ON SOME ASPECTS OF BASIC OXYGEN STEEL MAKING WITH PREREDUCED PELLETS

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Under normal circumstances, a BOF can consume upto 30% of scrap in the charge which otherwise consists of molten pig iron. In steel plants where the basic oxygen process has been adopted, this requirement of scrap is generally met by scrap generated within the plant and by that bought from external sources. The composition of scrap, especially that purchased from dealers, is notorious for its variation from wagon to wagon, batch to batch and even from season to season. This is particularly true of the sulphur content of the scrap which is a factor of fundamental importance in BOF steelmaking. This inconsistency in scrap composition tends to give rise to undesirable variations both in the final bath composition and in the general bath behaviour during blowing. To keep these fluctuations under control, BOF operators have to constantly monitor the blow and adopt corrective measures when necessary. A stricter control over the materials charged into the BOF would therefore appear to be necessary before automation is possible and the process is rendered less subject to variations. To this end, the substitution of scrap by prereduced pellets could prove worthwhile.

Although both these materials are rich in iron, the consistency in the analysis of prereduced pellets (or sponge iron)* cannot be matched by even the most stringent control over the scrap quality. Unlike scrap, the concentration of elements like sulphur in prereduced pellets can be adjusted within limits by carefully selecting the ore blend used in the manufacture of the green pellets. Thus, it may at least theoretically be argued that pellets could form an ideal substitute for scrap particularly in the manufacture of low or very low sulphur steels (maximum 0.008% S). Whether the use of pellets is a practical proposition under a given set of conditions, would depend primarily on factors like the availability of pellets, their cost in comparison to scrap and the effect of charging these pellets on furnace behaviour.

Thyssen Niederrhein (formerly HOAG) in Oberhausen, West Germany, have been developing the Purofer process(1) of direct reduction since 1958. In this process, either lump or pelletised ore is reduced in a vertical shaft furnace by passing a preheated mixture of hydrogen and carbon monoxide in the countercurrent direction. The gas mixture is obtained by thermal-catalytic refining of gaseous or liquid hydrocarbon, e.g. natural gas, coke oven gas or light virgin naphtha. The directly reduced iron is mechanically discharged at the bottom of the furnace without any prior cooling. The experiments reviewed here were carried out with pellets produced in the 500 t.p.d. Purofer pilot plant at Oberhausen which were transported after cooling to the steelmelting shop about twentyfive kilometres away.

Properties of pellets used

Until the end of 1971, almost 105,000 tonnes of ore were processed in the Purofer plant, the detailed break-up of which is shown in Table 1. It will be seen that Itabira pellets from Brazil and Carol Lake pellets from U.S.A. together constituted almost 90% of the total materials handled. The analysis of these pellets, both before and after reduction, is shown in Table II together with those of some of the other materials used. In all cases, the uniformly high degree of reduction attained is worth noting. The other significant feature of the Purofer process, i. e. the consistency in the analysis of the final product, is illustrated in the particular case of Itadira pellets in Table III. The physical properties after reduction of both Itabira and Carol Lake pellets are shown in Table IV.

TABLE I

Materials processed in the Purofer Plant before November 1971

Type of ore/pellets		No. of Tonnes
Carol Lake pellets		24,123
Itabira pellets		69,268
Swedish pellets	A	4,352
	B	4,964
	C	1,330
South American lump ore		382
Total		104,419

*In the available literature, the term sponge iron is often used to refer to prereduced pellets with a high degree of metallisation but in this paper, these two terms are considered synonymous.

Preliminary attempts to use either of these two types of pellets in the BOF gave some erratic results, the reasons for which were not immediately apparent. Subsequently, it was found that the exposure of the pellets to the open air in the scrap yard adjoining the steelmelting shop was affecting their performance within the converter. Laboratory tests, the results of which are summarised in Fig. 1 confirmed the suspicion that the pellets underwent reoxidation fairly rapidly, e.g. after 4 weeks storage, the metallic iron content of Itabira pellets decreased to 78% and the compression strength was reduced to 98 kg. This deterioration in the quality of the pellets(2) was also reflected in their size distribution. Table V, as well as in their physical appearance. The reoxidised pellets exhibited a reddish tinge which was clearly distinguishable from their original steel grey appearance. Subsequent trials were carried out with pellets stored in the stockyard for a maximum period of one week.

TABLE II
Analysis of the pellets and ores handled

Analysis %		Pellets					Lump Ore
		Carol Lake	Itabira	Swedish			South American
				A	B	C	
Before Reduction	Fe total	65.1	66.3	67.9	67.6	66.7	66.3
	Fe$_2$O$_3$	92.5	92.4	96.0	96.2	93.4	91.8
	SiO$_2$	5 61	1.50	0.95	1 30	1.18	1.18
	CaO	0.40	1.37	0.10	0.35	1.25	0.10
	MgO	0.43	0.18	0.30	0.36	0.35	0.05
	Al$_2$O$_3$	0.35	0.79	0.60	0.75	0.87	1.50
	P	0.014	0.024	0.010	0.010	0.015	0.041
	S	0.010	0.010	0.010	0.010	0.010	0.020
After Reduction	Fe total	80.0	92.7	94.8	93.7	93 1	91.0
	Fe met	85.3	87.5	90.4	89.7	88.2	80.4
	SiO$_2$	6.6	2.08	1.35	1.71	1.57	1.66
	CaO	0.5	1.65	0.15	0.30	1.65	0.17
	MgO	0.58	0 18	0.36	0.35	0.25	0.08
	Al$_2$O$_3$	0.46	1.04	0.76	0.94	0.93	2.21
	P	0.017	0.031	0.016	0.012	0.025	0.062
	S	0.004	0.003	0 004	0.004	0.003	0.004
	C	0.76	0.56	0.66	0.68	0.75	0.46
	Degree of reduction	96.7	95.7	96.3	96.7	95.9	91.0

TABLE III
Variation in the degree of reduction and the carbon & sulphur contents of Itabira pellets after reduction.

	Average %	% Standard deviation	Number of samples
Degree of reduction	95.68	±0.524	758
Carbon content	0.56	±0.27	694
Sulphur content	0.0031	±0.0013	694

TABLE IV
Physical Properties of Prereduced Pellets

Property	Carol Lake pellets	Itabira pellets
Absolute density, g/cm^3	6.88	6.94
Bulk density, t/m^3	1.71	1.70
Porosity, %	54.9	58.2
Compression strength, kg	120.3	118.2
Specific surface area, cm^2/gm	4100	4700

Theoretical evaluation of the economics of pellets usage

By setting up a heat and mass balance, an attempt was made to evaluate the requirements of hot metal. pellets, lime and oxygen for varying carbon and silica contents of the prereduced pellets.

The calculations were carried out(3) for four selected pellet compositions:

(a) 1% C, 2% SiO$_2$ 88.9% Fe met

(b) 1% C, 6% SiO$_2$ 85% Fe met

(c) 5% C, 2% SiO$_2$ 85% Fe met and

(d) 5% C, 6% SiO$_2$ 81.2% Fe met

While conditions (a) and (b) were chosen to correspond to the compositions of Itabira and Carol Lake pellets respectively, conditions (c) and (d) were included simply to investigate whether the use of high carbon pellets would prove more economic. Based on

these calculations, the maximum permissible price of pellets which would allow the total substitution of scrap without adversely affecting the process economics, was calculated as a function of the scrap price.

In all these calculations, the following assumptions were made:

(l) The hot metal contains 4.30% C, 0.80% S:. 0.80% Mn, 0.20% P and 0.030% S

(ii) The iron yield defined as:

$$\frac{Fe_{steel} + Fe_{slag}}{Fe_{hot\ metal} + Fe_{pellets}} \times 100$$

remains constant in all cases and is equal to 97%. This automatically implies that the liquid steel yield given by

$$\frac{Weight\ of\ liquid\ steel\ tapped}{Weight\ of\ (hot\ metal + scrap)\ charged} \times 100$$

varies.

(iii) 10% of the carbon available is oxidised to CO_3 and the remainder to CO.

(iv) The slag basicity required for fluxing the silicon from the hot metal is 4.1 and only 3.6 for flux-

Table V
Size distribution of the prereduced pellets
(Itabira and Carol Lake)

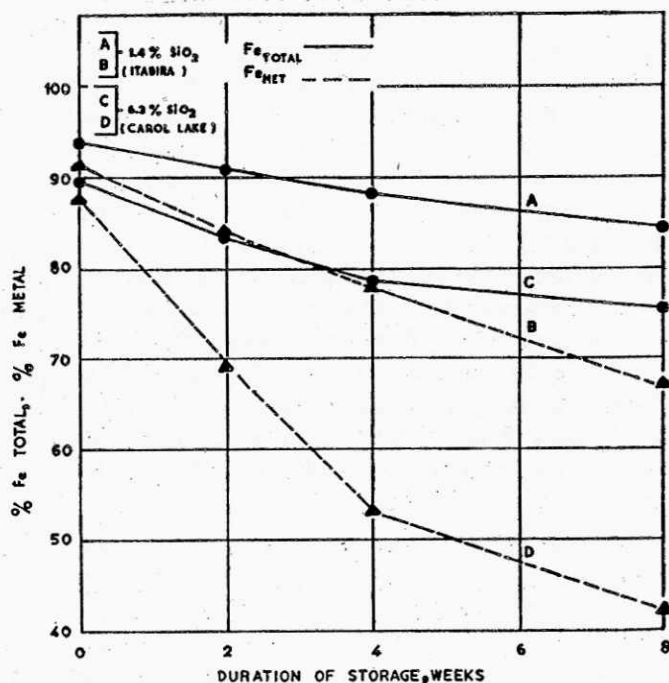| Size range	As delivered %	After 4 weeks storage %
< 3.15 mm	0.7	0.4
< 5.00 mm	0.9	0.9
< 6.30 mm	3.2	2.6
< 8.00 mm	6.3	7.3
< 10.00 mm	22.5	29.3
< 12.5 mm	71.2	76.7
< 16.0 mm	99.3	99.6
< 16.0 mm	0.7	0.4

Fig. 1— *Reoxidation of prereduced pellets with storage in open air.*

ing the silica in the pellets. The iron content of the slag is 20%, 55% of this iron being in the form of FeO and the remainder as Fe_2O_3.

