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MATERIAL AND ENERGY BALANCES FOR SERF PROCESS

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INTRODUCTION

The SERF process, which is being developed in the Pyrometallurgy Laboratory, CANMET, Department of Energy Mines and Resources, is a combined shaft-electric process for the smelting of ores and related materials. The objective is to develop a process that will economically produce the relatively modest amounts of iron required by the smaller steel companies, using a combination of electricity and low-rank coal as the major sources of energy and reductant. The process also can be used for the smelting of other oxide ores such as ilmenite, and for the melting of prereduced pellets but the most promising field for application is in the smelting of iron oxide pellets to produce hot metal to augment the supply of iron units currently being obtained by the smaller steel companies by melting scrap.

There has been much interest for many years in direct-reduction of iron ores, i.e. in processes other than the blast furnace for producing iron. In a recent review of the subject[1] it was pointed out that the processes that have received the most attention are (a) shaft, (b) static bed, (c) fluidized bed, and (d) rotary kiln. Most processes have used gaseous reductants and produced iron in the solid state, which was then transferred to a melting unit (usually an electric furnace) to separate the iron from the residual gangue material.

Considerable iron is produced in some parts of the world where electrical energy is reasonably abundant (such as Norway) by direct smelting in electric furnaces - the Tysland-Hole process. This requires a relatively large consumption of electrical energy per ton of metal obtained, and a CO-rich off-gas is produced which must be used in auxiliary plant operations such as steam-raising to make the overall process economic.

In the SERF process a shaft furnace is located above an electric furnace and the ore (usually iron ore pellets) is fed down through the shaft to be preheated and prereduced by the hot CO-rich off-gas that is produced in the electric furnace and drawn upward through the shaft, counter-current to the descending ore. The object is to preheat and prereduce the ore in the shaft to the maximum extent possible using the CO-rich furnace gas, thus reducing the amounts of electrical energy and reductant required in the electric furnace to complete the smelting. The reductant is not fed down through the shaft, but goes directly to the electric furnace, thus permitting complete combustion of residual CO to CO_2 at the top of the shaft. Expensive metallurgical coke is not required; low-to-medium volatile coals (which are abundant in Western Canada) are satisfactory - even advantageous because their volatile matter augments the supply of CO drawn from the electric furnace to the shaft. The process has been described in several publications [2][3][4][5].

Calculation of material and energy balances is an essential step in evaluating the potential of a new process concept and in measuring the progress achieved during development work. For a process such as the SERF these calculations are long and tedious, particularly because extensive calculations are needed to explore the effects of varying certain process variables. For this reason a computer program which contained provision for varying the most important process variables over wide ranges was written to do the calculations. Although the program was written for the SERF process configuration in which the ore is preheated and prereduced in a shaft, the information produced would be equally useful if the preheating and prereduction were done in another unit such as a rotary kiln.

From the viewpoint of material and energy balances, the main objectives of the SERF process may be outlined as follows:

(a) Minimize the amount of electrical energy used in the electric furnace.

(b) Minimize the amount of carbon required as reductant.

(c) Maximize the recovery of iron in the metal phase, i.e. minimize the losses of iron to the slag.

(d) Produce a slag of suitable composition for good flow, etc. at bath temperature.

MATERIAL AND ENERGY BALANCES

Assumptions

Commercially produced iron ore pellets consist mainly of hematite (Fe_2O_3) with relatively small amounts of other minerals such as SiO_2, Al_2O_3, silicates etc., and usually minor amounts of some sulphur-bearing and phophorus-bearing compounds. For rigorous material and energy balance calculations allowances should be made for these minor constituents but, because the Fe_2O_3 is by far the predominant component, and because the corrections to be made for the minor constituents will be different for each ore, a simplification was made for this program by assuming the ore to consist of Fe_2O_3, with small but defined amounts of SiO_2.

Reductants such as coal and coke rarely contain more than about 80 per cent fixed carbon, the balance being volatile matter, ash, moisture, etc. Again for simplification the reductant is assumed to be pure carbon, and it is assumed that it is fed directly into the electric furnace.

Lime (CaO) is required to flux the SiO_2 of the ore to produce a slag with a suitable CaO/SiO_2 ratio to give proper fluidity at furnace temperatures. In these calculations it is assumed that burnt lime (CaO) is added directly into the electric furnace.

Because the silica (SiO_2) is intimately associated with the Fe_2O_3 in the ore it is assumed that it gets preheated in the shaft before it enters the electric furnace.

It is assumed that the exhaust gases have all CO converted to CO_2 before they leave the shaft and that their exit temperature is 127°C (400°K). This temperature is sufficiently high to prevent condensation of water vapour.

The chemical reactions used in the calculations are listed below. It is assumed that the reduction of Fe_2O_3 proceeds step-wise through the lower oxides* to metallic iron.

(1) $Fe_2O_3 + 1/3\ CO \rightarrow 2/3\ Fe_3O_4 + 1/3\ CO_2$

(2) $Fe_3O_4 + 0.84211\ CO \rightarrow 3.15789\ Fe_{.95}O + 0.84211\ CO_2$

(3) $Fe_{.95}O + CO \rightarrow 0.95\ Fe + CO_2$

(4) $CO + 0.5\ O_2 + 1.88\ N_2 \rightarrow CO_2 + 1.88\ N_2$

(5) $Fe_2O_3 + 1/3\ C \rightarrow 2/3\ Fe_3O_4 + 1/3\ CO$

(6) $Fe_3O_4 + 0.84211\ C \rightarrow 3.15789\ Fe_{.95}O + 0.84211\ CO$

(7) $Fe_{.95}O + C \rightarrow .95\ Fe + CO$

(8) Fe + C $\rightarrow$ Fe (C in solution)

Reactions 1, 3 and 4 are exothermic; the remainder are endothermic.

Seven operating variables which significantly affect the material and energy balances were studied. These variables and the abbreviations that were used for them as parameters in the computer program are listed below. In the interests of brevity these abbreviations are used extensively throughout this report, particularly in Figures and Tables.

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* The chemical formula $Fe_{.95}O$ is used for wustite.

TC - temperature to which ore is preheated in shaft (°C)

PR - degree of prereduction in shaft, i.e. per cent removal of oxygen from Fe_2O_3

TBC - temperature of molten bath in electric furnace (°C)

PS - per cent SiO_2 in ore

REC - per cent recovery of iron from the ore into the metal

PC - per cent carbon in the metal

B - basicity of slag, i.e. ratio CaO/SiO_2 (weight basis).

In each computation, values were set for the above parameters, and the following were calculated:

(a) mols of reactants and products for Reactions 1 to 8.

(b) energy needed to heat ore (Fe_2O_3 plus SiO_2) from room temperature to TC.

(c) heats of shaft reactions (Reactions 1 to 4).

(d) energy needed to heat air for Reaction 4 from room temperature to TC.

(e) heat evolved when gaseous shaft products (CO_2 plus N_2) are cooled from TC to 127°C.

(f) energy needed to heat partially reduced ore, plus SiO_2, from TC to TBC.

(g) energy needed to heat carbon from room temperature to TBC.

(h) heats of furnace reactions (Reactions 5 to 8).

(i) heat evolved when CO produced in electric furnace by Reactions 5,6 and 7 is cooled from TBC to TC.

(j) mols of CaO required, energy needed to heat it from room temperature to TBC, and the heat of slag formation.

(k) the sum of the energy terms (positive and negative) for the shaft, and for the electric furnace.

(l) the slag composition.

A more detailed description of the calculation procedure is given in Appendix A. Thermodynamic data for the calculations was obtained from References (6), (7) and (8).

RESULTS

The most important output variables of the process from the practical viewpoint are the electrical energy required in the furnace, the amount of reductant required, and the amount and composition of the slag formed. Most of the input variables listed earlier affect all of the above output variables and there is an interrelationship among them, in that the effect of a certain input variable on an output variable is dependent on the values at which the other input variables are set. For this reason it is necessary to discuss the effects of varying the input variables on an individual basis, with other input variables set at predefined values.

The question of greatest interest is the determination of the minimum quantities of electricity and reductant that would be required to produce pure iron metal, at 100 per cent iron recovery, using pure ore and pure carbon as reductant. This represents an idealized situation which, though not attainable in practice, provides reference information against which to evaluate the more practical conditions of impure ore, incomplete iron recovery etc. Most of the information presented in this report has been chosen to illustrate the effects of moving from the "idealized" situation toward more practical operating conditions, e.g., increasing impurity of ore, less preheating of ore in the shaft, less prereduction in the shaft etc.

Based on a review of the experimentation done in developing the SERF process, a set of operating conditions are then chosen which are believed to represent what could be attained in a commercial-scale SERF operation, and figures are given for the expected performance of the process under these conditions.

1. Effects on Output Variables of Varying Certain Input Variables

(a) Electrical energy required in furnace

Because of its cost the electrical energy required in the furnace is one of the major concerns in the process. The factors which affect it most significantly are (i) the preheat temperature in the shaft, (ii) the degree of prereduction in the shaft, (iii) the bath temperature, (iv) the per cent SiO_2 in the ore, and (v) the recovery of iron in the metal.

(i) Preheat temperature in the shaft (TC)

The ore must be heated to a high temperature before the reduction reactions can occur. The higher the temperature to which the ore is heated in the shaft the more prereduction can be accomplished there and the less electrical energy is required in the furnace to complete the heating of the materials to bath temperature and finish the reduction. Experience has shown that the maximum temperature that can safely be used in the shaft is about 900°C. Attempts to use higher temperatures incur the danger of fusion of the partially reduced ore and sticking of this material in the shaft.

(ii) Degree of prereduction in shaft (PR)

The more prereduction that can be accomplished in the shaft by Reactions 1,2 and 3, the less oxygen remains to be removed in the electric furnace by Reactions 5,6 and 7. At 50 per cent prereduction a point of balance is reached where the amount of CO generated by Reactions 5,6 and 7 is just sufficient to supply the needs for Reactions 1,2 and 3.

The effects of these two variables (TC and PR) on the electrical energy required in the furnace are shown in Figure 1. In this case it is assumed that the ore is pure Fe_2O_3, the recovery of iron is 100 per cent, the bath temperature is 1400°C and the carbon content of the metal is 3 per cent. These last two figures (TBC = 1400°C, and PC = 3.0%) are realistic values based on our experience in the development of the process.

The curves in Figure 1 show that the electrical energy required, in kWh/nthm*, decreases as the ore is preheated from room temperature to 900°C. When no prereduction is done (PR = 0) the decrease is from 1633 to 1359 kWh/nthm - a saving of 274 kWh/nthm. For a 50 per cent prereduction (PR = 50) the decrease is from 958 to 761 - a saving of 197 kWh/nthm.

The benefit obtained by prereduction of the ore in the shaft is evident from the positions of the six curves in Figure 1. As the degree of prereduction increases the corresponding

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* nthm = net ton (2000 lb) hot metal

curves are located lower in the Figure. The effect can readily be appreciated by noting the values on the curves at some fixed temperature. At 900°C, for example, the required electrical energy decreases from 1359 kWh/nthm at PR = 0 to 761 kWh/nthm at PR = 50, which is a decrease of 598 kWh/nthm. The decrease is slightly greater at lower temperatures (1633 - 958 = 675 kWh/nthm at 25°C). However, at room temperature, the shaft reduction reactions (Reactions 1,2 and 3) would not occur at measurable rates. When both preheating to 900°C and prereduction to PR = 50 are considered together, the decrease in the required electrical energy is from 1633 to 761 kWh/nthm - a saving of 872 kWh/nthm.

