

MODELS OF LD CONVERTER FOR ITS AUTOMATION

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INTRODUCTION:

LD process for steelmaking and computer control of industrial processes, both were born almost at the same time. Both grew together and owe each other for their development. Unlike its forefathers, LD process was found to be quite fast and operators soon realized their inability to catch its speed and control the furnace accurately. The large capacities of the converters and stochastic nature of the process further aggravated the problem. Automatic control could be one of the solutions and therefore the efforts to automate the process began even before the process was hardly 5 years of age. First static control scheme using special slide rules was published by Slatosky in 1960 [ 1 ]. Since then several static and dynamic control schemes have been published each scheme claiming better results than all others.

The first converters of this type were installed at Linz and Donawitz of Austria in 1952 and hence the process was named as LD process. It is used for refining of pig iron obtained from blast furnace and converting it to steel by reducing carbon, silicon, phosphorus, manganese and other impurities to required level. A simplified diagram of the process is shown in Fig. 1. The furnace consists of a vessel to which molten pig iron obtained from blast furnace is charged along with scrap, cold pig iron and lime stone etc. Oxygen is then blown on to the charge from a water cooled lance. The oxygen reacts with the bath to refine the metal. The oxidation reaction that occur generate enough heat to melt a substantial amount of scrap

and to raise the temperature of resultant molten bath. Primary reactions are summarized in Fig. 2.

It is now well established that the function of any control scheme for LD process should be to control end point carbon, end point temperature and to stabilize the process by reducing slopping etc. The violent ejection of slag from the vessel is called slopping and is caused mainly by excessive oxygen in slag during the first phase of the blow. Thus a continuous control of the furnace reaction is required. A typical decarburization curve is shown in Fig. 3. The complete refining period can be divided into three phases. During the first phase commonly known as 'silicon blow' non-carbon impurities like silicon, phosphorus and manganese are preferentially oxidized. During the second phase called 'carbon blow' most of the oxygen is used for decarburization and during the third phase known as 'Finish blow' decarburization rate decreases and a part of oxygen goes to oxidise iron. Fig. 4 gives an idea of oxygen distribution between Si, C and Fe during the blow. This figure was obtained from a simulation of LD converter on IBM 360/44 at Indian Institute of Science [ 2 ].

#### I. STATIC MODELS:

Static models also known as 'Charge Control' are used to calculate the composition of the charge for the desired end point results. Though the first static model was proposed as early as 1960, all dynamic control schemes still use static models. The purpose is to achieve the best thermodynamically balanced charge for

the prescribed heat from the available materials. Several static models have been proposed e.g. by Slatosky [ 3 ], CNRM [ 4 ], Goel et al [ 5 ] and Katsura [ 6 ]. All static models are based on the same general principles of overall heat and mass balance, with the latter applied to Iron, Carbon, Oxygen slag, lime, wastegases, sulfur, phosphorus etc. etc. A simplified description of the equations is given in Table 1 [ 7 ].

These static models predict the required weight of scrap, lime and oxygen for a given end point temperature and composition. Katsura et al [ 6 ] have pointed out that a static model should also take into account the wear of refractories which is different for each heat. The inner shape of the lining of a vessel changes considerably during one campaign of lining. As reported by them, the inner volume and wall thickness change by 50 to 75% from the first heat after lining to the last heat before relining. This affects the FeO content of the slag, rate of dephosphorization, amount of slopping and particularly the heat loss through lining. Their static model takes this into account and also the slopping which if happens, is graded by the operator and the model is adjusted accordingly.

In general the static models do not give sufficient accuracy because they are based on over simplified assumptions and are entirely subject to the accuracy of initial conditions. Moreover, such a change calculation does not react to the inprocess variations occurring during blowing. Therefore it is only the beginning of the control of the BOF process. Its main utility is to thermodynamically balance the charge so that dynamic control can more readily bring the heat on specification.

II. DYNAMIC MODELS:

Dynamic models of LD converter can be broadly classified into three categories based on their approach to modelling and control as shown in Table 2.

Table 2 - Dynamic Models

Type	Example	Reference
Reaction Mechanism Based Models	Muchi	8-10
	Goel	5
	Humbury and Middleton	12
	CNRM Oxygen Distribution Model	13
Measurement Based Models	Fujii's Decarburization Model	14
	Blum	15
	CNRM fume temperature model	16-17
Modern Control Techniques Based Models	J & L (Meyer et al)	18-20
	CNRM transfer function approach	22
	Wells et al's estimation and filtering approach	23

2.1 Reaction Mechanism Based Models: Those models, which are derived from the physicochemical principles of steelmaking and generally involve minute details of internal process mechanism, come under this category. One major application of these models is

that when simulated on analog or hybrid computer, they can be used to test control schemes or control programmes and in that sense they can replace the actual furnace.

2.1.1 Model proposed by Muchi et al: Professor Muchi and others at Nagoya University Japan, have published a series of valuable papers [8-10] on dynamic modelling of LD converters. These papers contain a wealth of information and prove the applicability of fundamental chemical and metallurgical principles to actual processes. Based on the reaction mechanism of LD converter, this model predicts the variation of metal composition, temperature, flue gas analysis, gas temperature and slag composition etc. It is assumed that a parabolic cavity is formed by oxygen jetted against molten metal. The rate of oxygen absorbed in the cavity is determined assuming a high temperature ( $2400^{\circ}\text{C}$ ) layer saturated with oxygen at the cavity surface. Most of the reactions are assumed to occur in this zone. Distribution of oxygen between various elements (C, Si, P, Mn & Fe) depends on the available concentration of the elements and their affinity with oxygen. Lime dissolution in the slag is determined assuming a CaO saturated slag at the given bath temperature.

The model has the virtue of being truly general and dynamic. The condition of any variable at any instant of time can be predicted from the model. Complete model consists of over 100 equations including several nonlinear differential equations. However, the model needs to be further simplified and linearized, if complex and cumbersome calculations are to be avoided to minimise computer time.

The greatest objection to Muchi's approach is that in an actual furnace, reaction zone is not limited to the cavity surface, but it also extends to slag-metal interface, metal droplets surface etc. The total area of reaction zone thus, becomes several times the cavity area. This reaction zone is considerably increased by increased CO evolution. Another limitation is that the oxygen absorbed by slag (which if in excess leads to slopping and considerably affects the decarburization rate) has not been considered. Moreover, this may not allow correct end point temperature prediction because a common practice to raise the end point temperature while keeping carbon constant, is to raise the lance so that almost all oxygen is absorbed by slag only and heat is released by oxidation of FeO to  $\text{Fe}_2\text{O}_3$ .

The validity of the assumption of a high temperature zone at the cavity surface has been questioned by many including Meyer [11].

2.1.2 Model Proposed by Goel et al: This [5] is also a reaction mechanism model similar to that of Muchi. However Goel et al rejected the hot spot theory and use the following empirical relationship to determine the oxygen available to bath:

$$\text{Bath oxygen} = \text{Lance oxygen} (1 - \text{Exp}(-K \cdot dC/dt))$$

Where K is a positive constant and  $dC/dt$  is decarburization rate. Thus when carbon removal rate increases, it causes greater CO evolution with enhanced emulsification of metal and the oxygen absorbed by the bath increases. This is obtained from above equation also since  $dC/dt$  is a negative quantity.