(v) In the case of scrap cooled heats, 310 kg of scrap is charged per tonne of raw steel.

The results in Table VI(a) show that because of the higher proportion of gangue in the pellets compared to scrap, liquid steel yields are lower whenever the former are charged. As would be expected, the worst yield is in the case of pellets with 5% carbon and 6% SiO_2. For pellets containing the same percentage of silica, an increase in their carbon content substantially increases both the amount of pellets to be charged and the oxygen that is required to be blown. This in turn results in a corresponding increase in the quantity of waste

Table VI (a)
Specific input and output of materials for scrap and pellet charged heats

Materials in kg/tonne of raw steel	Sorap charge	Prereduced pellets charge			
		a) 1% C, 2% SiO₂	b) 1% C, 6% SiO₂	c) 5% C, 2% SiO₂	d) 5% C 6% SiO₂
Hot metal	795 8	839.7	876.1	794.7	839.8
Scrap	310.0	—	—	—	—
Pellets	—	294.6	289.2	355.8	348.0
Total metallic charge	1105.8	1134.3	1165.3	1150.5	1187.8
Lime (92% CaO)	59.4	85.3	131.9	86.6	142.7~
Oxygen (Nm³ per tonne of steel)	47.5	55.2	61.2	68.0	75.2
Slag amount (50% CaO)	108.2	156.3	243.2	159.0	263.5
Iron losses in slag	21.6	31.3	48.6	31.8	52.7
Exit gases (Nm³ per tonne of steel)	63.3	72.3	75.1	96.5	99.3
Iron yield %	97.0	97.0	97.0	97.0	97.0
Liquid steel yield %	90.4	88.2	85.8	86.9	84.2

gas generated, which directly determines the load on the gas cleaning plant. On the other hand, at a constant carbon content of the pellets, any increase in silica implies that a larger quantity of lime has to be charged to maintain the slag basicity required for efficient removal of elements like phosphorus and sulphur. This automatically lowers the amount of solid metallics which can be charged, increases the slag volume and decreases the metal yield. These disadvantages could, however, be overcome if the manufacturing cost of high silica pellets was appreciably lower Addition of extra lime also has an adverse effect on the thermal balance in the converter since lime cools about 1.7 times more efficiently than scrap. The cooling effect of the pellets in comparison to scrap may be estimated from Table VI(b).

The relative costs of production per tonne of stee' excluding the cost of the solid metallics (scrap or pellets), are calculated in Table VII(a). The maximum price of each type of pellet for which the total replacement of scrap would be economically attractive, is shown both in Table VII(b) and Fig. 2 as a function of the scrap price. Since a certain minimum cost is involved in the manufacture of pellets, it appears that an "in toto" substitution of scrap by pellets is feasible only when scrap prices are relatively high.

The production cost of prereduced pellets would depend primarily on two factors, the cost of the parent ore (or ores) and that of the fuel. The total cost of

Purofer pellets per tonne of Fe is shown in Fig. 3 as a function of these two parameters(1). For the Itabira and Carol Lake ores containing about 65% iron, the total cost of the prereduced pellets (90% Fe_{tetal}) would be between 90 to 100 DM/t assuming a typical ore price of 65 DM/t. For these two types of pellets, therefore, replacement of scrap would be economically viable only when it is priced above 125 DM/t. It should be mentioned here that the price of purchased scrap is generally above 150 DM/t.

Table VI (b)

Comparison of calculated heat capacities of pellets and scrap*

Pellet type (ref. table VI (a))	%C	%SiO$_2$	Heat capacity of pellets / Heat capacity of scrap
a	1	2	1.11
b	1	6	1.18
c	5	2	0.87
d	5	6	0.94

*These values agree well with the values given by L. von Bogdandy and H. Engell. "Reduction of Iron Ores," Verlag Stahleisen, Dusseldorf, 1971.

However, it should be pointed out that in certain cases additional benefits may accrue from the use of pellets which have not been accounted for and this could tilt the balance more in their favour. For exam-

Table VII (a)

Cost of material per tonne of steel excluding the cost of scrap or pellets

Item	Price DM/t	Scrap Amount kg/t steel	Scrap Cost DM/t steel	1% C; 2% SiO₂ Amount kg/t steel	1% C; 2% SiO₂ Cost DM/t steel	1% C; 6% SiO₂ Amount kg/t steel	1% C; 6% SiO₂ Cost DM/t steel	5% C; 2% SiO₂ Amount kg/t steel	5% C; 2% SiO₂ Cost DM/t steel	5% C; 6% SiO₂ Amount kg/t steel	5% C; 6% SiO₂ Cost DM/t steel
Hot metal	166.00	795.8	132.10	839.7	139.39	876.1	145.43	794.7	131.92	839.8	139.41
Scrap		310.0		—		—		—		—	
Prereduced pellets	69.00	—	—	294.6		289.2		355.8		348.0	
Lime	90.00	59.4	4.10	85.3	5.89	131.9	9.10	86.6	5.98	142.7	9.85
Oxygen	DM/ 1000 Nm³)	47.5 (Nm³)	4.30	55.2	4.97	61.3	5.52	68.0	6.12	75.2	6.77
Slag disposal	3.02	108.2	0.33	156.3	0.47	243.2	0.73	159.0	0.48	263.5	0.80
Total cost without cost of scrap or pellets			140.83		150.72		160.78		144.50		156.83

Table VII (b)

Break-even price of pellets as a function of the scrap price

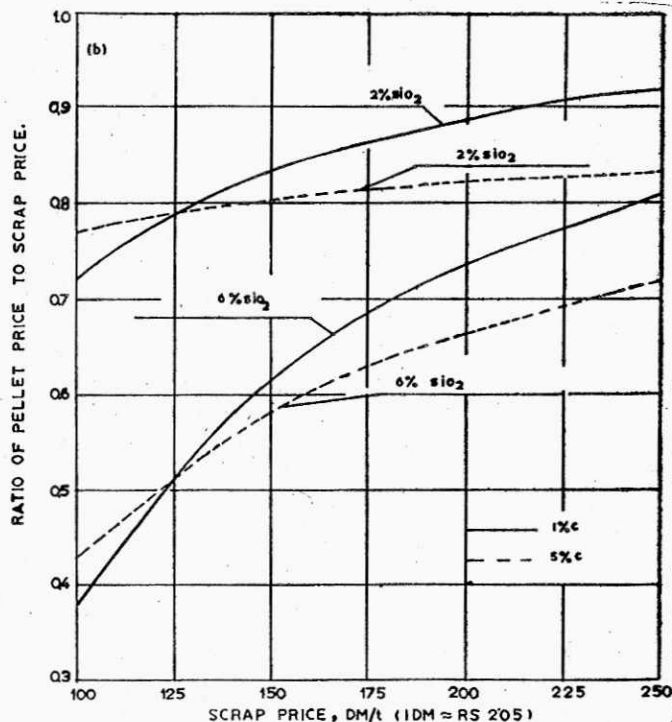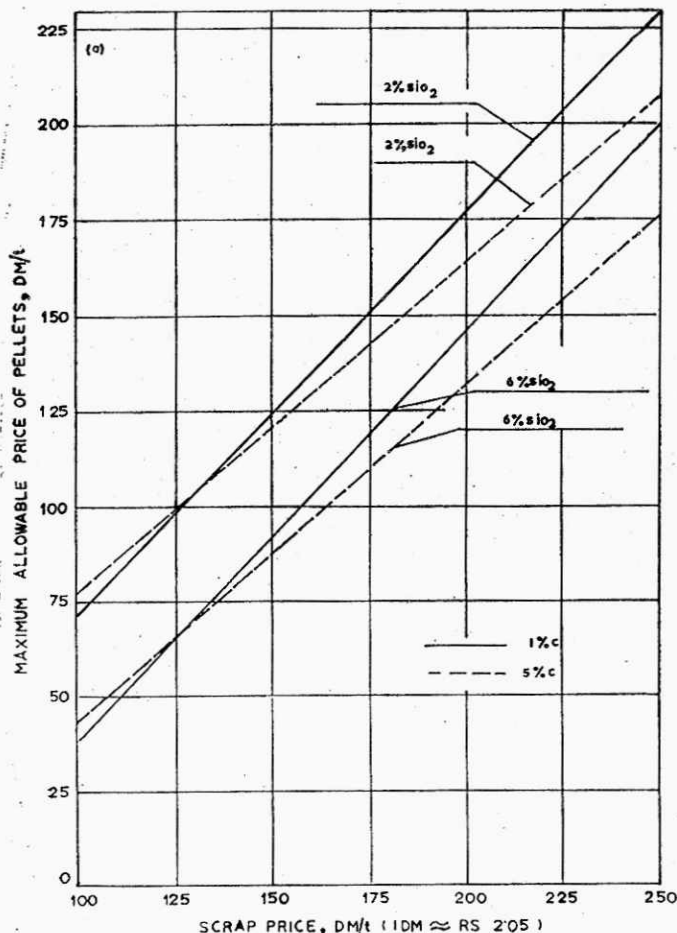| Scrap price DM/t	Scrap cost DM/t steel	Total cost for scrap charged heats DM/t steel	Maximum allowable price of pellets DM/t 1% C 2% SiO₂	1% C 6% SiO₂	5% C 2% SiO₂	5% C 6% SiO₂
100	31.00	171.83	71.65	38.21	76.81	43.10
150	46.50	187.88	124.27	91.80	120.38	87.64
166	51.46	192.29	141.11	108.96	134.32	101.90
200	62.43	202.83	176.88	145.40	163.94	132.18
250	77.50	218.33	229.50	199.00	207.50	176.72

Fig. 2-(a) Maximum allowable price of each type of pellets and

(b) The ratio of pellet price to scrap as a function of the price of scrap.

ple, in the manufacture of very low sulphur steels pellets are definitely preferable. The use of scrap in such cases would require abnormally high slag basicities which could lead to operational difficulties and a decrease both in the metal yield and the converter capacity. In such instances, the break-even point for substitution of scrap by pellets would be at a pellet price higher than what is indicated in Fig. 2.

