Monograph:
Morris , A.S. (1983) Direct Digital Control of the Electric Arc Furnace. Research Report. ACSE Report 233 . Dept of Automatic Systems Control University of Sheffield

DIRECT DIGITAL CONTROL OF THE ELECTRIC ARC FURNACE

by

A.S. Morris, B.Eng., Ph.D., C.Eng., M.I.E.E., M.Inst.M.C.

Department of Control Engineering,
University of Sheffield,
Mappin Street, Sheffield S1 3JD,
England.

Research Report No. 233

July 1983

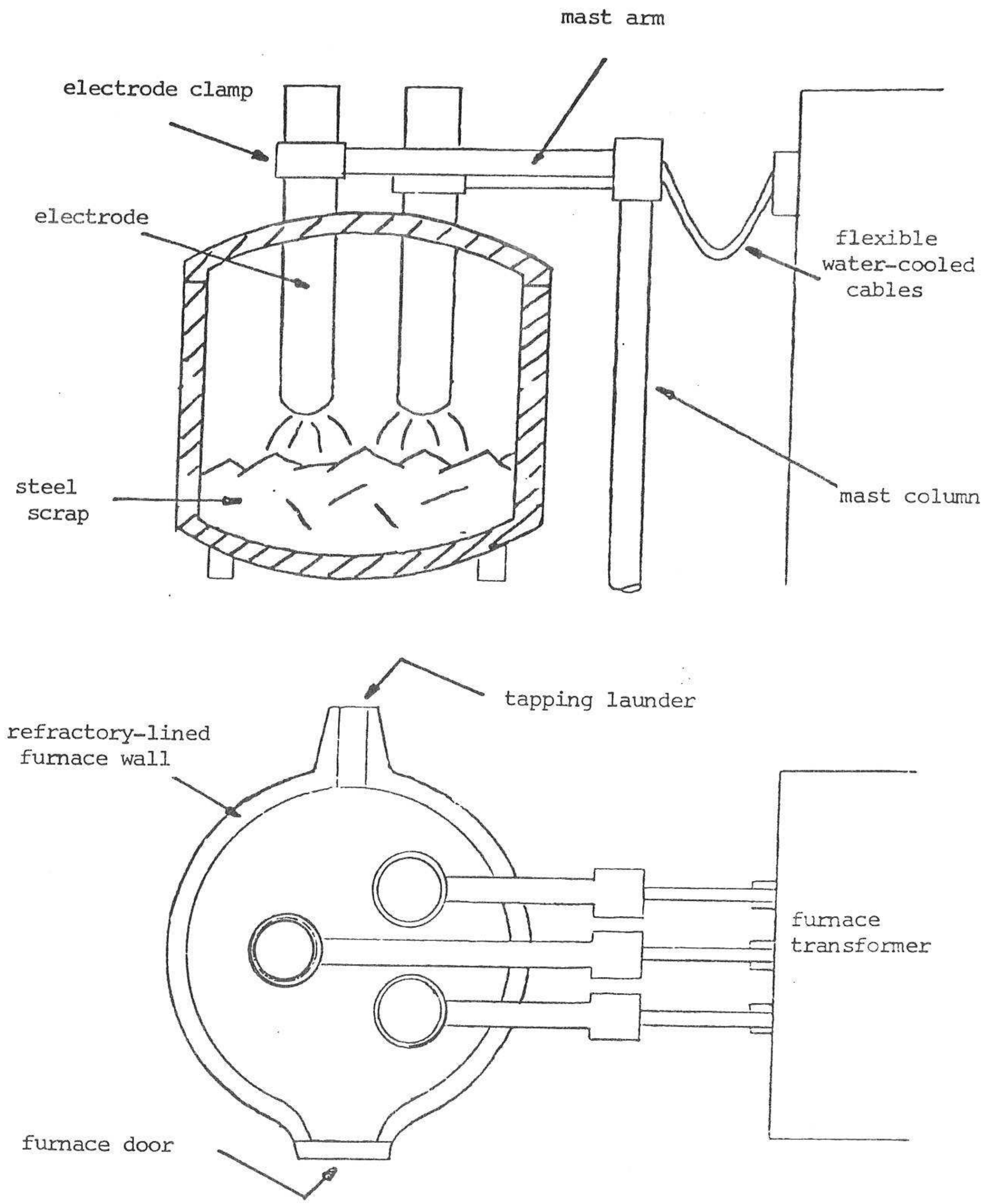
ABSTRACT

The paper explains the various aspects of control required in electric arc furnace operations and summarises the present status of research in these areas. The requirements for direct digital control are considered and suitable hardware and software schemes for digital control implementation are presented.

1. Introduction

The use of electric arcs for metal melting goes back to the very beginning of the electrical era, when it was realised that the electric arc excelled above all other energy sources as a means of obtaining high temperatures and a great degree of heat concentration . The electric arc furnace, invented by Heroult in 1905, is used to produce high quality carbon and alloy steels from a raw material of either steel scrap or a mixture of steel scrap and directly reduced iron pellets. Steel is produced to a degree of refinement considerably better than by its predecessor, the open-hearth furnace, and the modern electric arc furnace is now a very valuable tool in the steelmaking industry. Arc furnace production accounts for 20% of world steel output and this is predicted[1] to rise to 25% by 1990.

A typical furnace consists of a refractory lined metal shell of diameter 5-10M, having a removable roof, tapping launder at the rear to pour the finished steel from the furnace, and service doors at the front, as shown in Fig. 1. Three graphite electrodes, held in clamps on the end of a supporting mast arm, pass through holes in the furnace roof. The roof and electrodes can be raised and swung aside in a horizontal plane, allowing charging of raw materials into the furnace from steel baskets held by an overhead crane. Where it is the practice to use iron pellets as part of the charge, this is usually input to the furnace by a chute mechanism not shown in Fig. 1. Electrical power is supplied to the electrodes from a three-phase, multi-voltage-tap transformer, and the steel is melted by heat generated in arcs striking between the electrodes and the raw materials. Present day furnaces have power ratings up to 160 MVA and capacities up to 400 tonne[2].



CONSTRUCTION OF ARC FURNACE

(Front view and plan)

FIG 1

The electrodes are positioned by a controller to maintain the length of the electric arc at a preset value. The defined arc length value varies with the selected voltage tap and is optimised to suit particular conditions occurring at various stages of the melting process. Initially for instance, a medium voltage-tap with the controller set for a short arc length is used, as long, high-power arcs are very damaging to the roof and wall refractory materials exposed at this stage. After a short time, holes are bored into the raw material by the electrodes, shielding the furnace walls and roof from the arc, and allowing full power to be applied by a high voltage-tap and long arc.

