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## A study of the thermal dynamics of the reheat furnace

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UNIVERSITY OF NEW SOUTH WALES  
SCHOOL OF ELECTRICAL ENGINEERING

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## SYNOPSIS

Reheat furnaces are for heating slabs to the best temperature distribution in the shortest time and to do this with the highest thermal efficiency. But these two performance indices are difficult to control and have not been successfully controlled so far. With the advent of on-line digital computer systems this has become possible. A comprehensive study of the thermal dynamics of the reheat furnace is carried out in this thesis with the aim of developing a control system based on computers for these two performance indices.

Parameters for efficiency control are determined for both billet furnaces and slab furnaces. Mathematical models for the heating of billets and slabs are determined for both the constant coefficient case and the temperature dependent coefficient case. The models are solved using numerical methods and verified by experimental results.

An on-line computer control system has been designed and installed to carry out the control functions and is being implemented in stages. At present, the efficiency control has been implemented and is producing good results in terms of higher

furnace efficiency and lower scale loss.

This study reveals a number of simpler projects on reheat furnaces which can give high return for a very small amount of work. Other projects which must be completed before the temperature distribution control can be implemented are also described and recommended for further work.

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LIST OF SYMBOLS AND NOTATIONS

$\alpha$	Thermal diffusivity of steel = $\frac{K}{\rho C_p}$
$\alpha_1$	Mean thermal diffusivity of steel between 1600°F and 2540°F
$\left. \begin{array}{l} \beta_1 \\ \beta_2 \\ \beta_3 \end{array} \right\}$	Uncertainty factors by which the heat transfer has to be reduced due to non-ideal conditions for heat transfer from hot gas, wall and roof, and flame, respectively.
$\delta_q$	Small quantity of heat input to steel from furnace . . . . . BTU
$\delta_{f_x}$	Small change of heat flux to steel in the x-direction . . . . . BTU/ft <sup>2</sup>
$\sigma$	Stephan-Boltzmann constant
$\rho$	Density of steel . . . . . lb/ft <sup>3</sup>
$\rho_w$	Density of saltwater . . . . . lb/ft <sup>3</sup>
$\mu_w$	Viscosity of saltwater . . . . . lb/ft hr

$\eta$	Furnace thermal efficiency . . . . . BTU/ton of steel
$\eta_1$	Furnace thermal efficiency compensated for pushing rate . . . . . %
$\eta_R$	Efficiency in terms of rate of heat absorption by slabs and furnace in 3 minute intervals
$\tau$	Time . . . . . hr
$\tau_1$	Residence time of each slab in the soak zone . . . . . hr
$a_1$	Independent variables such as furnace pressures, air/fuel ratios, etc., used in the efficiency optimising control
$a_N$	
$b$	Width of slab . . . . . ft
$d$	Thickness of oxide . . . . . ft
$f_x$	Heat flux in x-direction
$f_y$	Heat flux in y-direction
$f_z$	Heat flux in z direction
$h$	Coefficient of forced convection heat transfer between hot gas and slab

$h_1$	Experimentally determined effective coefficient of heat transfer between furnace and slab
$h_s$	Heat transfer coefficient between steel pipe and water . . . . . BTU/ft <sup>2</sup> hr °F
$s$	Thickness of slab . . . . . ft
$t$	Time . . . . . sec
$t_{lx}$	Minimum soak time required for each slab, calculated in accordance with its thickness $x$ . . . . . sec
$v$	Velocity of travel of slabs . . . . . ft/min
$x$	Distance in the x-direction, vertical . . ft
$y$	Distance in the y-direction, direction of pushing slab . . . . . ft
$z$	Distance in the z-direction, direction along width of furnace . . . . . ft
$C_p$	Specific heat of steel . . . . . BTU/lb °F

$C_{p_w}$	Specific heat of saltwater . . . . BTU/lb °F
D	Internal diameter of steel pipe . . . . ft
E	Mean squared error for control of thin slabs
$E_1$	Mean squared error for control of thick slabs
$E'$	Emissivity of brickwork
$E'_1$	Emissivity of luminous flame
$G_1$	$\frac{2\alpha \Delta t}{\Delta x^2}$
$G_2$	$\frac{2 \Delta t h_1}{\rho C_p \Delta x}$
$H_{Fuel}$	Heat contained in fuel injected in 3 minute intervals
$H_{Flue}$	Heat contained in flue gas produced in the 3 minute intervals
$H_w$	Total heat loss through cooling water in skids in the 3 minute intervals
$H_{wa}$	Total heat loss through radiation from furnace, external walls and roof