In practice of course the ore would contain some impurities, (mainly SiO_2), some slag would be produced and 100 per cent recovery of the iron would not be achieved. In Appendix B, figures are given in Tables B-1, B-2, B-3 and B-4 for the amounts of electrical energy that would be required for ores containing 0,2, 4 and 6% SiO_2, respectively, if the iron recovery was 100%, and all other parameters were set at the same values as in Figure 1. In Tables B-5, B-6, B-7 and B-8, comparable figures are shown for the case when the iron recovery is 95%.

(iii) <u>Bath temperature (TBC)</u>

The effect of this variable on the electrical energy required in the furnace is shown in Figure 2, for various degrees of prereduction in the shaft, assuming that the ore is pure Fe_2O_3, the iron recovery is 100%, the shaft temperature is 900°C, and the carbon content of the metal is 3.0%. It is evident that there is only a modest increase in the required kWh/nthm as the bath temperature is increased from 1400°C to 1600°C. The increase amounts to 88 kWh/nthm at PR = 0, and 65 kWh/nthm at PR = 50.

Again, these figures refer to an idealized case, i.e. pure Fe_2O_3. In Tables B-9, B-10, B-11 and B-12 of Appendix B, figures are given for the kWh/nthm required for ores containing 0,2,4 and 6% SiO_2, respectively, with all other parameters set at the same levels as in Figure 2.

In practice this variable (TBC) probably would have a greater effect on the energy actually required than is indicated in Figure 2. It must be remembered that the figures presented thus far represent theoretical minimum values for the process - no allowance has yet been made for heat losses from the system. At these temperatures radiation plays a major role in heat losses, and since radiation heat losses increase in an exponential manner as temperature increases, it is to be expected that heat losses would be higher, proportionately, at 1600°C than at 1400°C.

(iv) Per cent SiO_2 in ore (PS)

The effect of increasing amounts of SiO_2 in the ore on the kWh/nthm is shown in Figure 3, for shaft temperature of 900°C, bath temperature of 1400°C, slag basicity of 1.2/1, iron recovery of 100%, 3% carbon in the metal, and shaft prereduction values of 0, 10, 20, 30, 40 and 50%. To simplify the calculations it was assumed that SiO_2 was the only impurity in the ore but in practice of course small amounts of other compounds, particularly oxides, are always present. All SiO_2 in the ore ends up in the slag, except under very strongly reducing conditions when some SiO_2 will be reduced to form silicon metal. Lime (CaO) must be added to react with the SiO_2 to form a slag having suitable fluidity and other properties at a reasonable bath temperature such as 1400°C. The more SiO_2 the ore contains, the more CaO is required, the more slag is formed and the more electrical energy is required in the furnace. In the range of 0 to 6 per cent SiO_2 the curves of Figure 3 are almost linear, and the slopes amount to an increase of approximately 8.5 kWh/nthm for each increase of 1% in the SiO_2 content of the ore.

When the iron recovery is less than 100%, the amounts of electrical energy required per nthm are somewhat greater. Figures are given in Tables B-13, B-14 and B-15 for the electrical energy required when the iron recoveries are 100, 98 and 96 per cent respectively, with all other parameters set at the values as in Figure 3.

(v) Recovery of iron in metal (REC)

The effect of this variable on the kWh/nthm is shown in Figure 4, for pure Fe_2O_3, shaft temperature of 900°C, bath temperature of 1400°C, slag basicity of 1.2, 3% carbon in the metal and degrees of prereduction of 0, 10, 20, 30, 40 and 50%. Again the curves are practically linear. In the range of REC = 96 to 100, the decrease in the required electrical energy is approximately 16 kWh/nthm for each 1% increase in recovery when PR = 0, and approximately 4 kWh/nthm for each 1% increase in recovery when PR = 50. Any iron oxide remaining in the slag results in a lowering of the iron recovery, hence the objective is to keep the iron oxide content of the slag as low as possible. The information shown in Figure 4 refers to the case for pure Fe_2O_3, i.e. PS = 0. For ores containing progressively greater SiO_2 contents, the kWh/nthm increases, as was shown in section (iv).

(b) Weight of carbon required as reductant

The weight of carbon required as reductant as a function of the per cent prereduction is shown in Figure 5 for two cases, i.e. metal carbon contents of 0% and 3.0% respectively. In each case the iron recovery was 100%. This illustrates that, when no carbon is dissolved in metal, the amount of carbon required for the process drops from 645 lb/nthm at PR = 0, to 322 lb/nthm at PR = 50, a decrease of 50%. When the metal contains 3% carbon, the amount required for the process drops from 685 lb/nthm at PR = 0 to 373 lb/nthm at PR = 50, a decrease of 45%.

The amount of carbon required is affected slightly by the iron recovery. The amounts of carbon required at several levels of iron recovery and per cent prereduction, at a metal carbon content of 3%, are given in Table B-16.

(c) Relationship of iron recovery with iron oxide content of slag and SiO_2 content of ore

This relationship is shown in Figure 6 where the iron oxide content of the slag is plotted against the iron recovery, for various levels of per cent SiO_2 in the ore. This illustrates that when the SiO_2 content of the ore is low, e.g., PS = 2, the iron oxide content of the slag can be high even when the recovery is as high as 98%, but it decreases rapidly as the iron recovery approaches 100%. This is a consequence of the fact that, when the SiO_2 content of the ore is low, very little slag is formed and slight improvement in iron recovery is associated with a sharp decrease in the per cent iron oxide in the slag.

As the SiO_2 content of the ore increases, more slag is formed and the iron oxide content of the slag become progressively lower at any given level of iron recovery. Moreover the slopes of the curves in Figure 6 become progressively less steep as the per cent SiO_2 in the ore increases from 2 to 8. The iron oxide content of the slag is controlled by chemical equilibrum between it and the carbon content of the metal; thus, as the SiO_2 content of the ore and the volume of slag produced increase, the total iron loss in the slag increases at any given per cent FeO. It is thus desirable to keep the slag: metal ratio as low as possible by using ores of low SiO_2 content to minimize iron losses to the slag.

(d) Weight and composition of slag

(i) Effect of per cent SiO_2

The effect of varying the per cent SiO_2 in the ore on the weight of slag formed is shown in Figure 7 for iron recoveries of 90, 95 and 100%. The increasing weight of slag with increasing per cent SiO_2 in the ore is obvious. At lower iron recoveries more iron oxide remains in the slag; thus the weight of slag increases and hence the line for REC = 90 lies above that for REC = 95 which in turn lies above that for REC = 100.

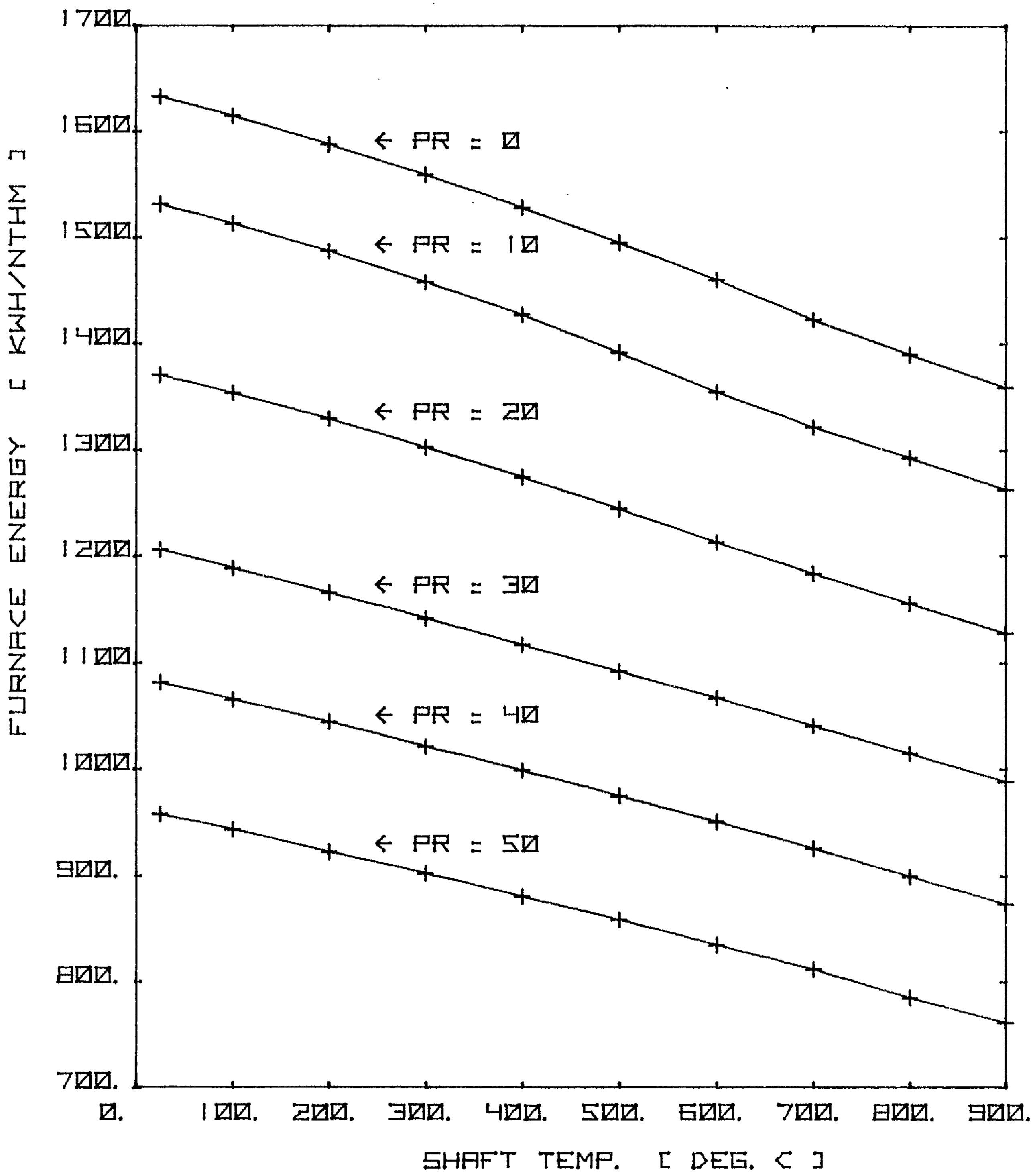

Figure 1. Electrical Energy Required in Furnace vs Shaft Preheat Temperatures at PR = 0,10,20,30,40 and 50%.