As the bulk density of the raw material, particularly when it consists of a high proportion of steel scrap, is less than that of molten steel, the raw material has to be added to the furnace in two or more baskets. The charging procedure therefore consists of loading an initial basket of raw material, and then loading further baskets as soon as the reduction in volume of the melting material permits. Where iron pellets are used, this material is often continuously charged into the molten steel in the furnace rather than being loaded by baskets.

This procedure entails a programmed sequence of voltage-tap changes, optimised to maximise energy input to the steel whilst minimising expensive damage to refractory lining materials caused by arc flare. This program has to be modified according to initial furnace temperature and the weight and bulk density of raw materials charged. Digital control of voltage tap changes is therefore not straightforward.

Steelmaking consists of two distinct phases, the melting-down period during which solid raw material becomes molten, and the refining period during which alloys are added to the steel and unwanted elements oxidised out until it is of the required specification. At the end of the melt-down period, a sample of the molten steel is analysed, following which oxygen is blown into the furnace via a lance pushed through a hole in the furnace sidewall, and bagged alloys are thrown in through the front service doors, with the aim of producing steel of the required specification. The correct temperature must be maintained during this refining process, with the necessary amount of heat being supplied both by the exothermic reaction of the oxygen and also by suitable choice of voltage tap for the electrical power supplied.

At the conclusion of the refining period in the arc furnace, the furnace is tilted backware and steel is poured from the furnace at the tapping launder into pre-heated ladles. From here it is either teemed into ingots or fed into continuous casting plant.

So far, computer applications in electrode position control and voltage-tap control have been mentioned. A further task which naturally falls to a melting shop computer is least cost mix calculation. This consists of choosing the optimal mix of raw materials to produce a given steel specification[3,4]. Information on weight and bulk density of raw materials charged can be readily integrated with adaptive control of the tap-changing sequence[5].

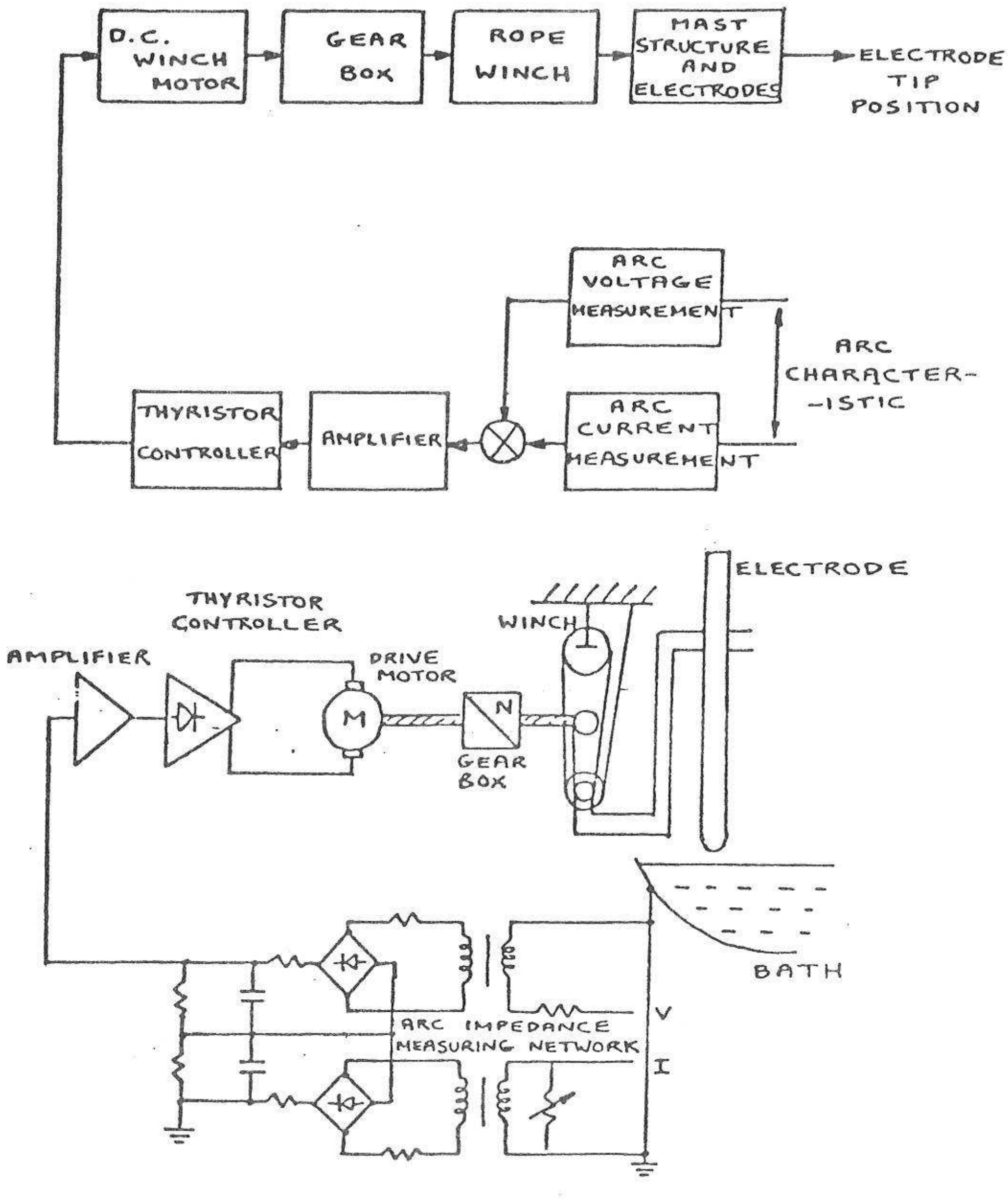
Computers can also be used to advantage in calculating the optimum addition of alloys to make following initial melt-out analysis[6], particularly where this analysis function is also computerised[7]. Computers also provide a 'get-out' clause in the form of cast-rescheduling, where it becomes either impossible or uneconomic to refine the steel to the required specification because of some mistake in the constitution of the raw material loaded into the furnace. In this case, the computer scans the order book looking for a suitable alternative cast to make[8].

The other common control function of the process computer in melting shops is maximum demand control. A single electric arc furnace imposes a large load on the electrical supply grid system, matching the domestic power nees of a large city in fact. Special tariffs are agreed with the supply authorities for the power consumed by arc furnaces, which generally give a very favourable price per unit, but which have a penalty clause setting a very high cost per unit during notified periods of high power demand. In this way, the electrical supply authorities impose a soft constraint on power usage, allowing them to cope with periods of high demand such as cold spells in winter by causing arc furnaces to be shut down. It is totally uneconomic to produce steel during such 'maximum demand' periods, but power remains available for emergency and safety reasons. Maximum demand control is an obvious application for direct digital control and this has been well discussed in technical publications[3,9].