K	Thermal conductivity of steel . . . . .	BTU/hr ft <sup>2</sup> °F
K'	Thermal conductivity of oxide . . . . .	BTU/hr ft <sup>2</sup> °F
K <sub>w</sub>	Thermal conductivity of water . . . . .	BTU/hr ft <sup>2</sup> °F
L	Total effective length of furnace . . . .	ft
L <sub>1</sub>	Length of furnace from entry to exit from UTZ . . . . .	ft
M		$= \frac{\rho C_p \Delta x^2}{K \Delta t}$
M <sub>2</sub>		$= \frac{\partial K}{\partial T} \frac{\Delta t}{\rho C_p \Delta x^2}$
N	Number of variables occurring in the optimising control	
P	Furnace pressure . . . . .	"WG
R <sub>1</sub>	Gas ratio index	
R <sub>f</sub>	Air/fuel ratio . . . ft <sup>3</sup> of air/BTU of Fuel	



$R_g$	BF gas/CO gas ratio	
$T$	Temperature of slab . . . . .	$^{\circ}\text{F}$
$T_1$	Slab surface temperature . . . . .	$^{\circ}\text{F}$
$T_2$	Temperature of slab $\Delta x$ from surface . .	$^{\circ}\text{F}$
$T_a$	Slab temperature . . . . . = Ambient temperature at entry to furnace	$^{\circ}\text{F}$
$T_{be}$	Billet temperature at exit . . . . .	$^{\circ}\text{F}$
$T_{be}'$	Required billet temperature at exit . . .	$^{\circ}\text{F}$
$T_{bs}$	Billet surface temperature inside furnace near exit door Actual measured temperature . . . . .	$^{\circ}\text{F}$
$T_{bs}'$	Required billet temperature inside furnace near exit door, i.e., setpoint for $T_{bs}$ .	$^{\circ}\text{F}$
$T_c$	Temperature of slab centre at UTZ exit calculated from mathematical model of heating process . . . . .	$^{\circ}\text{F}$
$T_E$	Temperature of slab surface just pushed out of furnace . . . . .	$^{\circ}\text{F}$

$T_F$	Furnace temperature as measured by inserting thermocouple into furnace through the roof . . . . .	$^{\circ}F$
$T_{Fi}$	Temperature of slab surface after roughing stand . . . . .	$^{\circ}F$
$T_{Fl}$	Flame temperature . . . . .	
$T_g$	Hot non-luminous gas temperature . . . . .	$^{\circ}F$
$T_i$	Temperature of a slice $i$ of slab at time $t$ . . . . .	$^{\circ}F$
$T_{i'}$	Temperature of a slice $i$ of slab at time $t + \Delta t$ . . . . .	$^{\circ}F$
$T_j^t$	Temperature at time $t$ , at a reference point $j$ of the mesh . . . . .	$^{\circ}F$
$T_j^{t+1}$	Temperature at time $t + \Delta t$ , at a reference point $j$ of the mesh . . . . .	$^{\circ}F$
$T_m$	Actual mean slab temperature at UTZ exit . . . . .	$^{\circ}F$

$T_r$	Required mean slab temperature at UTZ exit . . . . .	$^{\circ}\text{F}$
$T_{s1}$	Temperature of slab surface in soak zone . . . . .	$^{\circ}\text{F}$
$T_{s2}$	Temperature of slab surface in UTZ . . . . .	$^{\circ}\text{F}$
$T_{s3}$	Temperature of slab surface in LTZ . . . . .	$^{\circ}\text{F}$
$T_{s4}$	Temperature of slab surface in UPZ . . . . .	$^{\circ}\text{F}$
$T_{s5}$	Temperature of slab surface in LPZ . . . . .	$^{\circ}\text{F}$
$T_w$	Wall and roof temperature . . . . .	$^{\circ}\text{F}$
$T_{xL_1}$	Temperature profile of the slab in x-direction at the exit to UTZ, $y = L_1$ . . . . .	$^{\circ}\text{F}$
$T_{xy}$	Temperature profile of the slab in x-direction (through its thickness) while travelling along y-direction (along the furnace) . . . . .	$^{\circ}\text{F}$
$U_x$	Velocity component in x-direction . . . . .	ft/sec

$U_y$	Velocity component in y-direction . . ft/sec
$U_z$	Velocity component in z-direction . . ft/sec
V	Water flow velocity . . . . . ft/sec
X	Gas flow or oil flow