The dissolution of lime, limestone and iron ore has been assumed to follow a negative exponential rate:

$$dW/dt = -r W$$

where  $W$  is the weight of undissolved lime, limestone, or iron ore;  $r$  is a positive constant. The authors have made no attempt to justify this assumption.

Goel et al also remain silent about the amount of slag oxygen which is an important variable as discussed above.

2.1.3 Model proposed by Humbery and Middleton: The details of the model have not been published, however, as reported by the author [12] their model consists of 40 simultaneous first order non-linear ordinary differential equation and a similar number of algebraic equations based on reaction mechanism. This model was originally developed for LD-AC process and it has been successfully applied to LD process. All reaction are assumed to occur at interfaces between slag, metal and/or gas phases. The rate determining step is therefore that of diffusion of reactant species to the phase interface at which the reactions occur from within the bulk phase.

An important improvement over Muchi's model is that their model contains an expression which allows the interfacial area to vary according to the degree of turbulence currently existing. The latter is related to the rate of evolution of carbon monoxide. Also included in the model is a relationship which governs the distribution of oxygen between slag and metal phases as a function of the



lance height and the blowing rate. Further, since the model was developed mainly for computer control, several complex equations obtained from theory have been linearized to reduce computer time.

2.1.4 CFRM Oxygen Distribution Model: Researchers at Centre National de Recherches Metallurgiques are actively working on control of LD converter since 1962, with the final aim of realization of an optimal control scheme for it. They have tried several approaches to the goal. Nilies and Dennis [13] have proposed an oxygen distribution scheme. The main reactions considered by them are oxidation of silicon, formation of CO and CO<sub>2</sub> in the vessel; oxidation of iron and evolution of slag compositions. The total oxygen flow  $Q_T$  is assumed to be distributed into three parts: the oxygen combined with silicon  $Q_{Si}$ , carbon  $Q_C$  and iron  $Q_{Fe}$ . A part of oxygen already combined with iron can recombine with carbon as shown in Fig. 5.

The oxygen leaving the lance is supposed to reach successively four distributing centres  $C_1$ ,  $C_2$ ,  $C_3$  and  $C_4$  as shown in Fig. 6. At each centre flow is divided into two parts depending on several variables like lance height and total oxygen flow, lime dissolution speed and physical properties of slag and type of slag and evolution of the bath temperature. They have established the following relationships between various partial flows:

$$D_{CO_2}^o = f_1(T) * LH * D_{CO}^o$$

$$D_{Si}^o = f_2(T) * PJ * (\%Si - \%Si_{eq})$$

$$D^{\circ} \text{CO}_A = f_3(T) * PJ * (a D^{\circ} B - K_1 / \%C)$$

$$D^{\circ} \text{CO}_B = f_4(T) * A_s * (\text{FeO}/K_2 - f / \%C)$$

$$Q^{\circ} \text{Fe} = Q^{\circ} \text{T} - Q^{\circ} \text{Si} - Q^{\circ} \text{CO}_2 - Q^{\circ} \text{CO}$$

where  $D^{\circ}_i$  = Partial oxygen flow rate used for  $i$  (Kg/Sec)

$Q^{\circ}_i$  = Quantity of oxygen used for  $i$

LH = Lance height

PJ = Penetration of jet

$A_s$  = Metal slag interfacial area

$K_2$  = Equilibrium constant of the reaction  $\text{Fe} + \underline{\text{O}} = \text{FeO}$

$f$  is a parameter.

The slag composition is given by

$$d(\% \text{CaO}) / dt = f_5(T, V, P) * (Q_{\text{CaO}}^{\text{Total}} - Q_{\text{CaO}}^{\text{Diss}})^{2/3} * (\% \text{CaO}^{\text{sat}} - \% \text{CaO})$$

The empirical functions  $f_1, \dots, f_5$  are determined from experimental data.

These empirical models have general limitation in that they cannot be used for other furnaces and if so required, complete experimentation and derivation has to be repeated. Moreover, empirical equation may give a good correlation at one plant while at another plant they may not give acceptable correlation. In other words reproducibility of empirical models is limited.

2.2 Measurement Based Models: These models are different from reaction mechanism models in that these do not involve much of internal mechanism of furnace reactions. The sole aim of these models is to control the furnace dynamically and these may or may not predict all the variables in the process. These models are in general very simple in structure and make use of continuous measurement from the process such as gas analysis, bath temperature, fume temperature etc. For these reasons, these models are also called 'Control Models' or 'External feature models'.

2.2.1 Fujii's Decarburization Model: T. Fujii et al of Sumitomo Metal Industries Japan have suggested a very simplified scheme [14] obtained by approximating the decarburization curve in a trapezoidal form as shown in Fig. 7. The refining process is divided into three blowing periods with decarburization rate following the curves stated below:

$$\text{First Phase : Silicon Blow : } -dC/dt = K_1 t$$

$$\text{Second Phase: Carbon Boil : } -dC/dt = K_2$$

$$\text{Third Phase : Finish Blow : } -dC/dt = K_3 C$$

where  $K_1$ ,  $K_2$  and  $K_3$  are constants determined by blow conditions such as oxygen flow rate lance height etc.,  $t$  is the time and  $C$  is the carbon content.

It was found that the most accurate and most reliable way to control bath carbon using decarburization model is to control the time  $\overline{AD}$  to the end of the second blowing period or the time of

the third blowing period  $\overline{DE}$ . Since it is based on relative change of decarburization rate and the absolute values are not so important, the transition point D can be detected independently of the error of the measuring devices.

$$-dC/dt = KC$$

$$K = -(dC/dt)_{\max} / (C_D * W_D)$$

$$\text{and } t_{DE} = \frac{2.303}{K} \log \frac{C_D}{C_E}$$

where  $C_D, C_E$  = carbon content at the transition point D and end point E respectively

$W_D$  = Weight of metal at point D

$t_{DE}$  = Time from point D to the end point.

Thus if the carbon content of the point D has been given, blowing time can be calculated as soon as refining passed the point D.

This model has the virtue of being extremely simple. However, in actual practice, the decarburization curve is so much nonlinear and fluctuating that it is difficult to identify transition point D. This uncertainty together with oversimplified equation for  $dC/dt$  leads to an inaccuracy in control.

Fujii has also suggested a temperature control scheme on the basis of decarburization model. However, it is highly static in nature and accuracy obtained is expected to be similar to that obtained from a good charge control model.