(PS = 0, REC = 100, TBC = 1400, PC = 3, B = 1.2)

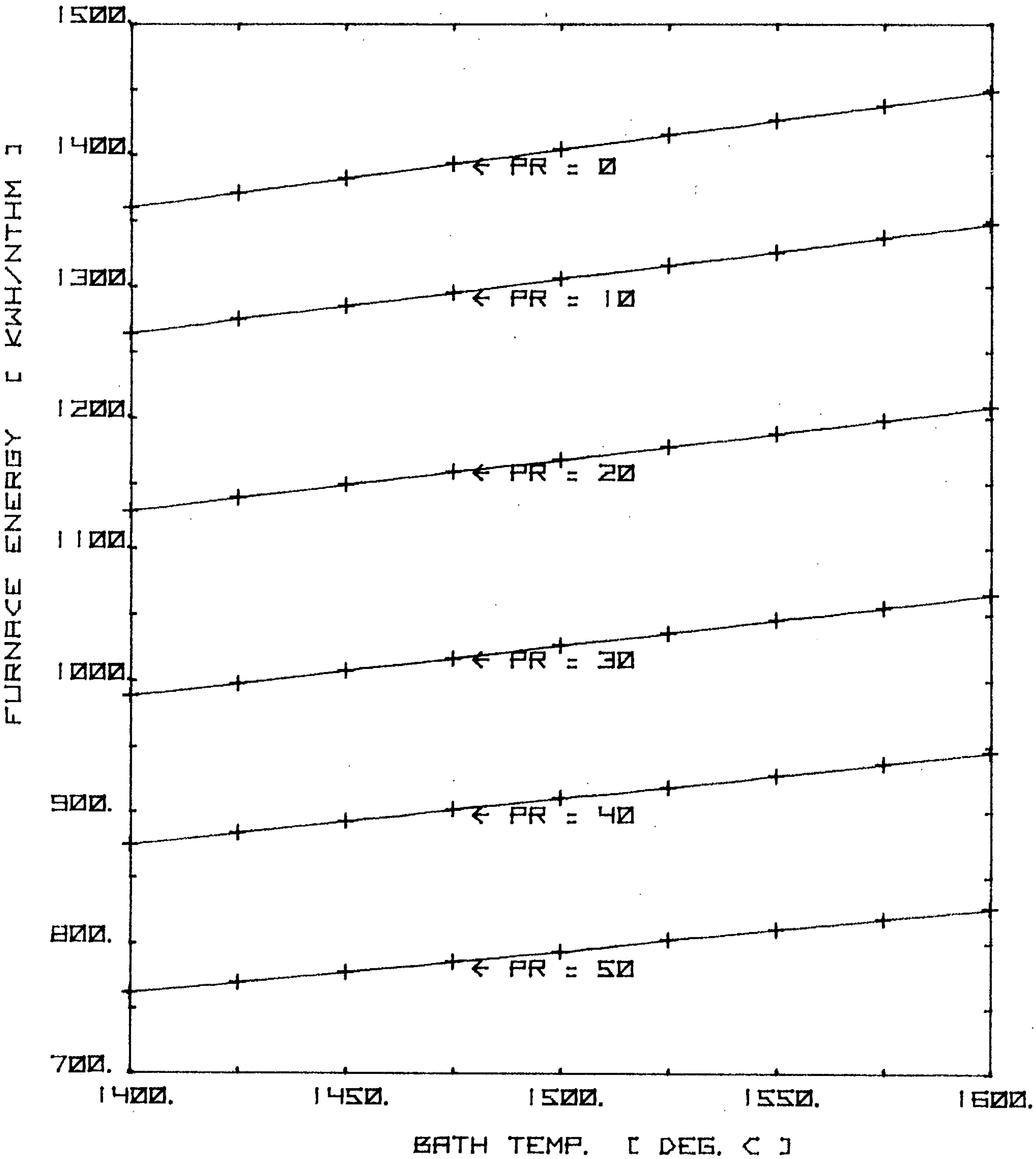

Figure 2. Electrical Energy Required in Furnace vs Bath Temperature at PR = 0,10,20,30,40 and 50%.

(PS = 0, REC = 100, TC = 900, PC = 3, B = 1.2)

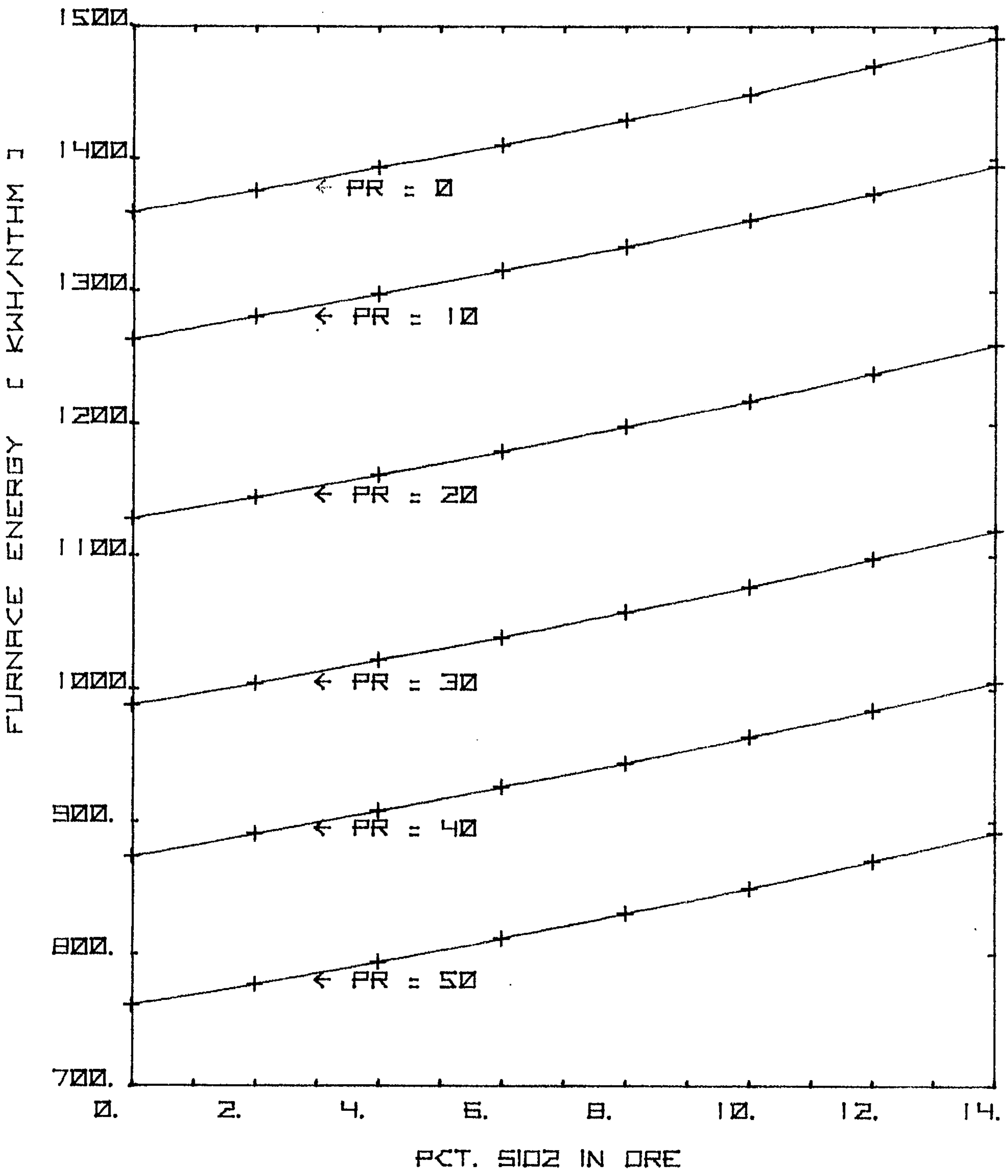

Figure 3. Electrical Energy Required in Furnace vs Per Cent SiO_2 in Ore at PR = 0,10,20,30,40 and 50%.

(REC = 100, TC = 900, TBC = 1400, PC = 3, B = 1.2)

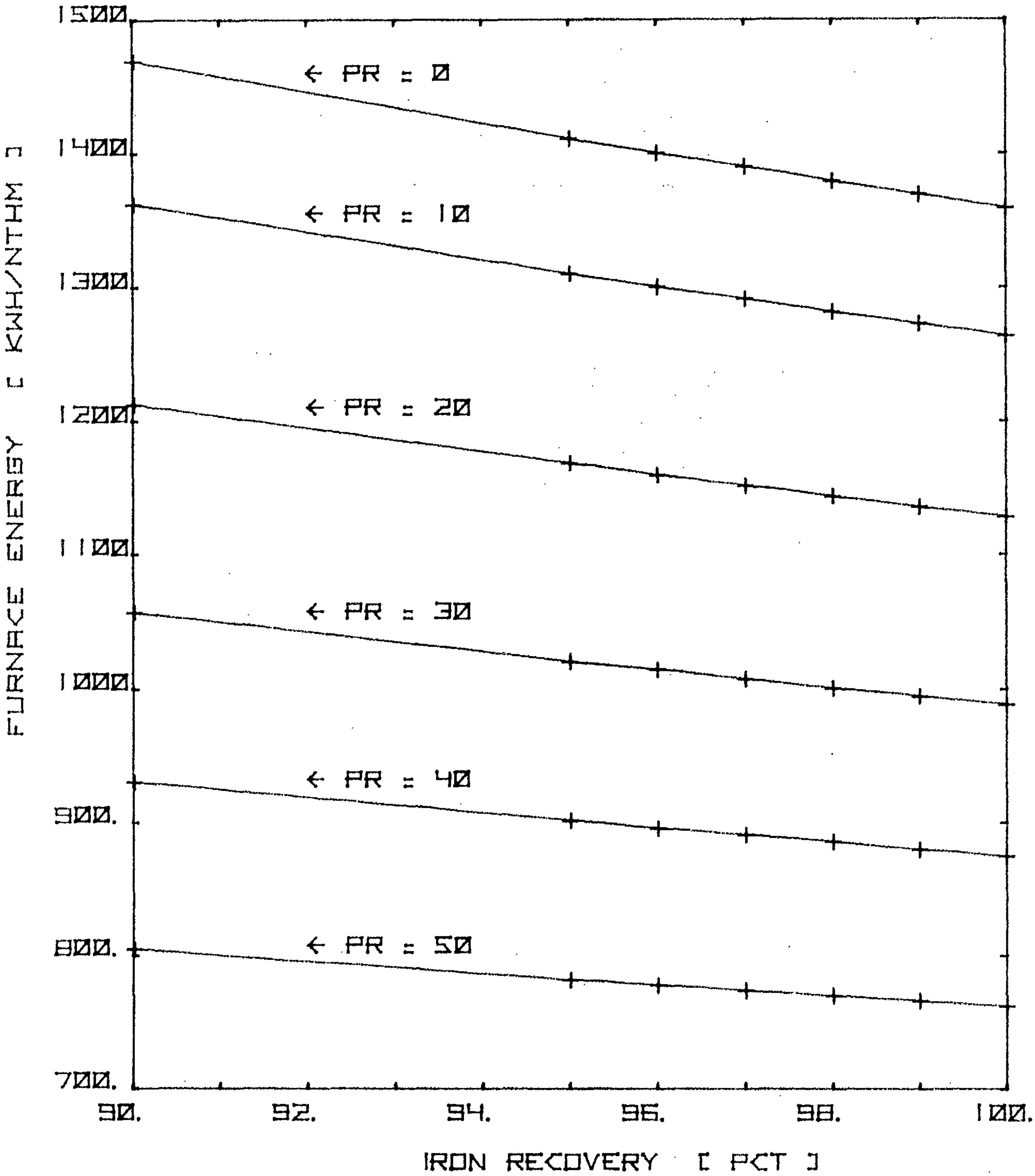

Figure 4. Electrical Energy Required in Furnace vs Iron Recovery at PR = 0,10,20,30,40 and 50%.

