CARBON MONOXIDE REDUCTION OF IRON ORE

New non-melting reduction process claims many advantages over previously reported sponge iron process; it is a continuous direct-reduction process making use of carbon monoxide in a fluidized bed. World rights to the new process are held by Stora Kopparbergs Bergslags A/B, Falun, Sweden.

by Otto Stelling

CERTAIN attention is paid today to the weaknesses of the classical blast furnace process, and interest is continuously increasing in methods for direct reduction without melting. Several different methods have been developed or suggested in the past, but so far only a few have been adopted for practical use.

Another tendency in the iron industry of today is the change-over to concentrates, with an agglomeration as the first stage before reduction. It would mean a big step forward if this agglomeration process could be avoided, as it is often difficult to carry it out.

A practical solution of these two problems—direct reduction in a continuously operating process adapted to large scale production, and based on fine-grained raw materials without previous agglomeration, would certainly be of great importance. But due to the many difficulties of various kinds which arose when the sponge iron methods were brought into practical use, some skepticism is natural.

There are many reasons for the comparatively slow progress in the sponge iron field. One is the gangue content in the raw material, which naturally is also to be found in the sponge iron. However, with a still further concentration, this problem might not be too serious. Perhaps the biggest problem is to proceed far enough with the reduction without the material sticking to the furnace wall or sintering, both of which cause operational difficulties. The sticking can be avoided by decreasing the reduction temperature, but the speed of reaction is also diminished. The conditions would, however, be different, depending on whether hydrogen or carbon monoxide is used as a reducing agent. When using hydrogen, the reduction can be carried through at 500°C with suitable speeds of reaction, but with a very unsatisfactory utilization of the hydrogen. With carbon monoxide, there is spontaneous decomposition into carbon dioxide and carbon, and the speed of reaction is also lower compared to that obtained with hydrogen. The further decomposition of carbon dioxide however, made it impossible to investigate the speed of reduction with carbon monoxide to temperatures below 800°C.

The fluidized bed, where a gas is pressed through a bed of fine-grained material with velocity so high that the solid particles make a turbulent movement, is characterized by a very intimate mixing of the solid material so that a constant temperature is acquired within the entire bed. Fluidization is reached at a certain linear gas velocity, determined by the physical properties of particles and gas, and occurs within a rather large speed interval. The particle size generally used in fluidized beds is 0.03 to 3 mm; the linear gas velocities generally range within 1 cm to 1 m per sec. The pressure fall in the gas stream corresponds roughly to the static pressure of the fluidized bed. Heat conduction of the fluid bed is very good; transmission from bed to wall is thus of the same magnitude as in a liquid. The small particle size and large surface between gas and solid phase contributes to the reaction speed.

At the end of the 1940’s, the problem of treating hard-sintered ore in a fluidized bed was taken up. Another investigation contained many negative results from similar enquiries, and emphasized that such reduction would not be possible in commercial operation as, at a low degree of reduction, sticking of the particles would occur.

Investigations soon revealed difficulties of that kind do arise if one tries to carry out the process at normal thermodynamic temperatures. Tests were started at about 800°C, where the reduction is rapid, and particles began to stick at a comparatively low content of metallic iron in the bed. If the temperature was lowered to 725°C, reduction was only 60 pct and sticking of particles in the bed started. By exposing the bed to horizontal vibrations, the degree of reduction could be increased to about 70 pct, but sticking would again start. Additions of inactive material such as lime, coal, etc., had the same effect. A bed with a reduction degree of 70 pct can easily be kept fluidized at 725°C in a nitrogen atmosphere, but sticking immediately sets in if the nitrogen is replaced by carbon monoxide. Also of interest is that a bed of pure FeO shows very strong tendencies to stick at temperatures ranging from about 540° to 580°C, probably because below 570°C FeO is transformed into Fe₃O₄ and Fe. This transformation seems to be strikingly catalyzed by cementite. Beds of Fe₃O₄ and Fe₂O₃ show no tendency to stick below 900°C.

