COMPUTER CONTROL OF LD CONVERTER PROCESS OF STEELMAKING

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By

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ABSTRACT

An LD converter can produce 200-400 tons of steel in 20-25 minutes. However, the fast dynamics of the process makes accurate manual control very difficult and necessitates computer control.

In this report, first a study of LD process dynamics has been presented; the influences of various inputs, disturbances and control variables on control objectives have been clearly identified.

A critical study of 14 different static and dynamic control schemes/models of LD converter has been done.

The most important goal attained in this work is a dynamic digital simulation of LD converter on IBM 360/44. A special integration algorithm requiring only 5 multiplication and 3 addition operations with very little memory requirement and computation time has been developed to solve the differential equations.

A timer routine has been used to find the time required for each section of the program. In its final form, the program takes merely 20-25 seconds for complete simulation of 30 minutes heat (one blowing operation). However, an additional one minute is required to plot the results in an elegant graphical form, if desired. The graphs show complete time history of bath composition, temperature, oxygen distribution (among C, Si and Fe), weight of slag and its constituents. Complete details of all simulation routines and derivation of integration algorithm are included in this report.

Finally a study of instrumentation and various LD computer control systems has been presented. Therein the need for computer control, various digital computer functions and subsystems to be interfaced with it have been discussed in detail. The type of computer, peripherals and sensors required have been briefly discussed. A list of new sensors proposed till todate has also been included.

In a nutshell, this work includes several diversified aspects of "computer control of LD process of steelmaking", such as metallurgical, chemical, control, instrumentations, computer hardware and computer software.

CONTENTS

* * *

CHAPTER - 1

INTRODUCTION

Mankind has made several technical advances during past few decades. The two most important being industrial revolution and invention of digital computer. The first one refers to the invention and construction of equipment that produces large quantities of specialized products from raw materials and energy. Examples are iron and steel complexes, petroleum refining complexes, paper making plants, ammonia plants etc. These complexes are large and variable enough to require some form of 'Control'. In slightly more than a decade, the digital computer has been widely adopted so that its arithmetic and logical power can be used to provide the 'control' required to operate today's complex processes efficiently.

Steel industry is the backbone of all other industries all over the world including India. The rapid Industrial revolution in our country after independence has tremendously increased the demands for steel. The National Council of Applied Economic Research New Delhi has estimated finished steel demands in India at 15.3 million tons by 1980 and 24.65 million tons by 1985. But many experts feel that it is necessary to plan for a minimum per-capita of 100 kg for a probable population of 1000 million. That would mean a total installed capacity of 100 million tons by 2000 A.D. [1]. Such large demands necessitate the use of a fast steel making process like LD converter which can produce 200-300 tons of steel in barely 20-25 minutes.

LD process of steel making has taken its name from the towns Linz and Donawitz of Austria where commercial operations of the process was first realized in 1952 at the works of Vereinigte Osterreichische Eisen and Stahlwerke (VOEST) and Osterreichische Alpine Montangesellschaft. Since then several converters have been installed all over the world. Today a major portion of the total steel output of the world is being produced by LD converter. A primary reason for the enthusiastic adoption of the LD converter by the world steel industry has been its ability to operate at extremely high refining rates. These converters have brought down the time needed for a single operation of steelmaking (one heat) from about 8-10 hours in the conventional open hearth process to barely 25 minutes.

India, though an early starter in the field of LD converters, with a 50 ton LD converter in Rourkela installed in late fiftees, has since lagged behind. At present only Rourkela plant of Hindustan Steel Ltd and Bhadravathi Plant of Mysore Iron and Steel Company are using LD converters. However, all new plants including Bokaro will use LD converters. In Bokaro and in expansion plants (Bhilai, TISCO etc) LDs of 200 tons and above are planned. 100-250 tons LD converters are to be installed at Vizag and Hospet.

India, could not exploit the new techniques of steelmaking for lack of an intensive research program. The high rates of LD converters, which make the process so attractive from production view point, have however rendered the manual control difficult.

The stochastic nature and the large capacity of the process further aggrieved the problem. The automation of LD converters is therefore a very promising direction for computer control engineers.

1.1 Phases of the Project:

This project was carried out in several phases as discussed below:

1. Study of Process Dynamics: The first phase in any computer control project should be the study of the process. This includes the study of its inputs, outputs, disturbances, control variables and control objectives. In the case of LD converters, process study required a working knowledge of chemical and metallurgical principles. Chapter 2 presents an essence of these studies.
2. Study of Process Models & Control Schemes: The second phase of project is the critical study of models and control schemes for LD converters proposed all over the world. Models are mathematical relations among variables in the process and form the heart of any control scheme. Also models are useful for simulation of the process and for testing of control algorithms. A critical study of 14 different models is presented in Chapter 3.

3. Process Simulation: The two most important requirements for a computer process control projects are the computer and the process to be controlled. In the absence of actual process, a common approach is to simulate the process on a hybrid/digital computer and to use the simulated model for testing control algorithms even when the

process is available, the simulation forms an essential step in order to avoid the risk involved in directly applying the untested control algorithms to actual process which may damage the process. With this in view a digital simulation of the process was done on IBM 360/44 at Indian Institute of Science. A special integration routine has been developed for this purpose. The similation provides a time history of important key variables like bath composition, bath temperature, oxygen distribution, slag weight and its composition. Details of simulation are described in Chapter 4.

4. Study of Computer System and Instrumentation: Lastly a study of instrumentation and various LD computer control systems has been presented in Chapter 5. Therein, the need for computer control, various digital computer functions and subsystems to be interfaced with it have been discussed in detail. The type of computer, peripherals and sensors required have been briefly discussed. A list of new sensors proposed has also been included.

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CHAPTER-2

STUDY OF PROCESS DYNAMICS.

A computer control project cannot be successful without a deep study of process dynamics. H.W. Meyer, the Vice President of Research and Development at Jones and Laughlin Steel Corporation remarks [1] that "For a very long time steel makers have successfully utilized processes which they did not properly understand. A melter was some one who had learned to ride a steel making bicycle and he controlled the steel making process with broadly the same skills utilized to control a bicycle: intuition, experience and a feel for what he was doing. In the middle 1950's, mathematicians with computers appeared and they promised marvels, but it was soon proved that a computer cannot rider a bicycle. The oxygen steel making bicycle proved quite difficult even for the most experienced melters because it went about 10 times faster than anything on which they had been taught to ride and there was no time to stop for check points along the way". This clearly dictates that study of process dynamics should form first step in a computer control project. A brief description of process equipment, operation, principle, control variables and control objectives is presented in this chapter.

2.1. Process Description:

2.1.1. Equipment: The process is conducted in a cylindrical steel vessel lined with refractory as shown in Fig.2.1. The vessel is equipped with drives to rotate it about the horizontal axis for charging, tapping and sampling operations. Vessel capacities range from 50 300 tons. The charge is refined by a high velocity oxygen jet from a water cooled lance.

2.1.2. <u>Operation:</u> The vessel is tilted and scrap and molten pig iron (from blast furnace) are charged. The steel scrap forms 20-30% by weight of total charge. The vessel is then rotated to a vertical position, the lance is lowered and oxygen blowing commenced. After a few seconds, ignition takes place.

As the blowing proceeds, more lime (or limestone) and ore is added if necessary. When it is judged that the specification is being approached, the vessel is turned down, samples taken for analysis and the temperature recorded. Depending upon the results, further blowing time will be arranged or more coolant and lime added if necessary.

When the steel is ready for tapping, in order to kill (remove) dissolved oxygen, deoxidizing agents may be added in the vessel, before tapping or into the laddle during tapping. The vessel is turned and steel is drained through the side hole. Later, the slag is poured in to slag boxes.

2.2. <u>Chemistry of the Process</u>:

2.2.1. Reactions: The high velocity oxygen jet reacts with the impurities and refines the iron according to the following reactions:

$$C + O = CO$$

$$Si + 2O = Si\,O_2$$

$$Mn + O = MnO$$

$$2P + 5O = P_2O_5$$

$$Fe + O = FeO$$

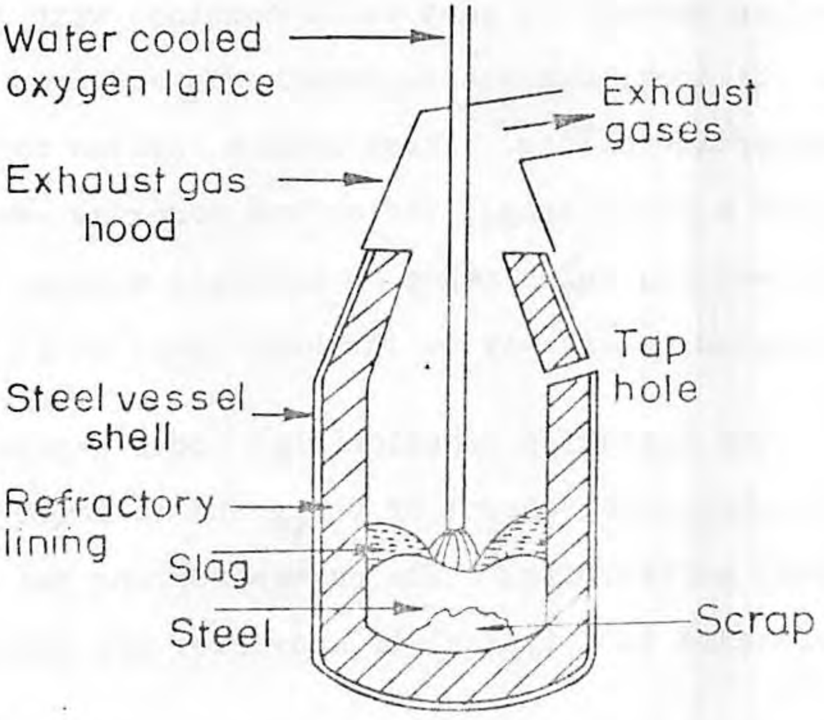

FIG.2.1: SCHEMATIC DIAGRAM OF A BASIC OXYGEN STEEL-MAKING VESSEL

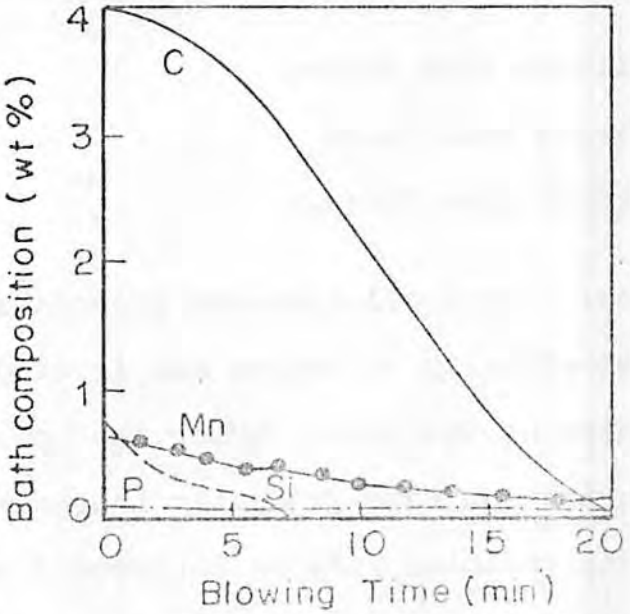

FIG.2.2: CURVES SHOWING THE REMOVAL OF ELEMENTS IN THE LD PROCESS

The carbon is oxidized to CO and is exhausted through the waste gas system. A part of CO combines with jet oxygen to form CO_2. Silicon, Manganese, Phosphorus and Iron are oxidized to the respective oxides. These acidic oxides combine with the lime to form a basic slag. The carbon monoxide evolution produces a stirring action, which makes an intimate mixture of slag and metal and contributes remarkably to the high speed of LD process.

The oxidation reactions that occur generate enough heat to melt a substantial amount of scrap and to raise the temperature of resultant molten bath. The curves showing the removal of various elements in a typical LD converter are shown in Fig 2.2.

2.2.2. Phases in Refining Process: The decarburization rate i.e. the rate of removal of carbon ($-\frac{dc}{dt}$) varies during the blow as shown in Fig. 2.3 [2] .The total refining period can be divided into three phases corresponding to dominant conditions.

i. Silicon Blow Phase.
ii. Carbon Boil Phase
iii. Finish Blow Phase.

i. Silicon Blow: Among all elements present in the furnace, silicon has the highest affinity to oxygen and is oxidized first i.e. during first few minutes of the blow. During the period called 'silicon blow', decarburization rate gradually increases and FeO builds up in the slag. The refining path is influenced by the oxygen flux across the gas metal interface. High oxygen flux produces undesirable path due to too high an initial rate of decarburization.

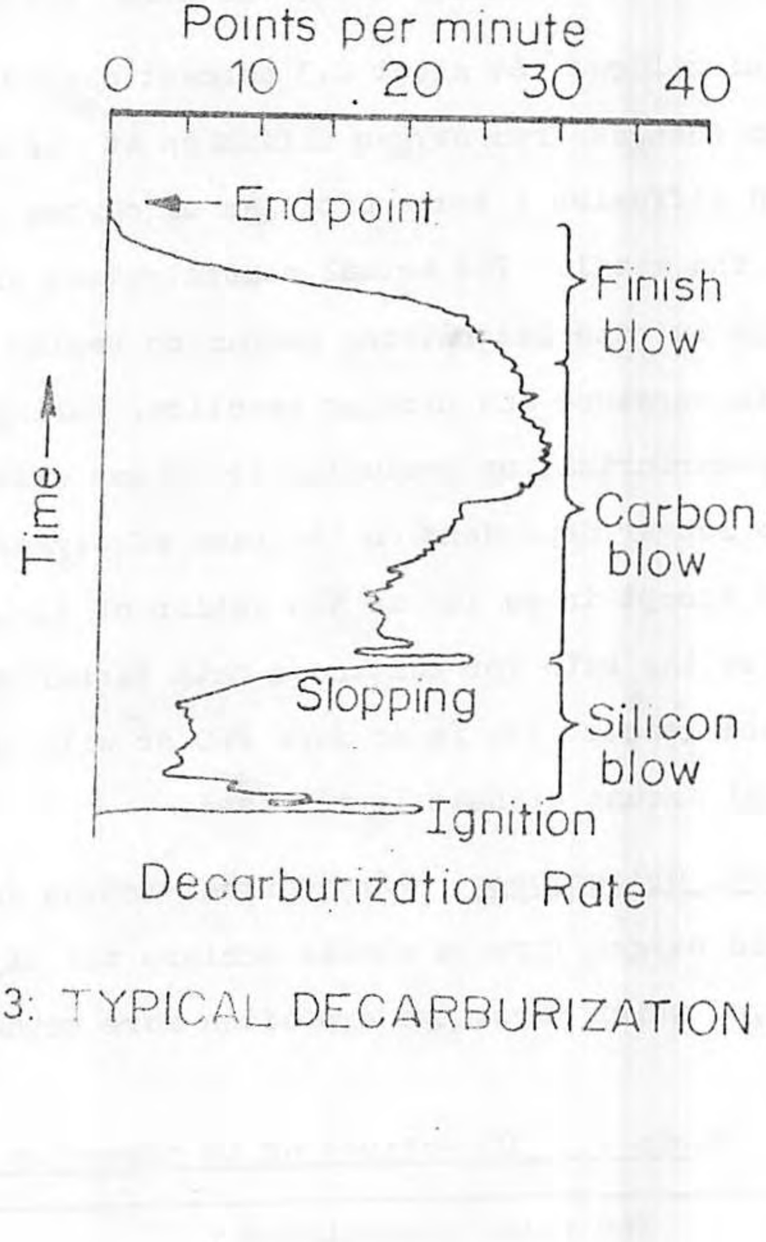

FIG. 2.3: TYPICAL DECARBURIZATION RATE CURVE

ii. Carbon Boil: As the refining proceeds and after the oxidation of metalloids, decarburization reaches a steady state. The rate determining mechanism is again the oxygen diffusion at the gas metal interface. The carbon monoxide formed by oxidation of carbon, bubbles out of the molten metal and produces a stirring action similar to boiling, hence the name' carbon Boil'.

iii. Finish Blow: At about 0.3 percent carbon the rate determining mechanism changes from oxygen diffusion at gas metal interface to carbon diffusion (transportation of carbon atoms to reaction zone) in the metal. The actual concentration of carbon at which the change in rate determining mechanism begins to occur is dependent on temperature and blowing practice. During this phase the rate of decarburization gradually decreases with decrease of carbon and is no longer dependent on the rate of oxygen supply through the lance except in so far as the action of the oxygen jet supplies momentum to the bath for continued bath turbulence. The excess oxygen used reacts with Fe to form FeO or with CO to form CO_2 and a substantial amount of heat is released.

2.3 Control Objectives: Any control scheme (manual or automatic) for a basic oxygen furnace should achieve the objectives shown in Table 2-1, of which first two are often more emphasized than others:

Table 2.1 Objectives of LD converter Control.

1. End point composition
2. End point temperature
3. Slag control
4. Control of furnace ejection.
5. Minimum time of blow.

2.3.1 End Point Composition: All properties and characteristics of steel are affected directly or indirectly by its chemical composition. Close control over such properties of steel as hardness, hardenability, ductility and tensile strength requires a close control over its composition. Table 2.II lists the principal functions of elements (when present in proper proportion) in steel. [3]

Table 2.II: Principal Function of Elements in Steel.

Elements	Principal Functions.
Carbon	1. Increases Hardness and Hardenability.
	2. Source of graphite formation in graphitizing steel. (Graphitizing steel has a porous structure useful for holding lubricant in bearings).
Silicon.	1. Deoxidizes steel.
	2. Increases resistance to oxidation.
	3. Improves electrical properties of magnetic steels.
	4. Increases hardenability.
	5. Aids graphitization of steel.
	6. At $Si \geq 0.4\%$ there is a marked decrease in ductility.
Manganese.	1. Increases Hardenability.
	2. Counteracts hot short or brittleness effect of sulfur.

Phosphorus	1. Improves machinability in free machining steel 2. Strengthens low carbon steel. 3. A large percentage will decrease ductility.
Sulfur	1. When present as FeS, it reduces hot working properties. 2. Improves machinability in free machining steels.

Of all the elements, carbon is most important constituent and should be reduced to a proper amount. This is because the elemination of other elements is closely related to the carbon control both by virtue of the fact that carbon determines the timing of the refining period and because of the influence of carbon on phosphorus and sulfur control and manganese recovery.

2.3.2 End Point Temperature: Regulation of temperature of steel bath is one of the most difficult and important function of BOF control system. Not only does the temperature influences the chemistry of refining reaction and the efficiency of alloys and deoxidizers, but precise control of tapping temperature is necessary also to obtain clean pouring and stripping together with best ingot structure, cleanliness and surface quality. A variation of as little as ± 10 °C from the optimum teeming temperature may at times be very evident in the quality of the product. Moreover a higher temperature may result in earlier deterioration of refractory lining.

2.3.3 Slag control: The need for slag control has been recognized only recently [4]. Formation of slag is the means of disposal of all the impurities, save carbon, which are removed from the charged materials in refining the steel. Therefore slag must be suited to receiving and retaining as much as possible of undesirable elements with minimum loss of iron and useful alloying elements.

Subject of slag control includes not only the adjustment of the composition of slag but also of its relative weight in terms of percentage of metal bath weight. The elements forming strongly acidic slag constituents SiO_2 and $P_2 O_5$ must be balanced by CaO the principal basic material. Thus if the phosphorus or the silicon content is high, it is necessary to increase lime input or to remove some of the silica in a preliminary or flush slag in order to maintain basicity desired in the final slag.

2.3.4. Control of Furnace ejections (smooth refining path):

There are two kinds of furnace ejections: splacing and slopping. Splacing or sparking is the ejection of small droplets of metal. This causes most serious loss to the yield and appears to be associated with lance heights which are too low in the early part of the blow and with unusually high impact pressures at the metal surface.

Slopping is the violent ejection of slag from the vessel. This also lowers the yield and curtails the production rate of the shop because of the time which must be taken to clean up the vessel lip ring.

Slopping is caused by a reaction at the slag metal interface between bath carbon and slag oxygen. Excess slag oxygen can come either from a large lance height and/or low oxygen flow rate or from excessive blowing rates during the silicon blow. Because of silicon's inhibiting effect on carbon oxidation, no slopping will occur as long as silicon is present in the bath. As a result, slag oxygen will increase creating an unstable situation, until the silicon is oxidized, then slopping occurs and is often reinforced by concurrent carbon boil, which brings large quantities of carbon rich iron to the slag metal interface.

A study of many hundreds of heats at J & L * [5] has shown that if slopping is to be avoided, decarburization curve during the early stages of refining should increase smoothly with absence of plateau region in the decarburization curve. Such plateau regions during transition period between silicon blow and carbon boil phase are indicative of the build up of appreciable quantities of FeO in the slag. At a later time reversion of FeO occurs and the resultant violent reaction can coincide with the slag's being in a viscous state and having a low basicity ratio.

Fig 2.4. shows three decarburization curves during the early part of the blow. In curve A slopping was extremely bad and the decarburization rate actually decreased prior to slopping. In both curves A and B severe slopping was accompanied by a sudden rise in decarburization rate after the plateau regions. Curve C is an average curve for a number of heats which had good blowing performance with little or no slopping.

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* 'J & L' stands for Jones & Laughlin Steel Corpn. U.S.A. .

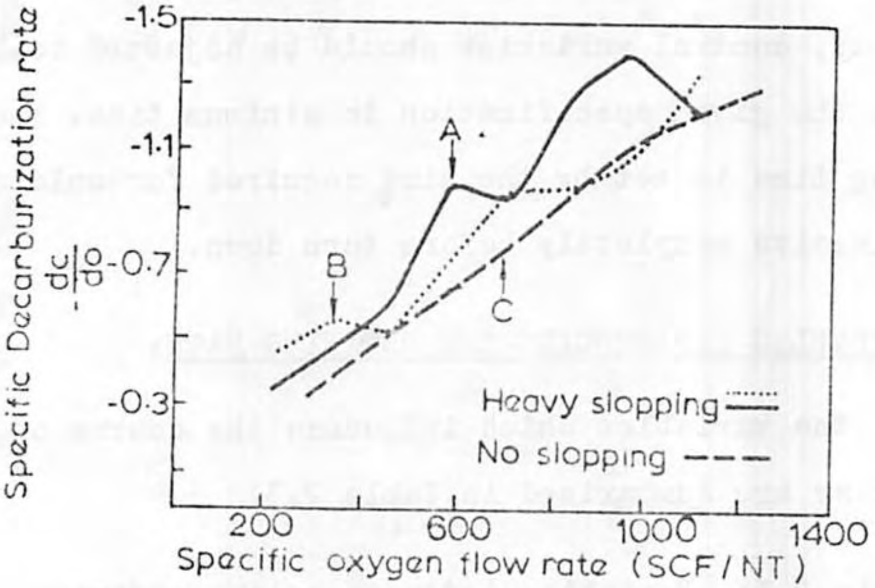

Fig.2.4 Refining curves during critical slag formation period.

Thus the control of sparking and slopping demands a continuous (or dynamic) control of decarburization path through out the blow.

2.3.5. Minimum time of Blow: The time per blow, decides the total yield over a given period say an year. Hence for maximum productivity, control variables should be adjusted to bring the heat on to the given specification in minimum time. The lower limit for blowing time is set by the time required for cold scrap and time to dissolve completely before turn down.

2.4 VARIABLES INFLUENCING THE REFINING PATH:

The variables which influence the course of refining of LD process are summarized in Table 2.3.

Table 2.3: Variables influencing the refining path.

1. Hot Metal	(a) Weight
	(b) Temperature
	(c) Composition
2. Slag Forming addition	(a) Quantity
	(b) Chemical and Physical characteristics
	(c) Time added in relation to progress of heat.
3. Other charged materials	(a) Weight
(i) Scrap	(b) Composition
(ii) Ore	
(iii) Cold pig iron.	(c) Size
	(d) Disposition in the furnace.
4. Refractory	(a) age
	(b) Thermal properties
	(c) rate of wear.
5. Oxygen Flow rate as determined by.	(a) Nozzle diameter
	(b) Nozzle shape
	(c) Oxygen pressure.
6. Lance height.	

It is evident that among the variables mentioned in Table 2.3 and discussed below, refractory wear, size and disposition of scrap are in no way under our control and can not be used for control purposes. Nevertheless these have been discussed here to emphasize the fact that they should be recognized as unmeasurable disturbances in the modelling and control of the process. Variables like temperature and composition of hot metal or other charged materials are most often specified or fixed by other processes and can not be varied. They can be treated as measured disturbances to the process. The weight of hot metal, slag forming additives and other materials are, of course, under our control but once charged, they can not be changed hence they are useful only for static control (See next chapter on modelling) For dynamic control purposes only lance height, oxygen flow rate and weight and and timing of ore/lime additions can be used as control variables. Fig 2.5 gives a simplified schematic of LD process variables.

2.4.1 Hot Metal: The temperature, weight and composition of the metal basically determine the heat which, under appropriate condition will become available to the process.

2.4.2. Slag forming additions : It is necessary that the slag be basic in nature. Lime balances the strongly acidic constituent of slag such as SiO_2 and P_2O_5. Thus if the phosphorus or silicon content is high, it is necessary to increase lime input in order to maintain the desired basicity in the final slag.

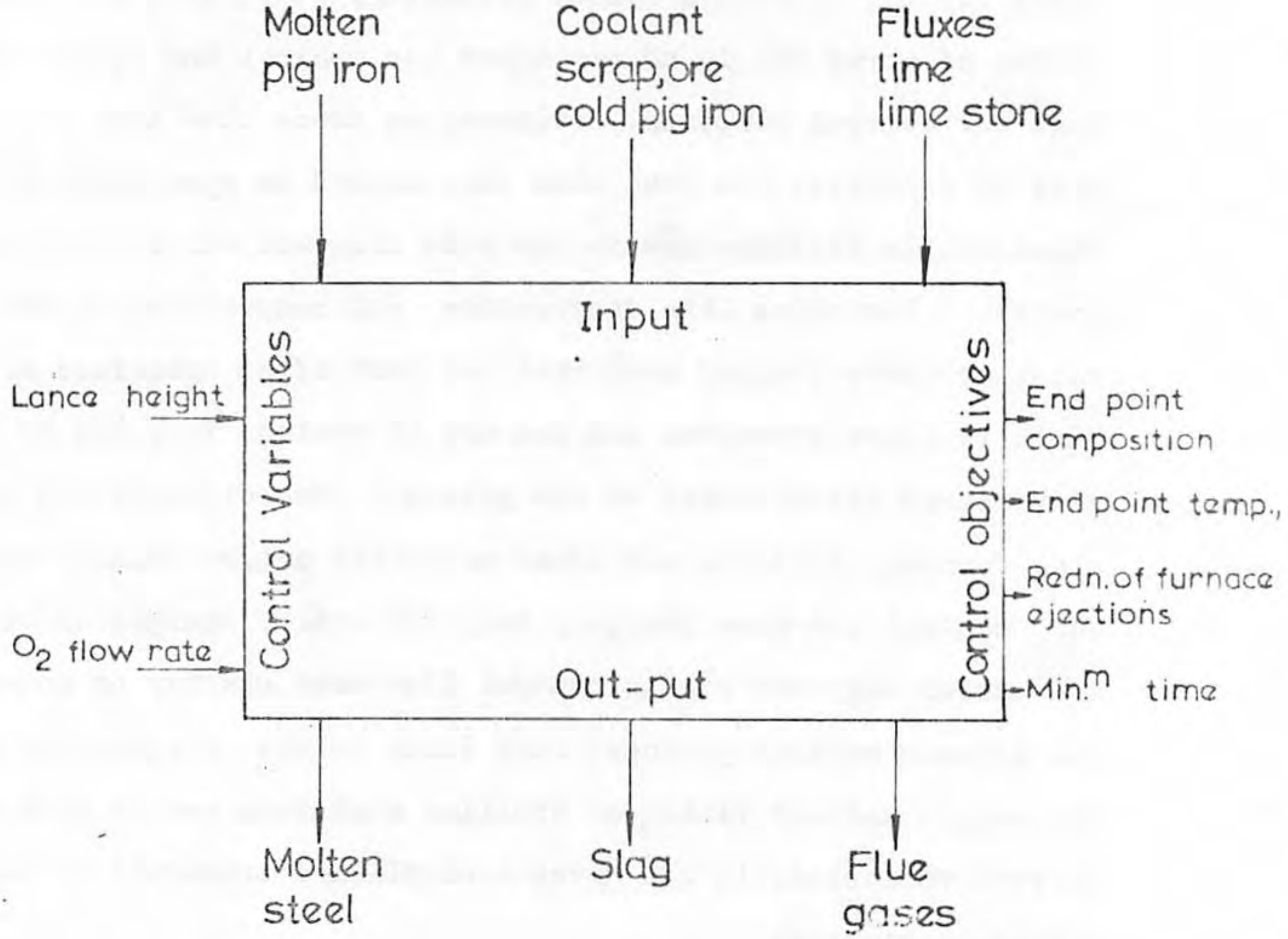

Fig. 2.5 LD PROCESS VARIABLES.

If lime stone is used as a flux instead of lime, it imparts a stirring action by vigorous evolution of carbon dioxide during the lime boil. It also acts as a coolant due to the heat required for driving off the CO_2 evolved and for endothermic (heat absorbing) decomposition of lime stone.

2.4.3 Other charged Materials (Coolants): When scrap is used as a coolant, there is little rise in metal temperature during blowing until it has melted, after which, the temperature rise is progressive. The size and physical disposition of scrap within the vessel affects the degree to which the scrap acts as a baffle and interferes with the development of bath turbulance. This adds to stochatic nature of the process.

When ore is added in place of scrap, the initial cooling effect is similar to that of scrap provided thermally equivalent quantities are added. In this case, however, in spite of adding ore to the charge the initial enrichment of FeO in the slag is significantly less while slag formation takes place earlier in the blow. The rate of fall of elements to be eliminated is more rapid in relation to carbon content of the bath than when scrap cooling is used.

The effect of adding cold pig iron is essentially same as that of adding scrap.

2.4.4 Refractory: The inner shape of lining of a vessel changes considerably during one campaign of lining. Katsura et al [[illegible]] have reported that 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 slag, rate of dephosphorization, amount of slopping and particularly the heat loss through the lining. Like scrap size and disposition, this also contributes to the stochastic nature of the process.

2.4.5 Oxygen Flow rate: The nozzle diameter, nozzle shape and oxygen supply pressure determine the oxygen flow rate, which, in turn, determines the refining time and in consequence the time available for the development of necessary reactions. Since the top blown oxygen is almost completely absorbed by the bath, the refining time is limited only by the progress of metal-slag reactions and the need to bring these to a desired nearness to equilibria at the end of the refining process.

Average decarburization rate increases linearly with specific oxygen rate (oxygen flow rate in Kg/min per unit weight of hot metal) as shown in Fig 2.6 . However oxygen efficiency (for carbon removal) decreases.

A very high oxygen flow rate will finish a heat too early resulting in unmelted scrap being left at the bottom. Moreover, a rather steep temperature gradient can be set up between the top and bottom of the bath and a heat brought too rapidly upto tapping temperature, as measured near the surface may be cold at the bottom unless time is allowed to equalize the temperature.

Thus if the oxygen flow rate is steadily increased it eventually passes the optimum for a given vessel and results in increased refractory consumption and decreased metallic yield. The output rate will however increase and an economic balance must therefore be struck for the plant.