(PS = 0, TC = 900, TBC = 1400, PC = 3, B = 1.2)

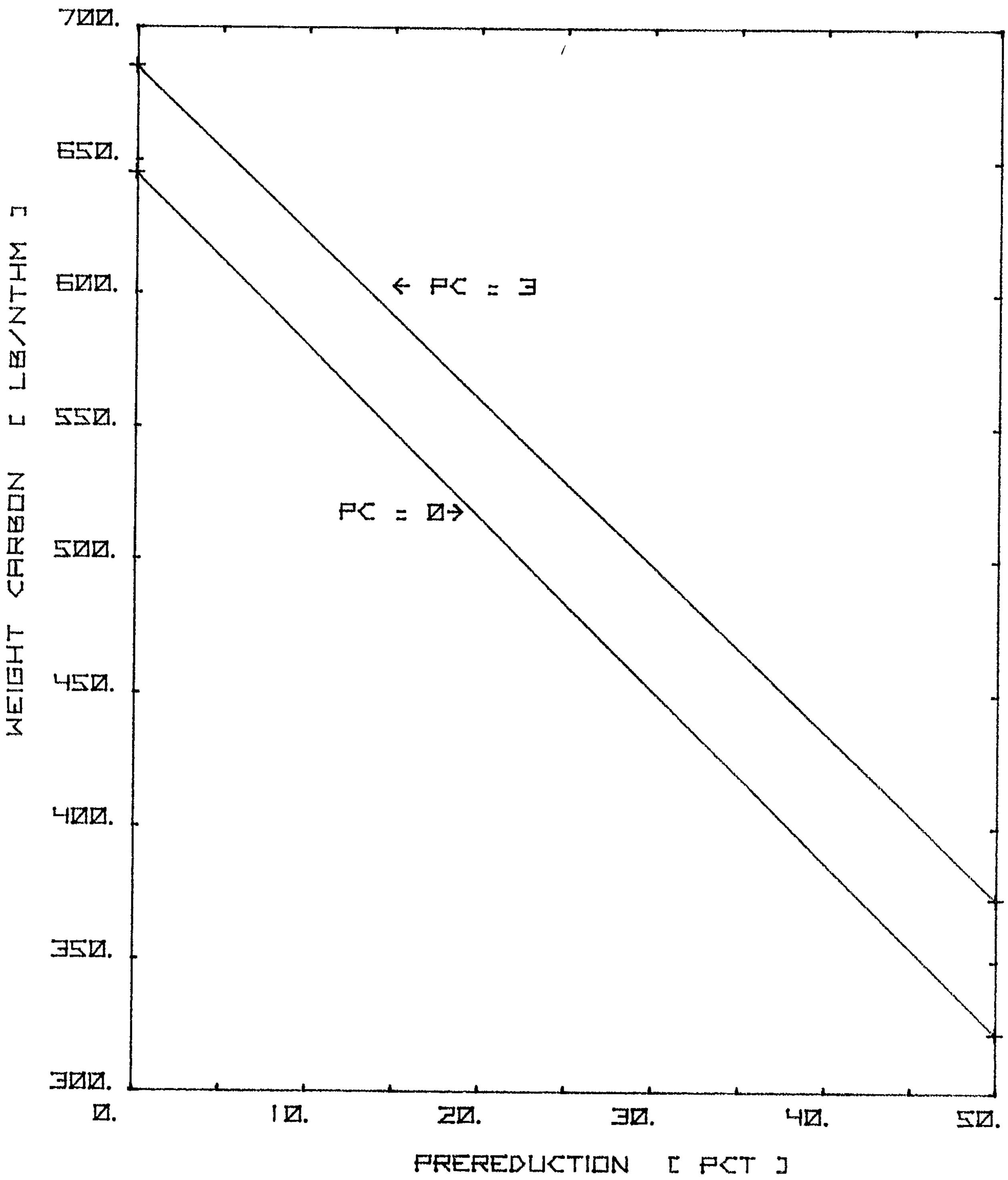

Figure 5. Weight of Carbon Required vs Per Cent Prereduction at Carbon Contents in Metal of 0 and 3%.

(REC = 100)

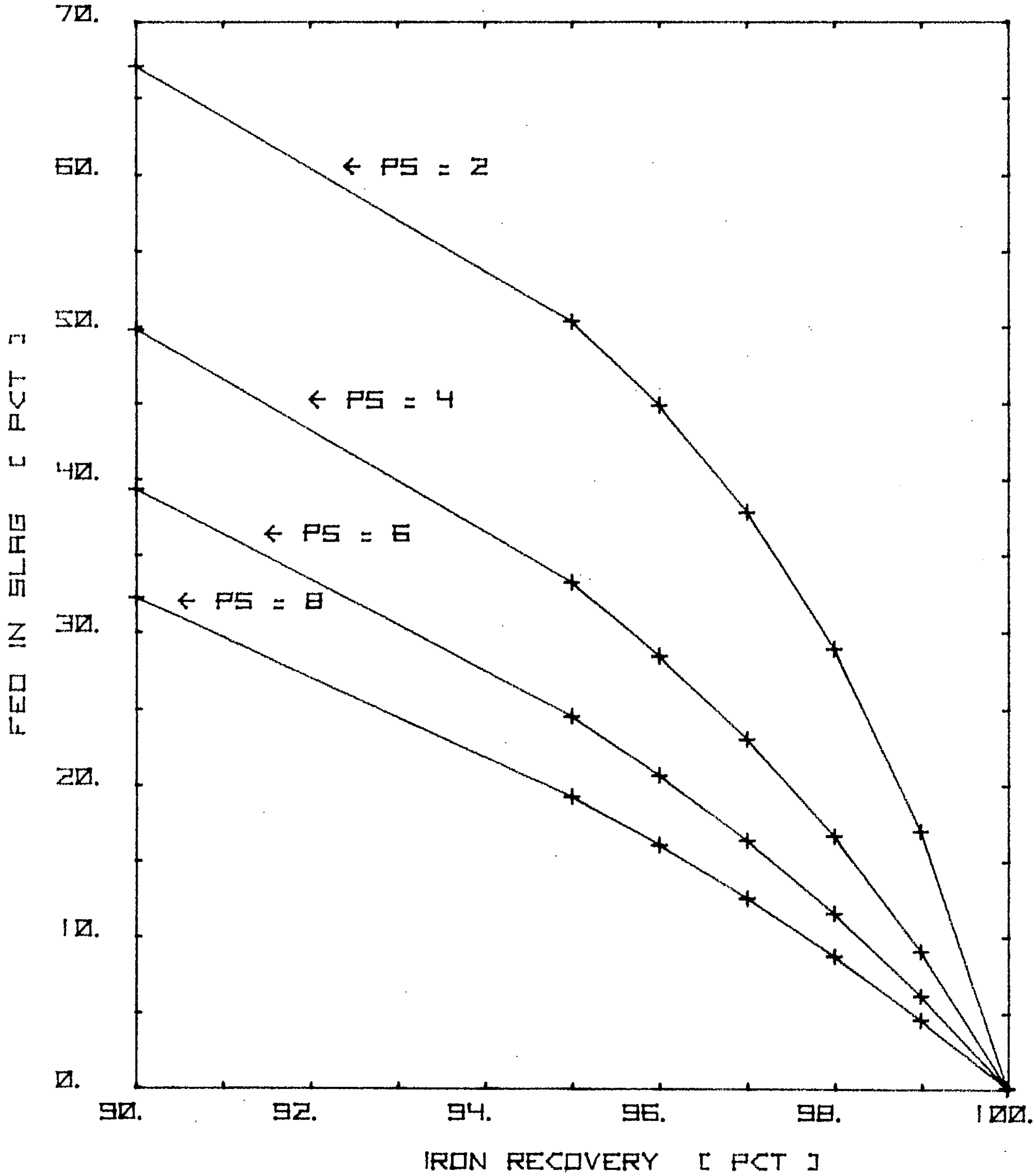

Figure 6. Per Cent $Fe_{.950}$ in Slag vs Per Cent Recovery at Ore SiO_2 Contents of 2,4,6 and 8%.
(B = 1.2)

The effect of varying the per cent SiO_2 in the ore on the slag composition is shown in Figure 8, at an iron recovery of 98% and a slag basicity of 1.2. It is obvious that the slopes of all three curves become steeper with decreasing percentages of SiO_2 in the ore. This of course is related to the fact that the weight of slag formed also decreases with decreasing percentages of SiO_2 in the ore, as was illustrated in Figure 7.

Additional information is given in Tables B-17, B-18, B-19, B-20, B-21 and B-22 for weights of slag formed and slag composition at iron recoveries of 100, 99, 98, 97, 96 and 95%, at a slag basicity of 1.2.

(ii) Effect of slag basicity

The effect of varying slag basicity on the weight of slag formed is shown in Figure 9, at an iron recovery of 98% and ore SiO_2 contents of 2.4 and 6%. This Figure shows not only the increase that occurs in slag weight as the basicity increases, but also the fact that the curves become steeper with increasing ore silica contents (PS). This means that a small change in basicity, e.g., from 1.1 to 1.2, would cause a greater change in slag weight at PS = 6 than at PS = 2.

The effect of varying basicity on the slag composition is shown in Figure 10, for an ore SiO_2 content of 6%, and an iron recovery of 98%. These conditions are reasonably typical of what might be expected in commercial practice. It is obvious that the major changes are in the CaO and SiO_2 contents. The

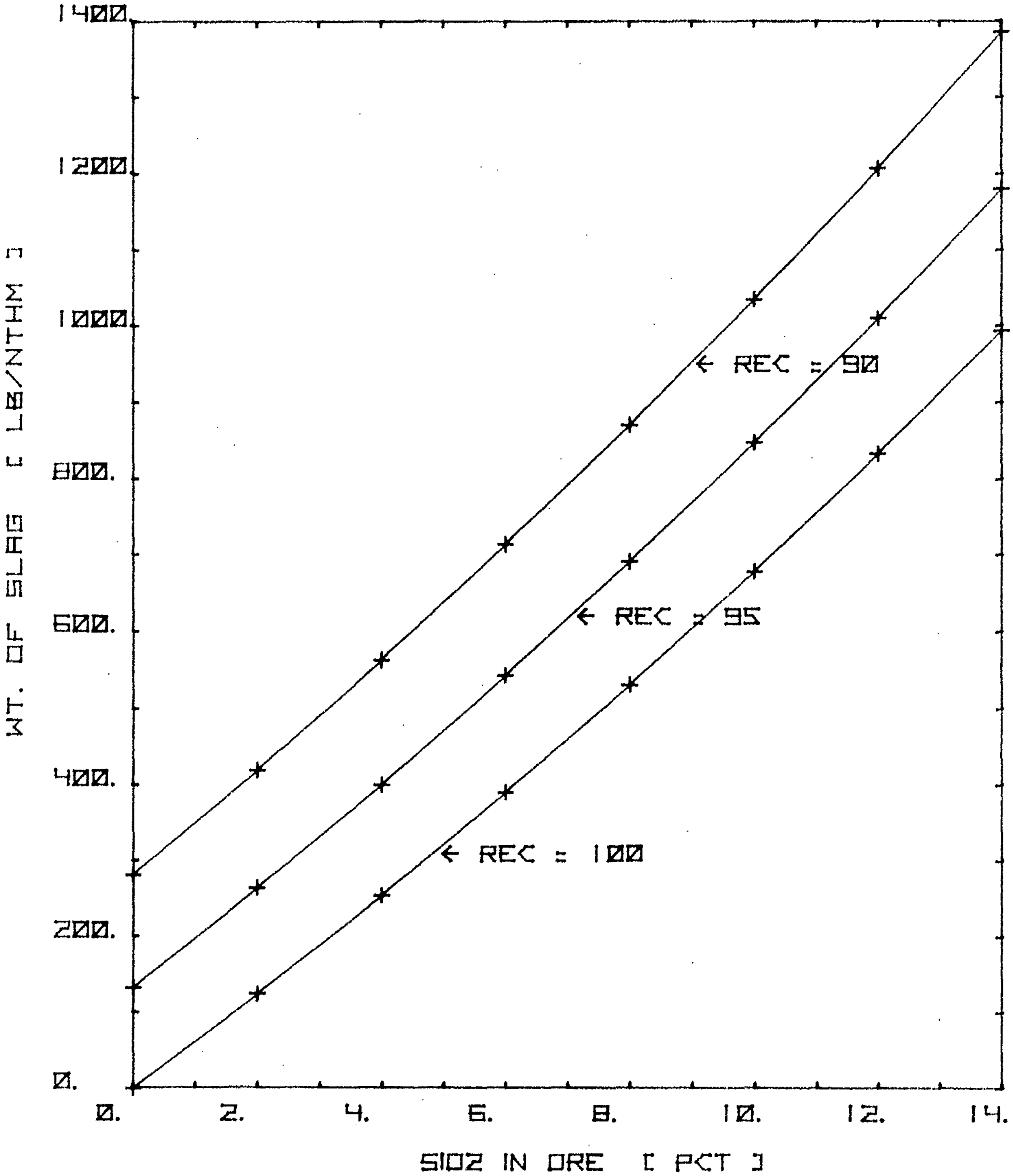

Figure 7. Weight of Slag Produced vs Per Cent SiO_2 in Ore at Iron Recoveries of 90,95 and 100%. (B = 1.2)

