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REDUCTION RATES OF IRON ORE-CHAR BRIQUETS USED IN CUPOLA SMELTING

J.F. GRANSDEN, J.T. PRICE AND N.J. RAMEY
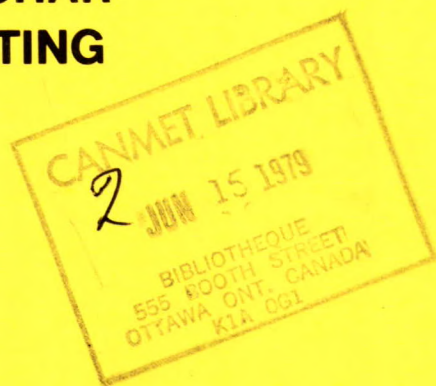
MINERALS RESEARCH PROGRAM

ENERGY RESEARCH LABORATORIES

REDUCTION RATES OF IRON ORE-CHAR BRIQUETS
USED IN CUPOLA SMELTING

by

J.F. Gransden,* J.T. Price* and N.J. Ramey**

ABSTRACT

CANMET recently examined the potential of the Peace River iron deposit as a source of iron for the steel industry in Western Canada. One unconventional ironmaking method was investigated - the smelting of iron ore-char briquets in a cupola. This report describes the reduction behaviour of the briquets determined in laboratory experiments.

Reduction was monitored by an O_2-sensing solid state cell and was complete in isothermal experiments above 950°C. Reduction in a counter-current reactor took place in a stepwise manner. Nearly all of the Fe_2O_3 was reduced to Fe_3O_4 before Fe_3O_4 was reduced to FeO and reduction to FeO was almost complete before iron was formed. Experiments at a heating rate similar to that occurring during cupola smelting showed the reduction rate was a maximum at 950°C and that reduction was near completion before melting took place. The relative quantities of CO and CO_2 produced are used to formulate a heat balance for a typical cupola smelting trial. The estimated and actual process heat requirements are in satisfactory agreement.

This report describes the reduction behaviour of the briquets on a lab scale and uses the results to learn more about what is going on in the cupola trials. The prospects for the process are commented on in a previous report (2) where the cupola trials are described.

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LES TAUX DE REDUCTION DES BRIQUETTES DE MINERAI
DE FER CARBONISE EMPLOYEES POUR LA FUSION DANS UNE COUPOLE

par

J.F. Gransden*, J.T. Price* et N.J. Ramey**

RESUME

Le CANMET a récemment examiné le potentiel des gisements de fer de Peace River comme source de fer pour l'industrie sidérurgique de l'Ouest du Canada. Une des méthodes conventionnelles de fabrication du fer analysée est la fusion des briquettes de minerai de fer carbonisé dans une coupole. Le présent rapport décrit le comportement de réduction des briquettes ainsi déterminé par les expériences effectuées en laboratoire.

La réduction était contrôlée par une cellule détectrice d'O_2 à l'état solide et est complète dans les expériences isothermiques à plus de 950°C. La réduction effectuée dans un réacteur à contre-courant s'est déroulée par étapes. Presque tout le Fe_2O_3 est réduit à Fe_3O_4 avant que le Fe_3O_4 soit réduit au FeO, et la réduction au FeO était presque complète avant que le fer soit formé. Les expériences effectuées à des températures sem- blables à celles qui se produisent lors de la fusion du minerai dans la coupole, ont démontré que le taux de réduction avait atteint un maximum à 950°C et que la réduction est presque complétée avant que ne se produise la fusion du métal. Les quantités relatives de CO et de CO_2 produites sont employées pour trouver un équilibre de température dans le cas d'un essai typique de fusion du minerai dans une coupole. Les exigences théoriques et actuelles de température pour ce procédé correspondent de façon suffisante.

Le présent rapport décrit le comportement de réduction des briquettes en laboratoire et les résultats permettent de comprendre ce qui se passe dans les essais de coupole. Un rapport précédent (2) décrivant les essais de coupole, expose les perspectives de ce procédé.

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INTRODUCTION

A joint study has been undertaken by CANMET and the Research Council of Alberta to evaluate the potential of the Peace River iron ore deposits as a source of iron for the steel industry in Western Canada. High-grade iron ore concentrates suitable for today's ironmaking processes cannot be produced from these deposits by conventional beneficiation techniques (1). Part of this study was therefore devoted to cupola smelting, a non-conventional ironmaking technique potentially suitable for unbeneficiated or partially upgraded Peace River iron ore.

In cupola smelting a mixture of iron ore and char or coal is agglomerated and charged into a cupola together with foundry coke and limestone. The iron ore is reduced to iron as the agglomerates are heated and melted. Liquid iron and slag are tapped separately from the cupola well. Smelting trials were made in a 0.4-m I.D. cupola in this laboratory (2), and in this report the reduction kinetics of the agglomerates used in the smelting trials are examined.

It is generally accepted that the reduction of iron oxides in mixtures with carbon proceeds according to the following reactions (3,4):

$$3Fe_2O_3 + CO \rightarrow 2Fe_3O_4 + CO_2 \qquad eq\ 1$$

$$Fe_3O_4 + CO \rightarrow 3FeO + CO_2 \qquad eq\ 2$$

$$FeO + CO \rightarrow Fe + CO_2 \qquad eq\ 3$$

$$C + CO_2 \rightarrow 2CO \qquad eq\ 4$$

$$C + \tfrac{1}{2}O_2 \rightarrow CO \qquad eq\ 5$$
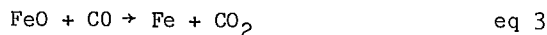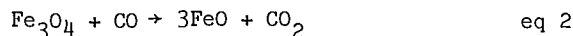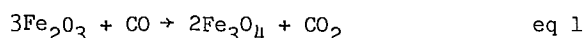
The extent of direct reduction of iron oxide by solid carbon, as shown by eq 5, is generally small. Gasification of carbon is considerably slower than reduction of iron oxide below about 1100°C and the rate of reduction is controlled by eq 4. At higher temperatures it is believed that oxidation of carbon and reduction of iron oxide jointly control the reduction rate (3).

The reaction kinetics are complex and conceivably are dependent on a number of chemical and physical factors. The reduction rate of iron oxide from a particular source has been shown to vary with the particle size of the oxide and carbon in the agglomerate, the type and quantity of carbon, and the reaction temperature (4). In addition, some elements are found to promote or inhibit the reaction and some influence is exerted by the gas atmosphere in which the reaction takes place (3).

REDUCTION RATES AT DIFFERENT TEMPERATURES

Agglomeration

Experiments were performed on samples of Peace River iron ore and a Carol Lake iron ore concentrate (Table 1). The Peace River sample had a low iron, high silica content compared with the concentrate and consisted of geothite, nontronite, ferruginous opal, siderite, quartz, amorphous phosphate and illite (1). The Carol Lake concentrate was used in smelting trials in a 0.23-m diameter cupola (5). A Saskatchewan lignite char, obtained from Luscar Sales Ltd., Edmonton, Alberta, was the carbon source in the agglomerates. The char contained 70.0% fixed carbon, 12% volatile matter, 8% moisture and 10% ash.

Table 1 – Chemical analysis of Peace River iron ore and Carol Lake iron ore concentrate

	Peace River ore wt %	Carol Lake ore wt %
Fe	31.83	64.8
SiO_2	24.48	6.10
Al_2O_3	5.56	0.16
CaO	3.10	0.41
MgO	1.01	0.38
MnO	0.14	0.19
S	0.07	0.01
P	0.68	0.01
Loss on ignition	14.48	–

The agglomerates were formed by briquetting in a roll press using asphalt as a binder. Char and ore crushed to minus 840 µm (20 mesh) were mixed in a double-arm kneader-mixer and heated to 120°C. The asphalt was type II which melts at between 71 and 80°C, and was added to the mixer at about 180°C. After blending for ten minutes the mixture entered the roll press which produced pillow-shaped briquets, 2.5 cm square and 1.5 cm thick. The briquets were hardened by curing in air at 200-230°C for three hours.