The first results obtained were thus not at all favorable for a technical adoption of this reduction method. Tests made at 700°C showed, however, a diminished tendency to sintering. A closer investigation of the final product showed that the metallic iron had been transformed into iron carbide, probably according to the equation.

\[ 3Fe + 2CO \rightarrow Fe₃C + CO \]

It could thus be assumed that a bed consisting of iron carbide would not stick. If the process is carried out under such conditions that cementite and not metallic iron becomes the main product, sticking is avoided at temperatures up to 900°C.

<table>
<thead>
<tr>
<th>Table I. Analysis of Concentrate Mixture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe₂O₃, pct</td>
</tr>
<tr>
<td>FeO, pct</td>
</tr>
<tr>
<td>Fe, pct</td>
</tr>
<tr>
<td>SiO₂, pct</td>
</tr>
<tr>
<td>CaO, pct</td>
</tr>
<tr>
<td>MgO, pct</td>
</tr>
<tr>
<td>Al₂O₃, pct</td>
</tr>
<tr>
<td>MnO, pct</td>
</tr>
<tr>
<td>P₂O₅, pct</td>
</tr>
<tr>
<td>S, pct</td>
</tr>
<tr>
<td>Cu, pct</td>
</tr>
<tr>
<td>Ignition loss, pct</td>
</tr>
</tbody>
</table>

OTTO STELLING is Professor of Metallurgy at the Royal Institute of Technology in Stockholm, Sweden.
In order to define the conditions necessary for the reactions desired, we are going to deal with the equilibrium data for the reaction of FeO + CO. The reactions that can take place are the following:

1) \( 3\text{Fe}_2\text{O}_3 + \text{CO} \rightleftharpoons 2\text{Fe}_3\text{O}_4 + \text{CO}_2 \)
2) \( \text{Fe}_3\text{O}_4 + \text{CO} \rightleftharpoons 3\text{FeO} + \text{CO}_2 \)
3) \( \text{FeO} + \text{CO} \rightleftharpoons \text{Fe} + \text{CO}_2 \)
4) \( 3\text{FeO} + 5\text{CO} \rightleftharpoons \text{Fe}_3\text{C} + 4\text{CO}_2 \)
5) \( 3\text{Fe} + 2\text{CO} \rightleftharpoons \text{Fe}_3\text{C} + \text{CO}_2 \)
6) \( \text{FeO} + \text{Fe}_2\text{C} \rightleftharpoons 4\text{Fe} + \text{CO}_2 \)
7) \( 2\text{CO} \rightleftharpoons \text{C} + \text{CO}_2 \)

Especially interesting are reactions 3, 4, 5, and 7. The equilibrium constants of these reactions, calculated in the usual way from thermodynamic data, are shown in Fig. 1, from which is seen that reaction No. 7, at temperatures above 710°C, leads to the stable state, i.e., that the final product that can be expected above 710°C is metallic iron. Below this temperature, reaction No. 7 is dominating from an equilibrium point of view, i.e., the carbon monoxide should in this case decompose into carbon and carbon dioxide instead of reacting with iron oxide. If, however, this decomposition of the carbon monoxide is disregarded, iron carbide ought to be the final stage below 690°C, either being formed by a reaction between FeO and CO or between primarily formed Fe and CO. A closer investigation of reaction No. 6 shows that FeO and FeC, at a carbon monoxide pressure of 1 atm, can exist at temperatures of 710°C or lower, but not at higher temperatures, as the reaction will then result in the formation of metallic iron. At 600°C, the partial pressure of the carbon monoxide, at which this limit is to be found, is 0.14 atm.

A comparison of reactions No. 4 and No. 7 shows that at 600°C the partial pressure of the carbon monoxide at equilibrium is 50 pct according to reaction No. 4, but only 25 pct according to reaction No. 7. Results proved that the speed at which No. 4 was formed under prevailing conditions is much higher than for reaction No. 7. The difference in reaction speed is so great that the carbon monoxide seems to react completely, forming cementite, whereas the spontaneous decomposition cannot be verified. This is a most surprising statement, as general metallurgical experience indicates that, at temperatures just below 700°C, the reduction of iron ore, under ordinary conditions, cannot be carried through on account of the precipitation of carbon. Later tests have, however, verified this observation and promoted the development of the method now described.

