ANALYTIC APPROACHES TO TECHNOLOGY OPTIMALIZATION IN FERROUS METALLURGY

AN ECONOMIC MODEL

By

L. LUKÁCS

(Received January 25, 1961)

Better capacity utilization in blast furnaces renders an economy with flux and consequently with coke possible. Though the pig-iron so produced is of an inferior quality, inasmuch as its contamination is thereby increased. An increase in contamination, however, leads to a decrease in capacity utilization in the Siemens—Martin type open-hearth furnaces.

This raises the question: how is it possible to *simultaneously* increase the *capacity utilization in pig-iron and in steel ingot production*. Or to phrase it in another way: what would be a feasible solution of the contradicting task of increasing the pig-iron production with decreasing coke input (resulting in a pig-iron of high contamination) and of increasing at the same time the steel ingot production with decreasing fuel input (requiring a pig-iron of low contamination).

The above exposition of the contradiction focuses the light of solution on the contamination of the pig-iron. There would seem to exist two possible ways to solve this problem

(i) keeping the charge of the blast furnace pure, *i.e.* dress and enrich the ore so as to minimize its contamination and/or utilize such fuels that do not introduce contaminating elements to the furnace (*e.g.* cokes with very low degree of ash contents or natural gas to replace cokes etc.);

(ii) the conditioning of the pig-iron. (The absurdity of purifying the crude steel during or after casting, a third possibility on a mere logical basis, will be evident when considering the metallurgy process of steelmaking to be described below.)

The applicability and economy of the first way depend mostly on the supply of the sorts of raw materials required by this type of technology. The scarcity of such in our country emphasizes the advisability to resort to the second process.

In this paper we will discuss a method for the economic optimalization of total steel production costs as depending on the technology of pig-iron conditioning.

We will proceed with:

(i) describing the necessity of pig-iron conditioning;

(ii) explaining some metallurgy aspects underlying the economic relations;

(iii) deriving a model from these technical features;

(iv) expounding the solving equations of our model;

(v) discussing some problems of the practical application of the proposed method.

(i) The necessity of conditioning

In the following section of this paper we will — for the sake of better elucidation — investigate the problem on the example of one of our integrated iron and steel works: Ózdi Kohászati Üzemek (Ózd Metallurgy Works, ÓMW in short).

In the past few years a large-scale reconstruction project began in this works, which is to be continued in the course of the second five-year plan. In the framework of this reconstruction two of the blast furnaces are to be rebuilt, enlarged and modernized resulting in all four furnaces being the most up-to-date ones. At the same time some other considerable measures to develop the iron plant will lead to a total renewal of its equipment. In the course of a reconstruction investment project the present 12 out-of-date open-hearth furnaces will be replaced by eight large, modern automatically operated and highly efficient new ones. An additional increase in efficiency will be obtained by intensifying the flame with O_2 injection.

The contradiction between the difference in the contaminations of pig-iron as the final output of profitable iron-making on one hand, and of pig-iron as the main input of profitable steel-making on the other, is not ruled out in the reconstruction plans.

Besides profitability contradictions, there are also some technical conflicts. The maximal Si contents of the first class quality pig-iron is fixed by our standards at 0.8 p. c. whereas the S contents at 0.08 p. c. Among the present circumstances the proportion of the first-class iron is rather low and it is not very seldom that the furnace turns out pig-iron with Si contents above 1.0 p. c. and S contents above 0.1 p. c. After the changes in iron-producing technology necessitated by the planned increase in the utilization of furnace capacity the Si contents may reach 1.4 p. c. and the S contents 0.16 p. c.

On the other hand the planned output of the open-hearth furnaces just being built is guaranteed only when the Si contents of the pig-iron do not exceed 0.5 p. c. There is no ceiling of the S contents mentioned in the guarantee, but the related figure is approximated well when assessed to be 0.06 p. c.

Before dealing with the calculation of economic efficiency, we feel it necessary to describe as much of the technical aspects of the metallurgy process as seems necessary to make easy the understanding of the assumptions and methods of the calculations.

(ii) Some metallurgy aspects

The charge of the blast furnace consists of iron-ore, the main raw-material of the iron production, flux (mainly limestone) and cokes. The essence of making iron is the reduction of the O of the oxide-ore by C and the removal of the refuse in the slag. By charging coke the C necessary for the reduction and for the heat to fuse the charge is introduced into the furnace. Together with iron-oxides some other metal-oxides are also reduced. Thus and in some other ways Mn, Si, P, S get mixed into the liquid ferrum. Besides ores, also the cokes introduce certain contaminating elements into the charge. Every ton of the coke generally consumed contains appr. 100 kg ashes, wherein S is making up for 10 to 16 kg.

One part of some of the contaminating elements (S and Si) gets into the iron, the other part flows out with the slag. The gangue contents of the pig-iron may be decreased by increasing the heat of the furnace, which may be attained by increasing the heat of the blast air, or by increasing coke utilization. Another way of decreasing contamination is by increasing the basicity (slag coefficient) of the slag. The basicity of the slag is shown by the ratio:

$$p = \frac{Ca\ O}{Si\ O_2}$$

A furnace is told to work with basic slag if the limestone charge is in excess of the quantity that is chemically necessary for balancing the silicic acid ($p > 1$). In the reverse case we speak of furnace operation with an acid slag ($p < 1$).*

Should the degree of the heat of the furnace be given, a higher proportion of contaminators may be expelled into the slag, thereby decreasing the contamination of the pig-iron by increasing the basicity. "As a rule, 25—30 p. c. of the S contents present... gets into the pig-iron at a basicity of 0.8." At $p = 0.3$ the proportion of the contaminators led into the pig-iron is 50—60 p. c. (Vaskohászati Enciklopédia, Budapest, 1955. vol. VI. p. 684.)

