Class			Application
Class 1	No. 1	A	Pig iron used for grey cast iron and shall be subdivided into No.1 and No.2 in accordance with the quality level. Further, No.1 shall be mainly subdivided into A, B, C and D by Si content.
		B	
		C	
	No. 2		
Class 2	No. 1	A	Pig iron used for malleable cast iron and shall be subdivided into No.1 and No. 2 in accordance with the quality level. Further, No. 1 shall be mainly subdivided into A, B, C, D and E by Si content.
		B	
		C	
		D	
		E	
	No. 2		
Class 3	No. 1	A	Pig iron used for nodular graphite cast iron and shall be subdivided into No. 1 and No. 2 in accordance with the quality level. Further, No. 1 shall be mainly subdivided into A, B, C and D by Si content.
		B	
		C	
		D	
	No. 2		

3. Shape

All ingots of the pig iron shall be nearly the same shape and the mass per piece shall be 2 to 10 kg as the standard, and for the ingot of over 5 kg in mass shall be able to be subdivided into 3 kg or so, and be convenient for handling.

4. Chemical Composition

The chemical composition of pig iron shall conform to Table B.

Table B. Chemical Composition

Class			Chemical composition %					
			C	Si	Mn	P	S	Cr
Class 1	No.1	A	3.40 min.	1.40 to 1.80	0.30 to 0.90	0.300 max.	0.050 max.	-
		B	3.40 min.	1.81 to 2.20	0.30 to 0.90	0.300 max.	0.050 max.	-
		C	3.30 min.	2.21 to 2.60	0.30 to 0.90	0.300 max.	0.050 max.	-
		D	3.30 min.	2.61 to 3.50	0.30 to 0.90	0.300 max.	0.050 max.	-
	No.2		3.30 min.	1.40 to 3.50	0.30 to 1.00	0.450 max.	0.080 max.	-
Class 2	No.1	A	3.50 min.	1.00 to 2.00	0.40 max.	0.100 max.	0.040 max.	0.030 max.
		B	3.00 min.	2.01 to 3.00	0.50 to 1.10	0.100 max.	0.040 max.	0.030 max.
		C	3.00 min.	3.01 to 4.00	0.50 to 1.10	0.130 max.	0.040 max.	0.030 max.
		D	2.70 min.	4.01 to 5.00	0.50 to 1.30	0.130 max.	0.040 max.	0.030 max.
		E	2.50 min.	5.01 to 6.00	0.50 to 1.30	0.150 max.	0.040 max.	0.030 max.
	No.2		2.50 min.	1.00 to 6.00	1.35 max.	0.160 max.	0.045 max.	0.035 max.
Class 3	No.1	A	3.40 min.	1.00 max.	0.40 max.	0.100 max.	0.040 max.	0.030 max.
		B	3.40 min.	1.01 to 1.40	0.40 max.	0.100 max.	0.040 max.	0.030 max.
		C	3.40 min.	1.41 to 1.80	0.40 max.	0.100 max.	0.040 max.	0.030 max.
		D	3.40 min.	1.81 to 3.50	0.40 max.	0.100 max.	0.040 max.	0.030 max.
	No.2		3.40 min.	3.50 max.	0.50 max.	0.150 max.	0.045 max.	0.035 max.

Remarks 1. For Cr in Class 1 the maximum value may be determined by agreement between the parties concerned. In this case, its maximum value shall be 0.10%.

2. For P in Class 2 No. 1 C and D the maximum value may be determined to 0.100% by agreement between the parties concerned.

3. In Class 3, for Ti, As and other chemical composition which will disturb the spheroidizing of graphite, the content thereof may be determined by agreement between the parties concerned.

5. Chemical Analysis

5.1 The test shall, as a rule, be conducted on one test specimen so sampled from each tap of molten pig iron as to represent it, at the time of casting at the manufacturing plant.

In case when it is recognized, however, that it is necessary, by the purchaser, the analysis may be conducted on the ingot of pig iron.

In this case, the sampling method shall conform to agreement between the manufacturer and the purchaser.

6. Marking

On the whole or a part of pig iron ingot, the mark of the manufacturer shall be cast out.

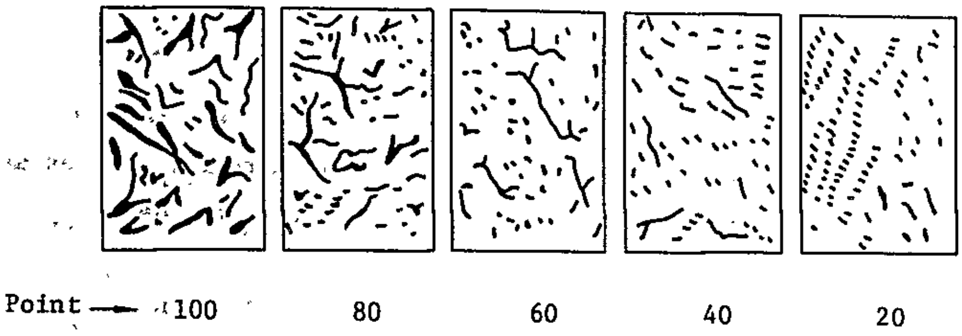
The chemical composition of pig iron has been discussed above with emphasis on the tramp elements closely relating to the heredity. Since the pig iron ingots are the final form of the products to be sold by the smelter, they are required to be uniform in unit weight and have a smooth, beautiful skin. The skin must be smooth and free of blisters, scabs, sinkage and other defects. The high-temperature molten iron reduced in good condition shows a low content of sulfur and oxygen, is high in surface tension, low in wettability against mold, and high in graphitizing ratio. Thus, ingots of agreeable skin conditions can be achieved. The graphitized structure may be affected by casting conditions.

It may constitute a disapproval by ingot fracture graphitizing test, while graphite structure is disappeared by remelting.

Fig. 2.8-4 shows statistical data obtained by experiments to study the effects of pouring temperature, molding temperature, etc. upon the graphitized structure.

As is seen, the graphitizing ratio can be improved by increasing the pouring temperature and molding temperature.

a) Standard scales for rating the graphitized conditions of ingot fractures



b) Effects of casting conditions on graphitization of fracture

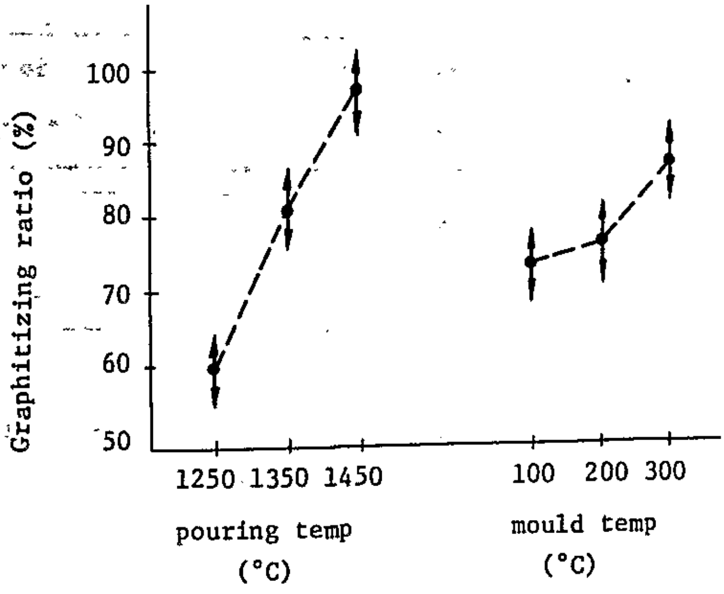


Fig. 2.8-4 Effects of casting conditions on ingot fracture

2.8.3 Appraisal of COLAR pig iron quality

The pig iron specimen taken at the pig iron stock yard and brought back home are estimated to be for steel-making use as their silicon values are as shown in Table 2.8-6.

[Note] COLAR's target silicon value by kind of pig iron

For steel : 1.0 to 1.5% Si
For cast iron : 2.5 to 3.5% Si

They are studied on presupposition that their material sources are just the same as those for the pig iron for cast iron use.

Table 2.8-6 Chemical composition of COLAR pig iron

i) 5 popular elements

C	Si	Mi	P	S	Sc
4.11	1.58	0.54	0.228	0.048	1.1188

ii) Tramp elements

Ni	Cu	Ti	As	Cr	Al	Co	Sb	Sn
0.017	0.129	0.056	tr	0.009	<0.001	0.006	0.002	0.004

Zn	Pb	V	Mo	Bi	ΣA	ΣPS	ΣPS/ΣA
<0.001	0.002	0.008	<0.001	<0.001	<0.237	0.170	71(%)

Fig. 2.8-5 shows the relationship between [C] and [Si] determined according to actual blast furnace operations.

The plot in the figure refers to Kobe Steel's 721 m^3 BF, "A" company's 184 m^3 BF and COLAR BF.

In the blast furnace operation, the [C] values usually are distributed parallel to the Ce line irrespective of [Si], and Sc is in in the range of 1.1 to 1.2.

Note: Ce = Carbon equivalent

$$Ce = 4.23 - [Si,\%]/3.2 - 0.275[P,\%]$$

The reason why (C) and (Si) in the pig iron are nearly in parallel to Ce is that the saturated carbon dissolution line for the Fe-C-Si system is running parallel to the Ce line. This will be well understood from the following two formulas.

For the Fe-C-Si system, the Ce formula can be rewritten as follows.

$$Ce = 4.23 - 0.3125[Si,\%]$$

Saturated carbon concentration, $C_T = [C_B,\%] - 0.31[Si,\%]$

Both formulas have almost the same coefficient for [Si]; namely, the coefficient may be approximated at 0.31.

As shown in Fig. 2.8-4, the [C]-[Si] relation of COLAR furnace is a little lower than that of Kobe Steel's 721 m^3 BF. In normal blast furnace operations, the product quality becomes higher with increase in reducing power in the furnace, furnace heat and Sc value as FeO and S in the pig iron become reduced.

In order to increase Sc value of COLAR pig iron up to 1.15, C is required to be increased by 0.18%C.

Then, according to the saturated carbon dissolution, the temperature must be increased by 75° C (= 0.18/0.0024).

In the actual operation, things are not so easy as calculated.

Under low tapping temperature conditions incidental to small blast furnaces, it will be important to improve the intra-furnace reducing conditions through the betterment of beneficiation.

The next problem is an extremely high P component.

The high P component is not only detrimental to high-quality ductile cast iron which is required to show a high elongation under as-cast conditions, but also do harm to grey cast iron because P stabilizes Fe_3C to increase the tendency toward chilling and reduce toughness.

P is said to promote the development of internal shrinkage and blowholes in the castings.

For the castings for machine use, P should be limited to within 0.150%. As already explained, all P in the furnace charges is reduced and taken into the pig iron. For this reason, efforts should be made to reduce the coke rate through strict control of brand selection and vigorous enforcement of beneficiation.

Assume that the coke rate has been reduced from 1,600 kg to 800 kg per ton of iron, then P to be entrained into the pig iron from the coke will be reduced by 0.4144 kg or 0.041%.

As regards the tramp elements, the COLAR pig iron is quite beyond reproachment, except for Cu. Cu is spoken of as graphitizer. It functions to consolidates and stabilize pearlite and at the same time fine down the graphite. When coexistent with Cr, Mo, V, etc. it synergizes with them to check graphitization, increasing the tensile strength, deflective strength, hardness and other mechanical properties. In this connection, attention should be paid to the fact that such mechanical properties may not go with the needs of some specific users.

Photo 2.8-1 shows a microstructure of COLAR pig iron.

The graphite is rather swerved, and its linear, flaky parts, though little, are uniformly distributed. There is no particular structural defect to speak of.

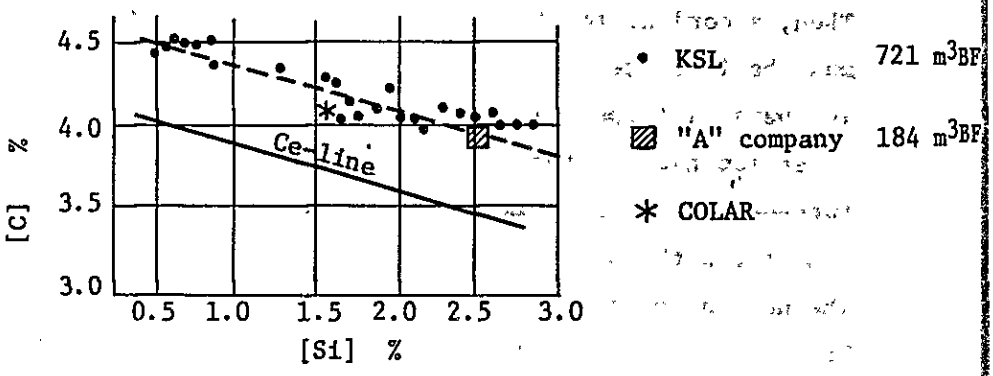
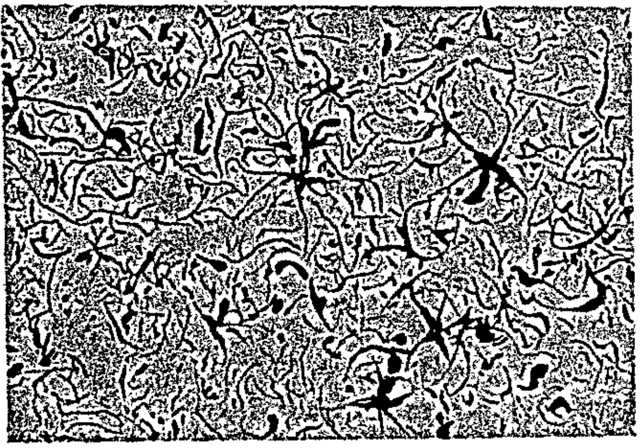


Fig. 2.8-5 Relationship between [C], [Si] and eutectic carbon in blast furnace operations

Photo 2.8-1 Micrographs of COLAR pig iron.

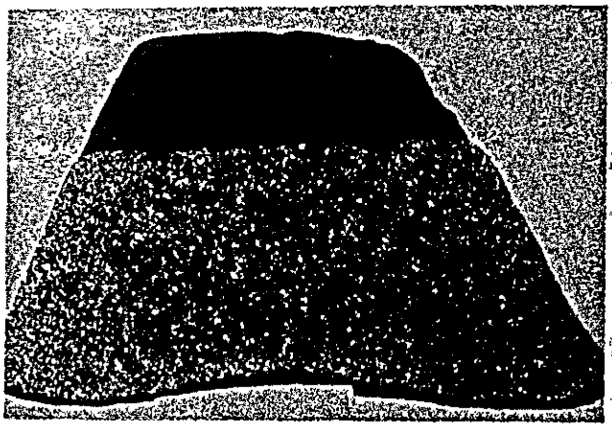
a) No-etching x 100



b) 5%-nital etching x 100

Photo 2.8-2 Foundry pig iron manufactured by Kobe Steel

a) Ingot fracture



b) Microstructure (5%, nital etching x400)

2.8.4 Measures against the variations of Si component in pig iron casting process

No matter how excellent the blast furnace operation control may be, variations in pig iron chemical composition can be developed because of secular change and because of fluctuations in smelting and fluxing conditions in both radial and axial directions in the furnace. Also, the smaller the furnace size is, and the higher the target value of Si is, the higher will become the change in the Si component. The pattern of Si change is not fixed even in the same single tap. For those users who call for a severe control of composition, utmost control care will be needed. As regards Si, the width of variation of Si will be reduced to a narrower value by ladle control than by tap control.

Fig. 2.8-6 shows the actually measured Si variations ($Si_{max.} - Si_{min.}$) within tap and within ladle of foundry pig iron producted at Amagasaki Works, Kobe Steel.
As shown, the width of variations within ladle are much lower than that within tap. For one thing, maldistribution of contents in the tap is normalized by being ladled into divisions. For another, the ladling is accompanied by churning due to pouring, convection due to temperature gradient in the ladle, and diffusion of Si, etc. to homogenize the components.

40 tons ladle/about 130 tons-iron/tap

$R_{si} = (Si_{max} - Si_{min})$/ladle, or/tap

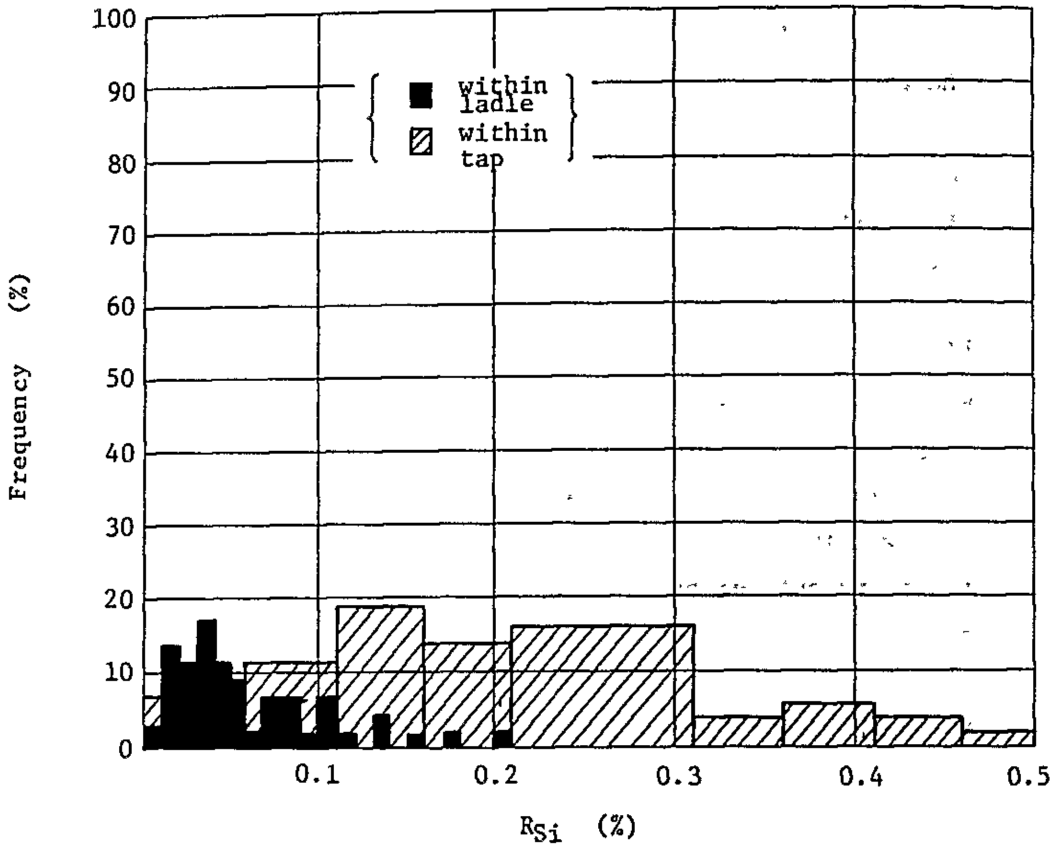


Fig. 2.8-6 Actually measures Si variations within tap and within ladle at Amagasaki Works, Kobe Steel

2.9 Instrumentation and Heat Control for Blast Furnace

2.9.1 Instrumentation control

Proper instruments should be installed and maintained for precise indication and recording of process data necessary for monitoring smooth operation, and/or betterment of the operations of blast furnace, hot air stove, charging facilities, gas purifier, etc. The COLAR's problems lie in the maintenance of instruments, storage and use of measured data rather than in a dearth of instruments.

