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DIVERSIFICATION OF ENERGY SOURCES
FOR THE BLAST FURNACE :
THE DOUBLE INJECTION PROCESS^{1/}

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S U M M A R Y

The best blast furnaces in the world are at present working with about 380 kg of coke per tonne of hot metal and 100 kg of fuel oil per ton of hot metal. Since there appears to be a limit to the amount of fuel oil that can be injected, other means have to be investigated to decrease this very expensive coke rate in the blast furnace.

The double injection process, which consists of simultaneously injecting fuel oil at the level of the main tuyere and reformed gas into the bosh, makes it possible to reduce this coke rate, so long as the effects of the injections are additive.

After successful experiments on the AIRFO furnace (hearth diameter 1.4 m), where 285 kg of coke per tonne of hot metal were replaced by the double injection process, some trials were carried out on the No. 3 furnace of Seraing E Works of Cockerill SA (450 t hot metal per day, 4.6 m hearth diameter).

With 615 kg/t hot metal without injection, the coke rate dropped to 436 kg/t with the injection of 428 Nm³ reducing gas per tonne of hot metal in the bosh (mainly H₂ + CO) and 78 kg fuel oil per tonne of hot metal. The replacement ratio of the reducing gas is situated at about 0.25 kg coke per Nm³ of reformed gas. The reformed gas was obtained by catalytic steam reforming.

Lack of time and of reducing gas made it impossible to inject more than those quantities over a sufficiently long period; 600 m³ reformed gas and 150 kg per t hot metal should be an attainable objective, reducing the total coke rate by 300 kg. The productivity of a given furnace should also be increased by about 25% through the injection into the bosh of reformed gas.

Reducing gas can be obtained easily from natural gas, propane, butane, naphtha, coke-oven gas, etc. In the future methods will be developed to obtain it at a reasonable cost from fuel oil and coals.

At this time, the blast furnace will have great flexibility, using coke (in due course formed coke), reducing gas from different sources injected into the bosh, and fuel oil injected at the main tuyeres.

Introduction

The rapid increase in the price of coking coals during the last few years forms the basis of two questions that confront the ironmaker :

1. To what limit can coke consumption in the blast furnace be reduced by the substitution of it by other fuels such as natural gas, liquid hydrocarbons, or formed coke ?
2. Is it possible economically to replace the conventional blast furnace - LD steelmaking route by the direct reduction - electric arc furnace route ?

Many studies have been made to try to answer these two questions, and the subject is far from being exhausted. There is, moreover, no answer that is universal in application to the second question, because local economic conditions play a major role.

It is for this reason that countries possessing large deposits of natural gas but not of coking coal find it better to make steel by the route using direct reduction based on natural gas followed by electric steelmaking. In this respect, the case of Mexico is typical.

Outside such special situations, the problem is more complex to resolve. It nevertheless would appear that when the various sources of energy available to a country are not abundant and have to be imported, or when an integrated iron and steel industry of the conventional type is already in existence, the traditional route, with certain improvements, is often more viable for outputs of over 0.5 million tonnes of crude steel per year (1).

It should also be added that, in the category of solid fuels needed for the operation of blast furnaces, account must be taken in the medium term of formed cokes made from non-coking coals which, as is well known, are very abundant throughout the world.

Moreover, it is apposite to emphasize the fact that the best furnaces in the world do not use more than about 370 kg of metallurgical coke per tonne of pig iron, with an additional 100 kg of fuel oil (or the equivalent in natural gas), employing, admittedly, certain techniques which have now become conventional.

Among the latter one may, in order to orientate oneself, include careful burden preparation, low slag volumes, high blast temperatures

(1) The manufacture of steel directly from scrap has been excluded from this paper, which is concerned solely with manufacture from ores.

(1250-1300°C), high top pressure, blast enrichment with oxygen to increase the amount of auxiliary fuel introduced through the main tuyeres, etc.

Faced with restrictions of various kinds, the blast furnace operator has considered the possibility of using new methods, among which may be quoted the introduction above the main tuyere level and in the bosh of a hot reducing gas.