Experimental details

The experiments described here were carried out with the particular motive of establishing the feasibility of using prereduced pellets as a BOF feed, as well as comparing the relative merits and demerits of using either scrap or pellets for the production of low sulphur (< 0.020%) steels.

The trials with both Carol Lake and Itabira pellets, which vary mainly with respect to their silica content, were conducted in a 120-tonne vessel equipped with facilities for lime powder injection. In the first series of trials, all the pellets were charged into the vessel by means of a charging box before the hot metal was poured. In the second and third sets of trials, the blow was started either with hot metal alone or in some cases after the addition of hot metal and a small quantity of scrap. The amount of pellets necessary to make the total solid metallics equal about 30% of the char-

ge, was added through a bunker during the initial stages of the blow.

In all the heats, the blast furnace hot metal was desulphurised with sodium carbonate prior to charging and in certain cases when very low surphur steels (<0.010%) were to be made, the hot metal was additionally treated with calcium carbide using a hollow T shaped stirrer[4]. In all cases, the slag formed was raked off before the hot metal was poured into the converter. Generally, the bath was blown for about 22 minutes to below 0.10% carbon before metal and slag samples were withdrawn and the steel tapped, but in some cases, samples were also taken at the end of the first blowing period, i.e. when the carbon content of the bath was around 0.70%.

For the withdrawal of metal samples, sampling spoons covered with a wooden lid were immersed into the bath after the converter had been tilted to the horizontal position. Slag infiltration was avoided because this lid burnt only after the sampling spoon penetrated through the slag layer and the sample was immediately deoxidised by an aluminium wire placed inside the spoon. It was withdrawn from the converter in the upright position, and allowed to solidify "in situ" before being sent for analysis. In addition to the normal analysis, the oxygen and nitrogen contents of these metal samples were also determined. Slag samples were col-

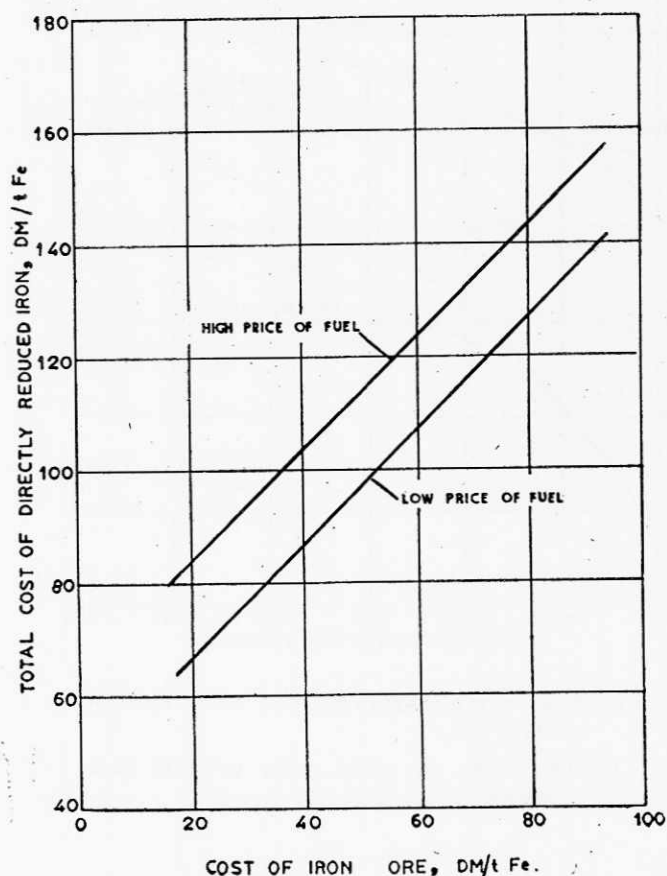lected from the slag adhering to the metal spoon and analysed in the laboratory.

Fig. 3–Cost of Purofer pellets as a function of the cost of the parent ore and the price of fuel used

Results and discussion

Series I: Itabira pellets containing about 2% SiO_2 were charged prior to the commencement of the blow in amounts varying between 9.0 and 17.5 tonnes, i.e. 87 to 200 kg/tonne of hot metal charged(5). 25 Purofer heats were blown along with a similar number of normal scrap cooled heats and the results of these fifty heats, in which no lime powder was blown, are discussed below.

The average amounts of materials which were charged into the converter during this campaign are tabulated in Table VIII(a). From Table VIII (b) it will be seen that the higher consumption of coolants during the Purofer heats cannot be ascribed either to the hot metal analysis or its temperature. Because the silicon content of the hot metal was slightly lower, the blowing time and the total amount of oxygen consumed were somewhat less during the Purofer heats. However, as shown in Fig. 4, the oxygen blown per tonne of hot metal charged was approximately the same as in the case of the scrap charged heats in other words, the oxygen consumed per tonne of hot metal per minute was distinctly higher for the heats in which pellets were used.

Table IX indicates the average analysis of the bath and its temperature at the end of the blow. In agreement with the rate of consumption of oxygen, the final carbon contents were lower for the heats in which pellets were charged. The distinctly higher iron contents of the slags shown in Fig. (5a & b) also prove the effectively harder blowing conditions in the case of these heats. This harder blowing was no doubt responsible for the higher consumption of coolants and the lower turndown carbon contents, Fig. 6 further illustratess that even when the final carbon contents of the bath were between 0.04 and 0.06% in both cases, the iron contents of the slags in the pellet charged heats were about 3 to 4% higher. It is thought that this was a consequence of a delay in the dissolution of the pellets because some of the pellets formed rigid clusters or lumps which remained undissolved for a large part of the blow, thereby making the slag heterogenous and decreasing its effective reactivity. In order to build-up a slag having the same capacity refining as in the case of scrap charged heats, it was necessary to operate the converter with slags containing higher percentage of iron. A higher MgO content of the slags in the pellet charged heats, was in agreement with their higher iron contents. In an effort to make these slags more fluid, a larger quantity of fluxes was also added (ref. Table VIII(a))but this was obviously not enough.

Table VIII (a)
Average amounts of materials charged during the scrap and pellet charged heats

	Heats with pellets	Heats without pellets
Hot metal, t	96 5	100.5
Scrap +pellets, t	35.5	23.0
Scrap + pellets, kg/t h.m.	36.5	23.0
Ore kg./t h m	22.0	30.0
Pellets, t	12.6	—
Pellets, kg/t h m.	131.0	—
Lime, kg/t h m.	72.5	68.0
Fluorspar or Colemanite*kg/t lime	75.0	57.0

*Colemanite is a hydrated calcium borate which is sometimes used instead of spar,

Table VIII (b)
Average hot metal analysis and temperature and the respective standard deviations

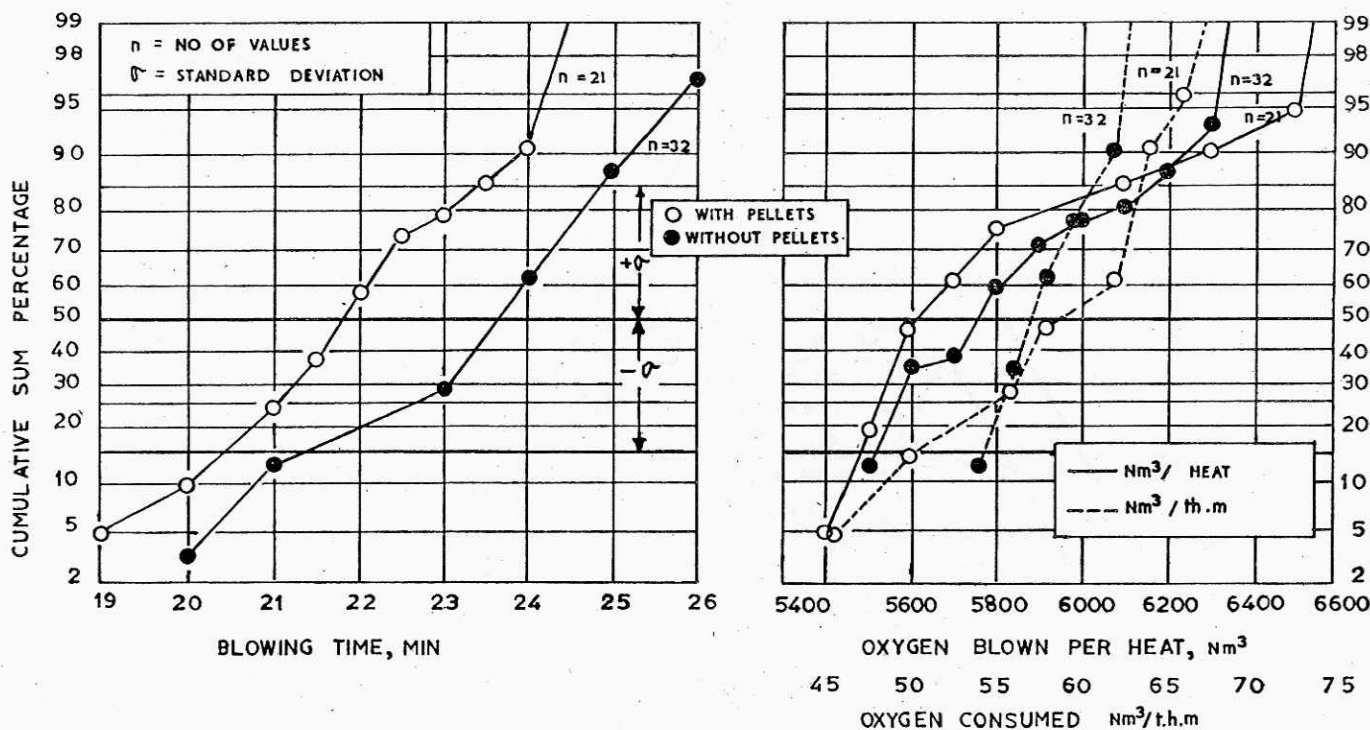|	Heats with pellets		Heats without pellets	
% Carbon	4.26	±0 26	4.25	±0.20
% Silicon	0.62	±0.15	0.72	±0.16
% Mangan se	0.73	±0.05	0.70	±0.08
% Phosphorus	0.16	±0.03	0.14	±0.02
% Sulphur	0.014	±0.008	0.016	±0.004
% Nitrogen	0.0042	±0.0012	0.0050	±0 0016
Temperature °C	1320	±16	1324	±13

