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Electrical Factors Affecting the Economic Optimization of Submerged-arc Furnaces

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An increase in the economic benefits derived from an existing plant without the expenditure of large sums of money is an attractive goal in difficult economic times. This paper reviews various ways in which this can be achieved in submerged-arc furnaces from the operational point of view.

Maximum economic benefit can be derived if the furnace throughput is maximized, subject to operational constraints, and the costs per ton of product are minimized.

The paper examines techniques that can be used to assist in maximizing the economic benefit from a furnace. The exact nature of the operational constraints are identified on characteristic curves that describe the electrical behaviour of a furnace, the constraints are analysed in detail, and ways to overcome them are suggested.

Introduction

The production from a furnace is related to the energy input by the furnace efficiency (MWh/t). Maximum production, without any change to the furnace hardware, is therefore achieved from

(a) operating conditions that maximize the furnace efficiency (i.e. minimize MWh/t)

(b) maximization of the power input to the furnace by each electrode within operational constraints.

The operational constraints, which limit the maximization of the power input to a furnace, should be known in order to ensure safe operation as close to these limits possible. Characteristic curves describing the electrical behaviour of a furnace are described in the second section of this paper, and the operational constraints are indicated on these curves. The operating point of a furnace can be identified on these curves, giving an indication of steps to be taken in order to maximize the power input while remaining within the constraints.

The third section suggests that the maximization of the throughput of all on-line furnaces will maximize the overall economic benefit to a plant. Means of maximizing furnace throughput are then discussed. The use of the characteristic curves as a means of identifying operating points and as a means of finding steps that can be taken to increase production is demonstrated. The importance of a balanced operation at equal electrode-to-bath resistances is also stressed. Furthermore, the section deals with ways of reducing energy costs by improving the furnace MWh/t. The reduction of operation and maintenance costs is also discussed. A furnace control strategy that incorporates the techniques for increasing throughput within operational constraints and for achieving balanced furnace conditions is suggested as a means of realizing these economic benefits.

This is followed by a section that takes a closer look at the operational constraints indicated on the characteristic curves. Methods are suggested to manage the operation efficiently within these constraints. Ways to extend some of these constraints are discussed.

Electrical Characteristics of a Typical Furnace

In a submerged-arc furnace, the secondary circuit can be described as a star, each phase of which represents an electrode. Each phase can be summarized as a fixed inductance, as determined by the electrode and busbar configuration, and a variable power-dissipating element in series[1], as shown in Figure 1. If the dissipation of power beneath the electrodes were purely resistive, the circuit would be a purely R–L circuit on an alternating-current (a.c.) supply. However, heating in this region is not purely resistive owing to the non-linear effects of arcing. The power-dissipating element exhibits some inductive characteristics as the arcing effects become more significant.

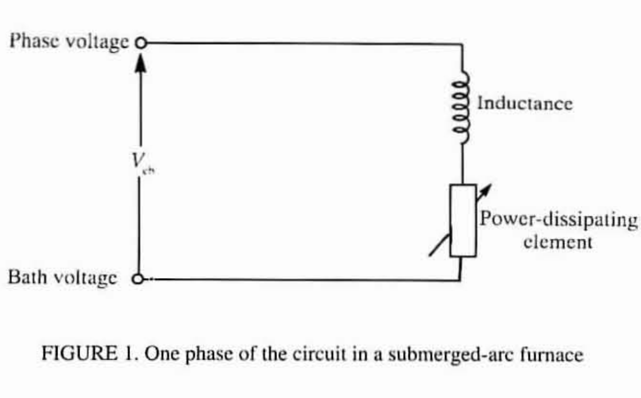

FIGURE 1. One phase of the circuit in a submerged-arc furnace

Figure 2 shows characteristic curves derived for a typical 65 MVA submerged-arc furnace. In this figure, the total power (P_{tot}) is plotted against the average electrode current (I_{elec}). These curves are based on a balanced circuit (i.e. equal reactances and equal power-dissipating elements), as well as on balanced supply conditions (i.e. equal transformer tap positions). These conditions result in equal electrode currents and equal magnitudes of electrode-to-bath voltages (V_{eb}). The concepts, however, can similarly be applied to unbalanced conditions.