(1) Maintenance of instruments for accuracy

For the operation, maintenance and management of instrumentation systems, it is necessary to employ and bring up highly trained expert engineers who may hold another post concurrently.

a) Daily maintenance

In the daily maintenance, the engineers or operators should carry out patrol inspection daily according to a check list on which inspection items are specified. Unlike periodic inspection, the daily inspection concentrates on checking instruments for abnormalities visually and repairing them, but checkup of accuracy is not made. Those who inspect the instruments are required to have an expert knowledge and experience about the instruments themselves and the operating conditions of the object to be measured by such instruments.

b) Periodic maintenance

The accuracy of the measuring instruments changes with time owing to various factors, and should be checked and corrected periodically.

The methods and cycles of periodic maintenance are given in Table 2.9-1 by way of reference.

Table 2.9-1 Periodic maintenance of instruments

Name of instrument	Methods	Master gauge	Frequency
Flowmeter orifice	The orifice for combustion gas is liable to be fouled up with dust laden in the gas, and should be cleaned periodically.		once a year
Flow transmitter	Adjust the reading by supplying a standard differencial pressure to the flow transmitter.	High-precision manometer	once every four months
Pressure transmitter	Adjust the reading by supplying a standard pressure to the pressure transmitter. For the pressure gauges of more than 2 kg/cm, the accuracy may be checked with a high-precision Bourdon pressure gauge.	High-precision manometer (High-precision Bourdon pressure gauge)	once every six months
Temperature detective element	The thermocouple, resistance bulb and other sensing elements should be checked and calibrated periodically. In the blast furnace, however, the checkup and calibration are sometimes omitted because of: a) negligibly small secular change and high element durability; b) high availability of high-quality sensing elements. It is therefore recommended to use products of proven electromotive force characteristics, stability and properties, available from reliable manufacturers and replace them within an effective service period warranted by respective manufacturers. The maintenance should be made by taking into account the fact that the temperature detective elements sometimes are a cause of process control error.		
Thermometer	The thermometer should be calibrated with account taken of the electro-motive force characteristics or resistance characteristics of the thermocouple used in combination with the instrument.	Standard e.m.f. generator, standard variable resistor	once every six months

Name of instrument	Methods	Master gauge	Frequency
Indicator, recorder	These are run on a unified system of voltage or current.	Standard voltage/ current generator	once every six months
Controller	Check the output by supplying a standard input signal, and calibrate as required.	Standard voltage/ current generator, standard voltmeter and ammeter	once every six months
Weigher	Calibrate the weigher by applying correctly adjusted tare weights.	Weights for inspection use (e.g., 20-kg weight)	once every six months

(2) Upgrading of existing instrumentation systems

<u>Wind indicating recorder</u>

The present scale range is 0 to 2,000 Nm^3/hr.
Usually, the scale is divided in hundredths; namely, the minimum division is 20 Nm^3/hr. for the existing wind indicating recorder. If the instrument is changed to take readings in Nm^3/min., its measuring range becomes 0 to 35 m^3/min. with an improved measuring accuracy of up to 1 Nm^3/min. if the scale is divided into 70 parts.

(3) Additional instruments required

a) Wind controller

For the purpose of stabilizing the blast, an automatic wind controller should be installed.

b) An instrument for analyzing residual oxygen in the hot air stove exhaust gas (0 - 10% O_2)

The oxygen gas analyzer should be installed for increased combustion efficiency of hot air stove.

c) Thermometer for detecting the temperature of furnace lining and shell

This instrument is necessary for the purpose of monitoring the loss of furnace lining and also monitoring the intra-furnace gas flow in order to improve the furnace operating efficiency. See Fig. 2.9-1.

d) Furnace gas analyzer (H_2, CO, CO_2)

The furnace gas analyzers are necessary for diagnosing the furnace conditions and for detecting water leakage at the time of tuyere failure.

e) Coke hygrometer (neutron hygrometer)
For weighing coke on a dry basis.

2.9.2 Heat control

The heat control should be regarded as the most important theme, as is the need for energy conservation today and tomorrow.
At present, all the furnace gas is wasted into the open air, except when it is used for heating the hot air stove or for the reducing kiln which is operated on and off.
For the purpose of turning the blast furnace gas to good account, the furnace gas balance is studied here.

(1) 1st phase (wind temperature, 600°C; coke rate, 900 kg/ton-iron)

Design conditions:-

Wind rate : 200 m^3-air/min.
Coke rate : 900 kg-coke/ton-iron
FC in coke : 84%
Direct reduction ratio : 33%
Reduced oxygen : 425 kg-O/ton-iron
Pig iron, C% : 4.0%
Dust, C% : 5 kg-C/ton-iron
Air composition : 21% O_2, 79% N_2
CO gas calorific value : 3,020 kcal/m^3-CO
For the purpose of simplicity of calculation, the limestone charge is assumed to be zero.

With reference to the conditions above, the stoichiometry shows the following results.

Blast furnace gas composition: 11.54% CO_2, 26.88% CO, 61.58% N_2
Furnace gas calorific value : 812 kcal/m^3
Furnace gas volume : 3,454 m^3/ton-iron = 15,398 m^3/hr.

Assuming that the hot air stove efficiency is 75% and that the wind temperature is 600°C, the blast furnace gas balance is calculated as summarized in Table 2.9-2.

Table 2.9-2 Blast furnace gas balance (I)

Gas generation rate	Consumption by hot air stove	Surplus
15,398 m^3/hr.	3,795 m^3/hr.	11,603 m^3/hr.
100%	24.65%	75.35%

Namely, the utilization by hot air stove of blast furnace gas is about 25%, and the surplus (loss) amounts to as much as about 75%. Studies should therefore be promoted in search of the ways for harnessing the blast furnace gas waste.

(2) 2nd phase (wind temperature, 900°C; coke rate, 830 kg/ton-iron)

Design conditions:-

The wind temperature and coke rate are as captioned, and others are just the same as (1), provided that the thermal efficiency of hot air stove is 72%.

Then, the following results are obtained.

Blast furnace gas composition: 12.7% CO_2, 26.1% CO, 61.2% N_2
Blast furnace gas calorific value: 788.2 kcal/m^3
Blast furnace gas generating rate: 3,138 m^3/ton-iron = 15,490 m^3/hr.

Hence, the blast furnace gas balance is as shown in Table 2.9-3.

Table 2.9-3 Blast furnace gas balance (II)

Generation rate	Consumption by hot air stove	Surplus
15,490 m^3/hr.	6,128 m^3/hr.	9,362 m^3/hr.
100%	39.6%	60.4%

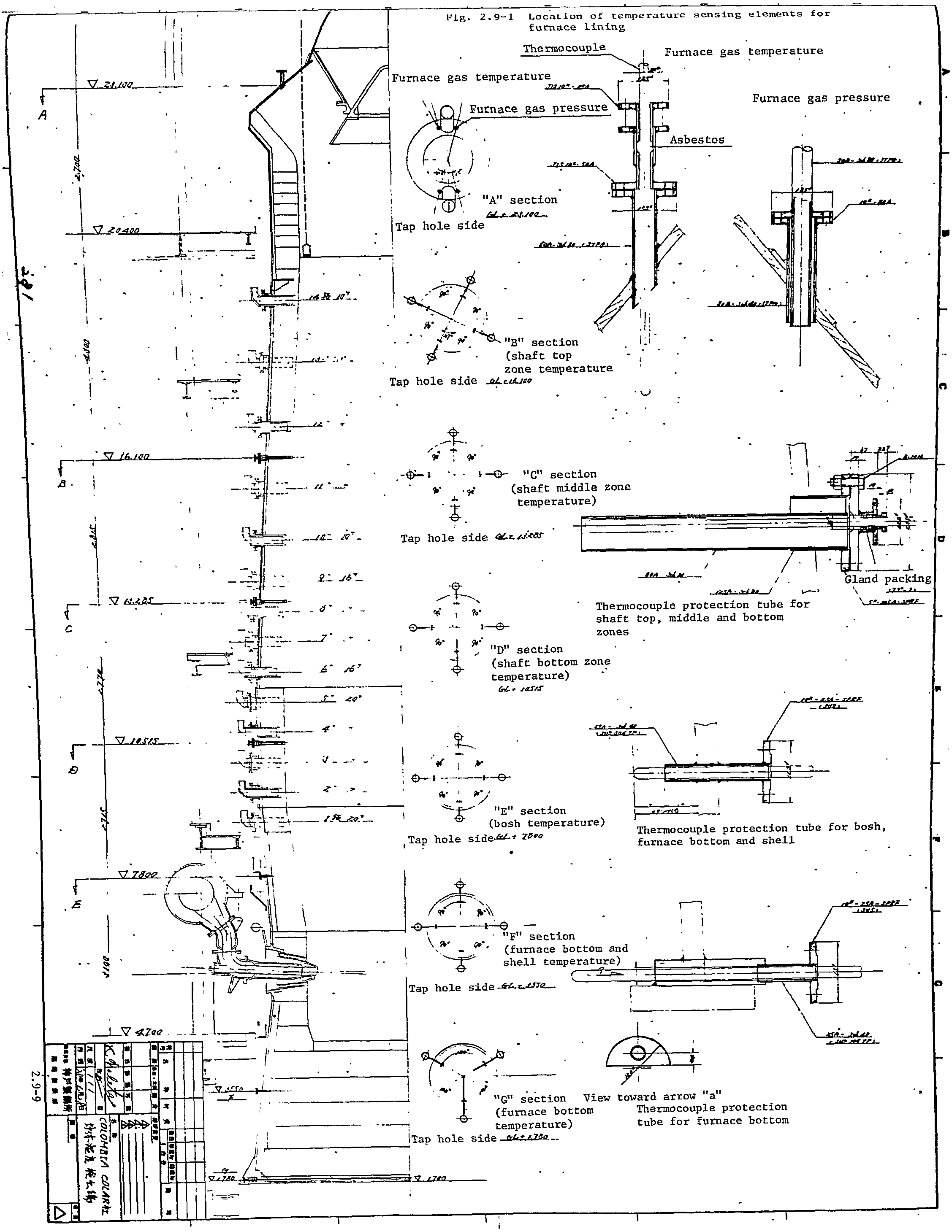
The blast furnace gas will be used for the following purposes.

a) As shown in Table 2.9-3, the gas utilization efficiency can be increased by about 15% if the wind temperature is increased up to 900°C by installing additional hot air stoves or by increasing the unit capacity of hot air stove. As a result, the coke rate can be reduced by some 70 kg/ton-iron.

b) The surplus blast furnace gas may be used for power generation or for steam turbine-blower instead of motor-driven blower to save energy, though this should be studied in economic comparison with the unit cost of commercially available electric power.
The steam turbine-blower can safety run on the blast furnace gas of shorther than 1,500 m^3/hr,

c) The blast furnace gas can also be used as a fuel for making reducing pellets.

Fig. 2.9-1 Location of temperature sensing elements for furnace lining



2.10 Gas Scrubbing and Cast House Work

2.10.1 Gas scrubbing

In the past, dust catcher, hurdle washer and Theisen washer were used in combination for the purpose of cleaning the blast furnace gas. In recent years, however, this combination has been superseded by one or other of the following combinations because it is poor in cleaning efficiency and because the furnace gas pressure has been given much allowance owing to increased blast furnace pressure.

- Ordinary pressure:- Dust catcher → Precooler → E.P.
- High pressure:- Dust catcher → 1st venturi scrubber → E.P.
  (or 2nd venturi scrubber)
- COLAR scheme: Dust catcher → Venturi scrubber

When using a venturi scrubber in the secondary cleaning system, 1st and 2nd venturi scrubber must be used in combination for reasons explained below. In this case, the furnace gas should allow for at least 2,000 mm Aq. of head loss as against the clean gas pressure.

As illustrated in Fig. 2.10-1, the blast furnace gas contains dust spreading over a wide range in size of particles. Thus, the dust collecting system should exhibit a high collecting efficiency over a wide range of particle sizes. However, the diameter of water droplet to be developed at the throat of venturi scrubber is determined by liquid/gas ratio, liquid properties and gas speed at the throat as given by Eq. (1) below.

$$D = \frac{585}{Vt} \text{ x } \sqrt{\frac{\sigma}{w}} + 597 \left(\frac{\mu w}{\sqrt{\sigma . \varrho w}}\right)^{0.45} . L^{1.5} \quad \text{..........} \quad (1)$$

Where, D : diameter of water droplet, microns

Vt : gas velocity at the throat, m/sec.

σ : surface tension of liquid, dynes/cm

ϱW: density of liquid, g/cm^3

μw : coefficient of viscosity of liquid, g/cm. sec.

L : liquid/gas ratio, lit./m^3-gas.

The collecting efficiency (Et) is given by the following formula with reference to the size of particle to be precipitated.

$$Et = 1 - \exp\left(-\int_0^x \varepsilon N \frac{\pi}{4} D^2 dx\right) \quad \ldots\ldots\ldots\ (2)$$

Where, ε : $Ur/(Ur + 11.7\ \mu a.D/d^2.\rho d)$

$Re = Ur.D.\rho a/\mu a$

N : number of droplets per unit volume

x : travel distance of droplet

Ur : relative velocity between gas and water droplet

μa : coefficient of viscosity of gas

d : diameter of fine dust particle

ρd : density of fine dust particle

ρa : gas density

Namely, in order to remove dust of large particle sizes, large droplets are required. For eliminating fine dust particles, fine droplets are required. (See Fig. 2.10-4)

Accordingly, if only a single venturi scrubber is used, there will be no theoretical or practical way that it can clean up to a satisfactory level the furnace gas containing dust of a wide range of particle sizes as shown in Fig. 2.10-1.

Now let us try to determine the operating conditions of venturi scrubber for the purpose of eliminating large particles prevailing in the blast furnace gas.

Given that the dust content at the outlet of dust catcher is 5 g/Nm^3 and that the content of fine dust particles of up to 1μ is 5%, i.e., 0.25 g/Nm^3 (= 5 x 0.05), and also that the dust collecting efficiency for particles of up to 1μ is as high as 70%, the dust content in the cleaned gas still will contain as much dust as 0.075 g/Nm^3.

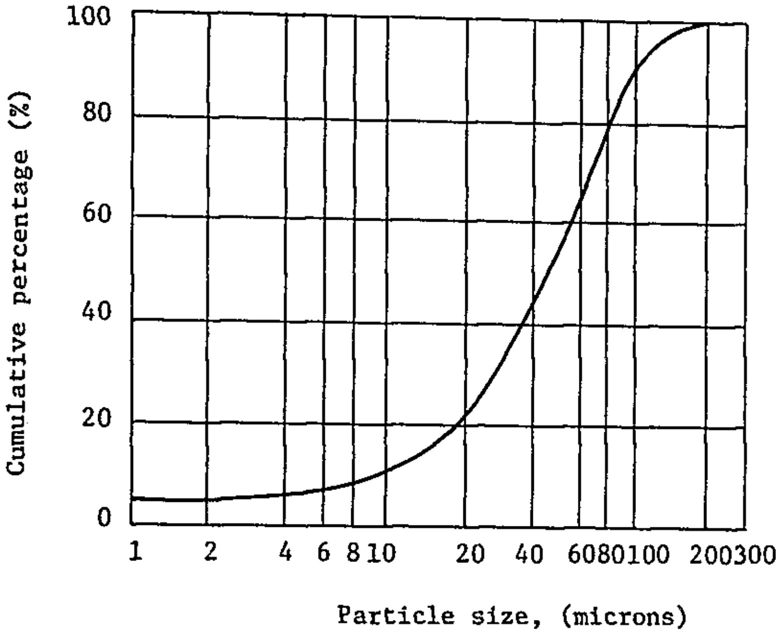


Fig. 2.10-1 A particle size distribution of dust in the gas at the outlet of dust catcher

Nevertheless, it is reported that COLAR's venturi scrubber has developed a head loss of as much as 400 mm Aq. as against a design value of 1,000 mm Aq. Under such circumstances, damage on the hot stove bricks as explained in 2.6-4 is a natural consequence. The survey mission could not obtain detailed information about the operation of venturi scrubber, and is unware of what action was taken to overcome the head loss.

But, it is surmised that the operating conditions would have been somewhere around the following range.

The gas head loss, ΔP, across the venturi scrubber is given by the following formual.

$$\Delta P = (0.3 + 0.65L)r_a.Vt^2/2g$$

If COLAR's operating conditions are as follows,

$$\Delta P = (0.0194 + 0.042)Vt^2$$

Operating conditions:

- Gas temperature, 50°C
- Gas composition, 12% CO_2, 26.7% CO, 61.3% N_2
- Gas pressure, 1,300 mm Aq.