Using this new technique it should be possible to reduce the coke rate to about 250 kg per tonne of pig iron and perhaps even lower, at the same time increasing the productivity of the furnace.

This means that there is a diversification of energy sources, which will make the blast furnace more independent of its sources of supply than the direct reduction processes. This is a very important element of security which will have to be taken into consideration in the future.

The object of this communication is principally to prove the validity of this statement by presenting the results of recent trials of the injection of reformed gas into the boshes of a blast furnaces, at the same time continuing to inject fuel oil or other fuels at the main tuyere level. This new technique has been called the "double injection process."

Some Theoretical Considerations

At the outset, it must be emphasized that in present-day blast-furnace operation on modern furnaces, which are characterised, as mentioned above, by coke rates of less than 400 kg per tonne of pig iron, the amounts of reducing gas passing through the tuyeres and through the mineral burden are inadequate to bring about complete reduction of the iron oxides.

Large amounts of wüstite (FeO_x) have to be reduced by a process of "direct reduction" using "solution-loss" carbon and therefore by definition large amounts of heat.

The two following equations are involved :



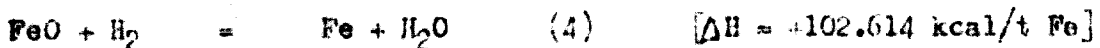
which produce together the wrongly entitled "direct reduction" equation* :



* In the "direct reduction" processes, reactions of the type shown in equations (2) or (4) preponderate. Blast furnacemen call these reactions "indirect reduction". Care must therefore be taken to avoid confusion and ambiguity.

If we succeed in reducing the wüstite completely according to reaction (2) at a low enough temperature level for CO₂ not to be produced in the hottest zones (e.g. above 1100°C), we shall have avoided the solution loss equation (2) and thereby taken a step forward.

This first reaction will also be avoided if reduction takes place according to the formula



Theoretically, injection into the bosh of a blast furnace of hot (900-1000°C) reducing gases, consisting essentially of H₂ and CO, should make it possible to reduce iron oxides completely according to equations (2) and (4) and to avoid the solution loss of equation (1), that is to say, to "lower the coke rate", by definition.

The yield of the operation is, however, limited by chemical equilibria, at 1000°C for example. Below this temperature, in fact, the reaction kinetics of wüstite reduction becomes lower.

This yield is at a maximum of :

$$\frac{\text{CO}_2}{\text{CO} + \text{H}_2\text{O}} = 0.28 \quad (5) \quad \text{for CO}$$

and

$$\frac{\text{H}_2\text{O}}{\text{H}_2 + \text{H}_2\text{O}} = 0.41 \quad (6) \quad \text{for hydrogen.}$$

In practice, the wüstite reduction yield does not attain this ideal level, but generally reaches a value lying between 80% and 95% of the maximum. The maximum ratios given above should therefore take account of this variation from the ideal.

Another important theoretical consideration must also be considered : the productivity of modern blast furnaces is usually limited by the constrictions that form in the lower zone and which result in a counter-current circulation of the rising gases and the descending liquid masses. The injection of reducing gases at the bosh level reduces the amount of gases rising from the tuyeres. According to our theoretical formulae that we have used, this can lead to the possibility of an increase in productivity of more than 25% when about 600 m³ of reducing gases are injected per tonne of pig iron. Industrial confirmation of this possibility is thus fundamental.

Blast furnace trials, both experimental and industrial scale, using materials that had already been prerduced, have shown that this technique makes it possible to achieve very low coke rates and considerable increases

Decrease of coke rate and increase of production (%)

