

# **PUROFER, INDUSTRIAL APPLICATION OF DIRECT REDUCTION**

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The basis for steel production is the reduction of iron ores; some 80% of the iron in finished steel derives from this source. Separation of oxygen from the iron requires a very high specific energy consumption amounting to more than half of the energy consumed by metallurgical plants.

Considering the large amounts of iron to be reduced, this single reaction is responsible for an appreciable portion of the total primary energy usage. Traditionally, this chemical process has been carried out exclusively in the blast furnace, on the basis of coke as the sole source of energy.

More recently, part of the coke for blast furnaces has been replaced by fuel oil or other reducing agents and, in view of the prospects of excessive and continued price increases for coke in comparison with other types of primary energy, efforts have been made to carry out the reduction of iron ores completely by using other types of fuel. Of many processes developed for this purpose, the direct-reduction processes, a few have seen application on an industrial scale.

These processes are based essentially on the use of non coking coal, lignite or natural gas. As far as the fuel is concerned, process development on a natural gas basis gives wider scope in design of plant and manufacture of reducing gas. Since natural gas needs to be reformed for reduction and, alternatively, also other fossil fuels can be converted to reducing gases, a wide field of application can be predicted for gas-type reduction processes.

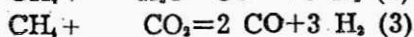
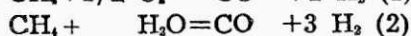
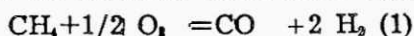
The PUROFER-process developed at Oberhausen<sup>4-7</sup> combines a number of potential advantages of a gas-type reduction process. It employs the shaft furnace as a counter-current reactor for the reduction and the regenerative

principle for the conversion of fuel gas to reducing gas. The Oberhausen pilot plant having been in operation since January 1970 with a capacity of 500 tons of metallized iron ore per day provides a sound basis for industrial application of the PUROFER-process. Although essentially a production plant it is fully available for testing and development, not being subject to any commitment for metallized iron-ore production. In consequence the process is being perfected on an industrial scale, reaching a state of the art which for newly developed processes can usually be attained only after erection and operation of several production units. Special emphasis is given to extended trials of newly developed plant components. The development work on the 500 tpd pilot plant is being carried on with financial aid from the European Coal and Steel Community.

## **Gas Conversion**

A vital feature of the PUROFER process is the unique method of gas conversion. Because the quality of the reduction gas has a considerable effect on the investment and operating costs of a direct reduction plant, the major factors therefore should now be discussed:

All gases available from natural resources and large-scale industrial facilities contain hydrocarbons. In principle the reduction of iron oxides by methane is feasible but in practice this method is limited to about 75% reduction beyond which methane decomposition to soot and hydrogen predominates<sup>8</sup>. In consequence all gases must be prepared for reduction, by reforming their hydrocarbon content to carbon monoxide and hydrogen. These transformations can be accomplished by partial oxidation according to the following three basic equations:



The processes<sup>9</sup> commercially available, essentially using steam for methane conversion according to equation (2), are only partly satisfactory for reduction processes. This arises from the importance of the degree of oxidation of the reduction gas: the residual content of carbon dioxide plus water vapour should be as low as possible relative to the carbon monoxide and hydrogen contents. This requirement is a consequence of the equilibrium diagrams of the systems  $\text{Fe}-\text{O}-\text{C}$  and  $\text{Fe}-\text{O}-\text{H}$ <sup>10</sup> and may be illustrated by the system  $\text{Fe}-\text{O}-\text{C}$  (Figure 1).

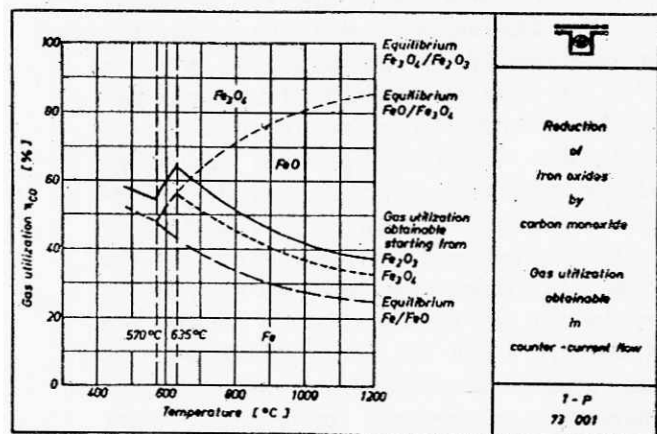


Fig. 1

In Figure 1, the term "gas utilization" is used rather than gas composition. It means the  $\text{CO}_2$  content generated during reduction from the originally pure carbon monoxide. From the diagram it can be seen that at  $900^\circ\text{C}$  a maximum of 30% of the CO can be utilized for FeO reduction. In a shaft furnace with counter-current flow of gas and ore this degree of gas utilization can be increased by one half through reduction from  $\text{Fe}_2\text{O}_3$  to FeO. Thus, under the conditions discussed, the maximum degree obtainable is 34%. Since  $600 \text{ Nm}^3$  of CO is required to combine with the oxygen from one ton of Fe in  $\text{Fe}_2\text{O}_3$ ,  $1,330 \text{ Nm}^3$  of CO per ton of Fe must be passed through the shaft furnace. If, however, the reduction gas contains  $\text{CO}_2$  initially, e.g. 6%, the gas utilization obtainable at the FeO/Fe stage is reduced by the same amount, i.e. to 24% under the conditions selected for the example. Total utilization will thus drop to 36% and the required gas flow will increase by 25% to  $1,670 \text{ Nm}^3$  per ton of Fe. As a consequence all facilities comprising the gas system must also be increased by 25% for the same production. In addition, the total energy

required by the process will be increased to supply additional sensible heat for heating up the reduction gases to the reaction temperature, and to the inevitably higher heat losses. From this it will be seen that the quantity of oxygen added for gas reforming should be as near as possible stoichiometric to the carbon content of the hydrocarbons.

An increase of the degree of oxidation in the reduction gas will lead not only to increased gas flows but, through a reduced reduction rate<sup>11</sup>, will demand an increase in size of the reduction apparatus.

The economy of the entire process is thus essentially determined by the reduction gas. The critically low degree of oxidation of the reducing gas is attained by

- Maintaining stoichiometric ratios of oxidation agents and hydrocarbons to be converted,
- Using a catalyst,
- Using high temperatures for gas reforming.

The better the last condition is met, the less critical will be the requirements for the catalyst, and the lower its cost. Such high temperatures can only be obtained by the use of regenerators which have an additional advantage in that the catalyst can not be poisoned by sulphur. Furthermore maintaining stoichiometric amounts for gas reforming is no problem when using regenerators, since at temperatures above  $1000^\circ\text{C}$  the possibility of soot formation is definitely reduced.

In the PUROFER process reforming is carried out by using either air or recirculated top gas. Up to a point the nitrogen introduced into the reduction gas when using air is advantageous in that it serves as a heat carrier, introducing into the shaft furnace the amounts of heat necessary for

- Ore reduction
- Heating up of the ores
- Heat losses.

The reducing components of the reduction gas can thus be utilized up to near the equilibrium, 45% in the example. In addition about 40% of the residual energy in the form of calorific value in the top gas can be used in the process itself. The remaining excess of top gas, which has been derived from natural gas, must be delivered to other consumers. In Figure 2

the rate of energy used under these conditions—with a gas utilization of 40%—is shown at a net calorific value of some 4.7 Gcal per metric ton of Fe. Introduction of recirculation of part of the top gas does two things:

1. The unreacted hydrogen and carbon monoxide are returned to the reduction process through simple heating up in the gas reformer.
2. After cooling and cleaning of the top gas, carbon dioxide remains in it. That carbon dioxide is used for conversion of the hydrocarbons in accordance with equation 3, replacing atmospheric oxygen.