2.2.2 Model proposed by Blum et al: They have used exhaust gas analysis and flow rate measurement to determine the bath conditions continuously during the blow [15]. Well known principles of heat and mass balance have been used to predict bath condition from gas analysis as follows:

$$\text{Decarburization rate. } -dC/dt = K * \text{Flow rate} * (\% \text{ of } (CO + CO_2) \text{ in exhaust gases})$$

$$\begin{aligned} \text{Slag oxygen} = & \text{Lance oxygen} + \text{oxygen from limestone and ore} - \\ & \text{Oxygen used for CO} - \text{oxygen used for } CO_2 - \\ & \text{oxygen in dust} - \text{oxygen dissolved in metal} \\ \text{weight of slag} = & \text{constant} * (\text{slag oxygen}) + \\ & \text{weight of excess lime} \end{aligned}$$

$$\begin{aligned} \text{Total heat gained by metal} = & \text{Heat generated by formation of CO} \\ & + \text{Heat generated by formation of } CO_2 + \\ & \text{Heat gained from FeO} - \text{Heat lost to} \\ & \text{vessel} - \text{Heat lost through sensible} \\ & \text{losses} \end{aligned}$$

$$\begin{aligned} \text{Carbon removal efficiency} &= \frac{\text{Units of carbon removed}}{\text{Oxygen delivered to the bath}} \\ &= 1.33 \frac{\text{Decarburization rate kg/min.}}{\text{Lance oxygen kg/min.}} \end{aligned}$$

The slopping is due to rapid decarburization during transition from silicon blow to carbon boil. Therefore, the derivative of the decarburization rate is a feedback signal to reduce oxygen flow rate and control slopping. Temperature of the metal can

be calculated from total heat gained and initial temperature. At carbon below 0.25%, following relationship is obtained between bath carbon and carbon removal efficiency by carbon/oxygen equilibrium:

$$\% \text{ C in Bath} = 0.04 \text{ EXP } (0.026 * \text{CRE})$$

The main disadvantage of exhaust gas analysis approach is time delay, caused by gas movement, sampling, cleaning, and analysis depending upon the position of the sampling point and quality of instrumentation. The delay may be 20 seconds to a few minutes. Considering the fast dynamics of the process it may cause unacceptable error in results obtained.

2.2.3 CNRM Fume Temperature Model: The sampling difficulties and rather long response time and problems in obtaining the required accuracy from gas analysis made CNRM researchers to find another approach to the control of LD converter. They experimented with fume observation cells, measurement of gas temperature in the hood, the sound recording, the temperature inside the lance etc., in order to determine those which were most appropriate to the dynamic control. The simplicity of fume temperature measurement and the fact that the thermocouple with short response times can be developed are the factors which encouraged them to use this measurement as a means of achieving automatic control of the blow. Miles and Dennis [16] have derived relationship of the following form between fume temperature and metallurgical reactions:

$$\text{Decarburization rate } dC/dt = T_f * f_1 (X_f) + f_2 (X_f)$$

$$\text{Oxygen used for carbon} = T_f * f_3 (X_f) + f_4 (X_f)$$

$$\text{Oxygen transferred to slag} = \text{Lance oxygen} - \text{oxygen used for carbon}$$

$$\text{where } X_f = \frac{(\% \text{ CO})}{(\% \text{ CO} + \% \text{ CO}_2)} \text{ in exhaust gases}$$

$$T_f = \text{Fume temperature}$$

Complete derivation of above relationships and forms of function  $f_1$ - $f_4$  is given in their paper.  $X_f$  is almost constant and lies between 0.7 and 0.9 during most of the blow. For a given  $X_f$ , it is evident that the relationship between  $dC/dt$  and  $T_f$  is linear. Nilles and Dennis have also found that decarburization rate as calculated from above equation is hardly influenced by observed variation in  $X_f$  as shown in Fig. 8. However, slag composition prediction is considerably affected by variation in  $X_f$ . Hence means of checking and controlling  $X_f$  are essential. All other factors being equal, it is known that  $X_f$  is a function of the lance height.

In a recent paper Voll and Kamelat [17] have reported the results of application of this technique to the industrial converters and compared them with those obtained from gas analysis as shown in Fig. 9.

This method though faster than gas analysis still suffers from the drawback that it requires frequent calibration of thermocouple data on the basis of data provided by exhaust gas analysis. Moreover, the fume temperature curve to be followed is different at different plants, since it depends on type of fume collecting hood and the intended slag.

2.2.4 J & L Models: A large number of papers on LD converter control has been published by researchers at Jones and Laughlin Steel Corporation U.S.A., in the period 1960-1969. A good summary of these can be found in [18]. For high carbon steel (  $C > 4\%$  ) they use an integration method to estimate carbon from gas analysis and flow rate. The latter is determined indirectly from the power required to drive the induced draft fan.

$$\begin{aligned} C(t)' &= C_0 - \frac{dC}{dt} dt \\ &= C_0 - K \text{ (percent } CO_2 \text{) (Fan H.P.) } dt \end{aligned}$$

where K is a constant to be determined empirically.

For low carbon steel, a curve fitting technique is used. A variable known as specific decarburization rate is defined as the quantity of carbon removed per unit of oxygen blow or

$$\phi = \frac{\frac{-dC}{dt}}{\frac{dO}{dt}} = - \frac{\text{Decarburization rate}}{\text{oxygen flow rate}}$$

Typical paths of  $\phi$  versus C the last phase of the blow are shown in Fig. 10. It can be represented by a function of the form

$$\phi = a - b * \text{EXP}(-r*C)$$

The parameters a, b and r are determined on line. It has been claimed that when these parameters are estimated for



an individual heat, the correlation coefficient is in excess of 0.99. The amount of oxygen  $O_G$  required to reduce carbon from  $C_1$  to  $C_2$  can be calculated as follows:

$$O_G = \frac{C_1 - C_2}{a} + \frac{1}{r a} \ln \frac{\phi_1}{\phi_2}$$

where  $\phi_1 = a - b * \text{Exp}(- r * C_1)$   
 $\phi_2 = a - b * \text{Exp}(- r * C_2)$

A sinker thermocouple is used to determine the temperature during the blow and final temperature is estimated as follows

[20]

$$\begin{aligned} \text{Final Temperature} &= \text{Measured Temperature} \\ &+ (K_1 - K_2 * \text{Measured Temperature}) \\ &* \text{Volume of oxygen blown after} \\ &\text{temperature measurement.} \end{aligned}$$

Corrective action is determined in the light of this temperature. For example, if it is realized that the oxygen requirement for carbon will result in too high a final temperature, the required quantities of coolant can be added prior to the end of the heat. Alternatively if the final temperature is too low, extra volumes of oxygen can be blown over and above  $O_G$ , with the lance being raised say 10 inches just before  $O_G$  has been blown. This causes a 'slag blow' and temperature is gained at almost zero decarburization rate, largely by converting slag  $FeO$  to  $Fe_2O_3$  so that yield loss is minimized.

2.3 Modern Control Techniques Based Models: Though most of the researchers working on automatic control of LD converters realize that their final aim is to obtain optimal control of LD converters so that desired results can be obtained with minimum cost, there are very few papers dealing with application of modern control techniques to control of LD converter. This may partially be due to highly nonlinear process phenomenon, noisy measurements and a large number of state variables in actual process. Some initiative has been taken by CNRM and System Control Inc. and their findings are briefly discussed below.