Average compression strengths for the briquet compositions used in this report, were 100 and 140 kg (220 and 310 lb) for Peace River and Carol Lake briquets respectively (Table 2) (6).

Experimental Method

Carbon monoxide and carbon dioxide are given off during reduction of iron oxide-carbon mixtures. The gas composition and rate of evolution varies with time and must be determined to allow calculation of the rate of oxygen or carbon removal. As reduction takes only a few minutes at high temperatures, a method of continuously measuring the composition of this gas is required. A galvanic cell was used to monitor the oxygen potential of the gas. Cell voltage and temperature were used to calculate the CO_2/CO ratio of the evolved gas (7). The gas was collected by liquid displacement and the rate of evolution was obtained by recording time and gas volume readings.

Specimens weighing about 1 g were cut

Table 2. - Briquet composition

	Peace River briquets wt %	Carol Lake briquets wt %
Ore	73	71
Char	11	19
Lime	6	3
Asphalt	10	7

from briquets and reduced in a high temperature tubular furnace. The galvanic cell, which consisted of a lime-stabilized zirconia electrolyte with platinum electrodes and air as the reference electrode, was located 4 cm downstream from the specimen (7). Experiments were started by quickly inserting the specimen into the furnace tube which had previously been flushed with nitrogen.

The weight of oxygen in the gas evolved during short periods of time was calculated from the average gas composition during the time period to obtain the oxygen lost by the specimen as a function of time. The results are presented in the form of plots of fraction reduction, F_o, versus time (Fig. 1 for Peace River ore and Fig. 2 for Carol Lake concentrate). The definition of fraction reduction used is:

$$F_o = \frac{\text{weight of oxygen removed from iron oxide during time } t,}{\text{initial weight of oxygen in iron oxide}}$$

Reduction Rates

The fraction reduction-time curves show that both ores were reduced rapidly and completely at temperatures above 1000°C. At temperatures below about 830°C the reduction rates were slow, especially in the later stages of reduction, and extensive metallization was not obtained at the lowest temperatures employed.

The rates of CO_2 and CO gas evolution during reduction of a Carol Lake ore specimen is shown in Fig. 3. Both rates initially increased quickly and after three minutes declined slowly. The behaviour of the CO_2/CO ratio, also plotted in Fig. 3, is of greater interest. The ratio became constant with reduction time between 0.8 and 1.2 min and again between 2.1 and 5.0 min.

This behaviour is interpreted as follows (8): Fe_2O_3 was reduced to Fe_3O_4 during the intial 0.8 min; the first period of constant CO_2/CO ratio corresponded to the reduction of Fe_3O_4 to FeO and the second to the reduction of FeO to Fe; hence the specimen was largely reduced to one oxide compound before reduction to
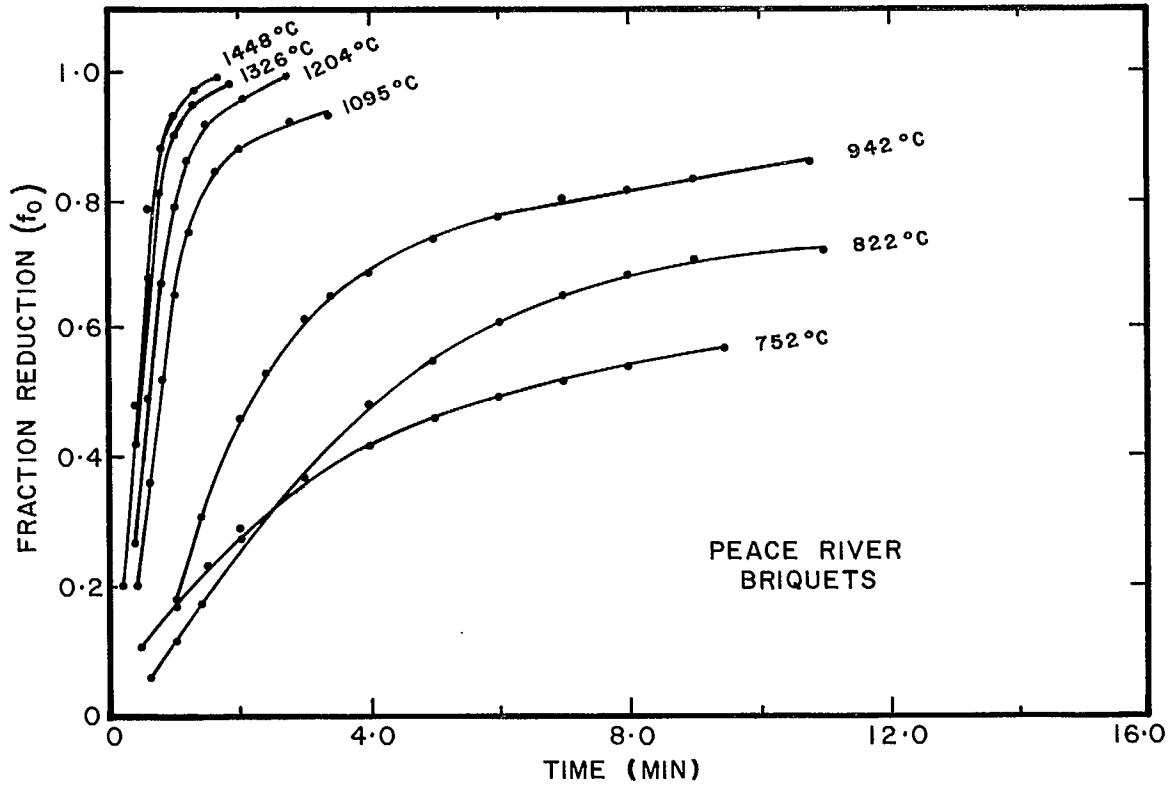
Fig. 1 - Effect of temperature on the reduction
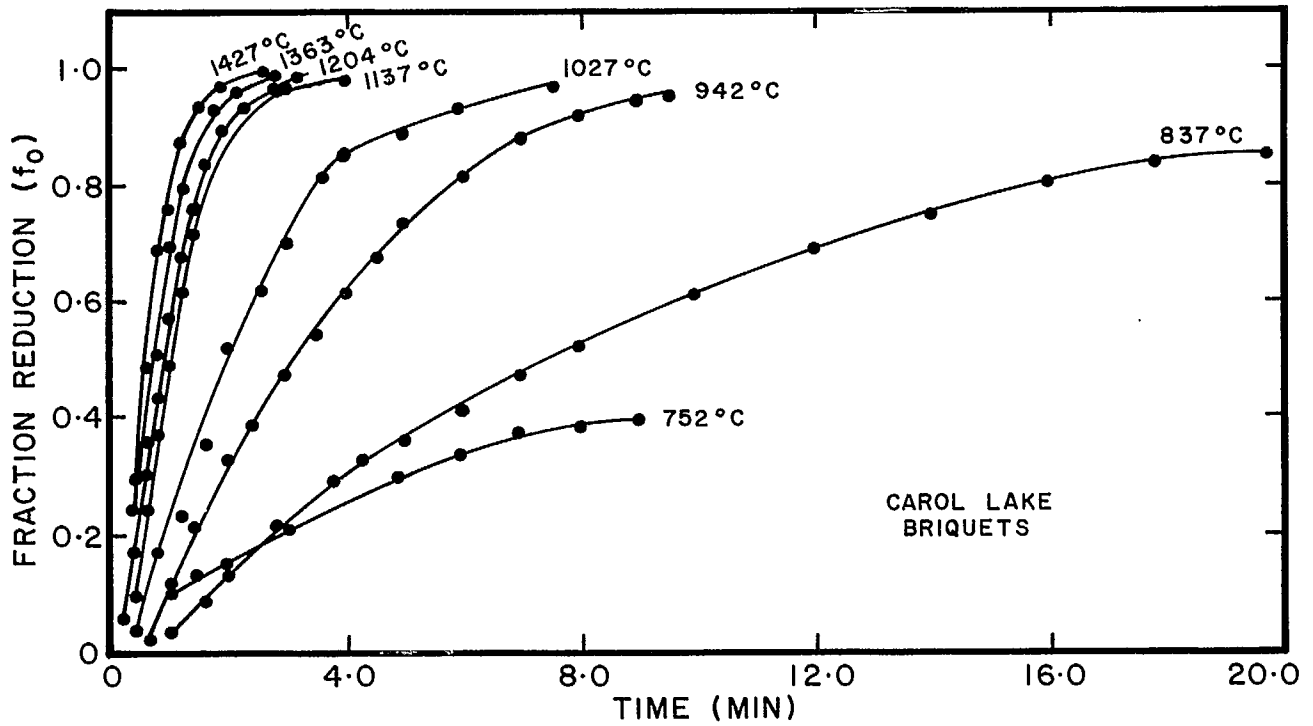rate of Peace River iron ore-char briquets