Thus, by recirculation, the overall utilization of the reduction gas is increased. As the recirculation rate increases, the total amount of natural gas required will decrease until a point at which natural gas is reformed 20% by top gas and 80% by air. A further increase of top gas recirculation up to the complete exclusion of air will lead to a reduction of natural gas requirement for chemical energy to only about 2 Gcal/ton of Fe. At this point the reaction is fully represented by equation 3. However, the heat required for gas reforming can no longer be provided by the top gas alone and some 1.1 Gcal per ton of Fe in terms of fresh natural gas must be used for heating. In the PUROFER process this amount of energy can be replaced by another less expensive fuel, unless it includes constituents having an adverse effect on the overall process.

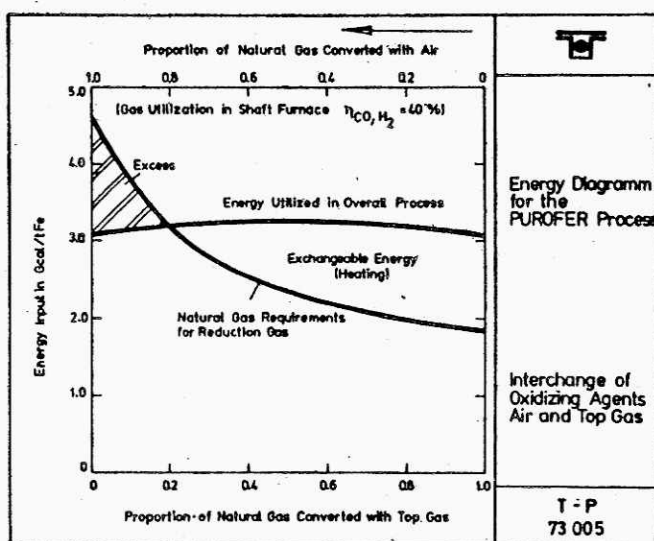


Fig. 2

When replacing air by recirculated top gas the volume of gas which must be passed through

the shaft furnace will be reduced (Figure 3). For a 95% ore reduction and variable degrees of gas utilization the following amounts of reduction gas will be required:

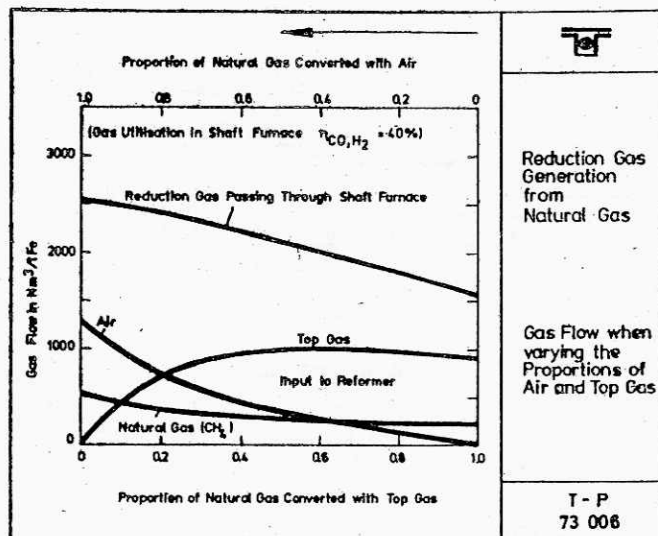


Fig. 3

Amount of reduction gas when gas reforming  
Total utiliza- Degree of with air with top gas  
tion within oxidation of (Nm / ton Fe)(Nm / ton Fe)  
shaft furnace the reduction

| gas  |      |       |       |
|------|------|-------|-------|
| 0.4  | 0.02 | 2,595 | 1,535 |
| 0.45 | 0.02 | 2,240 | 1,360 |

This permits smaller dimensions for the shaft furnace, gas ducts and gas washer. For this reason the method of operation with top gas recirculation is preferable. Nevertheless, during the first development stage, reforming with air according to equation 1 has been used, since with this method the reduction gas is passed through the plant only once, and the requirements to both apparatus and control equipment can be somewhat less. This also allowed all effort to be concentrated on testing and developing the PUROFER unit and its components.

Figure 4 shows the practical conditions for gas and energy flow in the 500 tons/day PUROFER pilot plant based on reforming with air. The two gas reformers of a PUROFER plant are arranged in the illustration one on each side of the shaft furnace. One of them serves for gas generation while the other one is being heated up. Each reformer consists of two chambers with reheat burners arranged between them. In

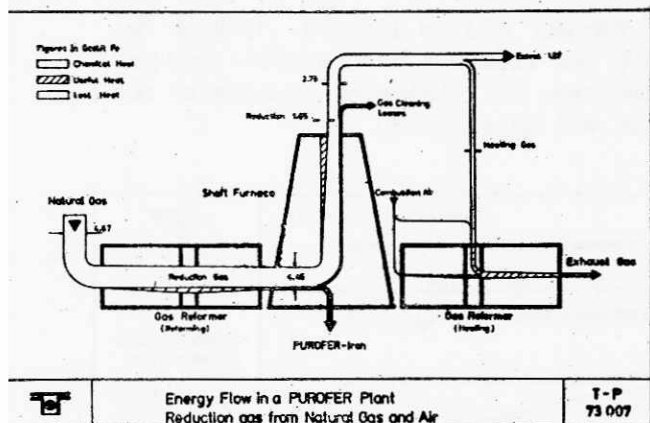


Fig. 4

the first chamber gas conversion takes place at a temperature as high as possible, that is to say, e.g. between 1250 and 1400°C. Since reduction itself must occur at a considerably lower temperature, the hot reducing gas produced in the first chamber is cooled in the second or heat-exchanging chamber to the reduction temperature, e.g. to 950°C, before being introduced at that temperature into the shaft furnace. The heat-exchanging chamber can take up heat from the reducing gas during the reforming period, because it has been cooled during the heating period by combustion air passed through it. The dimensioning of this chamber and the amount of air passed through it are determined by the difference between gas reforming temperature and the reducing gas temperature appropriate to the reduction of a given ore.

By this means a nearly constant temperature of the reducing gas is obtained. During a reforming period of about half an hour, the temperature of the reducing gas leaving the reforming chamber is falling but at the same time the heat exchanger chamber is warming up. As a result the temperature drop in it diminishes during the working period, so that the outlet gas temperature becomes constant.

By this simple method peculiar to the PUROFER process it is possible to perform both gas reforming and iron ore reduction at the most favourable temperature. Heat exchange from the reducing gas, which essentially consists of carbon monoxide and hydrogen, to combustion air at temperatures above 1000°C is only possible using regenerators.

Figure 4 (and also Figure 5) portrays diagrammatically the chemical and sensible heat contents of the gases with figures for the heat

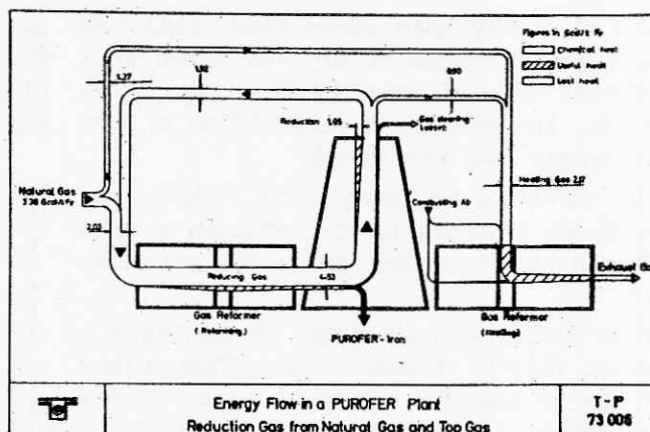


Fig. 5

values involved. When using natural gas in an amount corresponding to 4.67 Gcal/ton Fe, the off gas will include reducing gases having a heating value of some 2.75 Gcal/ton Fe, of which only 1.18 Gcal/ton Fe are used for heating up the second gas reformer. Thus, 1.57 Gcal/ton Fe cannot be utilized within the process.