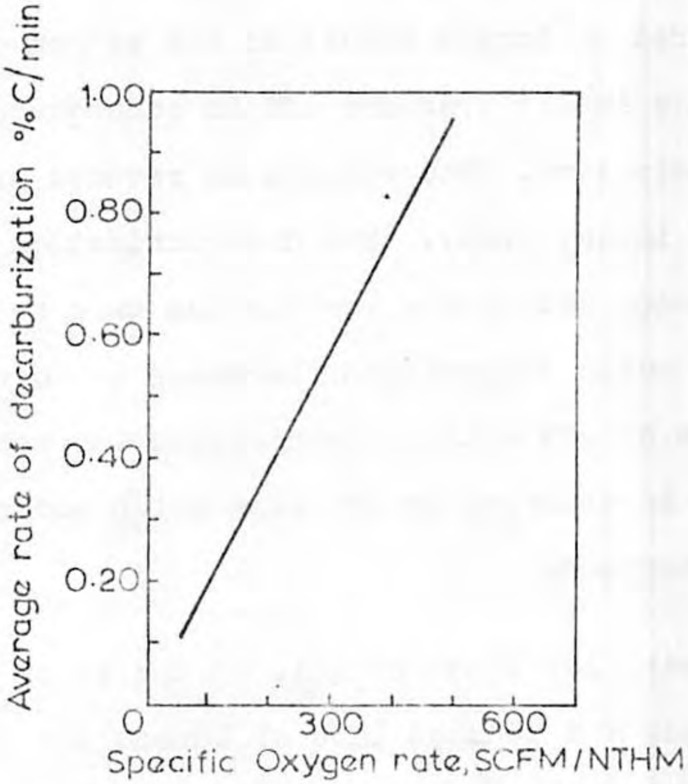

Fig. 2.6 Relation between Decarburization rate and oxyzen flow rate.

2.4.6 Lance height: The course of reactioms is influenced a lot by lance height (distance between nozzle outlet and static position of upper surface of metal bath). With constant oxygen supply pressure (and hence flow rate), the greater the lance height the greater the area of impact circle of the oxygen on the bath and the smaller the impact pressure and in consequence lower the degree of penetration. This results in reduced oxygen flux (flow rate per unit impact area). Thus decarburization rate as well as oxygen efficiency decreases. The blowing time required for a specified end point composition increases . Moreover, the reduced stirringeffect of jet will further reduce the reaction rate. Most of the oxygen is absorbed by the slag which under certain conditions may lead to slopping.

A very low lance height, on the other hand, may lead to metal sphcing and reduced life of lance. The speed of the carbon removal increases at the expense of phosphorus. One reason for reduced dephosphorization is high finishing temperature.

Thus the objective of a good lance practice should be to promote good slag formation, to protect lance, to have high oxygen efficiency and to ensure that the bottom is clean (no unmelted scrap) at the end of the blow. Slag formation is encouraged by a higher lance position. The higher the lance, the less the likely-hood of mechanical damage to it from sparking or hitting the scrap pieces protruding from the metal bath surface. On the other hand, bottom cleaning and oxygen efficiency are improved by lower lance position.

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CHAPTER-3

MODELS AND CONTROL SCHEMES.

A mathematical model of a system is defined as a set of equations or a logical and quantitative representation of the inter-relations among the variables of the system. In a sense, the model expresses and summarizes the analytical knowledge about the system [1]

Clearly, a mathematical model of LD converter is a key element in its computer control. The equations which permit the computer to calculate an unmeasured variable like bath carbon content, and the comprehensive set of equations required for optimization of raw material are all expressions of the mathematical model.

The derivation of a satisfactory mathematical model of the process is a crucial and time consuming step in a computer control project and in the case of LD converters it is the inadequacy of the process models which was the principal hindrance to more rapid progress in the application of computer control. This chapter presents a critical study of 14 different models (and control schemes) of LD converter.

LD converter control can be achieved by static control or dynamic control. Static control is the method in which heat balance and material balance in the reaction is assumed and charge calculation (i.e. raw material, scrap weight, and oxygen quantity) is done before blowing. Once the blowing has begun, further adjustments are not made. Whereas, in dynamic control, calculation, adjustments and control are done when the blowing is in progress.

3.1 STATIC MODELS:

Static models also known as 'Charge Control models', 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, [2] 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 in slag, lime, waste-gases, sulfur, phosphorus etc. etc. A simplified description of the equations is given in Table 3.1 [7].

These static models predict the required weight of scrap, lime and oxygen for a given end point temperature and composition. As an example Slatasky's static model is briefly described in Appendix A. 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

TABLE 3-1. THE GENERAL BASIS OF STATIC MODELS.

IRON MASS BALANCE

$$\left(\begin{array}{c}\text{Final weight of}\\ \text{blown metal}\end{array}\right) = \left(\begin{array}{c}\text{weight of}\\ \text{hot metal}\end{array}\right) + \left(\begin{array}{c}\text{weight of}\\ \text{scrap}\end{array}\right) + \left(\begin{array}{c}\text{weight of}\\ \text{iron ore}\end{array}\right) - \left(\begin{array}{c}\text{weight of nonferrous}\\ \text{impurities in hot metal,}\\ \text{scrap and iron ore}\end{array}\right) - \left(\begin{array}{c}\text{iron losses to slags}\\ \text{fume and spillage}\end{array}\right)$$

THERMAL BALANCE

$$\left(\begin{array}{c}\text{heat input from exothermic}\\ \text{reactions (oxidation of}\\ \text{C, Si, P, Mn and Fe}\end{array}\right) + \left(\begin{array}{c}\text{sensible heat in hot}\\ \text{metal and slag remaining}\\ \text{from previous blow}\end{array}\right) = \left(\begin{array}{c}\text{sensible heat in blown}\\ \text{metal, slags, waste}\\ \text{gases and fume}\end{array}\right) + \left(\begin{array}{c}\text{heat used in endothermic}\\ \text{reactions (reduction of}\\ \text{iron ore}\end{array}\right) + \left(\begin{array}{c}\text{heat loses from}\\ \text{vessel mouth}\\ \text{and walls}\end{array}\right)$$

OXYGEN BALANCE

$$\left(\text{weight of oxygen}\right) = \left(\begin{array}{c}\text{weight of oxygen}\\ \text{required to oxidise}\\ \text{hot metal impurities}\end{array}\right) + \left(\begin{array}{c}\text{weight of oxygen required}\\ \text{to form iron oxides in slag}\\ \text{and fume}\end{array}\right) - \left(\begin{array}{c}\text{weight of oxygen}\\ \text{added in combina-}\\ \text{tion with iron ore}\end{array}\right)$$

TABLE 3-1 (contd.)

SLAG BALANCE

$$\text{weight of slag} = \begin{pmatrix}\text{weight of}\\ \text{lime}\\ \text{added}\end{pmatrix} + \begin{pmatrix}\text{weight of oxidised}\\ \text{metalloids from hot}\\ \text{metal and iron ore}\end{pmatrix} + \begin{pmatrix}\text{weight of}\\ \text{iron oxides}\\ \text{dissolved}\end{pmatrix} + \begin{pmatrix}\text{weight of}\\ \text{refactory lining}\\ \text{dissolved}\end{pmatrix} + \begin{pmatrix}\text{weight of slag}\\ \text{remaining from}\\ \text{previous blow}\end{pmatrix}$$

LIME BALANCE (derived from the basicity relation)

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

WASTE GAS BALANCE

$$(\text{weight of waste gas}) = \begin{pmatrix}\text{weight of carbon}\\ \text{oxides evolved}\end{pmatrix} + (\text{weight of fume}) + \begin{pmatrix}\text{weight of lime}\\ \text{blown from vessel}\end{pmatrix}$$

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 charge calculation does not react to the inprocess variations occuring 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 easily achieve the objectives.

3.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 3-II.

Table 3-II - 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	1 6-17
	J & L (Meyer et al)	18-20
Modern Control Techniques Based Models.	CNRM transfer function approach	22
	Walls et al's estimation and filtering approach	23

3.2.1 Reaction Mechanism Based Models: The 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.

3.2.1.1 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°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 and 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 truely 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 $Fe_2 O_3$.

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

3.2.1.2. 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 used the following emperical relationship to determine the oxygen available to bath.

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

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:

$$dW/dt = -rW$$

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.

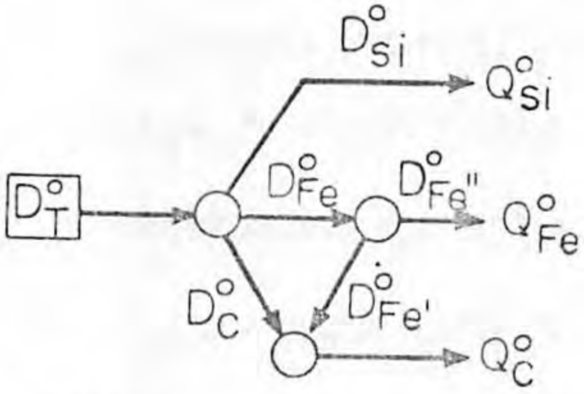
Goel et al also remain silent about the amount of slag oxygen which is an important variable as discussed above.

3.2.1.3. Model proposed by Hambury and Middleton: The details of the model have not been published, however, as reported by the authors [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 reactionsare 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 turbulance 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 theblowing rate. Further, since the model was developed mainly for computer control, several complex equations obtained from theory have been linearized to reduce computer time.

3.2.1.4. CNRM 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. Nilles and Dennis [13] have proposed an oxygen distribution scheme. The main reactions considered by them are oxidation of silicon, formation of CO and CO_2 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 3.1.

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. 3.2. At each centre flow is devided 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



D^o_T : Total oxygen flow

Q : Quantity of oxygen (Kg)

D : Oxygen flow rate (kg/sec)

FIG.3.1 OXYGEN FLOW BALANCE .

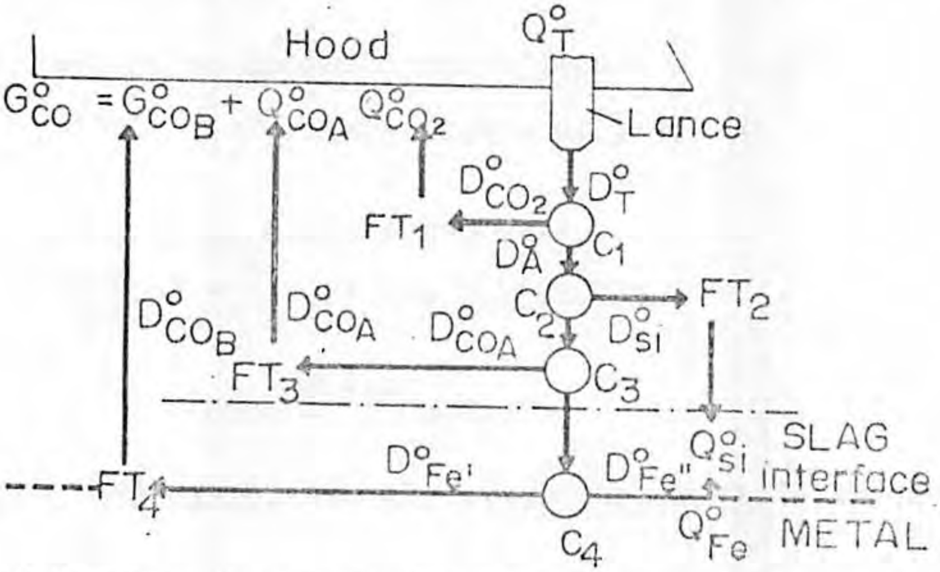


FIG.3.2 OXYGEN DISTRIBUTION CENTERS AND OXYGEN TRANSFER FUNCTIONS PROPOSED BY NILLES AND DENIS .

following relationships between variouspartial flows:

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

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

$$D^o_{CO_A} = f_3(T) * PJ * (a\ D^o_B - K_1 / \%C)$$

$$D^o_{CO_B} = f_4(T) * A_s * (FeO/K_2 - f/\%C)$$

$$Q^o_{Fe} = Q^o_T - Q^o_{Si} - Q^o_{CO_2} - Q^o_{CO}$$

Where D^o_i = Partial oxygen flow rate used for i(Kg/Sec)

Q^o_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 $Fe + O = FeO$

f is a parameter.

The slag composition is given by

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

The empirical functions $f_1 \ldots, f_5$ 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 have 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.

3.2.2 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'.

Measurement based dynamic control schemes can be further classified in to three categories as explained below:

1. Blowing control Method: Throughout the blow, the operating conditions are controlled to stabilize the blow as shown by path 1 in Fig 3.3. CNRM fume temperature control scheme is an example of this method.

2. Path Correction Method: The control action is started towards end of the blow, to modify the path of carbon and temperature in order to reach end points simultaneously as shown by paths 4 and 5 in Fig.3.3. J & L control scheme is an example of this method.

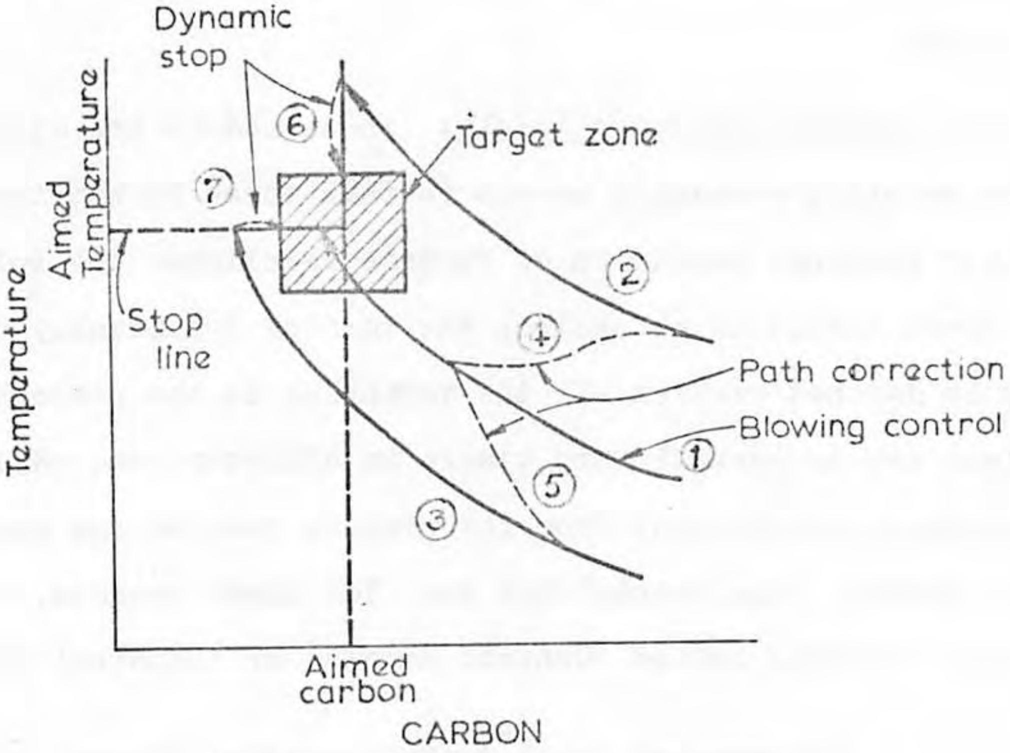


Fig. 3.3 Measurement based dynamic control schemes.

3. Dynamic Stop Method: Here we don't modify the path, but judge the best suitable instant of time for stopping the blow and at that instant the blow is stopped. Corrective measures are taken afterwards, if necessary. The chosen stop instant, should satisfy one of the following two conditions.

i. Aimed carbon and temperature are hit simultaneously(Path 1)

ii. Either carbon or temperature (only one of the two) is hit and a corrective meausre is required for the other. (Paths 6 and 7).

This method is used at Nippon Steel Corp.(Not discussed here).

3.2.2.1 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 trapazoidal form as shown in Fig.3.4. The refining process is devided into three blowing periods with decarburization rate following the curves stated below:

First Phase: Silicon Blow: $-dC/dt = K_1 t$

Second Phase: Carbon Boil : $-dC/dt = K_2$

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 peeriod $\overline{DE}$. 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.

$$- dC/dt = KC$$

$$K = - (dC/dt)\ \text{max.} / (Cd * Wd)$$

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

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.

3.2.2.2 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:

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

Slag oxygen = Lance oxygen + oxygen from limestone and ore Oxygen used for CO- oxygen used for CO_2- oxygen in dust - oxygen dissolved in metal

weight of slag = constant* (slag oxygen)+ weight of excess lime

Total heat gained by metal = Heat generated by formation of CO + Heat generated by formation of CO_2+ Heat gained from FeO - Heat lost to vessel - Heat lost through sensible losses.

$$\text{Carbon removal efficiency} = \frac{\text{Units of carbon removed}}{\text{Oxygen delivered to the bath}}$$

$$= 1.33\ \frac{\text{Decarburization rate Kg/min.}}{\text{Lance oxygen kg/min.}}$$

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 to control slopping. Temperature of the metal can be calculated from total heat gained and initial temperature. At carbon below 0.25%, the following relationship is obtained between bath carbon and carbon removal efficiency by carbon/oxygen equilibrium:

% C in Bath = 0.04 EXP (0.026 * 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 unacceptible error in results obtained.

3.2.2.3 <u>CNRM Fume Temperature Model</u>: The sampling difficulties, 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 approapriate 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. Nilles and Dennis [16] have derived relationship of the following form between fume temperature and metallurgical reactions:

Decarburization rate dC/dt = $T_f * f_1(X_f) + f_2(X_f)$

Oxygen used for carbon = $T_f * f_3(X_f) + f_4(X_f)$

Oxygen transfered to slag = Lance oxygen-oxygen used for carbon.

Where $X_f = \frac{(\% CO)}{(\% CO + \% CO_2)}$ in exhaust gases

T_f = Fume temperature

Complete derivations of above relationships and forms of function $f_1 - f_4$ are 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, itis 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. 3.5. However, slag composition prediction is considerably affected by variation in X_f. Hence means of cheeking 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 Ramelat [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 3.6.

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.

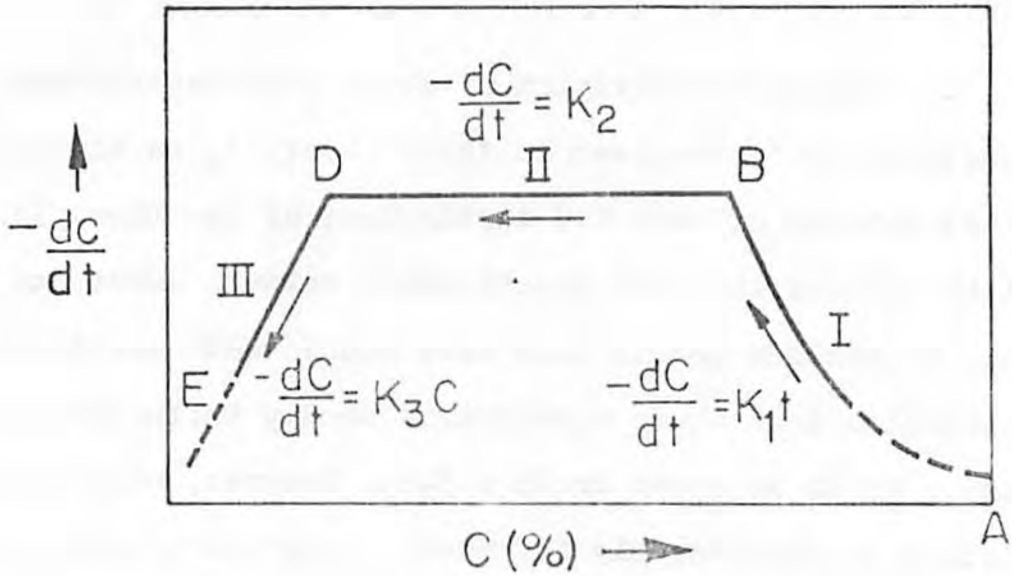


FIG.3.4: DECARBURIZATION MODEL

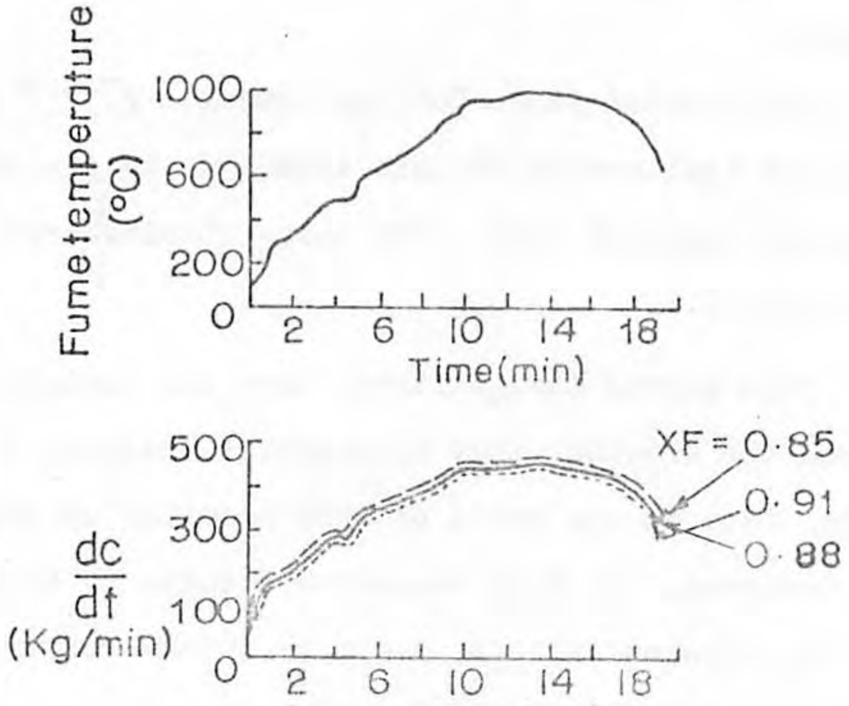


FIG.3.5: RELATION BETWEEN FUME TEMPERATURE(TF) AND DECARBURIZATION RATE, dc/dt.

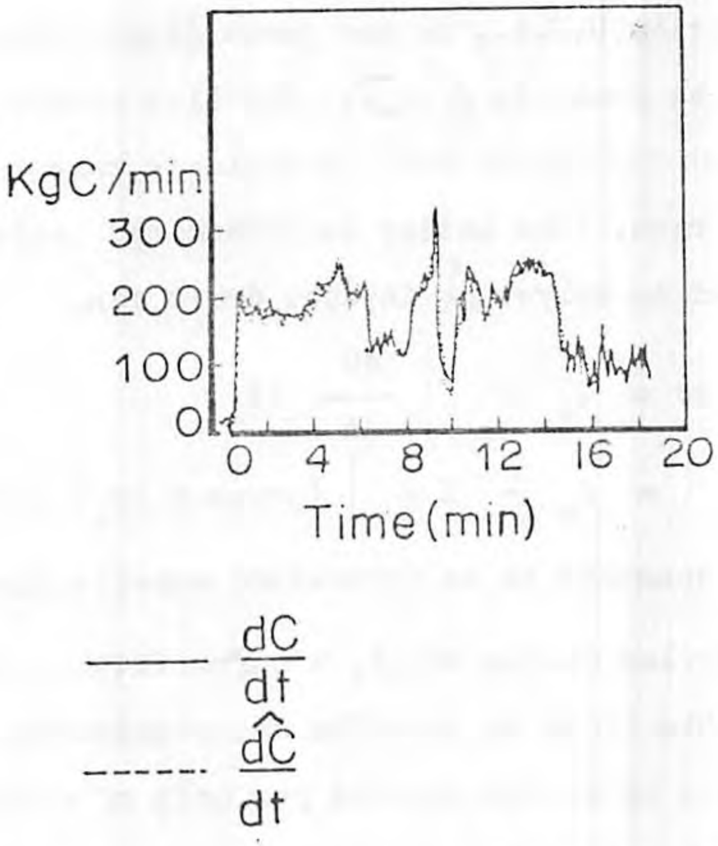


FIG. 3.6 COMPARISON BETWEEN THE DECARBURIZATION RATE OBTAINED FROM GAS ANALYSERS (dC/dt) AND THE DECARBURIZATION RATE ESTIMATED FROM FUMES TEMPERATURE MEASUREMENT ($d\hat{C}/dt$).

3.2.2.4 **J & L Model:** 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 ($C > 4\%$), an integration method is used to estimate carbon from gas analysis and flow rate. The latter is determined indirectly from the power required to drive the induced draft fan.

$$C(t) = C_o - \int \frac{dC}{dt}\, dt$$

$$= C_o - K \int (\text{percent } CO_2)\ (\text{Fan H.P})\ dt$$

where K is a constant to be determined emperically.

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 path of ϕ versus C the last phase of the blow is shown in Fig. 3.7. It can be represented by a relation 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. Theamount of oxygen O_C required to reduce carbon from C_1 to C_2 can be calculated as follows:

$$O_C = \frac{C_1 - C_2}{a} + \frac{1}{r \cdot a} \ln \left(\frac{\phi_1}{\phi_2} \right)$$

Where $\phi_1 = a - b * \mathrm{Exp}\,(- r^* C_1)$

$\phi_2 = a - b * \mathrm{Exp}(- r^* C_2)$

A sinker thermo couple is used to determine the temperature during the blow and final temperature is estimated as follows [20]

Final Temperature = Measured Temperature

+ (K_1 - K_2* Measured Temperature)

* Volume of oxygen blown after temperature measurement.

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_C, with the lance being raised say 10 inches just before O_C has been blown. This causes a 'slag blow' and temperature is gained at almost zero decarburization rate, largely by converting a slag FeO to Fe_2O_3 so that yield loss is minimized.

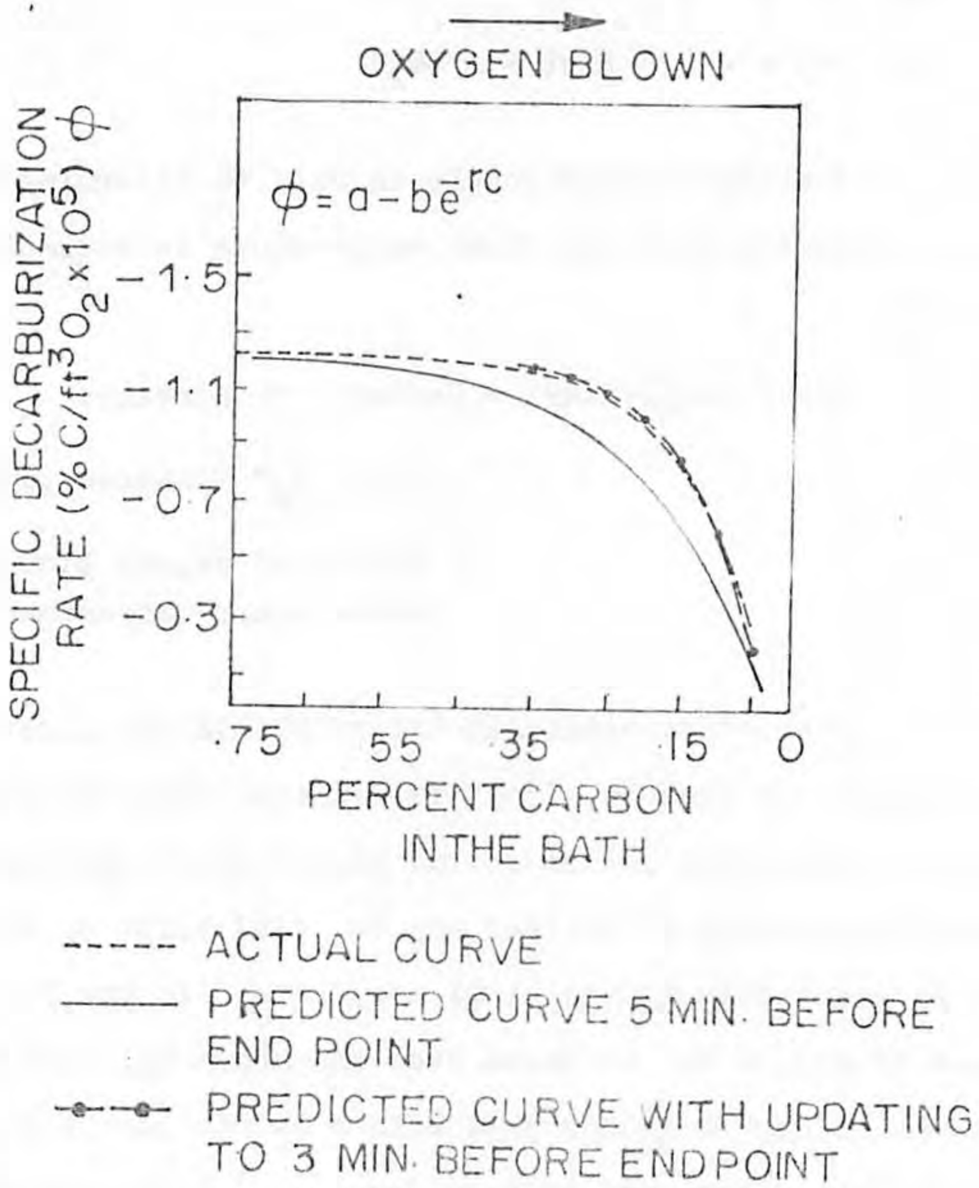


FIG 3.7 ACTUAL AND PREDICTED REFINING CURVES

3.2.3 Modern Control Techniques Based Models: Though most of the researchers working on automatic control of LD converter 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.

3.2.3.1 CNRM Transfer Function Approach: As early as in 1968, Decker has reported [21] that CNRM was 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 (dC/dt) and either oxygen flow rate QO_2 or lance height HL. Each type of H(s) has its own merits and demerits during different periods. An idea of their applicability can be obtained from Fig. 3.8

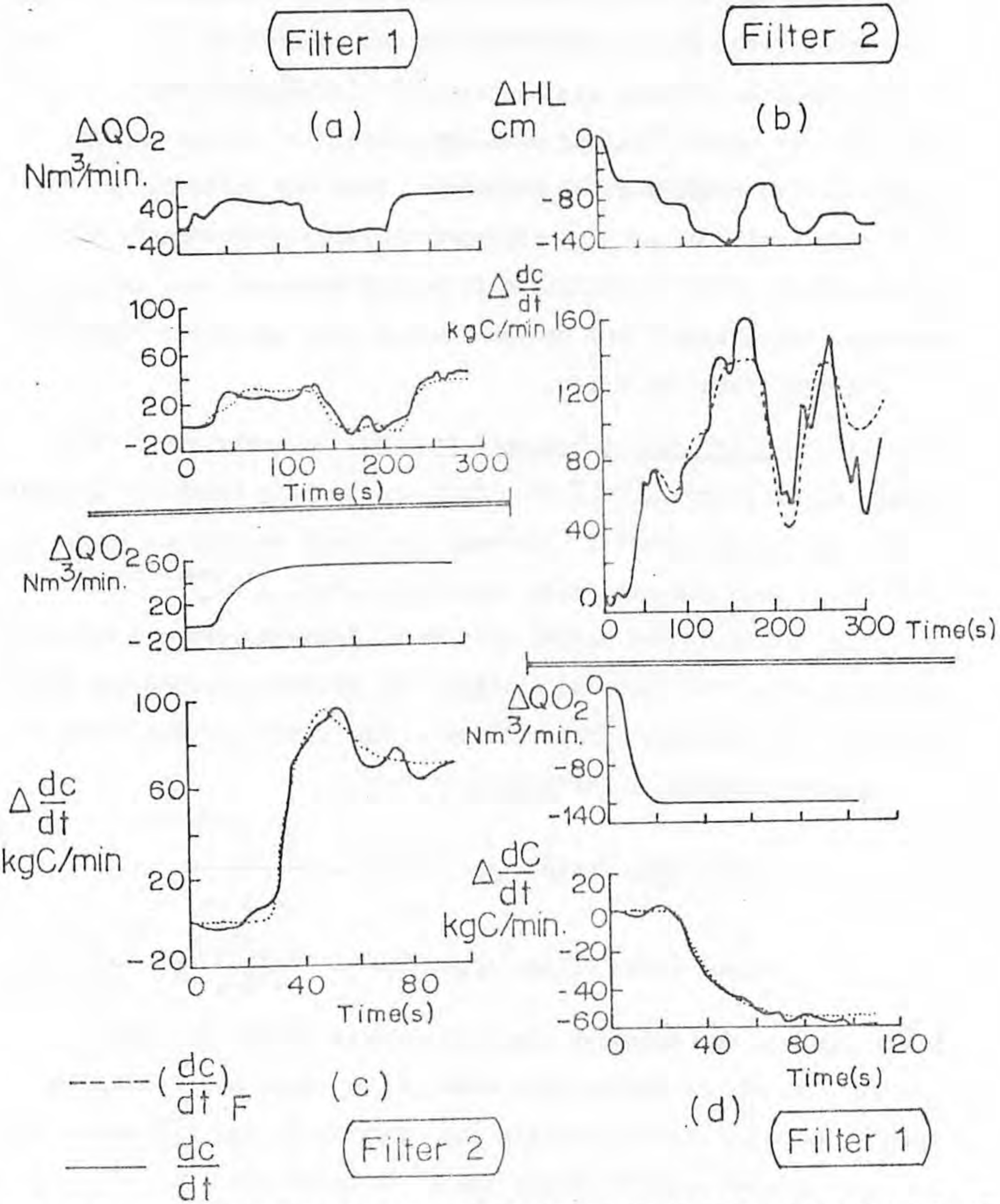


FIG.3.8 COMPARED EVOLUTIONS OF THE TRUE DECARBURIZATION RATE dC/dt AND OF THAT $(dC/dt)_F$ OBTAINED BY ADAPTIVE FILTERING AT DIFFERENT PERIODS OF THE BLOW.