* Besides the silicic acid contents of the refuse most of the gangue minerals are of an acidic nature, too. The basic lime is necessary to balance the acids. Lime is produced by burning out the limestone in the furnace. Basicity, in short, refers to the chemical equilibrium of acid and base contents of the charge.

Both an increase in the heat and in the basicity render a consumption of more coke necessary. An increase in basicity necessitates a higher coke input on account of having increased the proportion of limestone to be burnt out and fused. On the other hand, the additional S contents charged in the additional coke counteracts the decrease of the contamination.

If thus more coke or more limestone and coke are charged, the utilization of the furnace worsens. All this illuminates that a transition to a furnace operation with lower temperature or lower slag coefficient (basicity) would be favourable from the points of view of the furnace utilization and of the coke consumption per unit of pig-iron, only the contamination of the pig-iron thus increased should be decreased later on.

This leads to an investigation of the behaviour of the contaminating elements in the next vertical phase of ferrous metallurgy: steel production. Ninety per cent of the 1958 output of crude steel in Hungary was produced in SM open-hearth furnaces, while the rest in electric furnaces. In the SM process ferrum is introduced into the charge, partly in the form of scrap-iron and partly in pig-iron. The scrap-iron/pig-iron ratio is nearly constant within one plant. The contamination of the scrap-iron may, also, be taken for known and constant. It is more or less equal to the contamination of standard steel.

The only problem to be dealt with is that of the contamination of the pig-iron. In principle, standard quality steel can be produced from pig-iron with any rate of contamination. This formerly widely spread view seems to be debated by results of experimentations recently pursued at ÓMW, according to which steelmaking cannot counterbalance the inferioration of the quality of pig-iron beyond any limit.

There are, however, differences in technology process and in charge-to-charge time, *i.e.* in the utilization of the furnace, and in the costs through all this. A growth in Si contents of the pig-iron charged requires an increase in the quantity of the refreshing ore, of the limestone, and thereby in that of the slag. The latter is responsible for an additional fuel (oil) consumption per unit of steel.

The steel bath is heated by flames situated over its surface and this is why a thickening of the heat-insulating slag layer floating on the steel surface induces a further increase in fuel consumption. An increase of Si contents reduces the lifetime of the furnace, because silicic acid is of an aggressive nature against the refractory lining and also the higher degree of heating necessitated by the above reasons damages the lining, as well. What has been said is also indicative of the stretching out of the charge-to-charge period.

The S contents of the pig-iron has a similar effect on the slag quantity and thereby on the quantity of flux and fuel consumed, furthermore on the charge-to-charge time, as the Si, with the difference that S-containing slag is not aggressive. S has, however, another unfavourable feature: it is apt to return from the slag to the steel bath. This is why the slag must be drawn off from time to time, thereby causing loss of temperature, excess wages and additional outlay on flux and fuel.

The particularities of technology and raw materials and the plans to increase capacity utilization sufficiently justify an investment policy aiming at the desulfurization and desilication (called together: conditioning) of the pig-iron without the furnace, from the points of view of both technologic and quantitative equilibrium. The question is raised as to whether economic points of view support conditioning as well.

(iii) The economic model

In the ÓMW detailed calculations were made on pig-iron conditioning and were widely discussed there.

The process of the calculations according to one of the positions developed during the discussion is as follows:

The quantity of costs reduction attainable through the acid slag technology is calculated on the assumption that a p factor of 0.9 may be arrived at in lieu of the $p = 1.15$ of 1959. The possible economizing of limestone and thereby of cokes is taken into account, as well as the secondary limestone economizing, due to the diminishing quantity of coke ashes in consequence of the aforesaid reduction in coke consumption and the secondary reduction in coke consumption attainable therewith. In the balance sheet these economies are countered by additional outlays: costs of desulfurization and desilication and certain losses in the steel works. These losses are assumed, in the calculations, to arise from the supposition that only a proportion of 60 p. c. of the total pig-iron output may be conditioned, while the remaining 40 p. c. may only be consumed in steel production under increased costs (and possibly with deteriorating quality).

The other standpoint criticizes the above calculation method just in that of its suppositions, that conditioning will be restricted to 60 p. c. of the pig-iron output only. It is argued that it would be more reasonable not to produce the non-conditioned proportion with acid slag process at all, but in the traditional way, when the iron works would realize less economizing in prime costs, there will, however, be no need to calculate with any loss in the steel works.

The authors of the first mentioned method emphasize that the proportion of conditioned pig-iron was fixed by them at 60 p. c., a very low ratio, indeed, only to illustrate the minimal limit.

The second standpoint includes some total costs approximation according to which the reduction in costs per year calculated on the output volume of 1959 may be put at about 2.2 million Ft, if the conditioned part of the pig-iron will reach 60 p. c., whereas under circumstances of the conditioning of all the pig-iron produced, the amount of economized costs could reach appr. 3.7 million Ft/year.

The second author points out that some of the items of consumption per unit output will probably be much smaller than they were taken into account by the first method, and so the economy will surpass the assessed level.