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CHAPTER 1

INTRODUCTION

In hot rolling mills, steel in the form of billets, blooms or slabs are preheated to required rolling temperature in continuous reheat furnaces. The slabs, etc. are required to be heated to uniform temperature and at maximum thermal efficiency. The incorrect heating of the slabs have resulted in considerable difficulties for the rolling mills. As a result, a great deal of work has been done on automatic gauge control for the rolling mills. But very little work has been done to improve the control of the reheat furnace, which is the source of the problem. Because of the eclipsing effect of this heating problem, and the fact that furnace efficiency is difficult to obtain continuously, there has been no work done so far on efficiency control of the reheat furnaces. Chapter 2 gives a more detailed description of the reheat furnaces and the problem of controlling them. Appendix 9 gives definitions of the peculiar terminologies used in the steel industry concerning reheat furnaces and rolling mills. It is recommended that Appendix 9 be read first before continuing.

The slab temperature profile control and furnace thermal efficiency control have been impossible with conventional instrumentation. With

the advent of digital computers for on-line control this has become possible. Several people overseas, such as Kodz (11, 18, 19) and Hollander (15, 21) have started working on this problem using digital computers. Because of the more immediate problem of heating control, which results in difficulties of rolling, they have all dealt with the problem of heating control only. As the problem of steel heating is fairly complex, they have all made various simplifying assumptions which tend to restrict the problem, although some of them do claim a degree of success.

This project began with the aim of developing an on-line digital computer control system for reheat furnace control in general, using the two billet reheat furnaces as specific examples. The objectives are to increase furnace efficiency, to improve the temperature uniformity and to increase production by bringing the billets to target temperature in the shortest possible time. Experiments were carried out on the furnaces and a set of equations were obtained by Multiple Correlation analysis giving the relationship between thermal efficiency and furnace parameters. To control the throughput rate and temperature uniformity,

a mathematical model of heating billets was worked out. But, as a new large reheat furnace was to be built for the 140" Plate Mill and a computer was to be included, work on the billet furnace ceased and attention was focussed on the large slab reheat furnaces. Experiments on furnace efficiency control parameters were repeated on the No.1 furnace at 140" Plate Mill. Theoretical analysis was carried out on the thick slab heating model, and heating equations derived. Then experiments were carried out to check the validity and accuracy of the equations. These experiments showed up the necessity of considering the temperature dependent thermal properties for most carbon and low alloy steel. Only stainless steels have reasonably constant thermal properties. This resulted in fairly complex partial D.E. for the heating models.

The theoretical model of constant thermal properties case was solved on both analog computer and digital computer and found to agree closely. The temperature dependent case is too difficult to solve on the analog computer and was only solved on the digital computer using numerical analysis. The results do not exactly fit those from the experiments, but the overall shape is reasonably close. The

point of occurrence of temperature dip due to the transformation point of steel is different by about 200°F between calculated and measured values.

A search of the literature reveals very scanty information on thermal properties of steel. Information on some steels are not available, but the available information shows the possible difference in Specific Heats and Thermal Conductivity values for different steels. The inaccuracy may have been partly due to inaccurate specification of the steel slab sample used in the experiments. It may also have been due to inaccuracies in the approximation method used in solving the non-linear partial D.E. on the digital computer.

More precise solution of the equations is time consuming and is considered an applied mathematician's problem and not an engineering problem. It is beyond the scope of this thesis and is not pursued. However, analysis of the overall control strategy shows that the solution as it stands, although not exactly right, is more accurate than any previous versions used by Kodz (11), Hollander (15, 21), Lerner (23), etc. It can still be used to determine relative times required for slabs of different thicknesses and grades to reach

target temperature at the centre. An arbitrary datum can be obtained by trial and error in conjunction with the mill operators.

A complete computer control system was designed and installed at the No.2 reheat furnace of 140" Plate Mill. Some special instrumentation was designed and installed to aid interfacing, and to safeguard the furnace while under complete computer control. Some special measuring devices were also designed to provide the necessary signals to the computer. Due to inexperience with this type of on-line computer system, particularly with programming, the implementation has been divided into various stages. The implementation program is described in Chapter 8. The first three stages are basically to commission the hardware and the basic on-line programs, also to acquire experience with the on-line computer system. The next two stages are to implement the heat balance calculation and efficiency control in order to obtain some economic benefit before embarking on the more time consuming function of temperature control. The last two stages are to implement the temperature control function starting from a simpler version of using off-line compiled temperature set point tables. At present,



implementation is only up to stage 5 with optimising control of efficiency and calculation of heat balance. Work on stages 6 and 7 have commenced. Implementation will depend on availability of additional memory capacity.