3.2.3.2 Model Proposed by Wells et al: Wells, Wismer and Mehra, 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 decarburisation 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 decarburisation 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

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

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, $D^2 Z_i$ etc. (Fig. 3.9), it was concluded that a second order model of the following type can be used

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

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

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

Where $E(w_i) = 0$ $\quad E(w_i \, w_j) = q \cdot \delta_{ij}$ $\quad E(w_i \, V_j) = 0$

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.

$$d = K_1 \left\{ 1 - e^{-K_2 (C - C_o)} \right\}$$

where K_1, K_2 and C_o 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.

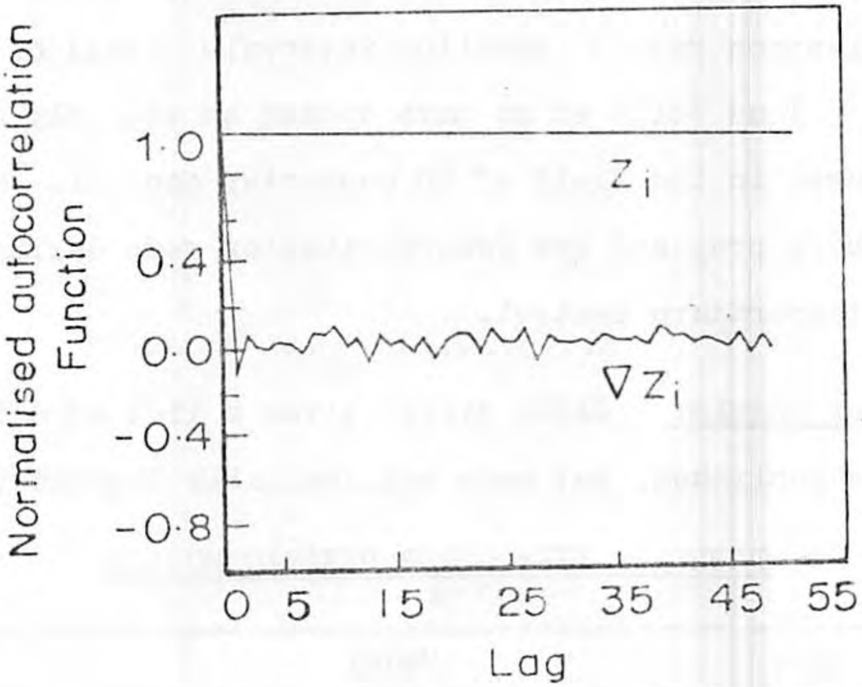


FIG.3.9 AUTOCORRELATION FUNCTION OF Z_i AND ∇Z_i

In state vector form the model becomes

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

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

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

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

u = white noise.

An extended Kalmàn filter was used for predicting the decarburization rate τ 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.

3.3. Other Models: TABLE 3.III. gives a list of models, which have been published, but were not available for studies here.

TABLE-3. III: OTHER DYNAMIC MODELS.

Type	Model	Reference
Reaction Mechanism Based Models	Yawata (Miyamura)	24
	Nippon Kokan (Ozeki)	
	VOEST (Krawz)	25
	USSR (Jameljanow)	26
Measurement Based Models	IRSID	27
	Yawata (Nagano)	28
	Yawata (Maeda)	29

3.4 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 todate 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 of LD converter control. However, future prospects are bright since several researchers have started appreciating its need.

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CHAPTER-4

DYNAMIC DIGITAL SIMULATION OF LD CONVERTOR.

The two most important requirements for a computer process control project are the computer and the process to be controlled. In the absence of actual process a common approach is to simulate the process on a hybrid/digital computer and to use the simulated model for testing control algorithms. Even when process is available, the simulation forms an essential step in order to avoid the risk involved in directly applying untested control algorithms to actual process, which may damage the process. With this in view, a comparative study of all available dynamic models of the LD converter [1] was done and the model suggested by Muchi [2,3] has been chosen for simulation. The main reason for this choice is that this model is applicable to a furnace of any size and that more details of this model are available as compared to others.

Since the model is very complex, some linearization and simplification was done to minimise computation time. At first, the simulation did not produce the desired results and soon it was realized that several model equations and parameter values were erroneous . Hence the model was modified and program was run several times with different parameter values to obtain the most appropriate ones. The total computer time used in the project amounted to 25 hours. Another important difficulty encountered was memory overflow problem; This problem has been overcome. A special integration algorithm requiring only 5 multiplication and 3 addition operations with very little memory requirements and computation time has been developed to solve the differential equations.

4.1 Memory Overflow Problem:

The simulation program for LD converter with all its subroutine requires a memory space almost equal to the maximum available memory on IBM 360/44 (of the total memory of 64 K bytes, first 16½ k bytes are permanently occupied by " Supervisory program" leaving 47½ K bytes or 12 K words for problem program). This leaves virtually no space for plotting program which is very essential for any simulation . Moreover, the plotting program (written for this simulation) which gives a very elegant output graph and has several options requires a large memory. Therefore a memory overflow problem was encountered.

The memory overflow problem was tackled by using a multiphase program execution technique [4,5] having a root phase commonly known as 'ROOT PHASE MEMORY OVERLAY TECHNIQUE'. In this technique, one phase of the program called root phase remains in the problem program area, throughout the execution of entire program. The other phases in the program, called 'subordinate phases', reside in the system disk and are loaded into the problem program area as and when they are needed. The whole program is so structured that the total memory requirements for allphases residing in memory at any one time does not exceed the size of problem program area.

In this simulation, the entire program was divided into three phases namely:

1. Root program(or coordinator.)
2. BOF Simulation program(or simulator.)
3. Plotting Program(or Plotter.)

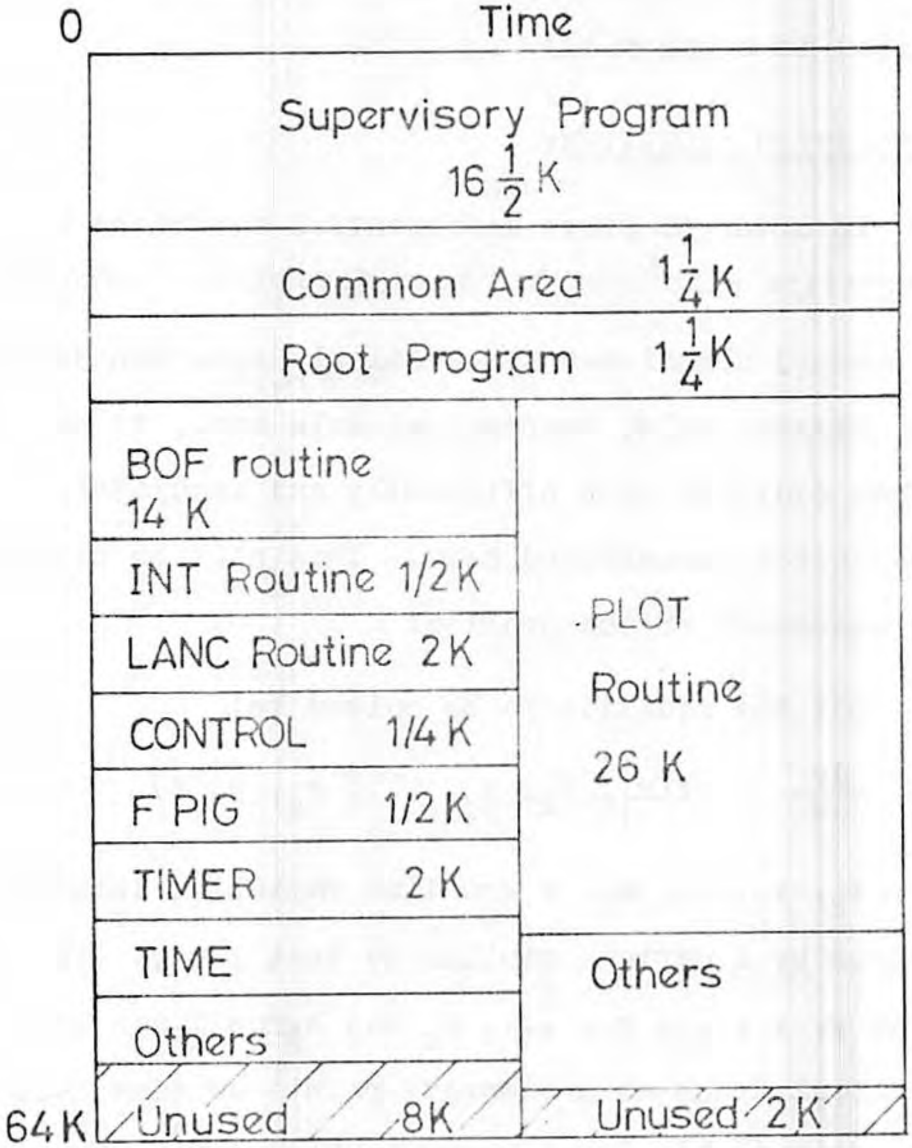

Fig. 4.1 MEMORY MAP OF SIMULATION PROGRAM.

The memory map for this program structure is shown in Fig. 4.1. The function and details of each section of program are described in section 4.3.

4.2 INTEGRATION ALGORITHM:

In order to solve differential equations in the model, a new integration algorithm has been developed. Though several standard algorithms are available e.g. Runge-Kutta-Gill algorithm, Simpson rule, trapazoidal rule etc., it was found that none of them could be used efficiently and accurately for the complex situation encountered here. This will be clear from the following statement of the problem:

Let the equation to be solved be:

$$\frac{dy}{d\theta} = f(x_1, x_2, x_3, \ldots, x_k, y, t) \qquad .. \quad (1)$$

Where $x_1, x_2, x_3 \ldots, x_k$, y are time variables interrelated to each other by equations similar to that for y. The values of variables $y, x_1, x_2, x_3, \ldots, x_k$ and hence f are known from previous calculations at n discrete points of time viz 0, Dt, 2Dt, 3Dt, ..., (n-1) Dt as shown in Fig. 4.2 . The next value y_n can be obtained as follows:

$$y = y_0 + \int_0^t f(x_1, x_2, x_3, \ldots, x_k, y, t)\, dt \quad ..(2)$$

$$\text{or} \qquad y_n = y_{n-1} + \int_{(n-1)\Delta t}^{n\Delta t} f(x_1, x_2, x_3, \ldots, x_k, y, t)\, dt \quad \ldots(3)$$

Thus y_n can be determined provided the integral on the right hand side of equation (3) can be evaluated. This requires the knowledge of value of function f during the interval (n-1)Dt ~

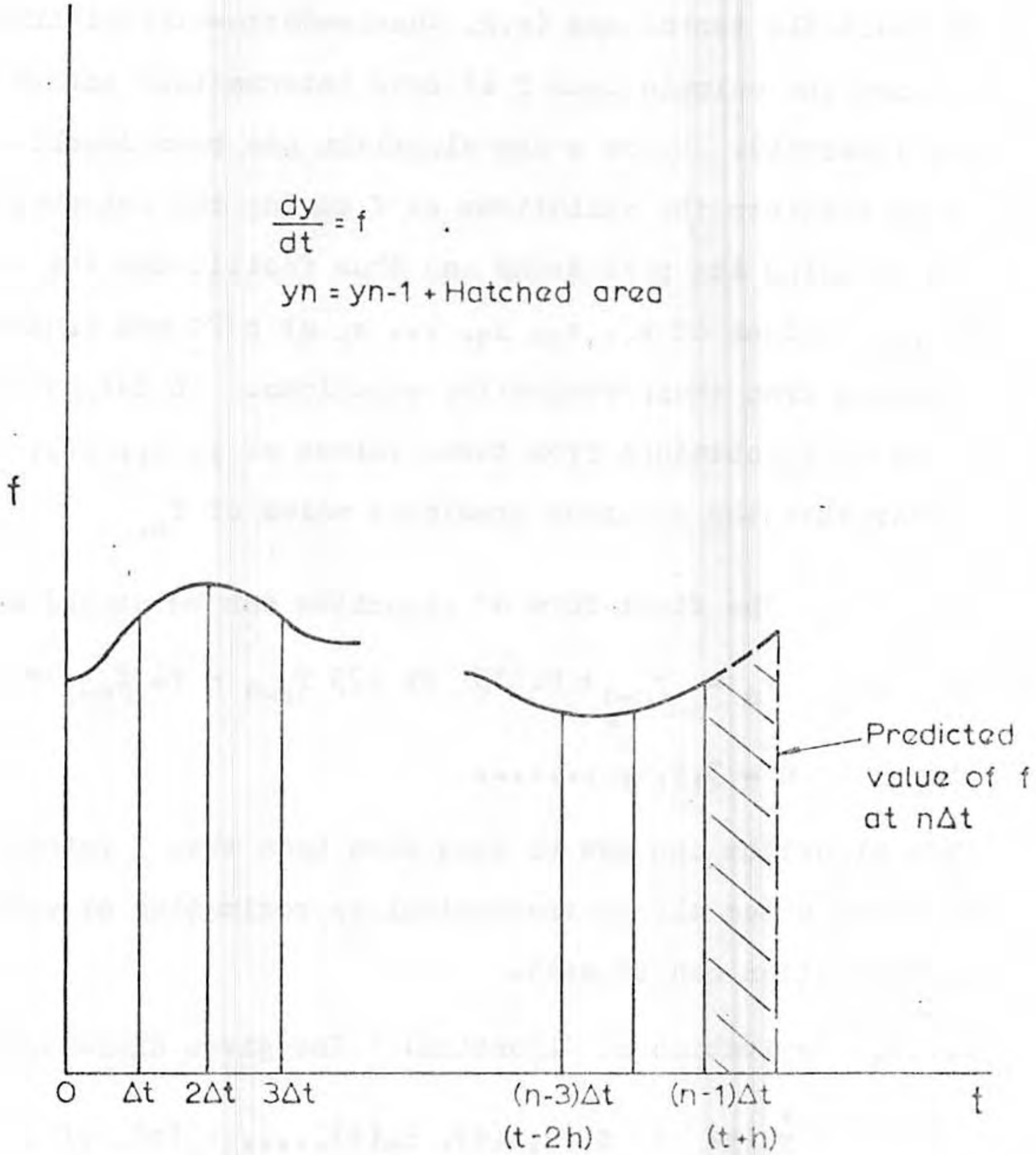

Fig 4.2 DERIVATION OF INTEGRATION ALGORITHM.

nDt, which in turn involves knowledge of $x_1, x_2, x_3, \ldots, x_k$, y during this interval. These are all unknown in present situation and some estimation of these has to be made. This prohibits the use of available techniques (e.g. Ruange-Kutta-Gill algorithm will require the calculations f at some intermediate points during the interval). Hence a new algorithm has been developed which first predicts the variations of f during the interval (n-1)Dt n Dt using its past trend and thus facilitates the determinations of y_n. Values of $x_1, x_2, x_3, \ldots x_k$ at n·Dt can similarly be obtained from their respective equations. In future calculations, value of f_n obtained from these values of $y, x_1, \ldots, x_k$ is used rather than the previous predicted value of f_n.

The final form of algorithm can be stated as follows:

$$y_n = y_{n-1} + 0.833\ Dt\ (23 f_{n-1} - 16 f_{n-2} + 5 f_{n-3}) \quad ..(4)$$

where $n = 3, 4, 5, \ldots\ldots\ldots$

This algorithm can not be used when less than 3 points are known. In these cases either trapazoidal approximation or rectangular approximation can be used.

4.2.1. Derivation of Algorithm: The given differential equation is

$$\dot{y}(t) = f(x_1(t), x_2(t), \ldots, x_k(t), y(t), t) \quad \ldots (5)$$

Since $x_1, x_2, \ldots, x_k$ and y all are functions of time t, equation (5) can also be written as

$$\dot{y}(t) = f(t)$$

The Taylor's series expansion for $y(t+h)$ is

$$y(t+h) = y(t) + \frac{h}{\underline{|1}}\dot{y}(t) + \frac{h^2}{\underline{|2}}\ddot{y}(t) + \frac{h^3}{\underline{|3}}\dddot{y}(t) + \frac{h^4}{\underline{|4}}\ddddot{y}(t)$$

$$= y(t) + \frac{h}{\underline{|1}} f(t) + \frac{h^2}{\underline{|2}}\dot{f}(t) + \frac{h^3}{\underline{|3}}\ddot{f}(t) + \frac{h^4}{\underline{|4}}\dddot{f}(t) \ldots (6)$$

If $y(t)$ is assumed to be a third order (cubic) function of t or equivalently, $f(t)$ is assumed to be a second order (parabolic) function of t in a small interval $(t-2h) - (t+h)$ around t(and not on whole time span) then third and higher differential coefficients of $f(t)$ can be assumed zero. With this assumption:

$$y(t+h) = y(t) + \frac{h}{\underline{|1}} f(t) + \frac{h^2}{\underline{|2}}\dot{f}(t) + \frac{h^3}{\underline{|3}}\ddot{f}(t) \ldots (7)$$

The differential coefficients $\dot{f}(t)$ and $\ddot{f}(t)$ can be determined from the known values of $f(t-h)$ and $f(t-2h)$ as follows:

$$f(t-h) = f(t) - \frac{h}{\underline{|1}}\dot{f}(t) + \frac{h^2}{\underline{|2}}\ddot{f}(t) \qquad \ldots (8)$$

$$f(t-2h) = f(t) - \frac{2h}{\underline{|1}}\dot{f}(t) + \frac{4h^2}{\underline{|2}}\ddot{f}(t) \qquad \ldots (9)$$

Equations 8 and 9 give

$$\dot{f}(t) = \frac{1}{h}\left\{\frac{3}{2} f(t) - 2 f(t-h) + \frac{1}{2} f(t-2h)\right\} . (10)$$

$$\ddot{f}(t) = \frac{1}{h^2}\left\{ f(t) - 2f(t)-h) + f(t-2h)\right\} \quad \ldots (11)$$

Substituting the values of $\dot{f}(t)$ and $\ddot{f}(t)$ from equation (10) and (11) in equation (7) we get

$$y(t+h) = y(t) + \frac{h}{12}\left\{23 f(t) - 16 f(t-h) + 5 f(t-2h)\right\} .. (12)$$

or

$$y_n = y_{n-1} + 0.833 \; Dt \; (23 f_{n-1} - 16 f_{n-2} + 5 f_{n-3}) .. (13)$$

Note that the values of $f_0, \ldots, f_{n-4}$ are not required for y_n and hence they need not be stored in memory, only last three values of f are sufficient. Further this algorithm does not require calculations of f at any point other than at discrete intervals of Dt.

4.2.2 Error Analysis: It can easily be shown using Taylor's series expansion that

$$y(t+h) - y(t) - \frac{h}{12} (23f(t) - 16\, f(t-h) + 5\, f(t-2h)$$

$$= -\frac{3}{8} h^4 \; \dddot{f}(t) - \frac{77}{360} h^5 \; f^4(t) + \frac{13}{120} h^6 f^5(t) + \ldots (14)$$

$$= \text{Truncation error.}$$

Thus truncation error will be zero if y is a third order function of t or equivalently f is a second order function of t. For higher order curves, the error depends on the 4th power of the integration interval h. It should be noted that for very small values of h, though the truncation error is less, the numerical calculations error may be more. Hence value of 'h' should be properly chosen. Further since estimation is based on previous trend, error will be more for rapidly fluctuating curve, e.g. sine curve (Furtunately, in LD converter simulation almost all variables are monotonic).