2. Direct Digital Control of Electrode Position

When raw materials containing steel scrap are charged into a furnace, the solid surface of the scrap forms an uneven surface with random contours. Step changes occur in the scrap surface level beneath electrodes as parts of the scrap melt and the melting phase is therefore characterised by a succession of step changes in arc length occurring at random points in time. In order to maximise power input efficiency, such disturbances in arc length must be corrected in the shortest possible time by the electrode position controller. Various types of electrode controller exist[10]. Figure 2 shows a typical electromechanical system, in which an arc length error signal derived from measurements of arc voltage and current is amplified and applied to a d.c. motor, which drives the electrode up or down to correct the arc length error. A state space model of the system can be readily obtained by calculation of the transfer functions of the individual components in the system, yielding the continuous vector matrix equation:

$$\dot{x}(t) = A\,x(t) + B\,u(t) \qquad (1)$$



A direct-haul d.c. motor driven electrode position controller

FIG 2

For digital control purposes, the state transition and driving matrices (ϕ and Δ) can be calculated, to yield the equivalent discrete vector difference equation

$$x([K+1]T) = \phi(T)\; x(KT) + \Delta(T)\; u(KT) \qquad (2)$$

where

$$\phi(T) = e^{AT}$$

and

$$\Delta(T) = \int_o^T e^{A(T-\tau)} B \, d\tau$$

2.1 Proportional Control

Proportional control is the simplest control algorithm to implement and is very prevalent in real arc furnace electrode control systems. The control law can be expressed as

$$u_n = K_p e_n$$

where u_n = e_n are the control input and error signals at the n^{th} sampling instant. Choice of the proportional gain constant K_p to achieve an acceptable step response time produces an oscillatory response as shown in Figure 3(a).

2.2 Three-term control

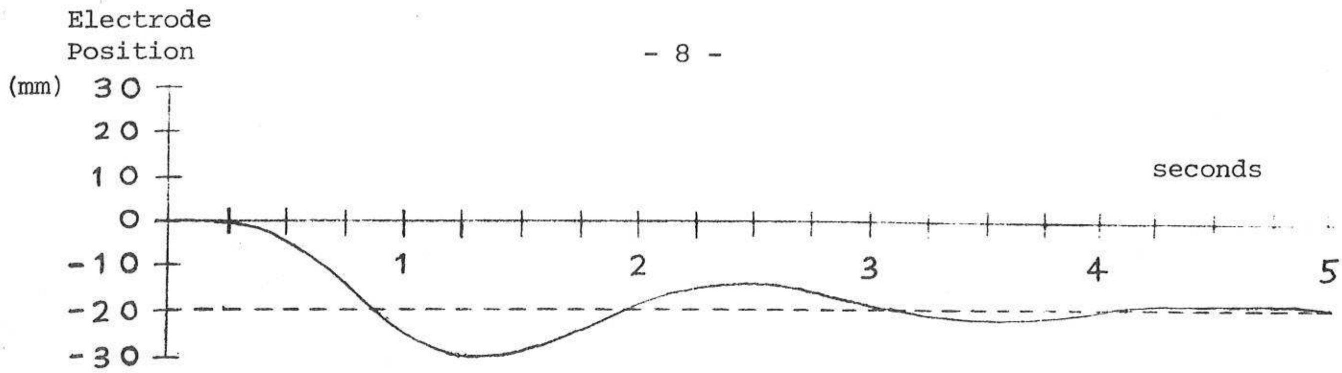
The general form of a three-term controller is

$$u_n = K_p e_n + \frac{K_d}{\Delta t}(e_n - e_{n-1}) + K_i \Delta_i \sum_{r=o}^{n} e(n-r) \qquad (3)$$

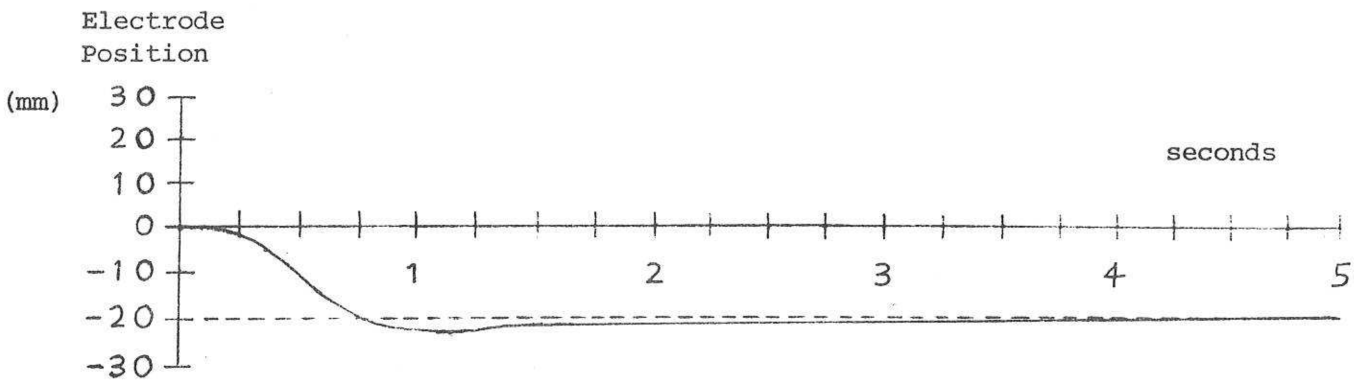
where u_n, e_n, K_p are as before

Δt is the sampling interval

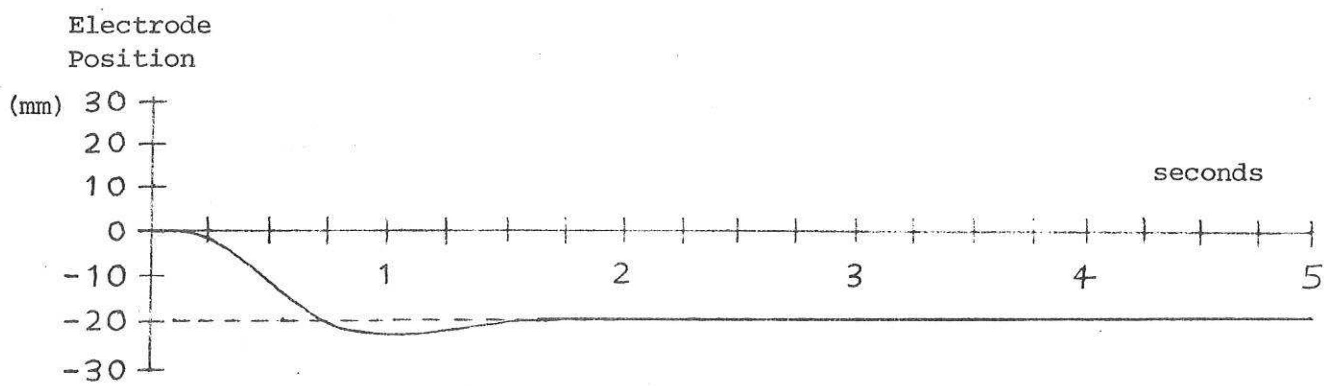
K_d, K_i are the derivative and integral gain constants. Figure 3(b) shows that whilst this maintains the step response time of the system and greatly reduces the oscillatory nature of the response, the integral term causes a small sustained overshoot of the required electrode position which only reduces to zero over a long time period.