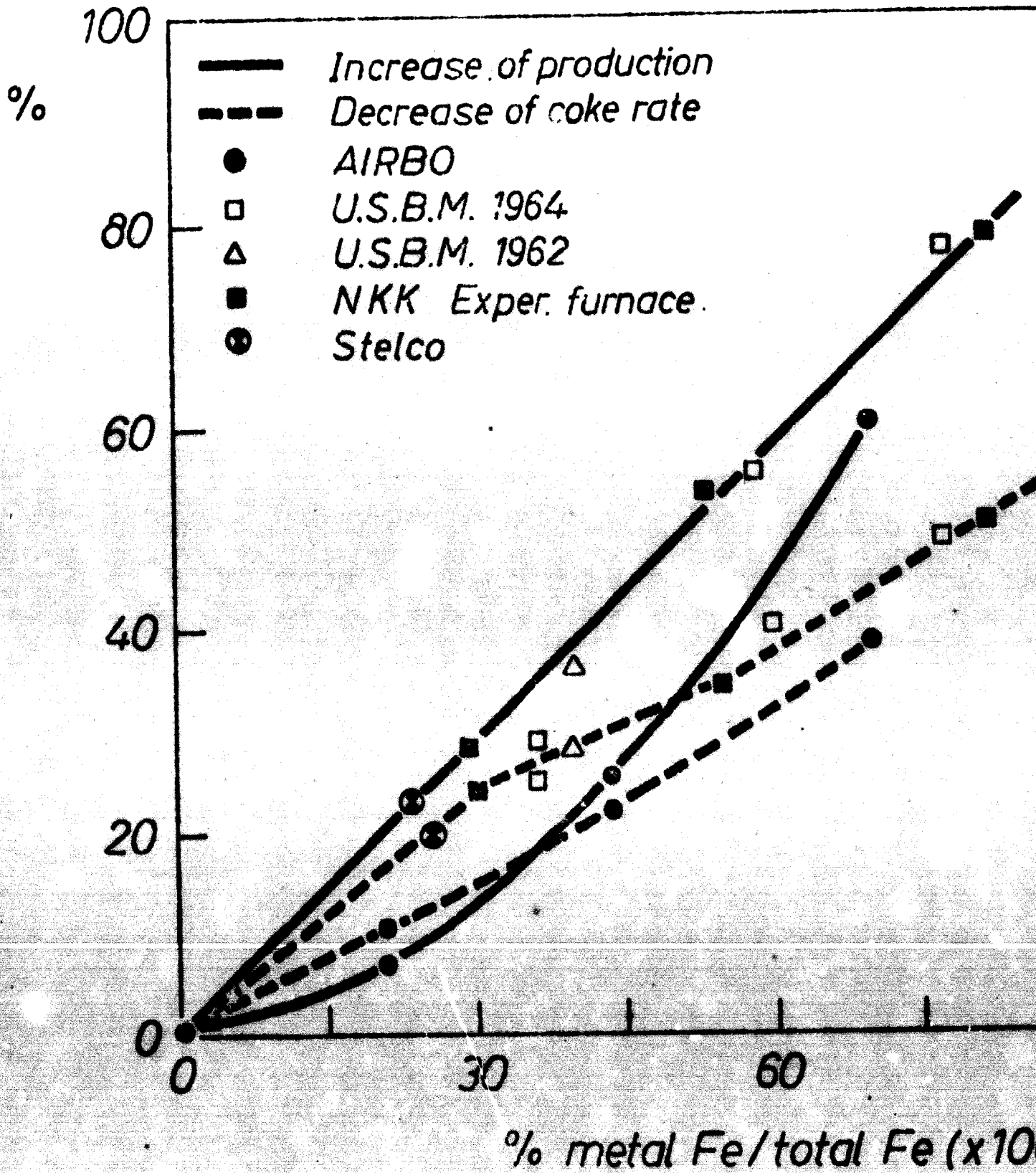


Fig. 1 - Evolution of the coke rate and of blast furnace productivity as a function of the metallic iron charged at the top

in productivity (Fig. 1). Our theoretical observations are thus confirmed indirectly.

Unfortunately, the very high cost of prerduced materials makes this technique inapplicable in most cases.

If the double injection process proves to be successful on an industrial scale - and we have no reason to doubt that it will - the prerduction or "direct reduction" will be carried out in the blast furnace itself, which will represent a substantial saving in heat and thereby of coke.