2.3.1 CNRM Transfer Function Approach: As early as in 1968, Decker had reported [21] that CNRM is studying about the identification of the LD process. However, the first results of their study have been reported only recently by Voll [22]. The three variables studied were oxygen flow rate, lance height and decarburization rate. The blow was divided into several periods and they compared the relative applicability of the following two forms of transfer function in different periods.

$$\text{First order filter type : } H(s) = \frac{K e^{-T_d s}}{1 + T s}$$

$$\text{Second order filter type: } H(s) = \frac{K e^{-T_d s}}{1 + T s} + \frac{K' e^{-T_d' s}}{1 + T' s}$$

where  $H(s)$  is the transfer function between decarburization rate ( $\frac{dC}{dt}$ ) and either oxygen flow rate  $Q_{O_2}$  or lance height  $H$ . Each type of  $H(s)$  had its own merits and demerits during different periods. An idea of their applicability can be obtained from Fig. 11.

2.3.2 Model Proposed by Wells et al: Wells, Wismer and Mehro, while working at Systems Control Inc. have investigated the application of estimation and filtering techniques to the LD converter process control. A wealth of information can be found in their paper [23]. They opine that the LD process can be considered to have two states (carbon and temperature) and two controls (Lance height and oxygen flow rate). The control objective is therefore to determine the best estimate of carbon and temperature in the real time and to terminate the blow when the desired state is reached. They have proposed a two stage dynamic model for decarburization rate, based on waste gas output data, for carbon boil and finish blow stages. The unknown parameters of the model are estimated online using measured decarburization rate.

Since there is a transport lag between waste gas measurement and current bath condition, the decarburization rate is predicted a head of the time to account for this lag. The measurement is noisy due to instrumentation and calibration errors and hence it needs filtering. It can be expressed as

$$Z_i = d_{i-\tau} + V_i$$

$$d_i = - \frac{dC_i}{dt}$$

where  $Z_i$  =  $i$  th measurement of decarburization rate

$d_{i-\tau}$  = Actual decarburization rate in the bath at time  $i-\tau$

$V_i$  = Stationary zero mean gaussian white noise sequence

$$E(V_i) = 0 \quad E(V_i V_j^T) = r \delta_{ij}$$

$C_i$  = Amount of carbon in the bath at time  $i$

Model of Carbon Boil Phase : This phase extends normally from 5th minute to 12th minute of blow. By observing the autocorrelation functions of  $Z_i$  and of increments  $DZ_i$ ,  $D^2Z_i$  etc. (Fig. 12), it was concluded that a second order model of the following type can be used

$$d_{i+1} = d_i + n_i$$

$$n_{i+1} = a n_i + w_i$$

$$Z_i = d_{i-\tau} + V_i$$

$$\text{when } E(w_i) = 0 \quad E(w_i w_j) = q \delta_{ij} \quad E(w_i V_j) = 0$$

The parameters  $a$ ,  $q$  and  $r$  are estimated online from the autocorrelation function of  $DZ_i$ . A Kalman filter can be used to provide the best estimate of actual decarburization rate  $d_i$  based on observation upto time  $i$ .

Model of Finish Blow Phase : A deterministic model proposed earlier for this phase had the form

$$d = K_1 (1 - e^{-K_2(C-C_0)})$$

where  $K_1$ ,  $K_2$  and  $C_0$  are constants. Wells et al included stochastic behaviour in the model by writing it as

$$\dot{d} = -d K_2 (K_1 - d) + n$$

where  $n$  represents a zero mean random process noise related to  $n_i$  in the first stage.

In state vector form the model becomes

$$\dot{x}_1 = -x_1 x_2 (K_1 - x_1) + x_3$$

$$\dot{x}_2 = 0$$

$$\dot{x}_3 = -\beta x_3 + u$$

where  $x_1 = d$  ,  $x_2 = K_2$  ,  $x_3 = n$

$u$  = white noise.

An extended Kalman filter was used for predicting the decarburization rate  $\tau$  sampling intervals ahead of time.

Thus Wells et al have opened an entirely new direction for research in the field of LD converter control. No similar model has yet been proposed for decarburization rate during silicon blow and for temperature control.

### III. CONCLUSION

Computer control is a must for precise control of LD converter. One important step in any computer control project is the development of static and dynamic models of the process. Dynamic models proposed till today can be classified into three categories viz., models based on reaction mechanism, measurement based models and models using modern control engineering techniques. There has been a very limited work in the application of modern control theory to LD converter control. However, future prospects are bright since several researchers have started appreciating its need.

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SLAG BALANCE

$$\text{weight of slag} = \left( \begin{array}{l} \text{weight of} \\ \text{lime} \end{array} \right) + \left( \begin{array}{l} \text{weight of oxidised} \\ \text{metalloids from hot} \\ \text{metal and iron ore} \end{array} \right) + \left( \begin{array}{l} \text{weight of} \\ \text{iron oxides} \end{array} \right) + \left( \begin{array}{l} \text{weight of} \\ \text{refractory lining} \\ \text{dissolved} \end{array} \right) + \left( \begin{array}{l} \text{weight of slag} \\ \text{remaining from} \\ \text{previous blow} \end{array} \right)$$

LIME BALANCE (derived from the basicity relation)

$$\text{(basicity)} = \left( \begin{array}{l} \text{weight of basic slag} \\ \text{components (lime and} \\ \text{dissolved lining)} \end{array} \right) \div \left( \begin{array}{l} \text{weight of acidic slag} \\ \text{components (silicon and} \\ \text{phosphorus oxides)} \end{array} \right)$$

WASTE GAS BALANCE

$$\text{(weight of waste gas)} = \left( \begin{array}{l} \text{weight of carbon} \\ \text{oxides evolved} \end{array} \right) + \left( \begin{array}{l} \text{weight of fume} \\ \text{blown from vessel} \end{array} \right)$$