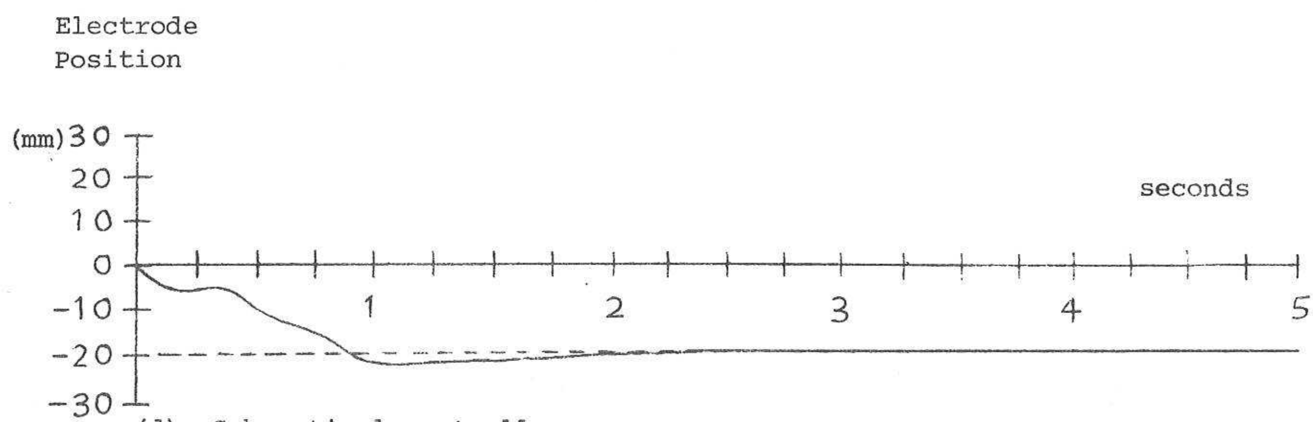
(a) Proportional controller



(b) Three-term controller



(c) Constrained integral three-term controller



(d) Sub-optimal controller

SIMULATED STEP RESPONSE OF DIFFERENT CONTROLLERS

FIG 3

2.3 Constrained three-term control

A solution to this sustained overshoot problem is to put a hard constraint on the magnitude of the integral term. This allows the integral term to perform its function of maintaining the steady-state accuracy of the system without unduly affecting its performance. The modified control law then becomes:

$$u_n = K_p e_n + \frac{K_d}{\Delta t}(e_n - e_{n-1}) + \begin{cases} K_i \; \Delta t \; \Sigma e(n-r) & \text{if } K_i \; \Delta t \;\; \Sigma e(n-r) \leq K_L \\ K_L & \text{if } K_i \; \Delta t \;\; \Sigma e(n-r) > K_L \end{cases} \quad (4)$$

Simulation, as shown in Fig. 3(c), demonstrates that this maintains the response time and non-oscillatory nature of the step response, whilst avoiding the small sustained overshoot of required electrode position.

2.4 Sub-optimal control using reduced order system model

Optimal control of a system expressed by the discrete vector difference equation (2) is obtained by calculating an input sequence u(o), u(1),..,u([n-1]t) which minimises a performance index given by:

$$J = \sum_{t=o}^{t=NT} \left[x(t)^T Q\, x(t) + u(t-1)^T \, R\, u(t-1)\right] \quad (5)$$

where Q is a symmetric state variable weighting matrix

and R is a diagonal control variable weighting matrix

The optimal inputs are then related to the system state vector by the matrix M:

$$u(KT) = M\, x(KT) \quad (6)$$

Calculation of the control law (6) at any sampling interval KT requires minimisation of the cost function (5) over all values of x and u at previous time steps. This procedure is therefore computationally tedious.

An alternative is to design a sub-optimal control law where a quadratic performance index is minimised over one sampling period only[11].

The performance index in this case is

$$J' = x([K+1]T)^T Q\, x([K+1]T) + u(KT)^T R\, u(KT) \tag{7}$$

Substituting for $x([K+1]T)$ in (7) using (2) yields

$$J' = [\phi(T)x(KT) + \Delta(T)u(KT)]^T Q [\phi(T)X(KT) + \Delta(T)u(KT)] + u(KT)^T R\, u(KT) \tag{8}$$

Differentiating (8) with respect to u(KT) and equating to zero yields the required condition for minimum J':

$$u(KT) = - [\Delta(T)^T Q \Delta(T) + R]^{-1} \Delta(T)^T Q \phi(T)\; x(KT) \tag{9}$$

Consideration of this control law (9) shows that it involves matrix inversion, which is still a computationally time consuming process in the case of the 10th order electrode controller. The solution to this is to calculate a control law based on an equivalent lower order system model.

Many techniques of model order reduction are available[12]. One which is of particular use in this case is a plane projection method.

This takes a system of the form $\dot{x}_n(t) = A_n x_n(t) + B_n u(t)$ and produces a lower order model $(r < n)$ of the form $\dot{x}_r(t) = A_r x_r(t) + B_r u(t)$, retaining the dominant eigenvalues of the system such that the original and reduced models have similar response to a given set of inputs.

Having calculated such a reduced order model, it is then necessary to calculate reduced order matrices $\phi(t)$ and $\Delta(t)$, from A_r and B_r. The control law now becomes:

$$u(KT) = - [\Delta_r(T)^T Q_r \Delta_r(t) + R_r]^{-1}\; \Delta_r(T)^T Q_r \phi_r(T) x_r(KT) \tag{10}$$

Before (10) can be used, values must be assigned to the matrices Q_r and R_r. Suitable choice of weighting factors is largely a matter of inspired guess-work, using physical constraints on various components of the system to indicate the relative magnitudes required for the individual elements of Q_r and R_r. For instance, a high weighting should be placed on mast and electrode position to reduce position errors quickly, and a low weighting must be placed on electrode acceleration to provide fast system response.