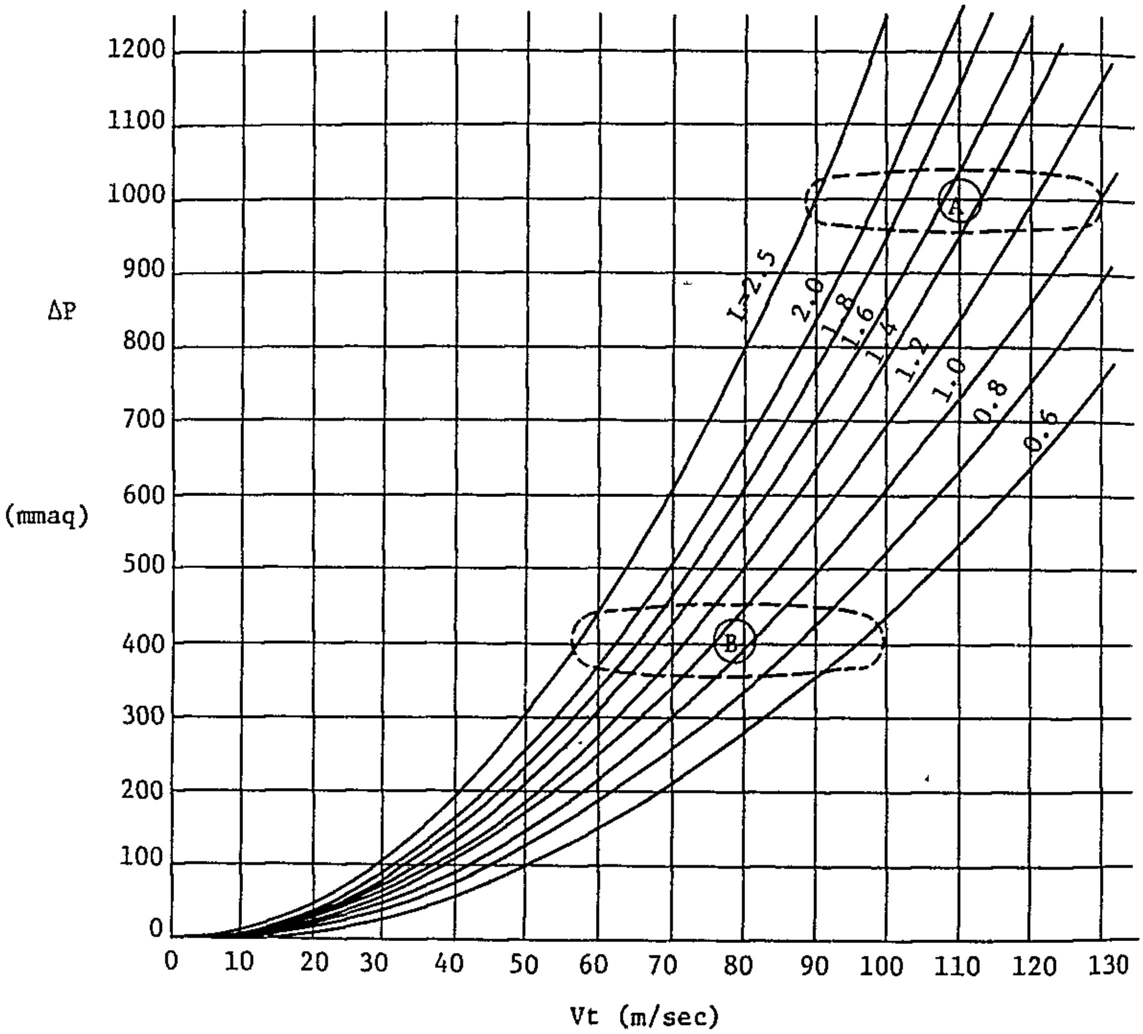


Fig. 2.10-2 ΔP vs. Vt relationship

With reference to Fig. 2.10-2, the COLAR may have changed the liquid/gas ratio or throat gas velocity from (A) level (1,000 mm Aq.) to (B) level (400 mm Aq.).

The change in Vt or L is accompanied by a change in the diameter of water droplet as dictated by Eq. (1).

Fig. 2.10-3 shows the relationships between diameter of water droplet, gas velocity at throat, and liquid/gas ratio.

Fig. 2.10-4 shows a calculation of collecting efficiency of dust particles of 0.1μ coming from a Kobe Steel high-pressure blast furnace.

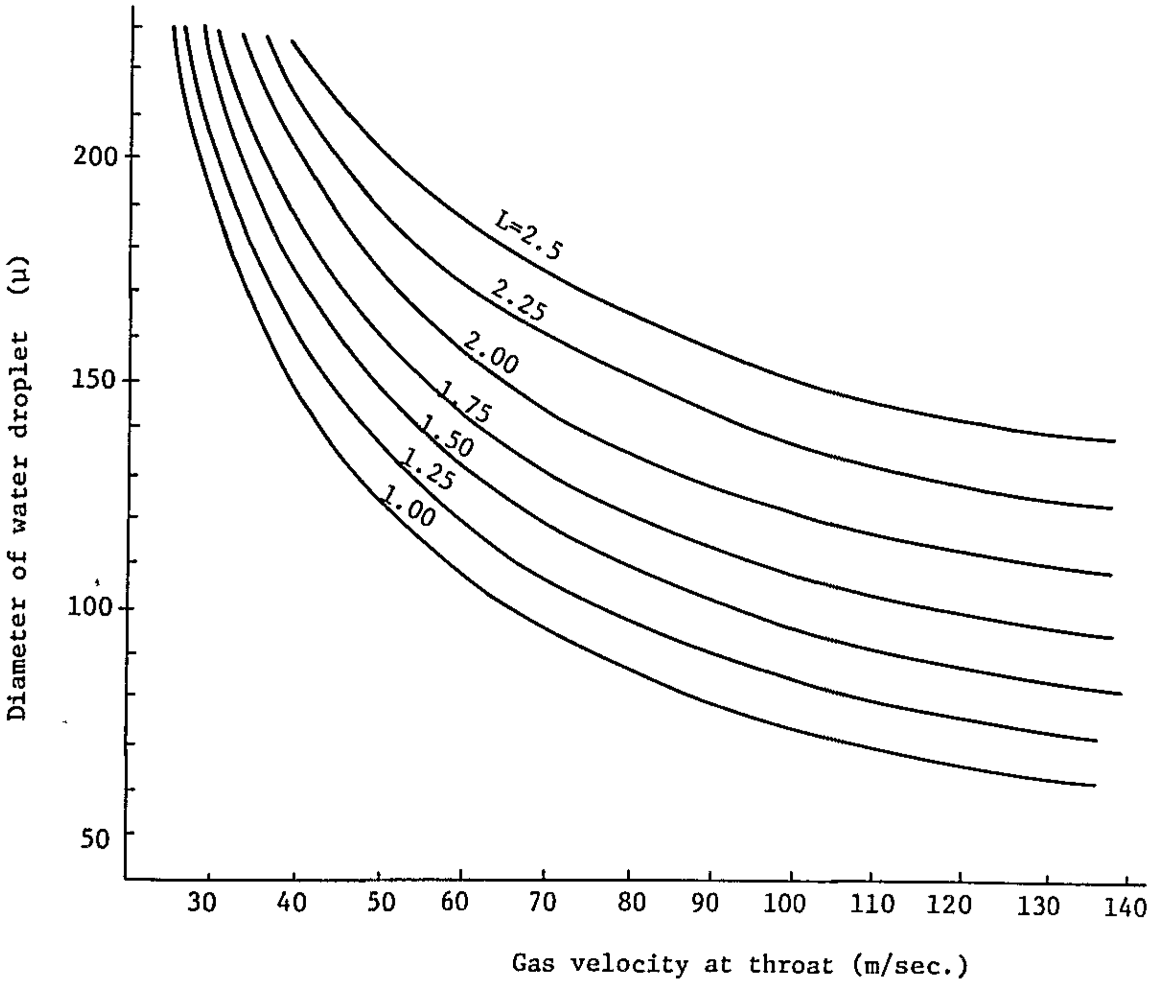


Fig. 2.10-3 Relationships between diameter of water droplet, gas velocity at throat, and liquid/gas ratio

As shown in Fig. 2.10-4, the dust collecting efficiency of the venturi scrubber varies depending on the diameter of water droplets to be determined by the gas velocity at the throat and liquid/gas ratio.

2.10.2 Cast house work

In recent years, the jobs at the cast house have been improved noticeably with respect to the following items concerning labor-saving, quantity control and pollution control, etc.

i) Mechanization as represented by mud gun, iron notch opener, slag notch opener, channel repairing machine, tuyere replacing machine, renewable seesaw channel, etc.

ii) Instrumentation as represented by automatic weighing of ladle charges, dead-beat analyzer used for assaying pig iron chemical composition, automatic pig iron temperature measuring recorder, tuyere failure detector, etc.

iii) Improvement in durability of channel materials.

iv) Improvement in working environments by dust collection from cast house.

v) Improvement in pig iron quality by chemical adjust-control process as represented by desulfurization.

The improvements concerning cast house work have been put into practice in diversified ways. Here it would be be best to discuss the renewable skimmer channel system which the COLAR will be able to adopt immediately.
The COLAR is producing high-silicon pig iron at a trickling rate, and the corrosion of channel lining is little, accordingly.
Use of high-quality lining material will not be payable.
The skimmer, however, is liable to be clogged up with molten metal and slag, and the damper suffers most from loss.
Thus, here is recommended a renewable channel system as illustrated in Fig. 2.10-5. Its lifting and lowering can be accomplished using a cast house crane.

For this reason, there should be installed two units of venturi scrubber, one capable of trapping large particles and the other capable of precipitating small particles.

Since the COLAR's furnace gas pressure is low, the following dust precipitating arrangement should be employed for improvement.

Dust catcher → Venturi scrubber → E.P.

Considering the gas cleaning capacity of the existing system, the hot air stove might possibly be forced to be shut down and repaired even when the ΔP of the venturi scrubber is readjusted to a design specification.

If the situation remains unremedied, the matter will be changed for the worse when the high-temperature blowing-in is practised in the future.

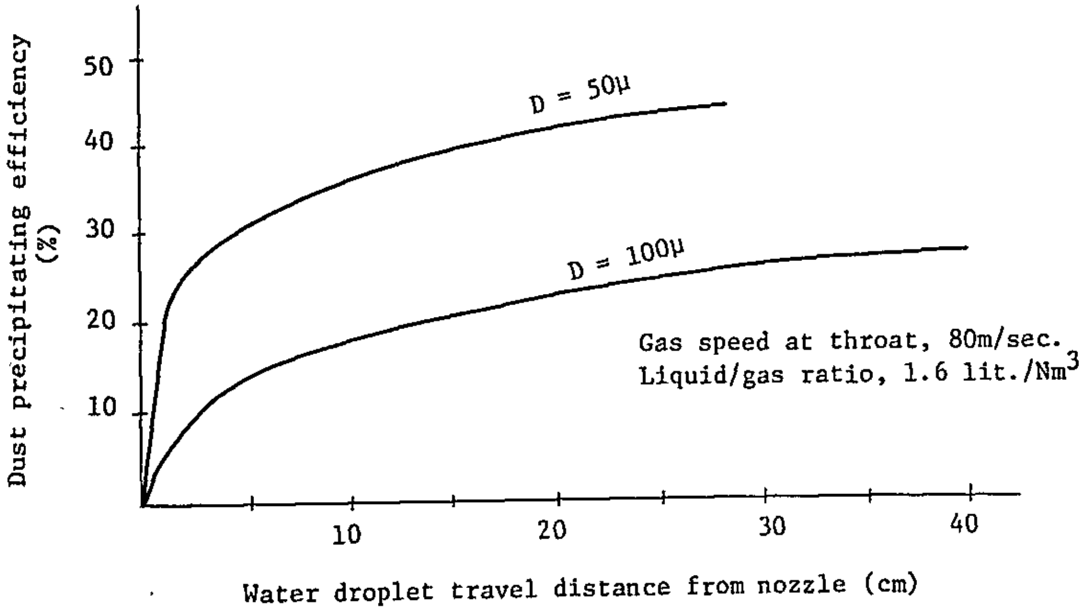


Fig. 2.10-4 Calculated efficiency of precipitating 0.1μ dust particles

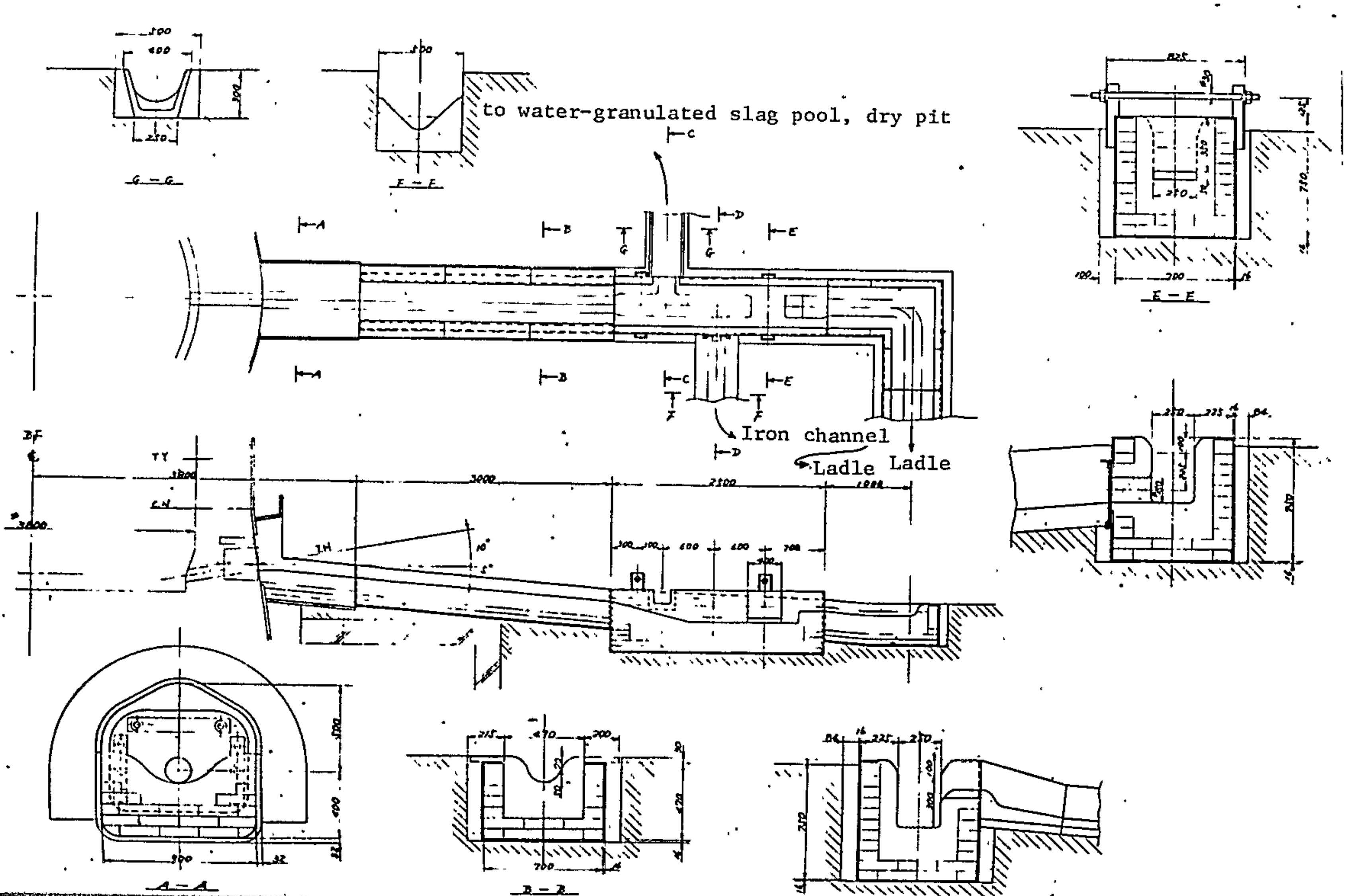


Fig. 2.10-5: Renewable channel for skimmer

2.11 Blowing-in of Fuel into the Blast Furnace

The coke serves as a spacer in the blast furnace.
In this respect, there is nothing like coke even these days when the blast furnace technology has made a progressive performance.
However, the coke has become partially replaced with subsidiary fuels with a view to diversifying the energy sources and reducing fuel cost.
In keeping with this, the technologies for blowing fuel into the blast furnace have advanced with great strides.
Today, there is a growing tendency that the coke is more and more replaced by subsidiary fuels.
The alternative fuels to the coke are available in various forms, including liquids, solids and gases.
These are selected depending on commercial availability, cost differential from coke, controllability in use and handling, effects on pig iron quality, installation conditions, etc.

Alternative fuels for blast furnace

1) Liquids : Heavy oil, tar, naphtha, crude oil
2) Gases : Coke oven gas, LNG, water gas
3) Solids : Coal
4) Slurry : Pulverized coal, heavy oil slurry

The blowing-in is made chiefly from the tuyeres.
Although bosh and belly have been tried, studies have yet to be made for full-scale implementation.
The method that is most widely in use is to blow in heavy oil or LNG from the tuyeres.
In this section, discussions are made with focus on the heavy oil in consideration of the fuel availability in Colombia as well as controllability.

(1) Intra-furnace gas permeability

The blowing-in of fuel can increase the ore/coke ratio as it is designed for increasing the ore/coke ratio of the furnace charges. The fuels used instead of coke usually have a higher hydrogen component than the coke which is produced by dry distillation. Thus, the bosh gas is increased on a same wind volume basis.

Also, the gas flow stability gets reduced. Fig. 2.11-1 is an illustrative example showing the relationship between ore/coke ratio and wind pressure/wind volume.

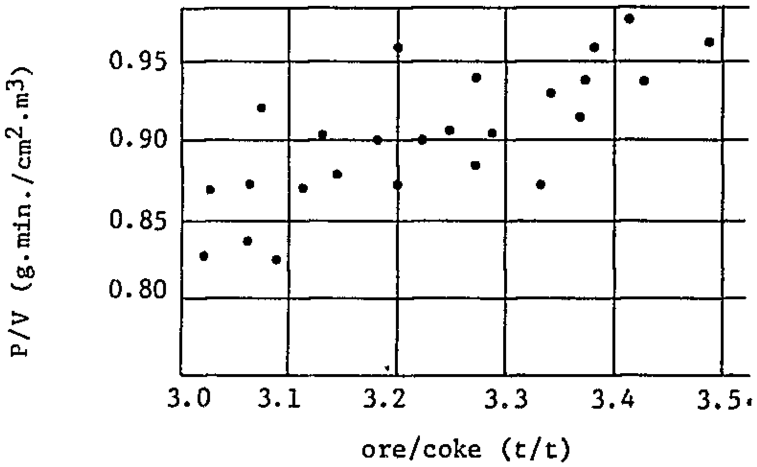


Fig. 2.11-1 Ore/coke ratio vs. wind pressure/wind volume relationship in the blast furnace operation

The increase in gas flow resistance and resultant increase in gas flow fluctuation make the descending motion of furnace charges astable, increasing the chances of hanging and slipping. Accordingly, the blowing-in of fuel presupposes that full measures have been taken for the improvement of gas flow beforehand.