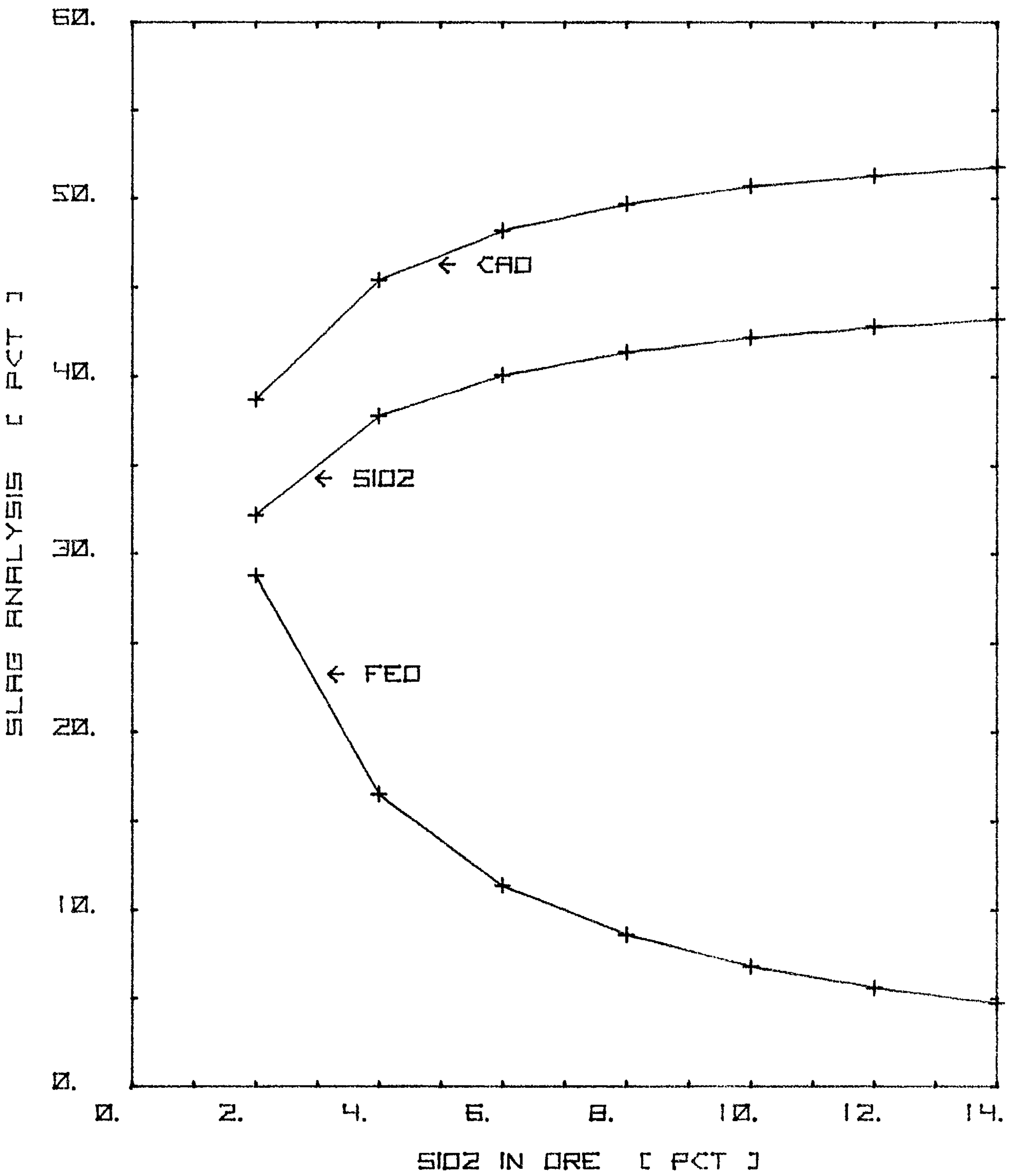

Figure 8. Composition of Slag vs Per Cent SiO_2 in Ore at Iron Recovery of 98% and Slag Basicity of 1.2

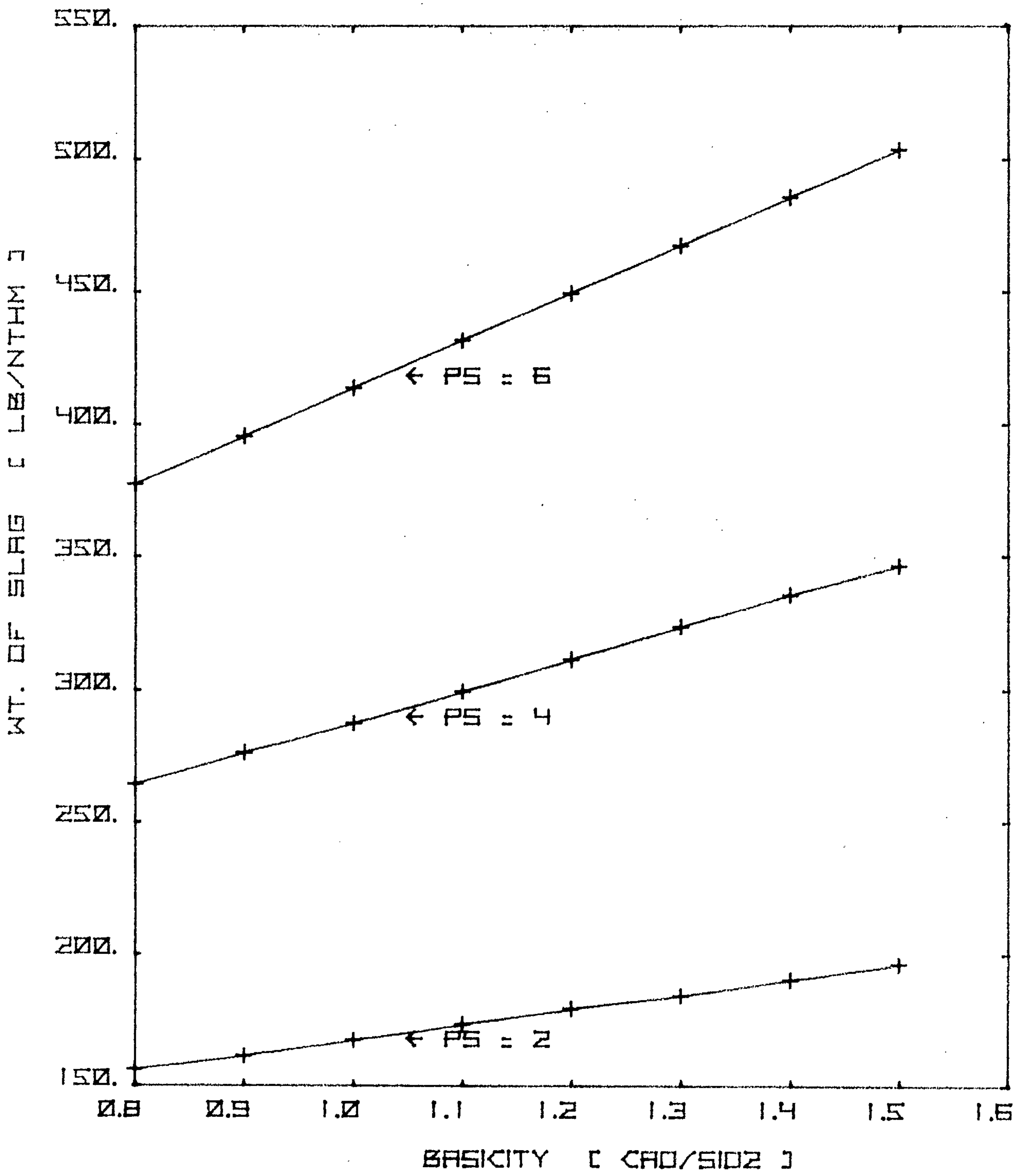

Figure 9. Weight of Slag Produced vs Basicity at Ore SiO_2 contents of 2,4 and 6% and Iron Recovery of 98%.

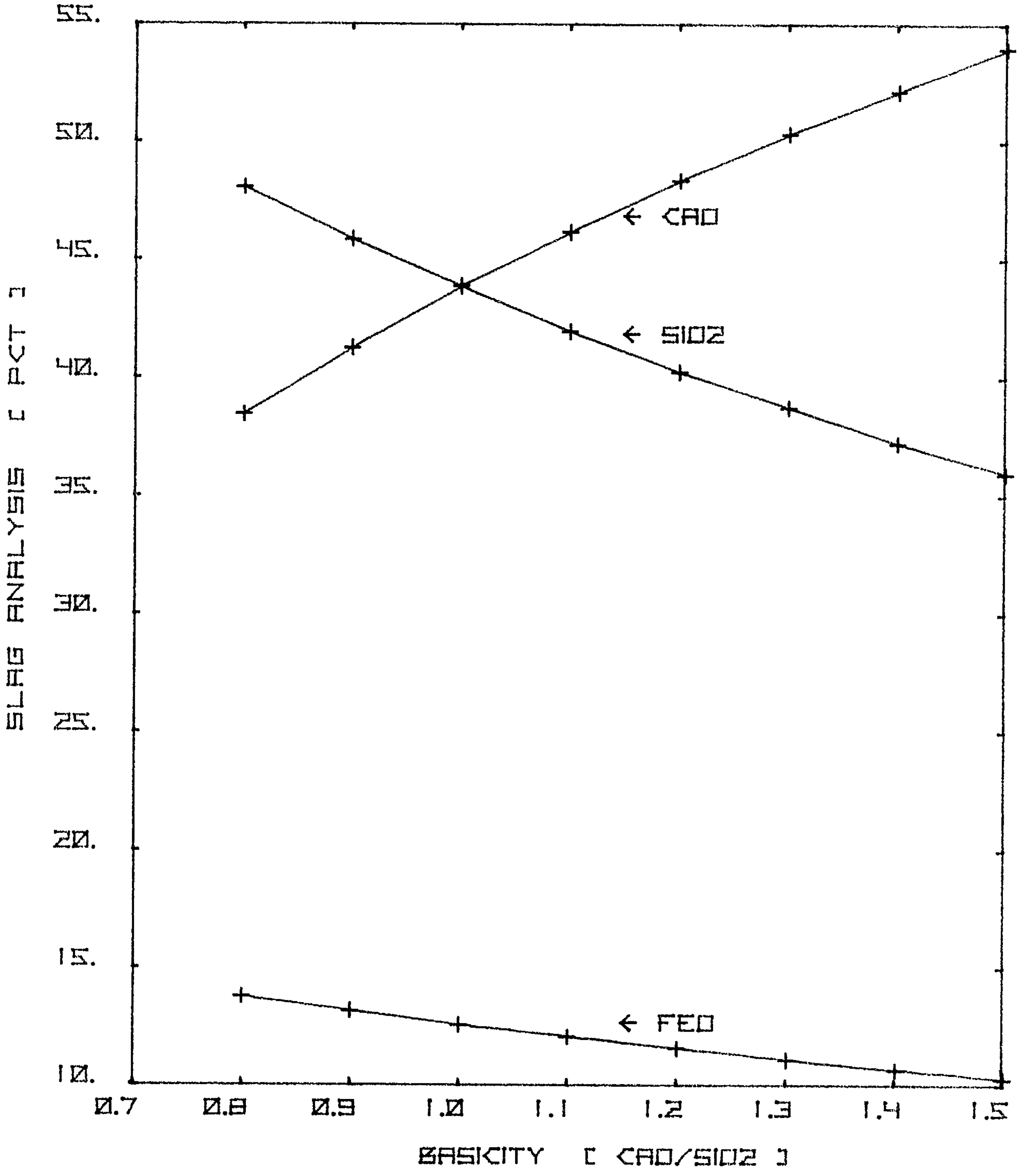

Figure 10. Composition of Slag vs Basicity at Ore SiO_2 Content of 6% and Iron Recovery of 98%.

iron oxide content only decreases from about 14 to 10 per cent as the basicity changes from 0.8 to 1.5.