In other words, we shall combine the advantages of the so-called "direct reduction" processes with those of the blast furnace, which is, it should not be forgotten, the iron and steel making apparatus with the best thermal yield.

Summary of Trials on the Ougrée Experimental Blast Furnace (AIRBO)

During 1970, AIRBO (Association Internationale pour les Recherches de Base au Haut Fourneau d'Ougrée), in collaboration with CRM and with the financial assistance of ECSC (European Coal and Steel Community), IRSIA (Institut pour l'Encouragement de la Recherche Scientifique dans l'Industrie et l'Agriculture), and of iron and steel making companies of the Community, and Sweden, with one Canadian company, carried out preliminary trials to check the validity of the theoretical considerations described briefly above and to quantify the coke replacement rate that had been evaluated with the aid of simulation models.

To manufacture the reducing gas needed, we chose for reasons of convenience the partial oxidation of Dutch natural gas with pure oxygen. The studies for this and the construction of the necessary plant were in the hands of Shell International.

The experimental furnace (1.4 m hearth dia., 8 m³ working volume, five blast tuyeres) was equipped with five Shell "reactors", and the five reducing gas injection nozzles were sited 1.7 m above the main tuyere level (Fig. 2).

Because of several restrictions, notably the supply of pure oxygen, it was possible neither to reach the optimum operating rate of the "reactors" nor to run the furnace at a normal operating or production rate. This resulted in a slightly over-oxidized reformed gas and excessive heat losses on the blast furnace. This, however, did not