Figure 5 shows the gas and energy flows in the PUROFER process when gas reforming is carried out by using top gas. As compared with Figure 4, it will be seen that the total energy requirement is reduced to 3.3 Gcal/ton Fe and that a portion of the natural gas, i.e. up to 1.27 Gcal/ton Fe, can be replaced by another fuel, since it is needed for heating purposes only.

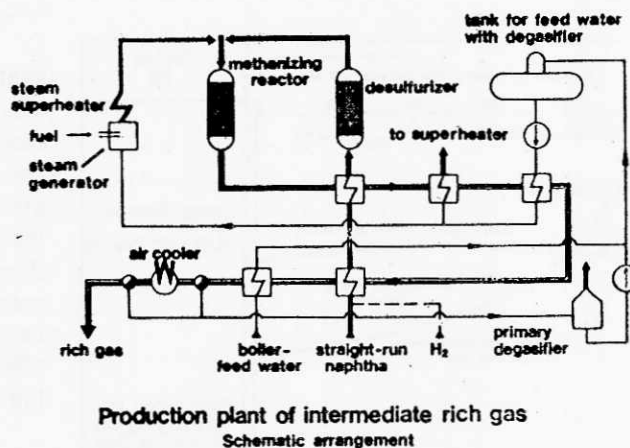


Fig. 6

When natural gas is not available from nearly sources in special cases it will be favourable to use LNG (Liquid Natural Gas) or LVN (Light Virgin Naphtha) as basic fuel for a PUROFER plant. LVN must be prepared before supplying

to the PUROFER gas reformers. It will be transformed to a gas with about 65% methane in conventional rich gas plants which are well known part of city gas plants (Figure 6). Total energy consumption will be only slightly higher than in case of natural gas.

## Reduction

Ores or pellets to be used in a PUROFER installation are screened to remove fines below 6 mm before charging. Lump ore having a normal reduction behaviour is limited to a top size of 25 mm. the ore is charged into the shaft furnace via a double bell-lock which also permits application of elevated pressure in the furnace. The entire charging operation is automatically controlled by monitoring the stock line in the furnace. The shaft furnace (Figure 7), which is free from internal devices has a continuous batter from top to bottom so that material flow is not obstructed. This makes it possible to reduce the

ore charge at temperatures just below its sticking temperature and to keep the shaft volume small due to the high reduction rate. The bottom of the furnace consists of a plate with reciprocating discharge ploughs covering the entire furnace cross section. By this action the metallized iron ore is pushed sideways into gastight collecting hoppers. From these the PUROFER Iron is unloaded via gas-tight double bell locks into containers for the transport to the steel plant. The size of the containers has been determined by the charge weight required in the steel plant.

## 500 Tons/Day—Pilot Plant

The PUROFER pilot plant (Figure 8) operating at Oberhausen with a capacity of 500 tons of metallized iron ore per day is used essentially for securing knowhow on process engineering, design, and construction in order to minimize risks in future production plants. This is one of the reasons why the design and operating of the Oberhausen PUROFER plant differs from a regular production plant. The build-up of the Oberhausen plant is shown by a model in Figure 9. In the centre of the picture is the shaft furnace with an effective volume of 90 m<sup>3</sup> and a burden-height of 7 m. In the background is the ore bins installation from which the ore is conveyed to the screening station at the extreme right. From the screening station the charging conveyor extends to the shaft furnace. All this ore handling installation operates automatically. At Oberhausen the screened out fines are shipped to the sintering plant. To the left are the two gas reformers with their larger lower reforming chambers and their smaller upper heat exchanging chambers. The natural gas is introduced into the gas reformer from the right; the reducing gas leaves the heat exchanging chamber at the top on the right and is conducted to the shaft furnace in the shortest way. For top gas cleaning and cooling there is a venturi-type washer of very small dimensions from which the gas is passed either to the burner for the gas reformer being heated, or to the compressor station for top gas recirculation (not shown). Any excess gas can be flared.

This plant has been in operation since January 1970, running trials for periods varying from two weeks up to three months. In this time, more than 150,000 tons have been processed and used for further processing in electric, basic-oxygen and openhearth steel plants as well as in blast furnaces.

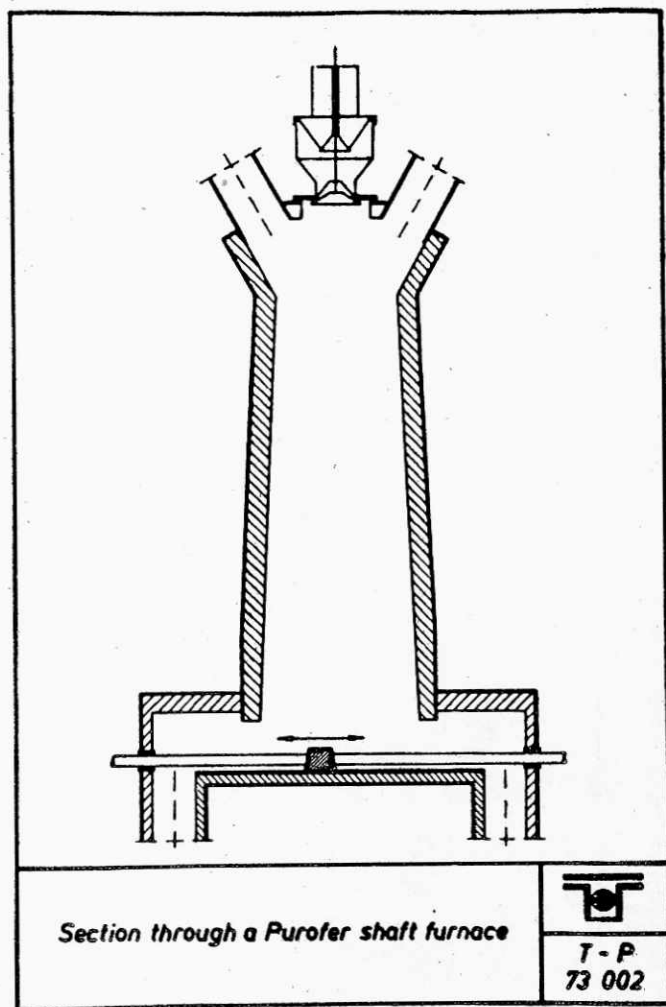


Fig 7

Table 1

| Ore                            | Type of Ore |       |       |       |       |       |
|--------------------------------|-------------|-------|-------|-------|-------|-------|
|                                | A           | B     | C     | D     | E     | F     |
| Fe <sub>2</sub> O <sub>3</sub> | 65.1        | 66.3  | 67.9  | 67.6  | 66.7  | 66.3  |
| Fe <sub>2</sub> O <sub>3</sub> | 92.5        | 92.4  | 96.0  | 96.2  | 93.4  | 91.8  |
| SiO <sub>2</sub>               | 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 <sub>2</sub> O <sub>3</sub> | 0.35        | 0.79  | 0.60  | 0.75  | 0.87  | 1.62  |
| TiO <sub>2</sub>               | 0.014       | 0.024 | 0.010 | 0.010 | 0.005 | 0.041 |
| P                              | 0.010       | 0.010 | 0.010 | 0.010 | 0.010 | 0.020 |
| S                              | 0.004       | 0.004 | 0.004 | 0.004 | 0.004 | 0.004 |
| Degree of Reduction            | 96.7        | 95.6  | 96.3  | 96.7  | 95.9  | 91.0  |

A few examples of the metallized iron ore produced at Oberhausen are shown in Table 1. Apart from a less suitable lump ore (Column F), which also causes trouble during blast furnace operation, the degrees of reduction obtained have been 95% or more. The contents of gangue and phosphorus are determined by the types of ore used and cannot be influenced by reduction in the PUROFER process, but part of the sulphur in the ore is taken up by the reducing gases.