Measures for improving gas permeability

i) Improvement of charges in grain size distribution (screening out of - 5 mm dust)

ii) Improvement of coke in quality

iii) Improvement of furnace charges in reducibility

iv) Distribution control of furnace charges

v) Keeping the combustion at the tip of tuyere in the optimum condition, and maintenance of raceway, etc.

(2) Reduction in tuyere service life

Excessive blowing-in of fuel without improvement in operating conditions leads to a loss of stability in gas permeability and an increase in the frequency of hanging and slipping. In addition, the combustion at the tip of the tuyere becomes poor, increasing the possibilities of burnout failure of tuyere due to melt in the furnace and at the same time bringing about the following evil symptoms due to tuyere flames.

i) Increase in gas temperature in the oxidizing zone at the tuyere.

ii) Increase in the wind velocity at the tuyere due to increase in combustion gas flow rate.

iii) Cu embrittlement due to SO_2 in the combustion gas

As a consequence, the upper tip edge of the tuyere gets worn out, cracked or broken more and more. Namely, the frequency of tuyere failure is increased a little more than is usually.

(3) Compensation for furnace heat

In the blast furnace operation, it is generally necessary to constantly supply heat ensuring intra-furnace reactions or to keep the temperature at each zone for the purpose of keeping a specific reaction rate in such zone.

The majority of heat input to the blast furnace is accounted for by the combustion heat of carbon in the coke in front of the tuyere and also the sensible heat of hot blast. Where the fuel is blown in, the combustion temperature ahead of the tuyere goes down for the reasons explained below.

i) Generally, the temperature of the fuel blown in is lower than the temperature of the coke which is just before combustion.

[Note] The temperature of coke in the furnace right before combustion is 75% of theoretical combustion temperature ahead of tuyere.

ii) The hydrogen content in the fuel to be blown in is higher than that in the coke; namely, the combustion gas volume increased gets to reduce the flame temperature.

iii) While there is no need of allowing for cracking heat for the carbon in the coke, petroleum-family fuel or hydrocarbon requires cracking heat for disbanding C-C bonds or dehydrogenation heat for cutting off C-H chains.
For example, the heat necessary for cracking down heavy oil is 520 kcal/kg-heavy oil.

Table 2.11-1 shows reaction heat per kg of carbon.
According to this table, it is found that the calorific value of coke bruning ahead of the tuyere is extremely large.

Table 2.11-1 Reaction heat of fuels

$$C + \frac{1}{2}O_2 = CO + 2340 \text{ kcal/kg}^\circ\text{C}$$

$$CH_4 + \frac{1}{2}O_2 = CO + 2H_2 + 740 \quad \text{''}$$

$$C_2H_6 + O_2 = 2CO + 3H_2 + 1350 \quad \text{''}$$

$$C_3H_8 + \frac{3}{2}O_2 = 3CO + 4H_2 + 1500 \quad \text{''}$$

$$C + H_2O = CO + H_2 - 2480 \quad \text{''}$$

(4) Behavior of S in the blowing-in fuel

When blowing in fuel containing a higher sulfur content than coke, care should be taken of sulfur in the pig iron.
Although the sulfur in the blowing-in fuel will show no particular difference in behavior from that in the coke, it should be noted that the slag basicity must be adjusted as against an increase in input sulfur content.

(5) Incomplete gasification of heavy oil at the time of blowing-in

When the heavy oil blown in runs through the furnace without being gasified completely in the oxidizing zone lying ahead of the tuyere, the dust collecting efficiency of electric dust precipitator will be impaired. Also, the effluent from the thickener will be fouled with unburned heavy oil (carbon black) detrimental to water environments.

2.11.2 Metallurgical considerations on fuel blowing-in

(1) Behavior of blast furnace reactions accompanied by fuel blowing-in

The blowing-in of fuel from the tuyere is accompanied by a considerable degree of endothermic reaction owing to thermal cracking and sensible heat, expanding the combustion zone and reducing the combustion temperature. As a consequence, the loss of temperature should ge recouped in some way or other.
In other words, the blowing-in of fuel is limited largely unless the wind is increased in temperature, reduced in moisture content or enriched with oxygen.
In the blast furnace operation, the gas volume to be produced by burning ahead of the tuyere and its temperature must be balanced properly for the purpose of heating up furnace charges thoroughly. If the combustion gas temperature declines, the coke combustion rate and gas volume must be increased, but this will soon climb up to a limit, making it difficult to keep the blast furnace operations.

Changes in the gas permeability in the furnace are also invited. The coke rate reduces with increase in the blowing-in rate of fuel, increasing the ore/coke ratio.

This is turn degrades the gas permeability. On the other hand, since the hydrogen component in the fuel is higher than that in the coke as already discussed, the hydrogen concentration in the bosh gas increased decreases gas viscosity and density in favor of gas permeability within the furnace. Should the combustion temperature decline, however, the fusion in the high-temperature zone will have an increased viscosity and to degrade the gas permeability.

For the purpose of stabilized blast furnace operation, the improvement in gas permeability is of vital importance.

The hydrogen gas in the bosh atmosphere is very conducive to the reducing reaction in the furnace.

The hydrogen gas is a violent reducing agent, and when high in temperature can be used at a high efficiency as illustrated in the equilibrium diagrams in Fig. 2.11-2.

Its reducing rate is higher than that of CO.

Because of its low viscosity and high diffusion coefficient, the hydrogen gas can penetrate fine pores at a faster rate than any other gas. It also undertakes water gas reaction, and helps reduction due to CO. The hydrogen gas is 7 to 10 times higher in thermal conductivity than other gases, promoting heat transfer with solids to reduce the stack gas temperature. In the low-temperature zones, however, CO is more advantageous in reduction over H_2.

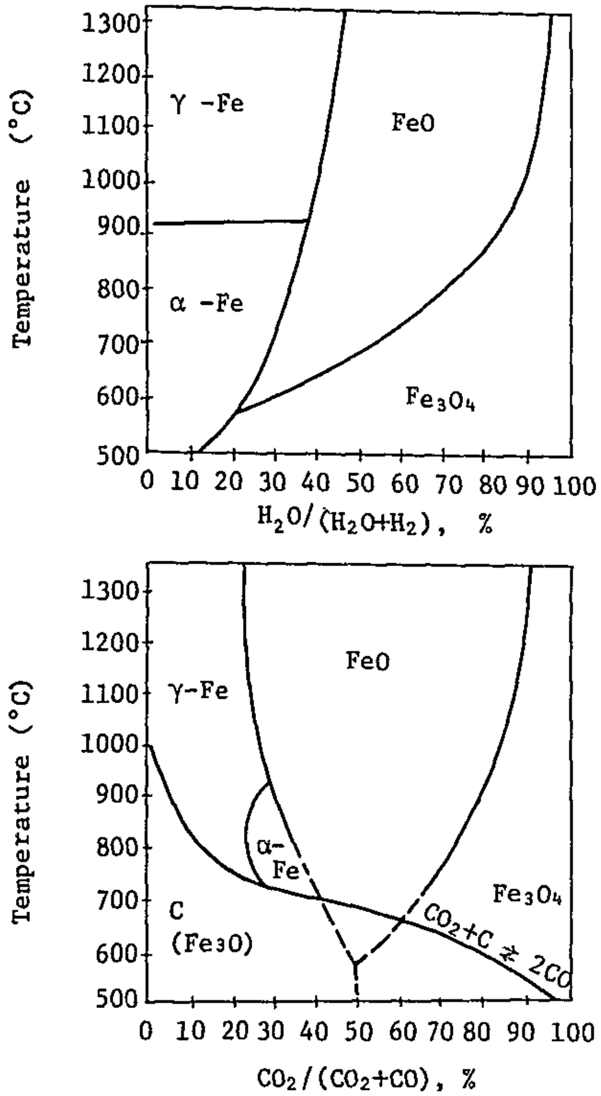


Fig. 2.11-2 Equilibrium diagrams of Fe-C-O and Fe-H-O systems

In the case of Amagasaki Works, the direct reduction ratio has been reduced by 1 to 2% with a heavy oil blowing-in rate of 45 kg/ton-iron, demonstrating that the hydrogen gas in the bosh atmosphere is very effective to reducing reactions in the high-temperature zones.

Fig. 2.11-3 and Table 2.11-1 show how much coke can be saved when the fuel blowing-in is practised.

It is to be understood however that the ratio at which the fuel can replace the coke is given only by way of reference as it is changeable depending on the furnace operating conditions.

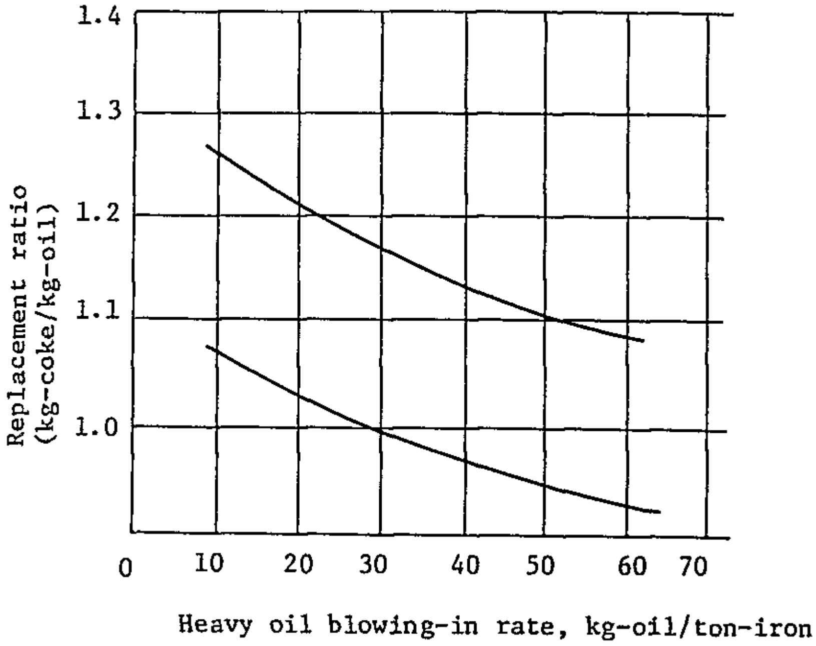


Fig. 2.11-3 Heavy oil blowing-in rate vs. replacement ratio at Amagasaki Works

Table 2.11-1 Replacement ratios of various fuels

Fuel	Replacement ratio
Heavy oil	1.0 to 1.2 kg-coke/kg-oil
Coke oven gas	0.4 to 0.5 kg-coke/Nm^3
L N G	approx. 1.0 kg-coke/Nm^3
Tar	1.0 to 1.8 kg-coke/kg-tar

2.11.3 Introduction of fuel blowing-in techniques

Much study has been devoted to the blowing-in of fuel into the blast furnace, and there are many reports concerning the techniqeus dealing with various fuels.
Approaches to this technique are wide varied, and their major differences are as follows.

a) Heat compensation at the time of fuel blowing-in
   - i) To keep the theoretical combustion temperature ahead of the tuyere constant.
   - ii) To keep the theoretical combustion temperature ahead of the tuyere constant, and also to keep the heat balance constant.

b) Heat balance
   - i) Heat balance in the high-temperature zone (e.g., above 1,000°C) in the furnace bottom.
   - ii) Partial heat balance (heat balance in each of reaction zones into which the furnace is divided).
   - iii) Overall heat balance.

c) Adjustment of furnace gas volume
   - i) To keep bosh gas volume constant.
   - ii) No special consideration to change in bosh gas volume.

As regards the intra-furnace reactions, there still is left much to be studied theoretically, analytically and technically. In practice, therefore, it is generally accepted to keep the combustion temperature ahead of the tuyere constant while regulating the coke rate to control the heat in other sections, because the combustion temperature ahead of the tuyere offers quite an important heat level for the blast furnace operation and at the same time permits easy control by the furnace operator.

However, it is almost impossible practically to keep the combustion temperature ahead of tuyere constant at all times. Thus, it is generally practised to control the fuel blowing-in in a manner to keep the mean combustion temperature ahead of tuyere which is registered before fuel blowing-in.
When quite a new fuel is to be blown in, investigations should be made with a high degree of accuracy.
Up until now, however, achievements of blowing-in have been reported with respect to various fuels, and it is quite easy to acquire data concerning replacement ratio and other factors.
When the blowing-in of fuel is to be tried for the first time, the following procedures should be observed.

a) Selection of fuel

   The fuel to be blown in should be selected from the viewpoint of economics after close investigation of the following factors.

   i) Replacement ratio, fuel cost, equipment investment requirements, etc.

   ii) Limitations of thermal compensation resulting from operating conditions and equipment conditions, etc.

b) Prior to blowing in fuel, keep the combustion temperature ahead of the tuyere nearly constant. Then, increase the fuel rate step by step while checking the furnace heat, gas permeability, stability of furnace charge sinking motion, troubles, etc.

c) Take stock of the blowing-in operations, and determine the fuel rate according to economics, operating stability, and other conditions.

2.11.4 Calculation of theoretical combustion temperature ahead of tuyere

Table A   The calculation here is made with respect to wind moisture content, heavy oil, coal, LPG and COG, and will be of some help in using other fuels.

		Coke burning ahead of tuyere (1 kg)	Wind moisture (1 kg)	Heavy oil (1 kg)	Coal (1 kg)	L P G (1 m³)	C O G (1 m³)
O_2 necessary for reaction ahead of tuyere, (m³/unit)		11.2/12 x FC/100 = 0.00933 FC	0	0.00933 OiC	0.00933 Cc − 22.4/32 x Co/100 = 0.00933Cc − 0.007Cc	2.0	CG_{CH_4}/100 x 1/2 = 0.005 CG_{CH_4}
Required wind volume (m³/unit)		$\frac{0.00933FC}{\frac{v_o}{100}}$ = 0.933FC/V_o	0	0.933 OiC/V_o	(0.00933Cc−0.007Co)/ v_o/100 = (0.933Cc−0.7Co)/v_o	200/v_o	$\frac{0.5CG_{CH_4}}{v_o}$
Bosh gas volume (m³/unit)	CO	22.4/12 x FC/100 = 0.01866FC	0 (CO generated in reaction with coke is included in the column for coke)	0.01866 OiC	0.01866 Cc	4.0	$\frac{CG_{CH_4}}{100} + \frac{CG_{CO}}{100}$
	H_2	0	22.4/18 = 1.244	22.4/2 x OiH/100 = 0.112 OiH	0.122 C_H	5.0	$\frac{CH_{CH_4}}{100}$ x 2 + $\frac{CG_{H_2}}{100}$
	N_2	0.933FC/v_o x (100 − v_o)/100	0	0.933 OiC/v_o x (100 − v_o)/100	(0.933Cc − 0.7Cc)/v_o x $\frac{(100 - v_o)}{100}$	200/v_o x (100−v_o)/ 100	0.5CG_{CH_4}/v_o x (100 − v_o)/100
Heat supply, kcal/unit)		Carbon calorific value + Coke sensible heat + Wind sensible heat $\frac{FC}{100}$ x $\frac{29,410}{12}$ + 0.75T x $\frac{FC\times0.4}{100}$ + $\frac{0.933FC}{v_o}$ x t x 0.340 = FC(24.51 + 0.003T + $\frac{0.31722t}{v_o}$)	Water vapor sensible heat + Cracking heat 0.4 x $\frac{22.4t}{18}$ − 2,580	Carbon calorific value + heavy oil sensible heat + Wind sensible heat + Cracking heat $\frac{OiC}{100}$ x $\frac{29,410}{12}$ + 0.5 OiT + $\frac{0.933\ OiC}{v_o}$ x t x 0.340 − 519 = OiC (2,451) + $\frac{0.31722t}{v_o}$ +0.5 OiT − 519	Reaction heat (carbon calorific value + cracking heat) + coal sensible heat + Wind sensible heat 1,942 + 0.25 C_T + (0.933Cc − 0.7Co)/ v_o x t x 0.340	LPG calorific value + LPG sensible heat + Wind sensible heat 2,313 + 0.450 L_T +200/v_o x t x 0.340	COG calorific value + COG sensible heat + Wind sensible heat 8,527/22.4 x CG_{CH_4}/100 + 0.330CG_T + 0.5CG_{CH_4}/v_o x t x 0.340

	Coke burning ahead of tuyere (1 kg)	Wind moisture (1 kg)	Heavy oil (1 kg)	Coal (1 kg)	L P G (1 m³)	C O G (1 m³)
Remarks	(1) COcoke) + 1/2 O_2 = CO + 29,410 kcal/k-mol (2) The sensible heat of the coke burning ahead of tuyere is set at 75% of theoretical combustion temperature. (3) Specific heat of C in the coke is 0.4 kcal/kg.C. (4) Specific heat of wind air is 0.340 kcal/m³.°C	(1) Specific heat of moisture, 0.40 kcal/m³.°C (2) Cracking heat of moisture, 2,580 kcal/kg	(1) C + 1/2 O_2 = CO + 29,410 kcal/k-mol (2) Cracking heat of heavy oil 519 kcal/kg (3) Specific heat of heavy oil, 0.50 kcal/kg°C	(1) Reaction heat of coal, 1,492 kcal/kg (2) Specific heat of coal, 0.250 kcal/kg°C	(1) LPG is assumed to be totally of C_4H_{10} (2) LPG blowing is in a gaseous state. (3) $C_4H_{10} + 2O_2 = 4CO + 5H_2$ + 74,210 kcal/k-mol (4) Specific heat of LPG, 0.450 kcal/m³°C	(1) COG is composed of CO_2, O_2, N_2, CO, H_2, CmHn, and CH_4. But, CO_2, O_2 and N_2 are omitted. Since CmHn is very little, the hydrocarbon is assumed to be entirely of CH_4. (2) $CH_4 + 1/2\ O_2 = CO + 2H_2$ + 8,527 kcal/k-mol (3) Specific heat of COG, 0.330 kcal/m³°C

Legend:-

V_O : Oxygen concentration in wind, %
FC : Fixed carbon in coke, %
t : Wind temperature, °C
T : Theoretical combustion temperature ahead of tuyere, °C
OiC : C in heavy oil, %
OiH : H in heavy oil, %
OiT : Heavy oil blowing-in temperature, °C
Cc : C in coal, %

C_H : H in coal, %
Co : O in coal, %
C_T : Coal blowing-in temperature, °C
L_T : LPG blowing-in temperature, °C
CG_{CH_4} : CH_4 concentration in COG, %
CG_{CO} : CO concentration in COG, %
CG_{H_2} : H_2 concentration in COG, %
CG_T : COG blowing-in temperature, °C

(1) Determination of data FC=88%, OiC=86%, OiH=12%, OiT=100°C, Cc=77.7%, C_H=5.3%, Co=6.8%, C_T=100°C, L_T=0°C, CG_{CO}=6.8%, CG_{H_2}: 55.7%, CG_{CH_4}=31.7%, CG_T=20°C

(2) Apply the data above to Table A, and prepare Table B as follows.