In order to test the accuracy of this algorithm the worst case situation of sinusoidal curve was programmed on the computer and the total error (truncation error + computation error) as obtained from the computer is plotted in Fig 4.3.

```
                 ACCURACY OF INTEGRATION ROUTINE
                 *******************************

NUMBER OF POINTS       STANDARD DEVIATION        STANDARD DEVIATION
   PER CYCLE           FOR A SINE CURVE          FOR A COSINE CURVE

      26                     0.016                     0.015
      27                     0.014                     0.013
      28                     0.013                     0.012
      29                     0.011                     0.010
      30                     0.010                     0.009
      31                     0.009                     0.009
      32                     0.008                     0.008
      33                     0.008                     0.007
      34                     0.007                     0.007
      35                     0.007                     0.006
      36                     0.006                     0.006
      37                     0.006                     0.005
      38                     0.005                     0.005
      39                     0.005                     0.005
      40                     0.005                     0.005
      41                     0.005                     0.004
      42                     0.004                     0.004
      43                     0.004                     0.004
      44                     0.004                     0.004
      45                     0.004                     0.004
      46                     0.004                     0.004
      47                     0.004                     0.003
      48                     0.003                     0.003
      49                     0.003                     0.003
      50                     0.003                     0.003
      51                     0.003                     0.003
      52                     0.003                     0.003
      53                     0.003                     0.003
      54                     0.003                     0.003
      55                     0.003                     0.003
      56                     0.003                     0.003
      57                     0.003                     0.002
      58                     0.002                     0.002
      59                     0.002                     0.002
      60                     0.002                     0.002
      61                     0.002                     0.002
      62                     0.002                     0.002
      63                     0.002                     0.002
      64                     0.002                     0.002
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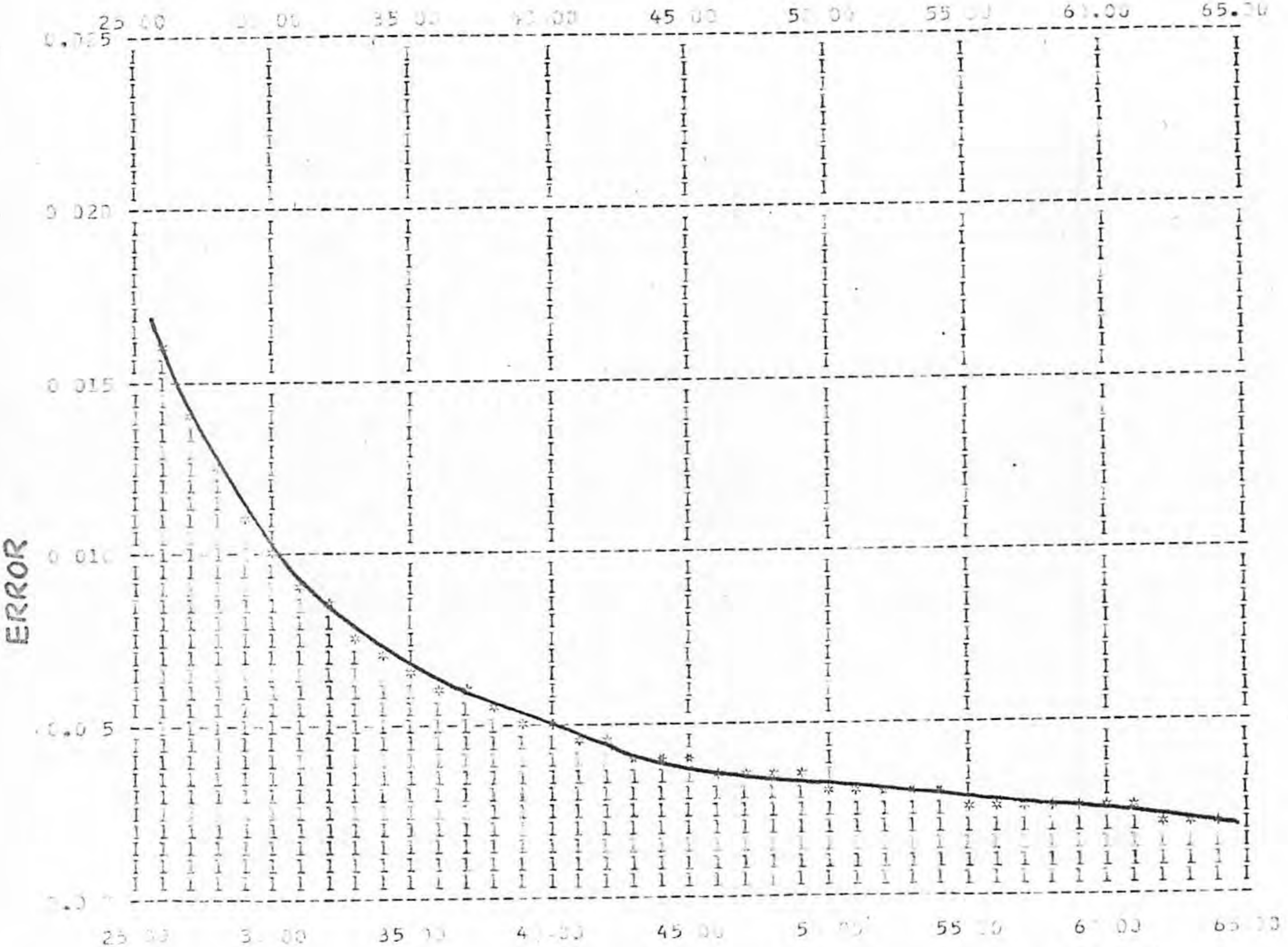


Fig.4.3 ACCURACY OF INTEGRATION ROUTINE: STANDARD DAVIATION VS NUMBER OF POINTS PER CYCLE

4.3 PROGRAM DESCRIPTION:

4.3.1 Root Program (Coordinator): The root program serves the function of coordinator between simulator and plotter. It first calls for the loading and execution of BOF simulation program, the results of which are stored in the common area. The root program then calls for loading of plotting program in memory and for plotting the results stored in common area.

During the program development and parameter estimation stage, this program also serves the purpose of repeating the execution of BOF and PLOT routine several times, each time with different values of parameters, so that the appropriate values of parameters can be determined.

4.3.2 BOF Simulation Routine (Simulator): This is the heart of the entire simulation. In its final form it has parameters which specify the type of output desired, integration interval, the total simulation time etc. The model equations used for simulation are given and briefly described in Appendix B. Details can be found in Muchi's paper [2]. Fig.4.4 shows a flow chart of this routine. Every attempt has been made to optimize the program for minimum computation time with elegant output format. The result is that the whole simulation of 30 minute process takes only 10-40 seconds on IBM 360/44 depending on the volume of output desired (Note that most of this time is spent on printing the result). Following particulars are noteworthy in this regard:

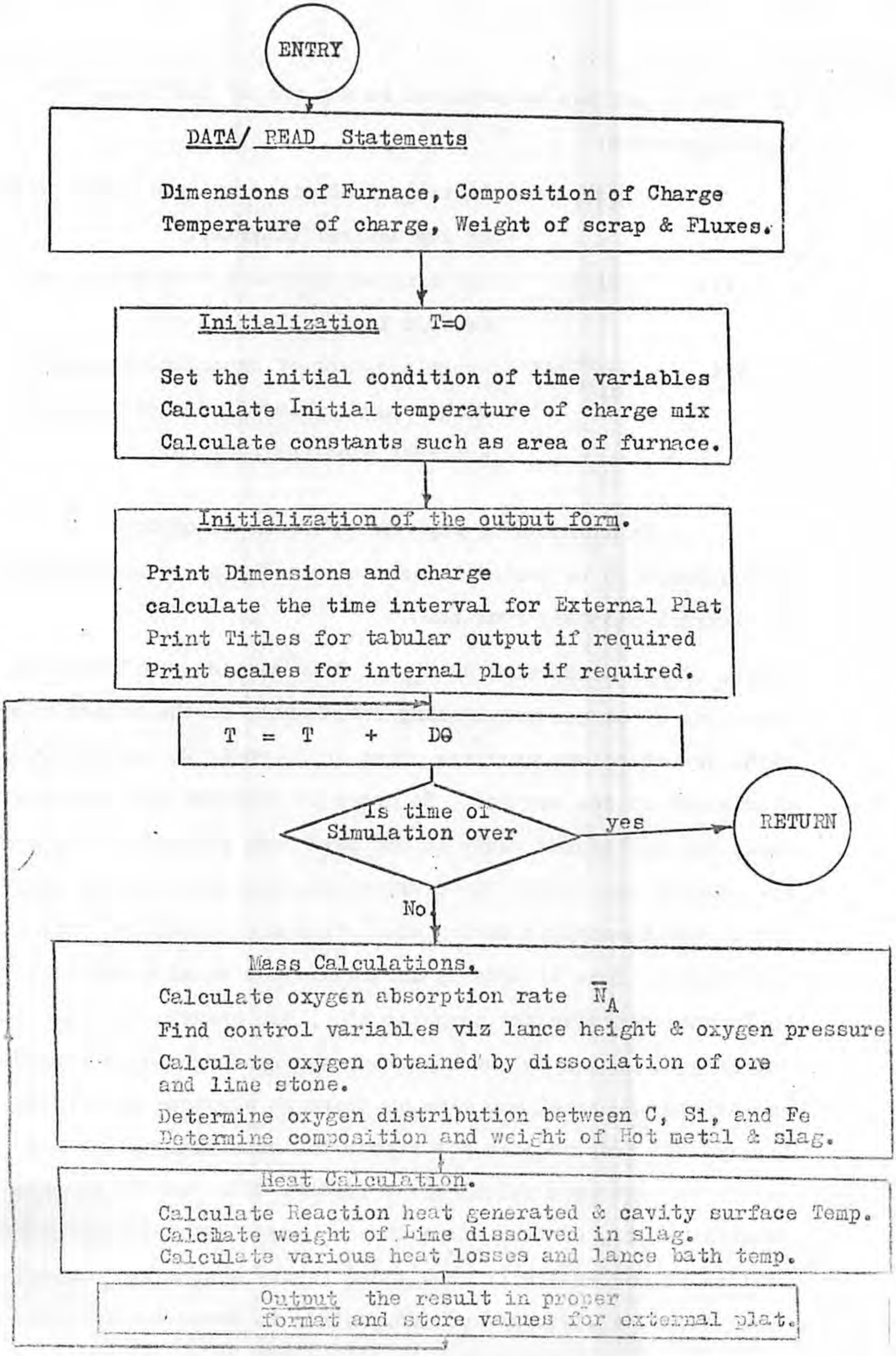
(a) During the initial development stage of the program, it was desired that all intermediate calculations should be printed. This would have involved several large format statements and difficulties of specifying exact formats since, magnitudes of variables were not known. Hence formatless 'WRITE' statements using 'NAMELIST' were used. This greatly simplified the task of checking intermediate calculations.

(b) The dimensions of the furnace, the compositions of charge, and various additives are all given as 'DATA' statements, though these could very well have been supplied as subroutine parameters or read by 'READ' statements. The latter not only increases the format statements but also involves the risk of data being wrong if any format is inappropriate or any data is punched out of format.

(c) The variables and those parts of the equations which remain unchanged during the whole simulation are calculated only once and stored for subsequent use. This minimises the computation time. The time varying calculations are done later in a DO loop.

(d) The calculation of reaction coefficient β which involves the solution of a very complex transcandental equation (see Appendix B) having exponential and error functions etc, has been simplified to a mere single direct calculation without much sacrifice in accuracy. This was found after relative trial of various equations solving algorithms in a bid to find the one with minimum time.

(e) The integration routine, discussed above has been used resulting in considerable time saving. This time saving is important because this routine is called nearly 7000 times during each simulation run (4 integrations are performed each second in a 30 minute simulation i.e. 1800 x 4 calls).


ENTRY
DATA/ READ Statements
Dimensions of Furnace, Composition of Charge
Temperature of charge, Weight of scrap & Fluxes.
Initialization T=0
Set the initial condition of time variables
Calculate Initial temperature of charge mix
Calculate constants such as area of furnace.
Initialization of the output form.
Print Dimensions and charge
calculate the time interval for External Plat
Print Titles for tabular output if required
Print scales for internal plot if required.
T = T + DΘ
Is time of Simulation over
yes
RETURN
No
Mass Calculations.
Calculate oxygen absorption rate $\overline{N}_A$
Find control variables viz lance height & oxygen pressure
Calculate oxygen obtained by dissociation of ore and lime stone.
Determine oxygen distribution between C, Si, and Fe
Determine composition and weight of Hot metal & slag.
Heat Calculation.
Calculate Reaction heat generated & cavity surface Temp.
Calculate weight of Lime dissolved in slag.
Calculate various heat losses and lance bath temp.
Output the result in proper format and store values for external plat.

(f) The output can be obtained in any one of the following available forms:

i.	LIST	: Listing of all intermediate calculations at any desired interval.
ii.	PRINT	: Printing of important variables at any desired interval.
iii.	INTERNAL PLOT	: Rough plotting of important variables on a single page. This eliminates the need for external plotting routine.

In addition to any one of the above options the output can also be stored in common area for subsequent plotting by external plotting routine.

4.3.3. Lance Simulation Routine: This routine simulates the behaviour of oxygen jet issuing from lance, on the molten steel bath. The equations used are given in Appendix C. Fig 4.3 shows flow chart of the routine. In order to minimize the computer time, two additional entry points have been provided in this routine Viz. LANCIN and LANCE. The coefficients and parts of the equations which remain constant during simulation are calculated only once and stored. This is done by initialization routine named 'LANCIN'. To further minimize the computer time, the program has been made intelligent enough to check whether the new parameters (Lance height and oxygen pressure) are same as those in previous calculations,. If same the program does not repeat the calculations but uses the results of previous calculations itself. This results in substantial saving of time since in a single simulation run LANCE routine is called nearly 1800 times (every second in 30 minute simulation). A flow chart of the routine is shown in Fig. 4-5.

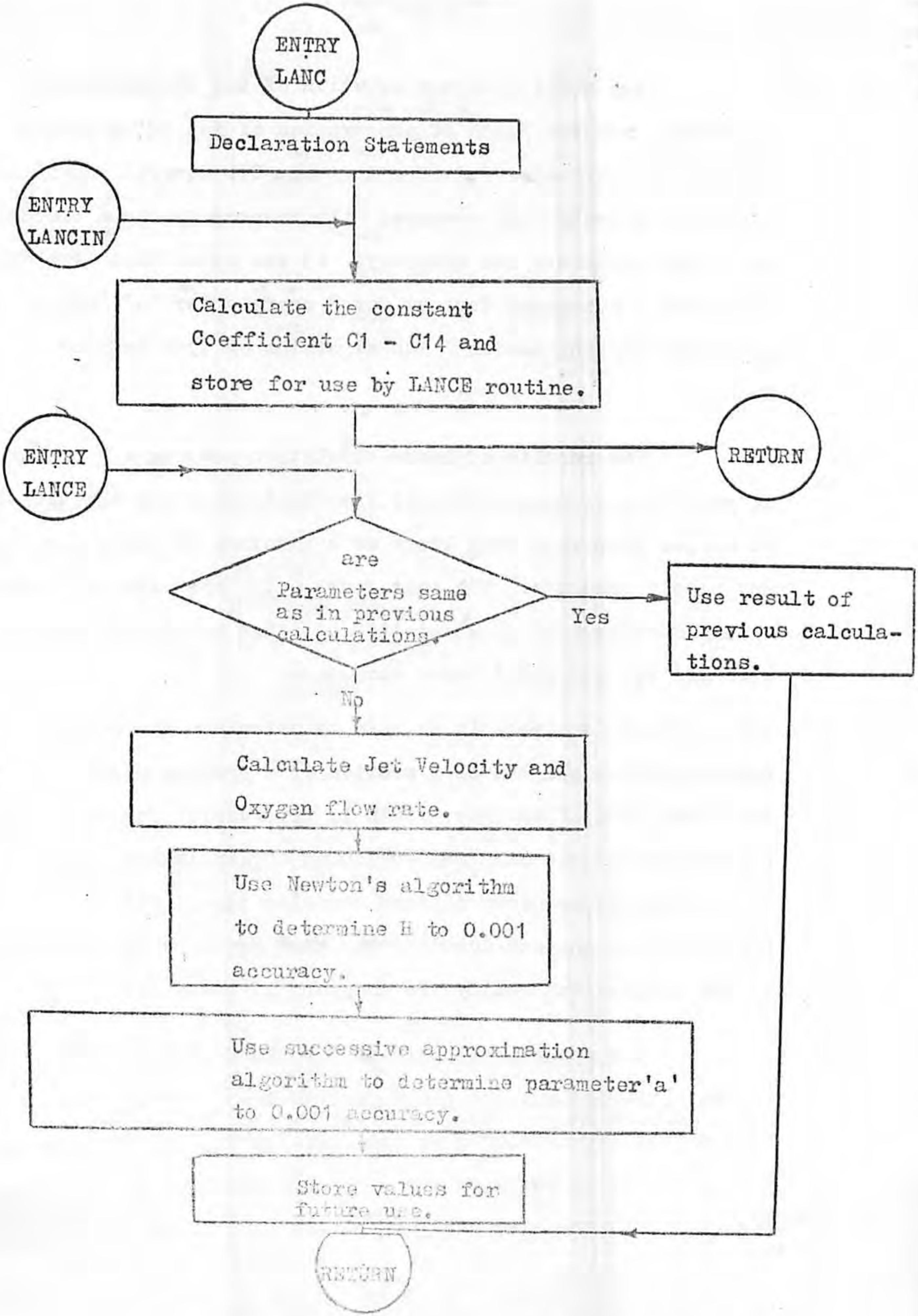


Fig.4.5 Structure of Lance simulation Program.

The model involves solution of two transcendental equations, one for depth of penetration of jet 'H' and other another for parameter 'a' (See Appendix C). Several known algorithms were tested and compared with respect to their time consumption, convergence, and accuracy. It was found that 'Newtons algorithm ' converges fastest for H whereas for 'a' "method of successive approximation " (an algorithm of type $x=f(x)$) is the best.

The results of lance simulation program are presented in next five figures(4.6-4.10). The first one shows the variation of oxygen flow rate from lance as a function of lance diameter and supply pressure. The next four figures show the variation of cavity surface area as a function of lance height and oxygen pressure for different lance diameters.

4.3.4 Timer Routine: It is used to calculate the computer time required for a program or a section of a program and/or to print the clock time of the day. This is very useful for any simulation because one of the aims in developing any simulation program is to see that it requires minimum computer time. With the help of timer routine one can identify the time required by each section of the program and modify the programs if necessary.

The program consists of a FORTRAN routine TIMER and an ASSEMBLY language [6] program TIME. In IBM 360/44, the time of the day is stored by the operator in the 80th byte of memory and is incremented every 1/50th of a second by a real time clock in the hardware [5] . The time is stored in

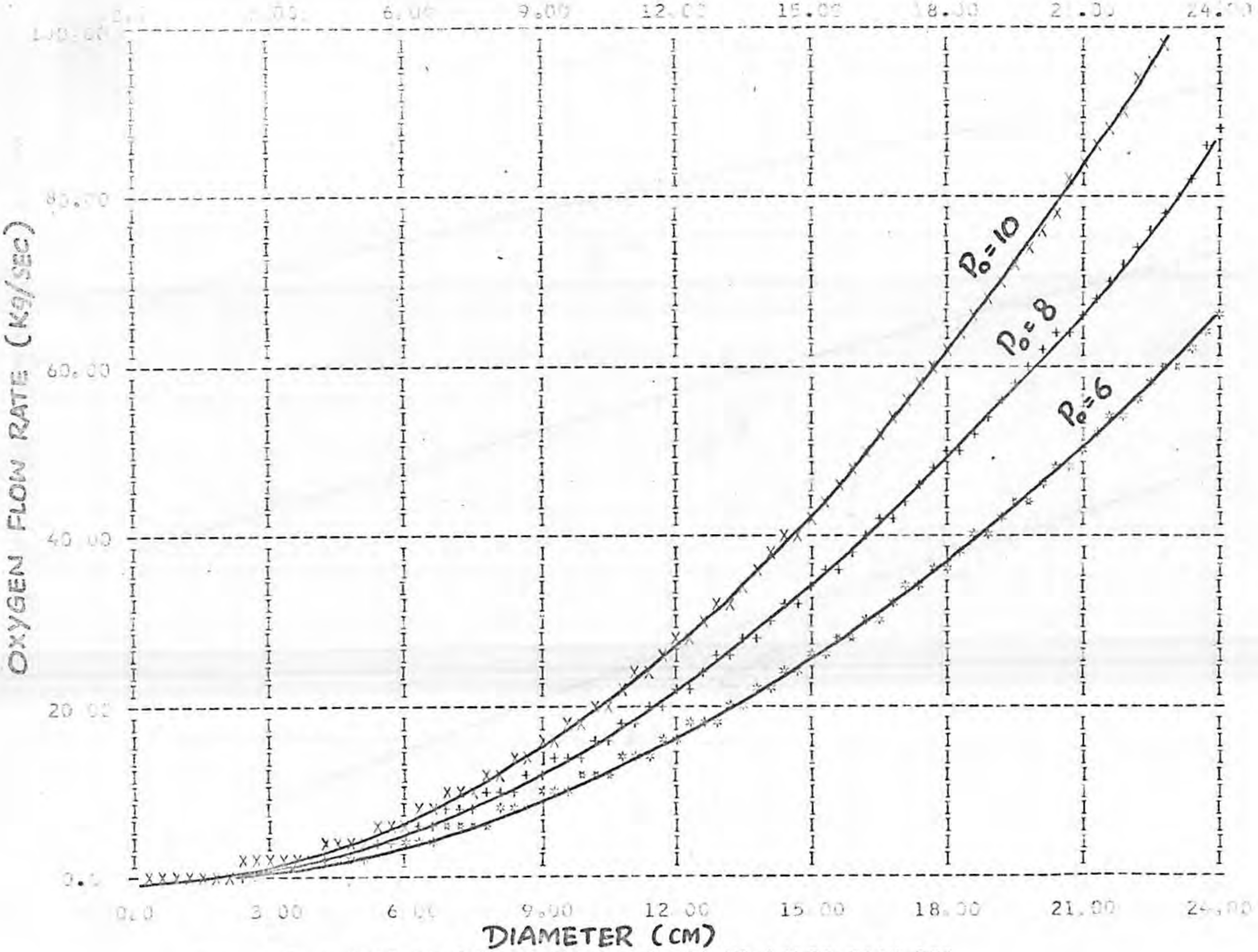


Fig. 4.6 : PLOT OF OXYGEN FLOW RATE G1 VS LANCE DIAMETER

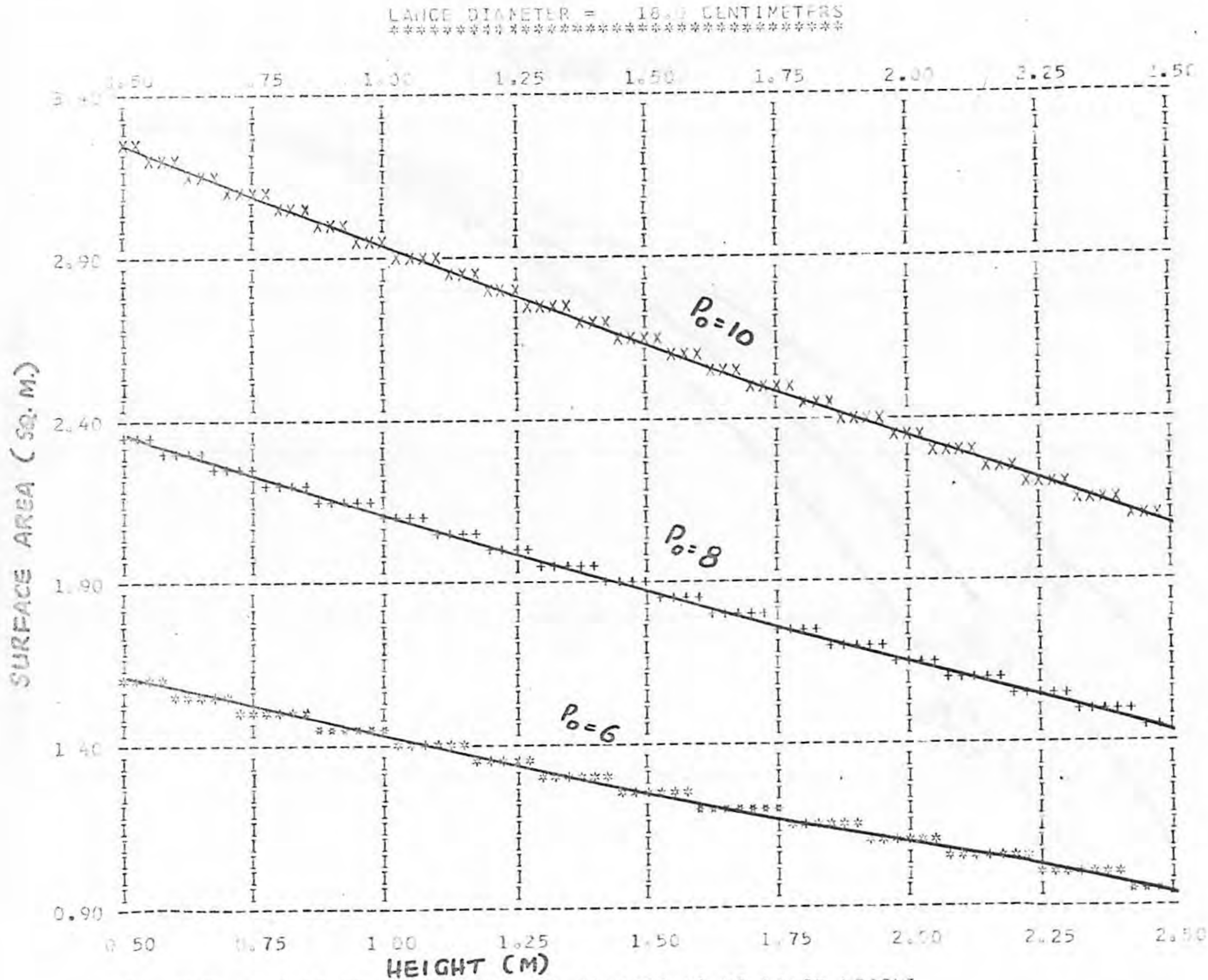


Fig. 4.7 : PLOT OF CAVITY SURFACE AREA(SQ.M) VS LANCE HEIGHT

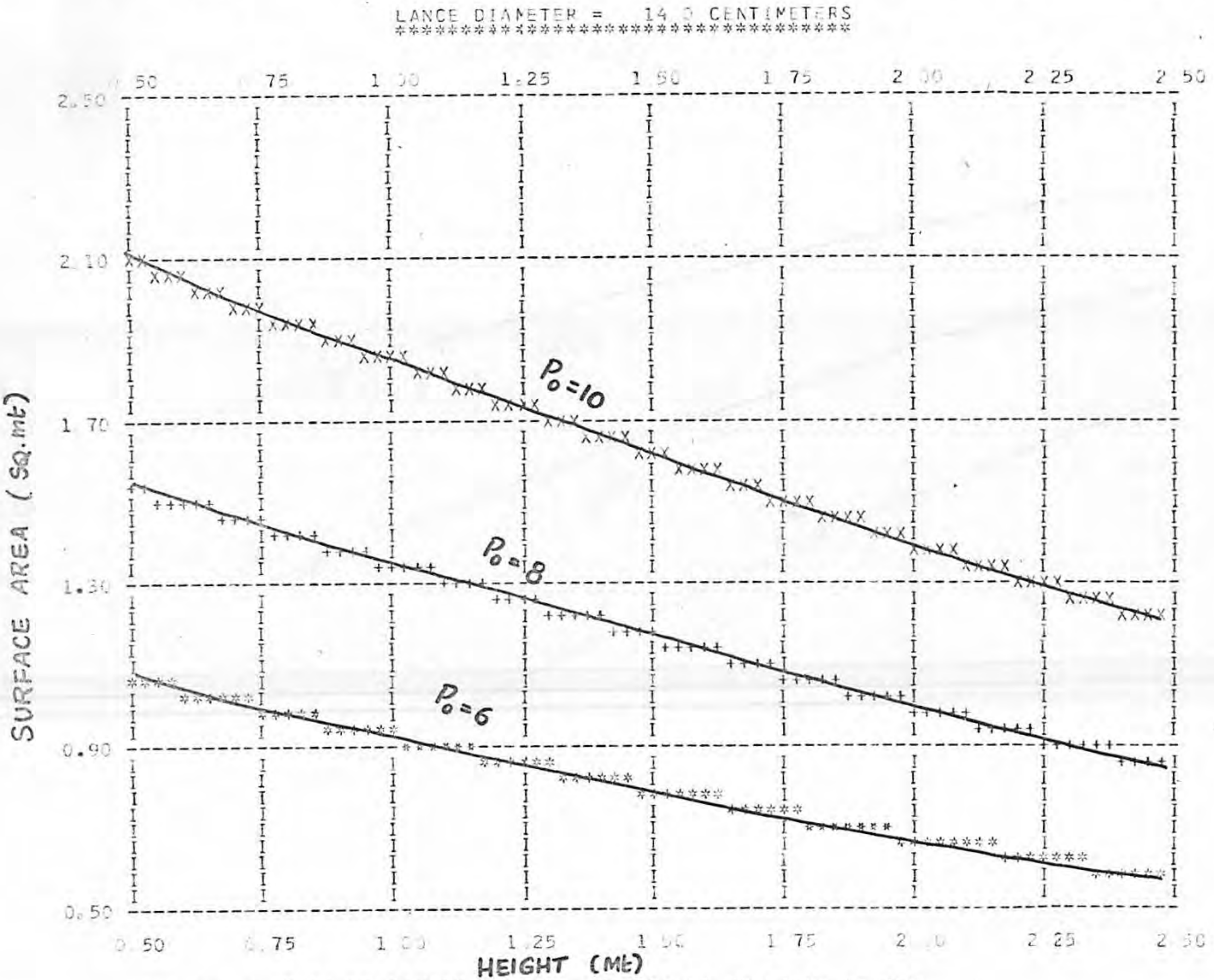


Fig. 4.8 : PLOT OF CAVITY SURFACE AREA(SQ M) VS LANCE HEIGHT

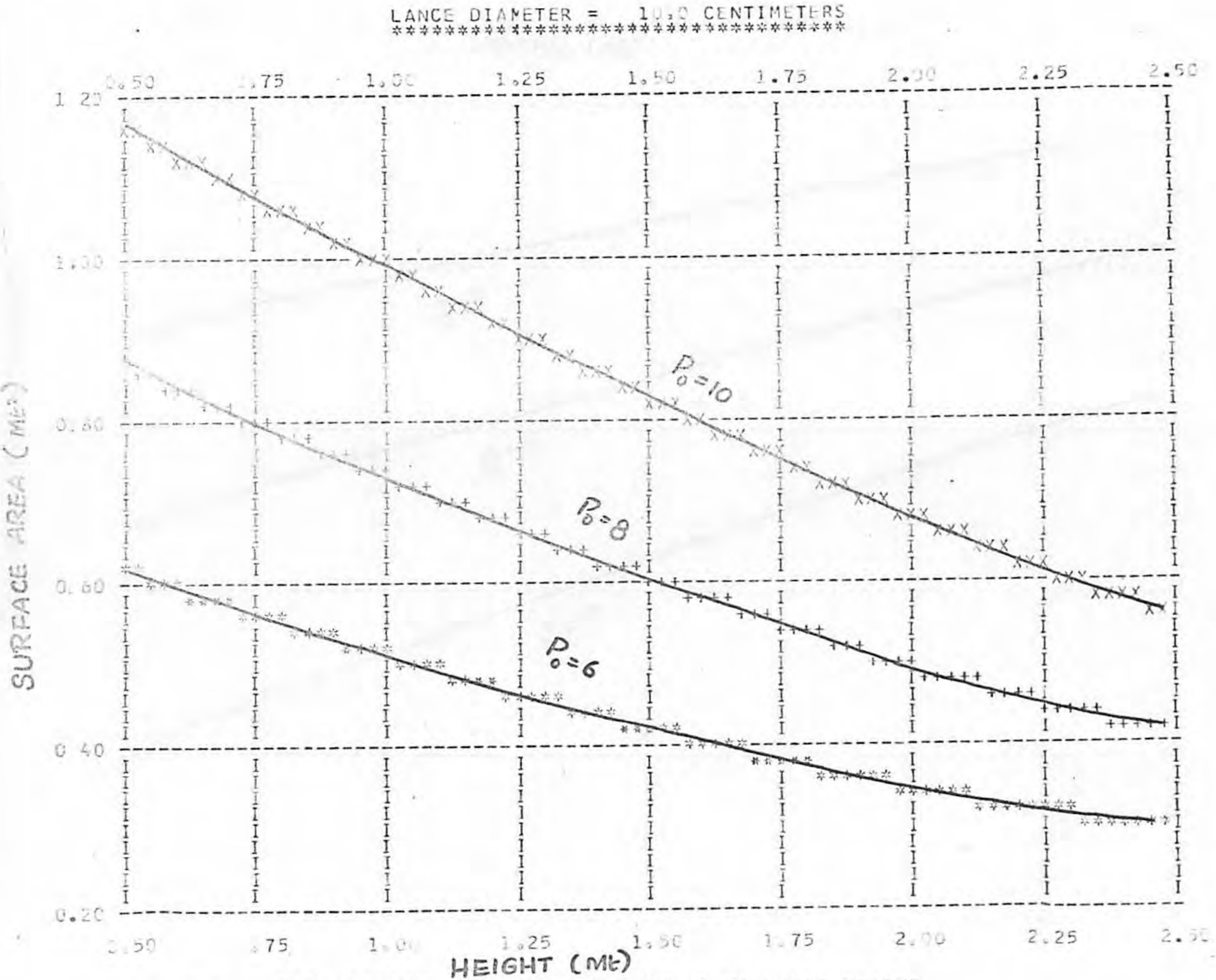


Fig. 4.9 : PLOT OF CAVITY SURFACE AREA(SQ M) VS LANCE HEIGHT

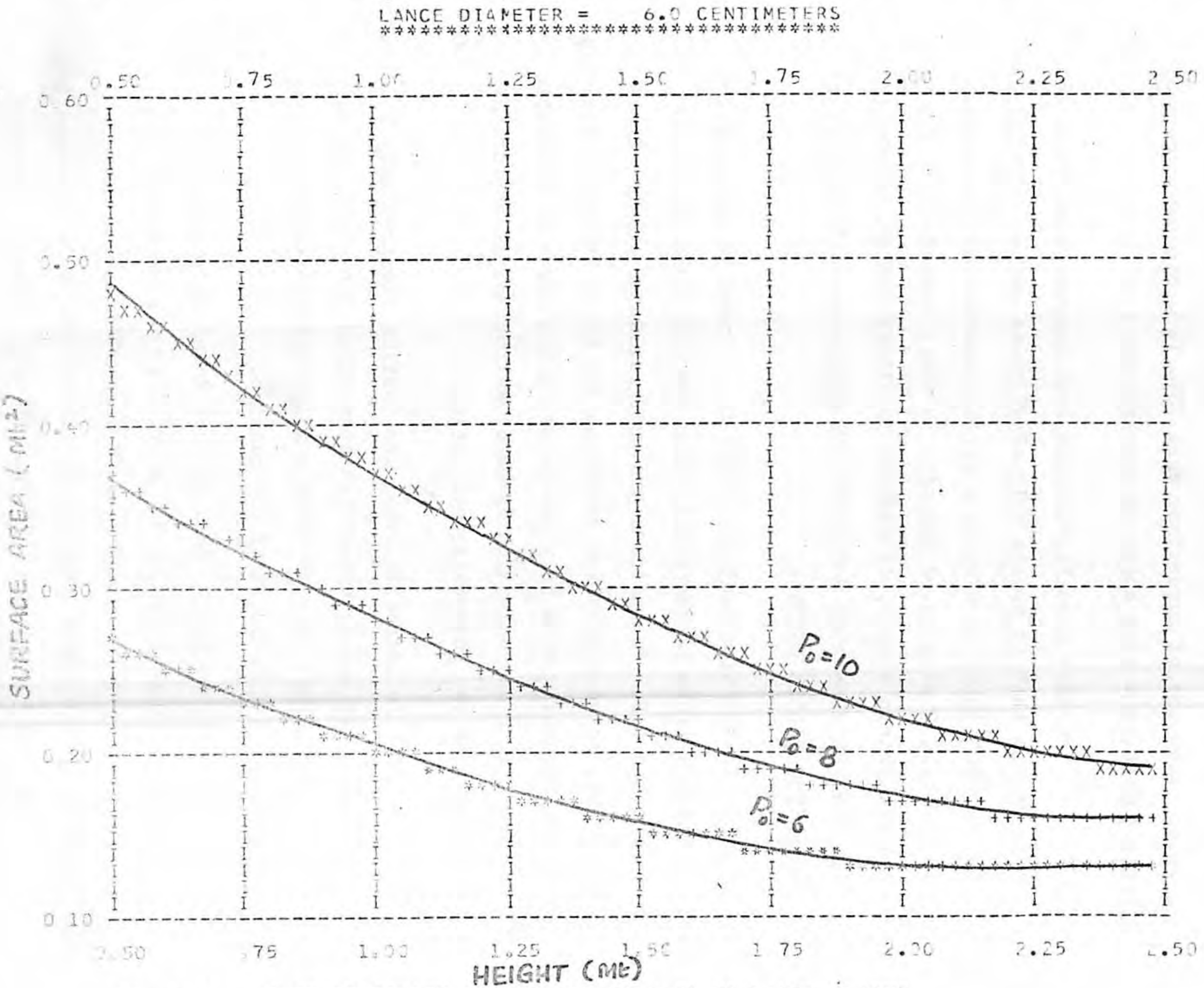


Fig. 4.10 : PLCT OF CAVITY SURFACE AREA(SQ.M) VS LANCE HEIGHT

units of 1/19200 th of a second. No FORTRAN instruction is available to access this time; therefore an ASSEMBLY program, which makes use of supervisor call 'SVC 16', has been written. Fig.4.11 shows a flow chart of time routine.

Further intelligence has been incorporated in to the program, so that it prints only significant units. For example if the time taken to execute a certain section of the program is 0 Hours, 0 minutes, 2 seconds, 30 milli seconds then the program prints simply, '2 SECONDS 30 MILLISECONDS', similarly for 0 Hours 0 minutes 0 seconds 350 milliseconds it will print only '350 MILLISECONDS'.

4.3.5. Integration Routine: This is used to solve differential equations in the model using the algorithm described in section 4.2. To initiate the integration algorithm, it is to be noted, three successive points on the curve should be available. In the beginning when only one point on the curve is available, a rectangular approximation is used; a trapezoidal approximation is used when two points are available.

It is noteworthy that the routine requires only 5 multiplication and four addition operations for each call and takes very little time to solve complex differential equations. Fig.4.12 shows flow chart of the routine.

4.3.6 Control Routine: This is used to specify the lance height and oxygen pressure during the blow. It will be useful during testing of control algorithms . At present both the control variables are assumed constant throughout the blow. However hardly one or two statements will be required, if these variables are to be varied during the blow.

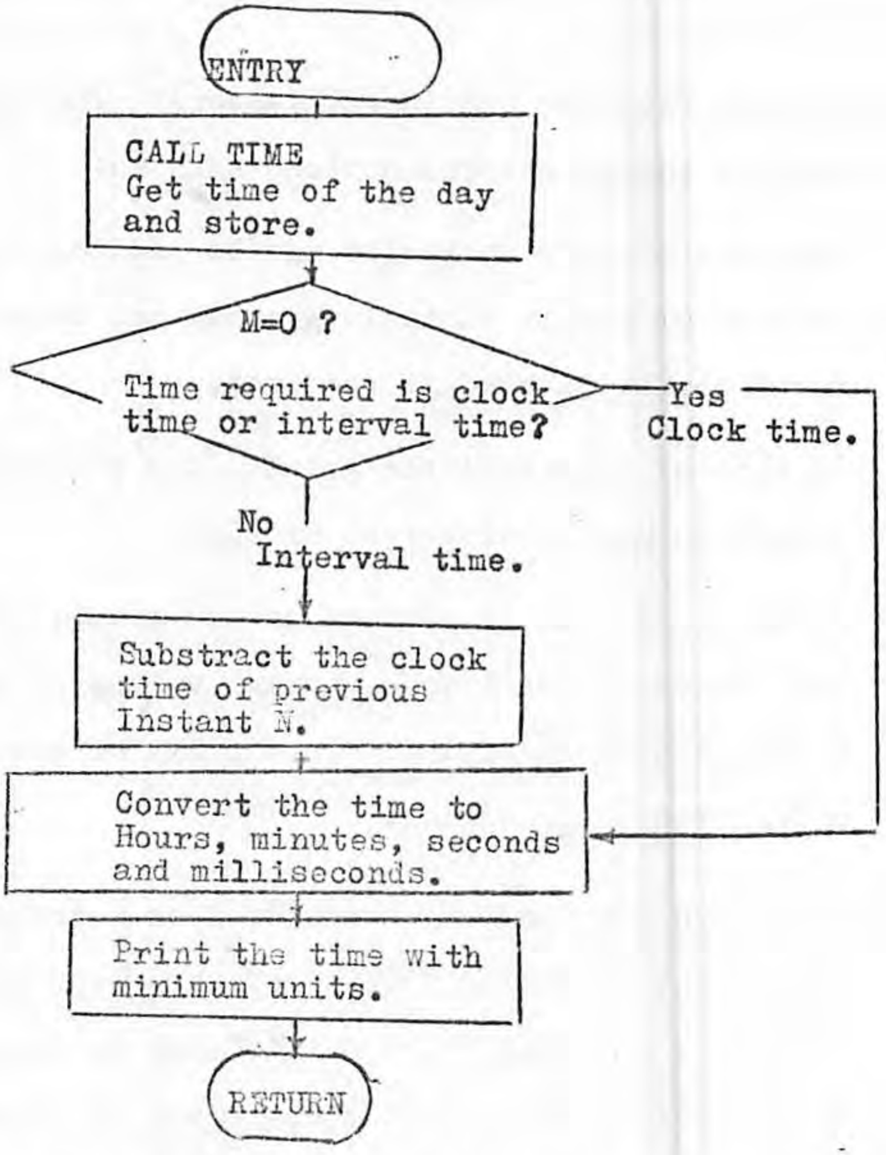


Fig.4.11 Flow chart of TIMER routine.

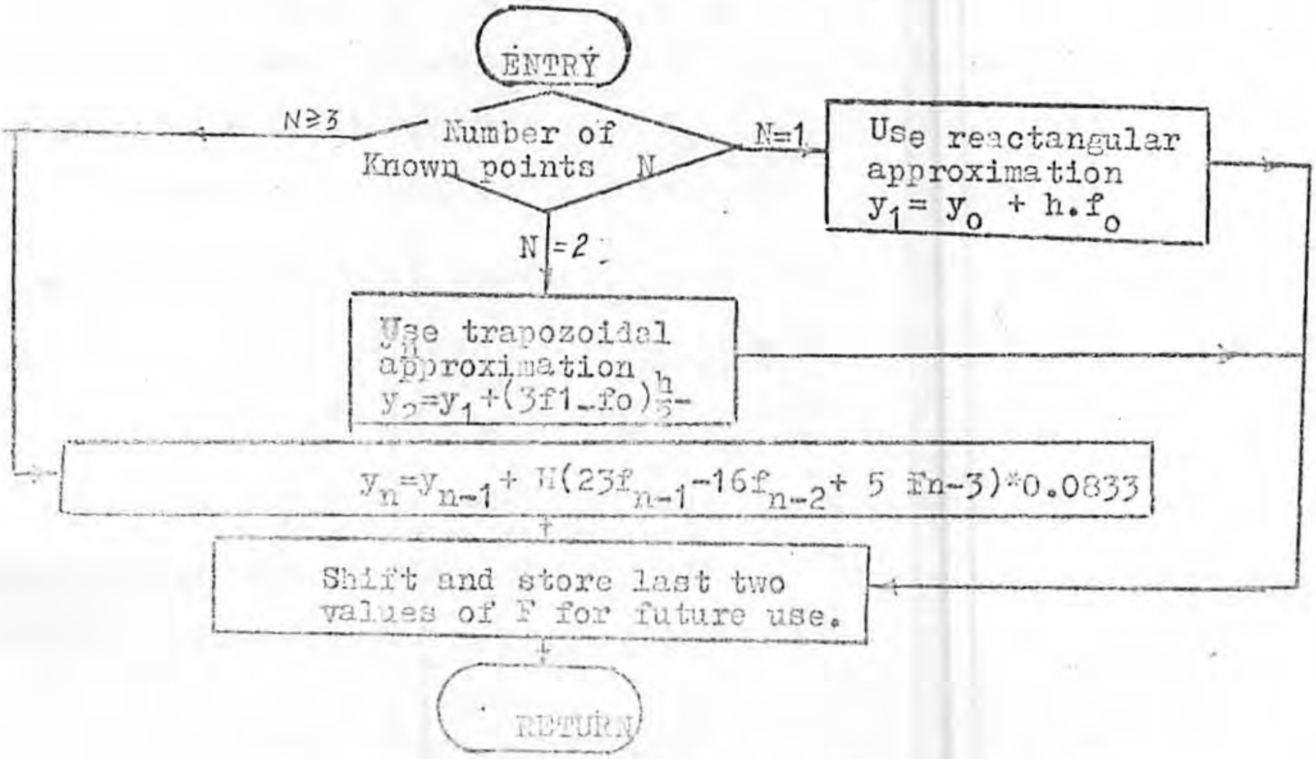


Fig. 4.12 Flow chart of Integration routine INT.

4.3.7. Graph Plotting Routine: (Plotter): This is an excellent plot routine having several options such as:

(a) Only one or more variables can be plotted on the same graph.

(b) In case of single variable graphs, the space below the curve can be hatched if required.

(c) In case of multivariable graphs, the scalefor different variables may be different or same.

(d) An internal grid is plotted on the graph, only if desired.

(e) The scales and maximum - Minimum values of variables may or may not be specified. In the latter case, the routine calculates these values.

(f) The graph plotting may be started on a fresh page if required.

(g) The format of scales printed of the graph can be either E format or F format. F format is easy to read but its range is limited. With E format any small or high value can be printed.

(h) The height and width of the graph can be specified upto a maximum of 100 lines x 100 columns. The program has built in safety if negative or larger than permitted size is specified. In such cases a standard size of 80 x 80 is used.

(i) A title if specified will be added below the graph. The program automatically centers the title and positions it properly depending upon the length of the title.

It is obvious that the larger the number of options the more complex will be the program. This routine requires 25 K bytes of memory on IBM 360/44. Though routines requiring lesser

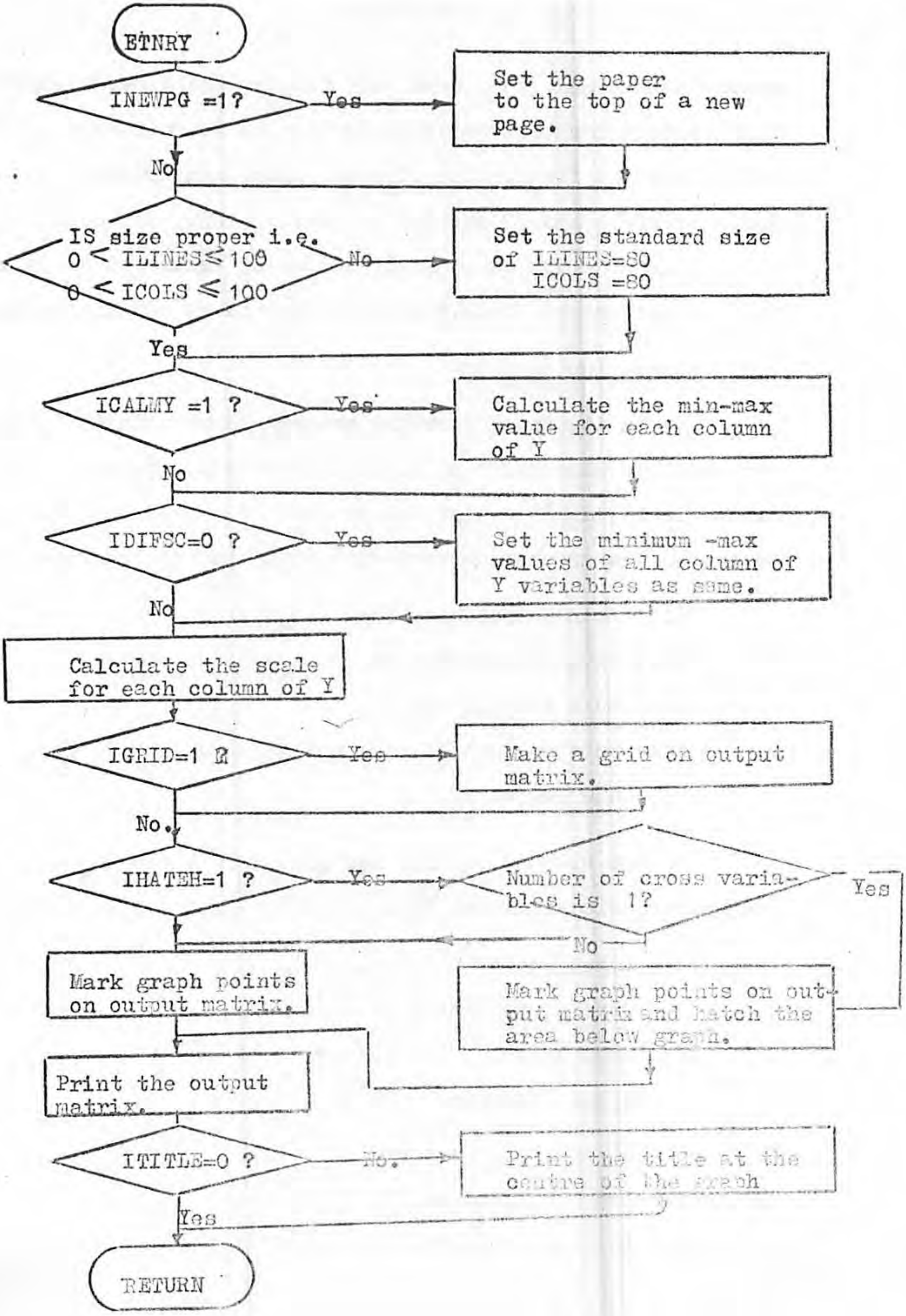


Fig. 4.13 Flow chart of PLOT routine.

memory were tried, they were very complex and time consuming. This routine has been selected in view of the elegance of its output and the flexibility offered by its numerous options. It takes merely 15 to 20 seconds to plot a graph, depending upon the number of cross variables, (number of variables to be plotted on a single graph). Fig.4.13 shows a flow chart of this routine.

4.4. Simulation Results:

In its final form the program takes only 20 to 30 seconds for complete simulation of 30 minutes heat. However, an addtional one minute is required to plot the results in a graphical form if desired. The graphsshow variation of following important variables:

(i) Bath Composition (% C & % Si)

(ii) Oxygen distribution (among C, Si and Fe)

(iii) Bath temperature.

(iv) Total weight of slag and weights of CaO, SiO_2 and FeO in it.

Two sets of results for following lance height and oxygen pressure combinations have been presented in Fig.4.14 to Fig.4.25

(1) Lance height = 1.0 m.
Oxygen pressure = 10 Kg/cm^2

(2) Lance height = 1.5 m.
Oxygen Pressure = 10 Kg/Cm^2

It is evident from the comparison of the two sets of graphs that for lesser lance height, oxygen efficiency is higher (since carbon is reduced to a lower percentage) and also end point temperature is more.