Curves for Constant Voltage

Each curve of the first set of curves in Figure 2 (broken lines) applies to the case where the supply voltage is held constant and the power-dissipating element is varied. This is equivalent, in a furnace, to holding the transformer tap fixed and moving the electrodes. The equation governing these curves, which is derived elsewhere[1], is as follows:

$$P_{tot} = 3 \times k \times X \times I_{elec} \times \sqrt{(I_{max})^2 - (I_{elec})^2}, \qquad [1]$$

where X is the reactance in each phase of the star circuit and I_{max} is the maximum average electrode current that will flow when there is no power-dissipating element ($I_{max} = V_{eb}/X$). The factor k is known as the arcing factor, which takes the inductive effects exhibited by the power-dissipating elements into account. It helps to take the arc factor into account when the electrical behaviour of a furnace is described, since this provides better accuracy over a wide range of conditions. The purely resistive case is easier to handle, but it limits the validity of the resulting characteristics to a small region around the normal operating point. For purely resistive heating (no arcing) beneath the electrodes, $k = 1$. Arcing causes k to become less than unity, typically around 0,95, under normal conditions in a submerged-arc furnace. The curves in Figure 2 are plotted for V_{eb} varying between 144,3 and 192,4 V, in steps determined from the tap ratios for tap positions 9 to 23, and for $k = 0{,}95$ and $X = 1{,}15$ mΩ.

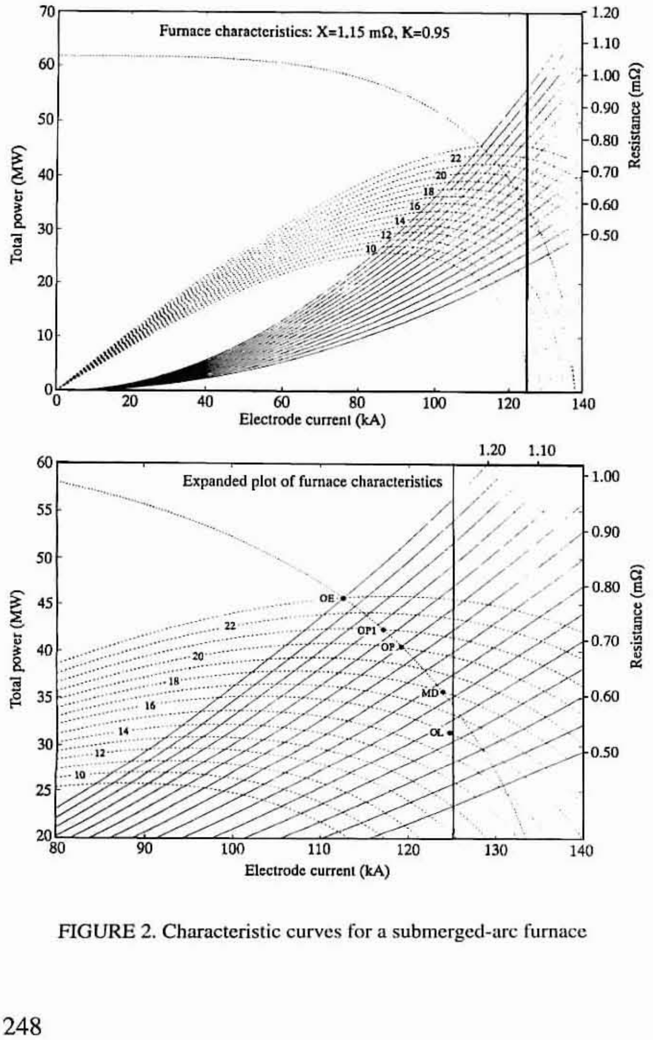

FIGURE 2. Characteristic curves for a submerged-arc furnace

Curves for Constant Resistance

Each curve of the second set of curves in Figure 2 (solid parabolic-shaped lines) applies to the case where the electrode-to-bath resistance (R_{eb}) is held constant and the supply voltage is varied. This is equivalent, in a furnace, to holding the electrode positions fixed and varying the transformer-tap changer. These curves are described by the equation