**Principles of the new method**

In a fluidized bed with cementite as the main component traversed by carbon monoxide of relatively high concentration, concentrates are introduced at a temperature below 700°C. As the bed can be considered homogeneous, the same quantity of bed material, consisting of a product with a certain ratio between FeC and FeO, according to the period of interruption, is removed. The free flowing product can be transported directly to an apparatus suitable for the treatment to follow, or, it can be taken out of the system after cooling to 300°C and stored. The product is then heated to 750°C or more, and a very rapid reaction takes place with subsequent sintering and formation of metallic iron.

**The laboratory scale plant**

Speeds of reaction were studied in a series of laboratory tests carried out in the apparatus described in Fig. 2. The fluidization pipe (f), made from 25 pct chromium steel had a diameter of 65.9 mm and was placed in an electric kiln. Reducing agent was carbon monoxide supplied from a gas tube after removal of iron carbonyl. Both in and outgoing gases were analyzed, as well as material taken from the bed.

In fluidized processes, a bottom limit for the gas velocity can be determined according to the following formula:

\[
G_{\text{min}} = \frac{g \cdot D_e \cdot \theta^2 \cdot \rho_s \cdot (\rho_a - \rho_g) \cdot \Sigma}{180 \cdot \gamma \cdot (1 - \Sigma)} \text{ kg per sq m, sec}
\]

where

- \( G_{\text{min}} \) = gas mass velocity in empty pipe (kg per sq m)
- \( D_e \) = avg size of particles (m)
- \( \rho_s \) = density of solid material (kg per cu m)
- \( \rho_g \) = density of gas (kg per cu m)
- \( \gamma \) = approximate pore volume—no dimension
- \( \Sigma \) = dynamic viscosity of gas (kg per m s)
- \( g \) = 9.8 = earth acceleration (m per sq s)
- \( \theta \) = factor of particle form—no dimension

Estimates of the top velocity can be based on the limit value for beginning transportation of material of a certain size. This is how the region of gas velocity, in which the tests must be carried out, is determined. By means of the so-called J factors, it is possible to estimate the influence of the gas diffusion on the process, or, in other words, to estimate the difference in the partial pressure of the carbon monoxide close to the reacting surface and in the

---

**Fig. 1—Equilibrium constants calculated from thermodynamic data taken from U. S. Bureau of Mines Bulletin 476 and 477, and Chem. Eng. Handbook (1950).**

**Fig. 2—Fluidized bed plant in laboratory scale: a) furnace, b) flow meter, c) monomenter, d) monomenter, e) furnaces, f) fluidization pipe, g) charging pipe, h) cyclone, i) dust collector, k) thermometer, and l) water absorber.**
gas flow. The higher the gas velocity, the smaller is the difference. Based on values obtained as well as estimated, such a difference is calculated to \( \Delta P = 3 \times 10^4 \) atm for the concentrate mentioned and at a gas speed of 2 litres per min. As the partial pressure of the carbon monoxide is about 1 atm, this difference of a millionth atm, is, of course, negligible. It is consequently possible to disregard the diffusion at these velocities when determining the equipment to be used. In the same way, it can be stated that the heat is transmitted quite satisfactorily so that the temperature of the mass particles can be considered equivalent to the average temperature measured.

**Determination of reaction speed**

The kiln was charged with about 400 g of concentrates (<1 mm) at room temperature, after which the bed was fluidized with pure nitrogen gas while the temperature was increased to the reduction temperature decided upon. When this had been reached, the nitrogen was substituted with carbon monoxide or a mixture of carbon monoxide and carbon dioxide. The values of in and outgoing gas were plotted as relative partial pressure of carbon dioxide vs time in Fig. 3. By estimating the surface below the curve at different lengths of time, it is possible to find the value of the degree of reduction, shown in Fig. 4. In order to control the process, the furnace was cooled at different intervals (under nitrogen) and samples were taken for X-ray investigations. The curves showing how the reduction degree is influenced by the time indicate, among other things, the good reproducibility of the tests. The shape of the curve in Fig. 3 reveals that the reaction is performed step by step. At first \( \text{Fe}_3\text{O}_4 \) forms rapidly, then slower forming \( \text{FeO} \), and at last, very slow, the \( \text{Fe}_3\text{C} \).