Work on this thesis reveals that skid marks are a major problem. It is treated in Chapter 7 but detailed solutions are not given here. The problem is not difficult but is time consuming to solve.

Work on reheat furnace control has been quite scanty, and this thesis takes an overall view of all the requirements for automatic control. Although work on these requirements is not within the scope of this thesis, all are described in a recommendation for further work.

## CHAPTER 2

### THE PROBLEM OF REHEAT FURNACE CONTROL

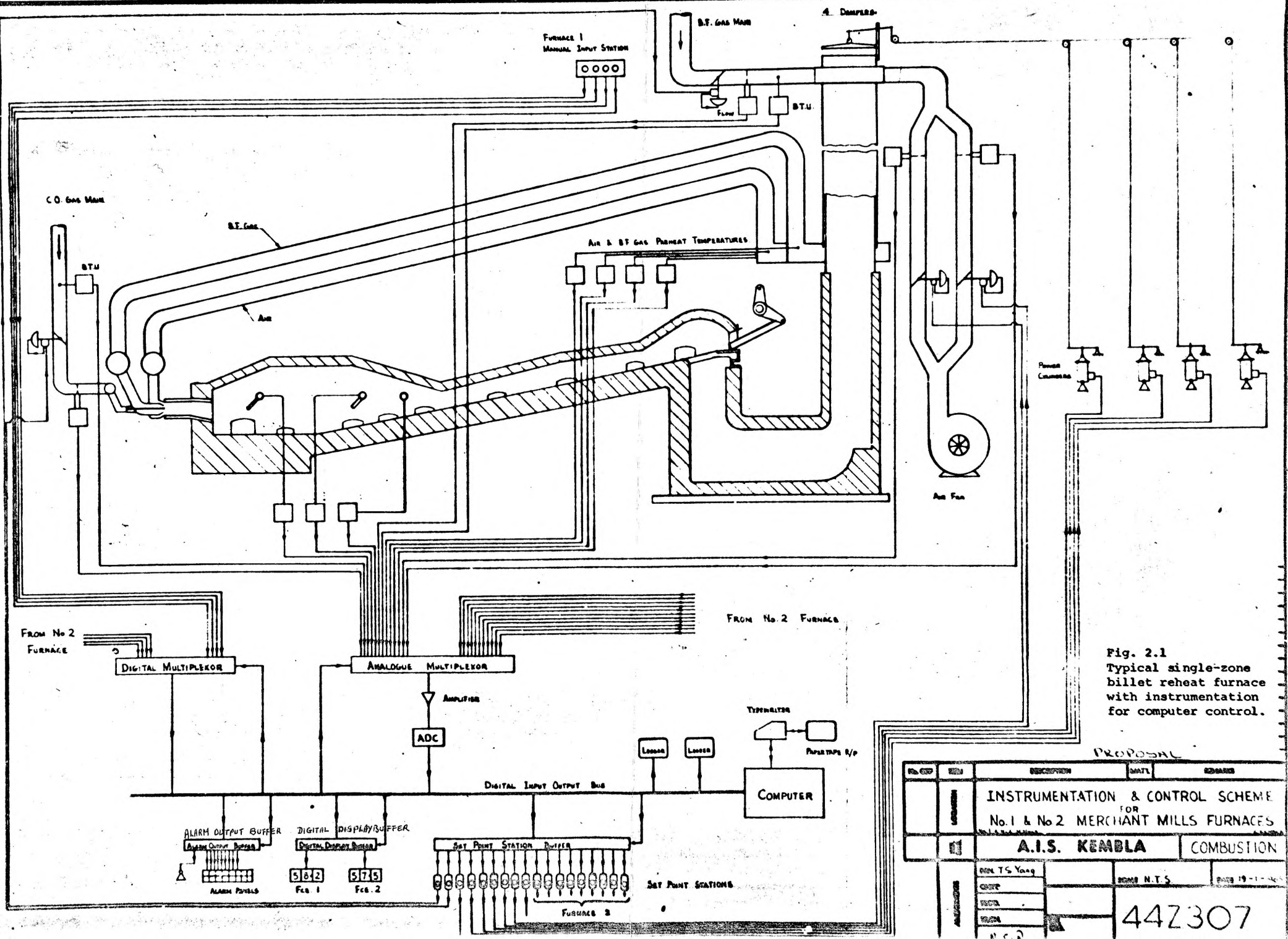


Fig. 2.1  
 Typical single-zone  
 billet reheat furnace  
 with instrumentation  
 for computer control.