$$P_{tot} = 3 \times (I_{elec})^2 \times R_{eb}. \qquad [2]$$

The curves in Figure 2 are plotted for resistances varying from 0,5 to 1,2 mΩ in steps of 0,05 mΩ.

Operational Constraints

The solid vertical line at 125 kA shown in Figure 2 is the electrode-current limit and indicates the maximum allowable current in an electrode. Operation is therefore constrained to the left-hand side of this line.

The broken line, starting higher up on the vertical axis and curving downwards, represents the MVA limit (MVA_{lim}). This curve is described by the equation

$$P_{tot} = 3 \times k \times \sqrt{\left(\frac{MVA_{lim}}{3}\right)^2 - \left(X \times (I_{elec})^2\right)^2}. \qquad [3]$$

Operation is constrained to within this curve. The MVA can be limited by either the electricity supply or by the furnace transformers.

Other limits may also apply, such as primary current or total furnace power. The electricity-tariff metering system may present a time-varying constraint (e.g. maximum demand), which also needs to be considered.

The relative location of the curves and the limits will differ from one furnace to another. However, in any particular furnace, whichever limit is encountered first while the furnace transformers are tapped up along a particular curve of constant resistance limits the overall optimization of a furnace. The MVA limit is normally significant under a high-resistance operation, whereas the current limit is normally encountered with a low-resistance operation.

Maximizing Economic Benefits within Operational Constraints

The economic benefits from the production in a particular furnace should be maximized within the operational constraints.

Experience has shown that, at most plants, individual furnaces are required to produce at their maximum design capacity. Production in some furnaces is even pushed to beyond the designed capacity, provided that this does not result in an escalation in maintenance costs due to excessive wear on the furnace shell. Economic benefits, resulting from the additional production and from the efficient employment of invested capital, would seem to be maximized in this way.

A common scenario is encountered where a plant has more than one furnace. Cutbacks in the total production from the plant are sometimes required, making it seemingly unattractive to maximize the production from individual furnaces. However, it would seem that it is better to mothball one or more of the furnaces during an extensive period of reduced demand. Production from the other furnaces can then remain at their maximum capacities, which usually means that maximum economic benefit can be derived from these on-line furnaces. This would also negate the cost of production on the mothballed furnace(s) and allow extensive off-line maintenance to be carried out. This stresses the economic benefits of ensuring that individual furnaces are always running at maximum production.

A reduction in the total cost incurred on a daily basis is the second way of deriving maximum economic benefit from a furnace. Methods should therefore be found to minimize the costs of production.

Means of Maximizing Furnace Production

Operation at maximum power (at constant MWh/t) is the first step to ensure that the furnace throughput is maximized. As can be seen from Figure 2, the maximum power is obtained by operating as close as possible to the limits and at as high a resistance as possible. The maximum power obtainable from the power supply is therefore achieved when operating at point OE in Figure 2 (resistance = 1,20 mΩ). At this point, the power input to the furnace is maximized within the maximum tap position, maximum MVA, and maximum electrode-current limits. The electrically optimum resistance at this point does not usually correspond to the optimum resistance for the process as a whole. The optimum resistance is generally lower, resulting in operation at, say, point OP in Figure 2 (resistance = 0,95 mΩ). A number of factors govern the selection of the optimum resistance for a process, and these are discussed later, when it is shown that there is generally no merit in increasing the resistance above the electrically optimum resistance.