It may be interesting to compare the thermodynamic states of equilibrium at 600°C, calculated to be

\[
\begin{align*}
\text{Fe}_3\text{O}_4/\text{Fe}_2\text{O}_3 & : 100 \text{ pct CO}_2 \\
\text{Fe}_2\text{O}_3/\text{FeO} & : 56 \text{ pct CO}_2 \\
\text{FeO}/\text{Fe}_3\text{C} & : 46 \text{ pct CO}_2
\end{align*}
\]

with the various steps. In a fluidized reactor, the solid phase has a constant composition, so all stages of reduction in the same charge are accomplished simultaneously. As the formation of \( \text{Fe}_3\text{C} \) takes place at the lowest speed, it is this that determines the total amount of reduced concentrates. In technical operation it is, of course, more advantageous to divide the process into several steps, and in that case to reduce to \( \text{FeO} \) in one step, which can be performed at a temperature of around 800°C and at an equilibrium concentration of about 70 pct \( \text{CO}_2 \). After this follows another step when reducing to carbide, the pressure of equilibrium then being 46 pct at 600°C. In this case the reaction

\[
3\text{FeO} + 5\text{CO} \rightarrow \text{Fe}_3\text{C} + 4\text{CO}_2
\]

will determine the speed. The problem is to determine the velocity in the latter process in order to make it possible to estimate the volume of the reactor.

The speed of reaction is usually expressed as

\[
\tau = \frac{\text{amount of reacted FeO}}{(\text{total amount of FeO in bed}) \times (\text{time in minutes})}
\]

The experiments so far have not aimed at finding an equation for the ratio between \( \tau \) and the different factors such as temperature, gas composition, etc., since this was determined with graphically established relations. Complications arise because material cannot be cooled down quickly enough. \( \text{FeO} \) is, as is known, not constant below 570°C; it reacts, forming \( \text{Fe}_3\text{O}_4 \), and \( \text{Fe} \). It is, therefore, necessary to make a correction of the established phase composition, corresponding to this decomposition. From the analyses made on the powder it can be seen that, at the beginning of the reaction, a certain content of metallic iron (5 to 10 pct) is at hand; the formation of carbide starts later. During the formation of carbide, the content of metallic iron is diminished, and the content of carbide is increased. As a consequence, it might be assumed that the reaction takes place in the following two stages:

1. \[
3\text{FeO} + 3\text{CO} \rightarrow 3\text{Fe} + 3\text{CO}_2
\]
2. \[
3\text{Fe} + 2\text{CO} \rightarrow \text{Fe}_3\text{C} + \text{CO}_2
\]

At low temperatures, the speed of [1] is so low that the reaction seems to continue directly into the carbide. At higher temperatures and in discontinuous operation, a certain amount of \( \text{Fe} \) can be found in the charge. Of even greater importance, however, is the discovery that the speed at which carbide is formed is of greater importance than the speed at which the carbon monoxide is decomposed into carbon and carbon dioxide. This seems to be the case in charges with a rather high metallic iron content as well as iron carbide. The spontaneous decomposition...
of the carbon monoxide is apparently catalyzed by metallic iron, and the velocity seems to be at its maximum at temperatures around 600°C. In spite of that, the formation of carbide is more rapid at 600°C than the decomposition of carbon monoxide.

**Preliminary oxidation important**

As will be seen from below, there are some very compact magnetite ores where the reaction speed is so slow that the decomposition of carbon monoxide preponderates. If, however, an oxidation of magnetite to hematite is carried through first, the speed of reduction will increase to such an extent that these ores can also be reduced while forming carbide, without any decomposition of carbon monoxide.

The established speeds of reaction are dependent on the composition of the gas. An increase of the relative content of carbon dioxide will result in a decrease of the reduction speed, which should be 0 at the pressure of carbon dioxide that corresponds to equilibrium. The speed of reaction can thus be expressed

$$ r = f(p_{CO}) $$

when assuming that $p_{CO} + p_{CO_{2}} = 1$.

The curve given in Fig. 5 represents the ratio between the reaction speed and the partial pressure of carbon dioxide in different concentrates. The quantity of reduced concentrate per unit time has been estimated for certain intervals and set in relation to the arithmetic medium for the partial pressure of carbon dioxide in the interval concerned.