2. Practical Operating Conditions

An assumed set of operating conditions which it is believed could be realized in practice and the amounts of energy and materials needed to produce a ton of hot metal under these conditions are given in TABLE 1.

Assumed conditions:

(a) SiO_2 content of ore = 6%

The world shipments of iron ore pellets in 1974 amounted to about 125 million tons[9] of which almost 70% contained less then 6% SiO_2, and about 30% contained less then 4% SiO_2. Consequently, the choice of 6% SiO_2 in the feed material appears to be a reasonable one.

(b) Recovery of iron = 98%

In nearly all the experimental work done on the SERF process in the 250 kVA furnace at the CANMET Pyrometallurgy Laboratory, and in the 1500 kVA furnace at Atlas Steels Co. a recovery of 98% or more was achieved. It is reasonable to assume that in a commercial-size SERF operation a recovery of 98% or better could be maintained.

(c) Preheat temperature in shaft = 900°C

Experience in the SERF development work has shown that 900°C is a reasonable target figure for the maximum shaft temperature. It is unlikely that successful operations could be sustained at higher temperatures because of the danger of softening of pellets and consequent sticking of the material in the shaft. It is essential that the solid material in the shaft remain free-flowing.

TABLE 1

Practical Operating Conditions and Projected Results for Production of One Ton (2000 lb) of Hot Metal

Assumed Conditions:	
SiO_2 content of ore (%)	6
Recovery of iron in metal (%)	98
Preheat temperature in shaft (°C)	900
Degree of prereduction in shaft (%)	50
Bath temperature (°C)	1400
Basicity of slag (CaO/SiO_2)	1.2
Carbon content of metal (%)	3.0
Electric furnace thermal efficiency (%)	75
Quantities required:	
Electrical energy (kWh) (minimum, theoretical)	821
Electrical energy (kWh) (allowing for 25% heat loss)	1095
Carbon (lb)	370
Coal (lb) (assuming 80% fixed carbon)	463
Ore (pellets) (lb)	3011
Lime (CaO) (lb)	217
Slag produced (lb)	449

(d) Degree of prereduction = 50%

In some of the experiments done in the Pyrometallurgy Laboratory, 54% prereduction was sustained for about 70 hours, and higher values (up to 60%) were sustained for shorter periods of time. In other prereduction processes such as the SL-RN, Midrex etc., higher degrees of reduction, e.g., 90 to 95%, are regularly obtained (at the expense of longer time in the reduction zone). Hence for the SERF process 50% prereduction appears to be a realistic target value.

(e) Bath temperature = 1400°C, Basicity of slag = 1.2, Carbon content of metal = 3.0%

Throughout the SERF development work it has been found that when the slag basicity is maintained at about 1.2, a bath temperature of 1400°C is hot enough to provide a safe margin of superheat for the slag so that it can be readily tapped and handled. Also, throughout most of the development work the carbon content of the metal obtained was close to 3%. Iron with this carbon content freezes at about 1250°C; hence a bath temperature of 1400°C also provides enough superheat for easy handling of the metal.

(f) Furnace thermal efficiency = 75%

This is a realistic figure for commercial-size smelting furnaces[10].

Projected quantities required

The projected amounts of electrical energy and materials required per net ton of hot metal shown in Table 1 are derived from theoretical considerations and application of the assumptions described above. They are somewhat more optimistic than the projections given in the report of the experimentation done at Atlas Steels[11]. The projections given in that report were based on the results of experimentation done up to that time using a shaft which was designed about 8 years ago. The knowledge gained during the experimentation at Atlas Steels and in the latter work in the Pyrometallurgy Laboratory has indicated where improvement could be made in shaft design and in operating techniques which should make possible the achievement of the operating conditions and the results set forth in Table 1.

SUMMARY

1. The theoretical minimum amounts of energy and materials needed for production of iron by the SERF process have been calculated for an "idealized" situation, i.e. pure Fe_2O_3, high degrees of preheating and prereduction of the ore in the shaft furnace, 100% recovery of iron, etc.

2. The effects of seven operating variables on the amounts of energy and materials required have been delineated to demonstrate the effect of moving from the "idealized" situation toward more realistic operating conditions.

The variables studied were:

(a) Preheat temperature in the shaft

(b) Degree of prereduction in the shaft

(c) Bath temperature

(d) Percent SiO_2 in ore

(e) Recovery of iron in metal

(f) Basicity of slag

(g) Carbon content of metal

3. The first two variables in the above list, i.e. the preheating of the ore and its prereduction in the shaft, are by far the most important in reducing the amounts of electrical energy and reductant required in the process. For example, the combination of heating the ore to 900°C and doing 50% prereduction in the shaft can reduce the theoretical amounts of both the electrical energy and carbon needed in the electric furnace by about 50%.

4. Based on the experience gained during the development work on the SERF process, assumptions have been made regarding the values of the above seven variables which are believed to represent attainable operating conditions. Calculations made using these values indicate that it should be possible to produce iron by the SERF process using about 1100 kwh of electrical energy and about 460 lb of coal per nthm. This compares very favourably with the typical electrical energy requirement (2040 kWh/nthm) and coal requirement (800 lb/nthm) for producing iron by the Tysland-Hole process[11]. It should be noted, however, that a modest amount of natural gas is required in the SERF process to assist in maintaining stable operating conditions in the shaft. Previous projections[11] indicated that the amount of natural gas required would be in the order of 900 to 1000 standard cubic feet per nthm.

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APPENDIX A

Material and Energy Balance Calculation Procedure

1. Material Balance

The chemical reactions involved in the process were listed on p5, and the abbreviations used for the variables were described on p6. The number of mols of the various oxides involved in the shaft reactions (Reactions 1,2 and 3) and in the furnace reactions (Reactions 5,6 and 7) depend on PR, the degree of prereduction achieved in the shaft. Completion of Reaction 1 corresponds to PR = 11.11%; completion of Reaction 2 corresponds to PR = 29.8%. It is thus convenient to divide the material balance portion of the calculation in three ranges, namely:

Range 1	$0 < PR < 11.11$
Range 2	$11.11 < PR < 29.8$
Range 3	$29.8 < PR < 100.$

The starting basis for the calculation was one lb-mol of Fe_2O_3 and the various quantities of intermediate and final products were calculated from this. For final evaluation it is more useful to see the various quantities expressed in units per unit of metal produced (e.g., per ton of metal) and conversion factors were built into the program to do this.

In describing the computation procedure it is convenient to deal with the three ranges separately, describing those calculations that are peculiar to each range. Some calculations that occur near the end of the program are common to all ranges.

Range 1 - involves Reactions 1,5,6,7,8 and 4.

Reaction 1. Reduction of Fe_2O_3 by CO, in the shaft, producing Fe_3O_4 and CO_2. From the value of PR calculate the number of mols of Fe_2O_3 reacting, the mols of Fe_2O_3 remaining unreacted, the mols of Fe_3O_4 formed, the mols of CO required, and the mols of CO_2 produced. The Fe_3O_4 formed, and the unreacted Fe_2O_3 then pass into the electric furnace for further reduction by Reactions 5 and 6.

Reaction 5. The Fe_2O_3 that was not reduced in Reaction 1 is reduced by carbon, in the electric furnace, to produce Fe_3O_4 and CO. Calculate the mols of Fe_3O_4 produced, the mols of carbon required and the mols of CO produced.

Reaction 6. The total Fe_3O_4 produced in Reactions 1 and 5 is reduced by carbon in the electric furnace to produce $Fe_{.95}O$ and CO. Calculate the mols of $Fe_{.95}O$ produced, the mols of carbon required and the mols of CO produced. The mols of $Fe_{.95}O$ available for Reaction 7 are now known. The mols of CO required for shaft reactions also are known from Reaction 1. Reactions 7,8 and 4 being common to all ranges will be discussed later.

Range 2 - involves Reactions 1,2,6,7,8 and 4.

Reaction 1. This reaction goes to completion. Calculate the mols of Fe_3O_4 formed, the mols of CO required and the mols of CO_2 produced.

Reaction 2. Some of the Fe_3O_4 produced in Reaction 1 is reduced by CO, in the shaft, to produce $Fe_{.95}O$ and CO_2. From the value of PR calculate the mols of Fe_3O_4 reacting, the mols of Fe_3O_4 remaining unreacted, the mols of $Fe_{.95}O$ formed, the mols of CO required and the mols of CO_2 produced. The Fe_3O_4 remaining and $Fe_{.95}O$ formed then pass into the electric furnace where the Fe_3O_4 reacts via Reaction 6.

Reaction 6. The Fe_3O_4 remaining from Reaction 2 is reduced by carbon, producing $Fe_{.95}O$ and CO. Calculate the mols of $Fe_{.95}O$ produced, the mols of carbon required and the mols of CO produced. The mols of $Fe_{.95}O$ produced by Reactions 2 and 6 are summed to establish the number of mols of $Fe_{.95}O$ available for Reaction 7. For the shaft reactions, the total mols of CO required and of CO_2 produced are established by summing the values from Reactions 1 and 2.

Range 3 - involves Reactions 1,2,3,7,8, and 4.

Reaction 1. This reaction goes to completion. Calculate the mols of Fe_3O_4 formed, the mols of CO required and the mols of CO_2 produced.

Reaction 2. This reaction goes to completion. From the known mols of Fe_3O_4 resulting from Reaction 1, calculate the mols of $Fe_{.95}O$ produced, the mols of CO required and the mols of CO_2 produced.

Reaction 3. Some $Fe_{.95}O$ is reduced in the shaft, by CO, producing metallic iron and CO_2. From the value of PR, calculate the mols of $Fe_{.95}O$ reacting, the mols of $Fe_{.95}O$ remaining unreacted, the mols of Fe produced, the mols of CO required and the mols of CO_2 produced. The metallic iron produced and the $Fe_{.95}O$ remaining pass into the electric furnace where the $Fe_{.95}O$ is available for Reaction 7. For the shaft reactions, the total mols of CO required and of CO_2 produced are calculated by summing the values involved in Reactions 1,2 and 3.

Reactions 7,8 and 4. These are involved in all three ranges. The steps involved in the calculations from this point are as follows:

(a) From the specified iron recovery (REC), calculate the mols of Fe to be produced by Reaction 7, the mols of $Fe_{.95}O$ that must react to produce this amount of metallic iron, the mols of $Fe_{.95}O$ remaining, the mols of carbon required and the mols of CO produced.

(b) Using the specified carbon content of the metal (PC) and the mols of iron produced, calculate the amount of carbon to be dissolved in the iron by Reaction 8 and the resulting weight of metal.