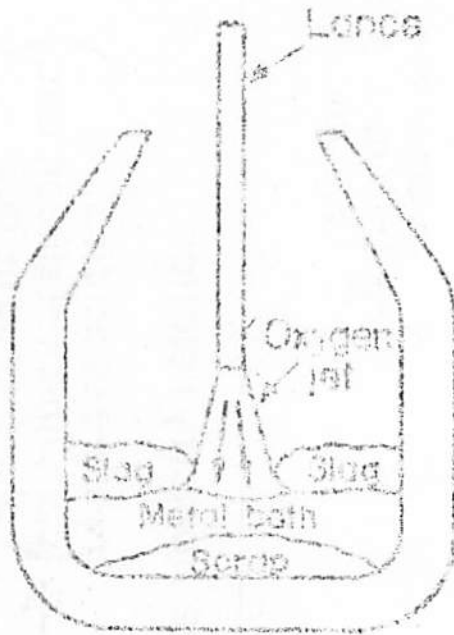


FIG. 1. LD CONVERTER

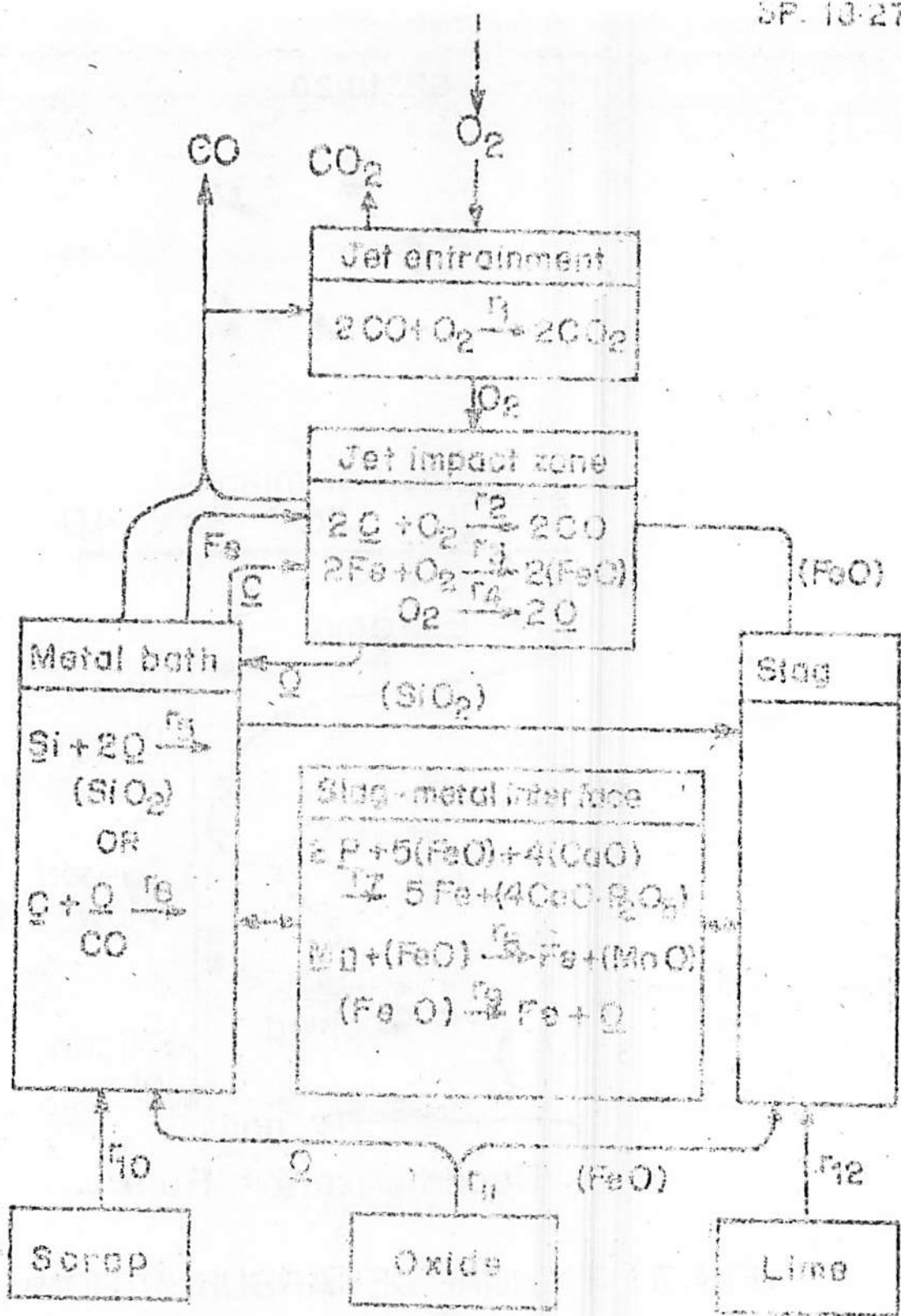


FIG. 2. SCHEMATIC DIAGRAM OF THE BASIC OXYGEN FURNACE SIMULATION

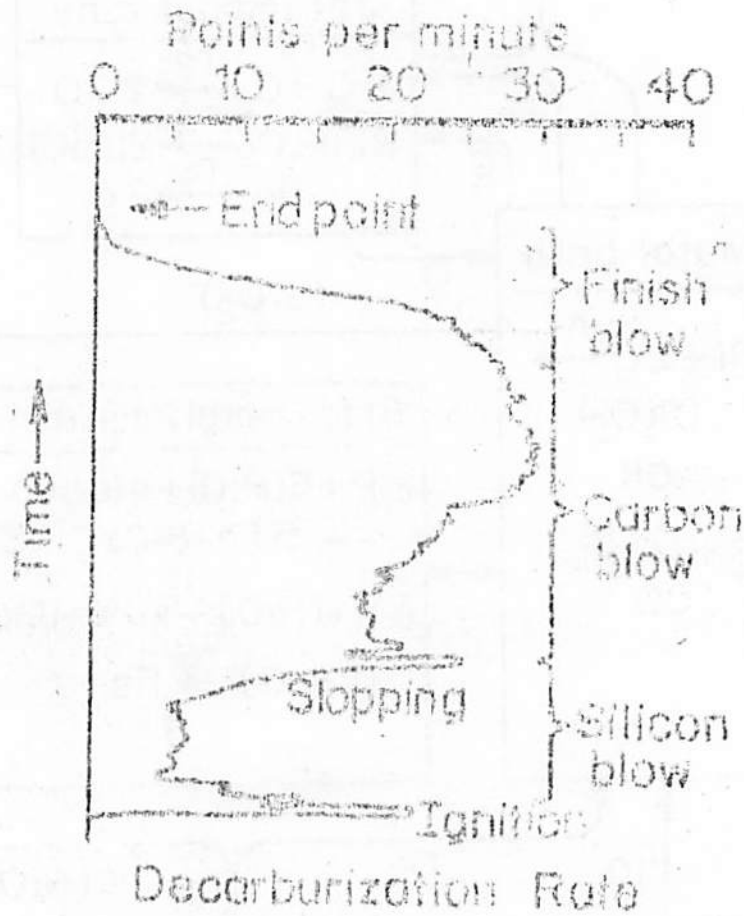


FIG. 3. TYPICAL DECARBURIZATION RATE CURVE