Fig. 3(d) shows the system step response obtainable by suitable choice of Q_r and R_r. Whilst the response time and overshoot characteristics are better than for the other forms of controller tried, there is a curious small oscillation in the simulated electrode movement a short while after time zero.

2.5 Controller performance measurement

Some quantitative method of comparison is necessary to evaluate the performance of the control schemes proposed so far. Arc power input efficiency is reduced whenever the arc length deviates from its set point and hence a suitable measure of performance is the area under the curve of arc length error v. time, following a unit step disturbance in scrap position. A performance coefficient P can be expressed as

$$P = \sum_{t=o}^{t=\infty} e(t)$$

where e(t) is the arc length error at time t following a unit disturbance in scrap position at time zero. The aim of the controller should be to minimise P.

Table 1 compares the controllers discussed so far in terms of this performance coefficient. This shows that, whilst a sub-optimal controller gives the best performance, the computationally much simpler, constrained integral, three-term controller has a performance which is almost as good.

TABLE 1

Controller	Performance coefficient
Proportional	18.8
3-term	15.9
Constrained 3-term	11.8
Sub-optimal	10.0

3. Direct Digital Control of General Operational Features

3.1 Maximum demand control

Maximum demand control entails monitoring the operating power level of the furnace and shutting the furnace down, if safety factors permit, whenever the power level exceeds a special 'maximum demand' level set by the power supply authorities. This 'maximum demand' level is set by the supply authorities to enable them to cope with periods of high general power usage, such as cold spells in winter. The financial penalty imposed if the maximum demand power level is exceeded during these periods is so severe that it is prudent to assign this control task to a computer lest human error should allow furnaces to continue operating.

3.2 Least cost mix calculation

Least cost mix calculation involves the selection of the optimum weights of alternative raw materials which will produce the required specification of steel for the lowest cost.

If n raw materials are available, and are assigned code numbers 1,2,.,n, then the problem can be expressed as minimising a cost function J given by[4]

$$J = \sum_{i=1}^{n} c_i x_i$$

subject to the following constraint applied separately to each chemical element required in the target steel specification:

$$p_{min} W \leq \sum_{i=1}^{n} p_i x_i \leq p_{max} W$$

where

c_i is price per kg. of raw material i

x_i is weight used of raw material i

p_i is the percentage of the chemical element in raw material i

p_{min}, p_{max} are the minimum and maximum limits of the chemical element in the target steel specification

and

$$W = \sum_{i=1}^{n} x_i$$

A similar algorithm can be applied to calculate the optimum alloy additions to make to bring the steel exactly to the correct specification following melt-out analysis at the end of the metling-out phase of operation.

3.3 Energy input control

Energy input control embodies a philosophy of minimising the total production cost per tonne of steel, where cost is expressed as a function of energy costs, refractory costs, electrode costs and time.

A prerequisite for energy input control is knowledge of the weight and bulk density of raw material charged to the furnace. The control computer is then able to calculate the energy input necessary to melt the raw material and bring the steel to the required temperature. This calculation is based on a thermal model of the furnace. The correct balance between heat supplied electrically and heat arising from the exothermic reactions due to oxygen injection is derived using a metallurgical process model.

Electrical power input is subject to constraints on refractory and electrode erosion. The optimal power input level at various stages of the melt is usually calculated taking account of a refractory wear index due to Schwabe[13], which relates refractory wear to arc voltage, arc current and arc length. Electrode erosion is a function of furnace atmosphere temperature[14], and hence of power input level, but is frequently ignored in calculating input energy levels as the time-cost penalties of operating at low power levels to reduce electrode consumption outweigh the savings achieved in electrode costs.

The furnace transformer offers multiple voltage-tap settings. A particular arc length, maintained by the electrode controller, is associated with each setting. Immediately following the charging of new raw materials to the furnace, a medium voltage, short arc-length transformer tap is used, minimising damage to the furnace roof through arc flare. After a short while, when holes have been bored into the raw material, a high voltage, long arc-length tap is used. Later, during refining phases of operation, low to medium voltage, short arc-length voltage taps are used.

The control computer uses knowledge of the raw material input to calculate a schedule of automatic voltage tap changes. It also uses this information to calculation when the raw material will be sufficiently melted, and can thus instruct the furnace operator when to load the next charge of raw material. In a similar fashion, it is able to guide the operator about the correct time to sample the steel to obtain a melt-out analysis. Following this, it calculates the best power input program to melt alloys added following the melt out analysis and bring the steel to the required temperature.

3.4 Cast rescheduling

The discussion so far has assumed raw materials of constant, known composition. However, the assumed composition of raw materials can vary both because of human error in analysis and because of unrepresentative samples being analysed. At the time of melt-out analysis during the steelmaking process the predicted and actual steel composition will vary, and sometimes it may be uneconomic, or even impossible, to bring the steel to the required specification. In such cases, the computer is usefully employed to scan the order book and select a suitable alternative cast to make where the target specification sufficiently matches the melt-out analysis, a procedure known as cast-rescheduling.

4. Implementation of Direct Digital Control

4.1 Hardware implementation

In the digital control of an arc furnace, control activities fall into two distinct categories of short term and long term aspects. Maintenance of the defined arc length is a short term control task, requiring quasicontinuous control action. The other control activities of maximum demand control, raw material input calculation and cast rescheduling are long term strategies, requiring processor power relatively infrequently.

This is an obvious application for hierarchical control, using dedicated slave processors to control arc length for each furnace, and one host processor in the melting shop to supervise all long term control aspects. Fig. 4 shows an appropriate host/slave processor configuration and the necessary input/output signals. The whole system can be supervised by the host, using visual display units to communicate with furnace operatives. The host calculates energy input and raw material loading schedules and passes them to the slave processor for execution. The slave processor is responsible for maintenance of the chosen arc length and for monitoring various furnace variables used in calculations by the host processor, besides executing energy input schedules.

4.2 Software implementation

For an n furnace melting shop, the program in the host processor must execute n supervisory programs in parallel as shown in Fig. 5. Each supervisory program is initiated on receipt of a 'furnace available' message from the appropriate furnace.

The initial task of each supervisory program, shown in Fig. 6, is to access a priority ordered cast-list file and select the next cast to be made. A suitable mix of raw materials is then calculated, using a least cost mix algorithm, and instructions passed to the raw material loading bay V.D.U. An optimal raw material loading, voltage tap changing and oxygen injection schedule is calculated and passed to the furnace slave processor. This calculation is carried out using thermal and metallurgical models. The thermal model calculates the required energy input based on physical and chemical data about the charge, taking into account energy gains from exothermic reactions and energy losses in water cooling, waste gases etc.