Table B

		Coke burning ahead of tuyere (1kg)	Wind moisture (1kg)	Heavy oil (1kg)	Coal (1kg)	LPG ($1m^3$)	COG ($1m^3$)
O_2 necessary for reaction ahead of tuyere (m^3/unit)		0.8210	0	0.8024	0.6773	2.0	0.1585
Wind volume required, (m^3/unit)		$82.1/v_o$	0	$80.2/v_o$	$67.73/v_o$	$200/v_o$	$15.85/v_o$
Bosh gas volume (m^3/unit)	CO	1.642	0	1.605	1.450	4.0	0.385
	H_2	0	1.244	1.344	0.594	5.0	1.191
	N_2	$82.1/v_o-0.821$	0	$80.2/v_o-0.802$	$67.7/v_o-0.677$	$200/v_o-2.0$	$15.85/v_o-0.1585$
Heat supply, kcal/unit		$2{,}156.9+0.264T+27.92t/v_o$	$0.498t-2{,}580$	$1{,}638.9+27.28t/v_o$	$1{,}967.0+23.03t/v_o$	$3{,}313.0+68.00t/v_o$	$127.6+5.389t/v_o$

(3) Calculation of theoretical combustion temperature ahead of tuyere

$$T = (\text{Total of the heat supply by various fuels})/(\text{Heat content of bosh gas}) = Q/M \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

a)
$$Q\ (\text{kcal/min.}) = (2{,}156.9 + 0.264T + \frac{27.92t}{v_o} \times C_{Tm}$$

$$+ (0.498t - 2{,}580) \times \phi.V_B + (1{,}638.9 + \frac{27.28t}{v_o})\ Woil.V_B$$

$$+ (1{,}967.0 + \frac{23.03t}{v_o})\ Wcoal.V_B + (3{,}313.0 + \frac{68.00t}{v_o})W_{LPG}.V_B$$

$$+ (127.6 + \frac{5{,}389t}{v_o})W_{COG}.V_B \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

Where, Q : heat supply, kcal/min.

ϕ : wind moisture, kg/m^3

W_{LPG} : LPG blowing-in rate, m^3/m^3-dry base

V_B : dry wind rate, m^3/min.

Woil : heavy oil blowing-in rate, kg/m^3-dry base

W_{COG} : COG blowing-in rate, kg/m^3-dry base

C_{Tm} : combustion rate of coke ahead of tuyere, kg/min.

Wcoal : coal blowing-in rate, kg/m^3-dry base

b) Combustion rate of coke ahead of buyere,

C_{Tm} (kg/min.) = (O_2 in wind (m^3/min.) + O_2 in wind moisture (m^3/min.) - O_2 consumed by blown-in fuel (m^3/min.)
÷ (O_2 necessary for burning kg of coke (m^3/kg))

$$= (V_B \times v_o/100 + 11.2/18 \times \phi.V_B - 0.8024Woil.V_B - 0.6773Wcoal.V_B - 2.0W_{LPG}.V_B - 0.1585W_{COG}.V_B)/0.821$$

$$= V_B(0.0122\ v_o + 0.7579\phi - 0.9773\ Woil - 0.8246\ Wcoal - 2.436\ W_{LPG} - 0.1931\ W_{COG}) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

c) Bosh gas heat content: M

CO (kcal/°C.min.) = CO generated by each fuel (m^3/min.) x specific heat (kcal/m^3°C) = $[1.642 \times C_{Tm} + V_B (1.605 W_{oil} + 1.450 W_{coal} + 4.0\ W_{LPG} + 0.385\ W_{COG})] \times 0.363$

H_2 (kcal/°C.min.) = $V_B(1.244\phi + 1.344\ W_{oil} + 0.594\ W_{coal} + 5.0\ W_{LPG} + 1.191\ W_{COG}) \times 0.340$

N_2 (kcal/°C.min.) = $V_B[(82.1/v_o - 0.821) \times C_{Tm} + (80.2/v_o - 0.802) \times W_{oil} + (67.7/v_o - 0.677\ W_{coal}) + (200/v_o - 2.0)W_{LPG} + (15.85/v_o - 0.1585)W_{COG}] \times 0.359$ .... (4)

M (kcal/°C.min.) = CO (kcal/°C.min.) + N_2 (kcal/°C.min.) .... (5)

From Eqs. (1) through (5),

$$T = [(0.340 + 0.498\phi + 21.16\phi/v_o) \times t + 26.31\ v_o - 945.3\phi - 469.1\ W_{oil} + 188.8\ W_{coal} + 8.058.8\ W_{LPG} - 288.9\ W_{COG}] / (0.359 + 22.34\phi/v_o + 0.00045\ v_o + 0.452\phi + 0.715\ W_{oil} + 0.455\ W_{coal} + 2.343\ W_{LPG} + 0.480\ W_{COG}) \quad \ldots\ldots (6)$$

For the sake of simplicity, Eq. (6) is developed into a Taylor series as given in Eq. (7) below.

$$T = 0.790\ t + 57.72\ v_o - 6{,}059\phi - 4{,}576\ W_{oil} - 1{,}826\ W_{coal} + 6{,}402\ W_{LPG} - 3{,}014\ W_{COG} + 380.9 \quad \ldots\ldots\ldots\ldots (7)$$

For example, if heavy oil is used as a fuel, and if $\phi = 0$ and wind rate = 2,000 m^3/ton-iron, and also given that the combustion temperature ahead of the tuyere is held constant before and after blowing-in of fuel, Eq. (7) can be rewritten as follows.

$$T = 0.790\ t + 57.72\ v_o - 4{,}576\ W_{oil} + 380.9 \quad \ldots\ldots\ldots (7')$$

If it is required to compensate for the decline in the combustion temperature ahead of tuyere due to heavy oil blowing-in by adjusting the oxygen content in the wind or the wind temperature, the following formula is established.

$$4,765\ \text{Woil} = 0.790\ \Delta t + 57.72\ \Delta v_0 \quad \text{(7")}$$

Where, Δt : Wind temperature increase

Δv_O : Oxygen concentration increase in wind

Eq. (7") is plotted in Fig. 2.11-4.

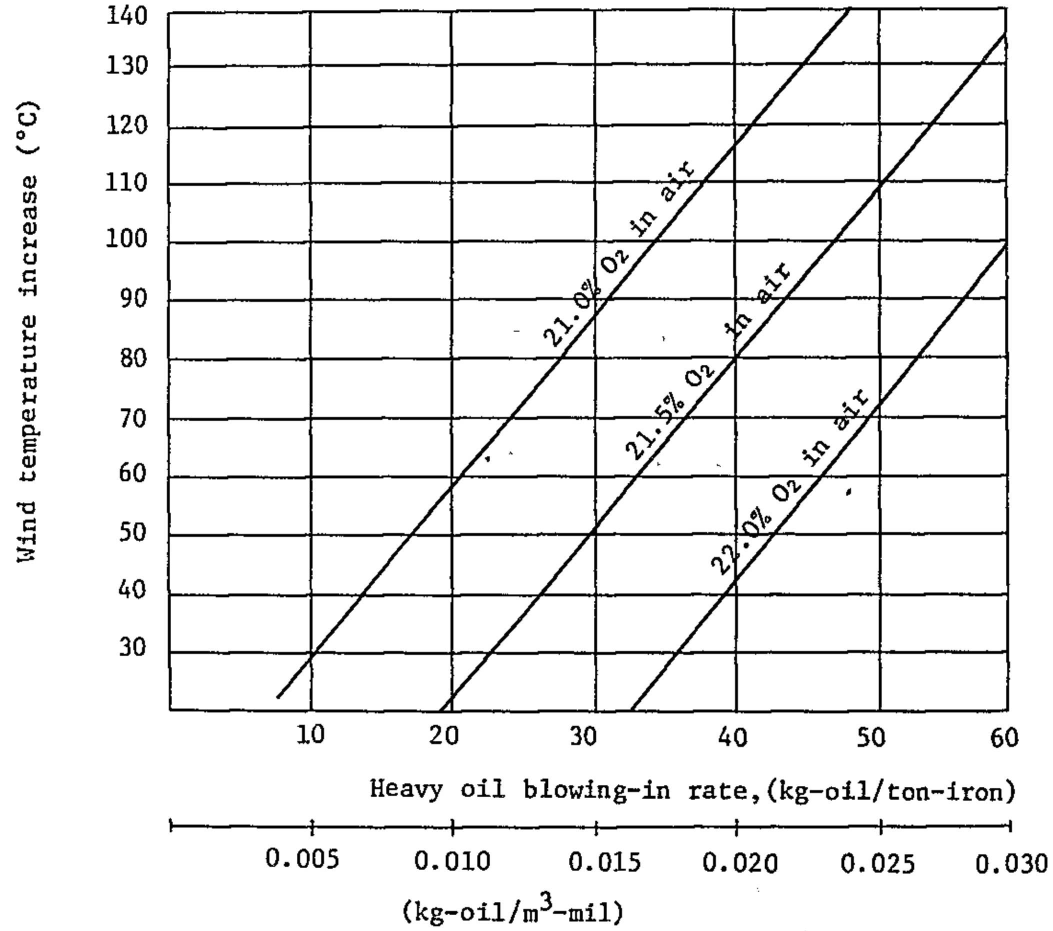


Fig. 2.11-4 Heavy oil blowing-in rate vs. temperature compensation by O_2 concentration in wind or wind temperature (In case the wind volume is fixed at 2,000 m^3/ton-iron)

2.11.5 Heavy oil blowing-in facilities

(1) Heavy oil temperature

The viscosity of heavy oil varies over a wide range depending on grade and temperature.

If the viscosity is too high, the oil feed will become hard, and its atomizing at the burner tip will become poor. On the other hand, the viscosity is too low, explosion hazards will be involved as the oil temperature will become above the flash point.

Usually, the higher limit of viscosity permitting oil delivery by pump is said to be in the range of 3,000 to 4,000 sec. in Redwood scale.

Table 2.11-2 shows the optimum temperature for atomization.

In Japan, the temperature is set at 30°C to 80°C in the delivery system and at 70°C to 120°C in the atomizing system.

Table 2.11-2 Viscosity of fuel oil & proper heating temperature

Viscosity at 50°C			Heating temperature
Saybolt furol sec.	Redwood sec	Kinematic viscosity centistoke	Mechanical atomize °C
30	250	62	54.0 ∿ 83.2
35	300	74	57.6 ∿ 88.5
40	350	86	61.8 ∿ 92.5
45	391	97	64.8 ∿ 96.0
50	441	109	67.5 ∿ 99.0
60	527	130	71.6 ∿ 102.0
70	610	151	75.2 ∿ 104.6
80	700	173	77.5 ∿ 107.6
90	791	196	79.5 ∿ 110.0
100	892	220	81.5 ∿ 111.8
120	1,052	260	84.4 ∿ 115.4
140	1,226	302	87.4 ∿ 118.0
160	1,400	346	89.5 ∿ 120.0
180	1,577	389	91.5 ∿ 121.4
200	1,743	432	93.0 ∿ 122.6
220	1,922	474	94.2 ∿ 123.8
240	2,096	518	95.4 ∿ 124.6
260	2,270	560	96.6 ∿ 127.5
280	2,455	606	97.8 ∿ 128.5
300	2,626	649	99.0 ∿ 129.5

(Petroleum Refinery Engineering (Nelson))

(2) Heavy oil blowing-in pressure

The heavy oil blowing-in pressure must be higher than the wind pressure as it is necessary to prevent the heavy oil running back into the hot air blowing pipe.

The high blowing-in pressure is also needed for the purpose of improving the atomizing conditions.

The nozzle pressure should preferably be more than 5 kg/cm^2 above the intra-furnace pressure in terms of static pressure.

The delivery pump pressure should be set to meet the distance and rate of delivery.

Usually, it is set at 3 to 5 kg/cm^2.

(3) Number of tuyeres used for heavy oil blowing-in

It is desirable to blow in heavy oil from every tuyere not only for the purpose of ensuring uniform heat balance in the radial direction of the furnace, but also for the purpose of making it ready for meeting a heavy demand for heavy oil. For some tuyeres which defy blowing-in operations because of structural restrictions or others, the blowing-in is omitted unavoidably.

(4) Burner tip diameter

In order to atomize the heavy oil into fine particles, a higher heavy oil pressure is needed. But, the burner tip diameter must be reduced with increase in heavy oil pressure in order to ensure a constant rate of heavy oil supply.

But if the burner tip diameter is too small, the aperture will be clogged up with foreign objects or by carbonization.

Usually, the burner tip diameter is set at 2.0 to 6.0 mmϕ.

The size distribution of heavy oil particles jetted out of the nozzle is governed by the law of logarithmic probability distribution. Here let us calculate the particle size with referenct to an instance of heavy oil atomizing at Kobe Works, Kobe Steel, by making use of a formula for determining the mean particle diameter proposed by Tanazawa.

$$d_m = 7.98\ t_o \sqrt[4]{\sigma / P_o t_o} \cdot \sqrt{(1 - k)^3}\,(1 + 0.37\sqrt{\ell / d_e})$$
$$\times\ (1 + 19.7\ e^{-4.13k})$$

Where, d_m : mean diameter of atomized particle, m

P_o : atomizing pressure, kg/m^2G

σ : surface tension of liquid, kg/m^2

k : characteristic value of vortex chamber

$= (4Ai/\pi . d_e^2)(d_e/d_i) = (4Ai)/(\pi . d_e . d_i)$

ℓ/d_e : ratio of parallel length of nozzle to nozzle diameter

κ : theoretical cavitation number (See Table 2.11-3)

t_o : theoretical thickness of liquid film at the nozzle port, m

$t_o = (d_e - d_c)/2 = (d_e/2)(1 - \kappa)$

d_c : inside diameter of annular flow of liquid at the nozzle port, m

d_e : nozzle diameter, m

d_i : outside diameter of vortex chamber, m

A_i : area of inlet port of vortex chamber, m^2

Table 2.11-3 Cavitation number: k, characteristic value: K, atomizing angle : α_o

k	K	α_o
0.70	0.3933	88.8
0.68	0.4420	85.7
0.66	0.4942	82.6
0.64	0.5501	79.6
0.62	0.6100	76.6
0.60	0.6742	73.7
0.58	0.7430	70.9
0.56	0.8168	68.1
0.54	0.8961	65.4
0.52	0.9815	62.7
0.50	1.0736	60.0

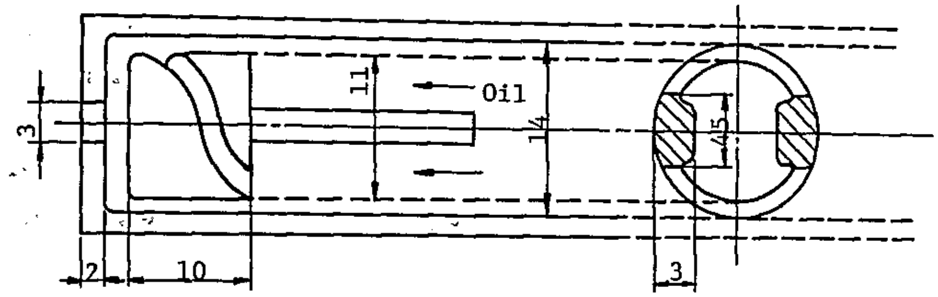


Fig. 2.11-5 Structural design of burner tip
(an example now in use at Kobe Steel)

$Ai = 4.5 \times 3 \times 2 \times 10^{-6} \cong 27 \times 10^{-6}\ m^2$

$k = 4Ai/(\pi . d_e . d_i) = 4 \times 27 \times 10^{-6}/(3.14 \times 3 \times 10 \times 10^{-6}) = 0.819$

From Table 2.11-13, $\kappa = 0.56$, and atomizing angle = 68.2°.

Hence, $t_o = (d_e/2)(1 - \kappa) = (3 \times 10^{-3}/2)(1 - 0.56) = 6.6 \times 10^{-4}\,m$

The surface tension, σ, of heavy oil at 100°C is 29.8×10^{-4} kg/m.