As a result of the comparison of different concentrates, it appears that hematite concentrates, quite in accordance with earlier experience, are reduced much more rapidly than the magnetite concentrates. If, however, the latter undergo a previous oxidation, the speed of reduction for the oxidized product becomes normal again. This is clearly seen from Fig. 6.

In the use of magnetite concentrates it is, consequently, necessary to reoxidize the magnetite before reduction. In order to study this process, the oxidizability of various magnetite concentrates in a fluidized bed was watched at temperatures from 800° to 1000°C. It is quite possible to use the latter temperature without any tendency to sinter. It may be that still higher temperatures can be considered, but this question has not been investigated. The fluidization was carried through by air and the gas leaving was analyzed as to its content of oxygen. X-ray tests were made on the solid phase. On the basis of analyses obtained, the reacted amount of oxygen was calculated, and from that the degree of oxidation. It is found that with the Rudgruve and Smaltarmosse concentrates, the ratio of $\frac{FeO_{x}}{FeO_{y}}$ after 30 min of oxidation at 900°C amounted to about 0.4, whereas the corresponding value of Grangesberg concentrates after 20 min was 1.3, and even after 75 min, 1.2.

The technical method from which the experiments described above were made is similar to the Wiberg-Söderfors method as regards its general outlining. There are three separate phases of reaction, one oxidizing and preheating step, then a prereducing step down to around the wüstite stage, and finally a reducing step to finished product, which, in this method, however, is continued to cementite instead of to metallic iron as in the Wiberg-Söderfors process.

**Possibility for continuous operation**

The laboratory tests carried out did not, however, give any reliable idea of what possibilities were offered by this method for a continuous operation. It was not possible to entirely exclude the possibility that changes could occur in the bed at longer periods of reaction and, thus, create technical difficulties. On account of that, it was decided to erect a pilot plant calculated for a capacity of about 100 kg of reduced Fe per 24 hr at continuous operation. This plant is shown in Fig. 7. The reactor (A) consists of a cylindrical pipe of 25 pct chromium steel with an inside diameter of 355×2500 mm with a conic bottom measuring 450 mm in height, all material with a thickness of 5 mm. Although the process in itself is exothermic, the pipe is equipped with a Kanthal winding for supply of electric power. The whole of it is insulated and enclosed in a casing. The material is charged on to the bed from a silo (1) via a feeding screw (2) and the vertical pipe (3). The finished reaction product is discharged via the pipe (6) to a bed (7) equipped with a cooling mantle, where the material, still fluidized, is cooled and then discharged via pipes (12). For discharging, double cocks (13) are installed. The reducing gas is preheated in the electric preheater (1) and led out via the cyclone (5) to the heat exchanger (B) through the electrical dust separator (D), and the cooler (E) to the washing tower (F), where carbon dioxide was analyzed as to its content of oxygen.

---

Fig. 5—Speed diagram for reaction (4) with a) Orlingruve concentrate, b) pyrite cinders, and c) mixture of different concentrates.

Fig. 6—Degree of oxidation where linear gas velocity equaled 1 cm per sec. A, hematite, and B, C, and D, different magnetite concentrates oxidized at 900°C with air; MgO content <10 pct.
generated is washed away by water. The liberated gas passes the drying towers (G), the fan (H), and the heat exchanger (B) to the preheater (I) back to the furnace.

As was mentioned in the description, there was only one furnace section, whereas in general three different sections will be necessary. For that reason the process was carried through in two steps successively. The magnetite was first oxidized, then reduced to iron carbide in a later campaign. The first stages of the reduction process, the transformation of hematite to wüstite, are carried through so rapidly and without any difficulties whatsoever that this dividing of the process was not considered necessary in the pilot plant tests.

**Pilot plant results**

The results obtained from the tests were in complete correspondence with the laboratory tests. The reaction speeds, as well as the general behavior of the bed, were thus in complete accordance with expectations. By varying the time during which the material was kept in the bed, it was possible to control the final composition of the bed as far as the ratio between carbide and wüstite was concerned.