The methods applied in the cited calculations are generally correct. For a better foundation of investment and production planning, however, some further aspects should be added to the calculations.

The main propositions as to these additional methods are the following:

1. The values (*e.g.* that of basicity at present and as planned) fixed now in a mostly arbitrary manner should be replaced by variables.

2. The costs of pig-iron production should not be calculated with given values either, but with variable costs varying according to the basicity or much more to the contamination, mostly depending on the basicity. Costs effects should be complemented by the influence of the improvement of capacity utilization on total costs.

3. The per unit costs of conditioning should be assessed according to the function of the following two contamination levels:

a) the contamination of the pig-iron after the iron-producing process, and

b) that before the steel-making process.

With such additions we would get a more objective picture on the possible economizing and a guide for a choice of economically optimal variant when metallurgic and investment conditions render more technology variants equally possible.

The simplifying assumptions adopted in our model

Assumptions of technological type

a) We take the composition of the ore burden as unvariable, i.e. the proportion of iron, refuse and contaminating elements in the ore as unchanged.

Anyhow, due to highly important economic interests the metallurgy industry is striving for such a stability. Due to a change, and an often not fully recognized change in the iron contents, or in what is more important: the non-iron elements (refuse and contamination) our blast-furnaces are operated with a considerable excess heat over the theoretically necessary one. But for this necessity the possible reduction in coke utilization is approximated to be near to 10 p. c. Since we do not know how much of the applied heat surplus is factually necessary for the metallurgy processes taking place in the furnace, and how much is surplus proper we cannot tell beforehand the distribution of the contamination in the charge, as between the pig-iron and the slag.

This is just the reason why the establishing of one or more ore averaging plant, the investment outlay of which is unimportant when compared with the usual metallurgy capital investments, is becoming more and more urgent, and it would considerably better the persistance of the composition of the ore burden.

b) We take the chemical composition and other characteristics of coke as unchanged. The effect of factors that are left out of consideration is much smaller here than in the case of ores.

c) We take the temperature of the furnace as unchanged so that we may express the dependence between the basicity and the S and Si contents of the pig-iron by one-variable functions.

The abstraction is tolerable for the effect of the change in temperature may be traced out easily. The heat demand of the furnace process naturally depends, when the proportion of contamination expelled to the slag is given, on the basicity of the slag and, besides this, on the chemical composition of the slag, *i.e.* eventually on the composition of the charge. This, however, has already been taken unchanged, which justifies the abstraction from the fluctuation of the temperature. By the way, it is not a long-wave motion, since the replacement of basic slag furnace operation by that with acid slag is not meant to serve an economy with heat. The intention is to fuse the slag at a temperature similar to the present one, the main purpose being a decrease in the quantity of the slag.

d) We take the scrap-iron/pig-iron ratio and the gangue contents of the scrap-iron as unchanged. The former change is unremarkable, but when it occurs its effect is easily accounted for; the latter one is, to all practical purposes, equal to zero.

e) We have to overlook the change in the contamination of the fuel (mainly fuel-oil), as well, though some of the kinds of oils used by us contain some sulfur and water, sometimes to an unfavourable degree.

f) We do not take into account, that the chemical process of desulfurizing is heat consuming and that of desilicating is heat producing and its balance influences the heat of the liquid pig-iron charge of the open-hearth furnace and thereby its heat demand.

g) Among the contaminating elements only sulfur and silicium are dealt with. Manganese is burning out all the same in the course of the steel production and what small proportion thereof remains, is usually deemed necessary at steel-making. Phosphorus does not get distributed between pig-iron and slag, it gets totally into the pig-iron. This is why it may not be reduced in the blast furnace, only in the charge. The composition of the charge was, however, already taken as given. The quantity of other gangue (copper, titanium, chrome, nickel, etc.) elements is unimportant, getting rid of them is hardly attainable under present steel technology, though, in some of the cases it would be desirable.

Assumptions of economic type

h) Our starting point is that all pig-iron should be conditioned, though it is not a technological necessity. (It could be a separate optimalization problem to determine how many per cents of the pig-iron should be desulfurized and how many desilicated so as to reach the optimal total economic efficiency.)

i) Only those of the direct prime costs are taken into account, that are the most sensitively changing under the impact of the technology changes discussed here. Thus: we count with the limestone and coke costs at the iron-production, with limestone and fuel-oil costs at the steel-production.

j) We do not keep in view the diminishing of the quantity of the slag of the blast furnace and the open-hearth furnace, which may cause a possible utilization of the slag to shrink somewhat.

k) Only production costs are taken in account, whereas the different investment outlays of the technological variants are not compared. If some method for adding investment and production costs might be applied to our case, in principle, there is no obstacle of taking investment costs into account, too. For the time being we felt reluctant to do this due to the fact that in the investigated ÓMW example, this constituting the reconstruction of an existing works, the difference in investment costs due to technology variants are not distinct.

Assumptions in calculation techniques

l) From S and Si, the two main contaminating elements we made calculations only in respect of S. There is no theoretic or other obstacle in making calculations for both in the course of the practical application, either separately, or simultaneously by way of a two-variable function. The behaviour of the two elements is the same as regards the tendency of the costs effects we investigate.

m) At this instance we do not investigate the impact of the technology connected with conditioning on the volume of output and through this on the costs. The method of assessing these is the same as that of the direct production costs. The total effect may simply be added up from the respective results of the two investigations, since the selected costs of our present calculation are not the same as the costs that are influenced by a change in the output volume, there being no or very little interdependence between their behaviour. The former are mainly direct costs, while the latter are mainly overhead charges.