(c) For each of the ranges sum the total mols of carbon required for the reactions involved, as follows -

For Range 1 - Reactions 5, 6, 7 and 8

For Range 2 - Reactions 6, 7 and 8

For Range 3 - Reactions 7 and 8

(d) For each of the ranges, sum the total mols of CO produced in the furnace, as follows -

For Range 1 - Reactions 5, 6 and 7

For Range 2 - Reactions 6 and 7

For Range 3 - Reaction 7

(e) Calculate the mols of CO to be burned in the shaft via Reaction 4, by deducting the total mols of CO required for shaft reduction reactions from the total mols of CO produced in the furnace.

(f) Calculate the mols of oxygen required for Reaction 4, the mols of nitrogen associated with it (as air) and the mols of CO_2 produced.

(g) From the defined SiO_2 content of the ore (PS) calculate the mols of SiO_2 per mol of Fe_2O_3. This SiO_2 will remain as part of the slag.

(h) From the defined CaO/SiO_2 ratio (B) and the mols of SiO_2 per mol of Fe_2O_3, calculate the mols of CaO to be fed. This CaO will remain as a constituent of the slag.

(i) Using the amounts of SiO_2 and CaO calculated in (g) and (h) and the calculated amount of $Fe_{.95}O$ remaining unreduced [from (a)], calculate the amount of slag produced, and its composition, i.e. $\%Fe_{.95}O$, $\%SiO_2$ and $\%CaO$.

2. Energy Balance

The heat contents of all materials at elevated temperatures were calculated relative to their heat contents at 25°C. Equations for heats of reaction at elevated temperatures were established by calculating the heats of reaction at 25°C (298°K) and adding the appropriate expressions for the heat content difference (products minus reactants) for the elevated temperatures. A multiplicity of equations were required in this study because over the temperature range of interest (25 to 1600°C), five allotropic forms of Fe, two of $Fe_{.95}O$, two of Fe_3O_4, three of Fe_2O_3 and two of SiO_2 were involved.

The computation procedure was as follows:

(a) Calculate the amount of heat needed to heat the Fe_2O_3 from 25°C to shaft temperature (TC).

(b) Calculate the amount of heat needed to heat the SiO_2 from 25°C to TC.

(c) Calculate the heats of Reactions 1,2 and 3, where applicable, at TC.

(d) For whatever Fe_2O_3, Fe_3O_4, $Fe_{.95}O$, Fe and SiO_2 remain after the shaft reactions are completed, calculate the heat required to heat these materials from the shaft temperature (TC) to the temperature of the furnace bath (TBC).

(e) Calculate the heat required to heat the carbon from 25°C to TBC.

(f) Calculate the heat required to heat the CaO from 25°C to TBC.

(g) Calculate the heats of Reactions 5,6,7 and 8 at TBC.

(h) Calculate the heat content of the slag at TBC.

(i) Calculate the heat evolved when the CO from Reactions 5,6 and 7 is cooled from TBC to TC.

(j) Calculate the heat needed to heat the air (O_2 + N_2) for Reaction 4 from 25°C to TC.

(k) Calculate the heat of Reaction 4 at TC.

(l) Calculate the heat evolved when the CO_2 and N_2 from Reaction 4 are cooled from TC to 127°C.

(m) Calculate the heat evolved when the CO_2 from Reactions 1,2 and 3 is cooled from TC to 127°C.

(n) Sum up all heat terms for the shaft.

(o) Sum up all heat terms for the electric furnace.

(p) Convert all terms from mols, weight or energy units per mol of Fe_2O_3 (the starting basis) to weight, volume (for gases) or energy units per net ton (2000 lb) of metal produced.

(q) Output all answers, including a listing of the defined parameters for each calculation.

TABLE B-1

CALCULATED FURNACE ENERGY vs PREHEAT TEMPERATURE AND PER CENT PREREDUCTION AT ORE SiO_2 CONTENT OF 0% AND IRON RECOVERY OF 100%. TBC = 1400, PC = 3, B = 1.2

Per Cent Prereduction	PREHEAT TEMPERATURE (°C)									
	25	100	200	300	400	500	600	700	800	900
	FURNACE ENERGY (kWh/nthm)									
0	1633	1615	1588	1559	1528	1495	1460	1422	1390	1359
10	1531	1513	1487	1458	1427	1392	1355	1322	1293	1263
20	1371	1354	1330	1303	1275	1245	1213	1184	1156	1128
30	1206	1189	1166	1142	1117	1092	1067	1041	1015	988
40	1082	1066	1045	1022	999	975	951	926	900	874
50	958	944	923	903	881	859	835	812	785	761

APPENDIX B

TABLE B-2

CALCULATED FURNACE ENERGY vs PREHEAT TEMPERATURE AND PER CENT PREREDUCTION

AT ORE SiO_2 CONTENT OF 2% AND IRON RECOVERY OF 100%, TBC = 1400, PC = 3, B = 1.2

Per cent Prere-duction	PREHEAT TEMPERATURE (°C)									
	25	100	200	300	400	500	600	700	800	900
	FURNACE ENERGY (kWh/nthm)									
0	1650	1632	1605	1576	1544	1511	1476	1439	1406	1375
10	1547	1530	1504	1475	1443	1409	1371	1339	1309	1280
20	1388	1371	1346	1320	1291	1261	1229	1200	1172	1144
30	1223	1206	1182	1158	1134	1109	1083	1057	1031	1004
40	1099	1083	1061	1039	1016	992	968	943	916	891
50	975	960	940	919	897	875	852	828	802	777

TABLE B-3

CALCULATED FURNACE ENERGY vs PREHEAT TEMPERATURE AND PER CENT PREREDUCTION

AT ORE SiO_2 CONTENT OF 4% AND IRON RECOVERY OF 100%, TBC = 1400, PC = 3, B = 1.2

Per cent Prere-duction	PREHEAT TEMPERATURE (°C)									
	25	100	200	300	400	500	600	700	800	900
	FURNACE ENERGY (kWh/nthm)									
0	1667	1649	1622	1593	1561	1528	1493	1456	1423	1393
10	1564	1547	1521	1492	1460	1426	1388	1356	1326	1297
20	1405	1388	1363	1337	1308	1278	1246	1217	1190	1161
30	1240	1223	1199	1175	1151	1126	1100	1075	1048	1022
40	1116	1100	1078	1056	1033	1009	985	960	934	908
50	992	977	957	936	914	892	869	845	819	794

TABLE B-4

CALCULATED FURNACE ENERGY vs PREHEAT TEMPERATURE AND PER CENT PREREDUCTION

AT ORE SiO_2 CONTENT OF 6% AND IRON RECOVERY OF 100%, TBC = 1400, PC = 3, B = 1.2

Per Cent Prere-duction	PREHEAT TEMPERATURE (°C)									
	25	100	200	300	400	500	600	700	800	900
	FURNACE ENERGY (kWh/nthm)									
0	1685	1666	1640	1610	1579	1546	1511	1474	1441	1410
10	1582	1564	1538	1510	1478	1444	1406	1374	1344	1315
20	1423	1406	1381	1355	1326	1296	1264	1235	1207	1179
30	1258	1241	1217	1193	1169	1144	1118	1092	1066	1039
40	1134	1118	1096	1074	1050	1027	1003	978	951	926
50	1009	995	975	954	932	910	887	863	837	812

TABLE B-5

CALCULATED FURNACE ENERGY vs PREHEAT TEMPERATURE AND PER CENT PREREDUCTION

AT ORE SiO_2 CONTENT OF 0% AND IRON RECOVERY OF 95%, TBC = 1400, PC = 3, B = 1.2

Per Cent Prereduction	PREHEAT TEMPERATURE (°C)									
	25	100	200	300	400	500	600	700	800	900
	FURNACE ENERGY (kWh/nthm)									
0	1700	1681	1652	1622	1589	1554	1517	1478	1443	1411
10	1591	1573	1546	1516	1482	1446	1407	1372	1341	1310
20	1424	1406	1380	1352	1322	1291	1257	1227	1197	1168
30	1250	1232	1208	1182	1157	1130	1103	1076	1048	1020
40	1119	1103	1080	1056	1032	1007	982	956	928	901
50	989	974	952	930	908	884	860	835	807	781

TABLE B-6

CALCULATED FURNACE ENERGY vs PREHEAT TEMPERATURE AND PER CENT PREREDUCTION

AT ORE SiO_2 CONTENT OF 2% AND IRON RECOVERY OF 95%, TBC = 1400, PC = 3, B = 1.2

Per cent Prere-duction	PREHEAT TEMPERATURE (°C)									
	25	100	200	300	400	500	600	700	800	900
	FURNACE ENERGY (kWh/nthm)									
0	1717	1698	1670	1639	1606	1571	1534	1495	1461	1428
10	1609	1590	1563	1533	1500	1463	1424	1390	1359	1328
20	1441	1423	1397	1369	1340	1308	1274	1244	1215	1185
30	1267	1249	1225	1200	1174	1147	1121	1093	1066	1038
40	1137	1120	1097	1074	1049	1024	999	973	945	918
50	1006	991	970	948	925	901	877	852	824	799

TABLE B-7

CALCULATED FURNACE ENERGY vs PREHEAT TEMPERATURE AND PER CENT PREREDUCTION

AT ORE SiO_2 CONTENT OF 4% AND IRON RECOVERY OF 95%, TBC = 1400, PC = 3, B = 1.2

Per Cent Prere-duction	PREHEAT TEMPERATURE (°C)									
	25	100	200	300	400	500	600	700	800	900
	FURNACE ENERGY (kWh/nthm)									
0	1735	1716	1688	1657	1624	1589	1552	1513	1479	1446
10	1627	1608	1581	1551	1518	1481	1442	1408	1377	1346
20	1459	1441	1415	1387	1358	1326	1292	1262	1233	1203
30	1285	1267	1243	1218	1192	1165	1139	1111	1084	1056
40	1155	1138	1115	1092	1067	1042	1017	991	963	936
50	1024	1009	988	966	943	919	895	870	842	817

TABLE B-8

CALCULATED FURNACE ENERGY vs PREHEAT TEMPERATURE AND PER CENT PREREDUCTION

AT ORE SiO_2 CONTENT OF 6% AND IRON RECOVERY OF 95%, TBC = 1400, PC = 3, B = 1.2

Per Cent Prere-duction	PREHEAT TEMPERATURE (°C)									
	25	100	200	300	400	500	600	700	800	900
	FURNACE ENERGY (kWh/nthm)									
0	1754	1735	1706	1676	1643	1608	1571	1532	1498	1465
10	1646	1627	1600	1570	1536	1500	1461	1427	1395	1364
20	1478	1460	1434	1406	1376	1345	1311	1281	1251	1222
30	1304	1286	1262	1236	1210	1184	1157	1130	1103	1074
40	1174	1157	1134	1110	1086	1061	1036	1010	982	955
50	1043	1028	1007	984	962	938	914	889	861	835

TABLE B-9

CALCULATED FURNACE ENERGY vs BATH TEMPERATURE AND PER CENT PREREDUCTION AT ORE SiO_2 CONTENT OF 0% AND IRON RECOVERY OF 100%

TC = 900, PC = 3, B = 1.2

Per Cent Prere-duction	BATH TEMPERATURE (°C)								
	1400	1425	1450	1475	1500	1525	1550	1575	1600
	FURNACE ENERGY (kWh/nthm)								
0	1359	1370	1381	1392	1403	1414	1425	1436	1447
10	1263	1274	1284	1294	1305	1315	1325	1336	1346
20	1128	1138	1148	1158	1167	1177	1187	1197	1207
30	988	997	1007	1016	1026	1035	1045	1054	1064
40	874	883	892	901	910	918	927	936	945
50	761	769	777	785	793	802	810	818	826