Best pilot plant tests were, for different reasons, carried out with a mixture of concentrates of a rather complicated composition, as shown in Table I. Oxidation was carried out at 900°C, as the experimental equipment did not allow any higher temperature. The content of ferrous iron was diminished to around 1 pct FeO within 40 hr. If the limit was fixed to 5 pct of FeO, the time of detention at 900°C would have been 14 hr, and at 1000°C, 3 to 4 hr. The yield of product discharged from the kiln was about 95 pct, while about 5 pct was found in dust collectors. The gas velocity used was about 0.166 m per sec. The counter-pressure in the apparatus at a charge of 390 kg, corresponding to a total height of the bed of about 2 m, amounted to about 5 m water column. The oxidation tests showed the same result as the laboratory tests. During oxidation, the sulfur content of the ore is decreased from 0.4 to 0.1 pct S. A higher temperature during the oxidation would probably cause a still higher removal of sulfur.

Two different reduction campaigns were made, one with carbon monoxide from a bottle, resulting in 85 pct CO and 5 pct CO₂ in the inserted gas; 60 pct and 30 pct respectively in the leaving gas. During the second period, a gas generated with charcoal was used, causing a lower total content of carbon monoxides, viz. around 65 pct CO and 2 pct CO₂ in the inserted gas, 50 pct CO and 20 pct CO₂ in the leaving gas. The contents of hydrogen in the gas generated with charcoal amounted to about 10 to 15 pct, and yet no disturbances arose in the process, whereas the content of nitrogen increased to about 15 pct.

Study of the results shows that the reduction obtained as regards the composition of the end products as well as the speed of reaction, are in excellent correspondence with the calculations based on the laboratory tests. The end products varied in content of Fe₃C between 60 and 90 pct with a total content of carbon of between 4.3 and 7 pct, out of which 0.1 to 0.2 pct consisted of free carbon and the remainder of carbide. The content of metallic iron is in general only a few percents, but an increase up to 10 or 14 pct does not cause any sticking. The time of reduction was, as expected, increased at higher contents of Fe₃C. The process can be driven to 100 pct Fe₃C without any noticeable difficulties. It seems, however, that in most cases it would be advisable to maintain a close equivalence between Fe₃C and FeO when continuing the reaction to metallic iron. When reducing extensively to Fe₃C, the material turns more and more brittle and tends to form more dust.

**Hydrogen in reducing gas checked**

When producing carbon monoxide on a technical scale or when carburizing carbon dioxide, there is always a certain amount of hydrogen formed in the reducing gas. It was to be expected that too high a content of hydrogen would facilitate the formation of metallic iron in the bed, with subsequent tendency to stick. The reaction

$$\text{Fe}_3\text{C} + 2\text{H}_2 \leftrightarrow 3\text{Fe} + \text{CH}_4$$

can take place, from a thermodynamic point of view, at a temperature of 600°C. The equilibrium conditions for this reaction are transferred to the right at decreasing temperature. The ratio between the partial pressures of methane and hydrogen at 550°C will thus be 1. As a consequence, it could be expected that, at a certain content of hydrogen in the reducing gas, a bed of iron carbide should be gradually transformed into metallic iron and sticking occur. The situation might also arise that wüstite is reduced into metallic iron more quickly by means of hydrogen than into carbide by carbon monoxide.

![Diagram of fluidized bed pilot plant for production of sponge iron](image)
However, experiments made as long-time tests on a pilot plant scale show that up to 30 pct H₂ may be used continuously without any disturbances of the fluidizing conditions. This statement is valuable inasmuch as that some day it may become desirable to use gas obtained by decomposition of oil or natural gas, in which case it will probably be necessary to maintain a not inconsiderable content of hydrogen.

Comparison with Wiberg-Soderfors method

The process can be carried out in different ways according to the requirements in each special case. In order to secure the most favorable heat economy, an adoption similar to the Wiberg-Söderfors method would probably be best. A comparison between flow of material and temperature in the two processes is shown in Fig. 8. The new method is here assumed to be carried out in three different steps: The concentrates are fed into an oxidizing room, where magnetite is oxidized to hematite at a temperature of about 900°C. After this, the material flows down to the prereduction zone, where it is reduced, at about 750°C, to the FeO stage. The material is then allowed to fall down into the final reduction zone, where the reduction is continued to carbide at 600°C. The material is then discharged via a cooler and can be tapped at about 200°C. The reducing gas, which is introduced into the final reduction zone at a relative content of carbon monoxide amounting to 96 pct CO and 4 pct CO₃, is divided in such a way after the final reduction stage that 82 pct is circulating through a carburettor, while the remaining 18 pct passes the prereduction zone and then the oxidizing zone, where the remaining CO is burnt. When leaving the final reduction zone, the gas consists of 65 pct CO and 35 pct CO₃.