Fig. 2 - Effect of temperature on the reduction
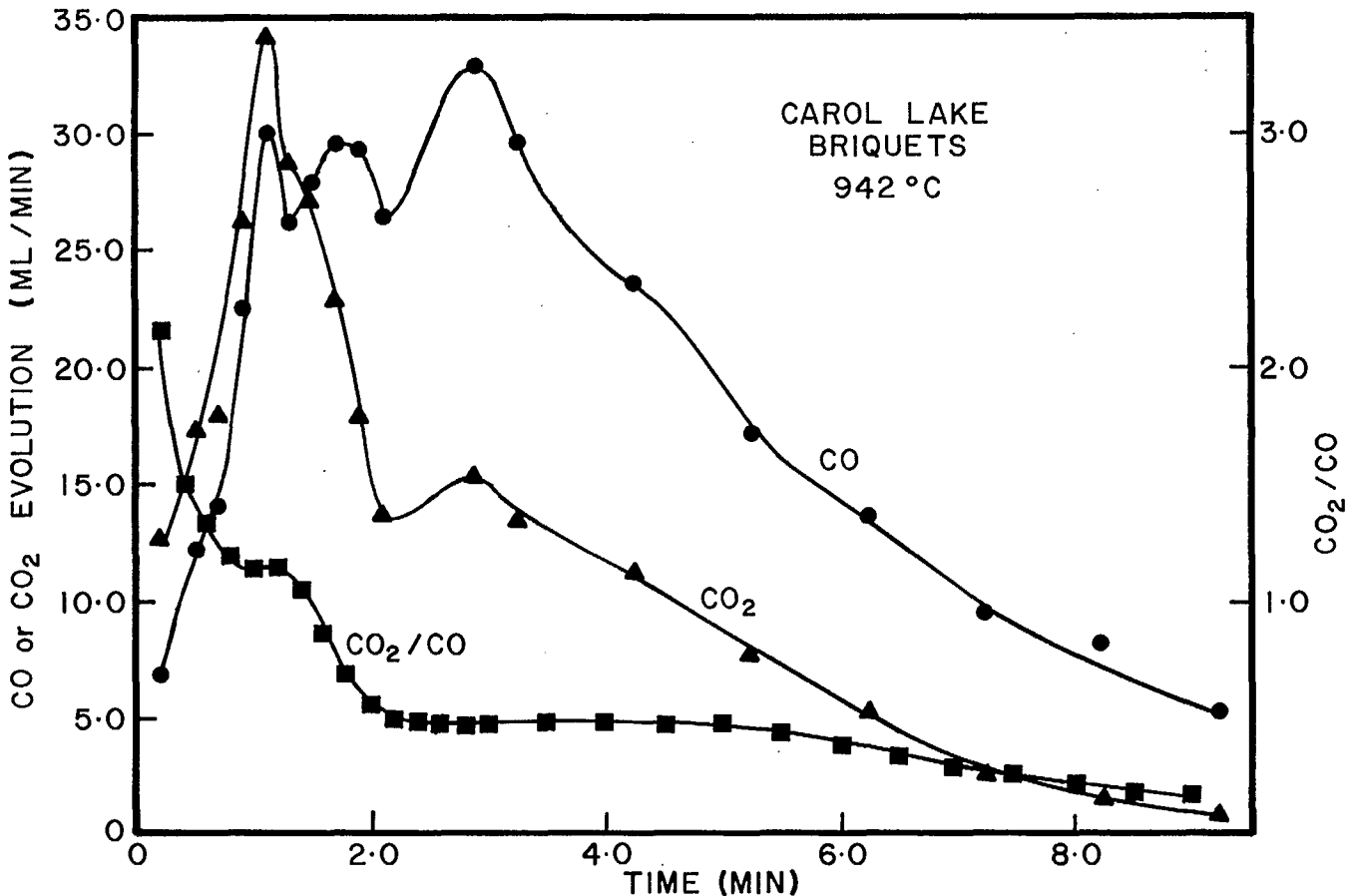rate of Carol Lake iron ore-char briquets

Fig. 3 - Rate of gas evolution during reduction
of Carol Lake briquets at 942°C

the next lower oxide occurred.

The gasification of carbon, eq 4, largely controlled the reduction rate during the time periods when the CO_2/CO ratio was constant. The CO produced by this reaction was then utilized in the iron oxide reduction reactions, eq 2 and 3, to the extent allowed by the thermodynamics of the systems. Hence the first constant CO_2/CO ratio should have approached the CO_2/CO ratio in thermodynamic equilibrium with Fe_3O_4 and FeO at 942°C and the second should have approached the CO_2/CO ratio in equilibrium with FeO and Fe at 942°C. The experimental CO_2/CO ratios are 1.15 and 0.48 and the thermodynamic equilibrium values, calculated

from data given in Reference 9, are 3.7 and 0.44 respectively. The equilibrium values cannot be exceeded and the small excess in the ratio for FeO and Fe is most likely caused by assuming the specimen temperature was equal to the furnace temperature, 942°C. The chemical reactions are endothermic and the true specimen temperature was probably lower.

Fe_2O_3 was reduced to Fe_3O_4 during the inital 0.8 min of reduction time before the first constant CO_2/CO time period. The gas in equilibrium with Fe_2O_3 and Fe_3O_4 consists almost entirely of CO_2 but only a moderately large CO_2/CO ratio, 2.3, was observed (9). Therefore, during this period and after the

second constant CO_2/CO period, other reactions or processes besides carbon gasification were important in determining the reduction rate.

Figures 4 and 5 show the CO_2/CO ratio of the gas evolved by the specimens during reduction at different temperatures. Periods of constant CO_2/CO ratio corresponding to the reduction of Fe_3O_4 to FeO occurred for Carol Lake concentrate at reduction temperatures of 942 and 1027°C and for Peace River ore at 822 and 942°C. None are discernible at higher reduction temperatures for either ore. Periods of constant CO_2/CO ratio corresponding to the reduction of FeO to Fe occurred at all reduction temperatures shown in Fig. 4 for Carol Lake concentrate, but only at 942°C for Peace River ore. It is concluded that gasification of carbon largely controls the rate of reduction only at the lower reduction temperatures. Fruehan has

suggested reduction of FeO by CO partially controls the reduction rate at temperatures close to 1200°C and assumes greater importance at higher temperatures (3).

The total amount of CO and CO_2 gas evolved by a specimen at a particular reduction temperature can be calculated from the experimental results. The ratio of these quantities, $(CO_2/CO)_t$, is plotted against temperature in Fig. 6 and is seen to decrease with increasing temperature. This is because the CO_2/CO ratio in equilibrium with Fe/FeO decreases with temperature.