The costs functions we arrived at are based on approximate costs data, hardly founded by facts and this is why no practical consequences must be drawn from the concrete trend of the curves. The methods may be judged this way, too; while practical calculations will anyhow have to be based on real factory data.

The economic model — The parameters

When setting out the determination of the total costs of pig-iron and steel production depending on the choice among the possible technological variants, we have to begin with iron production.

The curve on the Figure 1 shows the relation between basicity and that proportion of the total S charged, which gets into the pig-iron.

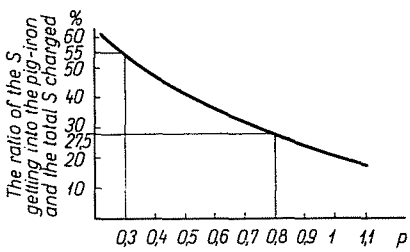

Fig. 1

Vaskohászati Enciklopédia (Encyclopaedia of Ferrous Metallurgy) Vol. VI. 681. p

The following equation describes the relation between the basicity and the S contents of the pig-iron:

$$S = A_1 + B_1 e^{-\lambda p} \quad [1]$$

where S = Sulfur contents
A_1 = a non-negative constant to express minimal S contents
B_1 = constant factor
λ = constant factor in the exponent
p = rate of basicity.

The curve drawn with the full line on Figure 2 is that of the actual case derived from the study made at Ózd. The dash line was published in Vaskohászati Enciklopédia (Encyclopaedia of Ferrous Metallurgy Vol. I. p. 105) on the basis of data originating from blast furnaces in the south of the Soviet Union, observed on utilizing of sulfur-containing coke.

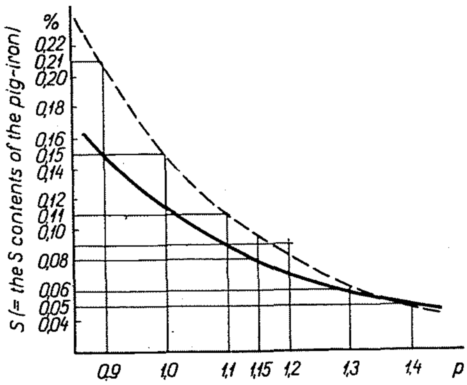

Fig. 2

It is striking to the eye that the production of first-class quality iron, that contains less than 0.08 p. c. S, necessitates a considerably high rate of basicity ($p \sim 1.2$), *i.e.* an expensive technology and one with unfavourable capacity utilization.

To every degree of basicity corresponds a certain limestone consumption and to this a certain coke consumption per unit of pig-iron. The secondary limestone and coke consumptions have to be taken into account, too.

The costs, *i.e.* the limestone and cokes costs of 1 ton of pig-iron depend on the basicity according to the following function

$$K_i = A_2 + B_2 e^{\mu p} \qquad [2]$$

where K_i = the costs of pig-iron
A_2 = a non-negative constant determined by the minimal limestone and cokes consumption
B_2 = a constant factor
μ = a constant factor in the exponent.

The curve based upon the actual case as described in the Ózd study is shown on Figure 3.

When the dependences illustrated by the curves on Figure 2 and Figure 3 are viewed simultaneously, a per-unit pig-iron production cost may be ordered to each degree of S contents. From the equations and their curves the new equation and the new curve, respectively, of the function describing the dependence of costs on S contents may be derived.

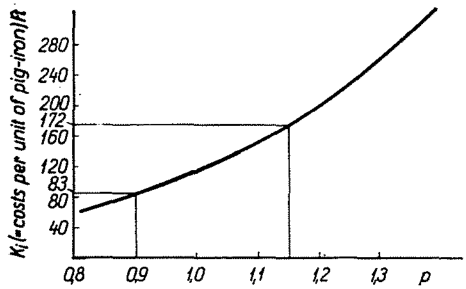

Fig. 3

The new curve will link the points where the p quantities of the two original functions are equal. Thus, we are to proceed by equalizing p of both.

First we express the powers of [1] and [2]:

$$\frac{S - A_1}{B_1} = e^{-\lambda p}$$

and

$$\frac{Ki - A_2}{B_2} = e^{\mu p}$$

where raising the second equation to $\frac{\lambda}{\mu}$ power we get

$$\left(\frac{Ki - A_2}{B_2}\right)^{\frac{\lambda}{\mu}} = e^{\lambda p}.$$

Now multiplying the corresponding sides of these equations with each other we get

$$\frac{S - A_1}{B_1}\left(\frac{K_i - A_2}{B_2}\right)^{\frac{\lambda}{\mu}} = 1$$

and so

$$\frac{K_i - A_2}{B_2} = \frac{1}{\left(\frac{S - A_1}{B_1}\right)^{\frac{\mu}{\lambda}}}$$

wherefrom we reach

$$K_i = A_2 + \frac{B_2 B_1^{\frac{\mu}{\lambda}}}{(S - A_1)^{\frac{\mu}{\lambda}}}. \qquad [3]$$

The new curve may be derived from the two original ones by geometrical construction, as well. This is shown on Figure 4.