Table 1 shows the very low sulphur contents of the PUROFER iron. It is for that reason, an

Table 2

| Ore                                   | Type of Ore |      |      |      |      |       |
|---------------------------------------|-------------|------|------|------|------|-------|
|                                       | A           | B    | C    | D    | E    | F     |
| Bulk Density (t/m <sup>3</sup> )      | 2.10        | 2.08 | 2.09 | 2.23 | 2.23 | 2.21  |
| True Density (g/cm <sup>3</sup> )     | 4.94        | 5.07 | 5.20 | 5.17 | 4.99 | 4.76  |
| Apparent Density (g/cm <sup>3</sup> ) | 3.60        | 3.80 | 4.04 | 4.02 | 3.79 | 4.10  |
| Porosity (%)                          | 27.1        | 25.0 | 22.3 | 22.2 | 24.0 | 13.9  |
| Specific Surface (cm <sup>2</sup> /g) | 700         | 800  | 500  | 500  | 900  | 400   |
| Sponge                                |             |      |      |      |      |       |
| Bulk Density (t/m <sup>3</sup> )      | 1.71        | 1.70 | 1.68 | 1.78 | 1.75 | 1.82  |
| True Density (g/cm <sup>3</sup> )     | 6.08        | 6.94 | 7.26 | 7.16 | 6.99 | 7.09  |
| Apparent Density (g/cm <sup>3</sup> ) | 3.10        | 2.90 | 3.82 | 3.81 | 2.69 | 3.50  |
| Porosity (%)                          | 54.9        | 58.2 | 47.4 | 46.8 | 61.5 | 50.6  |
| Specific Surface (cm <sup>2</sup> /g) | 4100        | 4700 | 5700 | 5800 | 6900 | 10700 |

Table 3

## Reforming Natural Gas with Air

| Chemical Composition [x] |                |      |                 |                  |                 |                               |                |
|--------------------------|----------------|------|-----------------|------------------|-----------------|-------------------------------|----------------|
|                          | H <sub>2</sub> | CO   | CO <sub>2</sub> | H <sub>2</sub> O | CH <sub>4</sub> | C <sub>2</sub> H <sub>6</sub> | O <sub>2</sub> |
| Natural Gas              | -              | -    | 5.4             | -                | 88.1            | 2.5                           | 0.2            |
| Reducing Gas             | 38.5           | 20.9 | 0.4             | 0.8              | 1.2             | -                             | 38.2           |

## Reforming of Natural Gas with Top Gas

| Chemical Composition [x] |                |      |                 |                  |                 |                               |                |
|--------------------------|----------------|------|-----------------|------------------|-----------------|-------------------------------|----------------|
|                          | H <sub>2</sub> | CO   | CO <sub>2</sub> | H <sub>2</sub> O | CH <sub>4</sub> | C <sub>2</sub> H <sub>6</sub> | O <sub>2</sub> |
| Natural Gas              | -              | -    | 5.5             | -                | 86.4            | 3.4                           | 0.2            |
| Reducing Gas             | 49.2           | 43.3 | 1.1             | 1.4              | 2.5             | -                             | 2.5            |

excellent charge material for the production of low sulphur steels. Another advantageous effect on steel production arises from the low nitrogen contents of the metallized iron ore (0.003%). In the PUROFER process the degree of reduction of the metallized iron ore is within very close limits. 758 samples from a test run 25,000 tons of metallized iron ore gave an average of 95.68% with a scatter of  $\pm 0.52\%$ . The carbon content of metallized iron ore averaged 0.56% with a scatter of  $\pm 0.27\%$ .

Physical properties are summarized in Table 2. Note the high porosity of the metallized iron ore, which is readily explained by the fact that during reduction the ore lumps retain their ori-

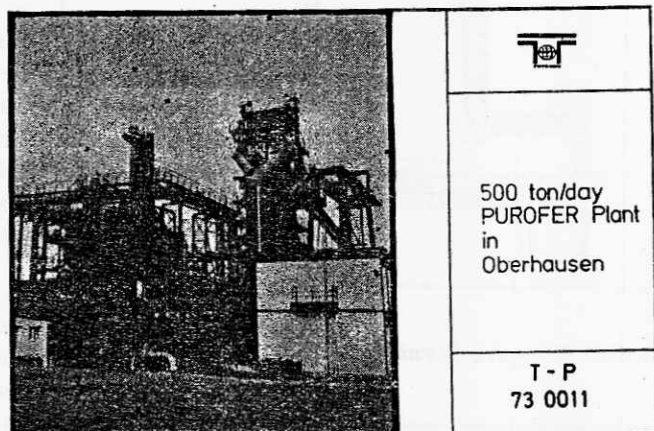
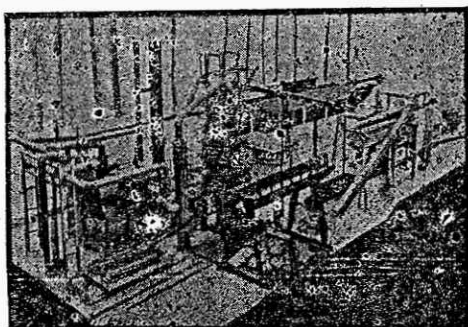


Fig. 8

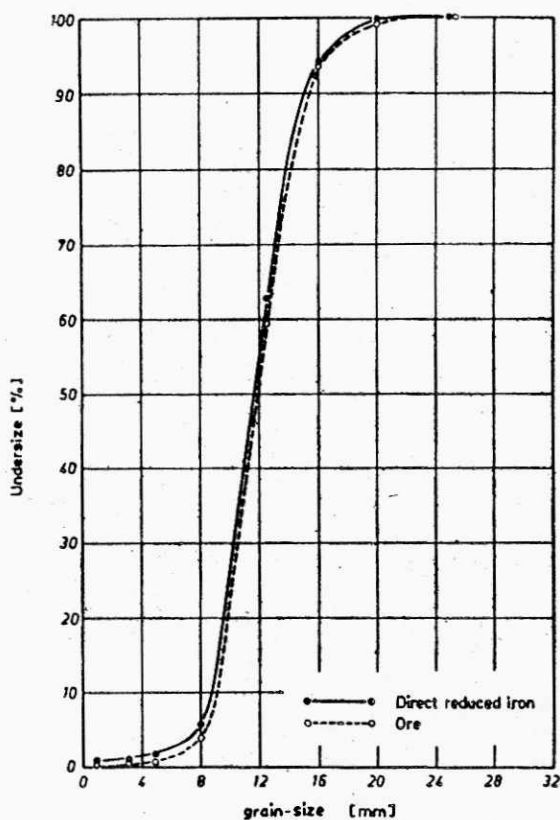


Model of the 500 ton/day  
PUROFER Pilot Plant

T - P  
73 0010

Fig. 9

ginal configuration while losing mass by oxygen removal. The size characteristics of the metalized iron ore produced can be the same as that of the ore used, as exemplified in a particular type of pellet in Figure 10. A similar behaviour has been found for a whole series of the pellets examined. However, there are types of ore