Although the relative amounts of carbon and oxygen in the two types were similar, the Peace River briquets had lower $(CO_2/CO)_t$ ratios at all temperatures. A possible explanation is the large amount of silica in this ore, some of which is intimately associated with the
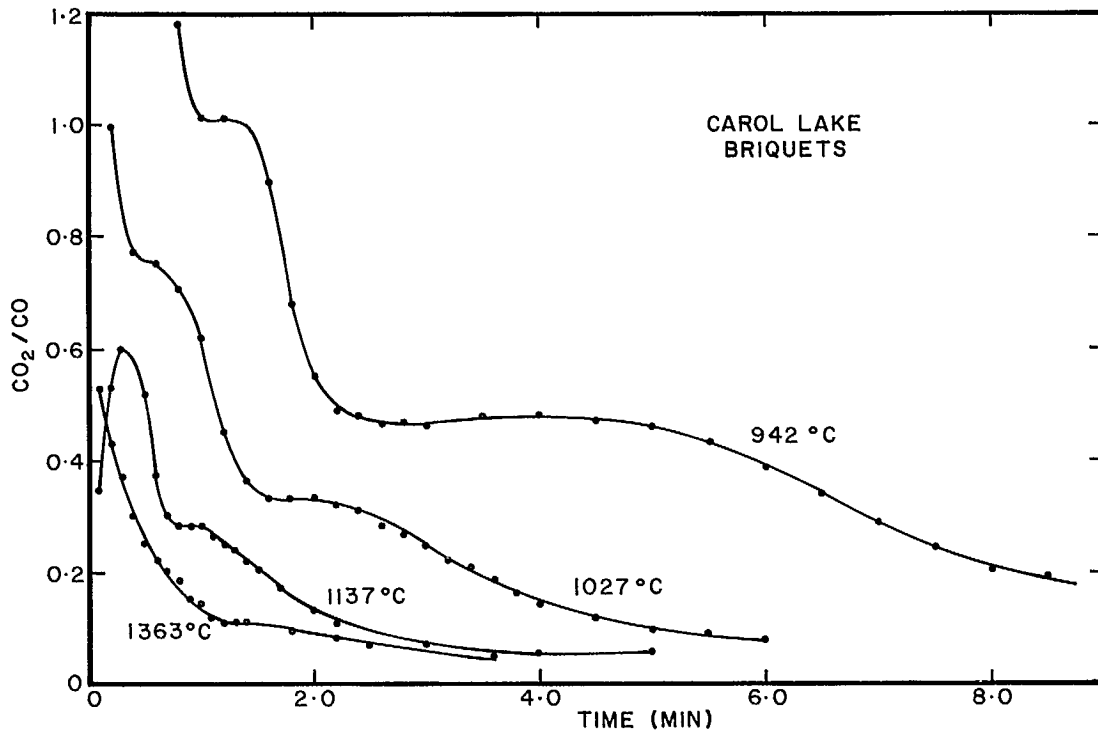
Fig. 4 - CO_2/CO ratio of gases evolved during reduction of Carol Lake briquets at various temperatures
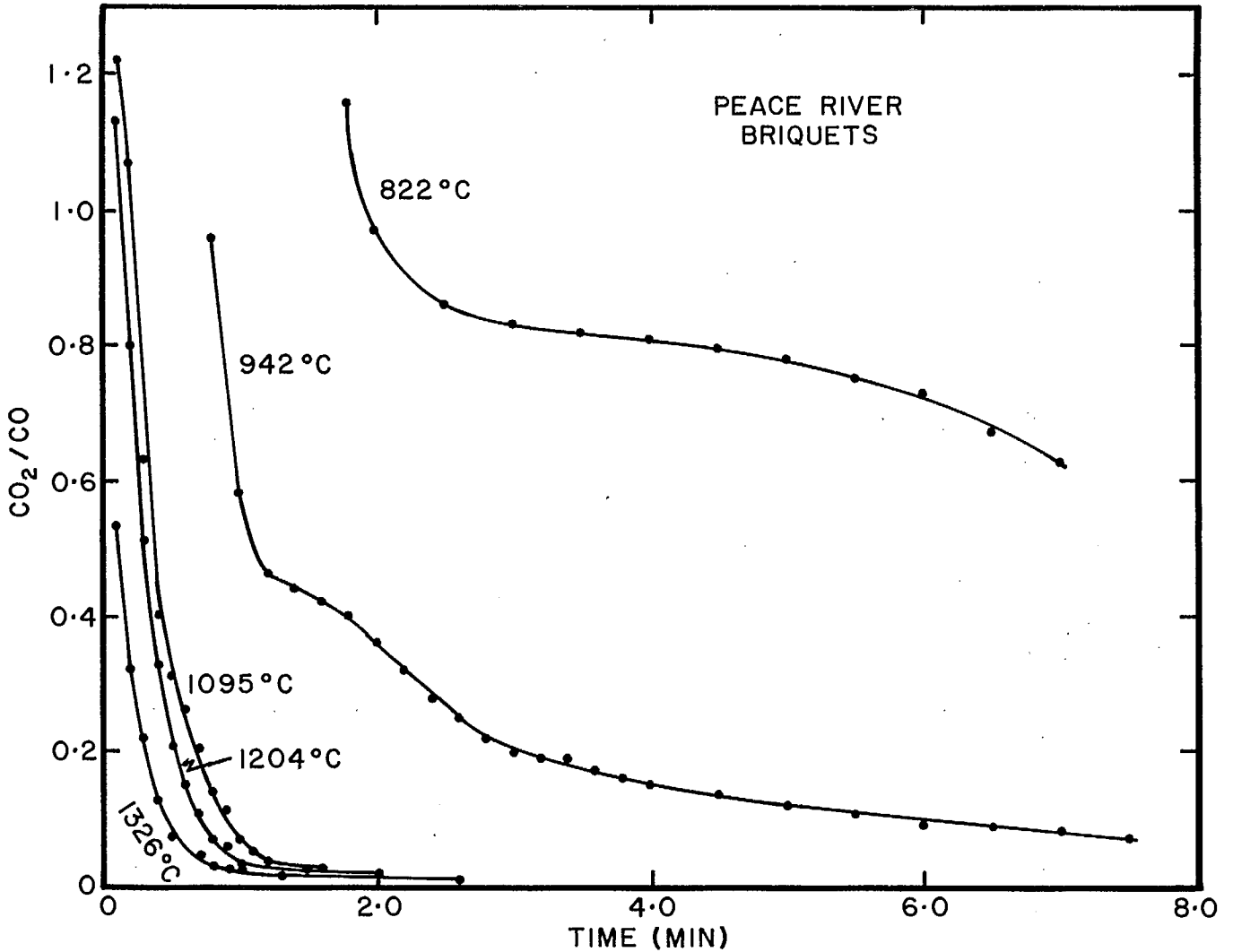
Fig. 5 - CO_2/CO ratio of gases evolved during reduction of Peace River briquets at various temperatures