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Fig. 4—Cumulative frequency distribution of the blowing time and the oxygen consumption

Although this explanation based primarily on a delay in the dissolution of the pellets is purely hypothetical, it is supported by substantial evidence. In some of the heats with Purofer pellets which were ultimately not taken into consideration, upto 3 tonnes of pellets were found at the bottom of the converter after the metal was tapped. It is worth stressing that scrap normally melts before 25% of the blow is complete, even in the case of large 380-tonne converters where about 100 tonnes of scrap are charged. Therefore, the extent of circulation within the BOF can certainly be regarded as adequate and the presence of pellets at the end of the blow cannot be ascribed to an inherent lack of turbulence. As a matter of fact, in many of the pellet charged heats, samples taken midway through

Fig. 5a—Cumulative frequency distribution of the total iron oxide content of the converter slag.

the blow clearly showed the presence of undissolved pellets embedded in a slag matrix. It may, therefore, be assumed that this layer of slag around the pellets encouraged the growth of pellet clusters and impeded their dissolution.

Table IX

Average bath analysis and its temperature at the end of the blow together with the respective standard deviations.

	Heats with pellets		Heats without pellets	
% Carbon	0.04	±0.01	0.06	±0.02
% Manganese	0 10	±0.05	0.15	±0.05
% Phosphorus	0.009	±0 003	0.011	±0.003
% Sulphur	0.013	±0.010	0.015	±0.005
% Oxygen	0.070	±0.013	0.063	±0.011
% Nitrogen	0.0021	±0.0009	0.0017	±0.0004
Temperature °C	1622	±24	1628	±18

Many of the low sulphur steel heats also demand good control over the removal of manganese. The relationship between the iron contents of the slag and the manganese partition coefficients plotted in Fig. 7 shows that at corresponding slag compositions, the efficiency of manganese removal was identical for both scrap and prereduced pellet charged heats. The lower manganese contents at the end of the blow with pellets (refer to Table IX) were a direct consequence of operation with higher iron bearing slags. Similarly, it may be seen from Fig. 8, that the higher iron content of the slag was also responsible for the lower turndown phosphorus contents in the same heats. In fact, Fig. 8 indicates that while the partition of phosphorus bet-
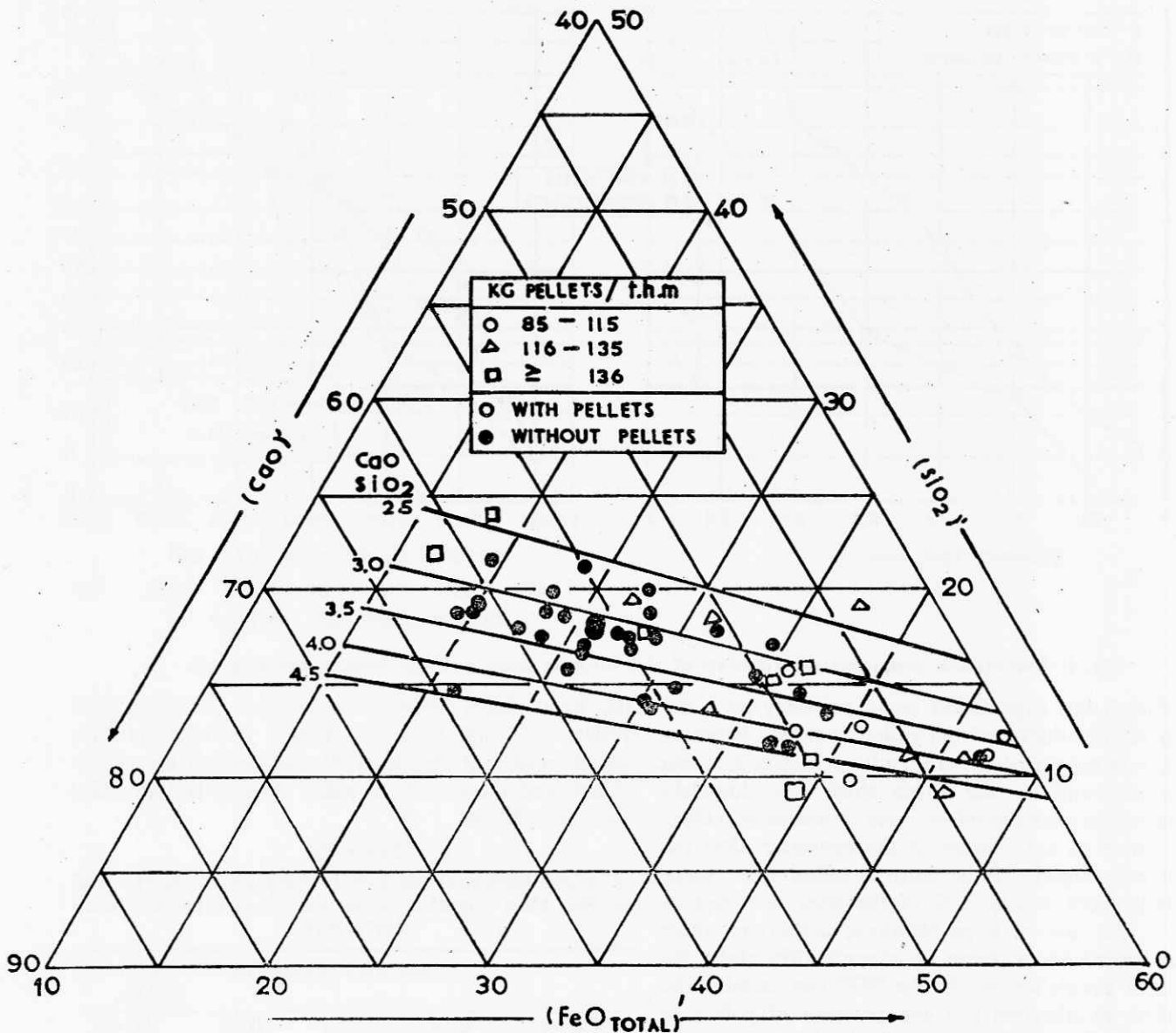
Fig. 5b—Composition of the converter slags shown in the CaO'-FeO' SiO'₂ ternary diagram.

ween the slag and the metal improved in both cases with an increase in either the basicity of the slag or its iron content, the phosphorus partition coefficients were somewhat lower for the pellet charged heats under corresponding conditions. This may again be taken as an indication of the effectively lower slag fluidity in the case of the Purofer heats.

The results on the removal of sulphur provided outstanding evidence that the charging of pellets definitely decreased the refining capacity of the slag. In Fig. 9, the sulphur contents of the last converter samples are plotted as a function of the initial sulphur in pig iron for various ranges of slag basicities. As shown in Table X(a), in achieving low final sulphur contents in steel, the use of Purofer pellets was distinctly advantageous when the sulphur content in hot metal was between 0.008 and 0.015%. This was because of the lower sulphur input through pellets (0.004 to 0.008 per cent)