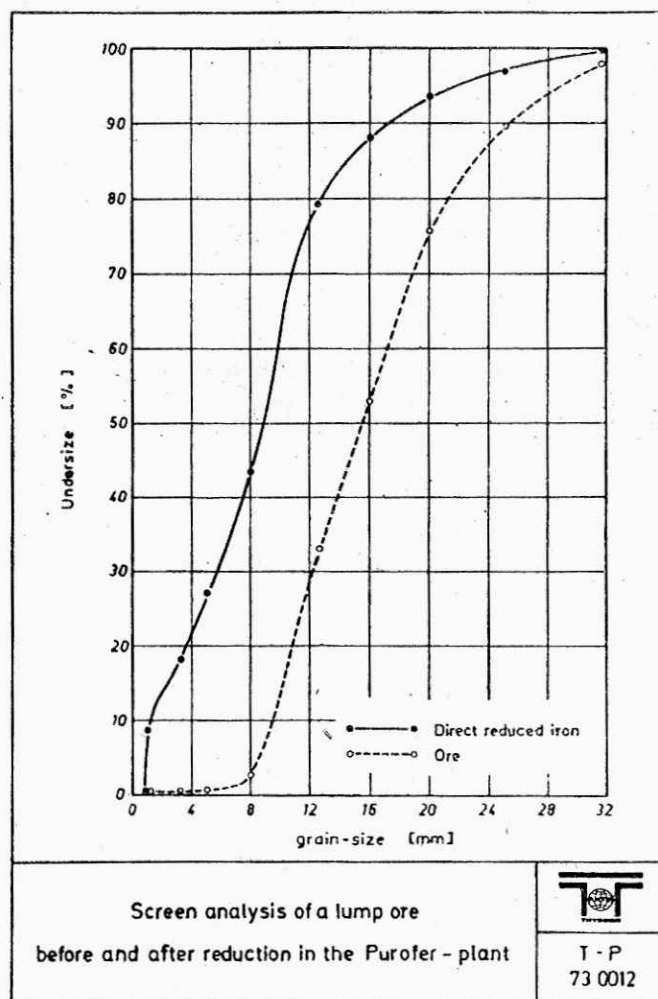


Screen analysis of pellets  
before and after reduction in the Purofer - plant



T - P  
73 0013

Fig. 10



Screen analysis of a lump ore  
before and after reduction in the Purofer - plant



T - P  
73 0012

Fig. 11

which tend to disintegration during reduction. The product will have unfavourable size characteristics, as shown in Figure 11. It is for that reason that all ores or pellets, prior to large scale industrial application, should be tested for their suitability. Even with extensive laboratory testing it is not possible to cover all



Hot Briquetted PUROFER Iron

T - P  
73 0014

Fig. 12

conditions to which the ore will be subjected when being processed in large industrial installations. A particular point of the investigations on the 500 ton day PUROFER installation at Oberhausen, therefore, is to determine optimum processing conditions for new ore grades. Such large scale tests essentially reduce teething troubles in production plants, thus reducing their starting up periods.

Energy consumption of the FUROFER plants is shown in Figures 2 and 3. The reducing gas generated from natural gas with air or recirculated top gas has the composition shown in Table 3.

### Hot Briquetting

In the PUROFER process the metallized iron ore is discharged hot, in which form it may be used immediately in the adjacent steel plant without cooling or other processing. Even if the metallized iron ore must in consequence be kept out of contact with air, this is by far the most economical form of further processing. Since the metallized iron ore leaves the shaft furnace at temperatures of some 800°C it can also be briquetted. Apart from transportation between PUROFER plant and briquetting machine, this does not necessitate any protective measures against reoxidation by the atmosphere. The briquettes produced in a ring-roller press (Figure 12 shows briquettes from an extensive briquetting) have a high density and, above all, a heavily compacted surface. On leaving the briquetting machine, the briquettes can be cooled by simply spraying them with water, whereas cooling of non-compacted metallized iron ores due to reoxidation hazards, requires the use of extensive equipment.

Briquetting can be useful for various reasons. It will be required when reduction of specific ores gives rise to excessive amounts of fines. Briquettes can be handled more easily also because of their high density, because reoxidation hazards are eliminated, and because they contain no fines. PUROFER briquettes can be stored both hot and cold without taking special precautions, e.g. it will not be necessary to protect the briquettes against inclement weather as any reoxidation can be neglected. For the same reasons briquetting offers special advantages for overseas and overland shipments.

### Reoxidation

Unless the metallized iron ore is briquetted, due consideration must be given to its tendency for re-oxidation, before further use or transport.

Investigations made in co-operation with Lurgi Chemie und Huttentechnik GmbH into the re-oxidation behaviour of metallized iron ore produced at high temperatures will be reported on in detail elsewhere<sup>13</sup>. Oxidation may be brought about

- by atmospheric oxygen when hot, or
- by moisture attack when cold.

If metallized iron ore is cooled to a temperature of 80°C, no oxidation by atmospheric oxygen will occur. On the other hand, metallized iron ore stored either in open heaps or in closed containers can be "ignited" by local heating. The ignition temperature for the grades of metallized iron ore hitherto examined is above 200°C. If ignition occurs the development of temperature and speed of propagation of the oxidising zone in bulk material is a function of atmospheric oxygen supply. If the heap is traversed by air, it will be oxidised almost completely with a considerable development of heat. If oxidation occurs only at the surface of a static pile, without air flowing through it, the oxidation zone will propagate only very slowly and may even stop for lack of additional oxygen supply. This slow process can last for weeks. Thus, as far as field operation is concerned, large heaps of material generally are less vulnerable to oxidation than smaller ones. Also, unless the heap is aerated, corrective action may be taken of further processing corrective action may be taken or further processing of the material may be accelerated.

Oxidation by water is quite different, seawater attack being more harmful than rain or fresh water. There is little heat development, the temperature observed remaining far below the ignition temperature for air oxidation. In the study of reoxidation under atmospheric conditions at Oberhausen, two batches each of 500

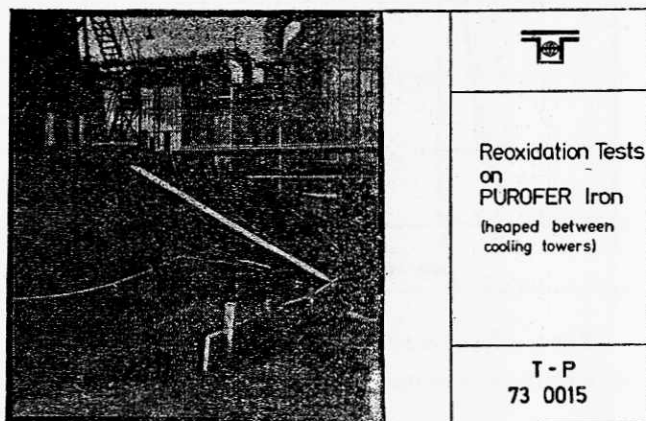


Fig. 13

tons of metallized iron ore were stored outdoors to provide field experience for comparison with results from the laboratory and from pilot tests. One batch was dumped between two cooling towers to give most adverse conditions (Figure 13). Observation of that heap over a period of one year has shown that only the surface is attacked; at a depth of more than 40 cm below the surface of the heap the metallized iron ore remains substantially unchanged (Figure 14). This can be explained in that atmospheric humidity only penetrates to a small depth, which effects an additional protection resulting from the fact that the rusting lumps of metallized iron ore form a solid skin in the heap. Figure 15 shows the unaltered metallized iron ore under a rusted surface layer.