Table 3 - Comparison of measured and thermodynamic equilibrium CO_2/CO ratios

Briquet Type	Temperature °C	Fe_3O_4/FeO Equilibrium CO_2/CO	Experimental CO_2/CO	FeO/Fe Equilibrium CO_2/CO	Experimental CO_2/CO
	942	3.7	1.15	0.44	0.48
Carol	1027	4.5	0.75	0.38	0.33
Lake	1137	-	-	0.34	0.28
	1363	-	-	0.27	0.15
Peace	822	2.5	0.83	-	-
River	942	3.7	0.45	0.44	0.18
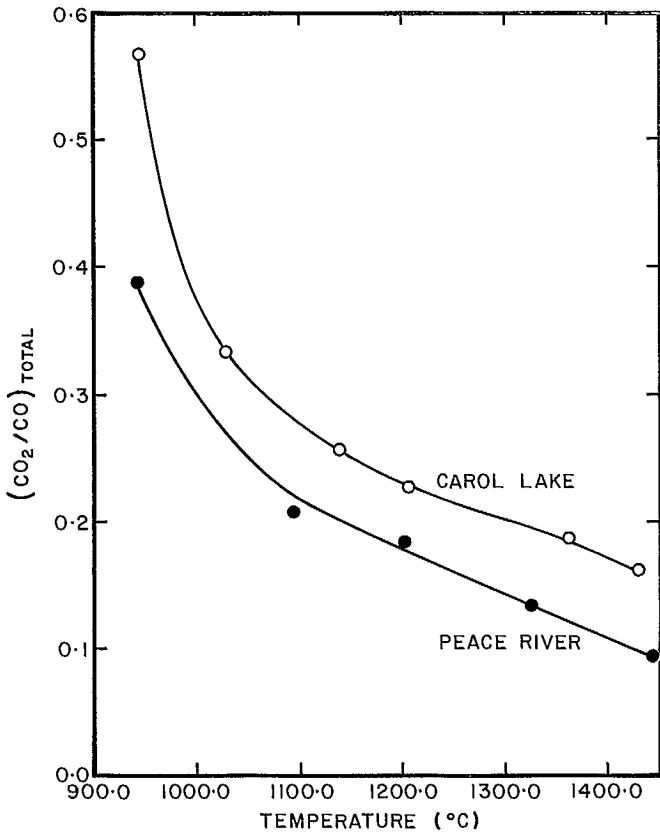
Fig. 6 - Ratio of the total quantities of CO and CO_2 evolved, $(CO_2/CO)_t$, during reduction at different temperatures

iron oxide (1). Iron-silica compounds, such as fayalite, $2FeO:SiO_2$, may have formed on heating (10). The CO_2/CO ratios in equilibrium with such compounds and iron are lower than the Fe/FeO equilibrium ratio. Therefore lesser amounts of CO_2 would be evolved during reduction of iron-silica compounds than during FeO reduction when the gasification of carbon was largely controlling the reduction rate.

REDUCTION RATES IN A COUNTER-CURRENT REACTOR

In the cupola the briquets were not reduced at a constant temperature as in the experiments just described, but at a continuously rising temperature as they descended through the furnace. Their reduction behaviour under this

condition was examined in a counter-current reactor (Fig. 7). This apparatus and its operation are fully described in Reference 11.

A weighed quantity of briquets was placed into each of the 100 trays contained in a vertical stainless-steel reduction tube 5 cm ID x 5 m in length. A tube furnace travelled along the reduction tube at a controlled rate. A thin stainless-steel tube, located axially within the reduction tube, contained a thermocouple with its hot junction about 1 m above the bottom of the reduction tube. A hole in this inner tube at the

Fig. 7 - Schematic diagram of counter-current reactor apparatus

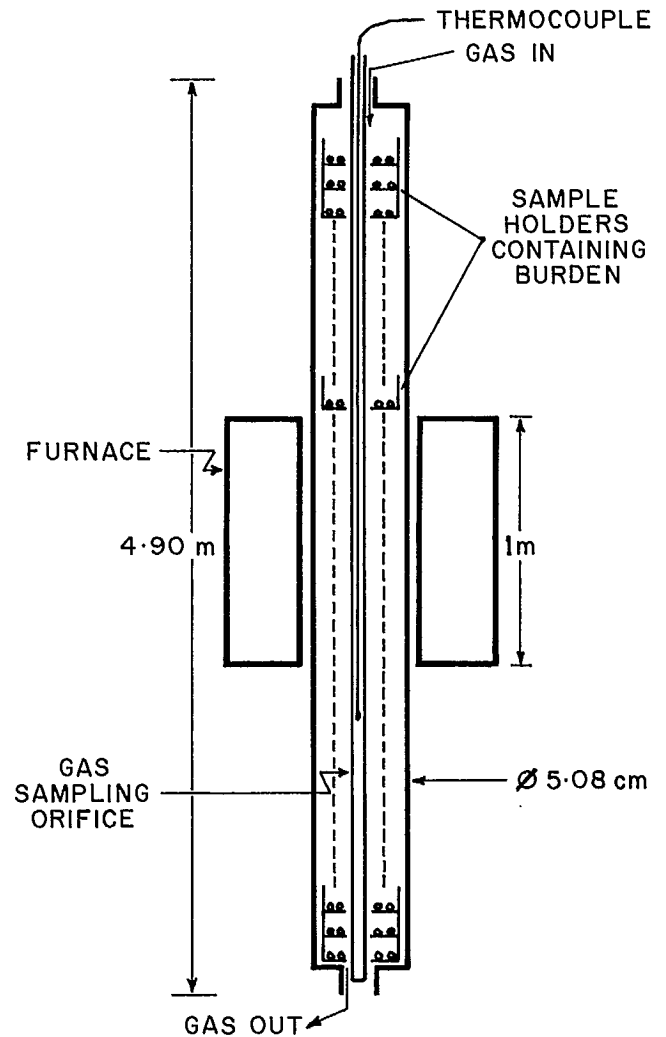thermocouple hot junction enabled gas to be extracted for analysis at the temperature measured by the thermocouple.

At the beginning of each experiment the furnace was positioned near the top of the reduction tube. Nitrogen flowed down the tube at a flow rate of 2 L/min. After the furnace had attained the required temperature, its descent was started at a rate of 0.8 cm/min.

$(CO_2/CO)_t$ was obtained from gas samples taken before the furnace reached the gas sampling hole. The ratios were peculiar to the rate of heating and amount of reduction experienced by the briquets, and were 1.19 and 0.78 for Peace River and Carol Lake briquets respectively.

The temperature profile measured by the thermocouple as the furnace passed by it is shown

in Fig. 8. The CO and CO_2 contents of the gas sampled at different temperatures during an experiment with Carol Lake briquets and one with Peace River briquets are also shown in Fig. 8. On reflection it will be seen that the CO and CO_2 content of the nitrogen carrier gas at any particular temperature has been evolved from the briquets at and above that temperature. The amounts of both gases and the CO_2/CO ratio, decreased as temperature and fraction reduction increased.