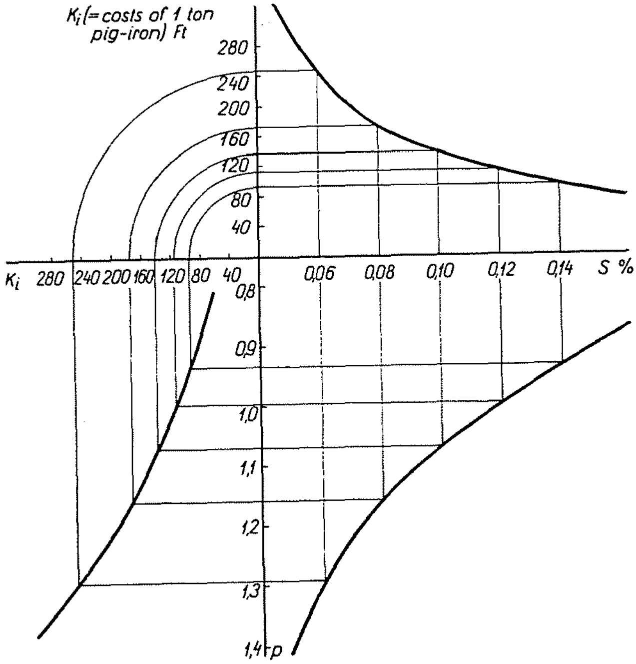

Fig. 4

This curve will show, as is naturally anticipated, that the production of more refined pig-iron is considerably more expensive. So the economic interests of the blast furnace would be to produce pig-iron containing more contaminator.

This is in conflict with the interests of the steel plant. The contamination of the steel is strictly limited by standardization. The upper limit of S contents of most kinds of steel is at about 0.04 p. c. To reach such a degree of purity is the more expensive the higher is the S contents of the pig-iron charge. This connection is expressed by the equation:

$$K_s = C_1 + D_1 e^{\nu_1 S} + D_2 e^{\nu_2 S} \qquad [4]$$

where K_s = the costs of steel-plant per unit of steel

C_1 = a non-negative constant expressing the minimal costs

D_1 and D_2 = constant factors of the two main costs items (limestone and fuel-oil)

ν_1 and ν_2 = constant factors in the exponent as above.

The equation applied to the actual case of the Ózd study leads us to the following curve.

In this function — in want of more detailed data — we estimated the change of the steel production costs in the following way. The costs of the

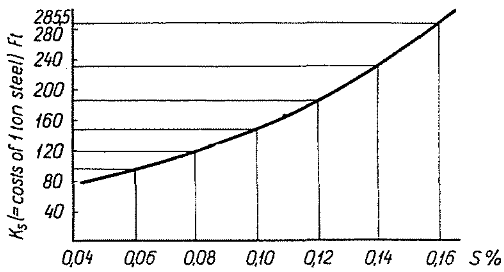

Fig. 5

limestone and fuel oil consumed for 1 ton of steel as recorded by the costing in the year of 1959 at the Ózd steel works (Ft 8.24, and Ft 139.67, respectively) were ordered to the pig-iron with 0.1 p. c. sulfur. We took ν_1 and ν_2 as equal to zero, $D_1 = 8.24$ and $D_2 = 139.67$.

At S contents differing from 0.1 p. c. we assessed $\nu_1 = ln\ 1.08 \cdot \frac{1}{S}$ and $\nu_2 = ln\ 1.12 \cdot \frac{1}{S}$

The cost conditions of conditioning are even less known than those of iron and steel production, since we have no such plants and the unavoidable uncertainties in economic data of experiments do not as a rule, allow the adaptation of such data to economic analysis. Due to the lack of other data, when aiming at the exposition of a method, however, the use of data derived from experimentation may also be permissible. In the course of the experiments pursued at Ózd 20 kg of lime powder was used up for the desulfurizing of 1 ton of pig-iron.

Though the level of the conditioning costs are not exactly known, much more may be said on the dependence of them, on the change of the contamination. The costs of desulfurizing obviously depend on the height of the previous S contents of the pig-iron to be conditioned and on what part of the S contents we want to expel. The experiments at Ózd have generally reached an efficiency of 50 to 60 p. c.; S contents were, as a rule, reduced from 0.08 to 0.04 p. c. and below that. There are theoretical proofs that the efficiency of conditioning increases with the increase of the commencing S contents without additional outlay. Namely, the richer the pig-iron in respect of S is, the higher the probability of the Ca atoms of the lime used for conditioning to encounter the S atoms of the ferric sulfide.

In this meaning there is no need to deal separately with the influence of efficiency on costs, since it is mostly counteracted by the costs effects of commencing S contents. This is why the costs of desulfurization depend more on the level of S contents to be attained than on the commencing S contents level.

$$K_c = G + E_e{}^{\varrho_c S_c + \varrho_c S_c} \qquad [5]$$

where K_c = costs of conditioning per unit of pig-iron
G = a non-negative constant expressing the minimal costs
E = a constant factor
ϱ_c and ϱ_e = constant factors in the exponent of the commencing and ending S contents resp.
S_c = commencing S contents
S_e = ending S contents.

The sum of the costs according to the actual data at our disposal will be modified by $\varrho_c = \ln 1.15 \frac{1}{S}$ in the direction of a change in the commencing S contents and by $\varrho_e = \ln 1.20 \frac{1}{S}$ in the direction of a change in the S contents to be reached.