compared to scrap (0.020 to 0.030 per cent). However, Table X(b) illustrates that in the range of sulphur concentrations in hot metal btween 0.016 and 0.033 per cent, the situation was reversed and scrap cooled heats finished lower in sulphur. This implies a change in the relative importance of the roles played by the total sulphur input into the converter and the partition of this element between the slag and the metal during the blow. At low sulphur contents in pig iron, the extremely low input through Purofer pellets was the dominant factor and low turndown sulphurs in the bath could be attained even when negligible amounts of desulphurisation occurred. At higher percentages of sulphur in pig iron, substantial amounts of this element had to be transferred to the slag if the bath was to be desulphurised. In the latter case, the use of pellets was disadvantageous since the presence of solids in the slag hindered efficient partition
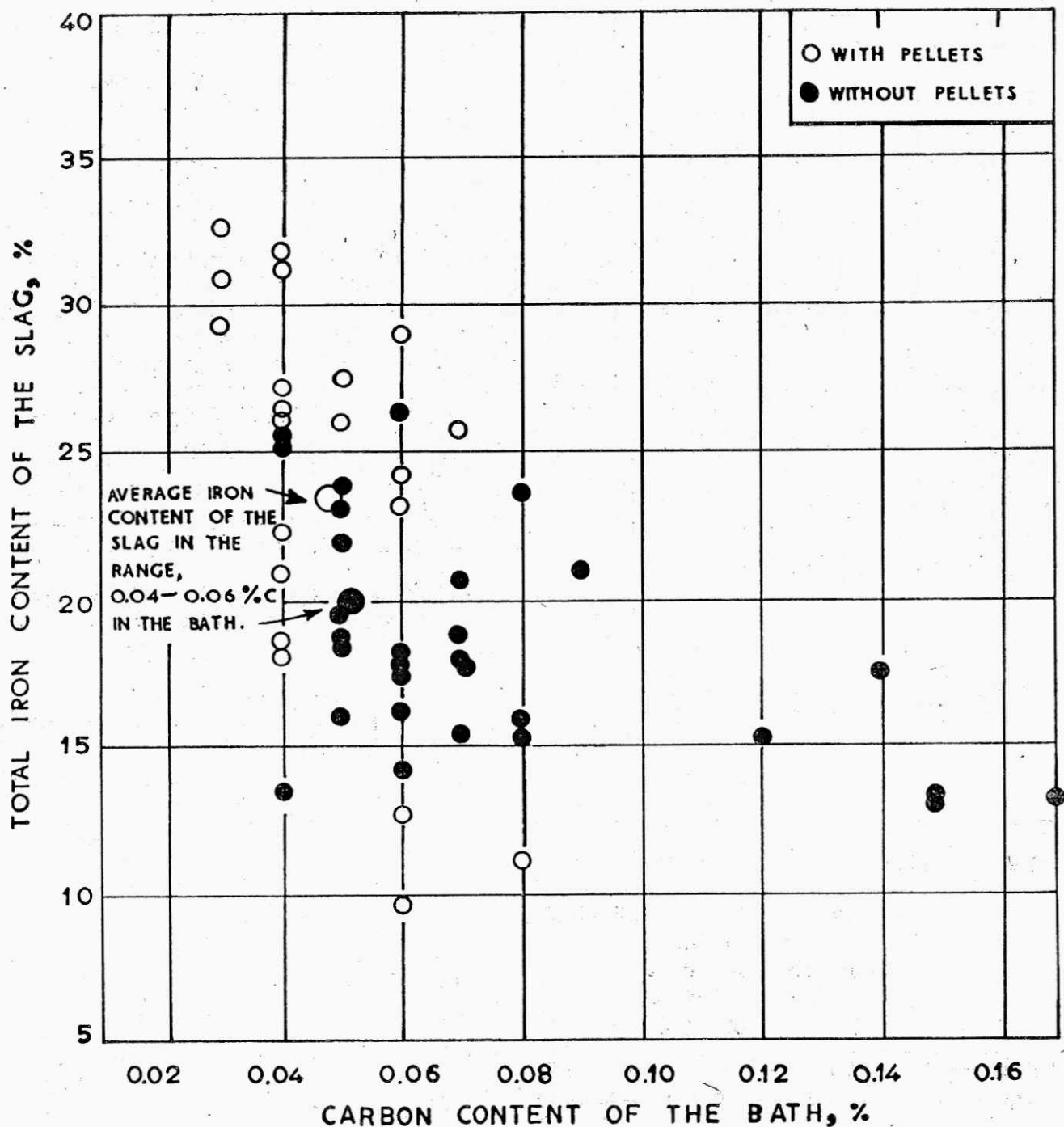
Fig 6— Relationship between the carbon content of the bath and iron content of the slag.

between the bath and the slag. Fig. 10 confirms that for the experiments reported here, the sulphur partition coefficients were actually between 1.0 to 1.5 points (20 to 25%) lower for Purofer charged heats over the entire range of slag basicity. In the range of slag basicities between 2.5 to 4.5, the ratio of the partition coefficient to the slag basicity varied between 1.5 to 1.8 for the pellet charged heats compared to 1.8 to 2.2 for the heats blown with scrap.

A sulphur balance may also be set up to verify the proposed explanation. By assuming typical concentrations of sulphur in the known amounts of pig iron, pellets or scrap to be charged and by arbitrarily assigning typical sulphur partition coefficients to each case,
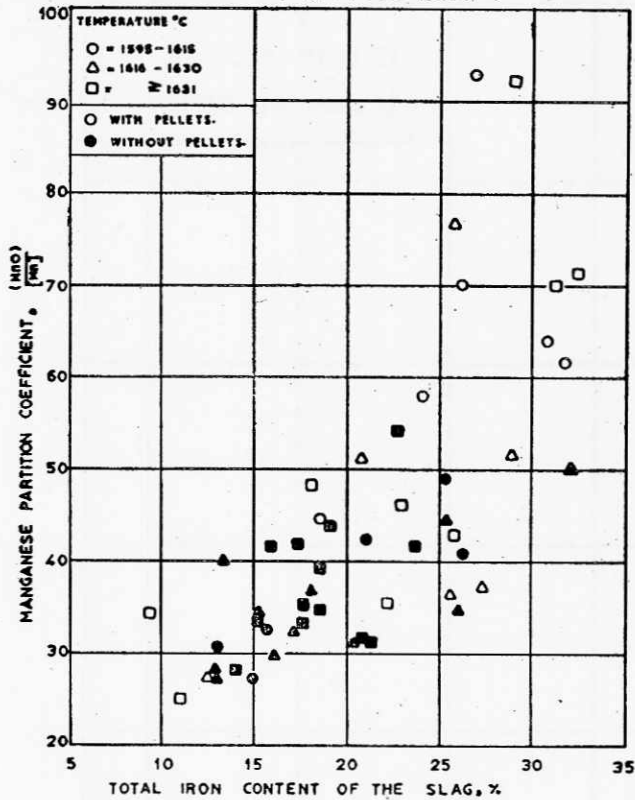
Fig. 7 — *Influence of the iron content of the slag on the partition of manganese.*

Table X

Comparison of the sulphur contents of the finished steel

(a) % sulphur in hot metal between 0 005 and 0.015

	Average % Sulphur in hot metal (S_{hm})	Average % Sulphur in bath at the end of the blow (S_c)	$\triangle S = S_{hm} S_c$
Pellet charged heats	0.011 (1)*	0.010 (2)	+0.000(9)
Scrap charged heats	0.010 (8)	0.015 (0)	—0.004(2)

(b) % sulphur in hot metal between 0.016 and 0.033

	Average % Sulphur in hot metal (S_{hm})	Average % Sulphur in bath at the end of the blow (S_c)	$\triangle S = S_{hm} S_c$
Pellet charged heats	0.022 (6)	0.020 (6)	+0.002(0)
Scrap charged heats	0.019 (2)	0.015 (6)	+0.003(6)

*The parenthesis indicates that the last place of decimal is only approximate.

it is possible to obtain Fig. 11. It will be seen that as long as the sulphur in the hot metal is below 0.028%. heats cooled by scrap containing 0.020% sulphur finish higher in sulphur than heats charged with pellets containing 0.008%, although the relevant partition coefficients are 6.5 and 5.0 respectively. Above this concentration, lower final sulphur contents can be achieved in the case of scrap charged heats where the partition coefficients are higher. Although the exact percentage of sulphur in the hot metal at which the accent would shift from lower input to better partition would vary as shown in Fig. 11 according to the initial conditions chosen; nevertheless this figure qualitatively illustrates that to take the fullest advantage out of prereduced pellets, it is imperative to ensure the availability of low sulphur hot metal. Fig 11 also predicts that below 0.010% sulphur in pig iron, scrap charging would almost invariably give rise to a pick-up of sulphur by the bath, while in the case of pellets a limited amount of desulphurisation could take place. This again confirms the experimental results presented in Fig. 10.

Fig. 12 shows that one distinct disadvantage of using pellets was the lowering of the metal yield by about 1% which may well be explained on the basis
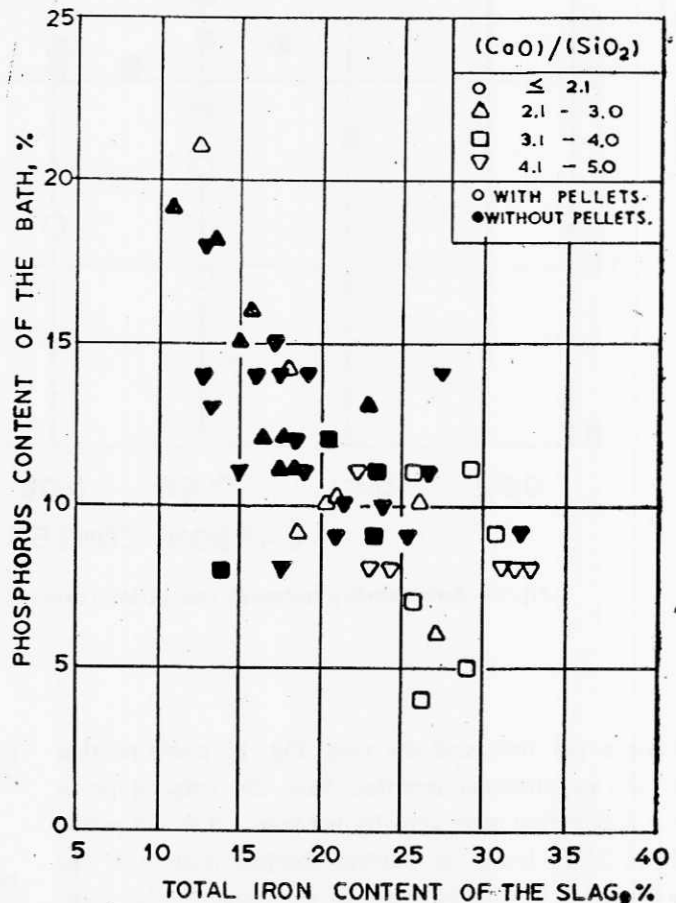