The furnace was quickly raised after it had descended past the hole in the axial tube, and the reduction tube was quenched with water. The trays were removed and the contents of selected trays were analyzed for total, divalent and metallic iron. The selected trays had been heat-
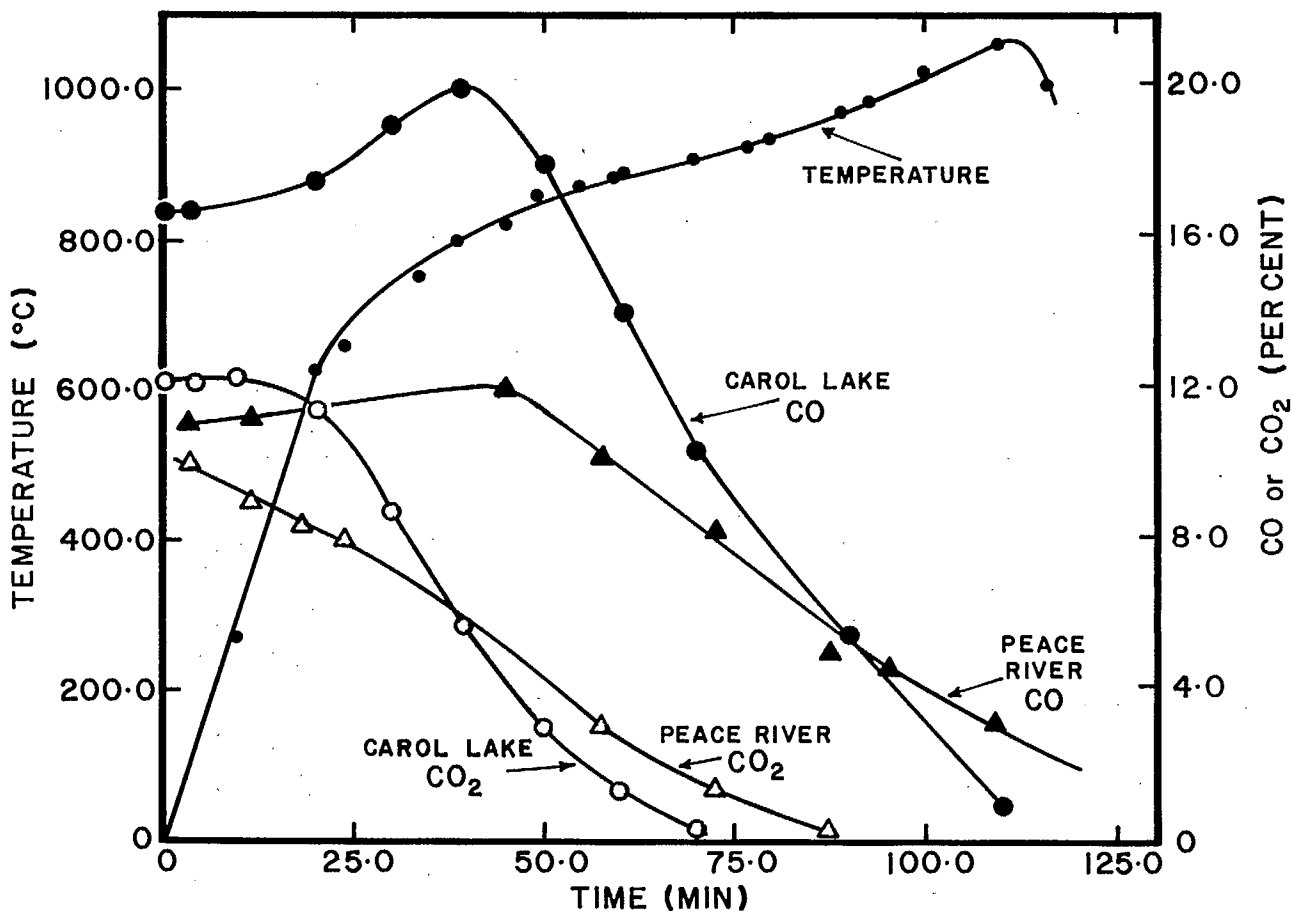
Fig. 8 – Analysis of gas evolved by briquets during heating in counter-current reactor

ed to a specific temperature calculated from their position in the reduction tube and from the temperature profile with respect to time. The results are presented in Fig. 9.

Figure 9 shows that the reduction behaviour of both types of briquets was similar and was stepwise in nature. Nearly all of the Fe_2O_3 was reduced to Fe_3O_4 before Fe_3O_4 was reduced to FeO, and reduction to

FeO was almost complete before Fe was formed. Reduction of Fe^{3+} to Fe^{2+} began between 300 and 400°C. Metallic iron was not formed until the temperature was above 700°C.

The counter-current reactor was not capable of attaining temperatures above 1040°C at the applied rate of heating, 4°C/min between 750 and 1000°C. Carol Lake briquets were 83% metallized and Peace River 66% metallized at

Fig. 9 — Chemical analysis of briquets from counter-current reduction experiments

1040°C. Values for $(CO_2/CO)_t$ can be estimated for complete reduction however, as the experiments described earlier show the gas evolved above 1040°C at these degrees of reduction contained predominantly CO. The $(CO_2/CO)_t$ values calculated using this assumption are 0.61 for Carol Lake briquets and 0.58 for Peace River briquets. These ratios correspond to reduction under constant temperature conditions at 930 and 880°C respectively (Fig. 6).
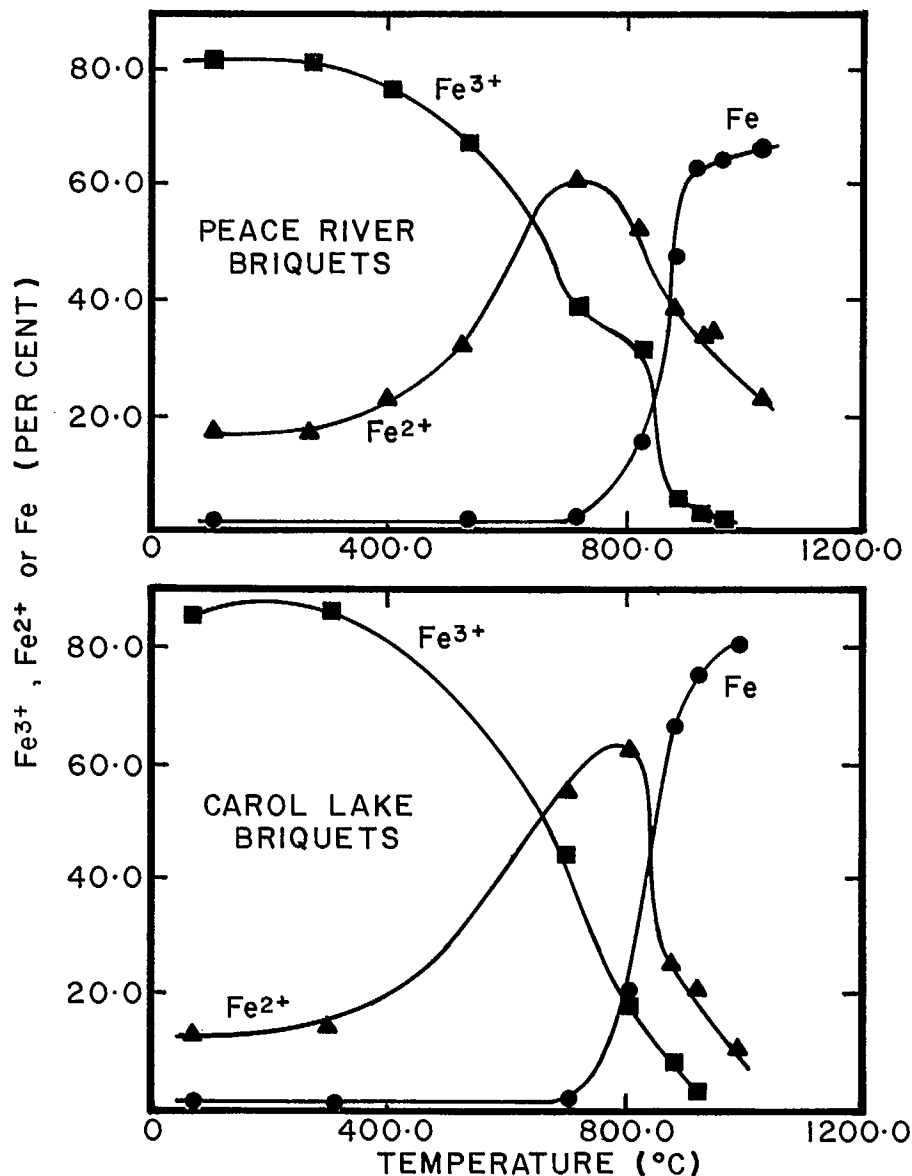
The rate of heating in these counter-current reactor experiments was about 4°C/min between 750 and 1000°C while the measured temperature rise in the cupola was about 20°C/min in this temperature range. Attempts to increase the briquet heating rate above 4°C/min by increasing the furnace speed did not succeed. Heat transfer from the furnace to the briquets was slow and higher furnace speed actually decreased the rate of temperature rise as the briquet temperatures attained were lower.

REDUCTION AT CUPOLA HEATING RATE

To reproduce the high heating rates encountered in the cupola, a third series of experiments was carried out. Single whole briquets were lowered into an alumina tube which extended through the hot-zone of an electric furnace. A thermocouple beside the briquet monitored the temperature and the rate of descent was adjusted so that the rate of temperature increase was 20°C/min in the temperature range of 500-1200°C. Nitrogen gas was passed through the tube at a flow rate of 0.61 L/min. The exhaust gas was analyzed by gas chromatography for CO, CO_2 and N_2. Hence the quantity of CO and CO_2 evolved could be calculated.