PROPOSAL

No.	REV.	DESCRIPTION	DATE	BY
1		INSTRUMENTATION & CONTROL SCHEME FOR No. 1 & No. 2 MERCHANT MILLS FURNACES		
1		A.I.S. KEMBLA		COMBUSTION
		DRG. T.S. Yang		
		CHKD.		
		ISSD.		
		APPR.		
			DATE N.T.S.	DATE 19-11-60
				44Z307

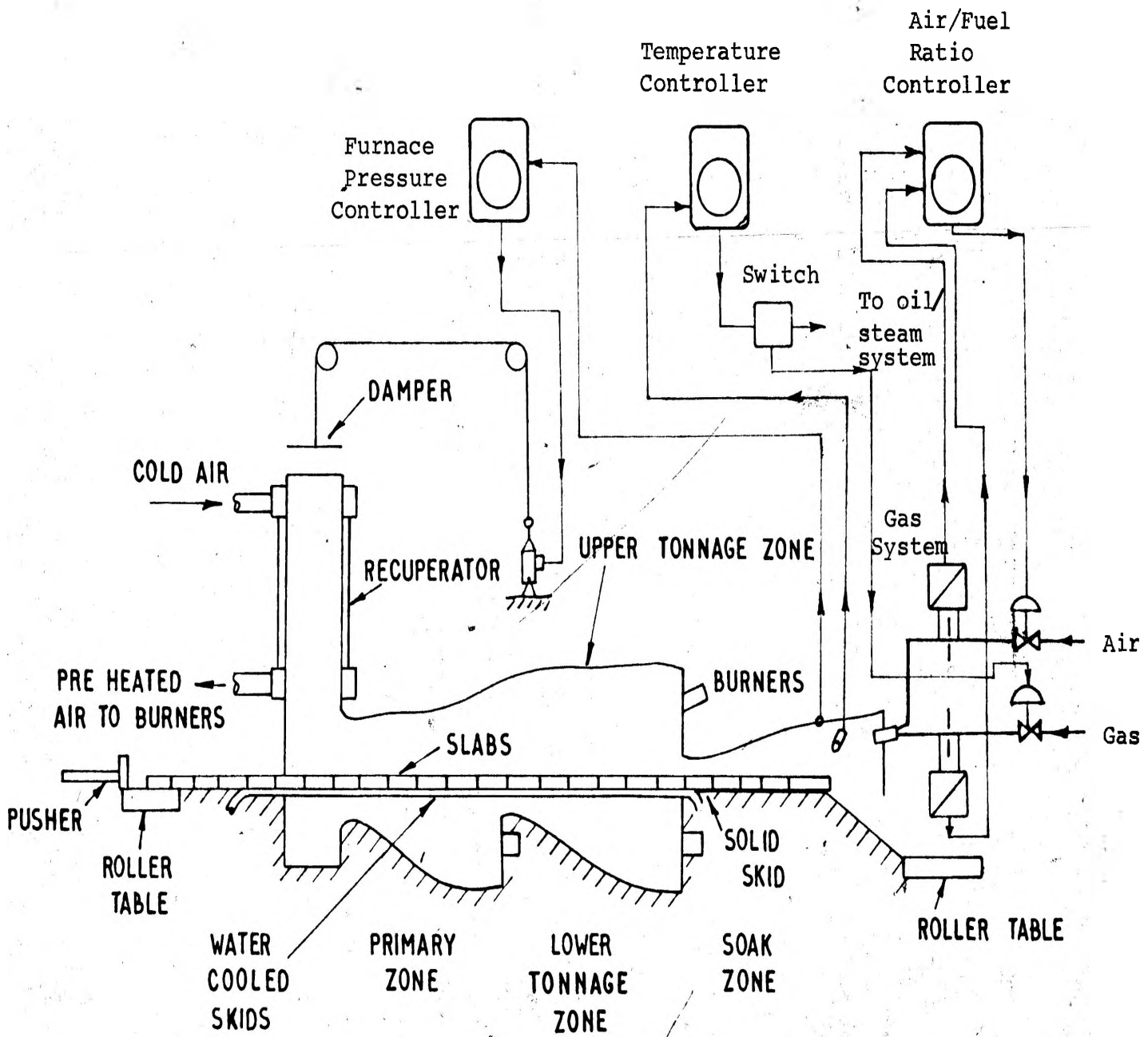
## 2.1 GENERAL

Billets, blooms and slabs are produced by the primary rolling mills and allowed to cool down. They are inspected and descaled, then reheated again in reheat furnaces before being rolled to strips or plates by the rolling mills.