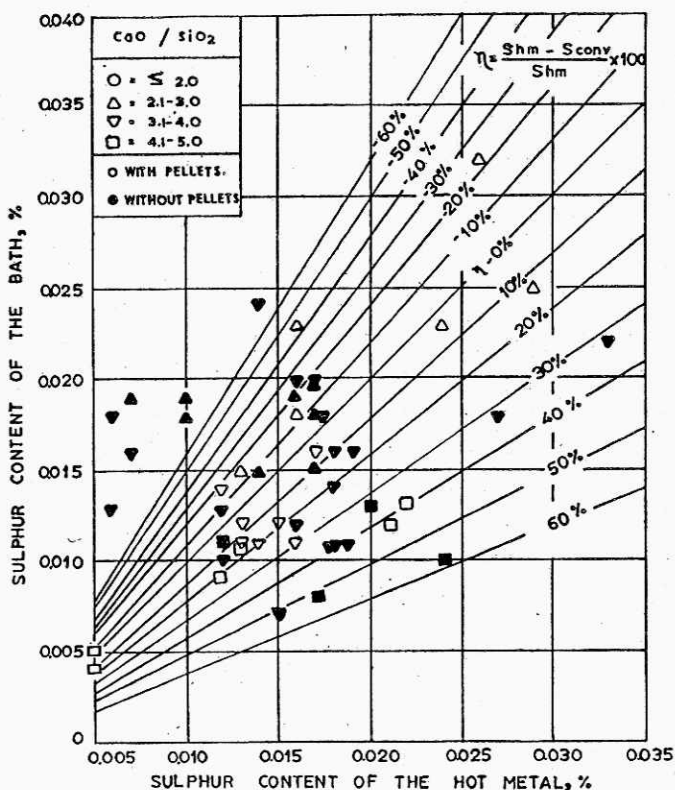Fig 8 — Dependence of the phosphorus content of the bath on the iron content of the slag (Series I).

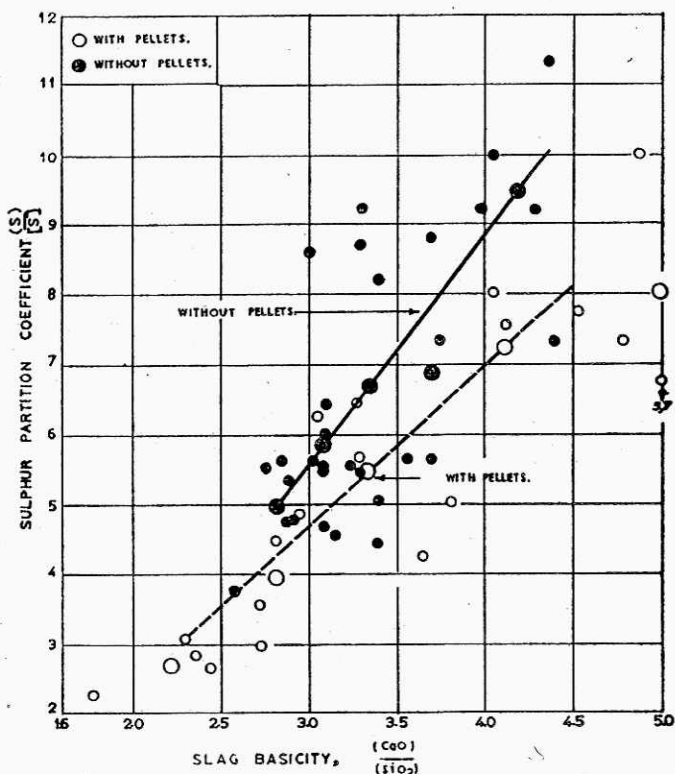Fig. 9—Sulphur percentage in the liquid steel as a function of sulphur in the hot metal.

Fig. 10—Variation in the sulphur partition coefficient with slag basicity.

of the higher slag volume and the resulting higher losses of iron in the slag as was outlined in the theoreitcal calculations presented in Table VI. In addition, during the trials it was observed that converter slopping increased markedly when the Purofer charged heats were blown. The operators shared this view but were willing to accept this problem because of the other advantages arising out of the use of pellets.

Since low sulphur steels generally require low nitrogen contents as well, the effect of charging pellets on nitrogen removal from the bath was studied in detail. Fig. 13 indicates that the extent of removal of nitrogen remained unaltered which substantiates the finding that the rate of decarburisation was almost the same during both sets of experiments.

Series II: This series of trials(2) was again carried out with Itabira pellets, but the pellets were charged through a bunker (with the converter in the vertical position) during the blow. It may be mentioned tha this is the normal way in which ore is added for cooling purposes in the case of scrap charged heats. In the fifteen heats blown in this manner, the amount of pellets used varied between 2 to 17.5 tonnes per blow corresponding to 17 to 180 kg per tonne of hot metal charged. A separate series of normal scrap charged heats were also blown for comparison purposes. In all these heats, metal and slag samples were taken both at the termination of the first blowing period and at the conclusion of the blow.

Generally speaking, no difficulty was experienced either in charging the pellets or in controlling the progress of the blow. However, the 2% silica in the pellets once again had to be fluxed with 60 kg of extra lime per tonne of pellets charged. This was over and above the 65 kg of lime (92% CaO) per tonne of steel tapped normally required to maintain a slag basicity of around 4. Since the slag from the normal heats contained around 50% CaO, the slag volume may be calculated as about 130 kg per tonne of steel made. The use of 20 tonnes of these low silica pellets, both in series I and II, therefore meant that the specific slag volume increased to 150 kg. This was probably the main reason why slopping increased as soon as pellets were charged and resulted in some loss in metal yield.

Fig. 14 represents the relationship between the phosphorus content of the bath as a function of the iron content of the slag and its basicity. It will be noted that at corresponding slag compositions, the addition of pellets had no effect on the removal of phosphorus. This agrees with the results obtained during the trials described in series I.

Fig. 15 demonstrates once again the advantage of using Purofer pellets in the manufacture of low sulphur steels. In this figure the individual sulphur contents of the samples at the end of each blowing period
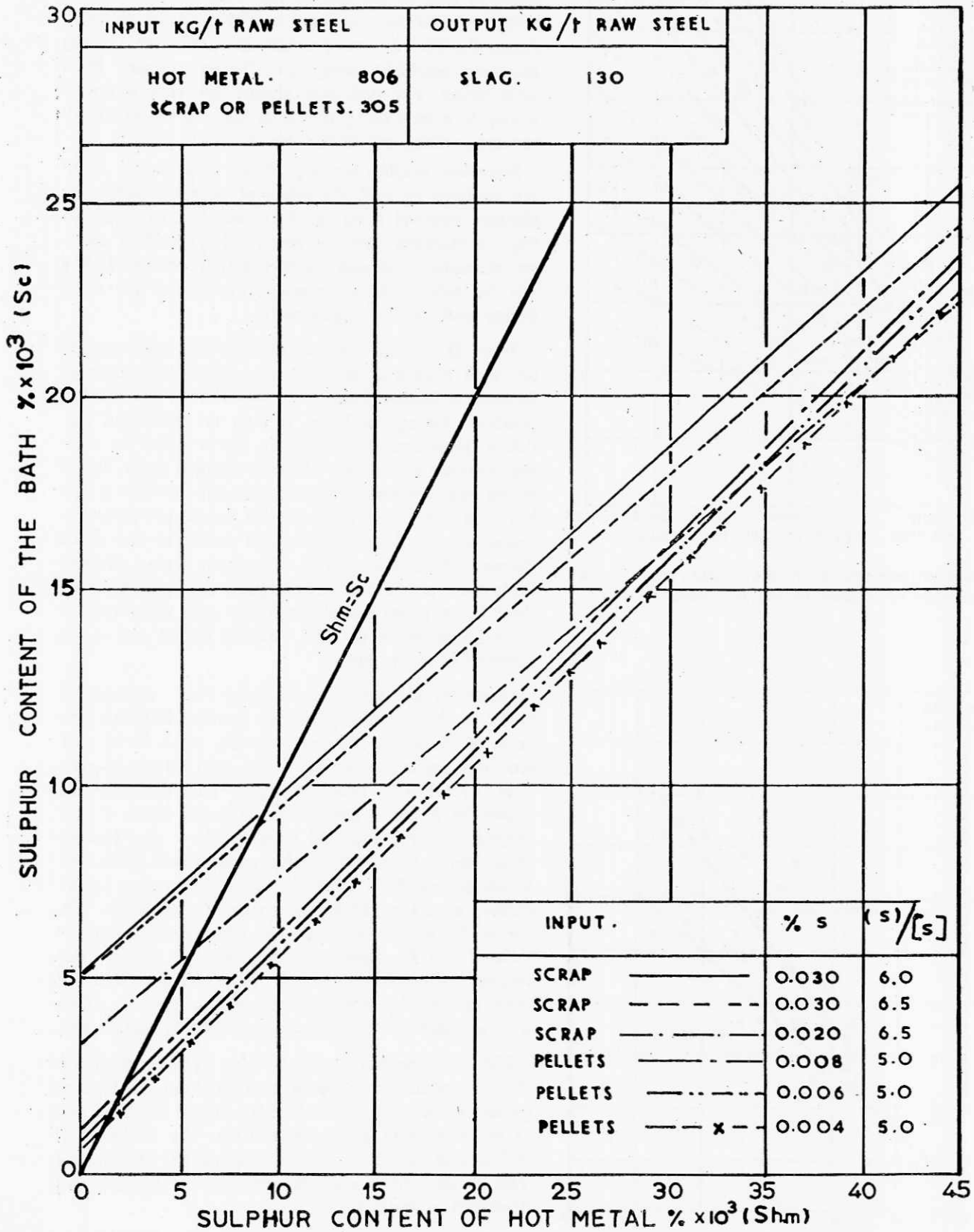
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Fig. 11—Results of sulphur balance showing the influence of the initial sulphur content of hot metal.
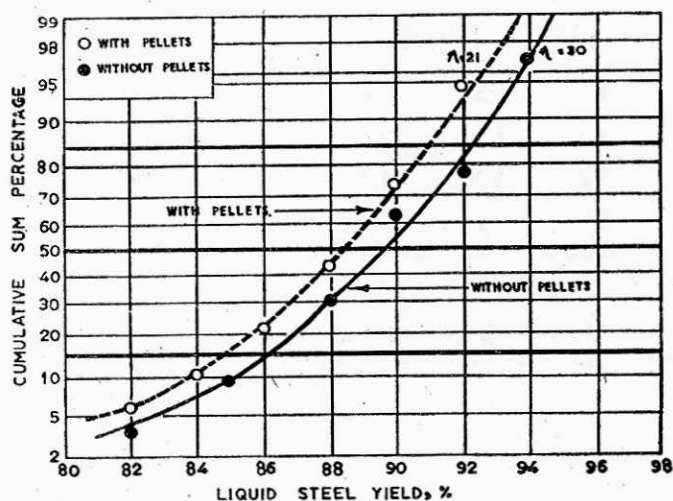
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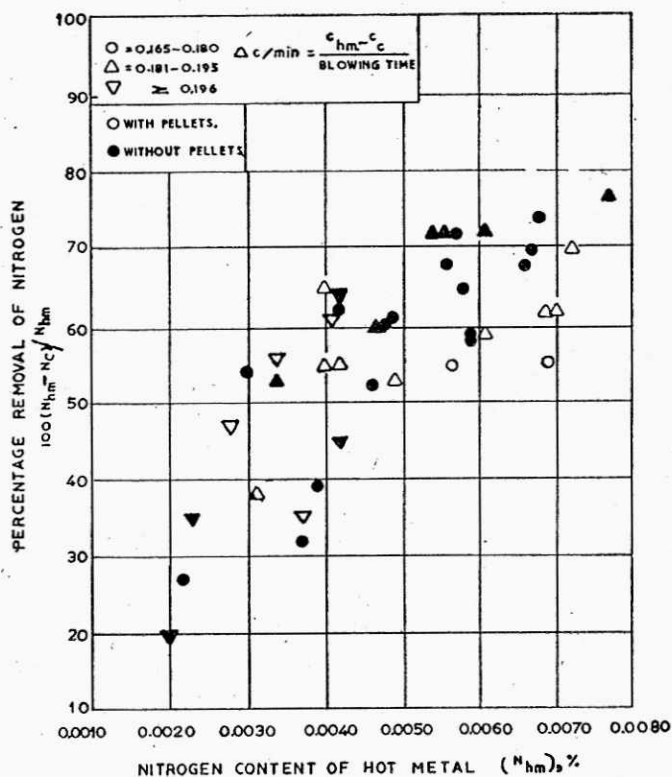**Fig. 12—Cumulative frequency distribution of the yield of liquid steel.**