Three experiments were carried out on Peace River briquets with similar results. The values of $(CO_2/CO)_t$ obtained were 0.181, 0.190 and 0.175, considerably higher than the values obtained at the slow rate of heating in the counter-current apparatus.

The rate of CO and CO_2 gas evolution and the fraction reduction, F_o, are plotted against temperature in Fig. 10. A minimum in the CO gas curve occurred when F_o was about 0.35 and was probably associated with the disappearance of Fe^{3+} from the sample and the beginning of metallization. The reduction rate was a maximum at 950°C where F_o was 0.75. The highest temperature reached in the experiments was around 1200°C when F_o was 0.92.

BRIQUET REDUCTION AND CUPOLA SMELTING PROCESS

Cupola smelting of Peace River iron ore-char briquets was investigated at CANMET using a 0.4 m I.D. cupola (2). A schematic diagram of the cupola is shown in Fig. 11. The bed of burning coke in the cupola supplies heat to reduce
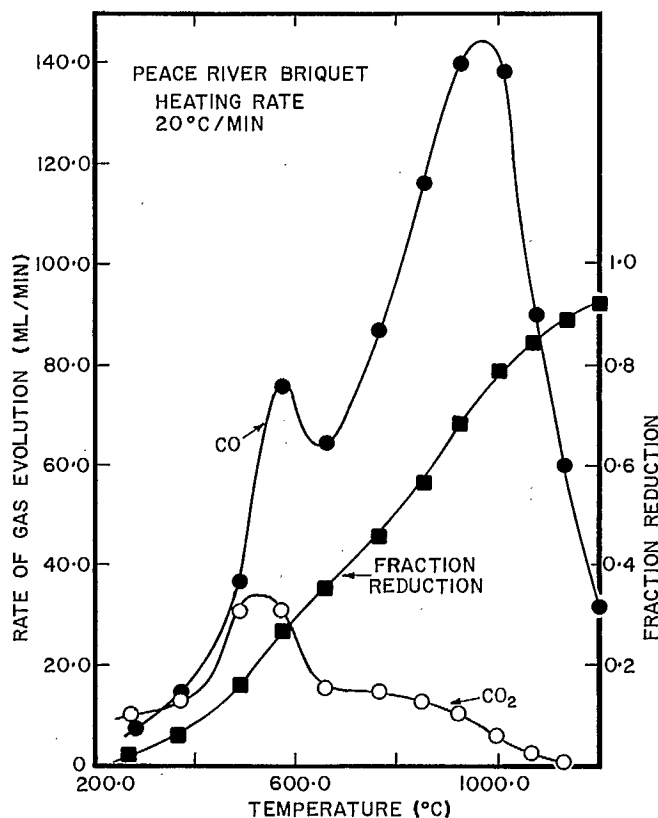

Fig. 10 - Rate of reduction of Peace River iron ore briquets heated at 20°C/min between 500 and 1200°C
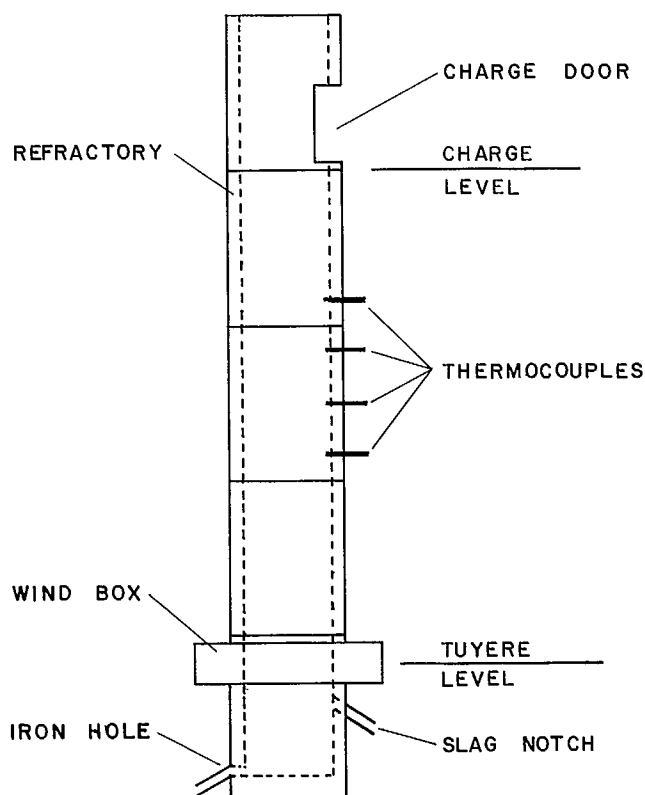
Fig. 11 – Schematic diagram of cupola

and melt the briquets. Ideally, melting only takes place at the top of the coke bed. Liquid iron and slag then trickle through the bed and collect in the cupola well.

In one trial, four sheathed thermocouples were inserted about 3 cm beyond the cupola refractory lining at 0.3 m intervals starting 1.2 m above tuyere level and their temperatures were continuously monitored. The temperatures reached a plateau about 30 min after the start of the trial and remained within ±30°C of their average temperatures thereafter.

Figure 12 shows the average temperatures plotted against height above tuyere level. The position of the top of the cupola burden, which has an average temperature of 220°C, is also shown. The height of the coke bed above the tuyeres during smelting was not accurately known,

but initially was 0.7 m. The temperature at the level was 1320°C by extrapolation of the temperature gradient in Fig. 12. This is a reasonable estimate as briquet melting occurred at 1326°C, but not at 1204°C in the constant temperature experiments described in Section 2.

Process data for this particular smelting trial appear in Table 4. On average, 442 kg of briquets and 103 kg of coke were charged into the cupola and 86.6 kg of pig iron and 214 kg of slag tapped from the cupola each hour. The average rage of descent of the briquets in the cupola was calculated from the smelting rate and the bulk density of the cupola burden, 888 kg/m^3, to 3.6 m/h. Using this information the time scale shown in Fig. 12 was calculated from the height scale of the figure. The resulting temperature-time relationship shows the briquets were heated at a rate of about 20°C/min in the temperature range of 700-1060°C.