```
                    SIMULATION OF BASIC OXYGEN FURNACE
                    **********************************


                        TIME INSTANT # 1.
CLOCK TIME :   21 HOURS   16 MINUTES    7 SECONDS       860MILLISECONDS



                         DIMENSION OF FURNACE
                         --------------------
             EXTERNAL DIAMETER OF FURNACE          =      6 66 METERS
             TOTAL HEIGHT OF FURNACE               =     11.00 METERS
             THICKNESS OF WALLS                    =        92 METERS
             MOUTH DIAMETER                        =      2 60 METERS
             LANCE DIAMETER                        =       .10 METERS
             HEIGHT OF CONICAL PORTION AT TOP      =        50 METERS



                               CHARGE
                               ------
          MASS OF HOT PIG IRON                  =   150 00   KG
          TEMPERATURE OF HOT PIG IRON           =     1 00   KG
          COMPOSITION OF PIG IRON               =  C =   4   %   SI =   1 2 %
          MASS OF SCRAP                         =    20 00.  KG
          MASS OF LIME                          =    12 00   KG
          MASS OF COLD PIG IRON                 =            KG
          MASS OF ORE IN KG                     =        00.  50 . 500. 500. 500. 50 .
              CHARGED AT ( IN SECONDS )                  90   21    330  45   570  69
          MASS OF LIMESTONE                     =        300  30    300  300  300
              CHARGED AT ( IN SECONDS )                  30   21    390. 57 . 750.
                       TIME INSTANT #  2
TIME FROM INSTANT #  1 IS :       3 SECONDS         9 0 MILLI SECONDS
```

SET 1 . LANCE HEIGHT = 1.0 M

Fig. 4.14

```
                         BCF SIMULATION RESULTS
                         **********************

   T       TH      C      SI        WS       WM    SIGMA1 SIGMA2 SIGMA3  (T FE)  (SIO2)  (CAO)

   60.   1316.7  3.444  0.376     4141.   168783.  0.504  0.479  0.0175    98.   2492.   1528.
  120.   1421.2  3.134  0.137     6244.   167728.  0.705  0.268  0.0270   192.   3358.   2664.
  180.   1472.7  2.899  0.061     8134.   167112.  0.817  0.149  0.0358   268.   3633.   4169.
  240.   1495.1  2.612  0.020     9039.   166446.  0.899  0.059  0.0413   369.   3783.   4794.
  300.   1517.8  2.416  0.009     9757.   166016.  0.925  0.030  0.0459   447.   3819.   5377.
  360.   1526.8  2.174  0.003    10293.   165492.  0.938  0.011  0.0517   544.   3841.   5761.
  420.   1539.8  1.988  0.001    10868.   165089.  0.939  0.005  0.0566   629.   3847.   6221.
  480.   1543.7  1.774  0.000    11300.   164618.  0.935  0.002  0.0632   730.   3850.   6512.
  540.   1556.0  1.635  0.000    11865.   164306.  0.931  0.001  0.0683   837.   3851.   6977.
  600.   1554.9  1.425  0.000    12217.   163829.  0.922  0.000  0.0776   939.   3851.   7165.
  660.   1563.9  1.310  0.000    12739.   163558.  0.916  0.000  0.0859  1018.   3851.   7585.
  720.   1562.6  1.164  0.000    13101.   163156.  0.905  0.000  0.0949  1140.   3851.   7786.
  780.   1567.4  1.030  0.000    13556.   162870.  0.896  0.000  0.1033  1243.   3851.   8116.
  840.   1574.0  0.943  0.000    14023.   162645.  0.887  0.000  0.1128  1322.   3851.   8478.
  900.   1579.9  0.862  0.000    14479.   162429.  0.878  0.000  0.1221  1424.   3851.   8827.
  960.   1585.2  0.787  0.000    14922.   162221.  0.868  0.000  0.1323  1488.   3851.   9162.
 1020.   1589.9  0.717  0.000    15354.   162022.  0.857  0.000  0.1433  1573.   3851.   9484.
 1080.   1594.0  0.652  0.000    15776.   161829.  0.845  0.000  0.1553  1660.   3851.   9795.
 1140.   1597.7  0.592  0.000    16189.   161642.  0.832  0.000  0.1684  1748.   3851.  10094.
 1200.   1600.9  0.537  0.000    16595.   161461.  0.817  0.000  0.1826  1836.   3851.  10384.
 1260.   1603.7  0.485  0.000    16994.   161286.  0.802  0.000  0.1981  1930.   3851.  10664.
 1320.   1606.2  0.438  0.000    17389.   161115.  0.785  0.000  0.2150  2024.   3851.  10945.
 1380.   1608.2  0.394  0.000    17783.   160948.  0.767  0.000  0.2333  2122.   3851.  11209.
 1440.   1610.0  0.354  0.000    18176.   160784.  0.747  0.000  0.2532  2218.   3851.  11476.
 1500.   1611.5  0.316  0.000    18570.   160623.  0.725  0.000  0.2747  2318.   3851.  11739.
 1560.   1612.8  0.282  0.000    18967.   160464.  0.702  0.000  0.2960  2422.   3851.  12005.
 1620.   1613.8  0.251  0.000    19369.   160308.  0.677  0.000  0.3221  2528.   3851.  12270.
 1680.   1614.6  0.222  0.000    19775.   160152.  0.650  0.000  0.3519  2637.   3851.  12536.
 1740.   1615.3  0.196  0.000    20192.   159998.  0.621  0.000  0.3790  2750.   3851.  12808.
 1800.   1615.8  0.173  0.000    20377.   159843.  0.590  0.000  0.4097  2865.   3851.  12839.

                             TIME INSTANT # 3
 TIME FROM INSTANT #  2 IS :        22 SECONDS          960 MILLI SECONDS

                             TIME INSTANT # 3
 TIME FROM INSTANT #  1 IS :        27 SECONDS          960 MILLI SECONDS
```

Fig. 4.15

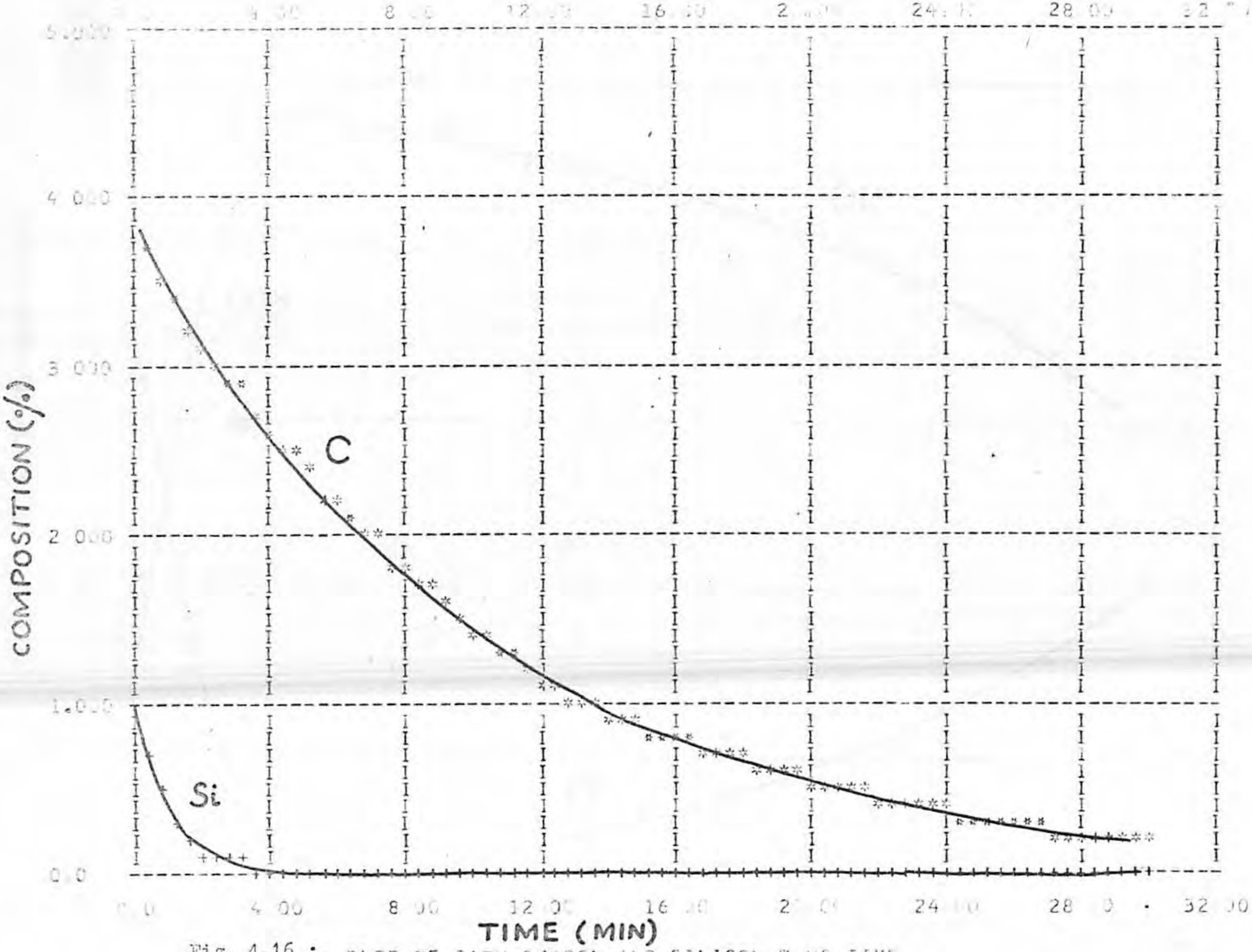


Fig. 4.16 : PLOT OF BATH CARBON AND SILICON % VS TIME

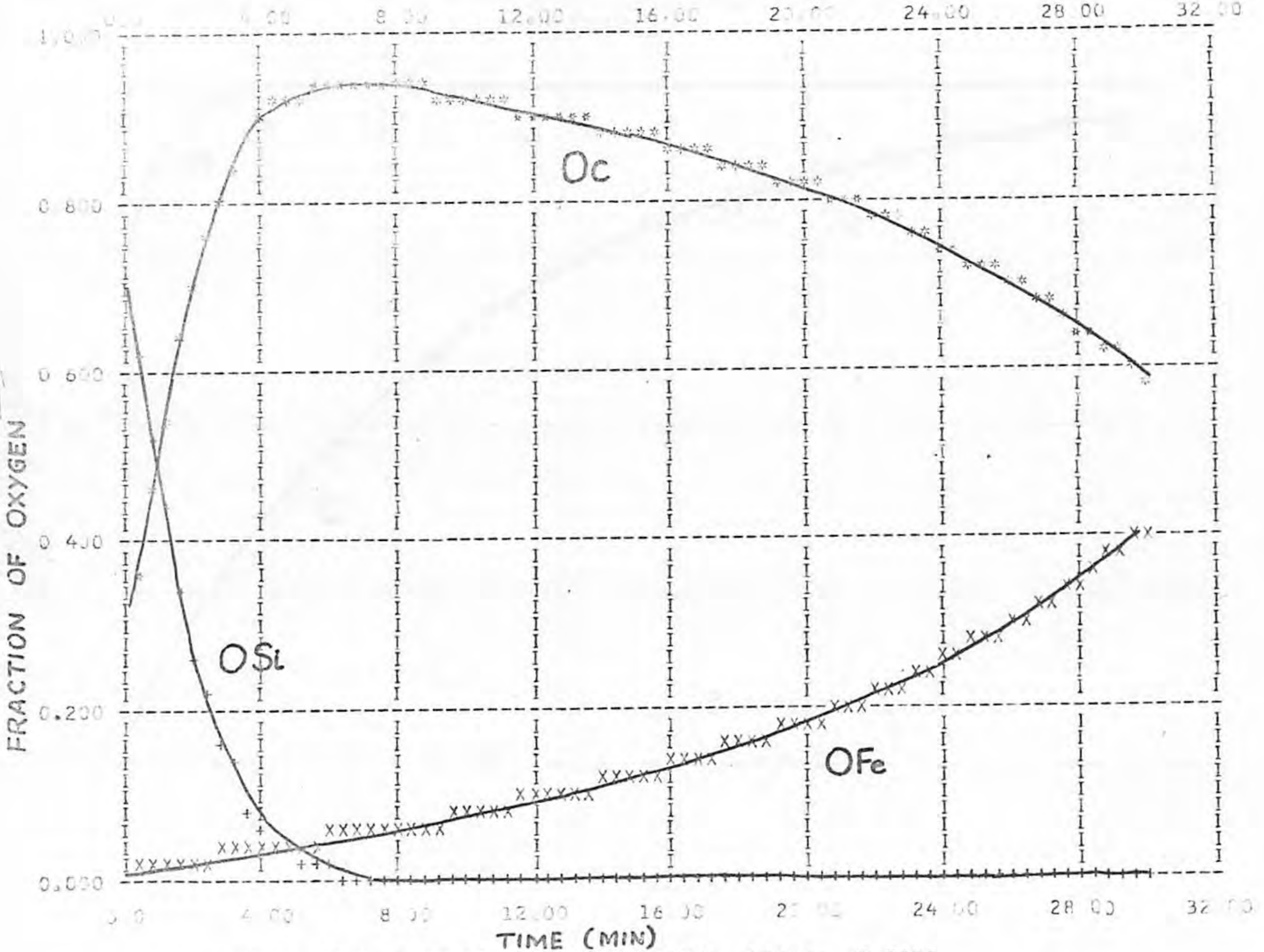


Fig. 4.17 : PLOT OF SIGMA1, SIGMA2, SIGMA3 VS TIME

OXYGEN DISTRIBUTION

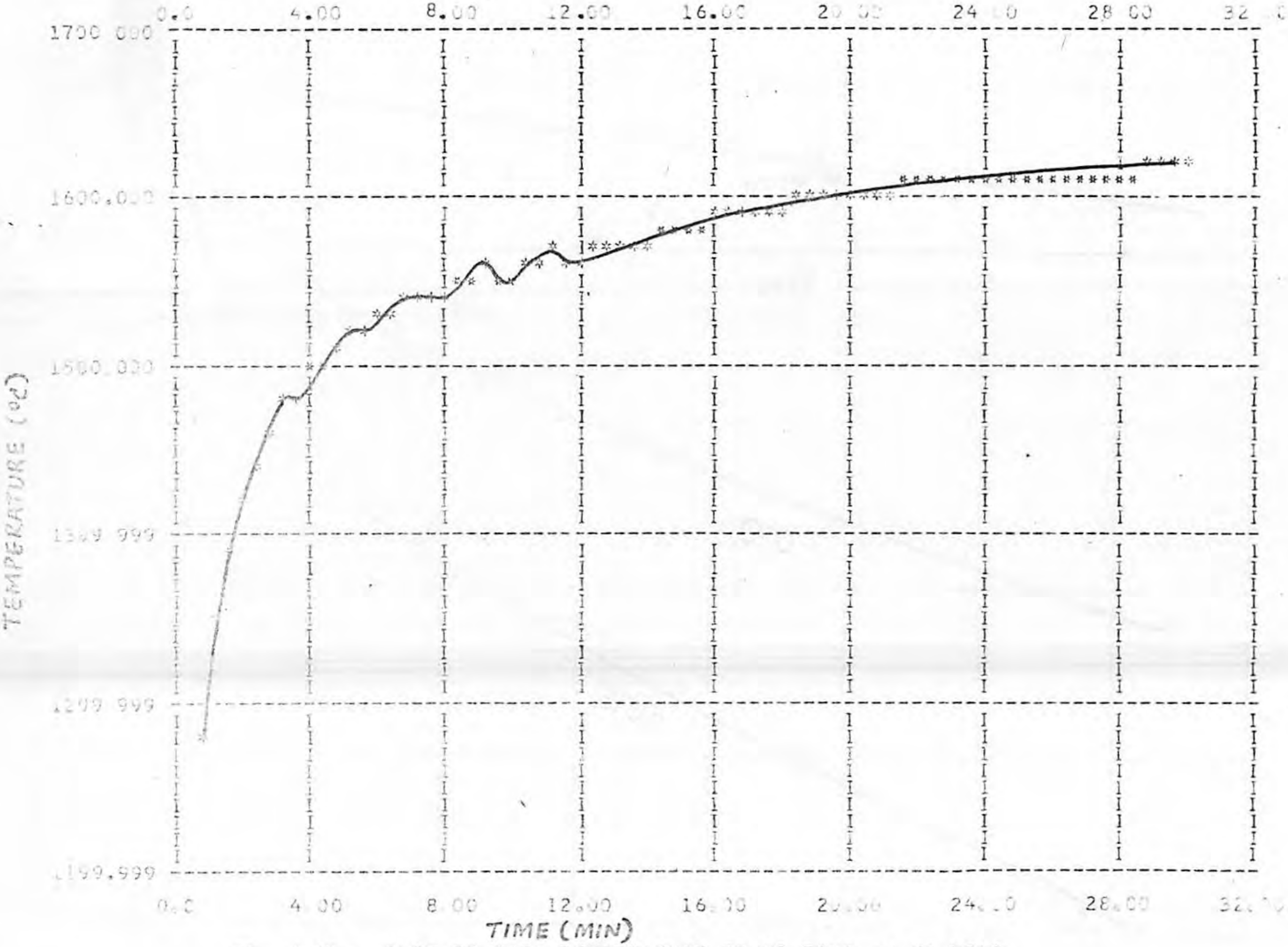


Fig. 4.18 : PLOT OF BATH TEMPERATURE TE VS TIME IN MINUTES

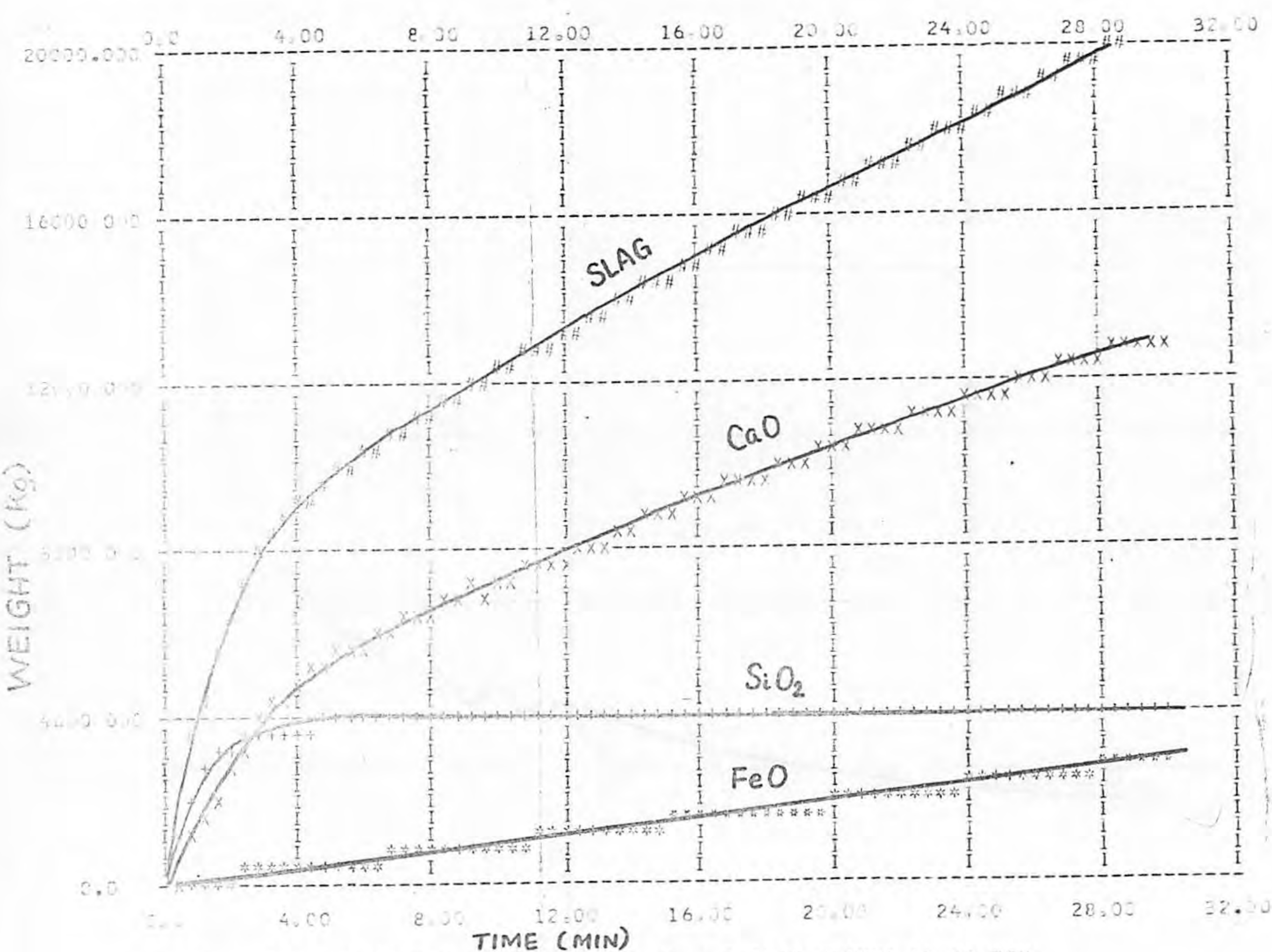


FIG. 4.19 : PLOT OF (T FE) , (SIO2) , (CAO) AND SLAG WEIGHT WS VS TIME

(X) ≡ X IN SLAG

```
                    SIMULATION OF BASIC OXYGEN FURNACE
                    **********************************


                    TIME INSTANT # 1
CLOCK TIME :   23 HOURS   25 MINUTES   52 SECONDS        820MILLISECONDS



                    DIMENSION OF FURNACE
                    --------------------
          EXTERNAL DIAMETER OF FURNACE           =        6.66 METERS
          TOTAL HEIGHT OF FURNACE                =       1 .00 METERS
          THICKNESS OF WALLS                     =         .92 METERS
          MOUTH DIAMETER                         =        2.60 METERS
          LANCE DIAMETER                         =         .10 METERS
          HEIGHT OF CONICAL PORTION AT TOP       =        3.50 METERS



                         CHARGE
                         ------
       MASS OF HOT PIG IRON             =     150000.0 KG
       TEMPERATURE OF HOT PIG IRON      =       1300.  KG
       COMPOSITION OF PIG IRON          =   C =    4.3 %   SI =   1.2 %
       MASS OF SCRAP                    =      20000.0 KG
       MASS OF LIME                     =      12000.0 KG
       MASS OF COLD PIG IRON            =          0.0 KG
       MASS OF ORE IN KG                =        500.0 500. 500. 500. 500. 500.
            CHARGED AT ( IN SECONDS )              90.0 210. 330. 450. 570. 690.
       MASS OF LIMESTONE                =        300.0 300. 300. 300. 300.
            CHARGED AT ( IN SECONDS )              30.0 210. 390. 570. 750.
                           TIME INSTANT #  2
TIME FROM INSTANT #  1 IS :         3 SECONDS        980 MILLI SECONDS
```

SET 2: LANCE HEIGHT = 1.5 M.

Fig. 4.20

```
                BOF SIMULATION RESULTS
                **********************

   T        I3       C      SI        WS        WM   SIGMA1  SIGMA2  SIGMA3   (T FE)   (SIO2)   (CAO)