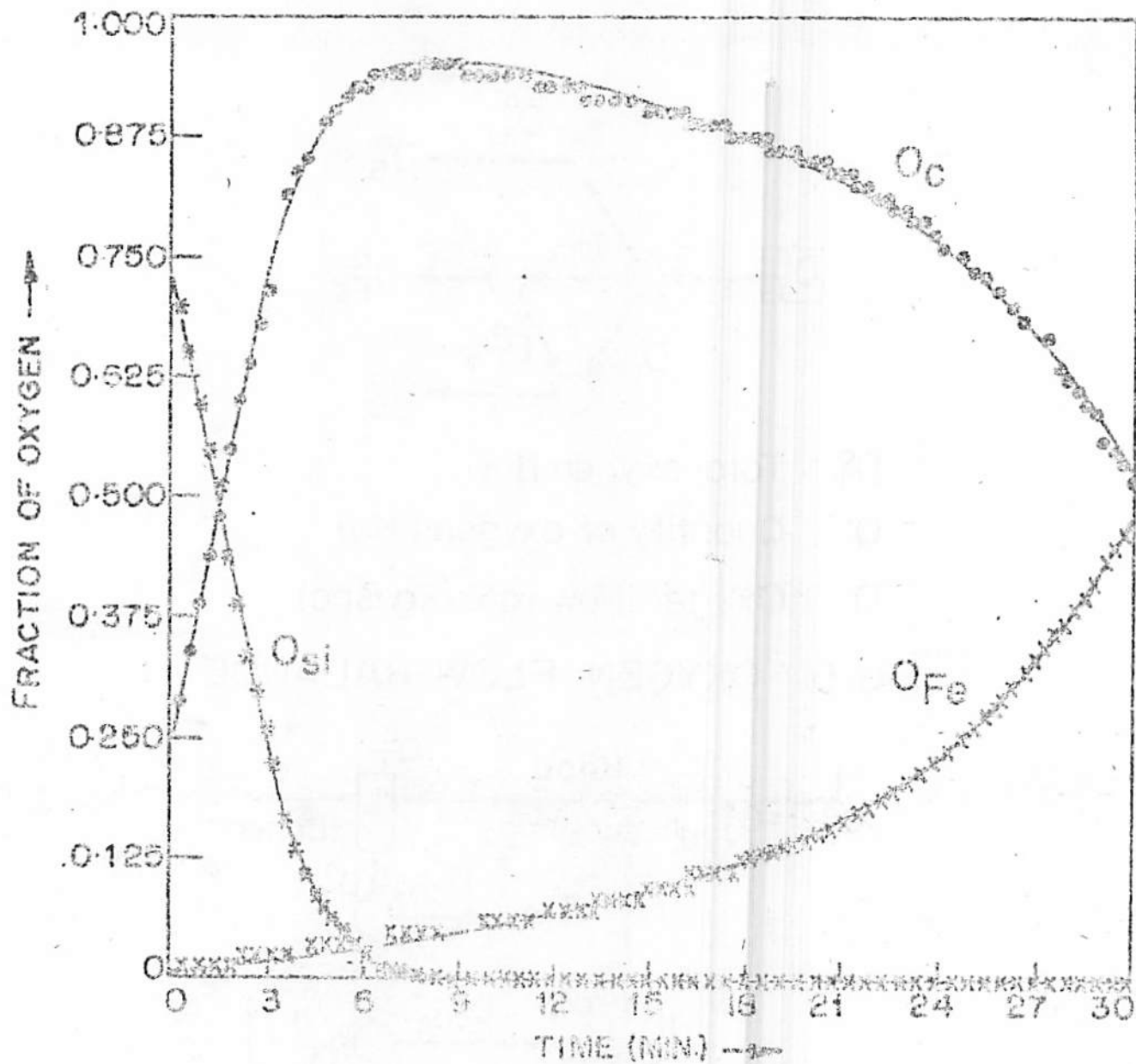
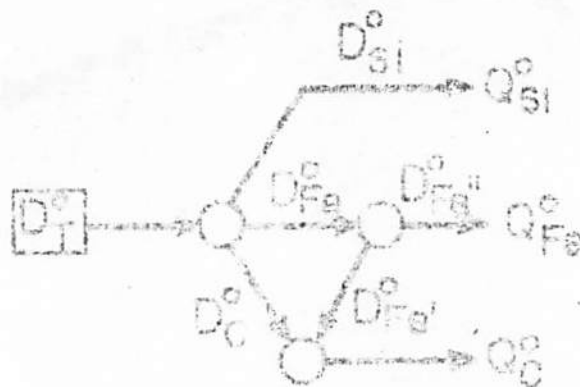


FIG. 4. FRACTIONS OF BATH OXYGEN USED FOR CARBON (●) SILICON (\*) AND IRON (x)



- $D_T^o$  : Total oxygen flow
- $Q$  : Quantity of oxygen ( Kg)
- $D$  : Oxygen flow rate (kg/sec)