TABLE B-10

CALCULATED FURNACE ENERGY vs BATH TEMPERATURE AND PER CENT PREREDUCTION AT ORE SiO_2 CONTENT OF 2% AND IRON RECOVERY OF 100%

TC = 900, PC = 3, B = 1.2

Per Cent Prere-duction	BATH TEMPERATURE (°C)								
	1400	1425	1450	1475	1500	1525	1550	1575	1600
	FURNACE ENERGY (kWh/nthm)								
0	1375	1387	1399	1411	1423	1436	1448	1461	1474
10	1280	1291	1302	1314	1325	1337	1349	1361	1374
20	1144	1155	1166	1177	1188	1199	1211	1223	1235
30	1004	1015	1025	1036	1046	1057	1068	1080	1091
40	891	901	910	920	930	941	951	962	972
50	777	786	796	805	814	824	834	844	854

TABLE B-11

CALCULATED FURNACE ENERGY vs BATH TEMPERATURE AND PER CENT PREREDUCTION AT ORE SiO_2 CONTENT OF 4% AND IRON RECOVERY OF 100%

TC = 900, PC = 3, B = 1.2

Per Cent Prere-duction	BATH TEMPERATURE (°C)								
	1400	1425	1450	1475	1500	1525	1550	1575	1600
	FURNACE ENERGY (kWh/nthm)								
0	1393	1405	1418	1432	1445	1459	1473	1488	1503
10	1297	1309	1322	1334	1347	1360	1374	1388	1403
20	1161	1173	1185	1197	1210	1223	1236	1249	1264
30	1022	1033	1044	1056	1068	1080	1093	1106	1120
40	908	919	930	941	952	964	976	988	1001
50	794	804	815	825	836	847	858	870	883

TABLE B-12

CALCULATED FURNACE ENERGY vs BATH TEMPERATURE AND PER CENT PREREDUCTION AT ORE SiO_2 CONTENT OF 6% AND IRON RECOVERY OF 100%

TC = 900, PC = 3, B = 1.2

Per Cent Prereduction	BATH TEMPERATURE (°C)								
	1400	1425	1450	1475	1500	1525	1550	1575	1600
	FURNACE ENERGY (kWh/nthm)								
0	1410	1424	1438	1453	1468	1483	1499	1515	1533
10	1315	1328	1342	1355	1370	1384	1400	1416	1433
20	1179	1192	1205	1218	1232	1247	1261	1277	1294
30	1039	1052	1064	1077	1091	1104	1119	1134	1150
40	926	937	949	962	974	988	1001	1016	1031
50	812	823	835	846	858	871	884	898	913

TABLE B-13

CALCULATED FURNACE ENERGY vs PER CENT SiO_2 IN ORE

AND PER CENT PREREDUCTION AT IRON RECOVERY OF 100%

TC = 900, TBC = 1400, PC = 3, B = 1.2

Per Cent Prereduction	PER CENT SiO_2 in Ore							
	0	2	4	6	8	10	12	14
	FURNACE ENERGY (kWh/nthm)							
0	1359	1375	1393	1410	1429	1448	1469	1490
5	1311	1328	1345	1363	1381	1401	1421	1442
10	1263	1280	1297	1315	1333	1353	1373	1394
11.1	1253	1269	1286	1304	1323	1342	1362	1384
15	1198	1215	1232	1249	1268	1288	1308	1329
20	1128	1144	1161	1179	1198	1217	1238	1259
25	1058	1074	1091	1109	1128	1147	1167	1189
29.8	990	1007	1024	1042	1060	1080	1100	1121
30	988	1004	1022	1039	1058	1077	1098	1119
35	931	948	965	983	1001	1021	1041	1062
40	874	891	908	926	944	964	984	1005
45	818	834	851	869	888	907	927	949
50	761	777	794	812	831	850	871	892

TABLE B-14

CALCULATED FURNACE ENERGY vs PER CENT SiO_2 IN ORE

AND PER CENT PREREDUCTION AT IRON RECOVERY OF 98%

TC = 900, TBC = 1400, PC = 3, B = 1.2

Per Cent Prere-duction	PER CENT SiO_2 IN ORE							
	0	2	4	6	8	10	12	14
	FURNACE ENERGY (kWh/nthm)							
0	1379	1396	1413	1432	1451	1470	1491	1513
5	1330	1347	1365	1383	1402	1422	1442	1464
10	1281	1298	1316	1334	1353	1373	1394	1415
11.1	1271	1288	1305	1323	1342	1362	1383	1404
15	1215	1232	1249	1267	1286	1306	1327	1349
20	1143	1160	1178	1196	1215	1235	1255	1277
25	1072	1088	1106	1124	1143	1163	1184	1205
29.8	1003	1020	1037	1055	1074	1094	1115	1137
30	1000	1017	1035	1053	1072	1092	1113	1134
35	943	959	977	995	1014	1034	1055	1076
40	885	901	919	937	956	976	997	1018
45	827	843	861	879	898	918	939	960
50	769	786	803	821	840	860	881	902

TABLE B-15

CALCULATED FURNACE ENERGY vs PER CENT SiO_2 IN ORE

AND PER CENT PREREDUCTION AT IRON RECOVERY OF 96%

TC = 900, TBC = 1400, PC = 3, B = 1.2

Per Cent Prereduction	PER CENT SiO_2 IN ORE							
	0	2	4	6	8	10	12	14
	FURNACE ENERGY (kWh/nthm)							
0	1400	1417	1435	1454	1473	1493	1514	1537
5	1350	1367	1385	1404	1423	1443	1465	1487
10	1300	1317	1335	1354	1373	1394	1415	1437
11.1	1290	1307	1324	1343	1362	1383	1404	1426
15	1232	1250	1267	1286	1305	1326	1347	1369
20	1159	1176	1194	1213	1232	1253	1274	1296
25	1086	1103	1121	1140	1159	1179	1201	1223
29.8	1016	1033	1051	1070	1089	1109	1130	1153
30	1014	1031	1049	1067	1086	1107	1128	1150
35	954	972	989	1008	1027	1048	1069	1091
40	895	912	930	949	968	988	1010	1032
45	836	853	871	890	909	929	950	973
50	777	794	812	831	850	870	891	913

TABLE B-16

WEIGHT OF CARBON REQUIRED vs PER CENT RECOVERY AND PER CENT PREREDUCTION AT CARBON CONTENT OF METAL = 3%

Per Cent Prere-duction	PER CENT RECOVERY OF IRON						
	90	95	96	97	98	99	100
	WEIGHT OF CARBON REQUIRED (lb/nthm)						
0	706	695	693	691	689	687	685
5	671	662	660	659	657	656	654
10	637	629	628	627	625	624	623
11.1	629	622	621	620	618	617	616
15	602	596	595	594	593	592	592
20	567	563	563	562	561	561	560
25	532	531	530	530	529	529	529
29.8	499	499	499	499	499	499	499
30	498	498	498	498	497	497	498
35	462	465	465	465	465	466	466
40	428	432	432	433	434	435	435
45	393	399	400	401	402	403	404
50	359	366	367	369	370	371	373

TABLE B-17

SLAG COMPOSITION, WEIGHT OF SLAG AND WEIGHT OF CaO

REQUIRED vs PER CENT SiO_2 IN ORE AT IRON RECOVERY OF 100%

B = 1.2

Slag Composition (per cent)	PER CENT SiO_2 in Ore							
	0	2	4	6	8	10	12	14
FeO	0.	0.	0.	0.	0.	0.	0.	0.
SiO_2	0.	45.5	45.5	45.5	45.5	45.5	45.5	45.5
CaO	0.	54.5	54.5	54.5	54.5	54.5	54.5	54.5
Weight of slag formed (lb/nthm)	0	125	254	390	531	678	832	993
Weight of CaO required (lb/nthm)	0	68	139	213	289	370	454	542

TABLE B-18

SLAG COMPOSITION, WEIGHT OF SLAG AND WEIGHT OF CaO

REQUIRED vs PER CENT SiO_2 IN ORE AT IRON RECOVERY OF 99%

B = 1.2

Slag composition (per cent)	PER CENT SiO_2 IN ORE							
	0	2	4	6	8	10	12	14
FeO	100.	16.9	9.0	6.1	4.5	3.6	2.9	2.5
SiO_2	0.	37.8	41.3	42.7	43.4	43.8	44.1	44.3
CaO	0.	45.4	49.6	51.2	52.1	52.6	52.9	53.2
Weight of slag formed (lb/nthm)	25	151	282	419	562	710	866	1029
Weight of CaO required (lb/nthm)	0	69	140	215	292	374	459	547

TABLE B-19

SLAG COMPOSITION, WEIGHT OF SLAG AND WEIGHT OF CaO

REQUIRED vs PER CENT SiO_2 IN ORE AT IRON RECOVERY OF 98%

B = 1.2

Slag Composition (per cent)	PER CENT SiO_2 IN ORE							
	0	2	4	6	8	10	12	14
FeO	100.	28.9	16.6	11.5	8.7	6.9	5.7	4.8
SiO_2	0.	32.3	37.9	40.2	41.5	42.3	42.9	43.3
CaO	0.	38.8	45.5	48.3	49.8	50.8	51.4	51.9
Weight of slag formed (lb/nthm)	52	179	311	449	593	743	901	1065
Weight of CaO required (lb/nthm)	0	69	142	217	295	377	463	553

TABLE B-20

SLAG COMPOSITION, WEIGHT OF SLAG AND WEIGHT OF CaO REQUIRED vs PER CENT SiO_2 IN ORE AT IRON RECOVERY OF 97%.

B = 1.2

Slag Composition (per cent)	PER CENT SiO_2 IN ORE							
	0	2	4	6	8	10	12	14
FeO	100.	37.8	23.0	16.3	12.5	10.0	8.3	7.1
SiO_2	0.	28.3	35.0	38.1	39.8	40.9	41.7	42.2
CaO	0.	33.9	42.0	45.7	47.7	49.1	50.0	50.7
Weight of slag formed (lb/nthm)	78	207	340	480	625	777	936	1102
Weight of CaO Required (lb/nthm)	0	70	143	219	298	381	468	559

TABLE B-21

SLAG COMPOSITION, WEIGHT OF SLAG AND WEIGHT OF CaO

REQUIRED vs PER CENT SiO_2 IN ORE AT IRON RECOVERY OF 96%

B = 1.2

Slag Composition (per cent)	PER CENT SiO_2 IN ORE							
	0	2	4	6	8	10	12	14
FeO	100.	44.8	28.4	20.6	16.0	13.0	10.8	9.2
SiO_2	0.	25.1	32.5	36.1	38.2	39.6	40.5	41.3
CaO	0.	30.1	39.0	43.3	45.8	47.5	48.6	49.5
Weight of slag formed (lb/nthm)	105	235	370	511	658	812	972	1140
Weight of CaO required (lb/nthm)	0	71	145	221	302	385	473	565

TABLE B-22

SLAG COMPOSITION, WEIGHT OF SLAG, AND WEIGHT OF CaO

REQUIRED vs PER CENT SiO_2 in ORE AT IRON RECOVERY OF 95%

B = 1.2

Slag Composition (per cent)	PER CENT SiO_2 IN ORE							
	0	2	4	6	8	10	12	14
FeO	100.	50.3	33.2	24.5	19.2	15.7	13.2	11.3
SiO_2	0.	22.6	30.4	34.3	36.7	38.3	39.5	40.3
CaO	0.	27.1	36.4	41.2	44.1	46.0	47.4	48.4
Weight of slag formed (lb/nthm)	137	264	400	543	691	847	1009	1179
Weight of CaO required (lb/nthm)	0	72	146	224	305	389	478	570