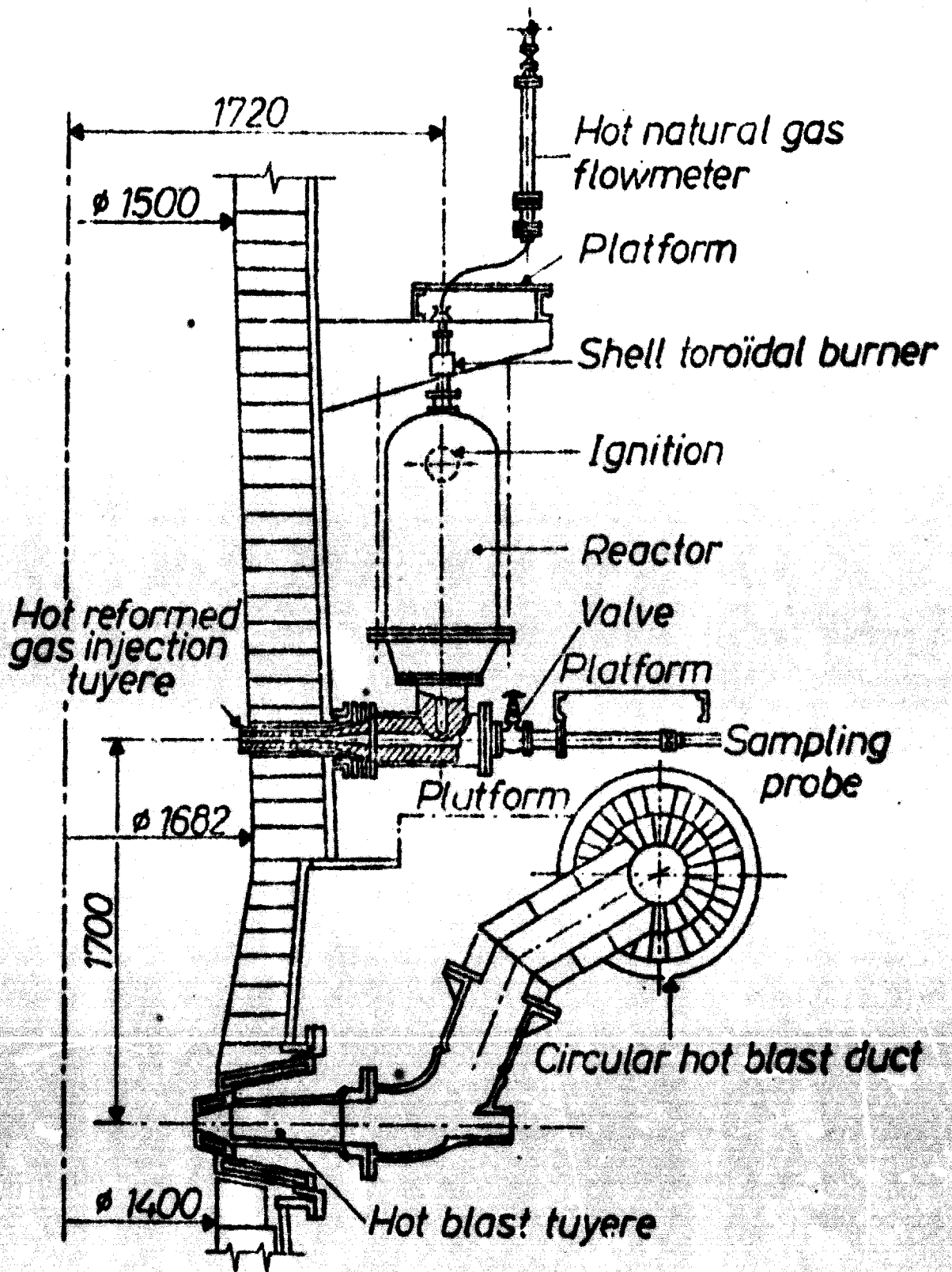


Fig. 2 - Location of the reactor

in any way hinder the performance of the trials; the only effect was that the replacement rates were lower and the residual coke consumptions were higher than one might have expected to achieve working with a better gas and at a more rapid rate.

The results of these trials are shown in Table I. They show that double injection led to an overall replacement of 28% of coke per tonne of pig iron. These results completely confirmed the theoretical predictions, both in the equivalence ratios between coke and reducing gas and the additive nature of the effects of double injection, which is very important from the operating and economical points of view.

Injection of Hot Reformed Gas and "Double Injection" on Blast Furnace No. 3 at Cockerill

Statement of the problem

At the end of the trials described very briefly above, several questions remained unanswered; they could only be resolved by trials on an industrial-scale blast furnace. These were as follows :

- the depth of penetration of reducing gases in the blast-furnace stack and their effect on the metallurgical results;
- determination of the optimum injection temperature and the effect of the reducing gas temperature on the blast furnace operation;
- the effect of a massive injection of reducing gases on burden descent;
- technological problems that might arise in applying this process on an industrial-scale blast furnace;
- the influence of the process on blast furnace productivity.

Selection and description of the blast furnace

The selection of the blast furnace for these industrial-scale trials was the result of a compromise. It had to be substantially larger than the experimental furnace at Ougrée. However, its output should not be too high in relation to the total works production, so that there could be a maximum degree of freedom in carrying out the experimental programme, without creating a disproportionate industrial crisis.

The No. 3 blast furnace of Cockerill fitted these conditions perfectly. Moreover, it had the additional advantage of being situated near a gas-reforming plant belonging to S.A. Distrigas which could be adapted to suit the requirements of the trials fairly quickly and more cheaply than would have been the case had it been necessary to build a new installation.

Thanks to the financial assistance of MCCG, IRSIA, Cockerill, Distrigaz, and CRM, it was therefore decided to carry out the new series of trials on this Cockerill furnace. The trials were performed with great enthusiasm on the part of everyone directly concerned.

The No. 3 furnace has a hearth diameter of 4.6 m and, with a well prepared burden consisting of roughly 70% agglomerated materials, 27% graded lump ore, and 3% of various additions, it is capable of producing about 450 t of pig iron per day (i.e. ten times the output of the experimental furnace), with a coke rate of the order of 600-620 kg/t with a blast temperature of 800°C.

The reformed gas, manufactured in two units with a total capacity of 8000 Nm³/h, was obtained by catalytic reforming with steam of Dutch natural gas, followed by decarbonization. The cold reformed gas contained 1.5-3% (CO₂ + H₂O) and was piped some 6 km to the Cockerill No. 3 blast furnace. In the immediate vicinity of the furnace it was heated to a temperature of 800-1000°C in a metallic tube heater, and this hot reformed gas was injected through 8 tuyeres located about 4 m above the main tuyere level. The composition of the hot reducing gas was approximately 70-73% H₂, 16-18% CO, 2-4% CH₄, 12% H₂O, ± 0.8% CO₂, 6-7% N₂.