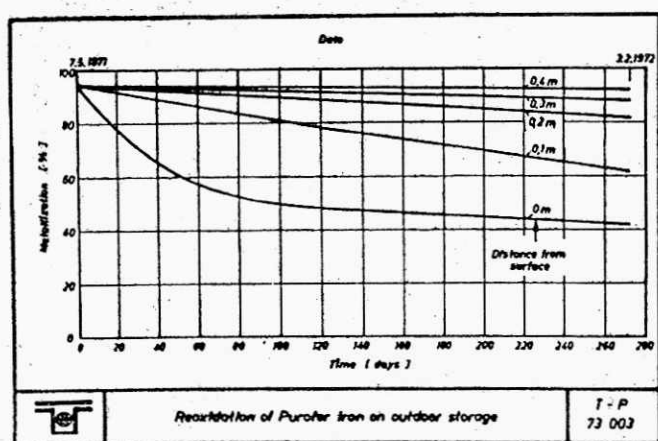


Fig 14

### 1000 Tons/Day Installation

When discussing the Oberhausen pilot plant, it has already been indicated that a PUROFER production plant would be of a simpler physical design than a test plant. In the meantime, the development work for a 1000 tons/day produc-

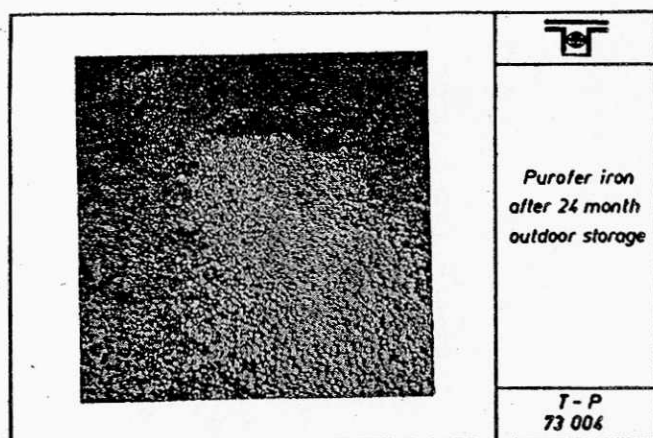


Fig. 15

tion plant has been concluded. Such an installation can be built for gas reforming either with air or with recirculated top gas. The flow diagram for the former case (Figure 16) shows again the two parallel gas reformers this time arranged in line, the larger reforming chamber and the smaller heat exchange section for temperature adjustment, with the burner for heating up located in between. Between the gas reformers and the shaft furnace a further heat equalizing chamber is provided for compensating residual temperature variations caused by the regenerator principle. Gas reforming essentially takes place in the temperature range 1400 to 1250°C, after which the gas is cooled for reduction to e.g. 950°C with a tolerance of  $\pm 50$  C. The final

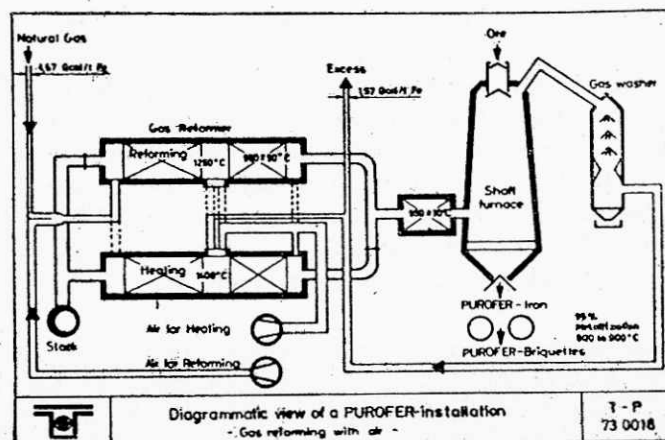


Fig. 16

equalizing chamber smooths out the temperature variation to  $\pm 10^\circ\text{C}$ . On cleaning and cooling, the shaft furnace top gas is only partially used for heating, the remainder must either be delivered to other consumers or be flared. In Figure 17 the same conditions are illustrated for gas re-

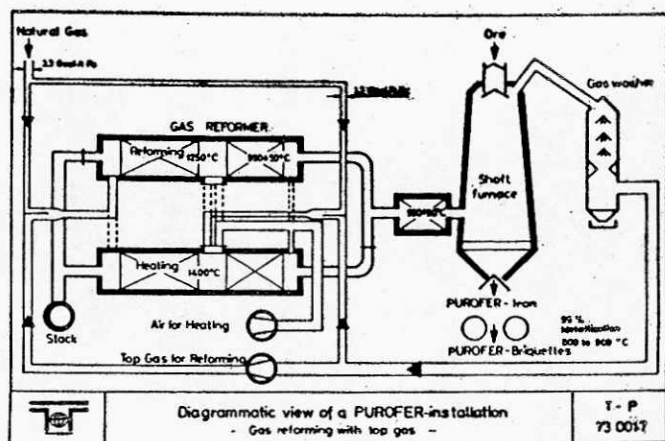


Fig. 17

forming with recirculated top gas. This version, because of its economy, is to be preferred. The essential difference as compared with the design of Figure 15 is that the compressor previously used for supplying air for reforming must now compress the top gas.

Finally, Figure 18 shows in isometric projection a 1000 ton/day PUROFER installation for operation on top gas recirculation. Installations of that size are appropriate for both large and small steel works.

Operation of a PUROFER installation can also be usefully associated with an ore mine, since this will provide metallized ore supplies in combination with savings in shipping cost. For operating such an installation on a top gas recirculation basis, the personnel required per shift is 5 men, including foreman. Consumption of natural gas is less than 3.3 Gcal per ton of Fe, of electric power less than 100 kWh per ton of Fe, and water consumption is 1.5 m<sup>3</sup> per ton of Fe. The investment costs for 1000 tons/day PUROFER installations as depicted are in the order of DM 140,—per annual ton of PUROFER iron. The operating availability of such installations on an annual average is more than 90%.

## Summary

The PUROFER process for direct reduction of iron ores uses natural gas for reduction in a shaft furnace. Reducing gas is produced in regenerative gas reformers at very high temperatures and, consequently, with very high degrees of conversion. The gas is then cooled in heat exchangers associated with the reformers to the reduction temperature appropriate to the ore. The heat stored in the heat exchangers is delivered to the combustion air during the subsequent heating cycle.

The cleaned top gas is normally recirculated to the gas reformers, the carbon dioxide of this gas serving as an oxygen carrier for conversion. With this method of operation the fuel requirement of the overall process is 3.3 Gcal per ton of which about one third is used only for heating and can be replaced by other, less expensive fuels. Gas conversion with air may lead to a degree of simplification, but will result in an increase of energy consumption to 4.67 Gcal per ton of Fe, of which one third cannot be used in the process properly speaking.