From the data of the Ózd experiments and efficiency calculations and with the application of the above function, the two-variable surface on Figure 6 may be constructed.

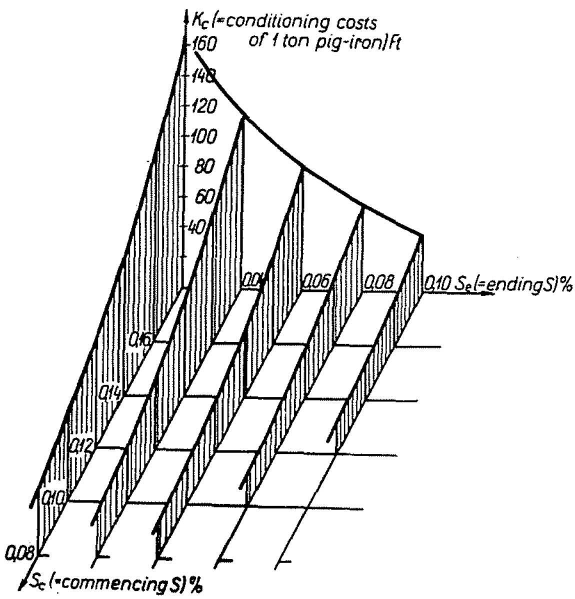

Fig. 6

One of the unchanged variables of this two-variable function expresses the starting S contents, the other the ending S contents, while the changing variable gives the total costs of the conditioning of one ton of pig-iron. For a better foundation of the efficiency calculations, in the case of conditioning not only selected raw-materials, but all the raw-material and wage costs are to be taken into account, since here a newly instituted process is dealt with where, as a matter of fact, every cost item of which is a varying element of the calculation. Overhead costs are omitted here, too, so as to avoid a mixing up with the effects of the change in production volume.

The actual costs data of the Ózd experiments, Ft 46.80 per ton of pig-iron is connected with the case when the commencing S contents is 0.14—0.16 p. c., the efficiency of desulfurizing is 60—70 p. c., and so the S contents reached is 0.042—0.064 p. c. The above mentioned sum was ordered in drawing our curve to the less favourable values, i.e. to 0.14 p. c. commencing and to 0.06 p. c. ending S contents.

(iv) The solution

Now we have to set out and discuss the solution of the system of equations as determined in our model. The model is considered as being solved by deciding the optimal costs of iron-furnace, pig-iron conditioning and steel-furnace altogether. The solution will have to give answer to the questions of how much the commencing and the ending S contents of the pig-iron should be before and after the conditioning.

Before proposing our formulae for this kind of solution we have to find ways to decide the minimal costs of iron and steel works having no conditioning plant. This no-conditioning optimum will serve as a basis of comparison for the solution of the more complete model.

When we want to investigate the total costs of the two production phases, *i.e.* iron and steel production, first we have to recalculate the selected costs of iron production into per unit costs of the steel ingot. In order to achieve this we have to multiply the costs of iron production per unit of pig-iron by an F factor which consists of the proportion of pig-iron in the charge of the open-hearth furnace and the non-iron elements in pig-iron. The actual multiplier is 0.6 at Ózd since the first element is 56 p. c. and the second is 4 p. c. when the appr. carbon contents of the pig-iron is kept in view.

Thus we obtain from [3] and [4] the following equation determining the total costs of iron and steel making in a no-conditioning works:

$$K_n = FK_i + K_s = FA_2 + G + \frac{FB_2 B_1^{\frac{\mu}{\lambda}}}{(S - A_1)^{\frac{\mu}{\lambda}}} + D_1 e^{\nu_1 S} + D_2 e^{\nu_2 S}, \qquad [6]$$

where K_n = the total costs of iron and steel production with no conditioning
F = is the multiplier of pig-iron costs as explained above.

The differential quotient of this equation will give the minimal total costs of a no-conditioning integrated iron and steel plant.

$$K'_n = -\frac{\mu}{\lambda} B_2 B_1^{\frac{\mu}{\lambda}} \frac{1}{(S - A_1)^{\frac{\mu}{\lambda}+1}} + \nu_1 D_1 e^{\nu_1 S} + \nu_2 D_2 e^{\nu_2 S} . \qquad [7]$$

This minimalization process is illustrated by the adding up of the iron-costs and steel-costs curves on Figure 4 and Figure 5, respectively, having previously multiplied the former by F factor (which is 0.6 in our case).

The sum-curve on this Figure expressing the total costs of the pig-iron and the steel production reflects some light on the fact that — from the point of view of the costs we selected for consideration — the production of a pig-iron with S contents of about 0.08 p. c., *i.e.* the first-class quality under present standardization, is the most favourable when no conditioning process is applied. A choice of such a technology where the average quality of pig-iron will reach the present first-class quality is spotlighted by this result, though the remark must be made that the inaccuracies of the data used in sketching our curves do not permit us to draw any eventual consequences.

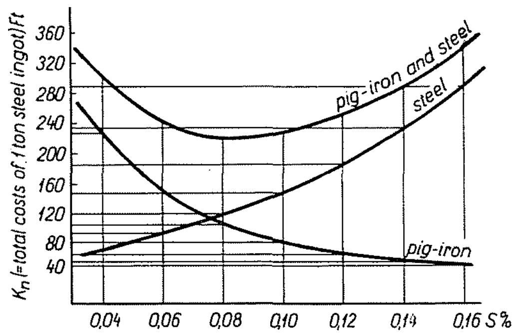

Fig. 7

We are aware of no similar calculation in ferrous metallurgy and this is why it is the most probable that there may be some as yet unexplored possibilities to develop some new technologies to improve economic efficiency even without establishing conditioning plants. True, the workshop operation based on technical knowledge and long-standing experiences usually chooses the most favourable variants or variants very closely approximating the optimal one even without detailed quantitative economic analyses.