Results of the trials

Coke rate - By injecting 409 m³ of reformed gas per tonne of pig iron alone, it was possible to reduce the coke rate to 519 kg/t, which represents a reduction of 99 kg/t over the corresponding reference periods (III and IV in Tables I and II). For all the tests, the replacement rate rose to 0.23-0.26 kg of coke per Nm³ of reformed gas. Having regard to the utilization rate of the reducing gas at the wüstite level which, for the blast furnace in question and the operating conditions prevailing, is as high as 80-85%, this replacement rate corresponds well with the predicted theoretical rate of 0.23-0.25. This was then a first result.

Additivity of "double injection" - The additivity of the effects of classical injection of fuel oil through the blast tuyeres and of hot reformed gas into the bosh could also be proved. The savings in coke are identical with those obtained by adding the savings achieved by each of these injections performed separately. In fact, with 78 kg of fuel oil and 428 Nm³ of reformed gas per tonne of pig iron, the coke rate fell to 436 kg/t, as compared with 543 kg/t with the injection of 76 kg of fuel oil, which leads to an additional saving of 105 kg of coke per tonne and to a coke/reformed gas substitution ratio of 0.24. By comparing this period with that with gas injection alone, a rate for fuel oil of 1.01 is arrived at.

Results of tests		Reference	Test period
% ₀₀ coke (85%)	kg/t HM	660	375
% ₀₀ fuel-oil	kg/t HM	—	155
Reformed gas	Nm ³ /t HM	0	751
Blast temperature	°C	1020	920
O ₂ blast	%	21	±40
Blast	Nm ³ /t HM	1802	±785
Top gas temperature	°C	235	235
<u>Top gas</u>			
CO	%	24.0	36.0
CO ₂	%	15.9	17.0
H ₂	%	1.0	19.5
N ₂	%	59.1	27.5
<u>Hot metal</u>			
Silicon	%	1.00	0.95
Production	t HM/h	1248	1.85
Replacement ratio	kg coke/Nm ³ R.G	—	0.174
	kg coke/kg fuel-oil	—	1.15

Table I Results of trials with injection of reformed gas into the bosh and of fuel-oil via the main tuyeres

Test period	RG 8000	RG 8000 + FU 75	FU 75	Ref. III	RG 8000 low T ^o	RG 8000 High T ^o	Ref. IV
Reformed gas Nm ³ /tHM	409	428	-	-	393	451	-
Fuel-oil kg/tHM	-	780	75.6	-	-	-	-
Coke (800° T _v , 0.5% Si) kg/tHM	519	436	543	612	517	515	625
Blast } Temperature } °C	811	840	822	803	786	817	768
Blast } Oxygen } %	21	25.8	25	21	21	21	21
<u>i:tot metal</u>	0.42	0.54	0.52	0.54	0.52	0.46	0.51
Si	0.034	0.037	0.043	0.048	0.040	0.025	0.037
S	358	328	340	340	365	336	350
Sleg Quantity: i = CaO/SiO ₂	1.23	1.12	1.18	1.20	1.16	1.16	1.16
<u>Top gas</u> CO	234	249	255	253	229	233	258
CO ₂	14.7	150	17.5	16.3	14.7	14.7	15.5
H ₂	10.3	15.4	5.1	1.6	10.6	11.6	1.2
Replacement ratio	-	-	-	-	0.26	0.23	-
	101		0.24				

Table II Injection of reformed gas B.F.3 Cockerill-Works

Penetration of gases into the stack - Although the interpretation of the probe curves was not always easy, it nevertheless would appear to be established that the penetration of the gases is carried out in a satisfactory way and that this penetration increases as the amount of gas injected rises (Fig. 3).