[illegible]  127[illegible].1  5.1[illegible]  0.466      587  169679  0.457  0.527  0.0157      77.    2158.    1352.
[illegible]  [illegible]  2.2[illegible]2  0.197    5355  168648  0.640  0.337  0.02[illegible]7     159     3140     2027
[illegible]  [illegible]8.8  [illegible]6  0.102    69[illegible]3.  168[illegible]78  0.752  0.219  0.[illegible]297     221     [illegible]483     3167
[illegible]  14[illegible]5.7  [illegible]799  0.041    8289  1674[illegible]6  0.855  0.108  0.[illegible]68     [illegible]     [illegible]704     421[illegible]
[illegible]  [illegible]  [illegible]  0.022    [illegible]903  1670[illegible]8  0.895  0.064  0.[illegible]9     [illegible]     [illegible]773     4677
[illegible]  [illegible]7.[illegible]  [illegible]8  0.009    9283.  16666[illegible].  0.925  0.029  0.0461     445     [illegible]820     4997
42[illegible]  15[illegible]9.5  2.243  0.004    9832  166248  0.935  0.015  0.0500     [illegible]13     [illegible]836     5343
[illegible]  15[illegible]2.5  [illegible]7  0.002   10162  165821  0.939  0.006  0.0550     [illegible]     [illegible]845     5550
[illegible]  [illegible]  [illegible]1  0.001   10588.  16554[illegible].  0.938  0.003  0.0586     660.     [illegible]848.    5896.
[illegible]  [illegible]  [illegible]722  0.000   10835  16510[illegible]  0.934  0.001  0.0651     762     3850     6009
[illegible]  [illegible]  1.614  0.000   11233  164862  0.930  0.001  0.0691     82[illegible]     [illegible]850     6[illegible]28
[illegible]  1528.8  1.432  0.000   11485  164490  0.923  0.000  0.0763     922.     [illegible]851.    645[illegible].
[illegible]  [illegible].5  1.[illegible]  0.000   11829  1[illegible]4228  0.918  0.000  0.0822     997     3851     670[illegible]
[illegible]  [illegible]  1.258  0.000   12[illegible]98.  164[illegible]2  0.913  0.000  0.0873    1[illegible]59     [illegible]851     699[illegible]
[illegible]  1546.4  1.172  0.000   12565  163821  0.907  0.000  0.0929    1122     [illegible]851     7275
[illegible]  1552.1  1.094  0.000   12925  163629  0.901  0.000  0.0988    118[illegible]     [illegible]851     755[illegible]
[illegible]  1557.[illegible]  1.021  0.000   13282.  163444.  0.895  0.000  0.1[illegible]51    125[illegible].    [illegible]851     7828
[illegible]  1562.0  0.953  0.000   13632  163265  0.888  0.000  0.1118    1[illegible]15     [illegible]851     8[illegible]94
[illegible]  1566.3  0.888  0.000   13975  163092  0.881  0.000  0.11[illegible]1    1[illegible]8[illegible]     [illegible]851     8[illegible]5[illegible]
[illegible]  1571.1  0.826  0.000   14311  162924.  0.873  0.000  0.1268    [illegible]46.    [illegible]851.    860[illegible].
[illegible]  157[illegible].8  0.768  0.000   14641  162762  0.865  0.000  0.135[illegible]    1513     3851     8848
[illegible]  1576.8  0.7[illegible]4  0.000   14964  162604  0.856  0.000  0.1[illegible]38    1581     [illegible]851     908[illegible]
138[illegible]  1579.6  0.66[illegible]  0.000   15282  162451  0.847  0.000  0.1[illegible]2    1649     [illegible]851.    9313.
[illegible]  15[illegible]2.[illegible]  0.614  0.000   15594  1623[illegible]  0.8[illegible]7  0.000  0.1[illegible]    1719     3851     9536
[illegible]  1584.2  0.569  0.000   159[illegible].  162158.  0.826  0.000  0.1741    1789     [illegible]851     9752
[illegible]  1586.2  0.526  0.000   162[illegible]3  162016  0.814  0.000  0.1855    186[illegible]     [illegible]851     9962
[illegible]  1587.8  0.486  0.000   165[illegible]2  161878  0.8[illegible]2  0.000  0.1978    193[illegible]     [illegible]851    10167
[illegible]  1589.2  0.449  0.000   16797.  16[illegible]74[illegible].  0.789  0.000  0.2[illegible]9    2[illegible]6.    [illegible]851.   [illegible]369
[illegible]  1[illegible].5  0.413  0.000   17090  161611  0.775  0.000  0.2248    2[illegible]81     3851    10565
[illegible]  1591.5  0.38[illegible]  0.000   17382  161481  0.760  0.000  0.2397    2157     [illegible]851    10759