Besides aiding a choice of the most efficient technology, our analysis as yet discussed will give some help in evaluating the excess amount of costs of technology differing from the optimal (the first-class quality pig-iron in our case).

The next step is the construction of the function that will show the behaviour of the total costs of all the three vertical phases: the pig-iron production, the iron conditioning and steel production combined in one. The equation of this function is a simple sum added up of [3], [4] and [5].

$$K_t = K_i\,(S_c) + K_c\,(S_c, S_e) + K_s\,(S_e) \qquad [8]$$

where K_t = total costs of the three phases of steel ingot production
S_c = S contents of pig-iron at the commencement of conditioning
S_e = S contents of pig-iron at the end of conditioning.

The surface of this two-variable function may be constructed from the corresponding points of the iron costs and steel costs curves on Figure 7 and from the corresponding points from the surface on Figure 6.

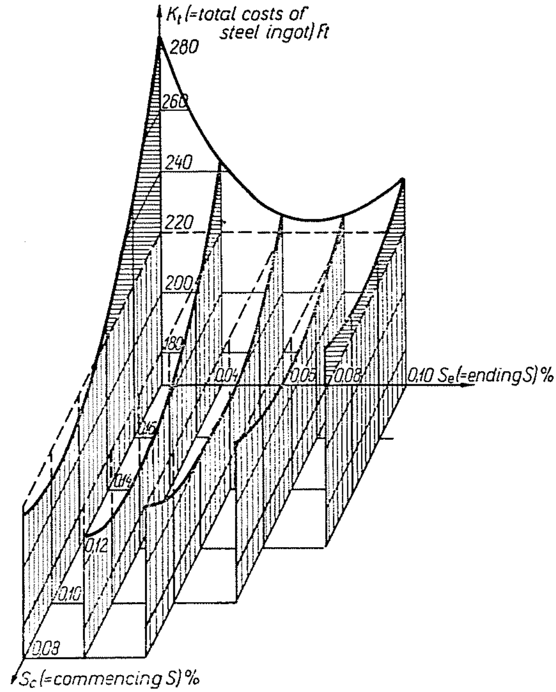

Fig. 8

The surface of the two-variable function thus derived, as is to be seen on Figure 8 gives the total three-phases costs of steel production depending on technology variants.

The line of intersection of the total costs surface by the plane of the minimal costs of the non-conditioning technology (Ft 220.— according to Figure 7) gives us the area of the total costs function wherein there is possible an economizing, when not compared with the present but with the minimal costs of the non-conditioning process. By deducting the corresponding values of the surface from those of the plane, the amount of costs that may be spared will remain.

(v) Application

In the furnace operation practice the task of maximalization of the economy is hardly to be solved by differentiation due to the intricateness of the functions involved. In order to enlighten the application of our method some additional means must be developed that do not require to resign much of the exactness of a solution of differentiating the two-variable function [8] described by the surface shown on Figure 8.

This seems to be achieved in the following way. First the surface of total costs must be deducted from the plane expressing the minimal costs with no conditioning, thereby obtaining the surface of the amount of costs that may be economized by means of conditioning. Naturally, this is a two-variable function itself. In order to make it more easy to handle, this function in three dimensions should be reduced to a function in two dimensions. This we achieved by applying the illustrating methods of the map with iso-level lines. Figure 9 thus shows the amounts of costs to be economized as depending on the commencing and on the ending S contents of the pig-iron in the course of the conditioning process.

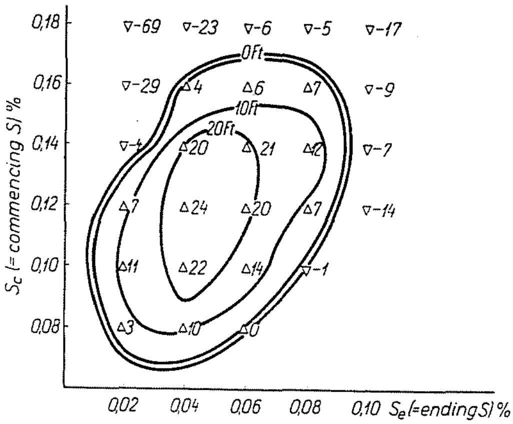

Fig. 9

Code: — iso-cost curves by each 10.— Ft economized
△ "height mark"
= "sea-shore", *i.e.* the iso-cost curve of zero economy, the area outside this denoting excess costs
▽ "depth mark" in case of excess costs
△14 height or depth figures giving the economy or excess costs in Forint per 1 ton of steel ingot in comparison with the minimal costs (Ft 220.—) in case of no conditioning.