Power maximization can be achieved only by balanced operation of a furnace, in which the three electrode circuits exhibit similar impedances (maximum power transfer occurs when a three-phase load is balanced). From an operational point of view, this means that the furnace should be balanced at some optimum resistance. The transformers can then be tapped up to maximize power input without reaching the MVA or electrode-current constraints of one phase before those of the others. This type of operation ensures maximum power dissipation in each electrode, which is essential for maximum production.

Maximizing furnace availability will also assist in maximizing production. Unstable and poorly controlled operation of a furnace often results in down-time, and frequent switching out of a furnace aggravates this condition.

The effective management of a furnace at a balanced resistance setpoint and within the operational constraints is therefore conducive to the stable and controlled operation required to maximize throughput.

Means of Reducing Costs

A reduction in the furnace MWh/t (which improves the energy efficiency) is the objective central to reductions in the marginal unit cost of production. Improvements of this nature have the additional benefit of increasing the production of a furnace at a particular power input.

Experience has shown that, for a given process, the maintenance of electrode penetration at some predetermined maximum has a number of economic advantages. Electrodes penetrating evenly at this predetermined maximum level will reduce energy losses from the top of the furnace burden, thus reducing the MWh/t. From an operational point of view, this implies a balanced operation at the corresponding minimum electrode-to-bath resistance (point OL in Figure 2, with resistance = 0,67 mΩ).

Deep, balanced, and consistent penetration results in the development of regions of high power density beneath the electrodes, and in optimal heat transfer from the hot furnace gases to the burden. These conditions usually boost the reduction of the oxides that require higher temperatures and larger amounts of energy. In some cases, these reduced materials are required to be of a high grade in the product from the furnace (e.g. a high percentage of silicon in the product of a ferro-silico-chromium or ferro-silico-manganese process). Deeper penetration can therefore result in a higher-grade product. Some plants experience significant losses as a result of the production of off-grade material. The problem can continue for indefinite periods of time, depending on the operating conditions. This problem often arises when metallurgically inefficient crater conditions occur as a result of poor control of the electrode penetration. From an operational point of view, this again implies balanced operation at point OL in Figure 2 in order to maximize penetration.

Experience has shown that the maximum allowable electrode penetration is determined by a number of factors, some of which are listed below.

(a) In some cases, high levels of reduced materials may be undesirable in the product tapped from the furnace. Excessively high power densities beneath the electrodes may boost the reduction of these oxides to an unwanted degree. For this reason, the maximum penetration in some furnaces is the penetration that results in an acceptable level of reduction of certain oxides.

(b) Overheating of the base of the furnace hearth may limit maximum penetration on some furnaces.

(c) Deeply penetrating electrodes may restrict the movement of the burden into the hot zones beneath the electrodes.

The maximum penetration for a particular furnace can be determined from any one, or any combination, of the aforementioned limiting factors. For a burden of given specific resistivity, this maximum penetration determines the minimum electrode-to-bath resistance.

A reduction in electrical resistance in order to realize the economic benefits arising from operation at the maximum allowable penetration could, and in most cases will, reduce the power that can be fed to the furnace, for the maximization of throughput (not operating at the electrically optimum resistance). This trade-off is common to most installations, and is analysed later. Ways to overcome the constraints are also suggested.

Energy efficiency, reflected in the MWh/t, is also affected by the way in which the electrodes are moved. Excessive electrode movement results in kneading of the burden, which impairs the formation of stable craters and consequently reduces efficiency. Strategies that control the current in each electrode are subject to the interaction effect in which compensatory movements in one electrode affect the current in another. Currents in the electrodes may also be insensitive to movements in the electrodes. These effects are particularly noticeable in large furnaces with low power factors. The interaction phenomenon results in hunting, where large control actions are required to keep to the electrode-current setpoints, leading to undesirable kneading of the burden by up-and-down movements. The interaction and insensitivity effects also mean that imbalances in electrode penetration are not visible when the furnace is operating under current control. However, resistance control is immune to the interaction effect, and resistances are sensitive to changes in the hoist positions[2]. Resistance control therefore reduces unnecessary control action, which should also reduce the kneading effects, and thus also reduce the marginal unit cost of production.