If $\ell = 2 \times 10^{-3}$ m, and $Po = 4.0 \times 10^4\ kg/m^2G$, then
$d_m = 0.450\ mm = 450\ \mu$

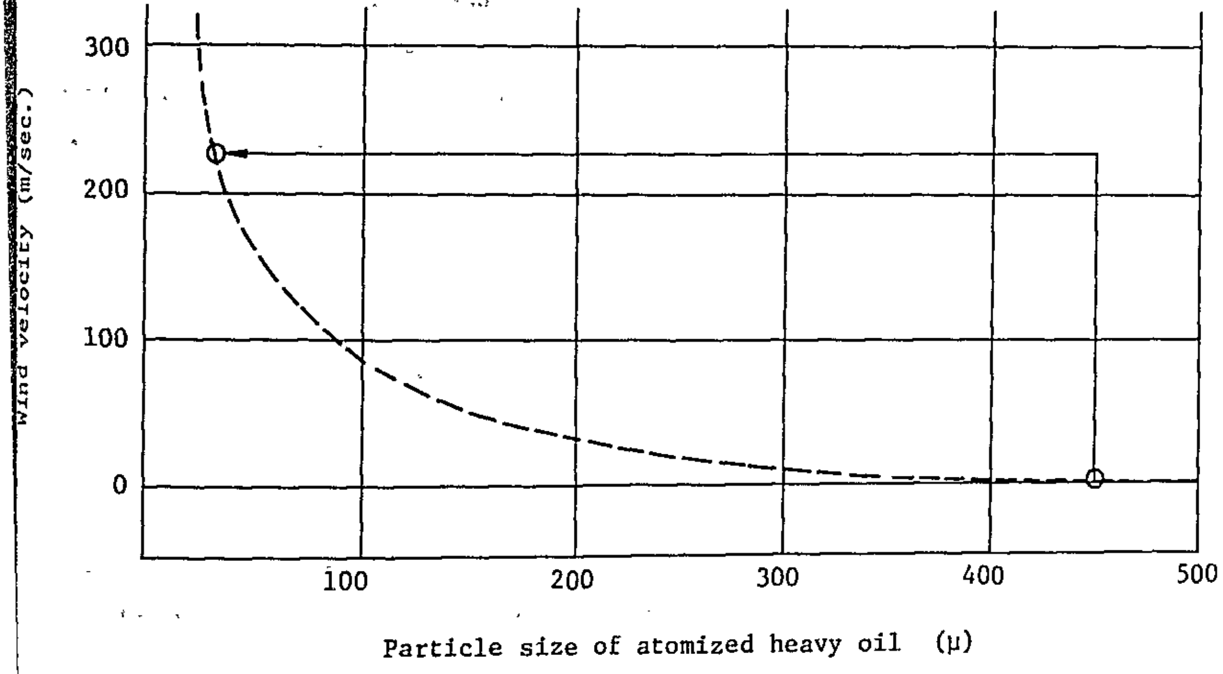


Fig. 2.11-6 Wind velocity vs. particle size of atomized heavy oil

At the wind tuyere, the air is not at rest, and the heavy oil is atomized and conveyed on a high-velocity jet of air. The mechanism involved is almost the same as the venturi scrubber offers.

Fig. 2.11-6 shows the relationship between the air velocity and particle size of atomized heavy oil as determined theoretically and experimentally.

A particle measuring 450μ in diameter atomized in a static atmosphere will be reduced to a diameter of about 30μ in a jet stream of 220 m/sec.

From the curve shown in Fig. 2.11-6, it is found that the size of atomized particle is governed more by the wind velocity than by the nozzle itself.

Although the burner nozzle tip diameter should preferably be as small as possible, its size on a thinner side is naturally limited because if it is too small the tip will be blocked up.

(5) Burner position

The oxidizing zone in the furnace is considered lying approximately 1.0 m from the tip of the tuyere.

For the complete combustion of heavy oil, the burner position should preferably be retracted at the back of the tuyere.

It should also be noted that the position should not be such that will make the blowpipe temperature too high. The atomized particles of the heavy oil burn while going through the following five processes.

i) Atomization of heavy oil through injection.

ii) Heating-up of atomized particles.

iii) Vaporization of atomized particles.

iv) Ignition of heavy oil vapor.

v) Combustion.

According to Kobe Steel's blast furnace operating conditions, the times for these five processes are calculated as follows.

0.020 m. sec. (heating-up time) + 0.32 m. sec. (vaporization time) + 0.76 m.sec. (burning time) = 0.0011 sec.

Hence, if the wind velocity is set at 220 m/sec., the atomized particles will complete combustion in about 25 cm of travel (220 m/sec. x 0.0011 sec.).

In Japan, the burner position is in the range of 450 mm to 700 mm retracted from the tip of tuyere, and the most representative value is about 550 mm.

In the case of the COLAR, the combustion time will take much longer time because the wind temperature is low.

For the injection of heavy oil, there are two systems - mechanical atomizing system and air atomizing system.

The mechanical atomizing system will do for the purpose.

The mechanical atomizing system is one in which the heavy oil is atomized and jetted out of the tip under the pressure it has.

Fig. 2.11-7 shows a view of a heavy oil blowing-in lance and its location.

Fig. 2.11-8 shows a piping diagram for heavy oil blowing-in system.

In the system shown in Fig. 2.11-8, the tuyeres are subjected to lumped control of heavy oil flow, but each tuyere should preferably be controlled independent of others so far as the installation conditions permit.

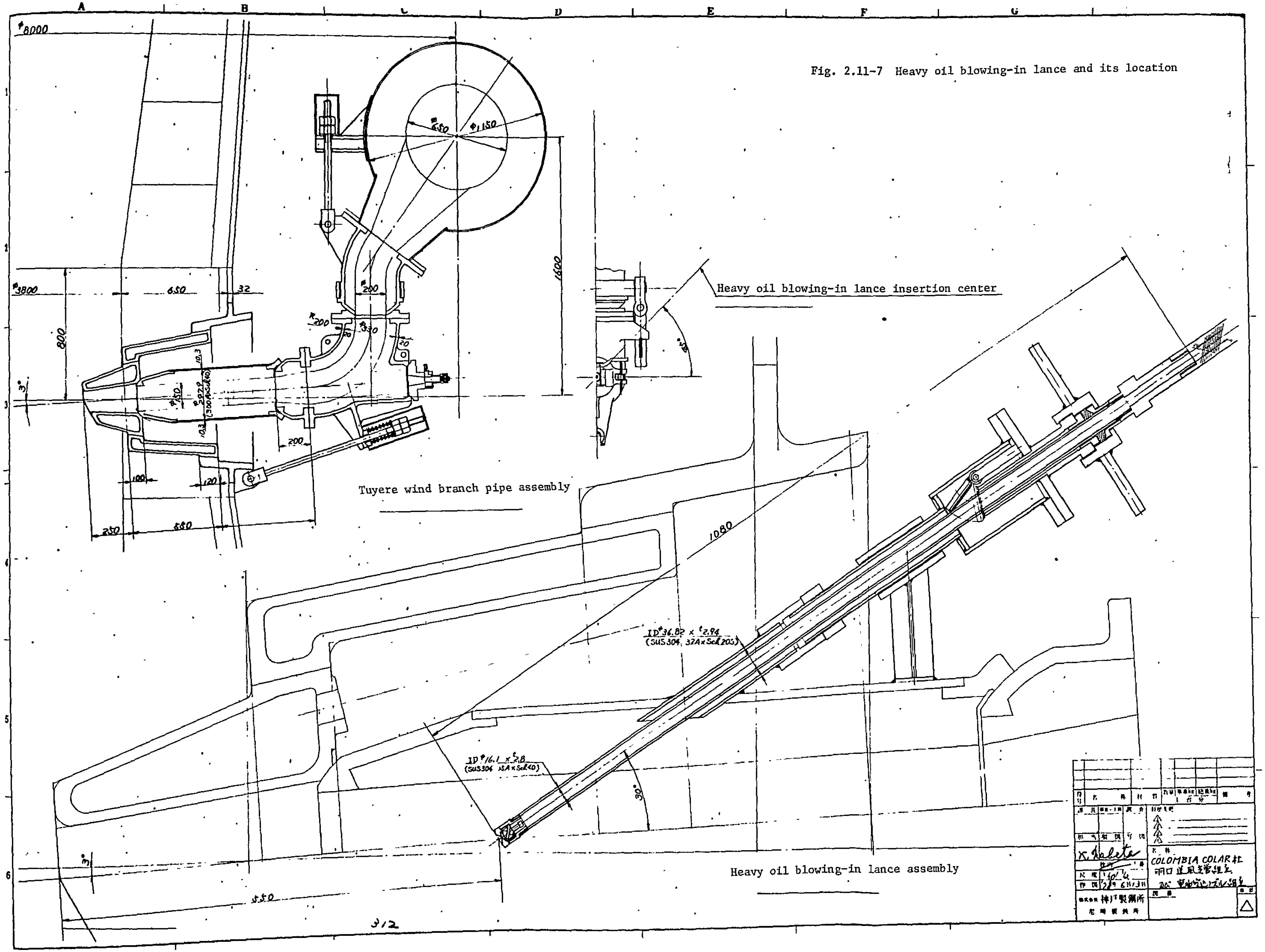
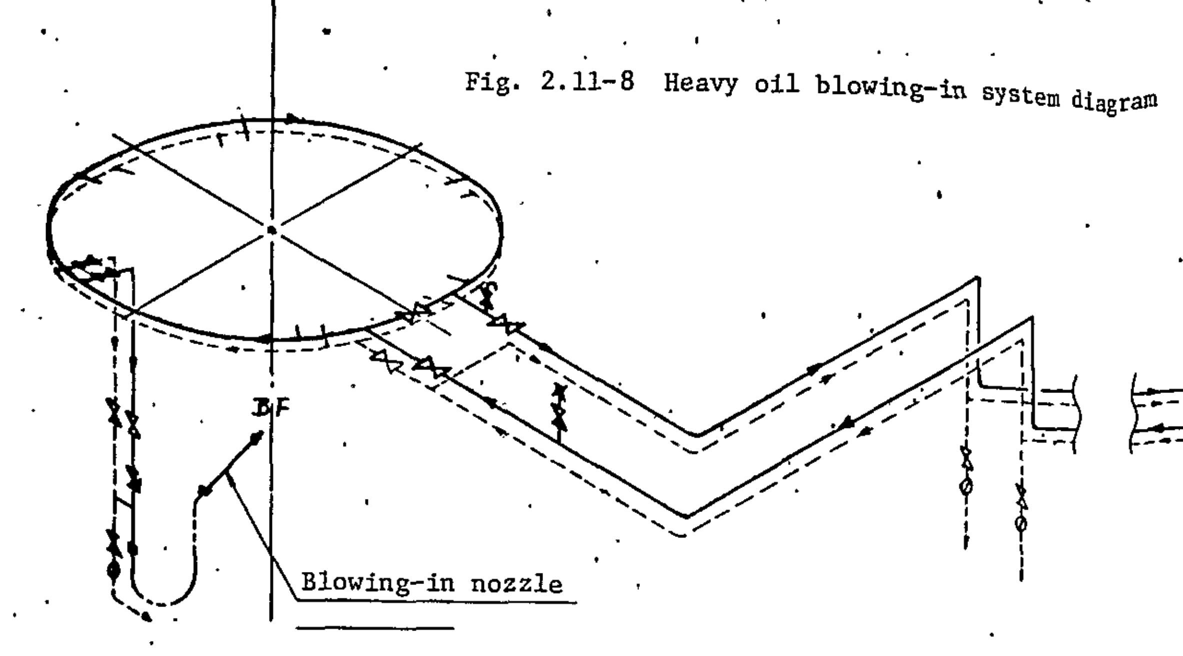
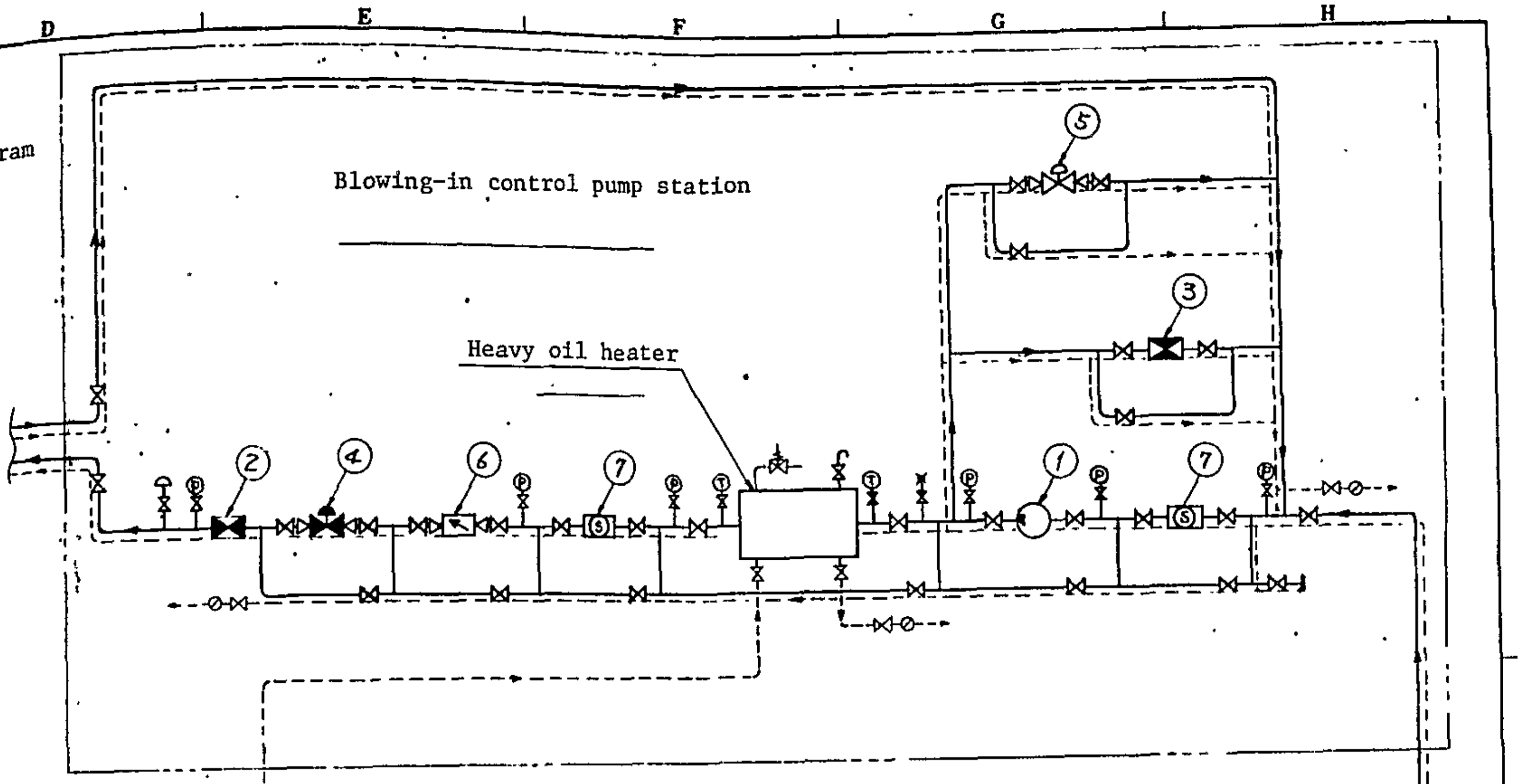
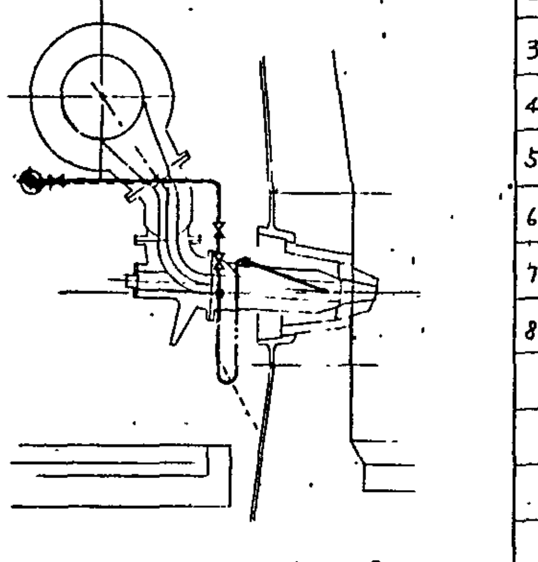


Fig. 2.11-7 Heavy oil blowing-in lance and its location

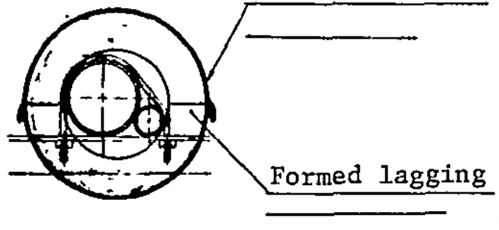
Fig. 2.11-8 Heavy oil blowing-in system diagram