The iso-cost curves on Figure 9 are obtained by intersecting the economy surface as described above or the negative of the total costs surface on Figure 8 by planes at every Ft 10.— costs level and projecting the borderlines of these sections on to a fundamental plane, *i.e.* to a plane of zero economy. The meaning of the areas delineated by the iso-cost curves and of the height and depth points are explained in Code of Figure 9 and are so obvious that they do not require us to further enlarge upon them. Only one last remark may seem necessary. The "summit" point (at Ft 24.—) is the highest only among those selected points on the basis of which the iso-cost curves were drawn, *i.e.* every crossing point by 0.02 p. c. of commencing and ending S contents, respectively. Should the selection of the points be chosen more densely, say by 0.01 p. c., one or more points might be found exceeding the present "summit". This is just where the issue of having resigned some of the exactness of the differentiating method turns up. In case of working out iso-cost curves for larger plants and for longer lapses of time a densifying of the selection of our "triangulation points" should be considered.

As to how our "map" of iso-cost curve should be read, on the basis of Figure 9 it may be stated that with the simplifications deployed in the case of the actual data reflecting the present Ózd works surroundings and assuming that our rough estimations are satisfactory approximations, a technology connected with about 0.12 p. c. commencing and about 0.04 p. c. ending S contents ought to be striven for. The suppositions as enumerated above, do not, of course, permit to appraise the actual sum of economy thus assessed as amounting to approximately 10 p. c. In our case the purpose of computing an actual sum can only serve to prove the applicability of the method we propose, should the necessary data be supplied. Therefore, we neither state that conditioning, nor any particular form of it as being good, nor that it be wrong. But we deem it emphatically necessary that economic measures of technical development of importance should always be preceded by such or similar calculations for a better foundation of both production and investment planning.

The kinds of data we need in our method are systematically recorded at our iron and steel works. The only exception, for the time being, is the cost accounting of the as yet not existing conditioning. Thus, there is no obstacle for the applications of the method from the point of view of the supply of data. It is just in this respect that the choice of not all, but some more essential of the cost items gathers importance.

The first step in developing our method into one directly applicable should be to replace estimated parameters in the functions by actual works data based on statistical records. This might be followed by inserting the planned development into these parameters. Till the collection of these past and projected parameters is completed, it is not worth while to refine our method, since there is no way to make sure that the result obtained (the sum of economy) would not fall between the accuracy limits of the computation process itself.

This is why the following proposals for further development of our method are intended to be applied only after a systematic collection of relevant works statistics and creating a system of parameters thereof.

The first task should be to solve one or several of the simplifying assumptions. Thus, *e.g.* when we have already got a diagram applied to a given composition of charge, or to a given ash contents of the coke, then we should consider say, the slag coefficient (basicity) for instance, as unchanged at several of its selected degrees and view whereto the maximal economy area and the summit therein is thrust over when the composition of the ore charge or the heat of the furnace, *e.g.* is varied. A series of analyses of that sort will, no doubt, be highly instructive.

The second step should aim at such a development of our method so as it could be directly applied in investment and technology planning, and, moreover to serve as a day-to-day help of the iron and steel works operation. In order to achieve this it is, first necessary to solve the most possible simplifying assumptions as yet applied, and mainly those that are in fact changing rapidly or the change of which has very important cost effects.

The final results irrespective of all details are to be comprised into one table or chart (nomograph) whereon the duty of the plant operators is read off directly. In such a chart the logical course of the calculation is reversed: not the optimal technology is to be determined from the basic data, but the choice of basic data, with the exception of very few conditions not or hardly influenced by the works, is to be decided as depending on the previously assessed optimal costs technology. There is, for instance, no obstacle of compiling by means of a slight alteration of our method as expounded above nomographs based on statistical or planned raw material utilization coefficients, showing, *e.g.* the heat of the blast or the basicity, the quantity of flux to be added in the conditioning process, the heat and intensity of the flame of the fuel in the open-hearth furnace, with which the blast furnace, the conditioning oven, or the open-hearth furnace respectively is to be operated when *e.g.* the chemical compositions of the ore charge and/or of the coke are given, so as to obtain the lowest possible total costs.

Such nomographs ought to be revised from time to time, let us say yearly, and the modifications considered necessary by co-operating metallurgists, economists and mathematicians are to be inserted into the charts involved. This systematic check, together with the original composition of the charts would underline the favourable qualities of the method itself. A regular practical application of the model would, no doubt, provide for considerable reduction in costs when compared with those of the present technology, not only because it would help us to find the economic optimum more easily than with the present mainly empiric and subjective ways, but also because it requires the systematic quantitative observation of technical and economic interdependences and relations, perhaps not fully kept in view up to now.

Finally, it is the possibility of the generalization of our model that we should like to call the attention to. Ferrous metallurgy was as yet investigated up to steel making and from only the point of view of the costs effects of contamination. The contamination of the steel ingot, however, considerably influences the attitude to rolling of the steel, and through this the capacity utilization of the rolling mills, the ingot utilization coefficient of the rolling process, the quality of rolled steel and eventually the costs of the rolling mill. Besides an extension of the application of our model in the direction of the verticality of the metallurgy technology phases, an extension to take other cost elements into account may also be mentioned.

Moreover: the model as outlined in this paper is very likely to stand not only in its application to the example employed here. It is not improbable that the method or some alteration thereof might be applied with success in every such industry (in oil refinery, inorganic chemistry, clothing, flourmills, etc.) where the relatively homogeneous product is made of raw materials which are numbering few and are measured easily, and where the chemical compositions or other patterns and the utilization coefficients play an important economic role.

L. LUKÁCS, Budapest, V. Nádor u. 7. Institute of Economics, Hungarian Academy of Sciences.