It is therefore suggested that the best way to ensure even penetration and to reduce excessive burden kneading is by the forcing of balanced operation at equal resistance for each electrode circuit. Absolute penetration can then be managed by changes in the resistance setpoint.

Electrode breakages increase operating and maintenance costs, contributing significantly to the costs of running a furnace. 'Pushing up' production sometimes results in an abnormally high incidence of breakages. The frequency of breakages can be reduced by safe and stable operation within the electrode-current constraints. The correct baking-in procedures will also reduce the incidence of breakages. These measures can result in major economic benefits since the cost of an electrode breakage is considerable.

Maximum-demand charges can constitute a major cost to some plants, where large differences exist between the off-peak and the on-peak charges for electricity. Considerable economic benefit can therefore be derived from effective maximum-demand management so that the costs of exceeding the prescribed limits can be avoided.

Analysis of Constraints and Methods to Manage and Extend Them

The constraints of MVA, primary current, maximum demand, electrode current, and operational resistance vary from plant to plant, and so do the methods that can be used to manage and extend them.

Constraints of Transformer MVA

Operation outside the curve indicating the MVA limit in Figure 2 could result in overheated transformers, cables, or switchgear, with possible disastrous consequences.

Consider a particular furnace that is MVA-limited to running at point OP in Figure 2. The power input within the MVA limit can be increased by an increase in the operational resistance towards the electrically optimum resistance. The operating point will then shift towards point OE as the result of an improvement in the power factor at the same MVA. An increase in resistance, however, results in poorer electrode penetration, as pointed out earlier. This trade-off is examined in more detail later. Also, this increase in power input is possible only if the voltage range of the furnace transformers allows the necessary voltages to be reached.

Many transformers, particularly in older furnaces, are conservatively specified in terms of their MVA limits. For this reason, many plants 'push' their transformers to a higher MVA than the specified limit. However, care should be taken if such operation is attempted, since the safety margin is less, and the life of the transformers may be shortened. Particular attention should be given to the transformer-cooling system. The relocation of the cooling system away from hot areas or the installation of larger cooling systems could be considered if temperatures rise above the acceptable level. Heat exchangers and cooling liquids should be kept clean at all times in order to avoid fouling and to ensure good heat transfer.

Again, consider a furnace that is MVA-limited to running at point OP in Figure 2. If the current limit is ignored, an increase in the MVA limit of 10 per cent from 65 to 71,5 MVA will have the effect of increasing the power input to the furnace by 10 per cent from 41,4 to 45,5 MW, with a similar increase in production. This occurs as a result of the operating point sliding upwards along the curve of the constant electrode-to-bath resistance (in this case, 0,95 mΩ) as the MVA limit is extended. Obviously, such increases are not insignificant, and they provide a strong motivation to extend the specified limit.

The methods discussed to increase the power within the MVA limit, or to increase the power by extending this limit, will increase economic benefits by increasing the production from the furnace.

Constraints of Maximum Primary Current

The electricity-reticulation infrastructure in a furnace sometimes requires a limit to be imposed on the maximum allowable primary current. Although the infrastructure is usually matched to the MVA of the furnace transformer, dips in the supply voltage sometimes allow higher currents to be drawn while the transformer remains within the MVA limit. Furnace operation should therefore always be conducted with this current limit in mind. Exceeding the limit could result in tripping or failure of the electricity supply, or in penalties being imposed on the plant for exceeding the rated supply current.