                      TIME INSTANT #  3
TIME FROM INSTANT #  2 IS :    22 SECONDS        960 MILLI SECONDS

                      TIME INSTANT #  5
TIME FROM INSTANT #  1 IS :    27 SECONDS        760 MILLI SECONDS
```

Fig. 4.21

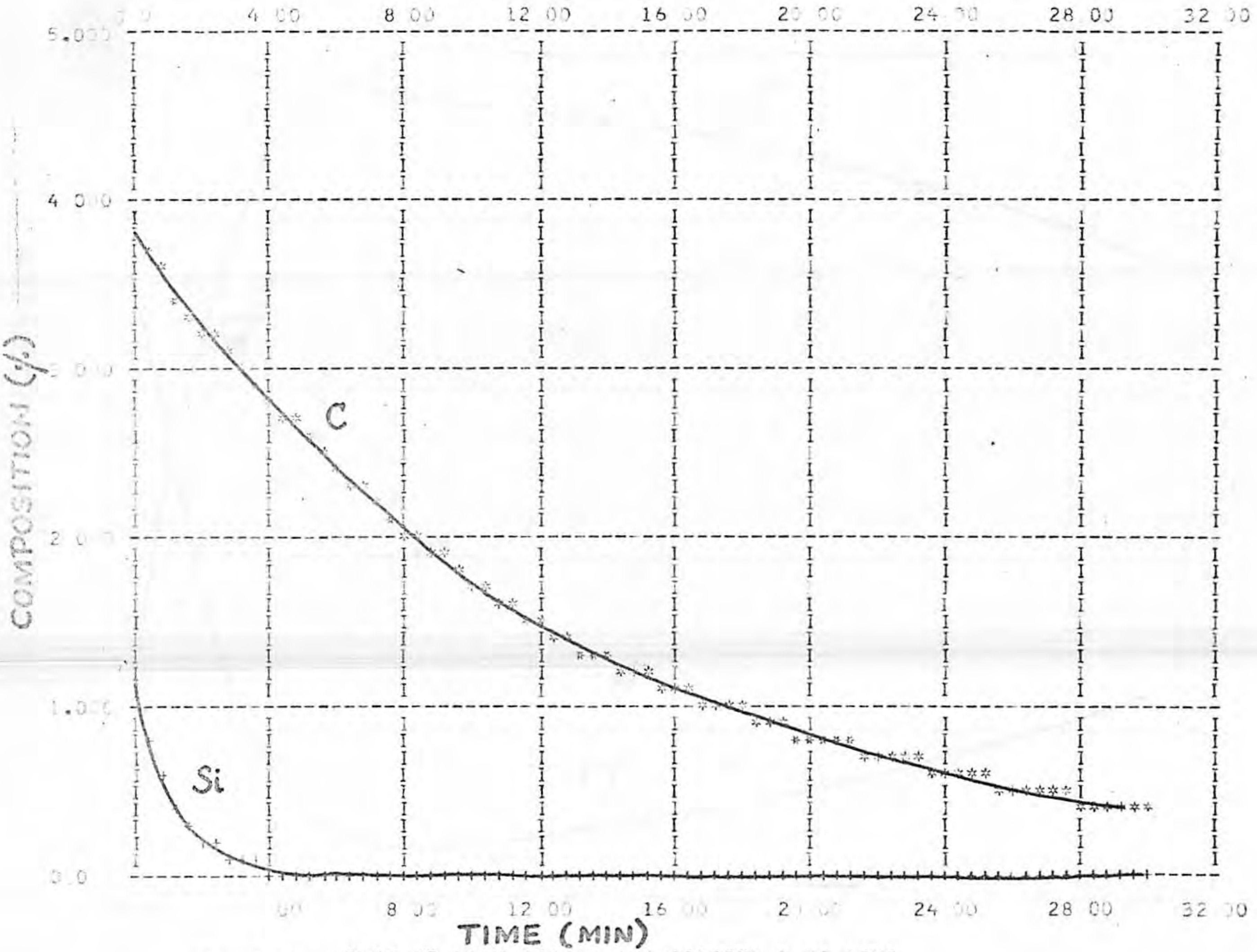


Fig. 4.22 : PLOT OF BATH CARBON AND SILICON % VS TIME

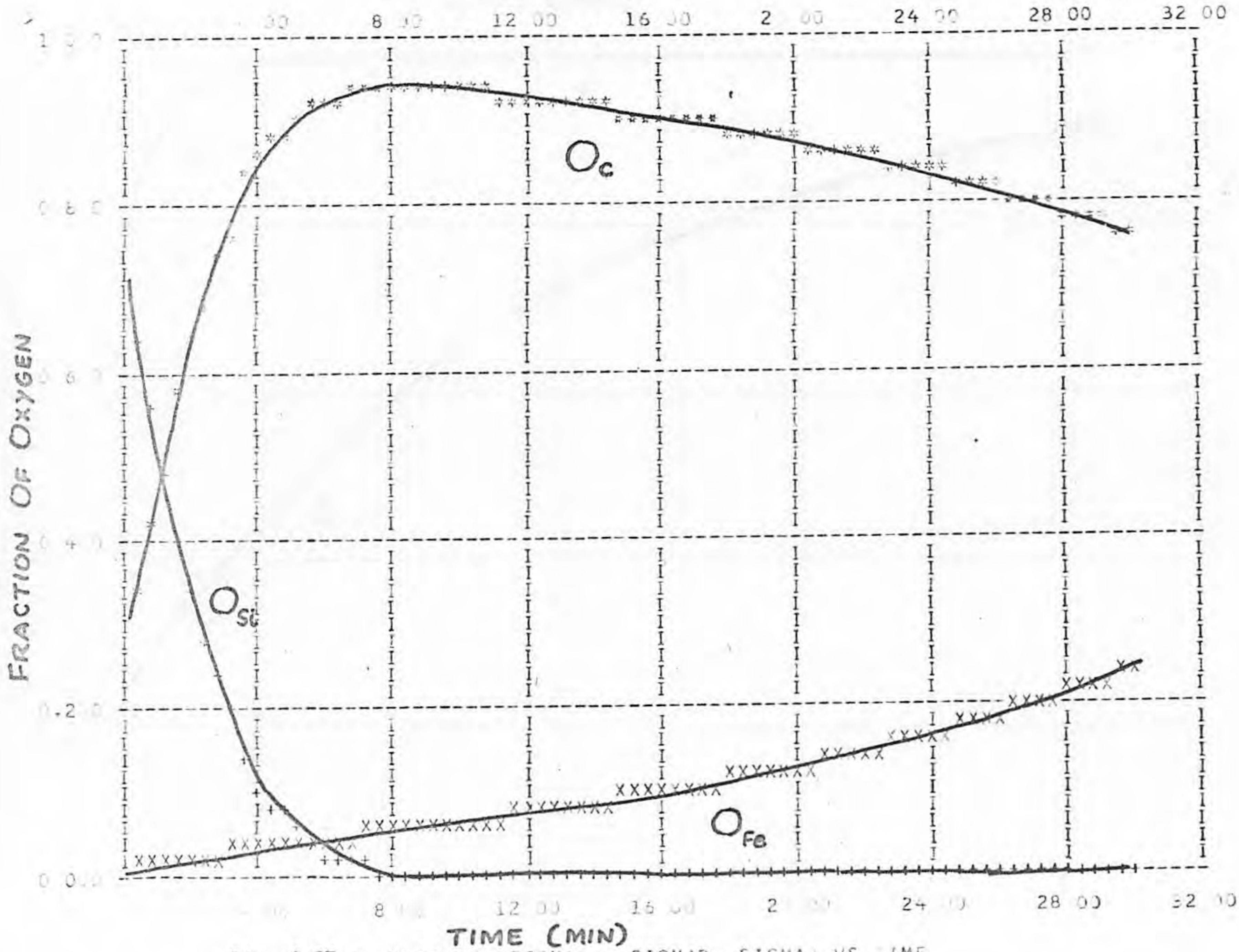


Fig. 4.23 : PLOT OF SIGMA1, SIGMA2, SIGMA3 VS TIME

OXYGEN DISTRIBUTION

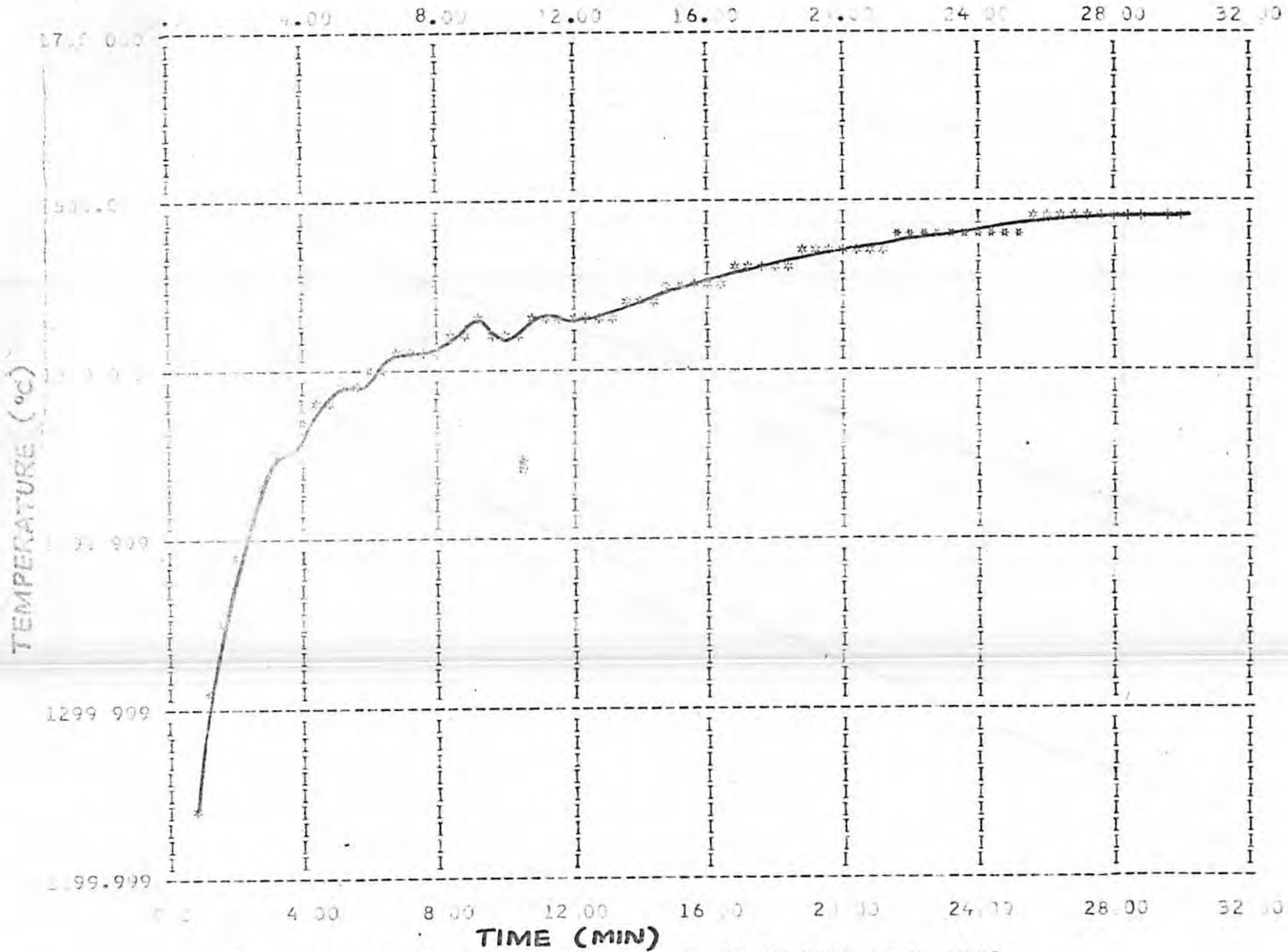


Fig. 4.24 : PLOT OF BATH TEMPERATURE TB VS TIME IN MINUTES

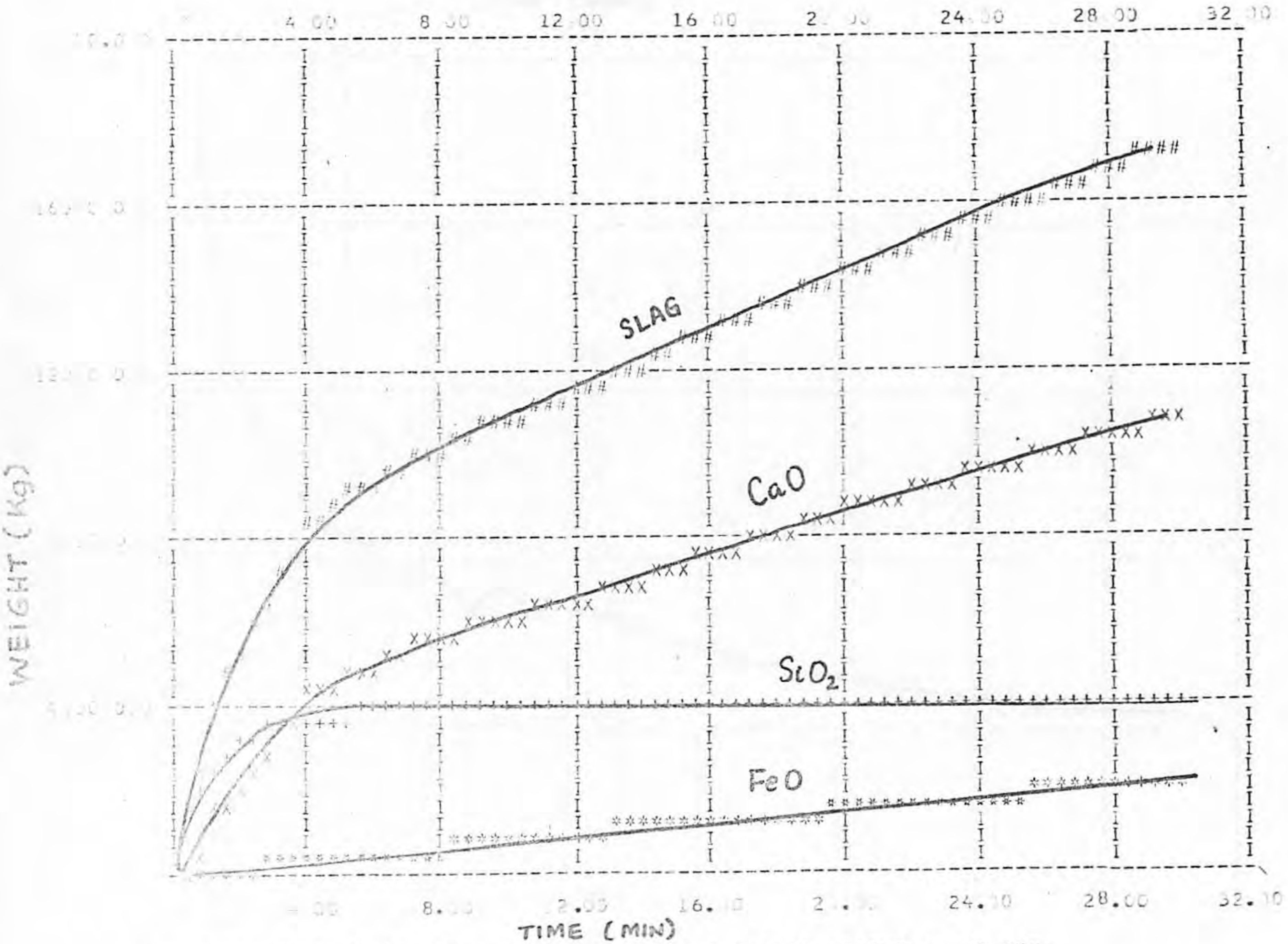


Fig. 4.25 : PLOT OF (T FE) , (SIO2) , (CAO) AND SLAG WEIGHT W. VS TIME

(X) ≡ X IN SLAG

Undulations in the temperature curves due to additions of lime and ore during the blow, are clearly noticeable. The results also show the computer time used in computation.

4.5 Future Modifications: A better correlation between simulation results and actual process can be obtained by further modifying the model equation, parameter values and simulation program. In particular the following modifications are suggested:

1. Incorporation of Exhaust gas simulation [2]
2. Further improvement in Lance simulation model [7]
3. Proper accounting of cooling effects of scrap melting [8] and limestone or ore dissociation.
4. Proper adjustment of values of following parameters.
    - i. Heat transfer coefficients (H_L and H_g)
    - ii. Activity coefficient of silicon (K_2).

References:

1. JAIN R.K., 'Models of LD converter for its Automation', Proc. Symposium on Industrial Automation, I.I.Sc. Bangalore, June 1974.
2. Asai S., and Muchi I., 'Theoretical analysis by the use of mathematical model in LD converter operation', Trans. ISIJ Vol.10, 1970, p. 250.
3. Otsuki M. and Muchi I., ' The behaviour of gas flow around the fire point of LD converter', Tetsu-to- Hagane, Vol.53, June 1967, No.7.

4. 'IBM System/360 Model 44. Programming System:Guide to System use for Fortran Programmer' Form C28 -6813 p 24.

5. 'IBM System /360 Model 44 Programming System: Guide to system use,'Form C 28-6812 p 60 and p 90.

6. 'IBM System /360 Model 44 Programming System: Assembler Language' Form C 28-6811.

7. Denis E., ' Determination and influence of jet characteristics in the LD and LD-AC Processes', CNRM Metallurgical report, No. 8, September 1966 p.17.

8. Asai S. and Muchi I., 'Effect of scrap melting on process variables in LD converter caused by the change of operating conditions', Trans. ISIJ Vol. 11 1971, p.107.

CHAPTER -5

COMPUTER SYSTEMS AND INSTRUMENTATION

5.1 Need for Computer Control:

Computer Control is essential for LD converter operation due to the reasons discussed below and summarized in Table 5.I.

i. Fast Dynamics of the process: The total blowing time for one heat of 50-250 tons of steelmaking by LD converter is merely 20-30 minutes as opposed to 9-10 hours by conventional open hearth furnaces. It is generally demanded that all the heats be controlled within the tolerance of 0.02% in carbon and 5°C in temperature without slopping & sparking [1]. In order to stop blow refining process which is proceeding at the decarbonization speed of 0.1% per min at the desired point, it is ncessary to accurately set the process with an allowance of only 10-12 seconds. Moreover, the reactions inside the converter are highly violent.

Thus LD converter requires a control system with capability to sense, judge and initiate control action in seconds time in a violent environment. The precise control of these fast operation is beyond the capabilities and judgement of a human operator.

ii. Stochastic and Metastable Nature of the Process: The decarburization curves for two heats with exactly similar blowing practices are not always same as shown in Fig 5.1 [2]. The most obvious explanation for variation in decarburization path is that the physical disposition of scrap within the vessel and/or its size

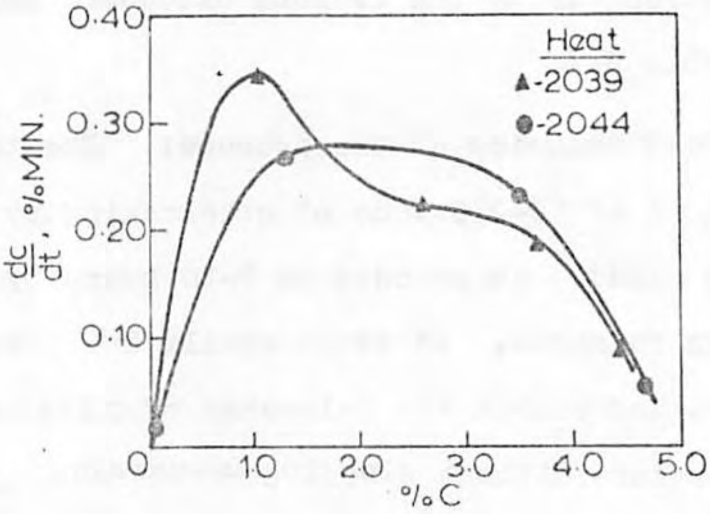


Fig.5-1: Decarburization rate Vs. carbon content for two heats under identical blowing conditions. [2]

affect the degree to which the scrap acts as a baffle and interferes with the development of bath turbulance.

Li and co-workers [3] have, however, shown that different decarburization paths can exist even when only iron-carbon melts are blown without any scrap. The conclusion is that that the process is metastable, that is, minor differences in chemistry or blowing performance may lead to major differences in paths of refining. This stochastic behaviour of the process makes the manual control with a fixed standard practice less reliable.

iii. Unavailability of Direct Measurements: The inaccessibility of the bath, the violence of the reactions as well as high levels of temperature in the bath make direct measurements of important variable like carbon and temperature impossible. The time delay and noise introduced by indirect methods e.g. via exhaust gas analysis necessitate some kind of prediction and filtering techniques to be incorporated in control schemes. This task is almost impossible for a human operator.

iv. Increased Production: With manual control, it has been experience that 50% to 70% of the heats will have incorrect end point conditions and hence require corrective measures. A reblow extends the process time by 20-30% and reduces the number of heats per day and hence the productivity of the system. With computer control, the proportion of off specification heats is considerably reduced.

Table 5-I:Reasons for computer control of LD converters.

1. Fast dynamics of LD process
2. Stochastic and metastable nature of LD process.
3. Unavailability of direct measurements.
4. To reduce the number of off specification heats.

Significant improvement in the quality of product can be achieved with the help of a real time computer. A real time computer is versatile and flexible enough to provide an effective and economical control of LD converters. The pay off period based on savings due to reduction in scraploss, iron loss in slag, in flux requirements and further increase in production by reducing tap to tap time etc is claimed to be 4 years.

5.2 Computer Functions:-

A real time computer installed for process control of LD converters can perform several functions, depending upon the level of control (data logging, operator guide, closed loop control) [4]. A common practice is to use data logging only during the first year of installation of computer and slowly incorporate operator guide and then closed loop control.

In data logging phase, computer's only function is to scan the various process signals and record them. In operator guide phase, computer calculates control variables, however, control action is actually performed by process operator. In close loop mode, control is done directly by the computer.

Various possible computer functions in the most advanced stages are discussed below and summarized in Table 5-II:

5.2.1. Charge calculation: Using a static model the computer can calculate the weights of raw materials like hot metal (from blast furnace), scrap, lime etc required to achieve the specified end point conditions.

5.2.2. Sequence Control: It consists of identifying a series of steps in vessel cycle by automatic or manual signals sent to the computer, so that the computer has the possibility to know what point of operational sequence has been reached. The instants identified can be for example:

- start charging scrap
- start charging hot metal
- start blow or reblow
- charge flux
- end blow
- tap heat.

These signals serve also for time records, so that the main operations of the cycle can appear on the heat log.

5.2.3 Dynamic Control: When the signal 'start blow' is detected by the computer, the lance is lowered and oxygen opened under control and from this time on a scanning cycle is initiated. Every five seconds, for example, information is read from the gas analysis system and computation of total carbon having left the bath as well asdecarburization rate is made. In a close loop installation the computer directly controls the process using results of gas analysis . The different control schemes used for LD converters have already been discussed in Chapter 3.

Table 5. II: Functions of computer control Systems:

	Function	Objective	Action	Inputs data
1.	Static Control	Aimed end point specifications.	wt.of hot metal, wt.of scrap, wt.of Flux, wt of O_2	Aimed steel weight Molten Pig Iron Compsition. Desired end point composition. Desired end point Temperature.
2.	Sequence control.	Partial automation of operations.	Automatic action and displays.	Process Data Manual Input.
3.	Dynamic Control.	Adequate blowing conditions and Aimed end point specifications.	Lance Height oxygen flow-rate .	Gas analysis Bomb thermocuple reading.
4.	Adjusting calculations.	Tapping Temp. Laddle carbon.	Cooling time coolant wt. Reblow time.	End point Temp. End point C Aimed tapping temp. Aimed laddle C.
5.	Laddle Addition Computation.	Deoxidation Laddle Analysis.	Coke, Fe-Mn Fe-Si Si-Mn, and Al weight.	End point Analysis Aimed laddle Anal. Alloy [illegible] yield Alloy cast.
6.	Adaptive Control.	Correct Model.	Parameters Adjustments.	System performance.
7.	Data Logging.	Heat sheets shift report daily report.	Data logging.	Operation control data. Technical anal.data Daily data.
8.	Spectrometer Interpretation and Limit checking.	Metal and gas analysis accuracy.	Calibration and interpretation of spectrometer signals.	Spectrometer signals.
9.	Monitoring Equipment Status.	Detection of Faults.	Indication to-operator.	Process supervision signals.
10.	Back-ground Functions.	Off line tasks		Program.

5.2.4 Adjusting Calculations: After the 'end blow' signal the final metal composition and temperature are measured and sent to computer. It decides whether any adjustments such as cooling or reblowing is to be done and if so it prints out:

i. Coolant weight and cooling time.

ii. Reblow time.

5.2.5. Laddle Additive Computations: During tapping laddle additions are usually made to raise concentration of non-ferrous elements in steel to the level suitable for the grade of steel being manufactured. .

It is important that the laddle addition be made accurately and consistently. This is because the grade specification can be missed entirely by misuse of additives and that the several of the additives are expensive. Therefore the additive calculations are performed by the computer and displayed to the operator.

5.2.6. Adaptive Control: Adaptive control is a way of learning from experience. The computer maintains a running statistical appraisal of the system performance and adjusts the control model to compensate for trend errors. Such adaptive corrections will over a long period improve, the models fit to the process. Fig 5-2 shows the static, dynamic and adaptive controls diagrametically[7]

5.2.7. Data Logging: A log can be obtained for each heat, each shift or each day.

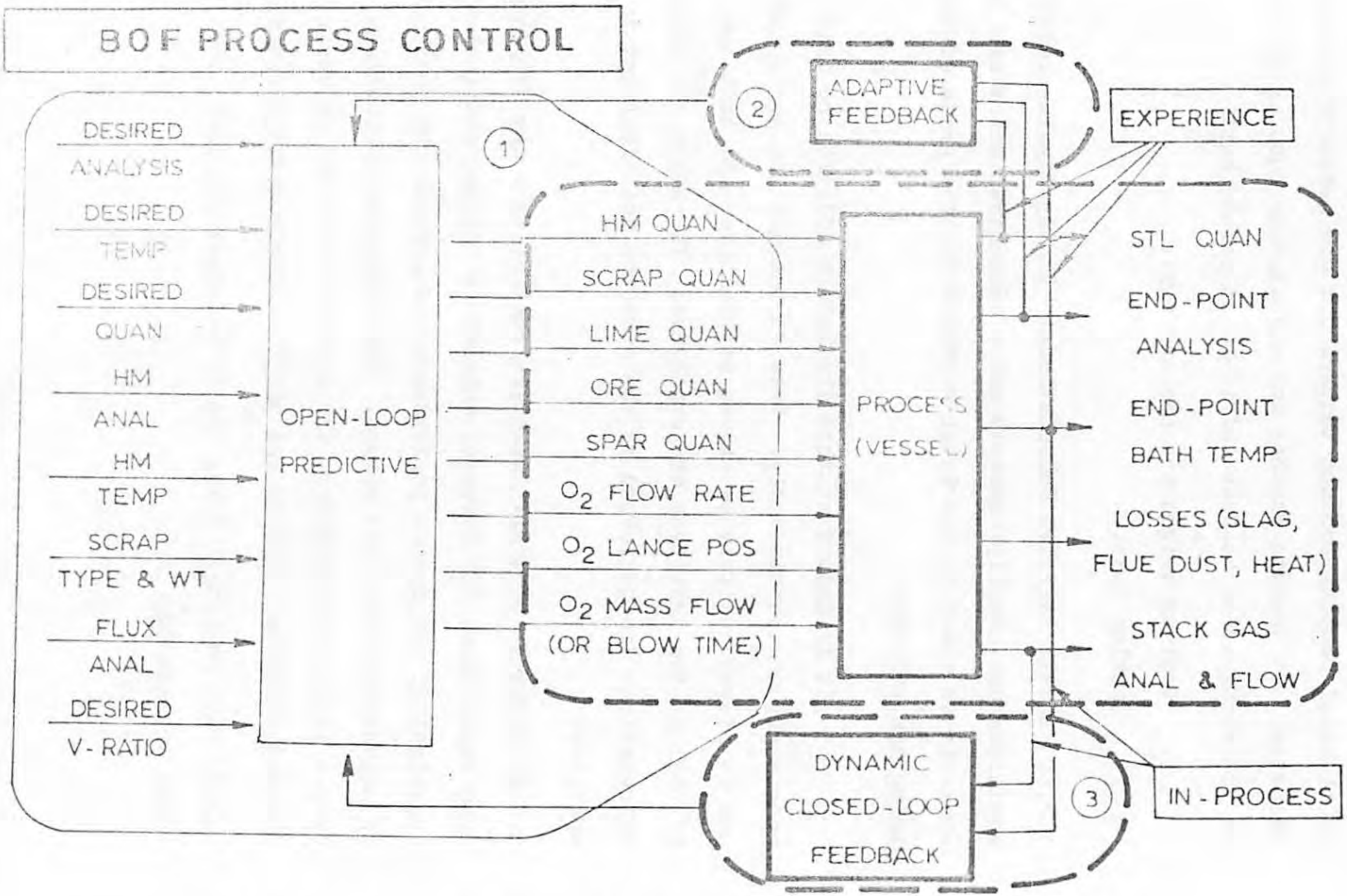


Fig. 5-2 STATIC, DYNAMIC AND ADAPTIVE CONTROLS.

i. Heat Sheets: The heat reports are generally written on paper carrying pre-printed headings in plain languages. The heat sheet can be more or less elaborate depending on the amount of information that the user will deem necessary to keep for records. Generally speaking, it could contain all information from the arrival of blast furnaces metal to teeming or even stripping information.

ii. Operator's Sheet: This sheet supplies the operator with all instantaneous information that he might need in the control of the process.

iii. Shift report. This may be done on a separate typewriter. Informations about each heat is typed in one line. At the end of the shift, the summary of all the heats in this shift is recorded.

iv. Daily report and Administrative Management: Every day the computer may issue a report on the administration management, which, for example may include the total amount of material consumed on the day before and similar information.

5.2.8 . Spectrometer Interpretation and Limit Checking: Vacuum spectrometers are commonly used to determine bath chemistry. They can be linked directly to computer, which provides interpretation of the count information received from the spectrometer and calculates the 'percent analysis' of the sample. In addition the computer provides a number of limit checking functions and averaging functions.

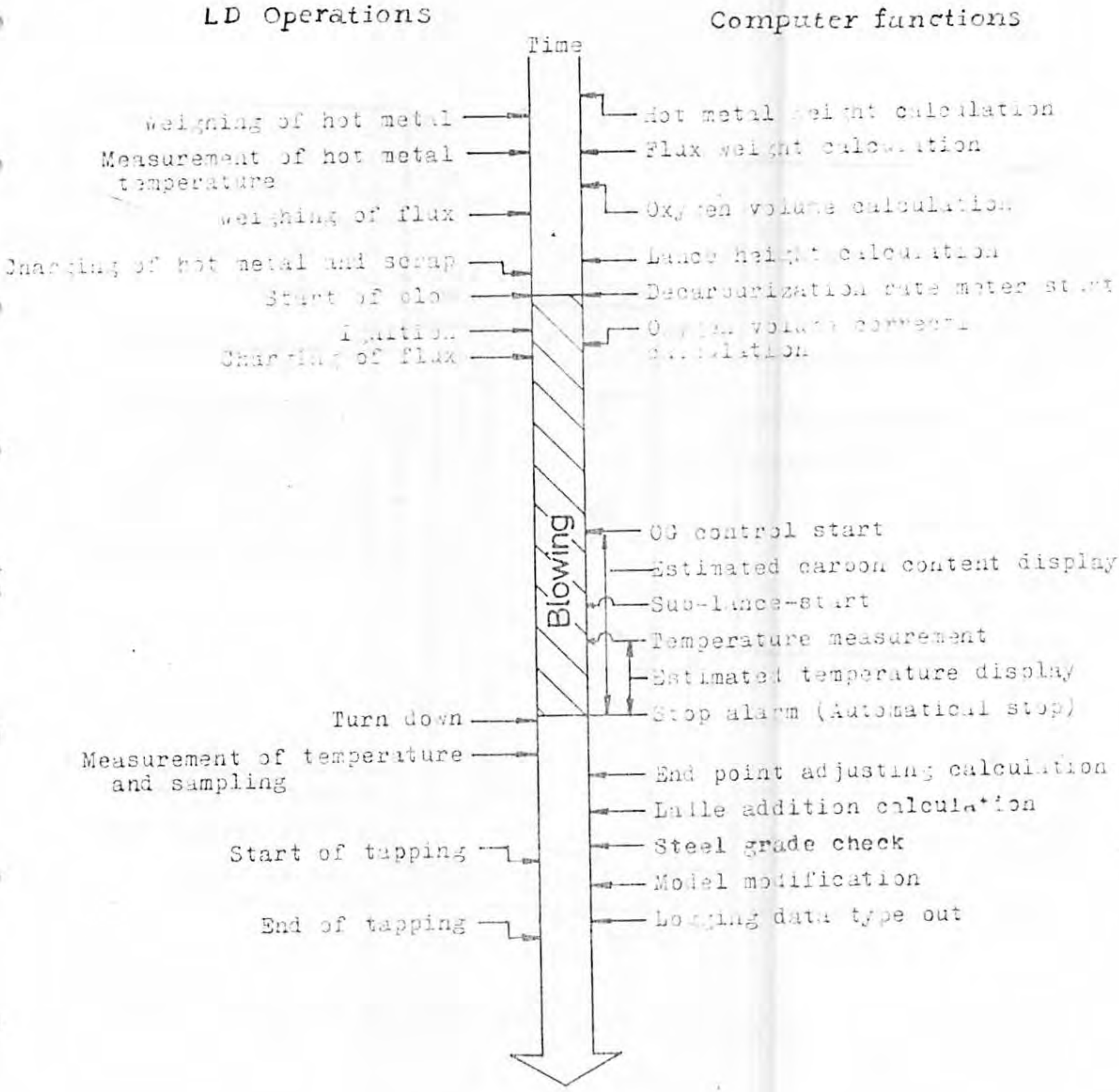
5.2.9. Monitoring Equipment Status: The computer can be used to signal defects in blowing equipment, fan motor and measuring instruments. It can also guard against for bidden combinations of input data (for example a bath temperature of 3600°C may not be accepted by computer) etc. This kind of monitoring effort may prevent some of the occasional mistakes which result in injuries, severe equipment damage, or material losses of many thousands of rupees.

5.2.10. Back ground Functions: Reported results in the case of LD converter computer control [8] show that in the data logging stage, only 10% of the computer's time is taken up by the operations described above; in the operator guide stage this proportion rises to 13%. It will not exceed 30% in the most advanced dynamic control. Thus there are huge possibilities of carrying out other tasks such as book keeping, cost accounting, production reporting, inventory management etc. This results in considerable saving in expenses on management functions.

5.3. Computer Control System and Sequence of its functions:-

Various possible control computer functions have already been discussed in section 5.2. However, the actual functions utilized vary from installation to installation . A representative example of the timing sequence of various computer functions and LD operations is shown in fig 5-3. It is very commonly used with medium sized computers. [5].

Fig 5.4 shows a schematic of commonly used computer control system organization. This schematic is self-explanatory. [9].



Computer control sequence (containing dynamic system)

Fig.5-3

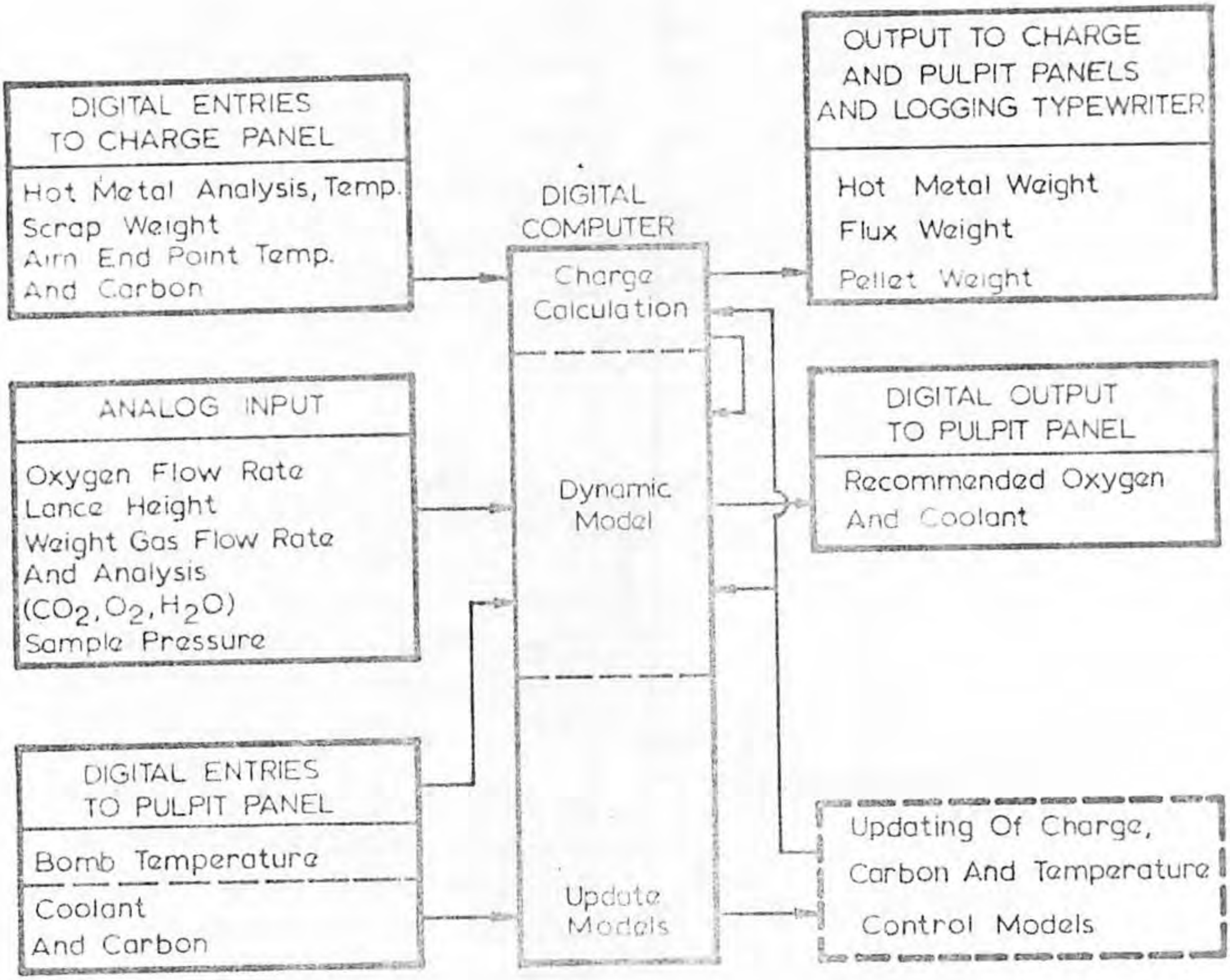


Fig.5-4:SIMPLIFIED DIAGRAM OF LD CONVERTER COMPUTOR CONTROL SYSTEM.

5.4. TYPE OF CONTROL COMPUTERS AND PERIPHERALS:

The selection of the control computer is a difficult and crucial task in any computer control project. The characteristics of competitive offerings must be compared and evaluated in terms of their ability to satisfy the requirements. The problem is compounded by many features that are available, the typical requirement for special features, and the lack of common specifications and terminology.

Different personnel may have different criteria for selecting a control computer. The microsecond speed of the CPU alone does not have any meaning. One computer may compute twice as fast as another, yet the advantage is last if the speed can not be utilized because of an I/O limitation. Similarly a system can have overall hardware advantage that are all but worthless if programming systems are not available to utilize these features. In developing countries like India, the problem is further complicated by non-technical reasons e.g. availability of foreign exchange, political relations with vendor countries and so on.

Therefore, one may conclude that it is not of much use to compare the computers at different installations of the world. Nevertheless, such a comparative study gives an idea of the capabilities and kind of computers required for a typical application. In case of an LD converter, therefore, such a study has been done and a summary is presented in Table 5-III. It can easily be concluded from this table that a 16 K core memory with a disk for backup is sufficient for a LD shop with 2-3 converters.

Table 5-III: Control Computers Used for LD Converters.

Installation	Capacity	Computer	Core Memory in words	World length	Cycle time	Back up memory	Ref.
1. Muroran Works (Japan)		HIDIC-100	16K	16 bits + parity	2µs	64 KW drum (10ms)	[10]
2. ARBED (Belgium)		IBM-1800	16K	16 bits + parity + memory protection bit	4µs	512kx2 Disks	[8]
3. Chertal works (Belgium)	120 tons x 2	IBM 1130 + IBM 1800	8 K 16 k	16 bits 16 bits	3.6µs 4 µs	512K x 2 Disks	[11]
4. Cockerill-Ougree Providence steelworks seraing (Belgium)	180 tons x 2	IBM 1130 + (IBM 1050 (for data processing)	8 K	16 bits	3.6 µs	512 K Disk	[12]
5. J & L Cleaveland (U.S.A)		Westing-House Prodac-250	16 K		4.5µs		[9]
6. Chiba works Kawasaki steel Corp. (Japan)	150 tons x 3	Honeywell DDP-516	16 K	16 bits + parity	0.96µs	160 K Disk	[13]
7. Mizushima works Kawasaki Steel Corp. (Japan)	7 LDS Total 8.5 M tons per yr.	Melcom 350/30	32 K			262 K Mag. drum	[14]
8. Fukuyama Works Nippon Kokan K.K. (Japan)	180 tons x 3 + 250 tons x 3	IBM 1800 x 2 (with IBM 360/50 central computer)	16 K each	16 bits	4 µs	512 K x 2 Disks.	[1]
9. Usinor Plant at Denain (France)		RW-300					[6]
10. Italsider Bagnali (ITALY)		CAE-510	8 K	18 bits		200 K drums	[6]
11. Tarant Plant (ITALY)		CAE-510	8 K	18 bits		200 K drums	[6]

A similar survey of peripherals used at various installations shows that for a typical LD shop following peripherals will be generally required:

1. A card read/punch or paper tape read/punch for program input/output.
2. A fast printer/type writer for heat, shift and daily logs.
3. A teletypewriter and a operator's console for operator-computer communications.
4. A teletypewriter to serve as a back up.
5. CRT display may be added at an advanced stage. (Most of the Japanese steel plants are using CRTs).

The code used for computer - process communication is also an important consideration. A single error detecting BCD code with odd parity bit (to increase reliability) has been successfully used at ARBED steel plant Belgium [8]. A very interesting paper on signal transmission in a computer controlled steel plant has been published recently by Shiramatsu et al [15].

An idea of the size of process interface controller required for an LD shop can be obtained from the example shown in Table 5-IV.

Table 5-IV: LD Process Interface Controller [13]

Input Signal	Interrupt	:	96 Channels
	Digital Signal	:	768 bits
	Analog Signal	:	72 channels 0 ± 50 mV
Output Signal	Digital	:	One shot 564 bits Flip flop 480 bits
	Stepping Motors	:	x 12
	Analog	:	12 channels 10 bits 0-20mA

5.5. Operator's Panel:

The communication between the operator and the computers system is of paramount importance. It provides the operating personnel the ability to guide and monitor the process.

LD converter operator's panels, in general, include continuous display of the key variables, setters for input and push buttons to transfer control. The details vary with the number of converters, level of control (data logging, operator guidance, closed loop etc) and method of control (gas analysis, fume temperature etc)and so on. For example, a panel in a dynamic closed loop controlled shop consists of following [16] :

Display meters

Slag weight
Finish Carbon
Carbon removal efficiency
Bath temperature
Estimated Tap temperature

Setters

Measured Bath Temperature
Maximum finish carbon
Minimum finish temperature
Lance height
Oxygen flow rate.

Push buttons

Reset
Manual
Lance - Automatic
Oxygen flow rate-Automatic
Finish blow.

Status display lights

Silicon blow
Carbon blow
Finish blow
Tap

In the above case, the operator's only duty is to set maximum finish carbon and minimum finish temperature and once ignition has been established, to push the two automatic buttons. At the end of heat after the oxygen has been shut off and the lance raised, the operator pushes the manual button to take over control and the reset button to prepare the computer for the next heat.

On the other hand, in a operator guided installation, weights of raw materials (hot metal) fluxes (lime, fluorspar,mill scale) coolant (iron ore, scrap, cold pig iron) and laddle additives may also be displayed or printed on console typewriter.

5.6 <u>Interfacing Subsystems and Instruments:</u> There are a large number of subsystems which must interface with the process control computer [6,17]. Some of the more important of these subsystems are briefly described below and listed in table 5-V.

5.6.1. Lance positioning drive and regulator: The distance from the lance nozzle to the bath can be obtained by a numerical decoder coupled to the lance winch by means of a differential mechanism. A seperate device is generally provided to check at regular intervals the distance from the bath to a fixed reference mark; the differential displacement of the coder disk serves to correct any possible error in the determination of the level. Another method commonly used to measure lance position is by means of a slide wire transmitter.

5.6.2. Oxygen measurement and Control System: Oxygen flow rate is generally measured by means of an orifice plate; a remotely located flow meter senses differential pressure across an orifice in the oxygen supply line [17]. It then transmits the signal to an indicator, a total integrator and a batch integrator on the pulpit panel.

Since quick starting and stopping of oxygen flow is desirable a piston operated blocking valve and a solenoid valve are provided which operate from close to open in 2 seconds.

Oxygen pressure in the oxygen supply header is indicated and alarmed when low. Oxygen lance pressure is displayed in the pulpit.

5.6.3. Lance Cooling water System: A remotely operated motorized valve can control the lance inlet water flow; with an indicator displaying the valve position.

Lance inlet flow and pressure are measured, recorded and alarmed at unsafe conditions. Low flow indicates throughput failure; low pressure indicates the pump failure.

Inlet and outlet temperatures are recorded sequencially on a multipoint recorder. High outlet temperature is alarmed indicating insufficient cooling water flow.

5.6.4 Vessel Coolant System (Flux Batching): Generally each vessel will be provided with a flux batching system comprised of the necessary weigh hoppers, vibrating feeders, conveyors etc to preweigh a batch of flux materials for each heat in accordance with preset instructions from an operator or from the computer control system. Normally, operations of this batch system is indicated from the central operator's pulpit. Alternatively in a two-vessel shop, a single flux batching system may be shared by the two vessels.

5.6.5 Alloy addition system (Alloy batching): There is normally an alloy batching system for each vessel which again "batches" out the required alloy additives for addition to laddle ina accordance with instructions from either an operator or the computer control system. Once again, operation is normally initiated from control operator's station.

5.6.6 Gas sampling and analysis system: The gas sampling and analysis system is critical to successful operation of the closed loop dynamic control systems. Accordingly, the design must be such as to achieve reliability and maintenability consistant with steel mill practice. The following measurement techniques are commonly used [18]:

- CO_2 contents in the fumes: obtained by mean of an infrared absorption analysis.
- O_2 contents in the fumes: by means of a paramagnetic analyser.
- the flow rate of water injected into the fumes: by $\Delta P/I$ converter unit connected to an orifice plate.
- the electric power consumed by the fan: a signal proportional to this power can be obtained by two wattmeter method.
- the temperature of the fumes entering the fan: by a platinum resistance thermometer followed by a m^{V}/I converter.
- the intensity of radiations emitted by the fumes: by germanium or silicas photocell.

The pressure of the water into the fumes is also recorded and a low pressure is alarmed, indicating nozzle failure. High temperatures in the exhaust gas main, located after the precipitator is also alarmed. The vacuum of the exhaust system is measured recorded and alarmed when low . Low vacuum indicates an exhaust fan failure or an insufficiently opened fan damper.

5.6.7 Bath temperature measuring system: A disposable sinker thermocouple is commonly used to measure bath temperature. The thermocouple and the associated release mechanism are critical to an effective dynamic control system. Accordingly the system must be designed to not only provide feedback information to the computer, but to receive control impulses from the computer.

5.6.8. Vacuum Spectrometers: It has become essentially standard practice for most basic oxygen steel shops to utilize one or more vacuum spectrometers as the basic mean of determining bath chemistry. The spectrometers are linked directly to the computer, the latter providing interpretation of the count information received from the spectrometer, and calculating the "percent analysis" of the sample. In addition, the computer provides a number of additional limit checking functions and averaging functions. Again the spectrometer must be designed to not only provide feed-back information to the computer, but to receive control impulses from the computer.

5.6.9. Hot metal and scrap scales: The LD shops usually include one scrap preparation scale in the scrap yard and one scrap trim scale at the furnace charging level. One or two hot metal weigh stations are normally utilized to weigh out the hot metal from the submarines which transport the hot metal (iron) from blast furnace. Hot metal weighout is controlled from the hot metal weigh station located near the hot metal track scale and is performed in accordance with instructions from the computer control system.

5.6.10 Operator's panel: Operator's panel may be used to introduce the numerical data which are not supplied by measuring instruments connected to the computer at that particular installation (e.g., the temperature, the alloy addition in the laddle, the scrap weight charged, the data related to teeming, the correction of errors originating from the failure of a measuring instrument with an automatic output).

Table 5-V: Subsystems to be interfaced with computer.

---

1. Lance positioning drive and regulator.
2. Oxygen measurement and control systems.
3. Lance cooling water system.
4. Vessel coolant systems.
5. Alloy additive system.
6. Gas sampling and analysis system.
7. Bath temperature measuring system.
8. Vacuum spectrometers.
9. Hot metal and scrap scales.
10. Operator's panel

5.7. MEASUREMENTS ON A COMPUTER CONTROLLED LD SHOP:

The measurements can be divided into following three categories, according to their intended usages:

1. Measurements used to control the process.
2. Measurements used to supervise the operation of the plant.
3. Measurements ensuring the safe working of the plant.

Table 5-VI gives a general idea of measurements made in a typical LD plant [18]. Scanning is generally done every 3-5 seconds.

Table 5-VI: Measurements of LD Converter.

Location	Measured Variable	Use			Range		Destination		
		Process Control	Supervision	Safety	Absolute	Relative	Desk/ panel	Data Lagger	Computer
Lance	Oxygen Pressure	x	x		0-16 ata	0-20mA	x	x	x
	Water Temperature		x	x	0-100°C	0-20mA	x		
	Flow		x	x	225 m^3/h	0-20mA	x		