FIG. 5. OXYGEN FLOW BALANCE

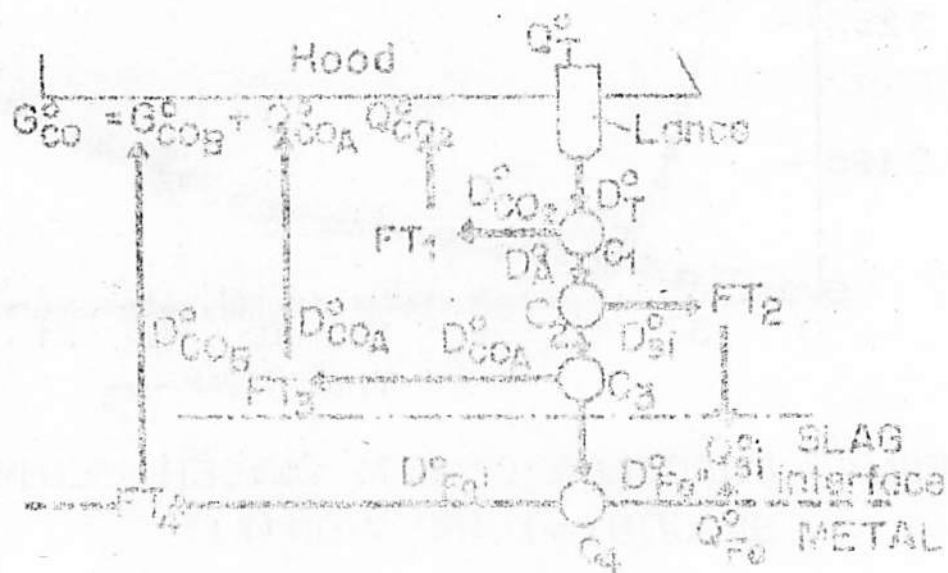


FIG. 6. OXYGEN DISTRIBUTION CENTERS AND OXYGEN TRANSFER FUNCTIONS PROPOSED BY NILLES AND DENIS

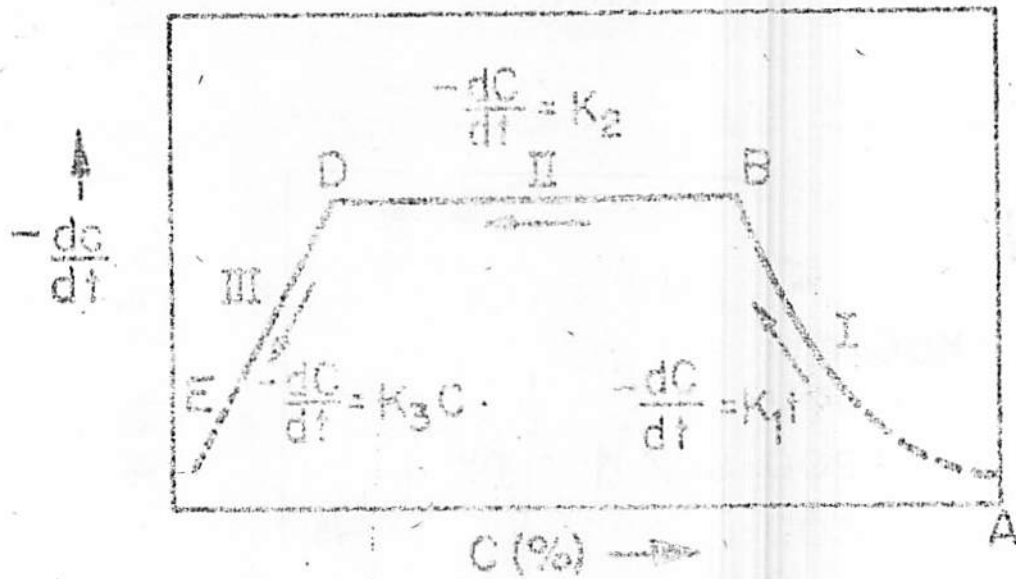


FIG. 7. DECARBURIZATION MODEL

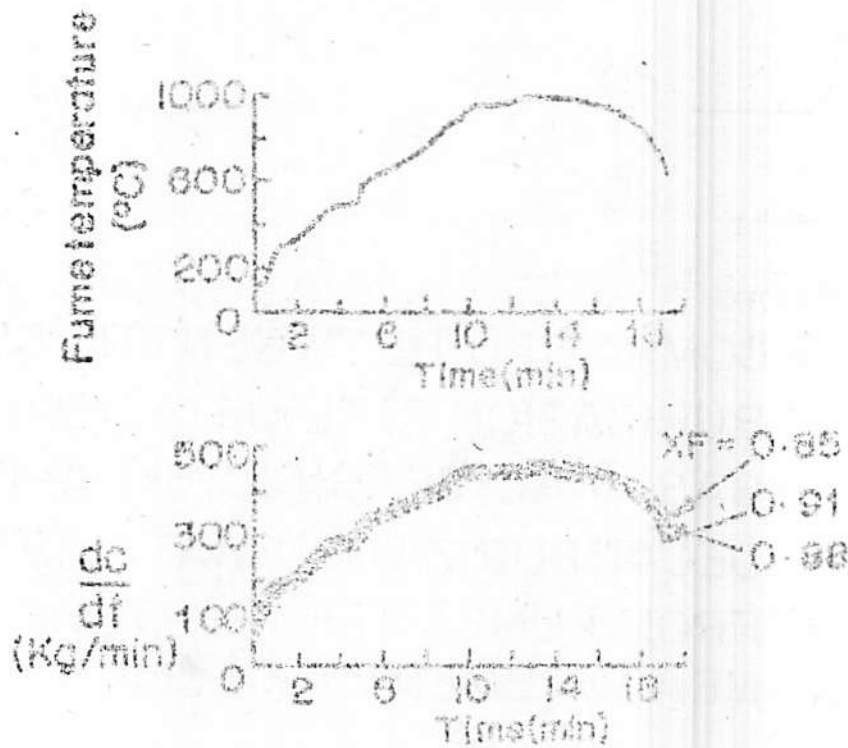
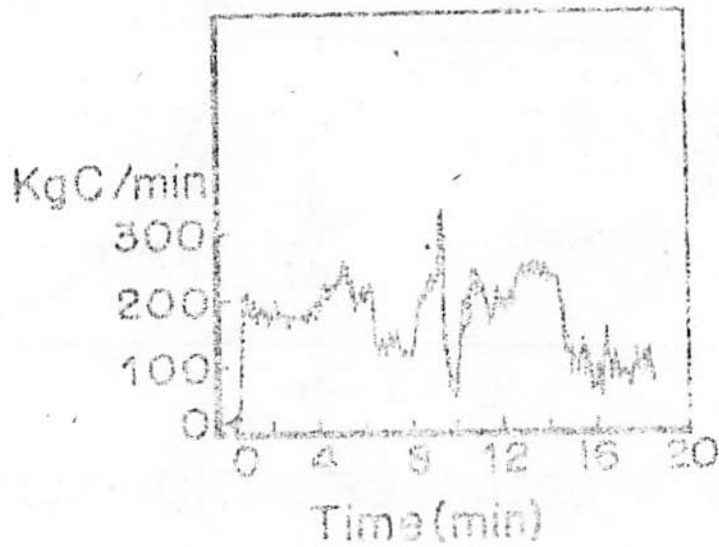


FIG. 8. RELATION BETWEEN FUME TEMPERATURE (TF) AND DECARBURIZATION RATE,  $dc/dt$ .





———  $\frac{dC}{dt}$   
 - - -  $\frac{d\hat{C}}{dt}$

FIG. 9. COMPARISON BETWEEN THE DECARBURIZATION RATE OBTAINED FROM GAS ANALYSERS ( $\frac{dC}{dt}$ ) AND THE DECARBURIZATION RATE ESTIMATED FROM FUMES TEMPERATURE MEASUREMENT ( $\frac{d\hat{C}}{dt}$ ).