The fraction reduction-time relationship determined for single briquets at a heating rate of 20°C/min has been plotted in Fig. 12 to provide an estimate of the rate of briquet reduction in the cupola. This indirect method of obtaining the reduction rate in the cupola is not considered precise, but circumvents the formidable problem of extracting samples for analysis from the furnace. Extrapolation of the fraction reduction-time relationship indicates the briquets were probably fully reduced to iron before melting at the top of the coke bed. This is ideal for efficient process operation as any molten unreduced ore would quickly have trickled through the coke bed and joined the slag phase. However in the smelting trial, 15.5% of the iron in the iron ore charged to the cupola was lost to the slag, which analyzed 9.9% FeO. Although this high percentage strongly suggests the briquets were not, in fact, fully reduced before melting, it cannot be used to estimate the actual degree of reduction as other processes must also be considered. For example, some iron re-oxidation probably occurred in the oxidizing atmosphere of
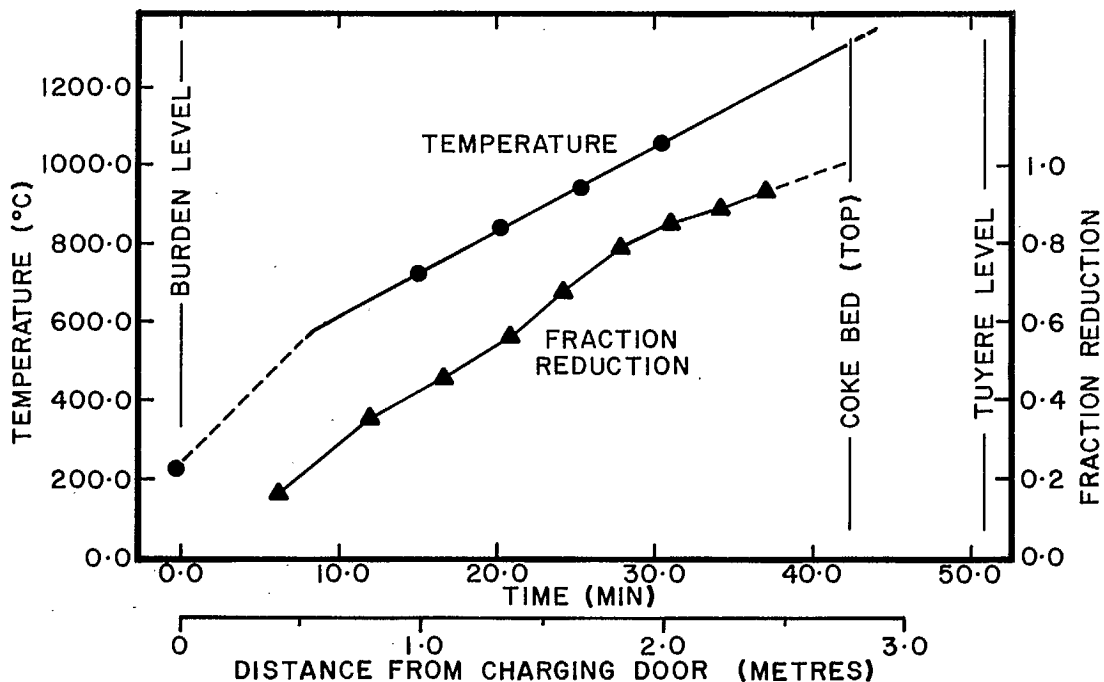
Fig. 12 - Cupola temperature profile and inferred
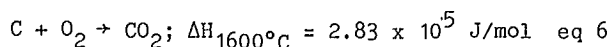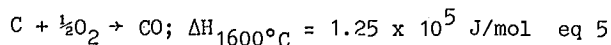rate of reduction of Peace River iron ore briquets

Table 4 - Process data for cupola smelting trial
Peace River briquets (2)

Coke rate	1190 kg/metric ton hot metal
Blast volume	11.89 m³/min
Smelting rate	442 kg briquets/h
	86.6 kg pig iron/h
Metal yield	75.1%
Slag weight	2476 kg/metric ton hot metal
Typical pig iron	
analysis	1.51% carbon
	0.51% silicon
	1.48% phosphorus
	1.45% sulphur
Typical slag	
analysis	38.7% SiO₂
	25.5% CaO
	10.9% Al₂O₃
	9.5% FeO
Typical off-gas	
analysis	25.0% CO
	10.1% CO₂
	58.0% N₂

the cupola tuyere region.

The ratio $(CO_2/CO)_t$ measured for briquet reduction in the laboratory can be used to formulate a heat balance for the cupola smelting trial. The major sources of CO_2 and CO in the cupola off-gas were the burning coke bed and the iron ore reduction reactions. Minor sources of CO_2 and CO were limestone decomposition and the volatile matter of the ore, coke and char and were calculated from the chemical analysis and the quantity of each component in the cupola burden.

An estimate of the CO_2/CO ratio to which the coke bed burned was made using the average value of $(CO_2/CO)_t$ for briquet reduction of 0.18, and the measured composition of the cupola off-gas shown in Table 4. This ratio is important as it determines the amount of heat liberated in the cupola (12).

$$C + \tfrac{1}{2}O_2 \rightarrow CO; \quad \Delta H_{1600°C} = 1.25 \times 10^5 \text{ J/mol} \quad \text{eq 5}$$

$$C + O_2 \rightarrow CO_2; \quad \Delta H_{1600°C} = 2.83 \times 10^5 \text{ J/mol} \quad \text{eq 6}$$

The value obtained for the CO_2/CO ratio was 0.303 and calculation showed 17.6 J/t hot metal was released in the cupola.

A simplified heat balance for the cupola smelting trial is presented in Table 5. Only the major heat requirements are listed. Minor requirements such as for silica reduction, blast moisture decomposition, carbon solution and the latent heat of water evaporation are neglected. A large slag volume was obtained by smelting this low-grade ore and its heat content was almost one third of the process heat requirement.

The reduction reaction

$$Fe_2O_3 + (x + y)C = 2Fe + xCO_2 + yCO \qquad \text{eq 7}$$
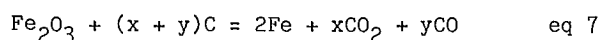
where $x/y = (CO_2/CO)_t$, has the second highest heat requirement of those appearing in Table 5. The heat required by this reaction depended on the values of x and y appearing in eq 7 and on the temperature at which reduction took place. This is illustrated in Table 6 where the reaction

Table 5 - Simplified heat balance for cupola smelting based on production of one metric ton of hot metal

	x 10^9 J	% total
Heat content of iron	1.28	8.2
Heat content of slag	4.87	31.7
Sensible heat in off-gas	2.67	17.4
Heat of reduction reaction	4.15	27.3
Calcination of limestone	0.81	5.3
Heat loss	1.53	10.0
TOTAL	15.3	100

heat requirements for four different x/y or $(CO_2/CO)_t$ values at three different temperatures have been calculated from data given in Reference 9. The table shows that the heat requirement increases significantly as $(CO_2/CO)_t$ decreases and moderately as the temperature decreases. The heat required in the smelting trial is estimated to have been 3.55×10^9

Table 6 - Heat of reaction for hematite reduction to iron at different temperatures and evolved gas compositions

$(CO_2/CO)_t$	Temperature °C	Heat of reaction for 100 kg iron x 10^9 J
0.66	800	2.90
0.66	1000	2.86
0.66	1200	2.81
0.33	800	3.29
0.33	1000	3.24
0.33	1200	3.19
0.2	800	3.55
0.2	1000	3.50
0.2	1200	3.44
0.125	800	3.74
0.125	1000	3.69
0.125	1200	3.63

J/t hot metal using the $(CO_2/CO)_t$ value measured in the laboratory experiments 0.18 and assuming the reduction took place at 950°C. This latter assumption was made as the reduction was near maximum at 950°C.

The heat requirement for the reduction reaction appearing in Table 5 is 0.6×10^9 J/t (metric) hot metal more than the value estimated above for the following reason. Only 75.1% of the iron in the iron ore charged to the cupola reported to the pig iron tapped from the cupola. The remainder was lost to the slag and as dust in the cupola off-gas. Chemical analysis showed that, on average, the iron compounds in the slag and dust were 50% chemically reduced. The heat requirement for this reduction was therefore added to the requirements for the iron ore reduced and reporting to the pig iron.

Some explanation of the other heat requirements appearing in Table 5 is necessary. A heat loss of 10% was assumed as larger cupolas are found to suffer losses of about 7.5% (12). The sensible heat in the cupola off-gas was calculated from its temperature, composition and rate of flow derived from the air blowing rate. The heat required for calcination of limestone has been reduced to half that theoretically required as about this amount is recouped when CaO combines with SiO_2 to form the slag (12).

The estimated heat requirement of 15.3×10^9 hot metal, is considered to be in satisfactory agreement with the estimated quantity of heat released in the cupola 17.6×10^9 J/t ton hot metal.

CONCLUSIONS

Briquets of both Peace River and Carol Lake iron ore-chars reduced in a stepwise manner and were fully reduced to iron in experiments conducted at constant temperatures above about 950°C. The reduction rate was largely controlled by gasification of the carbon. The CO_2/CO ratio of the gas evolved during reaction decreased as the reduction temperature increased.

Laboratory experiments simulating the rate of heating experienced by Peace River iron ore-char briquets in the cupola showed the reduction rate was a maximum at 950°C and that the briquets were fully reduced before melting. The experimental results were used to estimate the heat released in a cupola smelting trial and the heat required by the reduction reactions. This allowed formulation of a successful heat balance.

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