Constraints of the Electricity-tariff Metering System

The metering system may impose limitations on either the MW or the MVA being drawn by the furnace at particular times of the day. The strategies that could be adopted for effective operation depend on which one of the two limits is being imposed. Phase-correction equipment also plays an important role in this situation. Consider, once again, a furnace operating at point OP in Figure 2.

Constraints on MW

A constraint on the MVA of a plant in the presence of automatic phase-correction equipment simply becomes a problem of reducing the MW drawn by the furnaces connected to the corrected electrical supply. Periods requiring a reduction in the active power consumption suggest a strategy of tapping transformers down and reducing the operational resistance. This should be done in such a way that the operating point moves downwards along the limiting curve. Consider, for example, a reduction in the MW limit from 41,4 to 36 MW. The following steps are then appropriate.

(a) Tap the transformers down from position 20 to position 18 in order to reduce the power input to the furnace.

(b) Reduce the electrode-to-bath resistance from 0,95 to 0,775 mΩ (i.e. until the operating point moves to point MD against the MVA limit) in order to further reduce the power. This step is taken to increase the penetration of the electrodes so as to compensate for the reduction in the power density as the power input to the furnace is decreased. This action would give rise to the same economic benefits as those from maximizing the electrode penetration.

Constraints on MVA

Periods requiring a reduction in the MVA drawn by the furnace, in the absence of automatic phase-correction equipment, suggest a strategy of simply tapping the furnace transformers down. Consider, for example, a required reduction from 65 to 61 MVA. Tapping the transformers down from position 20 to position 18 will achieve this.

A reduction in resistance may not be appropriate, since this will have the effect of reducing the power factor of the furnace, thus reducing the possible power input (and hence production) at the limiting MVA. However, such an action could be taken if it is necessary to increase the electrode penetration at the lower power density when the transformers are tapped down.

Effective management of a furnace, within the constraints of the electricity-tariff metering system, by the use of the techniques described can therefore result in considerable economic benefits.

Constraints of Electrode Current

Excessive electrode currents typically cause cracks and breaks in the leg region of the electrode following any shutdowns for periods longer than about 3 to 4 hours. This may also subsequently result in electrode-tip losses owing to thermal stresses developing within the electrodes as a result of excessive internal heating. The upset to a furnace caused by an electrode break can affect the operation so severely that it negates any attempt at optimizing the furnace by 'pushing' the current limit. For this reason, the limit should be very carefully monitored.

As was the case for the MVA, one way to increase the power within the current limit is to increase the resistance towards the electrically optimum resistance. This can be applied, for example, to a furnace that is current-limited to running at point OL in Figure 2. An increase in resistance will result in an increase in power input, with a corresponding increase in furnace throughput. The power factor will also improve as the consequence of increasing resistance. Increases in the resistance will eventually result in the furnace becoming MVA-limited, when the optimization steps already indicated are applicable.

A situation may occur under balanced furnace conditions where no problems are being experienced with electrode-tip or leg breaks. In such cases, it may be possible to extend the electrode-current limit. The benefits become clear from a consideration of the following situation: a 5 per cent increase in the 125 kA current limit in a furnace operating at point OL in Figure 2 ignoring the MVA limit. This increase will result in an increase in power from 31,4 to 34,6 MW. This 10 per cent increase in the power input to the furnace will result in a similar increase in production, and, again, this potential increase is a strong economic motivation to 'push' the limit further.

Constraints on Operational Resistance

Operation at the electrically optimum resistance (point OE in Figure 2) will result in the maximum possible power input to the furnace, with the accompanying production benefits. This high resistance is usually achieved only at the expense of good electrode penetration and is not generally practical under normal operation. As the minimum resistance (point OL in Figure 2) occurs at the maximum permissible electrode penetration, good penetration reduces heat losses from the top of the burden, improving the MWh/t, and resulting in the economic benefits outlined earlier. A trade-off therefore exists between the benefits of operation at high and low resistances. An optimum resistance, giving rise to operation at point OP in Figure 2, needs to be determined for each plant. This point is arrived at by experience in operating at different resistance setpoints. An effective analysis, however, is possible only under stable operation at balanced resistances.