Fig. 13—Influence of the nitrogen content of the hot metal and the decarburisation rate on the percentage removal of nitrogen.

have been included to indicate the direction and the change in the sulphur content of the bath in the latter part of the blow. It will be seen that a large number of the scrap cooled heats showed a higher percentage of sulphur in the finished steel than was present in the original hot metal, but this was never the case with any of the heats in which pellets were charged. This was without doubt due to the low sulphur input through the pellets. Since all these experiments were conducted with the hot metal containing relatively low percentages of sulphur, the effect of a lowering in the partition coefficient during the pellet charged heats was not much in evidence.

Series III: In this campaign (3), Carol Lake pellets containing about 6.3% SiO_2 were charged through a bunker at the rate of about 2 tonnes per minute. The total amount of pellets charged in the 24 heats blown in this manner was 335 tonnes in amounts varying between 10 and 22 tonnes per heat. In most cases, the pellets were charged before the carbon content of the bath decreased below 0.50%, the final carbon contents again being below 0.10%. One special feature in this series of experiments was the injection of lime powder in the case of heats, henceforth referred to as OLP heats, where high phosphorus hot metal was used.

To maintain a slag basicity of 4.0 with these high silica pellets, the extra lime addition should theoretically have been about 270 kg for every tonne of pellets charged. However, because of the particularly favourable composition of the pellets (0.011% P and 0.005% S), it was found that such high slag basicities were not necessary to achieve the same turndown sulphur and phosphorus contents as in the case of the scrap cooled heats. In general therefore, these heats were blown with only half the theoretically required amount of excess lime. As shown in Fig. 16. the resulting lower slag basicities affected the phosphorus contents of the bath both at the end of the first and the final blowing period, but this effect was only marginal.

The results from both the OLP and the normal BOF heats in which high silica pellets were used once again showed a lowering of the refining capacity of the slag. This is clearly manifested in Fig. 17 where the sulphur partition coefficients are shown as a function of the basicity of the slag. The performance of Carol Lake pellets was identical in this and all other respects to that described for Itabira pellets in series I & II.

Conclusions

On the basis of these trials it is possible to conclude that:—

(1) Prereduced pellets can be used to replace the scrap normally charged in oxygen steelmaking processes. Whether pellets are charged before or during the early stages of the blow does not influence the converter performance but to avoid reoxidation, it is important to reduce the period for which the pellets are exposed in the open prior to charging to a bare minimum.

(2) In the manufacture of low carbon steels, the final carbon, phosphorus, manganese, oxygen and nitrogen contents of the steels tapped would be approximately the same for pellet as well as for scrap charged heats.
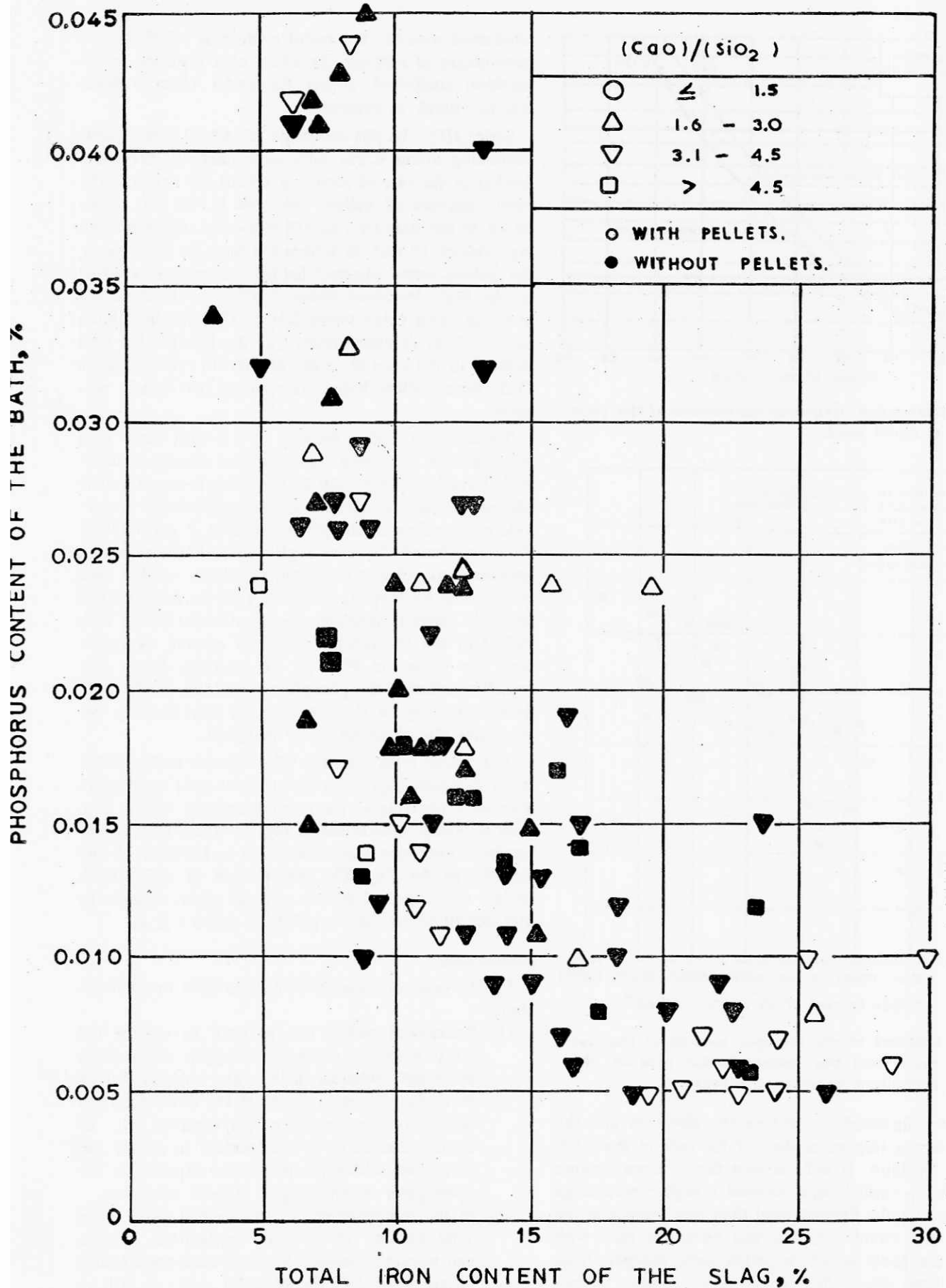
Fig. 14—Relationship between the iron content of the slag and the phosphorus content of the bath (Series II)
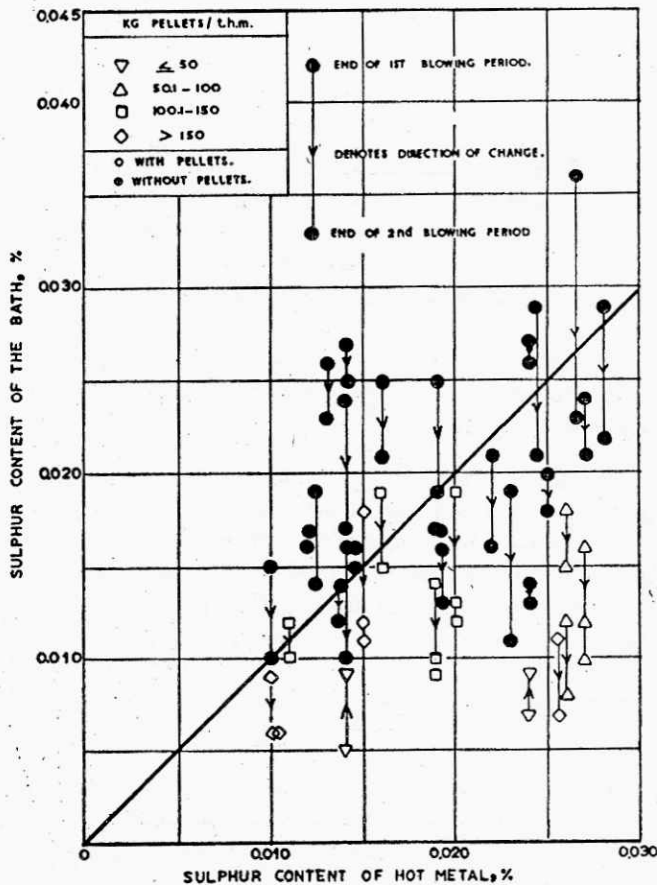
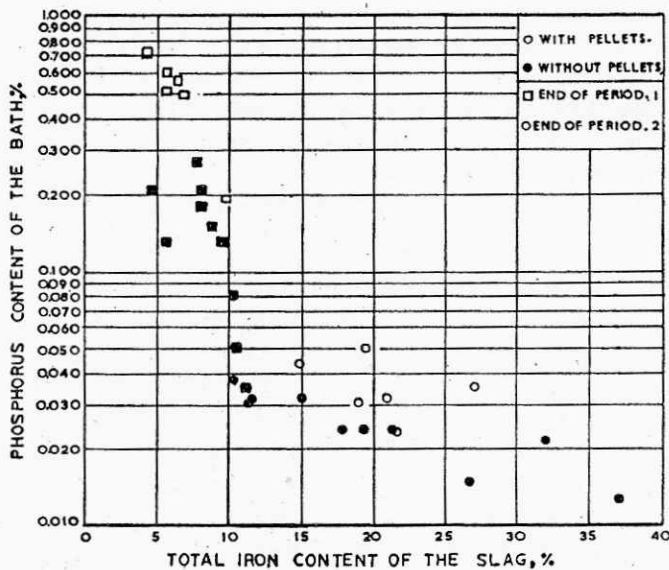Fig. 15—Change in the sulphur content of the bath during the second blowing period.