Fig. 8 also indicates the temperature conditions; the gas coming from the carburettor must be cooled from about 1000°C down to about 300°C in order to secure equilibrium of temperature in the zone for final reduction. In the figure we have presumed preheating of the air to the oxidizing zone. On the whole, the two processes turn out to be equivalent as to consumption of material and power; the new method might have a somewhat lower consumption as to consumption of material and power; the new method might have a somewhat lower consumption of material and temperature in the two processes is shown in Fig. 8. The new method is here assumed to be carried out in three different steps: The concentrates are fed into an oxidizing room, where magnetite is oxidized to hematite at a temperature of about 900°C. After this, the material flows down to the prereduction zone, where it is reduced, at about 750°C, to the FeO stage. The material is then allowed to fall down into the final reduction zone, where the reduction is continued to carbide at 600°C. The material is then discharged via a cooler and can be tapped at about 200°C. The reducing gas, which is introduced into the final reduction zone at a relative content of carbon monoxide amounting to 96 pct CO and 4 pct CO₃, is divided in such a way after the final reduction stage that 82 pct is circulating through a carburettor, while the remaining 18 pct passes the prereduction zone and then the oxidizing zone, where the remaining CO is burnt. When leaving the final reduction zone, the gas consists of 65 pct CO and 35 pct CO₃.

Fig. 8 also indicates the temperature conditions; the gas coming from the carburettor must be cooled from about 1000°C down to about 300°C in order to secure equilibrium of temperature in the zone for final reduction. In the figure we have presumed preheating of the air to the oxidizing zone. On the whole, the two processes turn out to be equivalent as to consumption of material and power; the new method might have a somewhat lower consumption of coke. The consumption of electric power for the carburization may be somewhat lower than in the Wiberg-Söderfors process, but the fan work for the gas circulation will be a little higher.

A question that will not be dealt with in this article is the further treatment of the final product, which is highly rich in cementite. The product will, under all circumstances, become a valuable complement to ordinary sponge iron.

Conclusions and discussion

The main result of the experiments reported above can be summarized as follows:

1) In a fluidized bed of iron oxides reduced with carbon monoxide at high temperatures, disturbing tendencies to sticking will be found at a certain content of metallic iron.

2) If, however, the reduction is carried out at lower temperatures (around 600°C) in a fluidized bed under favorable conditions, cementite is formed instead of metallic iron, and the bed does not show any tendencies to sticking.

3) The forming of cementite takes place so quickly, under the conditions used, that the decomposition of the carbon monoxide into carbon and carbon dioxide does not set in.

4) The speeds of reduction for different hematite ores, as for oxidized magnetite ores, have been determined. Also the speed of oxidation for some magnetites was studied.

5) The features of a technical process based on the results gained has been described and studied on a pilot plant scale. The results were very promising. The method is operating entirely continuously and can, to judge from experiments with other fluidizing processes, be constructed in widely varying sizes. The capital requirements are relatively limited. A comparison with other methods will designate the process described here as the most advantageous in many respects. Risks for hanging of the material are entirely eliminated. The heat economy is at least equal to that of the Wiberg-Söderfors method. The cementite is resistant to air and does not show any pyrophoric properties. Cementite or cementite and wüstite as final product opens many prospects for the further treatment of the product. It can easily be incorporated in a fully continuous system.

6) In comparison with the H₂ reduction in a fluidized bed developed in the US, the above method presents many advantages. It is, for instance, operated at atmospheric pressure and without any cooling or heating cycles for the reducing gas. A production of hydrogen will normally be more complicated than producing carbon monoxide. It may not be impossible to use oil as well as natural gases for producing a suitable reducing gas.

Fig. 8—A comparison between the Wiberg-Söderfors process and the carbon monoxide fluidizing process. U. S. Representative of the owners of the new process is Stora Kopparberg Corp., New York.