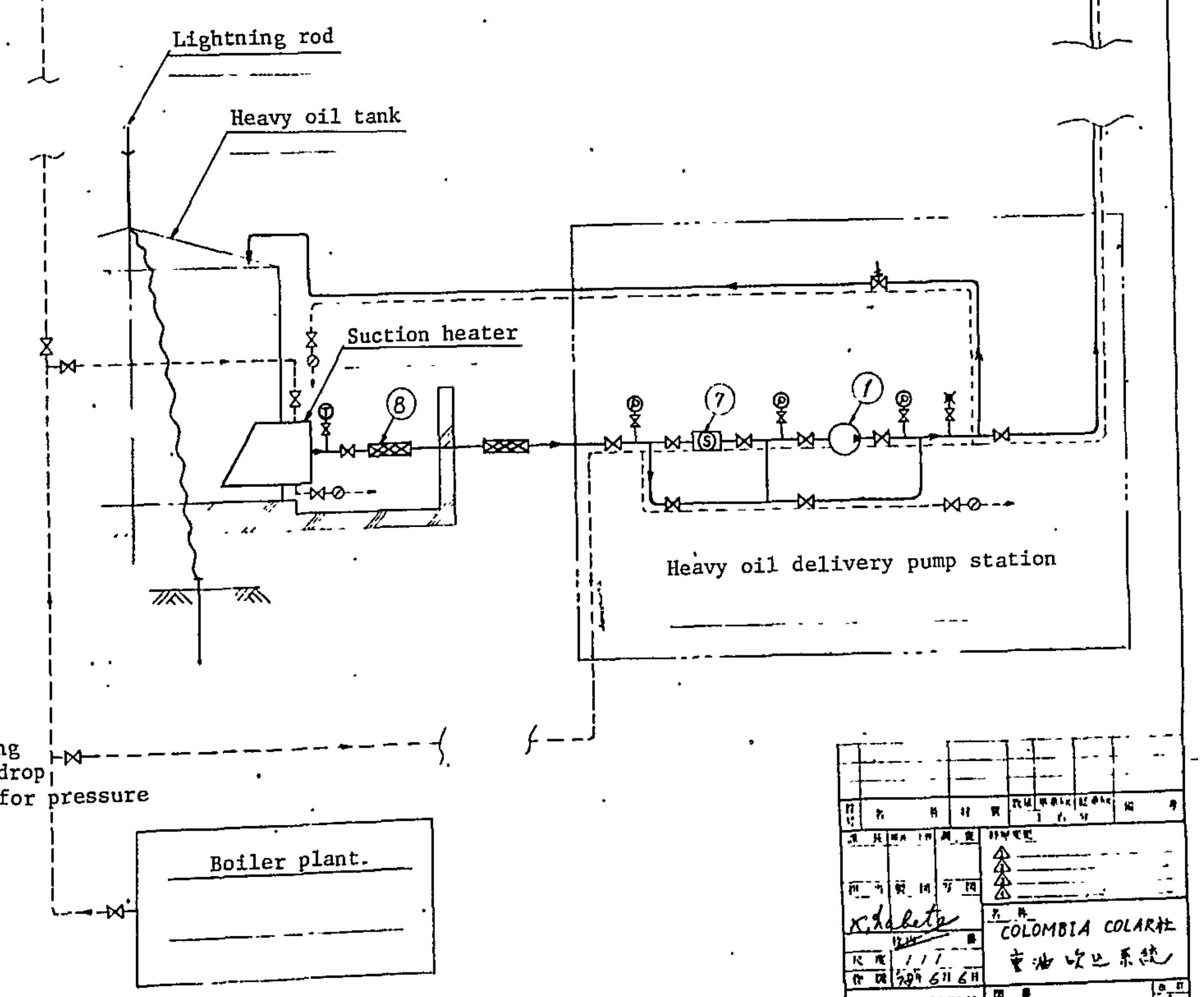


Sectional view of blowing-in system



Piping lagging procedure

Item No.	Symbol	Name	Remarks	Note
1	○	Heavy oil gear pump	w/relief valve, directly coupled to motor	
2	⧓	Emergency shutoff valve	Normally close type solenoid valve	
3	⊠	Emergency relief valve	Normally open type solenoid valve	
4	⧓	Flow control valve	Pneumatically operated diagragm valve	
5	⋈	Pressure regulating valve	Pneumatically operated diaphram valve	
6	⍂	Flowmeter	Displacement type oval flowmeter	
7	(S)	Strainer	Manual cleaning cylinder cage type	
8	⊠	Flexible hose	Heat- and oil-resistant rubber hose	
	-·-·-	Stainless steel flexible tube	w/quick joint on each end	
	——	Heavy oil pipeline		
	- - -	Steam pipeline		
	-⋈-	Sluice valve		
	-⊘-	Steam trap		
	Ϙ	Temperature detector	Thermocouple (I.C)	For monitoring temperature drop
	✱	Pressure detector	Pressure transmitter	Transmitter for pressure control use
	Ⓟ	Pressure gauge	Bourdon tube type	Local indicator
	Ⓣ	Thermometer		Local indicator
	⋈	Safety valve	Spring type	



COLOMBIA COLAR社
重油吹込系統
K. Takata
1/1
S.49年6月6日
株式会社 神戸製鋼所
尼崎製鉄所

3. MANAGEMENT PROFILE – STATUS QUO, PROBLEMS INVOLVED AND RECOMMENDATIONS

3. MANAGEMENT PROFILE – STATUS QUO, PROBLEMS INVOLVED AND RECOMMENDATIONS

3.1 Sales

3.1.1 Status quo and problems

3.1.1.1 Domestic market

3.1.1.1.1 Monopoly

The COLAR is the only foundry pig iron manufacturer in Colombia.
It is a nearly wholly state-owned enterprise, the stock of which as of May 9, 1978, went 97.9% to the Instituto de Fomento Industrial (IFI), an extra-governmental organization of the Ministerio de Desarrollo Económico, and the majority of the remaining 2.1% to the companies in which IFI invested.
The Colombian Government has laid an embargo on the import of foreign pig iron for the purpose of protecting this state-owned enterprise in its infancy.
Such being the circumstances, the COLAR is literally monopolizing the foundry pig iron market in Colombia.

3.1.1.1.2 Customers

Over the past five years (1973 to 1977), the COLAR's sales were around 20,000 tons annually.
The foundries in Colombia were leading the list of customers, amounting to 45% to 70% of the total of the COLAR's sales. A considerable amount of COLAR's pig iron went to the Colombian steel producers as a substitute for scraps when the international prices for scraps for steel-making use were moving at a high level.
The exports, which will be detailed later, were fluctuating over a wide range from 15% to 55% of total sales.
The business showings in the past five years are as given in Table 3.1.-1.

Table 3.1-1 COLAR's records of foundry pig iron sales in the past five years (in tons)

Classification / Year	Domestic market			Exports	Grand total	Actual production
	Foundries	Steel producers	Total			
1973	9,252 (49.5)	5,720 (30.6)	14,972 (80.1)	3,709 (19.9)	18,681 (100)	20,087
1974	11,645 (43.3)	1,832 (6.8)	13,477 (50.1)	13,431 (49.9)	26,908 (100)	28,441
1975	12,932 (71.9)	2,196 (12.2)	15,128 (84.1)	2,850 (15.9)	17,978 (100)	27,836
1976	8,802 (44.3)	85 (0.4)	8,887 (44.7)	11,000 (55.3)	19,887 (100)	26,129
1977	13,854 (62.6)	0	13,854 (62.6)	8,284 (37.4)	22,138 (100)	18,954

(Note) The values parenthesized denote the ratio in per cent to the grand total.

The foundries, which are the major users of COLOR's foundry pig iron, are located everywhere across the country.
In Cali, the COLAR's products are sold through a sales agent called "QUIMIA". In other areas, the COLAR is selling its products direct to the users.
The largest market is Medellin, followed by Bogotá.
In 1975, Medallin bought 4,613 tons (35.7%), and Bogotá 3,194 tons (24.7%).
According to the business statistic data available to the survey mission, the number of client foundries, quantity and amount sold by area in 1973, 1974 and 1975 are as shown in Table 3.1-2.

Table 3.1-2 Sales to domestic foundries (in tons)

Classification / Area	1973			1974			1975		
	Number of foundries	Quantity sold, tons	Amount sold, thousand pesos	Number of foundries	Quantity sold, tons	Amount sold, thousand pesos	Number of foundries	Quantity sold, tons	Amount sold, thousand peros
Medellin	11	4,777	10,136	7	3,519	10,988	5	4,613 (35.7)	18,354
Bogotá	23	2,561	5,435	34	3,405	11,003	25	3,194 (24.7)	12,887
Boyacá	2	550	1,178	6	2,551	8,110	5	2,841 (21.9)	11,457
Cali	7	793	1,614	8	1,403	4,271	4	1,723 (13.3)	7,028
Santander	6	230	502	6	290	947	4	275 (2.1)	1,120
Cundinamarca	2	232	376	2	354	981	6	162 (1.3)	620
Caldas	4	109	220	4	111	349	5	124 (1.0)	502
Others	-	-	-	1	12	36	-	-	-
Total	55	9,252	@2,103 19,461	68	11,645	@3,150 36,685	54	(100) 12,932	@4,019 51,968

Note: ° The values parenthesized denote the ratios to the total.

° @ means the mean selling price (pesos) per ton.

The sales department of the COLAR is set up with five members, including a sales manager (Jefs Division Comercial) and secretary (secretaria), undertaking all the sales activities.

3.1.1.1.3 Types of castings made of COLAR's foundry pig iron

The foundries in Colombia to which the COLAR is supplying its foundry pig iron are turning out parts of ordinary castings as cited in Table 3.1-3, and the high-quality machine parts are not produced. This is because the foundry pig iron the COLAR is offering contains as much phosphorus as 0.2% and is not applicable to high-quality castings for machine use. The major castings produced by the foundries in Colombia are as listed in Table 3.1-3.

Table 3.1-3 Major castings manufactured by foundries in Colombia

Grain mills, coffee mills, cane sugar mills, brake shoes, engine casings, motor shells, agricultural machinery, tubes and pipes for construction, balls of ball mills, ingot moulds, aqueduct covers, pinion gears.

3.1.1.1.4 Selling prices

The prices of the foundry pig iron have been on a steady rise reflecting the inflationary trend in Colombia; the prices (ex-factory, free on truck) per ton of pig iron for the foundries which were around 2,100 pesos in 1973 went up to 3,100 pesos in 1974 and then to 4,000 pesos in 1975. As of May 1978, the pig iron was priced at about 5,400 pesos per ton. As for the average prices in the years 1973 to 1975, refer to Table 3.1-2.

3.1.1.2 Export markets

3 .1.1.2.1 Importing countries

The countries that are importing the COLAR's foundry pig iron include Venezuela and other Latin American countries, U.S.A. and European countries.

The major countries to which the COLAR had exported from its starting-up of operation till the end of 1977 and the quantity exported are as listed in Table 3.1-4.

In Venezuela, the largest importing country, the COLAR is competing with Brazilian companies.

Table 3.1-4 Exports of COLAR foundry pig iron by country
(1973 ∿ 1977) (in tons)

Venezuela	15,000	U.S.A.	10,000
Italy	5,000	West Germany	3,000
Mexico	3,000	Chile, Ecuador, Peru, etc.	3,000

All the COLAR's exports are handled by an agent called "IPRCA."

3.1.1.2.2 Export prices

According to the 1978 COLAR's budget, the average selling price for the domestic market is set at about 5,400 pesos (ex-factory, free on truck) per ton while the exports are priced at a moderate value of about 4,400 pesos (FOB Colombia) on the average in anticipation of a fierce competition in the foreign markets.

Quoted on FOB Colombia terms, the export prices include about 1,000 pesos per ton of overland transportation to port or the border and agent commissions. Thus, the net price difference between exports and domestic uses amounts to as much as 2,000 pesos, provided that as for the exports, the COLAR is entitled to the following two types of government-offered incentives.

One is that the COLAR can take loans at a low interest rate as export working capital from the Colombia Export Promotion Funds (PROEXPO), a government-owned company coming under the Ministry of Economic Development (Ministerio de Desarrollo Económico).

The terms offered are very favorable because the interest rate is 13% per annum and the repayment term 6 months when the short-term loans (6 months to 1 year) available from private banks are 18 to 22% in prime rate and 25 to 30% in prevailing rate.

The other is the export subsidies granted by the Government on exports, and is called the Certificado de Abono Tributario and abbreviated as C.A.T., in which the export prices (FOB) are subsidized by the Government at a fixed ratio. The subsidy ratio has been varying year by year, registering 15% in 1974, 0.1% in 1975 and 1976 and 12% in 1977.

3.1.1.2.3 Restrictions on export of COLAR's products

There are some conditions that have checked the COLAR's products from growing in export business.

First, a net price difference of 2,000 pesos between exports and domestic uses exists to the disadvantage of exports, discouraging the COLAR from export business.

Secondly, the COLAR's pig iron contains much phosphorus, and is not suitable for high-quality castings. Namely, its merchandizability is limited.

Thirdly, the lot size is as small as about 100 tons, and a comparatively high unit transportation cost makes it difficult to conclude negotiations with remote countries.

3.1.1.2.4 An outline of foundry pig iron industry in South America

As already discussed, Venezuela is the leading importer of COLAR's goods. There, the COLAR is vying with Brazilian goods. COLAR's pig iron is also exported to Ecuador, Chile and Peru, etc.

Here it is worth looking over the demand-supply conditions of foundry pig iron in South American countries.

The information available about the foundry pig iron and foundry industry is meagre, and for detailed analysis of the market conditions, a separate survey will be needed.

Brazil

The foundry pig iron is produced by mostly small manufacturers who use charcoal, and not by integrated iron and steel manufacturers. These small manufacturers are said to amount to more than 100. The majority of them are situated in Minas Geraice. The foundries gather in Sao Paulo.
The small manufacturers are turning out about 4 mil. tons of pig iron annually for foundries and steel manufacturers. The annual demand by the foundries is about 1 mil. tons.
The major foundry pig iron manufacturers include:

CIMETAL SIDERUGIA S.A.
USINA QUEIROZ JR. S.A.
CIA SIDERUGIA PITANGUI

Venezuela

The demand for castings is estimated at 50,000 tons or more a year. There are no significant foundries except for SIDOR (with an annual pig iron production capacity of 1.3 mil. tons of which the bulk is used for steel-making, and about 30,000 tons for making cast iron pipes and ingot molds in its own works), and SIVENSA-HITACHI and METALURGIA ANDINA (both manufacturing foundry pig iron, a combined total of about 4,000 tons a year for making malleable fittings for their own use). These manufacturers are importing about 10,000 tons of castings annually.
It is reported that BRONX (U.S.A.) and FUNDICION NODULAR (Spain) have plans to install foundries in Venezuela in around 1980, but the fact needs to be confirmed. The dependency on imports of fundry pig iron in Venezuela is estimated to be as little as 6,000 to 7,000 tons a year.

Peru

SIDER PERU is manufacturing about 11,000 tons a year (7,000 tons for own use and 4,000 tons for sale).
It is believed to have been importing some, but nothing definite is known about the quantity.

Chile

The largest foundry pig iron manufacturer in Chile is FABRICAS Y MAESTRANEA DEL EJERCITO (FAMAE).
Its annual gait is estimated at about 10,000 tons.
Other manufacturers include COMPAÑIA ELECTROMETALURGICA S.A. (ELECMETAL) and S.A. FUNDICION LIBERTAD.
Little is known about the market profile including production and demand in foundry industry.

3.1.2 Recommendation

3.1.2.1 To promote exports

As already discussed, the COLAR is a monopoly under the care of the Government, and is obliged to supply foundry pig iron to the foundries in the country.
At present, the domestic demand is estimated at about 15,000 tons a year, and will be 18,000 tons at best if additional consumption due to industrial development and steel-making purposes is counted.
On the other hand, the COLAR's annual output capacity is 36,000 tons. This means that the COLAR will never be able to achieve a high production efficiency.unless nearly the same amount of pig iron as the domestic demand is exported abroad. If the exports are promoted to the extent that the COLAR's facilities can be run to the full capacity, the fixed cost per ton of product can be decreased. On the other hand, the promotion of the exports will bring about more chances for the COLAR to benefit from PROEXPO and C.A.T.
How will the output increase contribute to the profitability of the COLAR?
Following is the estimation of profit increase with other things being equal.
See Table 3.1-5.

Table 3.1-5 Estimate of profit increase due to full-capacity operations

Production

COLAR's sales volume expected for the year 1978 consists of 18,000 tons for domestic market and 11,000 tons for overseas market or 29,000 tons in all. With the domestic sales fixed at 18,000 tons, if 7,000 tons more are increased in the exports to realize the full-capacity production and sales of 36,000 tons, the profit increase may be calculated as follows.

Profit increase per ton of increased output

Export price (FOB Colombia)		4,400 pesos/ton (according to '78 budget)
Materials cost:	Iron ore	1,050 pesos/ton of iron
	Coke	1,430
	Limestone	230
	Total	Δ 2,710 pesos (according to '78 budget)
Electricity, industrial water, molds		Δ 300 (estimated)
Export expenses (domestic transportation + commission payable to agent)		Δ 1,000 (according to interview survey at site)
Operating cost (export loans from PROEXPO)		Δ 290 (4,400 pesos x 13%/Yr. x 6 months)
C.A.T.		530 (4,400 pesos x 12%)
Profit increase per ton of increased output		630 pesos

Total profit increase

7,000 tons x 630 pesos/ton = 4,410,000 pesos

3.1.2.2 To improve quality to launch into the market of high-quality foundry pig iron

The foundry pig iron the COLAR is now producing contains much phosphorus, and cannot be used except for ordinary castings. Its marketability is limited, accordingly.

The domestic demand for ordinary castings exists in its own way, and the COLAR as a monopoly is obliged to fill it. On the one hand, the COLAR must fulfil its duties and responsibilities as a monopoly, and on the other hand, the COLAR should enter upon the production of high-quality foundry pig iron by improving product quality for the purpose of expanding the outlets both at home and abroad to attain a high productivity.

Expanded market will make it possible for the COLAR to keep a high level of productivity with ease and to improve profitability.

The raw materials used are to blame for the fact that COLAR's foundry pig iron shows a high content of phosphorus. For particulars about this problem, refer to the chapters concerning technical assessment and recommendations.

It is learned by hearsay that studies are being made for the production of malleable cast iron and nodular cast iron for automotive use in Columbia.

The studies may, and should, call the monopolistic COLAR to take upon itself to undertake such production.

3.2 Organization and Manning

3.2.1 Status quo and problems

3.2.1.1 Organizational setup and staff

The organization of the COLAR as of May 9, 1978 is shown in Table 3.2-1 in which location and manning are shown. The main office functions which concentrate in Bogotá are staffed with 43 persons, the Cajica blast furnace plant employs 151 persons, and the Motecristo coke works is operated by 51 employees.

The total manpower is 245.

Pericos Iron Mine has been closed temporarily since Dec. 1977, and is under the care of one or two guards dispatched from Dept. Materias. It is said that 140 to 150 miners were working at Minas Pericos when the iron ore was extracted.