Burden descent - The injection of reformed gas does not appear to have affected the burden descent which remained very regular throughout the trials.

Pig iron quality - The quality of the pig iron produced proved to be excellent throughout the whole experimental period. With $\pm 0.4-0.5\%$ Si, $\pm 1.70-1.9\%$ P, $\pm 0.50-0.90\%$ Mn, it was always very well carburized for a phosphorous pig iron (C = $3.8-4.0\%$), and its sulphur content was very low, which is a not inconsiderable advantage.

Increase in production - maximum quantities that can be injected - Unfortunately, our trials were limited by two factors. First, the amount of reducing gas coming from the reforming unit was restricted to a maximum of $8000 \text{ m}^3/\text{h}$. Secondly, the No. 3 blast furnace was restricted in terms of the means available for removing pig iron from the base of the furnace. These circumstances prevented us from studying the problems of maximum quantities of reformed gas that could be injected and of the increase in production.

Techno-economic Aspects

To appreciate the techno-economic interest of double injection, one must take account of the relative prices of fuels.

The reducing gas $\text{CO} + \text{H}_2$ does not exist as such in nature and so it has to be manufactured.

At the present time it is a simple matter to obtain it from natural gas, from coke-oven gas, and from light hydrocarbons (such as naphthas), either by catalytic reforming with steam or by partial oxidation using pure oxygen. Certainly a small proportion of CO_2 , H_2O , and CH_4 remain in the reformed gas that is manufactured. These residual fractions must be kept down to as low a level as possible, since the reduction of wüstite by the indirect route decreases very rapidly when there is an increase in the degree of oxidation of the reducing gas, defined by the formula :

$$\frac{\text{H}_2\text{O} + \text{CO}_2}{\text{H}_2 + \text{H}_2\text{O} + \text{CO} + \text{CO}_2}$$

This results immediately in the theoretical considerations set out at the beginning of this paper.