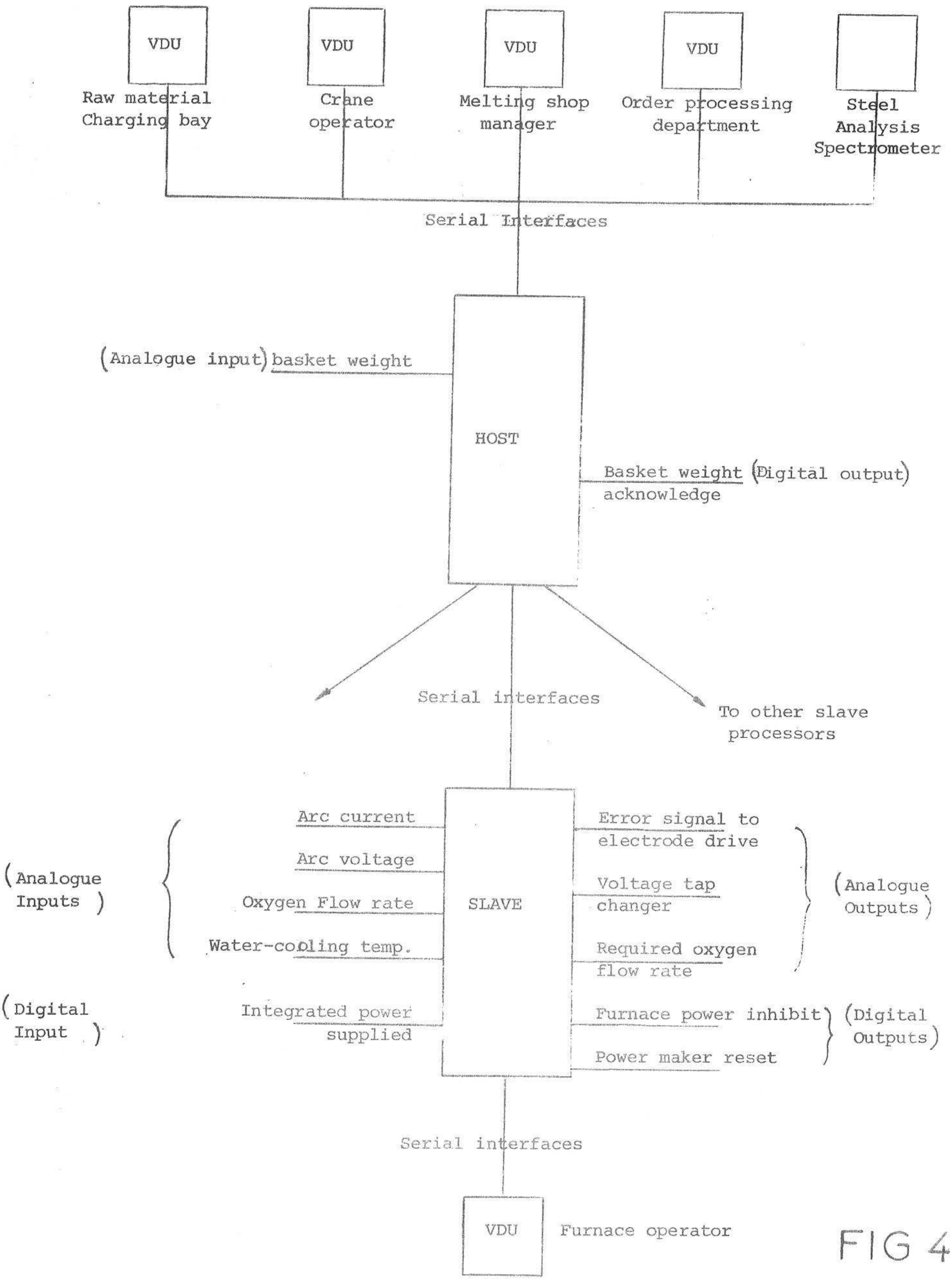

VDU
Raw material
Charging bay
VDU
Crane
operator
VDU
Melting shop
manager
VDU
Order processing
department
Steel
Analysis
Spectrometer
Serial Interfaces
(Analogue input) basket weight
HOST
Basket weight (Digital output)
acknowledge
Serial interfaces
To other slave
processors
(Analogue
Inputs)
Arc current
Arc voltage
Oxygen Flow rate
Water-cooling temp.
(Digital
Input)
Integrated power
supplied
SLAVE
Error signal to
electrode drive
Voltage tap
changer
Required oxygen
flow rate
(Analogue
Outputs)
Furnace power inhibit
Power maker reset
(Digital
Outputs)
Serial interfaces
VDU
Furnace operator