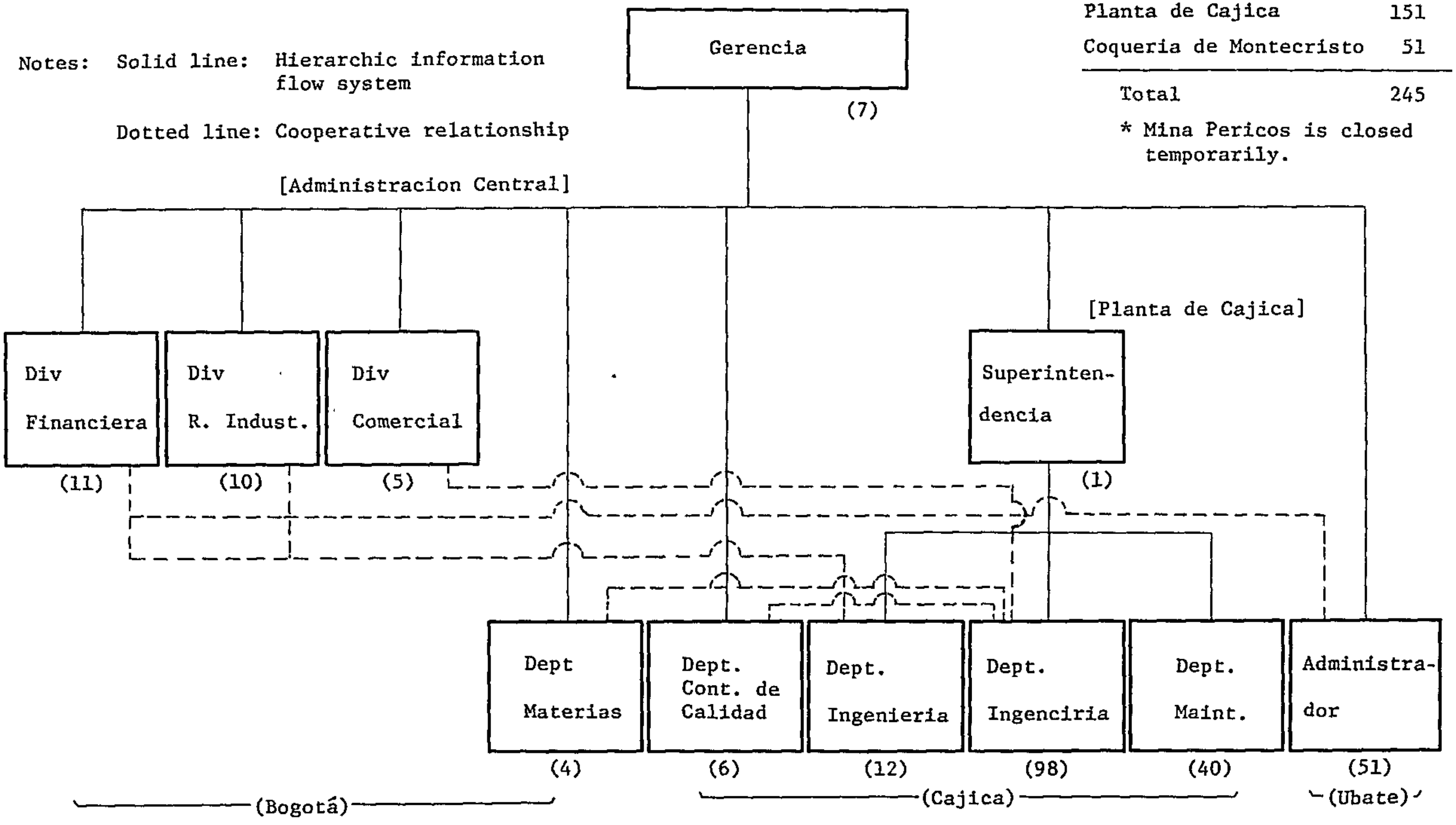
3.2.1.2 Organization and management

The solid lines in Table 3.2-1 show hierarchic information flow. Div. Financiera and Div. R. Indust., which are main office functions, are extending a cooperation to such production departments as the Cajica blast furnace plant (especially Dept. Admi.) and the Montecristo coke works in terms of finance, accounting, personnel and logistics.

Div. Comercial, which is also a main office function, is cooperating with Dept. Ingeniera of Cajica plant.

Since the main office functions gather in Bogotá which is far apart from Cajica and Montecristo, both production sites are forced to own staff for personnel and storage control.

Table 3.2-1 ORGANIZATION CHART OF THE COLAR (as of May 9, 1978)



Notes: Solid line: Hierarchic information flow system

Dotted line: Cooperative relationship

Administration Control	43
Planta de Cajica	151
Coqueria de Montecristo	51
Total	245

* Mina Pericos is closed temporarily.

Dept. Materias and Dept. Cont. de Calidad are also in close cooperation with the Cajica plant.

While the Superintendent determines the specifications of the raw materials for the blast furnace, Dept. Materias controls the suppliers so that the raw materials either from captive or outside sources may conform to the specifications. On the other hand, Dept. Cont. de Calidad is assigned to analyze and control the quality of procured raw materials and produced foundry pig iron.

(As shown in Table 3.2-1, Dept. Cont. de Calidad is stationed at Cajica.)

The cooperating relationships among the functions are represented by dotted lines in Table 3.2-1.

3.2.1.3 Comité de Gerencia

While the daily business routine is operated as explained above, the Comité de Gerencia, which is, as it were, a cadre liaison committee, is held once a week.

Presided by Gerente, the Comité de Gerencia is participated in by Assistente de Gerencia, Div. chiefs of Financiera, R. Indust., and Comercial, Cajica Superintendente, Dept. chiefs of Materias and Cont. de Calidad, and the Administrador of Montecristo.

The members exchange information and discuss the matters relating to sales, production, materials, technology, financial affiars, personnel and what not.

3.2.1.4 Problems arising out of the geographic distance between head office and Cajica plant

The head office in Bogotá and the Cajica plant are about 40 km apart from each other, and the Cajica plant and Montecristo plant are about 50 km apart. The personnel is no more than about 250, and the activities specialize in the production of foundry pig iron alone. All these do not constitute the reason why the head office must be located apart from the production sites. Since the functions are dispersed as explained above, it is hard to promote inter-functional communication and take the necessary prompt actions.

Also, superfluous managerial staff are needed who may be assigned to other tasks if Bogotá and Cajica were closely located.

3.2.1.5 Problems involved in the organization

The COLAR has too many branch organizations for its size. The materials-related functions vital to the blast furnace operations are not under the direction of the Superintendente of the Cajica plant. This lack of unity in production activities runs counter to the COLAR's efforts to improve productivity and product quality.

3.2.1.6 Dearth of experienced engineers

The blast furnace operation is an experience-sensitive industry. The Superintendente of the COLAR is the topnotch blast furnace engineer found in Colombia, but the engineers assisting him have no operating experience in other than COLAR's furnace. The blast furnace productivity and product quality depend largely on the quality and characteristics of raw materials as well as blast furnace operating techniques. The COLAR is in need of expert staff in the field of materials engineering, accordingly.

3.2.2 Recommendation

3.2.2.1 To relocate the main office functions to Cajica

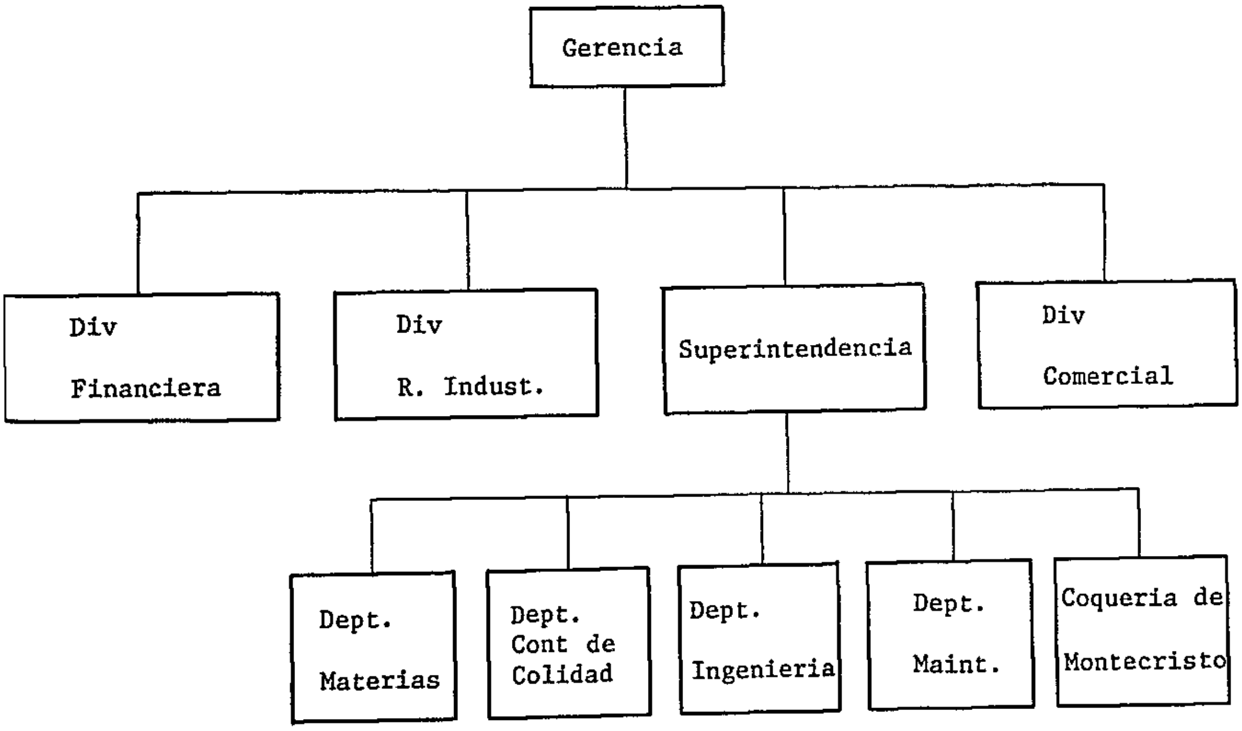
All the main office functions is recommended to be relocated to Cajica because the present geographical distance between Cajica and head office is of no use to the COLAR's activities. It is also recommended to move the sales department to Cajica while keeping communications (telephone, telex, etc.) with customers and agents. As the physical distance is made up, the communication between administrative and production departments will be improved, the actions prompted and the managerial staff cut short.

3.2.2.2 To consolidate Cajica plant and materials-related functions into unity

The fact that the quality and characteristics of raw materials to the blast furnace have a gear bearing on the productivity and product quality has already been expatiated in the technical paragraphs in this report. Thus, it is recommended that Dept. Materias and Dept. Con. de Calidad, both currently under the head office, and Coqueria de Montecristo should all be assembled and put under the direct control of the Superintendente of Planta de Cajica. The activities for improvement in productivity and product quality will get off the ground. At the same time, a clear-cut system of duties and responsibilities will be established and enforced.

As a result of this consolidation, the COLAR's organization chart will have to be modified as follows.

Table 3.2-2 Recommended organization chart after consolidation



Note: Principal place of business: Cajica, provided Coqueria de Montecristo alone is located at Ubata.

3.2.2.3 To train furnace operating engineers and materials engineers abroad

As touched upon in the foregoing, there is required a built-up echelon of engineers in order to assist the Superintendente in improving the furnace productivity and upgrading and stabilizing the quality of both raw materials and products. So far as the Colombian iron-making industry stands, it will be difficult to employ expert engineers from winthin the country.
It is therefore recommended emphatically to pick up two qualified engineers (1 furnace engineer and 1 materials engineer) out of the COLAR staff and expatriate them to the most advanced iron-making country (like Japan) for training for 6 to 12 months.
In the accommodating country, the tooling, materials used and other are different from the COLAR's, and the knowledge and experience acquired by the trainees may not be applicable direct to the requirements of the COLAR. However, such knowledge and experience will be very useful for the improvement and upgrading of the COLAR furnace, beneficiation facilities, instrumentation and the ways to operate them as the trainees should learn the world's foremost technologies, years of knowhow, and what they stand behind.

3.2.2.4 To make efforts to adjust workforce

Not only the main office functions, but are Dept. Maint. and Dept. Ingenieria of the Cajica plant likely to have been overstaffed.
It is therefore recommended to train each employee to be able to process various types of jobs so that each can substitute himself for another. In this way, the superfluous workforce will be eliminated. In "A" company, of Japan, which is almost the same in furnace inner volume and production process as the COLAR, about 150 employees are working while turning out foundry pig iron about three times as much.

3.3 Finance

3.3.1 Status quo and problems

3.3.1.1 Unit consumption of raw materials

The specific unit of consumption of iron ore, coke and limestone is as shown in Table 3.3-1.
Namely, the iron ore is 2,300 kg, the coke 1,600 kg and the limestone about 900 kg.

Table 3.3-1 COLAR's unit consumption of raw materials so far achieved.

(Unit: kg/ton of iron)

Year / Classification	1973	1974	1975	1976	1977
Iron ore	2,408	2,379	2,276	2,196	2,382
Coke	1,616	1,593	1,679	1,697	1,635
Limestone	830	830	784	965	919

The specific unit of consumption of iron ore varies depending on the grade of iron ore used.
The ore from Pericos, the captive mine of the COLAR, contains a scanty 45% of iron as already described in the technical paragraphs.
Since it is a prime source of iron ore, the specific unit of consumption of iron ore is destined to remain at a high level.
But the specific unit of consumption of coke and limestone is too high, and the poor beneficiation and pretreatment are to blame for.

3.3.1.2 Costs of raw materials

The supply of limestone is entirely dependent on outside sources.
The iron ore and coke are partly produced by the COLAR itself and partly supplied from outside sources. According to the '78 budget, 54% of the total coke demand is expected to be sustained by the COLAR itself.

As regards unit costs, the iron ore and coke supplied by the COLAR itself are 70 to 80% (45% in 1977) higher than those available from outside. The costs of raw materials are as shown in Table 3.3-2.

Table 3.3-2 Cost statistics of COLAR's raw materials

(Unit: pesos/ton)

Year / Classification		1973	1974	1975	1976	1977
Iron ore	Own	296	336	612	824	-
	Outside	291	398	361	432	-
Coke	Own	-	745	873	1,070	1,246
	Outside	296	411	510	598	863

3.3.1.3 Financial expenses

Since 1975, the COLAR's financial expenses have moved at as high a level as 23.8 to 43.5% of total sales. Table 3.3-3 shows a comparison between the COLAR and the Japanese foundry pig iron manufacturer of the same size as the COLAR, though there is a moot point in its justifiability as the interest level is different between the two countries.

Table 3.3-3 Ratio of financial expenses to total sales

(%)

Year / Classification	1973	1974	1975	1976	1977
COLAR	14.2	18.9	29.9	23.8	43.5
Foundry pig iron manufacturers in Japan of the same scale as COLAR	6.9	6.5	8.2	9.4	11.2

The reasons why the financial expenses ratio of the COLAR is so high may be boiled down to the following three.

1) The deficits have snowballed as the facilities have not yet been operated to their full capacity.
   At the end of 1977, the capital account declined to about 68 mil. pesos as against about 93 mil. pesos of paid-in capital. As a consequence, the COLAR becomes dependent heavily on the loans; at the end of 1977, the outstanding debts amounted to 122 mil. pesos, or 20% above the 1977 total sales of 103 mil. pesos.

Table 3.3-4 Outstanding debts

(in thousand pesos)

Outstanding debts at the end of 1977	Short-term loans	43,118
	Long-term loans	79,443
	Total	122,561
Sales recorded in 1977		103,045

(Note) About 10% of the long-term loans, that is, 8,369 thousand pesos was borrowed from the foreign banks on the occasion of constructing COLAR plants, and is to be reimbursed by 1979. All the short-term loans have been raised from the local financial institutions.

2) Although the greater part of the loans is mostly from the local finnacial institutions, their interest rate is more than 25% with the exception of 13% offered by PROEXPO, as shown in Table 3.3-5.

Table 3.3-5 A list of interest rates for borrowings

(%)

Classification	Source	Interest rate
Short-term loan	PROEXPO (de facto by way of private banks)	13
	Private banks	28
Long-term loan	IFI	*25
	Foreign banks	**25

Notes: * In 1978, the rate will be floated from 20 to 23% depending on the transactions.

** The nominal interest rate is 12%, but the real rate has been sent up to about 25% because the loans were taken on a dollar basis and because the peso was devalued.

3) Of the working assets, the ratio of products to the total sales (called the inventory ratio) is as high as over 50%. Table 3.3-6 shows the annual statistics of inventory ratios.

Table 3.3-6 Inventory ratios of COLAR

(%)

Year / Inventory ratios	1975	1976	1977
$\frac{\text{Mean level of products in stock at the end of term}}{\text{Annual total of sales}}$	44.9	53.0	57.2

3.3.2 Recommendation

3.3.2.1 To reduce the specific unit of consumption of coke and limestone

Detailed discussions on this matter have been made in the chapters concerning technical assessment and recommendations.

The specific unit of consumption of coke may be reduced about 43% (700 kg) from the present 1,600 kg level to somewhere around 900 kg through intensive sizing of iron ore and limestone and improvement of coke in properties, though the said cutback ratio may change largely depending on the ramified factors involved in the blast furnace operations.

If the coke ratio is reduced by 700 kg, it might lead to a saving of a little more than 100 kg in the specific unit of consumption of limestone. For details, refer to 2.7.2

3.3.2.2 To reduce the unit prices of the raw materials supplied by COLAR itself

For the iron-making business, it is of paramount importance to get tight hold of stable channels for ensuring supply of inexpensive raw materials.

In this respect, it is significant that the COLAR owns Pericos mine and Montecristo coke plant. These offer a big edge in bargaining for purchases on favorable terms.

The COLAR should make every effort to cut down the unit prices of raw materials by increasing the productivity of own facilities, including the Montecristo coke plant and Pericos mine scheduled for reopening, through a sweeping study of problems such as manning, or by commissioning the production to other parties.

3.3.2.3 To promote exports for the purpose of achieving a high production

As per 3.1.2.1.

3.3.2.4 To raise foreign funds of low costs

It is recommended that the COLAR should raise inexpensive funds from overseas with the permission of National de Planeaction. Practically, the following two methods may be recommended.

1) Use of Euro-dollars

The capital cost will be LIBOR (London inter-bank offered rate) plus about 2%. Of late, the LIBOR is showing an upward turn. As of Aug. 21, 1978, the 6-month term rate was 9 3/16%, and if it still holds good, the interest rate is figured to be about 11% per annum. Since the rate is on a dollar basis, the real rate to be charged will become higher as the Colombian peso is devaluated against the U.S. dollar. The devaluation for the year 1978 is expected to be 12 to 15% a year; a 6-month loan will be available at a real interest rate of 24 to 27%, and will be advantageous over the local fund-raising which is accompanied by as high an interest rate as 28% as shown in Table 3.3-5.

2) To raise funds from international non-profit financial institutions

For example, Corporacion Andina de Fomento (CAF) offers operating funds at an annual interest rate of 9%, by far lower than the local banks quote.

3.3.2.5 To ask IFI and other government organization for favorable credits

The COLAR is required to build up its constitution through sweeping reforms both in technical and managerial aspects. But, until the COLAR will take shape, it should be supported financially by the government agencies, including the largest shareholder IFI, and should also be granted favorable terms on interest rate.

JICA