	Height	x			0-4 m	0-20mA	x	x	x
Bins	Addition weight(3)	x			16t, 5t, 15t	0-1000	x		x
Converter	Steel Temperature	x			1350-1750°C	Pt-Pt Rh	x	x	x
	Trunnions temperature		x		0-400°C	Fe-Cst	X		
	Walls Temperature		x		0-400°C	Fe-Cst	x		
	Nose Temperature		x		0-400°C	Fe-Cst	x		
Hood	Water Temperature	x	x		0-150°C	Fe-Cst	x	x	x
	Level	x	x	x	0-2mH_2O	0-20mA	x	x	x
	Steam flow	x			500mm	0-20mA	x	x	x
	Fumes radiation	x			0-100	0-10mA	x	x	x
Flue	Fumes % CO_2	x			0-25%	1-10mV	x	x	x
	% CO^2	x			0-3%	1-10mV	x	x	x
	% O_2	x		x	0-21%	1-10mV	x		x
Cooling Tower	Fumes Exit temperature	x			0-200°C	4-20mA	x		x
	Pressure		x	x	0-150mm	0-20mA	x		
	Water flow	x			0-250m^3/h	4-20mA	x	x	x
Fan	Inlet Temperature	x			0-150°C	R_{pt}-100		x	x
	Power	x			0-1115Kw	0-10mA		x	x
	Inlet Pressure		x	x	0-400mm	0-20mA	x		

Note: 'x' implies that the measured variable in that row is used for / sent to destination mentioned in that column.

5.8 SENSORS:

5.8.1. Desired Characteristics: The sensors play a key role in dynamic control. The process control sensor must possess the following properties:

1. Repetitivity
2. Easiness of operation.
3. Durability
4. Cost.

Very often, the actual plant results (i.e. measured values) are compared with the results predicted from a model. By such a comparison, it is not possible to say whether the sensor is wrong or the system model is imperfect. A good discussion on the effect of instrumentation errors on control of basic oxygen furnace has been given by Fisher [19].

5.8.2. Bath Carbon Measurement: For continuous, however indirect, measurement of carbon, exhaust gas analysis is very commonly used. In this method, it is common to determine first the gas flow rate and percentages of CO and CO_2 and then the product of the two is used for decarburization rate indication as explained below:

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

$$\text{Bath carbon} \quad C = CO - \int \frac{dC}{dt} \, dt$$

Where K = constant

C_o = Initial carbon content.

t = Time.

A schematic of the decarburization rate indicator is shown in Fig. 5-5.

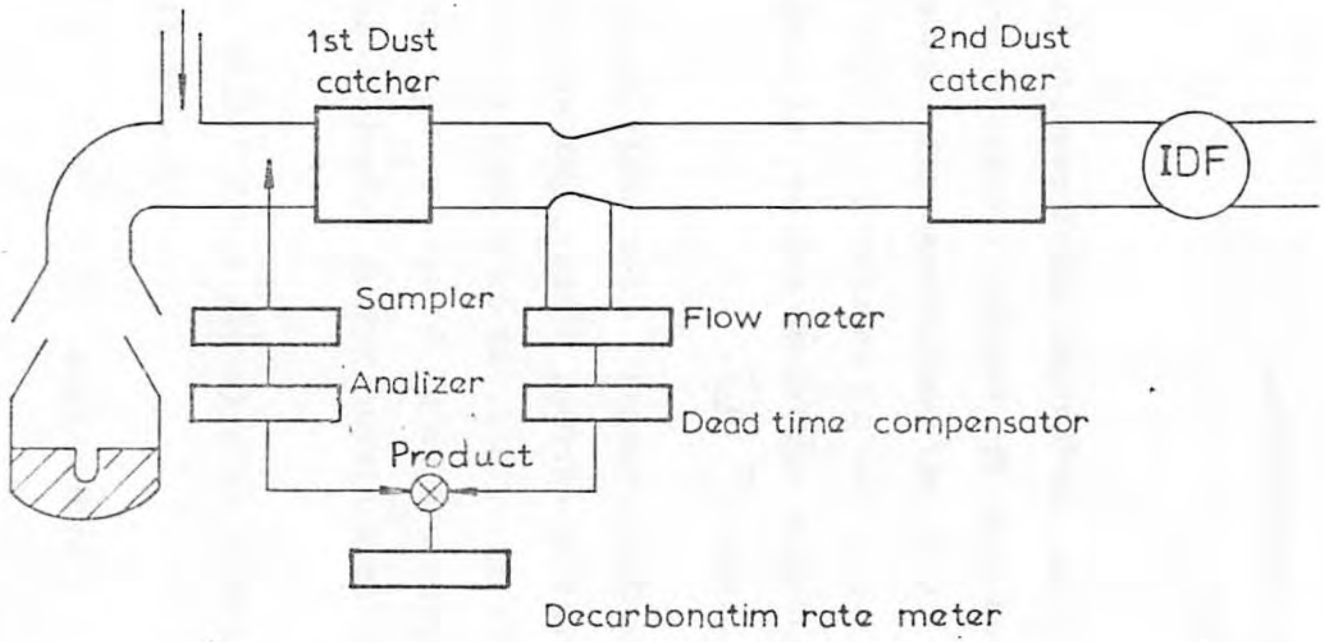


Fig. 5-5 SCHEMATIC DIAGRAM OF DECARBURIZATION RATE METER METHOD.

5.8.3 Bath Temperature Measurement: The most commonly used method for temperature measurement is by an expendable thermocouple (i.e. a thermocouple which is destroyed after measurement) variously known as Bomb thermocouple, Jet Bop, Sinker thermocouple and so on. It consists of a thermocouple junction with a cast iron "sinker" and a long extention wire. Using an appropriate release mechanism, the thermocouple bomb is dropped into the vessel at an appropriate time during the course of the blow. It survives for sufficient time to allow bath temperature to be sensed and recorded by the computer.

Recent papers (on LD converter control) in Japanese language frequently refer to "sublance" method of temperature measurement. However, no literature in English language, as far as the author is aware, has described this technique.

5.8.4. New Sensors Proposed: For a very long time, the main stigma in LD converter control was the unavailability of reliable and accurate sensors particularly for carbon and bath temperature measurements. Several industries therefore started working in this direction. Table 5-VII lists all the attempts made till todate in developing new sensors [5].

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Table 5-VII: Dynamic Sensors. [5]

Measurement	Method	User
Continuous carbon.	Flame-photometer	Sumitomo.
	Exhaust gas thermometer	CNRM
	Lance cooling water - thermometer.	Nippon Kokan
	Exhaust gas analyser	J & L
	Exhaust gas flow meter	Yawata
	Decarburization rate meter	IRSID, J&L, Krupp, Yawata, Sumitomo.
Intermittant carbon.	Sublance carbon determinator	Republic, Bethrehem, Nippon Steel.
	Bomb-carbon determinator	Kobe.
Continuous temperature.	Vessel wall protective tube-thermometer.	Max-planck, Kobe, VÖEST.
	Vessel wall-Ruby-two colour pyrometer.	BISRA
	Vessel wall- Air purge Water cool-tube Pyrometer.	USSR
	Sublance-protective tube thermocouple.	VOEST
	Sublance -Two colour pyrometer.	Sumitomo, Nippon Kokan.
Intermittant temperature.	Sublance-protective tube-thermocouple	VOEST
	Sublance-Expandable-thermocouple.	Nippon Kokan, Yawata, Nippan Steel.
	Bomb-expendable-thermocouple.	J&L, Kawasaki, Yawata.
Continuous slag formation.	Wistle Lance	Nippon Kokan
	Audiometer.	Nippon Kokan, CNRM, Mannesmann
	Lance electrical conductivity.	Krupp
	Oxygen balance meter.	Dot mund.
Intermittant slag formation.	Sublance electric pole method.	Yawata.

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CHAPTER-6

SUMMARY AND CONCLUSION

Computer control of LD process of steelmaking is an important issue currently facing the nation because the large demands of steel in India require installation of fast methods of steel making like LD converter, which produce 200-250 tons of steel in merely 20-25 minutes. However, the fast dynamics of this process, the large capacity and stochastic nature of the process as well as the unavailability ofdirect measurements make the manual control very difficult.

The main control variables of the process are lance height and oxygen flow rate. The control objectives of the process are to minimize ejections from the furnace and to simultaneously achieve specified end point carbon and temperature within minimum time.

These can be achieved by static or dynamic control schemes. The dynamic models of LD converter proposed till todate 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 applications of modern control theory to LD converter control . However, recently several researchers have started appreciating its need.

A simulation of the LD process on IBM 360/44,with a view to test various control schemes, has been done.

The simulation provides a time history of important key variables like bath composition, bath temperature, oxygen distribution, slag weight and its composition.

Computer (in a LD plant) can perform static, dynamic, sequence and adaptive control functions in addition to data logging, and monitoring instrument status. The computer should be interfaced with various subsystems like lance position control, oxygen flow rate control and gas analysis subsystems etc.

The unavailability of direct measuring sensors was the main hurdle in the development of better computer control schemes. However future prospects are bright since several installations have started to seek solutions in this regard.

APPENDIX-A

STATIC MODEL FOR LD CONVERTER.

A static model is a set of mathematical equations which make possible the calculation of quantities of scrap, lime and hot metal needed to attain the specified end point specifications.

A detailed derivation and explanation of the model equations, presented here, can be found in Slatosky's paper (1). The assumptions made in its derivation are enumerated in Table A.I.

TABLE A.I: ASSUMPTIONS USED TO WRITE THE HEAT BALANCE.

1. 95% CO and 5% CO_2 is formed in bath.
2. CO and CO_2 leave furnace at average temp.of 2700°F.
3. All SiO_2 and P_2O_5 combine with lime in slag.
4. Amount of fume loss is constant at 10,000 lb per heat.
5. Fumes leave at an avg.temperature of 2700°F.
6. Slag and metal have same temp. at turn-down.
7. FeO and Fe_2O_3 in the slag replaced by total FeO.
8. Heat losses are for a steady state.
9. Compositions of ore and mill scale are 47.5 pct Fe_2O_3 and 47.5% Fe_3O_4.
10. All heats are blown to approx 0.05 % C in about 20.5 min with an oxygen flow rate of 6500 cu ft per min.
11. The following variables are considered as constants:
    - Blowing Time
    - End-Point Chemistry (C,Si,Mn,P, and Ti)
    - Iron Chemistry (P and Ti)
    - Fume Losses
    - Ratio of CO and CO_2 Formed in the Bath
    - Slag Constitutents (TiO_2 and P_2O_5)
    - Heat Lost through the Furnace Lining.

In general for any thermal process a heat balance equation can be written as fallows:

$$\begin{pmatrix} \text{Rate of} \\ \text{increase of} \\ \text{Heat} \end{pmatrix} = \begin{pmatrix} \text{Rate of} \\ \text{Income of} \\ \text{Heat} \end{pmatrix} - \begin{pmatrix} \text{Rate of} \\ \text{Outgo of} \\ \text{Heat} \end{pmatrix} \quad \ldots (A.1)$$

In its simplest form this balance, in the case of LD converters, appears as follows:

Rate of Heat Gain by Hot Metal =

Rate of Heat Generation by the Enthalpy Changes for the Following Reactions occurring at 77°F.

$$Fe_3C + \tfrac{1}{2}O_2 = 3Fe + CO$$

$$Fe_3C + O_2 = 3Fe + CO_2$$

$$Fe_3Si + O_2 + 2CaO = Ca_2SiO_4 + 3Fe$$

$$Mn + \tfrac{1}{2}O_2 = MnO$$

$$2Fe_3P + \tfrac{5}{2}O_2 + 4CaO = Ca_4P_2O_9 + 6Fe$$

$$Fe + \tfrac{1}{2}O_2 = FeO$$

$$Ti + O_2 = TiO_2$$

\+ Rate of heat radiation from flame to bath

\- Rate of heat loss through lining

\- Rate of heat absorbtion by dissociating mill scale and ore pellets.

\- Rate of heat absorbtion bymelting scrap.

\- Rate of heat absorbtion by uncombined lime.

\- Rate of heat loss by fume generation. ...(A.2)

END-POINT TEMPERATURE EQUATION

The derived end-point temperature equation is of the form

$$
\begin{aligned}
T_F = \Big[& W_{hm} (87.35 + 0.255\, T_m + 131.4\,Si + 30.34\, Mn.) \\
& + 16.47\, W_s + 29.57\, W_{CaO} + (2.26\, V.V. + 19.93)\, (10^{6}) \\
& - 3125\, T_m - (121.4 \times 10^{6} - 1618\, W_s)\, (-93 \times 10^{-5} L.H. + 0.165) \\
& - 1225\, (W_{ms} + W_p) \Big] \div \Big[W_{hm} (0.211 + 0.0041\, Si \\
& + 0.00025\, Mn - 285 \times 10^{-8}\, T_m) + 0.214\, W_s + 0.384\, W_{CaO} \\
& + 140\, V.V. + 0.19\, (W_{ms} + W_p) + 1225 - (7500 - 0.10 W_s) \\
& (-93 \times 10^{-5}\, L.H. + 0.165) \Big]
\end{aligned}
\qquad \ldots \quad (A.3)
$$

Where

T_f = the end-point tem (°F)

W_{hm} = wt of hot metal (lb)

T_m = measured Fe temperature (°F)

Si = measured Si (%)

Mn = measured Mn (%)

W_s = wt of scrap (lb)

W_{CaO} = wt of lime (lb)

V.V = bascity ratio (dimensionless)

L.H = lance height (inches)

W_{ms} = wt of mill scale (lb)

W_p = wt of ore pellets (lb)

CONTROL EQUATIONS

By assuming that all heats are to be turned-down within 2880° to 2920°F, finishing temperatures becomes an independent variable while scrap, lime and hot metal are made dependdnt.

It is important to point out that the charge additions, mill scale, fluorspar and ore pellets (whenused) are chosen at the discretion of the melters; so they are not obtained from control equations.

The equations for hot metal, lime and scrap are of the form:

Hot Metal

$$W_{hm} = W_c - W_s \quad \ldots \quad \ldots \qquad (A.4)$$

Lime

$$W_{CaO} = \left(\frac{60.06}{28.06}\right) \left(\frac{1}{0.92}\right) (V.V.) \left(\frac{Si}{100}\right) (W_{hm}) \quad \ldots \quad \ldots \qquad (A.5)$$

Scrap

$$\begin{aligned} W_s = \Big\{ & W_c \Big[(117.93-25.3\ V.V.)\ (Si) + 29.41\ (Mn) \\ & 0.257\ (T_m) - 502.19 \Big] + 1.8 \times 10^6 (V.V) + 16.22 \\ & \times 10^6 - 3125\ (T_m) - 96.3 \times 10^6\ (-93 \times 10^{-5}\ L.H. \\ & 0.165) - 1808\ (W_{ms} + W_p) \Big\} \div \Big\{ (117.93 - 25.3 \\ & V.V.)\ (Si) + 29.41\ (Mn) + 0.257\ (T_m) + 93.82 \\ & - 1285(-93 \times 10^{-5}\ L.H. + 0.165) \Big\} - 67\ t_d \end{aligned} \quad \ldots \quad \ldots \qquad (A.6)$$

Where

W_c = charge weight (lb)

t_d = time of delay between tapping of one heat and the charging of the next (min).

Other symbols are defined in Equation. A.3

Caution:

The above equations are valid only for a particular installation and only for heats finished at 0.05% carbon with oxygen flow rate of 6500 cu ft/min. For different carbon contents and different oxygen flow rates, adoptation of the above equations requires modification of coefficients.

Reference:

1. Slatosky W.J., "End point temperature control of BOF", Trans.AIME Vol. 221, Feb.1961, p 221.

APPENDIX-B.

MODEL EQUATIONS USED FOR BOF SIMULATION.

The detailed explanation and derivation of the model can be found in Muchi's paper [1]. A very brief description of the equations used in this simulation has been presented here.

1. Oxygen Distribution:

The oxygen jet striking against the molten metal bath creates a parabolic cavity. The rate S_{cav} of absorption of oxygen in the bath is given by

$$S_{cav} = \overline{N_A} \cdot S_T \qquad \text{Kgmol/sec} \qquad (1)$$

Where S_T = Area of cavity (m^2). It is determined from the lance height and oxygen pressure as explained in Appendix C.

$\overline{N}_A$ = Oxygen flux (Kgmole/sec/m^2)

$$= \beta \cdot 2 \sqrt{D/\pi t_e} \cdot C_{Ai} \cdot \rho_L \qquad (2)^*$$

Where

D = Diffusion coefficient (Kg/sec)

t_e = mean residence time of small element of molten steel at the surface of the cavity (sec)

ρ_L = Density of molten steel (Kg/m^3)

C_{Ai} = Interfacial concentration of oxygen at the cavity surface.

β = reaction coefficient for absorption.

---

* This equation in original paper is errorneous.

Interfacial concentration is given by:

$$C_{Ai} = \frac{1}{1600} \mathrm{Exp} \left\{ \frac{DH_{FeO}}{R_1 (T_w + 273)} - \frac{DS_{FeO}}{R_1} \right\} \quad (3)^*$$

Where T_w = Temperature of surface of cavity (°C)

R_j = Gas constant (Kcal/Kgmol °C)

DH_{FeO}, DS_{FeO} = Reaction heat and entropies of $Fe + \underline{O} \rightleftharpoons FeO$

The reaction coefficient for absorption β is given by

$$\beta = \frac{\gamma_3}{2} + \frac{\pi}{4\, r_3} \mathrm{erf} \left(\frac{\gamma_3}{\sqrt{\pi}} \right) + \frac{1}{2} \exp \left(\frac{-\gamma_3^2}{\pi} \right) \quad (4)$$

where

$$\gamma_3 = \sqrt{\pi k_1 \left\{ (1-\beta)\; C_{Ai} + C_{Bb} + \left(\frac{k_2}{k_1} \right) C_{Cb} + \frac{k_3}{k_1}\; C_{Db} \right\} \; t_e} \quad (5)$$

k_1, k_2, k_3 = rate constants of decarbutization and that of oxidation of silicon and iron respectively.

C_{jb} = concentration of j component in bath

j = B (cabbon), C (silicon), D(Iron)

In order to determine β from equation 4 and 5 following simplification has been done in present simulation.

Since γ_3 is of the order of 100 : $\mathrm{erf} \left(\frac{\gamma_3}{\sqrt{\pi}} \right) = 1.0$

$$\exp \left(-\frac{\gamma_3^2}{\pi} \right) \cong 0$$

$$\beta = \frac{\gamma_3}{2} \quad \cdots \quad \cdots \quad (6)$$

$$\gamma_3^{\;2} = \; = \pi k_1 \left\{ (1- \quad) C_{Ai} + C_{Bb} + \frac{k_2}{k_1} C_{cb} + \frac{k_3}{k_1} C_{Db} \right\}$$

$$= Z_1 (1-\beta) + Z_2 \quad (7)$$

---

* In original paper, this equation is erroneous.

Where

$$Z_1 = \pi k_1 C_{Ai}$$

$$Z_2 = \pi \{ k_1 C_{Bb} + k_2 C_{Cb} + K_3 C_{Db} \} \qquad \ldots. \qquad (9)$$

Equation 6 and 7 give

$$4\beta^2 = Z_1(1-\beta) + Z_2$$

$$\text{or} \qquad \beta = \frac{\sqrt{Z_1^2 + 16(Z_1 + Z_2)} - Z_1}{8} \qquad \ldots \qquad (10)$$

Thus equation 10 avoids the need for solving equations 4 and 5 iteratively.

Additional Oxygen is generated by dissociation of lime stone and ore, hence:

Total Oxygen

$$S = S_{cav} + S_{sub1} + S_{sub2}$$

$$= S_{cav} + 3 \frac{{}_iW_{ore}}{M_{Fe2O_3}} \delta(\theta - {}_i\theta_{ore})$$

$$+ \frac{{}_iW_{ls}}{M_{CaCO_3}} \delta(\theta - {}_i\theta_{ls}) \qquad \ldots. \qquad (11)$$

Where

M_j = Molecular weight of j

${}_iW_j$ = ${}_i$th addition of j at time ${}_i\theta_j$

$\delta(\theta)$ = Impulse function of time θ.

The fractions σ_1, σ_2 and σ_3 of bath oxygen distributed to C, Si and Fe respectively are given by

$$\sigma_1 = K_1 C_{Bb}/K_c \qquad \ldots \qquad (12)$$

$$\sigma_2 = K_2 C_{Cb}/K_c \qquad \ldots \qquad (13)$$

$$\sigma_3 = K_3 C_{Db}/K_c \qquad \ldots \qquad (14)$$

Where

$$K_c = K_1 C_{Bb} + K_2 C_{Cb} + K_3 C_{Db}$$

K_j and C_{jb} are as explained earlier.

2. Variation of composition.

The transitional variation of various components can easily be written as follows:

Moles of carbon removed = moles of oxygen 'O' used for carbon.

$$\frac{d\ W_m C_{Bb}}{d\theta} = -\sigma_1 S \quad \ldots \quad (15)$$

Similarly

$$\frac{d\ W_m C_{Cb}}{d\theta} = -\tfrac{1}{2}\sigma_2 S \quad \ldots \quad (16)$$

$$\frac{d\ W_m C_{Db}}{d\theta} = -\sigma_3 S \quad \ldots \quad (17)$$

$$\frac{d\ W_{(sia)}}{d\theta} = \tfrac{1}{2}\sigma_2 S\ M_{SiO_2} \quad \ldots \quad (18)$$

$$\frac{d\ W_{(FeO)}}{d\theta} = \sigma_3 S\ M_{FeO} \quad \ldots \quad (19)$$

$$\frac{d\ W_{(T.Fe)}}{d\theta} = \left(\frac{M_{Fe}}{M_{FeO}}\right) \frac{dW_{(FeO)}}{d\theta} \quad \ldots \quad (20)\ *$$

where

W_j = Weight of J (Kg)

Suffix J; m: Molten metal, Sia: Silica, T.Fe : Total Iron

( ) : in slag.

---

* In original paper , this equation is errorneous .

Equation for total weight of molten metal can be obtained as follows:

Rate of change of Molten Steel Weight

= Rate of scrap melting.

\+ Rate of cold Pig iron melting

\+ Rate of iron produced by dissociation of ore

\- Rate of carbon loss

\- Rate of silicon loss

\- Rate of iron loss of form FeO

i.e.

$$\frac{d\,W_m}{d\theta} = \frac{dW_{sc}}{d\theta} + W_{pig}\,\frac{dF_{pig}}{d\theta} + {}_iW_{ore}\,\frac{2M_{Fe}}{M_{Fe_2O_3}}\,\delta(\theta - {}_i\theta_{ore}) - M_c\,\frac{d\,W_m C_{Bb}}{d\theta} - M_{Si}\,\frac{d\,W_m\,C_{Cb}}{d\theta} - M_{Fe}\,\frac{d\,W_m\,C_{Db}}{d\theta} \quad ..(20)^*$$

Similarly for slag:

$$\frac{d\,Ws}{d\theta} = \frac{d\,W_{(Sia)}}{d\theta} + \frac{dW_{(FeO)}}{d\theta} + \frac{d\,W_{(CaO)}}{d\theta} \quad ..\ (22)$$

Where

$W_{(CaO)}$ = Weight of CaO dissolved in slag.

3. Lime Dissolved in Slag:

Weight of CaO in slag is a function of bath temperature T_b and is obtained empirically as follows.

---

* equation is errorneous in original paper.

$$W_{(CaO)} = V_1 \cdot V_2 \cdot V_3 \cdot W_s \qquad \ldots \quad (23)$$

Where

$$V_3 = -1.267 \times 10^{-8}\, T_b^{\,3} + 5.961 \times 10^{-5} T_b^{\,2} \ldots ($$

$$- 9.186 \times 10^{-2}\, T_b + 47.050 \qquad \ldots (24)$$

$$V_2 = - 2.111 \times 10^{-8}\, T_b^{\,3} + 9.745 \times 10^{-5}\, T_b^{\,2}$$

$$- 1.517 \times 10^{-1}\, T_b + 75.925 \qquad \ldots \quad (25)$$

V_1 is determined by different relations for different temperature ranges as explained below:

For $T_b \leqslant 1200°C$ $\quad V_1 = 0$

$1200°C < T_b \leqslant 1240°C$ $\quad V_1 = 0.4(T_b - 1200)/100$

$1250°C < T_b \leqslant 1290°C$ $\quad V_1 = (0.25\ T_b - 282.5)/100$

$1240°C < T_b \leqslant 1250°C$ $\quad V_1 = (1.4\ T_b - 1720)/ 100$

$1290°C < T_b \leqslant 1370°C$ $\quad V_1 = (0.13\ T_b - 127.7)/100$

$1370°C < T_b \leqslant 1465°C$ $\quad V_1 = (0.23\ T_b - 264.7)/100$

$1465°C < T_b \leqslant 2390°C$ $\quad V_1 = (0.03\ T_b + 28.3)/100$

... (26)

4. Surface Temperature of Cavity T_w:

Heat generated due to reactions on the surface of the the cavity is given by:

$$Q = \left\{ \sigma_1 \; (- DH_{CO}) + (1/2)\, \sigma_2 \; (-DH_{SiO_2}) + \sigma_3 \; (DH_{FeO}) \right\} S_{cav} \qquad \ldots \quad (27)$$

$=$ Heat transferred to bath Q_L + Heat transferred to gases Q_G

$$= H_L \; (T_w - T_b) \; S_T + H_G (T_w - T_g) \; S_T \quad \ldots \quad (28)$$

This gives

$$T_w = \frac{Q + (H_L\ T_b + H_g\ T_g)\ S_T}{(H_L + H_g)\ S_T} \qquad \ldots \qquad (29)$$

Where

H_g, H_L = heat transfer coefficients (Kcal/m^2 sec°C)

T_g = Temperature of gases (°C)

T_b = Temperature of bath (°C)

S_T = Area of cavity.

Total heat transferred to the bath Q_{Lt}

= Heat transferred from surface Q_L

+ heat generated by oxygen S_{sub} produced by dissociation of ore and lime stone.

$$Q_{Lt} = Q_L + \left\{ \sigma_1(-DH_{CO}) + (1/2)\sigma_2(-DH_{SiO_2}) + \sigma_3(-DH_{FeO}) \right\} S_{sub} \qquad \ldots \qquad (30)$$

5 <u>Heat Losses</u>.

Heat lost by convection and radiation from the sides and bottom of furnace $= A_1\ H_{c_1}\ (t_{wo} - t_R) + A_2\ H_{c2}\ (t_{wo} - t_R) + (A_1 + A_2)\ H_r\ (t_{wo} - t_R)$ ... (31)

Where

A_1 = Area of sides = $\pi D_1\ H_1$ ... (32)

A_2 = Area of bottom= $\frac{\pi}{4} D_1^2$ ... (33)

t_{wo} = Temperature of outer surface of the Converter °C

t_R = Room temperature °C.

H_{c_1} = Heat transfer coefficient for natural convection from vertical surface to ambient air (Kcal/m^2 sec°C)

$$= \frac{1.1}{3600} (t_{wo} - t_R)^{1/3} \quad \ldots\ (34)$$

H_{c_2} = Heat transfer coefficient for natural convection from horizontal surface to ambient air (kcal/m^2 sec °C)

$$= \frac{0.9}{3600} \left[(t_{wo} - t_R) / D_1 \right]^{1/4} \quad \ldots\ (35)$$

H_r = Heat transfer coefficient due to radiation.

$$= \frac{0.0013\ E_s \left(\frac{t_{wo} + 273}{100} \right)^4 - \left(\frac{t_R + 273)^4}{100} \right)^4}{t_{wo} - t_R} \quad ..(36)$$

E_s = Emmissivity of surface

Heat lost due to radiation from month Q_R

$$= \sigma\, \phi_{12} \left[E_s\ (T_b + 273)^4 - (t_R + 273)^4 \right] A_3 \quad ..(37)^*$$

where = Stefan Boltzman constant

ϕ_{12} = overall interchange factor. It is evaluated as follows:

$$\phi_{12} = 1/\left[(1/\bar{F}_{12}) + (1/E_S - 1) \right]$$

$$\bar{F}_{12} = \left[(R_2'/R_1')^2 - F_{12}^2 \right] / \left[1 + (R_2'/R_1')^2 - 2F_{12} \right] \quad ..(38)^*$$

$$F_{12} = \left\{ R_1'^2 + R_2'^2 + H_2^2 - \sqrt{(R_1'^2 + R_2'^2 + H_2^2)^2 - 4R_1'^2\, R_2'^2} \right\} / 2\, R_1'^2$$

$$H_2 = H_1 - DD_1 - W_m / \rho_L\ A_3 \quad ..\ (39)$$

$$A_3 = (\pi/4)\ (D_1 - 2.\ DD_1)^2 \quad ..\ (40)$$

$$R_2' = D_2/2 \quad ...\ (41)$$

$$R_1' = (D_1 - 2\ DD_1)/2. \quad ...\ (42)$$

---

* Equations in original paper are errorneous.

H_1, D_1, D_2, H_2, DD_1 are dimension of the furnace as shown in Fig. B-1.

6. Initial Temperature of Steel bath:

Using a heat balance immediately before and after charging, following equation is obtained for the initial temperature of charge mix.

$$T_{bi} = \Big\{ W_o \, C_{p_{Fe.m}} \cdot T_{ch} + (W_{pig} \, C_{p_{pig}} + W_{sc} \, C_{p_{sc}} + W_l \cdot C_{pl}) \cdot t_R + W_{pig} \, \alpha_{pig} \, (- DH_{Fe}) \Big\} \Big/ \Big\{ (W_o + W_{pig} \, \alpha_{pig}) \cdot C_{p_{Fe.m}} + W_{pig}(1 - \alpha_{pig}) \cdot C_{p_{pig}} + W_l \, C_{pl} + W_{sc} \, C_{p_{sc}} \Big\} \quad \ldots (43)$$

where W_o = Mass of molten pig iron charged into converter.

W_{pig} = Mass of cold pig Iron charge into converter

W_{sc} = Mass of scrap charged

W_l = Mass of lime initially charged into converter

α_{pig} = Fraction of pig iron which has melted before beginning of blowing.

C_{p_j} = Specific heat of j.

Suffix Fe.m = molten iron.

7. Heat Balance in the steel bath: Following equation can be obtained by taking heat balance for molten steel:

$$\frac{d\, T_b}{d\theta} = \frac{Q_{Lt} + Q_{Sf} - Q_{Sc} - Q_{pig} - Q_R - Q_o - Q_{am}}{W_m \, C_{p_{Fe.m}} + W_s \, C_{p_s} + Q_s} \quad \ldots (44)$$

where Q_{Lt}, Q_o, Q_R are heat transfer rates given by following equations.

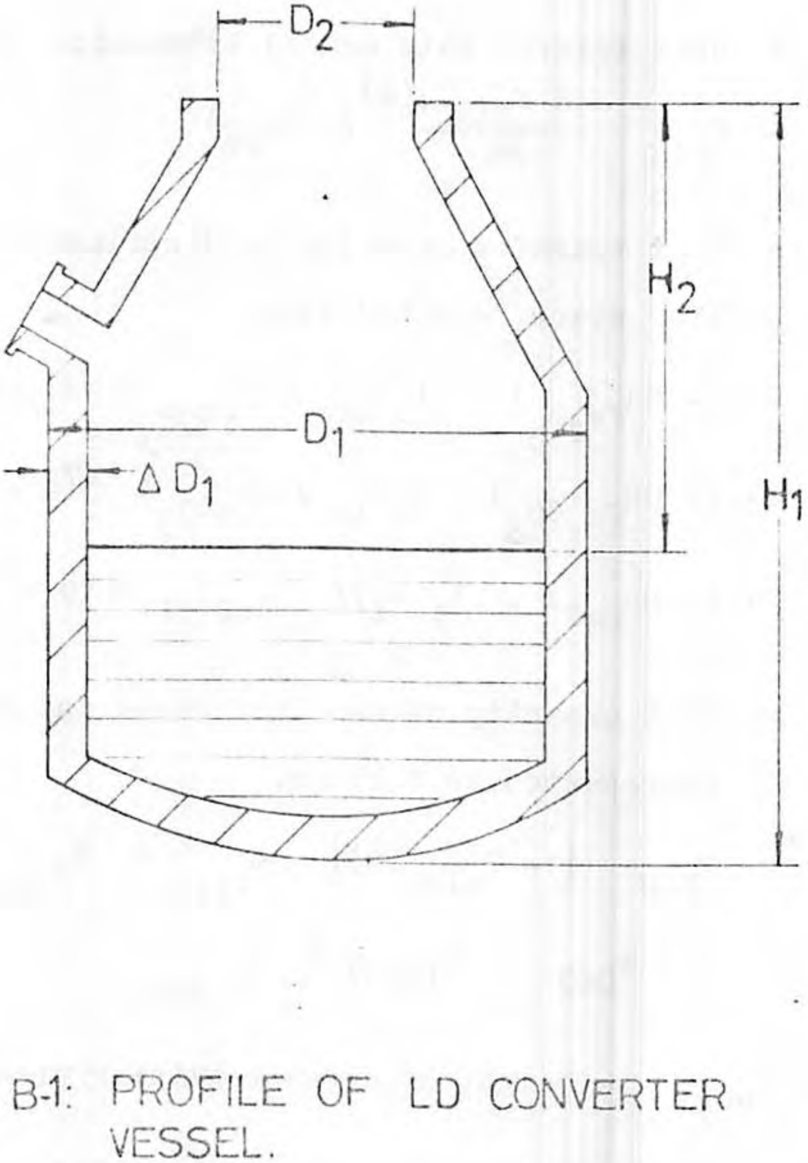

Fig. B-1: PROFILE OF LD CONVERTER VESSEL.

Q_{Sf} = Heat generation rate due to process of slag formation.

$$= (-DH_{(FeO)}) \frac{d\,W_{(\underline{feO})}}{d\theta} + (-DH_{(SiO_2)}) \frac{d\,W_{(\underline{sia})}}{d\theta} + -\left(DH_{(CaO)}\right) \frac{d\,W_{(C_{a}O)}}{d\theta} \quad \ldots \quad (45)$$

Q_{pig} = Heat traafer rate caused by melting of pig iron.

$$= W_{pig} \frac{d\,F_{pig}(\theta)}{d\theta} (-DH_{Fe}) \quad \ldots \quad (46)$$

Q_{am} = Heat transfer rate due to dissolution of lime stone, ore and lime.

$$= (-DH_{Fe_2O_3}) \cdot ({}_{i}W_{ore} / M_{Fe_2O_3}) \; \delta(\theta - {}_{i}\theta_{ore})$$
$$+ (-DH_{Ca\,CO_3}) \cdot ({}_{i}W_{ls} / M_{CaCO_3}) \; \delta(\theta - {}_{i}\theta_{ls})$$
$$+ (-DH_{CaO}) \cdot ({}_{i}W_{l})/ M_{CaO}) \cdot \delta(\theta - {}_{i}\theta_{ls}) \ldots \quad (47)$$

Q_S = Heat capacity of unmelted solid and may be represented as follows.

$$= W_{pig} \left[1 - F_{pig}(\theta)\right] C_{p_{pig}} + W_{sc_{rem}} C_{p_{sc}} + (W_{CaO} - W_{(CaO)}) \; C_{p\,CaO} \quad \ldots. \quad (48)$$

Where $W_{sc_{rem}}$ = Weight of scrap remaining unmelted.

Q_{sc} = Heat transfer rate caused by melting of a scrap.

In order to handle scrap melting it has been assumed tentatively that scrap absorbs nearly 80% of the heat gained by bath. Once steel is completely molten, heat generated is utilized solely for raising temperature.

Reference: (1) Asai S., and Muchi I,'Theoretical analysis by the use of mathematical model in LD converter operation', Trans.ISIJ Vol.10,1970 p.250.

APPENDIX-C.

MODEL EQUATIONS FOR LANCE AND OXYGEN JET BEHAVIOUR SIMULATION.

The detailed explanation and derivation of the model can be found in Otsuki's paper [1]. A very brief description of the equations used in this simulation is presented here.

1. Gas condition in the nozzle exist:

For adiabatic gas flow through a nozzle, following equation can be written [Fig.C-1]

$$M_1 = \left[\frac{2}{r-1} \left\{ \left(\frac{P_o}{P_1} \right)^{\frac{r-1}{r}} - 1 \right\} \right]^{\frac{1}{2}} \quad \text{....(C1)}$$

$$U_1 = \left[\frac{2r}{r-1} \left(R\ T_o\ g_c \right) \left\{ 1 - \left(\frac{P_o}{P_1} \right)^{\frac{1-r}{r}} \right\} \right]^{\frac{1}{2}} \quad \text{... (C.2)}$$

$$G_1 = \left\{ r \left(\frac{2}{r+1} \right)^{\frac{r+1}{r-1}} \Big/ \frac{R\ T_o}{gc} \right\}^{\frac{1}{2}} \left(\frac{\pi}{4} D^2 \right) P_o \quad \text{(C.3)}$$

Where

M = Mach number

G = Mass Flowrate of oxygen Kg/Sec.

P = Static Pressure of gas

T = Absolute temperature (°K)

R = Gas constant (Kgfm/Kg°K)

r = Specific heat ratio.

U = Velacity (m/sec).

D = Throat diameter of nozzle (m)

g_c = Gravitation conversion constant (kg m/kg sec^2)

Subscript '1' refers to values at nozzle exit (See Fig. C.1)

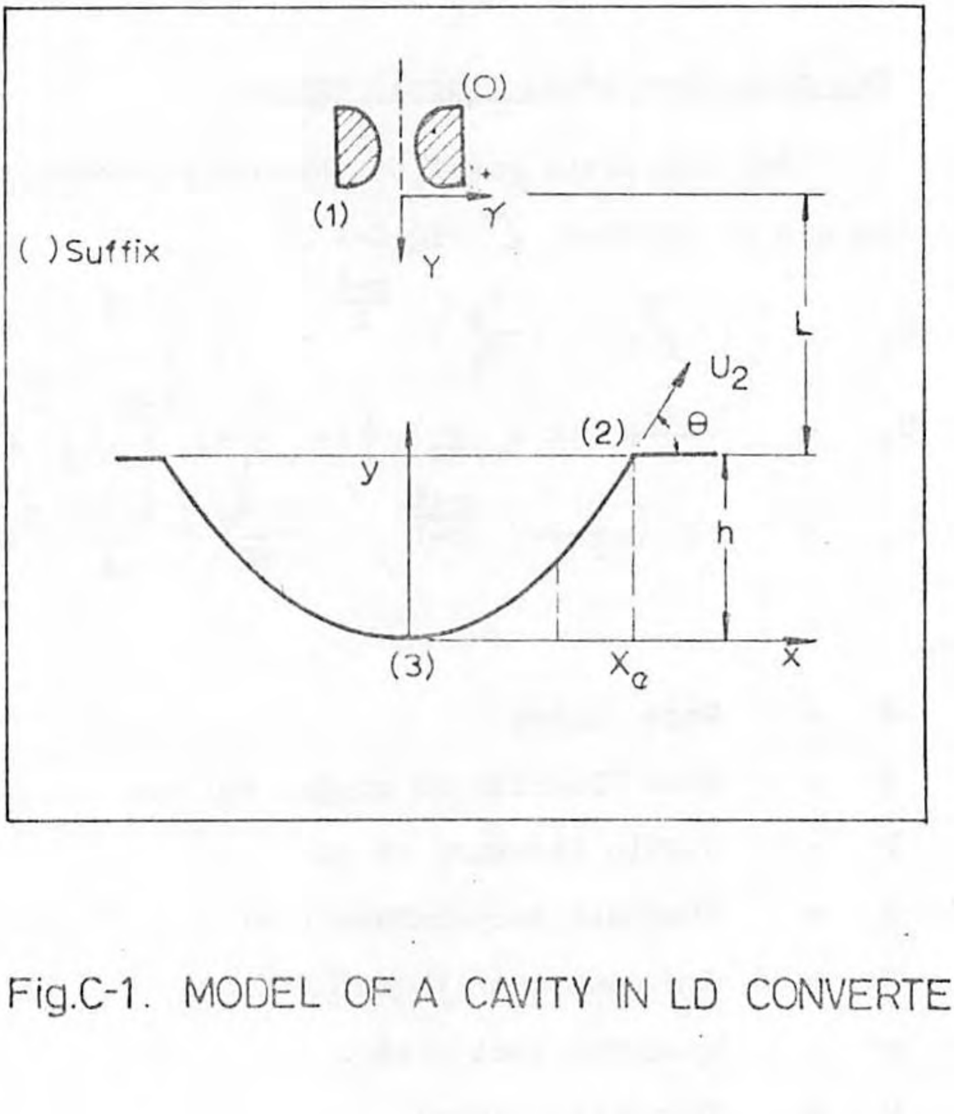

Fig.C-1. MODEL OF A CAVITY IN LD CONVERTER.

2. About Jet Stream:

Following empirical relation have been obtained for velacity in jet stream.

$$\frac{U_{ym}}{U_1} = \frac{K}{(Y/D - Y_o)} \qquad \ldots (C.4)$$

$$Y_o = 1.817 \times 10^{-4} P_o - 3.434 \qquad \ldots (C.5)$$

$$\frac{U_Y}{U_1} = \frac{K}{(Y/D - Y_o)} \operatorname{Exp} \left\{ -2K^2 \left(\frac{R'}{Y} \right)^2 \right\} (C.6)$$

Where

U_{ym} = Velocity along jet axis.

U_y = Velocity at a distance of R' from jet axis

K = Constant (= 8.9)

Y = Axial Distance of the point under consideration from nozzle exit.

3. Shape of cavity and Behaviour of Gas flow:

The maximum infiltration depth of the cavity 'h' can be determined from the following force balance equation.

$$\left(\frac{k}{2} \right) \rho \, U_{ym}^2 = \rho_L \, g \, h \qquad .. (C.7)$$

where

ρ = Gas density (Kg /m^3)

ρ_L = Liquid density (Kg/m^3)

k = 0.9

Application of the principle of conservation of momentum along the gas path from 1 to 2 (Fig. C-1) gives:

$$G_1 U_1 + \alpha G_1 U_2 \sin\theta = (F_{cy} + F_{fy})\, g_c \quad \ldots (C.8)$$

This equation is solved to give the value of parameter (h')

Where

F_{cy} = Y direction component of Buoyant force

$$= \frac{\pi \rho_L \, g \, h^2}{2a} \quad \ldots (C.9)$$

F_{fy} = Y component of drag force exerted by cavity surface on gas (negligible as compared to F_{cy})

α = Parameter of variation of gas flow rate.

$$= \frac{\pi \rho \, U_1 \, D \, Y^2}{2K \, G_1 (Y - D \, Y_0)} \quad \ldots (C.10)$$

$\tan\theta = 2\sqrt{ah}$

a = parameter of cavity shape. The cavity shape is assumed to be a parabole $y = a\,x^2$.

The total surface area S_T of the cavity is given by:

$$S_T = \frac{4}{3}\pi a \left\{ \left(\frac{h}{a} + \frac{1}{4a^2} \right)^{3/2} - \frac{1}{8a^3} \right\} \ldots (C.11)$$

References:

1. Otsuki M. and Muchi, S., "The behaviour of gas flow around the fire point of LD converter", Tetsu-to-Hagane Vol. 53, June 1967, No.7.