FIG 4

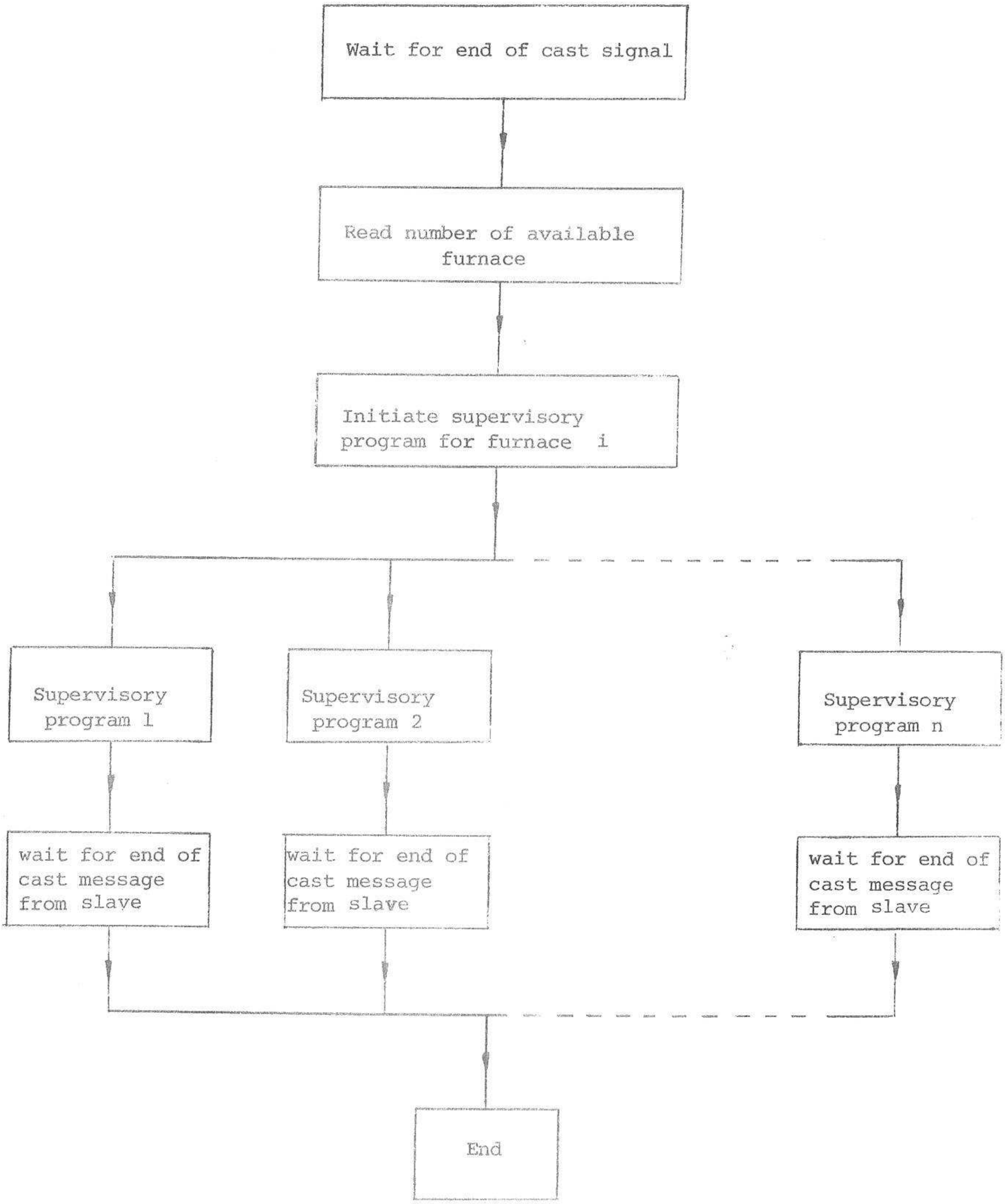
The metallurgical model is used to calculate the required alloy additions and oxygen injections based on chemical process models.

The slave processor executes production schedules received from its host processor supervisory program. A VDU is provided in each furnace control room to allow certain operations to be offered to the furnace operator for confirmation before execution. Fig. 7 shows the slave processor program flow chart, which is in effect three parallel processes executing simultaneously. These processes consist of the execution of host processor schedules, monitoring of furnace variables and control of arc length. At the end of the melting period for each basket of raw materials, control is passed back to the host processor. This calculates new raw material or alloy inputs and sends a further operations schedule to the above processor for execution.

Superimposed on this operating software is an interrupt service routine (not shown) which responds to maximum demand messages by shutting furnaces down, subject to safety considerations.

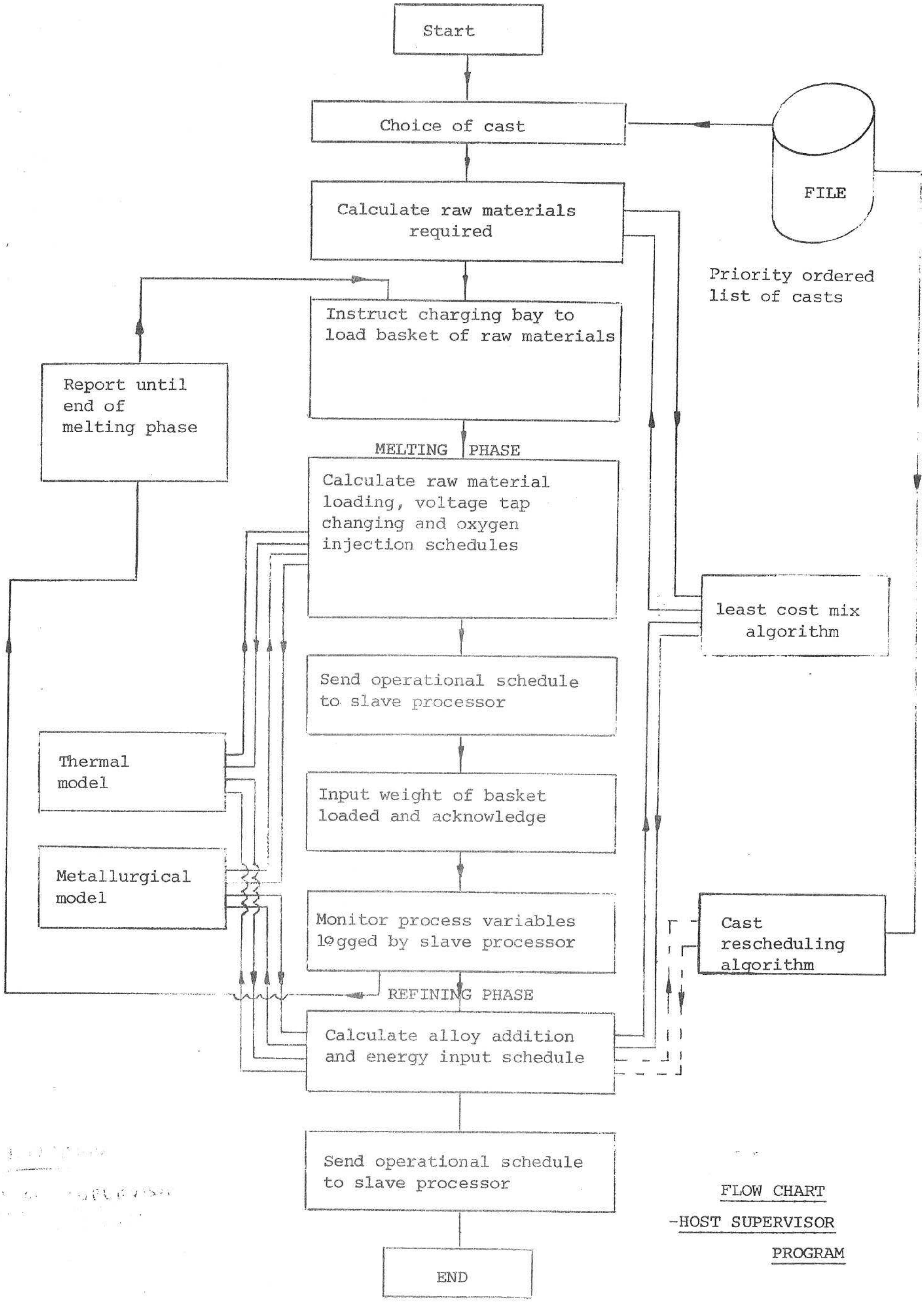
5. Summary

The control requirements for electric arc furnace operation within the areas of electrode position control, voltage tap changing, least cost mix calculation and maximum demand control have been discussed. Alternative schemes for electrode position control have been presented and their performance compared by digital simulation. Finally, the requirements for direct digital control have been considered and a suitable scheme for hardware and software implementation of furnace control algorithms suggested.