Fig. 17—Comparison of sulphur partition coefficients with and without pellets for BOF and OLP heats.

Fig. 16—Relationship between the iron content of the slag and the phosphorus content of the bath (Series III)

(3) The use of pellets, necessitates the use of additional amounts of lime to maintain the slag basicity normally required for efficient refining. This increases the slag volume.
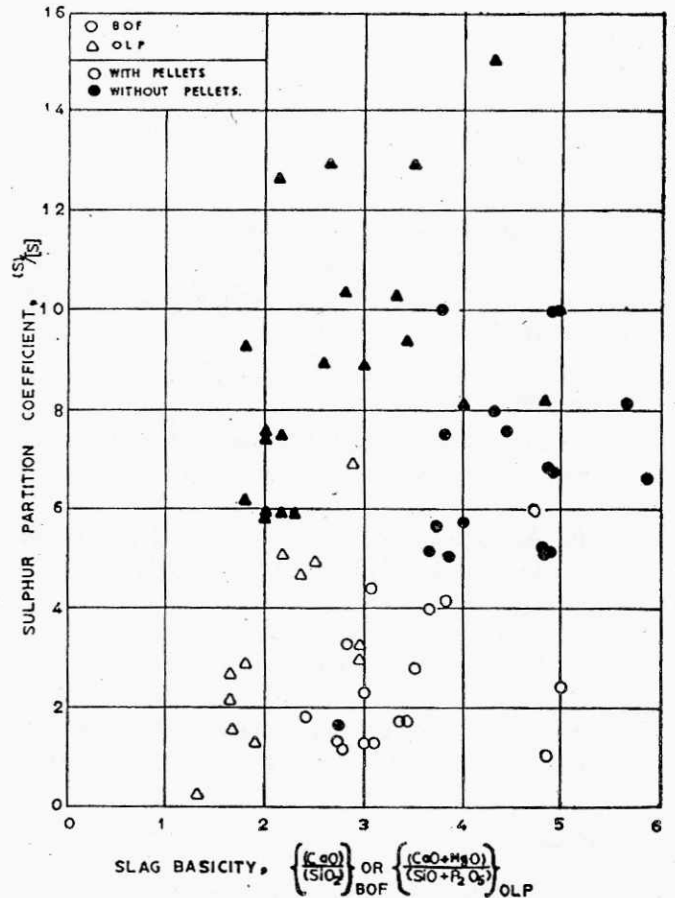
(4) Charging of prereduced pellets is accompanied

by an increase in converter slopping and the resulting loss in the yield of liquid steel is about 1%

(5) Pellets tend to remain undissolved fairly long after the commencement of the blow because they cluster together to form aggregates insulated by molten slag. The presence of such undissolved pellet clusters lowers the refining capacity of the slag which may affect the removal of the metalloids unless the converter is operated with a slag containing a higher percentage of iron than is the case of scrap charged heats. This of course, would have a deleterious effect on the converter yield and the consumption of refractories.

(6) For the production of very low sulphur steels, pellet constitute an ideal substitute for scrap. In such cases, however, it is essential to use low sulphur hot metal to extract any benefit from the pellets.

(7) At times when scrap prices are high, the metallurgical benefits arising out of pellet charging could also be supplemented by a saving in the cost of steel production. However, at all times, it is more economic to use pellets with as low a content of silica as possible.

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Acknowledgement

The author would like to take this opportunity to thank Dr. Ing. F. Winterfeld and his colleagues at August Thysen-Hutte AG for their cooperation during this work.

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Discussion

Dr. S. R. Pramanik, (Hindustan Steel Ltd., Ranchi) · I would like to know the comparative performance data while using sponge iron vis-a-vis iron ore as replacement to the scrap in B.O.F. practice.

Dr. Amit Chatterjee (Author): No comparative data is available as such, but some inferences can be drawn from our experience in Germany with 100% ore and sponge iron cooled heats.

Firstly, ore cools about 3.0 to 3.5 times as much as scrap; while in the case of sponge this figure varies between 1.0 and 1.1. Secondly, 100% ore cooled heats are notoriously difficult to control even if the ore is added in small doses continuously through the blow. In the case of sponge iron, our experience was markedly different in that the heats could be controlled as well as scrap charged heats and the slopping tendency. though understandably somewhat more than what it is with scrap charged heats, was nowhere near as much as what it is with 100% ore cooled heats.

The crux of the difference between sponge iron and iron ore lies in the fact that good sponge can be looked upon as very poor grade scrap with 90 to 95% metallic iron; while in the case of ore, the iron is almost exclusively in the oxidised state and carries a lot of gangue material along with it.

Mr. S. Samarapungavan (Bhilai Steel Plant, Bhilai): Due to quality of refractory lining and higher Si in hot metal the lining life of B.O.F. in India is already low, resulting in low furnace availability. Use of pre-reduced pellets with even 25% SiO_2 as mentioned by the author could have further deleterious effect on lining life. Could the author elaborate the experience in this respect during experiments in Germany as compared to scrap charging?

Dr. Amit Chatterjee (Author): There is no reason to believe that the use of sponge iron containing 2% or even 6% silica would bring down the lining life of BOF's if enough lime is added to flux the silica. Our experience in Germany showed that the lining life in the case of a campaign in which the majority of the heats were cooled with sponge, was no different from the normal campaigns in which heats were cooled with scrap and ore.

BOF lining life in India is low primarily because of the reasons you have given. I feel confident that the use of sponge iron would not adversely affect this already low lining life.

Mr. R. D. Gupta (National Metallurgical Laboratory, Jamshedpur): In normal steel making pratice of basic oxygen converters the use of steel scrap serves two functions: (i) Utilising the heat in the bath which has been blown to high temperature and (ii) Relieving the stress on refractories by chilling the bath. I do not think, the use of pre-reduced pellets, which have a much lower density than steel, will serve the above functions. Could the author please enlighten us on these points based on his experience.

Dr. Amit Chatterjee (Author): Your assumption that pre-reduced pellets would not fulfil the two functions you have stated, is incorrect. As outlined in my paper, the cooling efficiency of pellets is just as good if not better than scrap. However, it is not for the cooling effect alone that scrap is normally charged in the BOF. If that were the case, ore or even limestone would be used because these substances cool far more efficiently than scrap. Scrap cooling is generally preferred because not only can the bath be cooled but the blow also can be controlled. From this point of view, scrap and sponge can be considered a synonymous once adequate measures are adopted to ensure that the pellets dissolve in the bath in the early stages of the blow.