The 500 tons per day PUROFER plant exist-

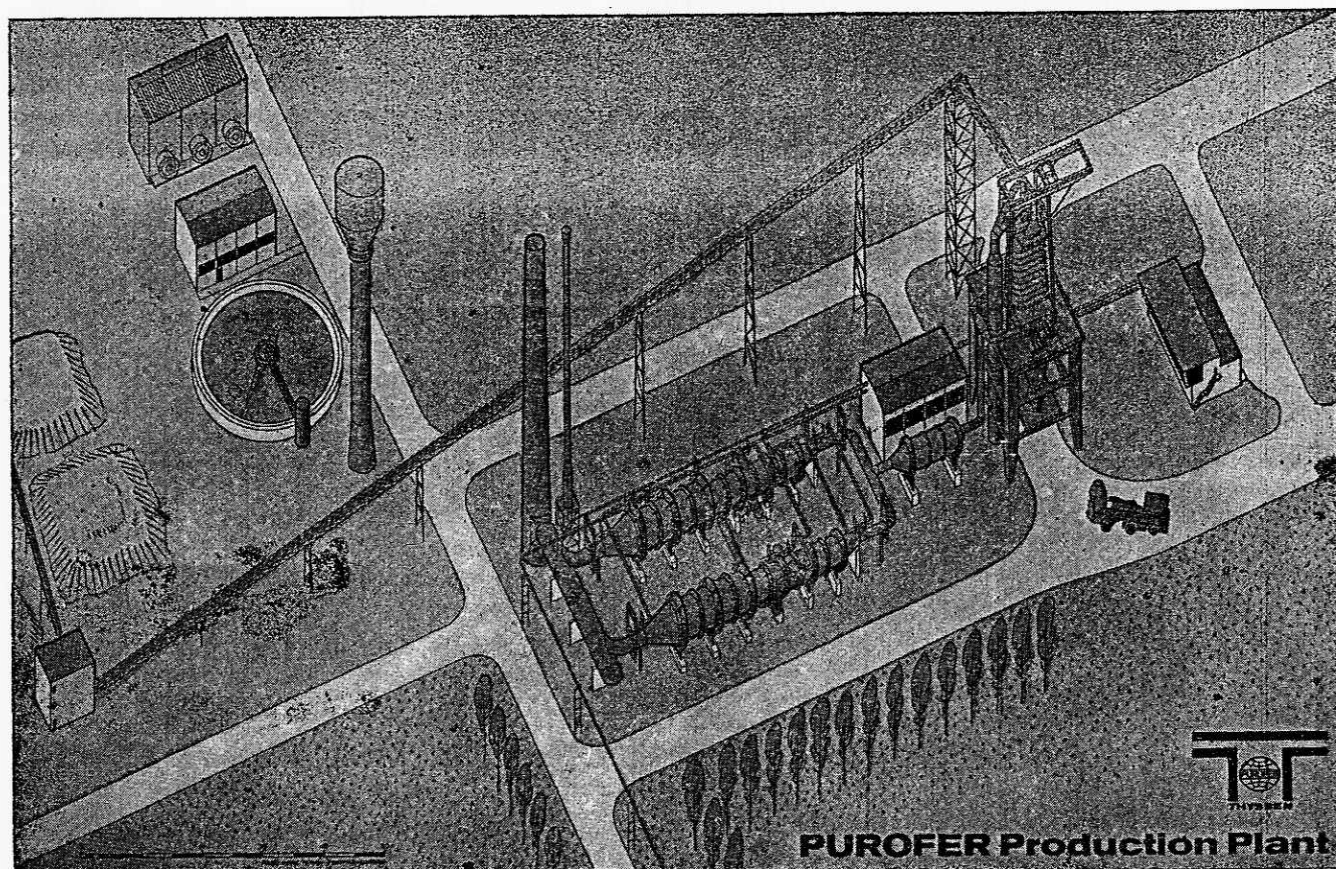


Fig. 18

ing at Oberhausen serves for the development of process engineering and, for this purpose, is operated for test series only. Research work is being carried out in co-operation with the European Coal and Steel Community. 150,000 tons of metallized iron ore with a degree of reduction of as high as 95% have been processed, and supplied to various steel works. A large number of pellets and ores has been examined, the majority proving suitable for processing by the PUROFER method. Since PUROFER metallized iron ore is discharged from the shaft furnace hot, it can readily be briquetted in that state. Thus, re-oxidation hazards are almost eliminated. PUROFER metallized iron ore in bulk or briquette form are materials well suited for continuous charging to electric steel furnaces. The reoxidation behaviour has been examined at Oberhausen in a large number of semi-industrial tests, including storage of substantial amounts of metallized iron ore under adverse weather conditions. The development of PUROFER plants for a size of 1000 tons per day has been concluded.

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## Discussion

Dr. U. N. Bhargava (Indian Iron & Steel Co. Ltd., Kulti). What is the size of the ore used in your reactor? While briquetting are you hot briquetting the material and what is the recycle fines coming out in the briquetting process? What is the size of the Briquettes?

Dr. H. D. Pantke (Author). The grain size for burned pellets is the same for both for the PUROFER shaft furnace and for the blast furnace, i.e. mainly in the range from 8 to 16 mm. The grain size for lumpy ore is from 8 to 40 mm. The upper limit depends on the reducibility of the ore: the lower the reduction speed, the smaller is the maximum size of the ore. We briquette the PUROFER iron hot, the temperature is above 700°C. The fine material eventually obtained after briquetting will not be recycled. The size of the briquettes is approx. 25 x 40 x 50 mm.

Dr. A. B. Chatterjea (National Metallurgical Laboratory, Jamshedpur) Regarding the question of maintenance of the desired temperature profile from the top vertical sector to the bottom of the shaft furnace, although Dr. Pantke has explained it very carefully, somehow or other, I am not very clear. The natural gas is heated to  $960^{\circ}\text{C} \pm 10^{\circ}\text{C}$ . to reform the gas and that reformed gas is sent through the Purofer reactor. Is there any other method of heating the charge by burning a part of the gas on the top by injecting limited quantity of oxygen or air? I am talking in the same wavelength as Prof. Altekar when he enquired as to how was the temperature profile in the shaft or vertical cross-section of the furnace maintained? Similarly, the maintenance of identical isothermal temperature across the furnace cross sector at a particular height is of importance.

What is the volume of reducing gas which has to be circulated over the stoichiometric quantity per ton of sponge iron produced. A certain

quantity of gas is required for the reduction of certain quantity of iron oxide. By how much is this circulating gas exceed the stoichiometric quantity?

With nitrogen in the reforming of the gas as a carrier of heat, does the situation seriously effect the rate of reduction of ore in the Purofer Plant?

Dr. H. D. Pantke (Author). In the example given in the paper, the reduction gas has a temperature of about 95°C when it is injected into the shaft furnace. In the explanation to an earlier question, we have demonstrated that the decrease in temperature is very low while the reduction gas ascends in the furnace. Only in the last 10% of the high of the shaft furnace a temperature drop occurs. From this it can be concluded that there is enough heat energy in reserve, so that for heating up the burden no other measure is to be taken. Since in our shaft furnace the gas flow is homogeneous over the cross section, there are no differences in the temperature over the cross section.

The question about the amount of recirculated top gas is partly answered to question No. 2. The amount of the gas can be taken from figure No. 5 in the preprint. It should be understood that this figure gives only a typical example for the process.

To the last question we have to explain that a limited portion of nitrogen in the reduction gas is useful as a heat carrier for the process in the shaft furnace. When the nitrogen content rises, there is no further advantage, on the contrary there is a little heat loss because the heat combined in the nitrogen will be transferred into the cooling water (for cooling the top gas). The recirculated part of this nitrogen should be heated up and pass through the shaft furnace newly.

Mr. K. N. Gupta (National Metallurgical Laboratory, Jamshedpur). (i) I am not very clear about the top gas which is being recirculated. I am pointing this with reference to the water formed during reduction with hydrogen of the reformed gas and this, if not separated, is likely to give rise to sticking problem inside the reactor. I would like to know from you more details about such operational problems like sticking, channeling, non decent of charge etc. while working with a vertical reactor particularly for sponge iron production (ii) The outlet gas from the reactor has been shown to have 20% carbon monoxide and 40% hydrogen. Is it not

advisable to increase the height of the reaction zone so that we may get product gases containing very low hydrogen and carbon monoxide? (iii) What is the latest position of Purofer installation in Germany and in other countries?