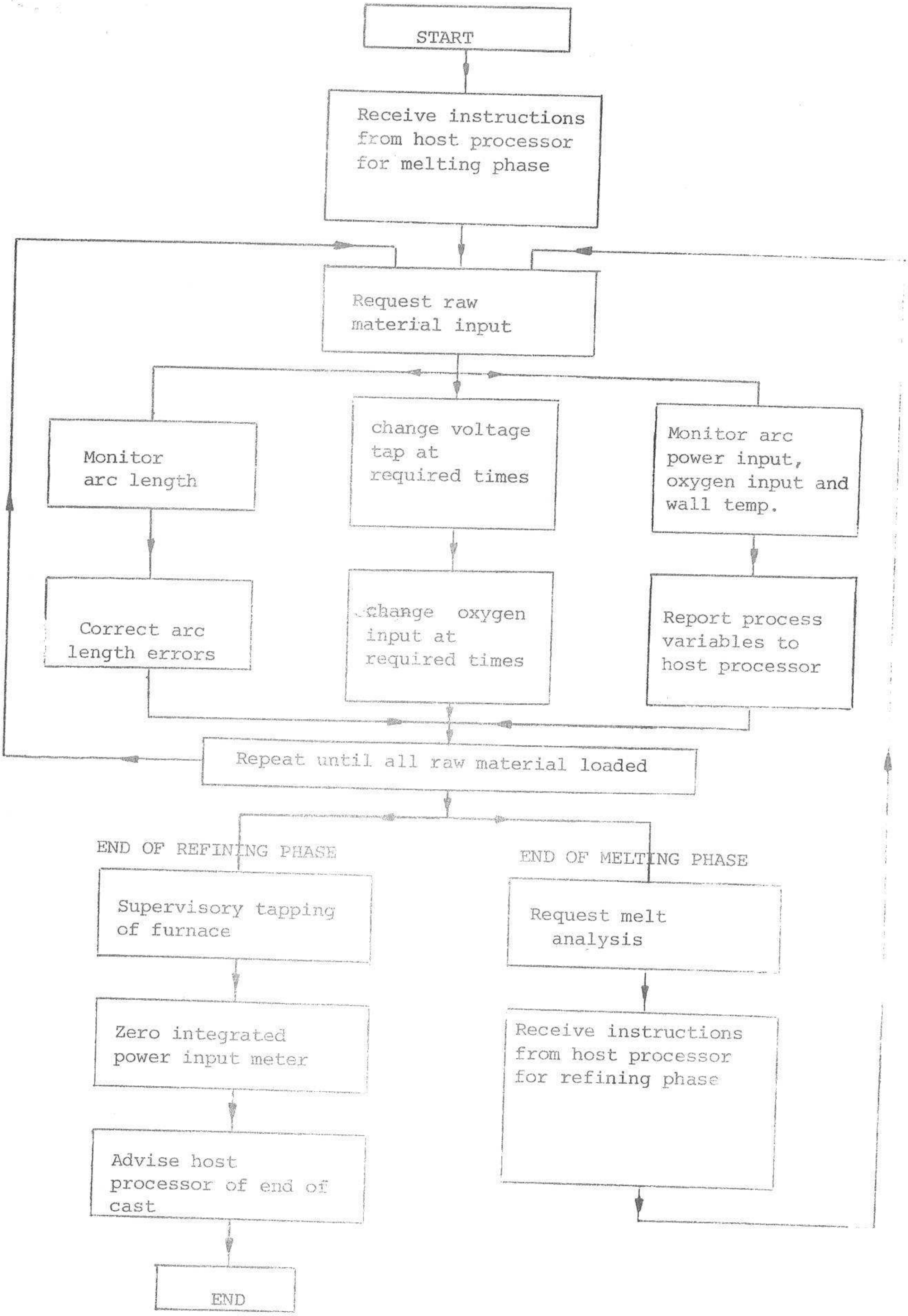
FLOW CHART-HOST PROCESSOR

FIG 5



FLOW CHART
-HOST SUPERVISOR
PROGRAM

FIG 6



FLOW CHART - SLAVE PROCESSOR

FIG 7

6. References

1. SHARP, J.D. 'The role of the electric arc furnace in the 1980's, Proc. electric arc steelmaking conf., Sheffield, England, 1979, Inst. of Metallurgists, pp. 1-12.

2. MOORE, C and MARSHALL, R.I. 'Modern steelmaking methods', Inst. of Metallurgists, Monograph No. 6, 1980.

3. CIFFORD, J.D., MORRIS, A.S. and ROEBUCK, R. 'Arc furnace controls in the electric melting shop', Fourth Special Steels Division Steelmaker's Conf. (British Steel Corporation), Harrogate, England, 1972.

4. CUSSON, J.G. 'Computerised charge calculations at Dominion Engineering Works Ltd., Elec. Furnace Proc. (AIME), 36, 1978, pp. 184-193.

5. GILL, L.L. 'Operational aspects of arc-furnace computer control' Ironmaking and Steelmaking, 5(5), 1978, pp. 217-223.

6. BRANDT, S. 'Automation of Electric Arc Furnaces', AEG - Telefunken Progress, 2, 1977, pp. 42-5.

7. PALMER, L.W. 'Automation of Polyvac Melt Analysis', Iron and Steel International, 51(6), 1978, pp. 363-372.

8. MENON, U. 'Computer Control of arc furnace operations' Fourth Special Steels Division Steelmaker's Conf. (British Steel Corporation), Harrogate, England 1972.

9. JONES, D.R. and MONTIETH, W.F. 'Arc furnace power demand control', Electric Furnace Proc. (AIME), 29, 1971, pp. 189-194.

10. MORRIS, A.S. and STERLING, M.J.H. 'Analysis of electrode position controllers for electric arc steelmaking furnaces', Iron and Steel International, 48(4), 1975, pp. 291-298.

11. NICHOLSON, H. 'Dynamic optimisation of a boiler', Proc. IEE, 111(8), 1964, pp. 1479-1499.

12. MORRIS, A.S. 'Design and performance optimisation of an electric arc furnace electrode position controller', Ph.D. Thesis, University of Sheffield, 1978.

13. SCHWABE, W.E. 'Arc heat transfer and refractory erosion in the electric steel furnace', Proc. Electric Furnace Conf. (AIME), 1962, pp. 195-206.

14. SCHWABE, W.E. 'The mechanics of consumption of graphite electrodes in electric steel furnaces', Journal of Metals, 1975, pp. 65-71.