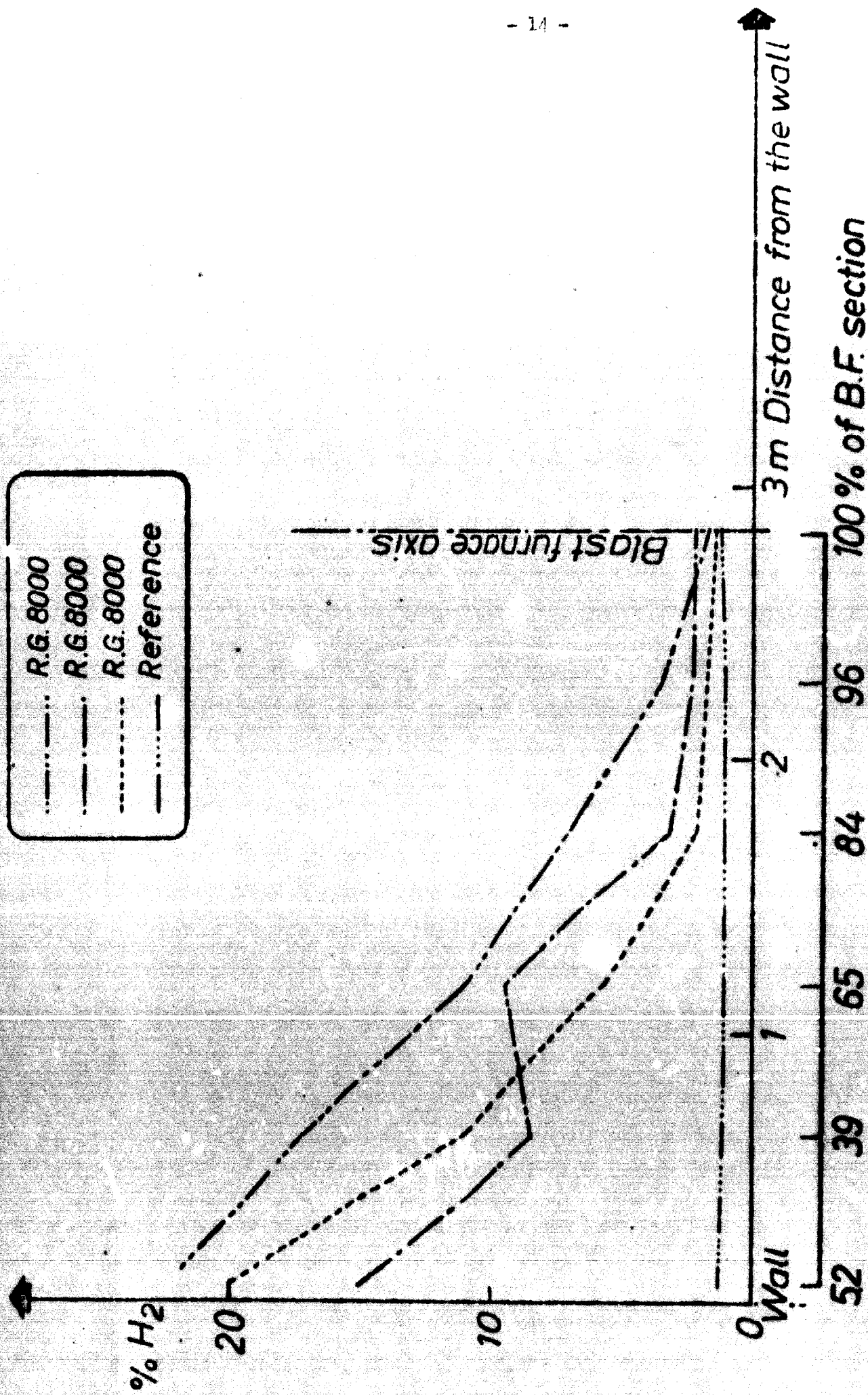


Fig.3

Naturally, the reducing gas that is injected can also be obtained from heavy fuel oils or solid fuels, but no doubt under much more difficult and arduous conditions than those which we used. This is a matter of chemical engineering.

The price of reducing gas can thus be evaluated for each of the chemical technologies concerned and compared with the price of metallurgical coke. We have found that in the conditions prevailing at the present time in most of the countries of the European Community the double injection process is already a competitive one. It is certain that in the future the price of natural gas will rise more slowly than that of metallurgical coke. Without wishing to set ourselves up as oracles, we feel that prices, while they will increase in parallel for all energy sources, will rise more steeply for metallurgical coke because labour is a major cost item and because the deposits of coking coal are becoming exhausted at an increasing rate.

In our opinion, if the ironmaker makes use of reforming units for the injection of about 600 m³ of reducing gas per tonne of pig iron and also uses fuel injection through the main tuyeres (up to 150 kg/t), the coke rate will be of the order of 250 kg/t. The ironmaker will then have great flexibility in the choice of energy sources that he requires, and in this respect he will be considerably better off than those ironmakers who are employing "direct reduction" processes based on a single fuel and on electric power for arc furnaces.

As we have said, the coke rate is not the sole element that must be taken into account. The productivity of the blast furnace is of equal importance, but unfortunately the conditions of our trials did not allow us to check the viability of our hypotheses.

Nevertheless, we should point out that Messrs A. Poes, R. Vidal, and R. Michel have established, on the basis of the best world results and on the improvement resulting from the injection of reformed gas, that one may expect that two blast furnaces of 6.3 m hearth diameter, equipped with all the most up-to-date improvements and with double injection, should be capable of producing 2 million tonnes of pig iron per year. These figures are worthy of serious consideration.

Let us end by saying that in evaluating the process described in the paper the importance of a reduction in the sulphur content of the pig iron should not be overlooked. This is of the order of 25%, which will make it possible in most cases to avoid a desulphurization treatment, or at any rate to improve its efficiency.

Acknowledgments

We should like to express our gratitude to ECSC, IRSIA, Cockerill, Shell, and Distrigaz, who supplied the financial support needed to carry out our research.

We are also grateful to the engineers of Shell, Distrigaz, and Cockerill who spared no effort to carry out the trials successfully, together with the specialists from CRM.





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