A stable, balanced operation permits further analysis on the effects of reductants and slag chemistry on the electrical specific resistivity of the hot zone. An increase in the coke bed in a furnace usually has the effect of reducing the specific resistivity. Experience has shown that the use of small-sized and reactive reductants results in a higher specific resistivity. A high specific resistivity of the hot zone allows operation at a higher resistance without a reduction in penetration. In the example, such changes will result in the operating point moving from point OP towards point OE, say to point OP1, with the resultant production benefits and without compromising the beneficial effects of good penetration.

In general, there are no merits in increasing the resistance to a level above that for point OE in Figure 2 (unless it is possible to increase the voltage of the maximum tap position). Such an operation will simply result in the operating point sliding down the curve of constant voltage at the maximum tap position (tap position 23). As the resistance is increased, the power input to the furnace (and hence production) will be reduced, as will the electrode penetration.

The ultimate goal is therefore to maximize the specific resistivity of the arcing region, which will result in good electrode penetration at a high operational resistance.

Conclusions

The economic benefits from a furnace can be increased by the application of the techniques suggested in this paper to maximize the furnace throughput and reduce the costs of production. These techniques have been applied automatically to a number of furnaces. The resulting improvements, some of which are reported elsewhere[3-7], have been considerable.

The characteristic curves shown in Figure 2 can be used to locate furnace-operating points and to indicate the operational constraints. Steps that can be taken to increase furnace production, and so derive maximum economic benefit without large capital investment, then become apparent. The steps include successful furnace management within the constraints and a possible extension of some of the appropriate constraints.

Consistent maximization of the production within the operational constraints is possible only if the furnace is kept under tight control with stable, balanced operating conditions for most of the time. Balanced conditions enhance the furnace stability, and result in reductions in energy per ton of product and in a reduction in other costs, giving rise to further economic benefits. The best way to ensure balanced furnace conditions is to balance the three electrode-to-bath resistances.

The integrated furnace-control system developed by Mintek combines the balanced control of a furnace to a given resistance setpoint and the maximization of the power input within the operational constraints. The system also implements the suggested maximum-demand management routines, and provides automatic control of the baking of electrodes.

Effective control creates a climate conducive to more precise experimentation, so that the conditions that maximize the electrical specific resistivity of the hot zone can be determined. These conditions will allow a high-resistance operation without the loss of electrode penetration. Economic benefits will result from the increased production obtained at a higher resistance, and from the cost savings achieved when electrodes penetrate deeply.

References

1. Barker, I.J. (1980). Arcing in the electrical circuit of a submerged-arc furnace. *Electrowarme Int.*, 38, B 1/80, pp. 28-B 32.
2. Barker, I.J., *et al.* (1991). The interaction effect in submerged-arc furnaces. 49th Electric Furnace Conference, Toronto, Canada.
3. Bennie, J.P.W., *et al.* (1983). Sub-arc furnace optimization at Middelburg Steel and Alloys. (INFACON '83). Third International Ferro-alloy Congress, Tokyo.
4. Technology International. (1990). MINTEK's electrode controller increases production and reduces costs at AECI. MINTEK Publication, *Special Issue* 5/90, Electrode Control.
5. Barker, I.J. (1980). An electrode controller for submerged-arc furnaces. Preprint from the 3rd IFAC Symposium on Automation in Mining, Mineral and Metal Processing, Montreal.
6. Sommer, G. (1979). The Cancer project: A summary of the computer-aided operation of a 48 MVA ferrochromium furnace. Randburg, National Institute for Metallurgy, *Report* no. 2032.
7. Stewart, A.B. (1981). The measurement of electrical variables in a submerged-arc furnace. Randburg, National Institute for Metallurgy, *Report* no. 2093.