Dr. H. D. Pantke (Author). All the top gas will be cleaned and cooled down in a gas washer, only after this the gas stream is divided. One part is recirculated, the other part is used in the burner to heat up the second gas reformer. On this basis, we have had no problems with the water vapour contained in the top gas.

In our shaft furnace we have a continuous and homogeneous descent of the burden. Also we have an homogeneous gas throughout for the reduction gas. The conical construction of the shaft furnace is chosen to ensure an operation without any channeling. To prevent sticking, we test every ore in the laboratory to find the sticking temperature. After this we operate the shaft furnace below this sticking temperature. Let me explain that we — as PUROFER — can use the highest possible reduction temperature because we have no additional devices in the furnace so that there is no dynamic pressure in the burden. Due to the dynamic pressure sticking temperature can be lowered more than 150°C.

The next question I will answer as follows.

The reduction gas has a composition of 20% Co and 40% H<sub>2</sub> when it is injected into the shaft furnace (when the natural gas is reformed with air). The chemical utilization of this gas is limited by the equilibrium between H<sub>2</sub> — H<sub>2</sub>O/Fe — FeO. There is no possibility to pass this limitation. The maximum chemical utilization of pure hydrogen for the reduction of hematite at a temperature of 900°C is about 58%. The obtainable value in practice is below this figure.

We run in Oberhausen an industrial scale pilot plant. In the very near future some contracts for 1,000 t/day plants in other countries will be signed.

Dr. Bhanu Prakash (Banaras Hindu University, Varanasi). (1) I would like to know the composition of the circulating gas. What is the proportion of the carbon-monoxide to hydrogen which is circulated through the shaft. As reaction with H<sub>2</sub> is endothermic and that with CO is exothermic, the ratio is of significance for maintaining the temperature (2) I would also like to know the volume of gas passed through the reduction shaft furnace per tonne of ore reduced.

Dr. H. D. Pantke (Author) Table 3 of the chemical composition of the reducing gas on the basis of reforming of natural gas with recycled top gas. The recycled top gas is introduced into the gas reformer together with natural gas. After reforming, we get the reducing gas with the chemical composition given in Table 3. There is no another way of recycling the top gas. The explanation for the temperature profile is given in the answer to the previous question.

Concerning the second question, I add a figure from another paper of ours about the PUROFER process 'PUROFER — Development and Industrial Application' by 'H. D. Pantke et. al.

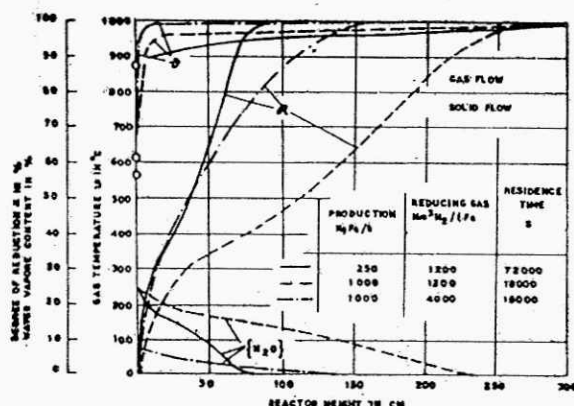


FIG. 1. VARIATION IN DEGREE OF REDUCTION, GAS COMPOSITION AND GAS TEMPERATURE IN A COUNTER CURRENT REACTOR

GAS COMPOSITION: 50%  $\text{H}_2$ , 50%  $\text{N}_2$   
INITIAL GAS TEMP: 1000°C  
REACTOR HEIGHT: 3M  
REACTOR CROSS SECTIONAL AREA: 1  $\text{m}^2$

Dr. S. K. Gupta (Indian Institute of Technology, Bombay). Firstly, I would like to know the composition and form of raw materials used. I would also like to know further about the temperature profile in the shaft furnace as shown by the author. According to the known phenomena in such shaft furnaces this type of temperature profile can exist only when at the upper part we have endothermic reactions followed by a constant temperature zone where the apparent thermal capacity of charge does not increase with increase in temperature due to compensatory effect of exothermal heats of reactions leading to a third zone characterised by endothermic reactions. The gas composition used in this process does not possibly show evidence of such heat effects of reactions involved. The author is requested to explain.

Dr. H. D. Pantke (Author) Concerning the chemical composition of the ores processed, some of them are given in Table 1 of the paper. In

our process we have used both lumpy ore and burnt pellets.

The following figures (Fig. No. 13 & 14 from the report of L. V. Bogdandy and Wartmann, (Arch. f. d. Eisenhüttenwes. 36 (1965) S. 221 — 236) give you an idea about the temperature profile in the PUROFER shaft furnace.

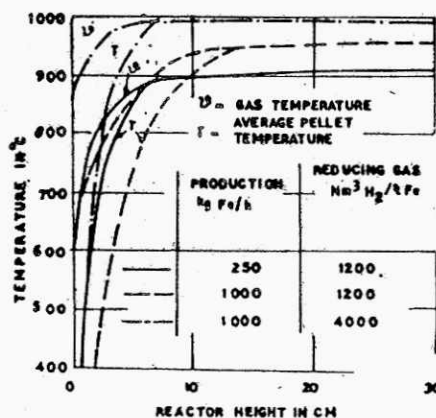
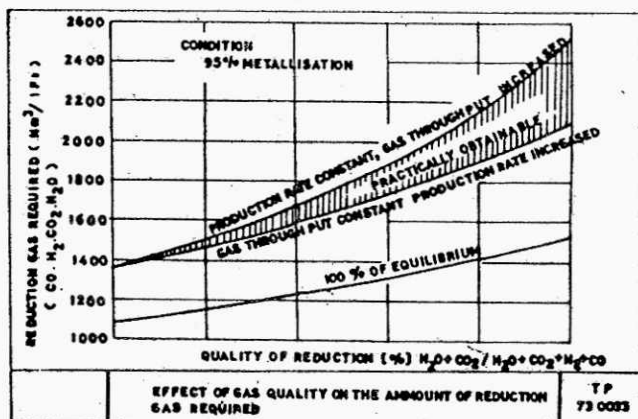


FIG. 2. VARIATION IN GAS AND SOLIDS TEMPERATURE IN A COUNTER CURRENT REACTOR

GAS COMPOSITION: 50%  $\text{H}_2$ , 50%  $\text{N}_2$   
INITIAL GAS TEMP: 1000°C  
REACTOR HEIGHT: 3M  
REACTOR CROSS SECTIONAL AREA: 1  $\text{m}^2$



The curves about the temperature, calculated on the basis of hydrogen (in the mixture with nitrogen 50:50) as the reductants, show nearly equal temperature in more than 90% of the high of the shaft furnace. The practical experiences in our shaft furnace give nearly the same result. The real top gas temperature is measured between 400 and 700°C. Detailed information, especially about the heat demand for the reaction, for the heating up, and for the heat transfer, are given in the paper cited above.



#### **SESSION IV - GASEOUS REDUCTION OF IRON ORE TO SPONGE AND SUBMERGED ARC FURNACE SMELTING**

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**Tuesday, 20 February, 1973**

The Session was convened at 2.30 P. M. The Chairman was Mr. J. Astier, Director, IRSID, France, the Co-Chairman was Dr. V. G. Paranjpe, Director, Research & Development, Tata Iron & Steel Co. Ltd., Jamshedpur and the Rapporteur was Mr. M. J. Shahani, Assistant Director, National Metallurgical Laboratory, Jamshedpur.