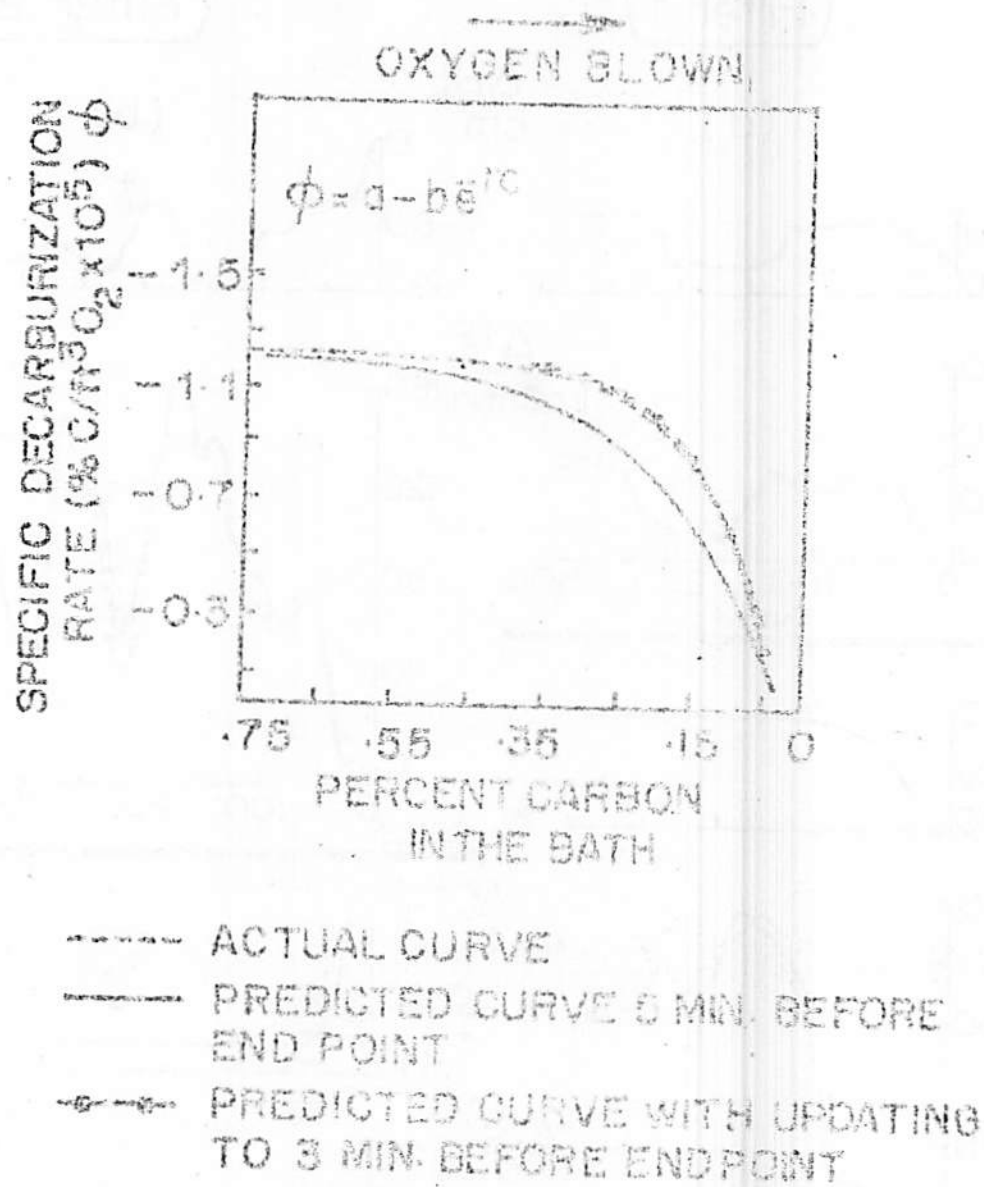


FIG.10. ACTUAL AND PREDICTED REFINING CURVES

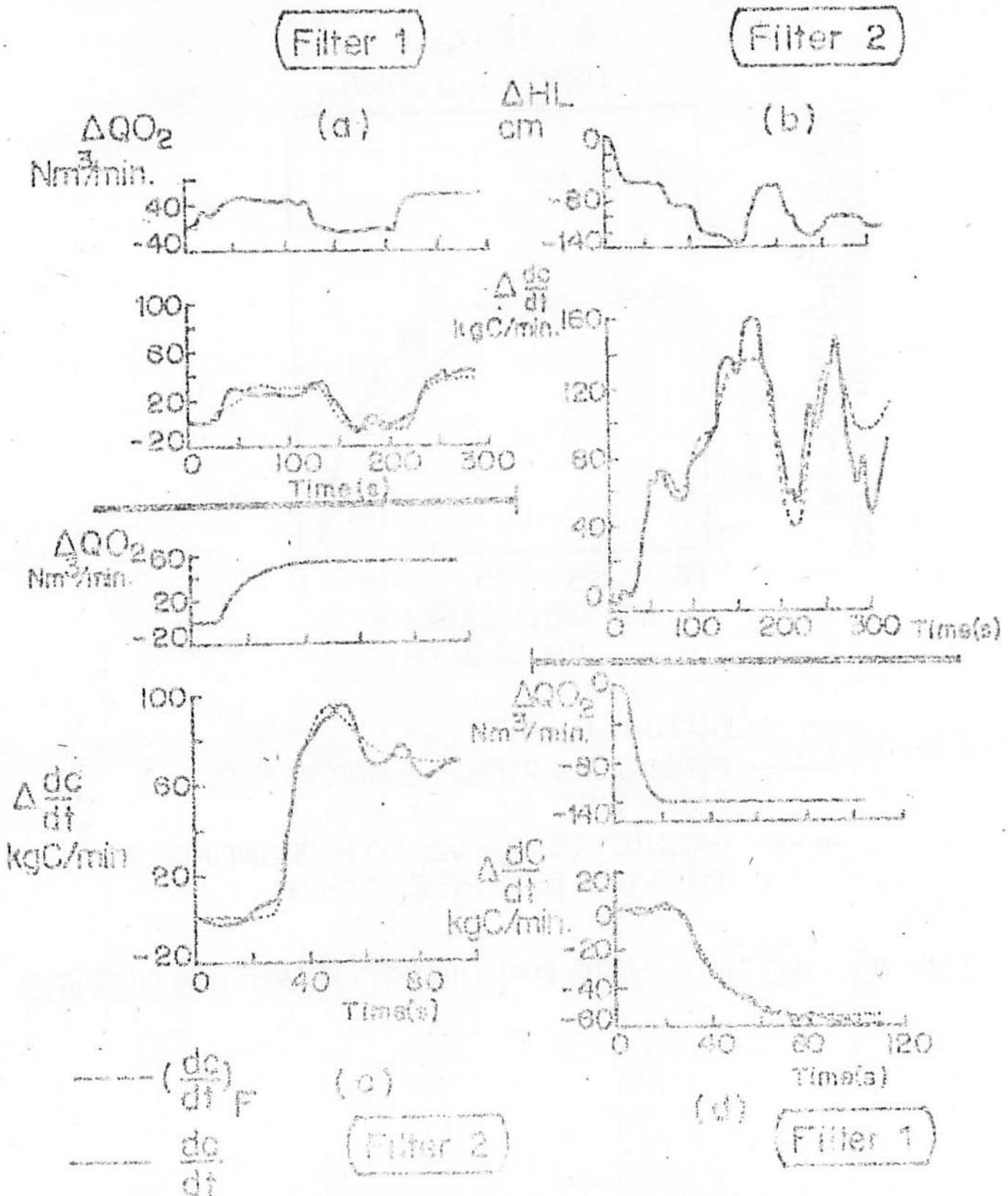


FIG. 11. COMPARED EVOLUTIONS OF THE TRUE DECARBURIZATION RATE  $dc/dt$  AND OF THAT  $(dc/dt)_F$  OBTAINED BY ADAPTIVE FILTERING AT DIFFERENT PERIODS OF THE BLOW.

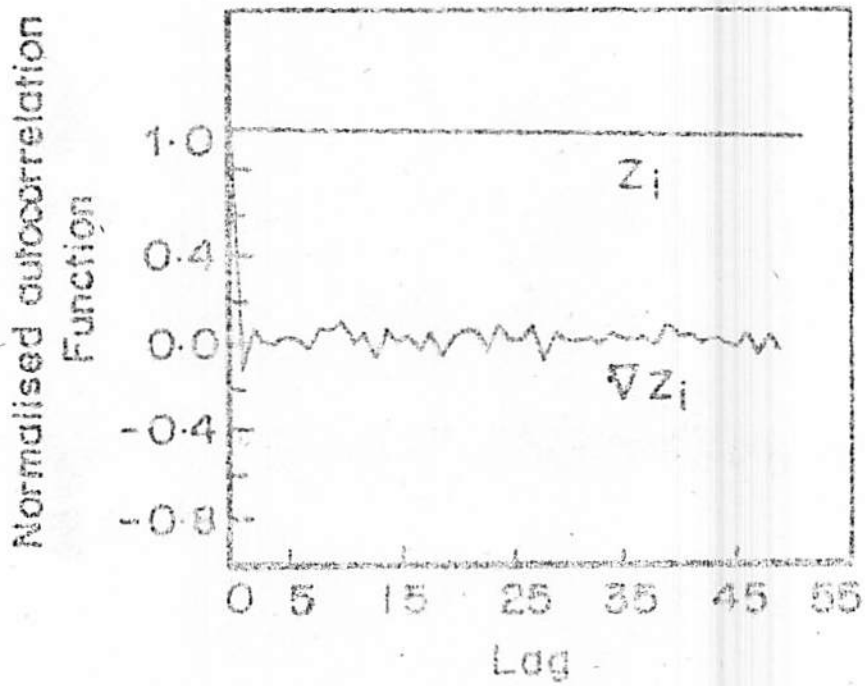


FIG.12. AUTOCORRELATION FUNCTION OF  $z_i$  AND  $\nabla z_i$