The reheat furnaces are all continuous furnaces where cold slabs (or billets or blooms) are charged in from one end and pushed through the furnace to drop out at the other end with uniform rolling temperature. This must be done in the shortest possible time, with the maximum possible thermal efficiency, and with minimum scale loss and surface defects.

For billets, the reheat furnaces are generally small with only one or two zones, and are single sided firing. That is, the billets rest on solid hearths and fuel firing is from the top side of the billets only. The solid skids on which the billets slide when pushed do not result in noticeable skid marks. Fig.2.1 shows a typical single zone billet reheat furnace with instrumentation for computer control.

For blooms and slabs, the reheat furnaces



**FIG. 2-2 FURNACE CROSS-SECTION**

**TYPICAL 4-ZONE SLAB REHEAT FURNACE**

A greatly simplified pneumatic control system for furnace pressure and combustion control for one zone is shown as an example.

are much larger and have either 3, 4 or 5 zones. They are heated from both top and bottom in order to reduce the total heating time. When the slabs are heated from the bottom, they must be supported by water-cooled skids which produce skid marks on the bottom surface of the slabs. Hence the soak zone is required to soak out the skid marks and produce uniform temperature in the slabs before feeding to the rolling mills. Soak zone is only heated from the top and has solid hearth with solid skid on which the slabs slide when pushed. Fig.2.2 shows a typical 4-zone furnace. A 5-zone furnace has an additional Upper Primary Zone.

Most reheat furnaces have burners firing in the direction reverse to the direction of pushing the slabs. But some reheat furnaces have been built with the preheat zone firing in the same direction as the slab pushing, or with the preheat zone replaced by a series of roof burners or sidewall burners. To overcome the skid marks problem, new designs of furnaces such as the walking beam furnace have been designed, but to date have not been widely adopted.

The slabs are charged from one end of the furnace completely cold. In the preheat zone they

are heated to about 1,500°F and in the tonnage zone they are heated to approximately 2,400°F. The slabs are pushed through the furnace at varying pushing rates, depending on thickness of slabs, temperature of the furnace, mill demand, etc.

In 4 and 5-zone furnaces, preheat zones are used to speed up pushing rates. These zones are very powerful zones as the slab temperatures are very low and heat transfer rate is very high. But the use of preheat zones are inefficient because they are too close to the end of the furnace. The hot flue gas discharges directly into the stack and recuperator without first dissipating some heat to colder parts of the furnace and colder slabs as does the flue gas from tonnage and soak zones.

The fuel used in the furnace is either coke oven gas or fuel oil - atomised by steam. The fuel is burned ideally with slight excess of air to ensure complete combustion. The ratio of fuel to air has a large bearing on the overall thermal efficiency of the furnace. With varying amounts of air leakages, varying fuel calorific values and varying mixing of fuel and air at different flow rates, the exact air to fuel ratios are impossible to set manually. For some furnaces, the ratios are

reset once a week after heat balance checks and gas analysis tests by combustion engineers, while for most furnaces, the frequency of checking varies up to once per year. The flames from the gas are quite different in characteristics to those from the oil. Oil atomised to different degrees also results in different flames. These differences in flames also affect the heating capability and efficiency of a furnace, but cannot be controlled in a normal furnace. Oil flames are also affected by design of the oil burners.

The soak zone ends with the discharge door which is opened whenever a slab is to be discharged. The opening of this door causes cold air to rush into the soak zone chilling the front edges of the slabs. In some furnaces a flame curtain is used along the discharge door to heat up the cold air before it reaches the slabs. In some furnaces such as No.2 furnace at 140" Plate Mill a soak zone recuperator is provided. The cold air is drawn into the soak zone recuperator together with some hot flue gas before it reaches the slabs.



## 2.2 CONVENTIONAL INSTRUMENTATION AND CONTROL TECHNIQUE

Conventional instrumentation for reheat furnaces vary widely from furnace to furnace. Fig.2.2 shows a typical pneumatic control system as used on the No.1 furnace at 140" Plate Mill. This system is fairly typical for the more advanced reheat furnaces around the world.

Combustion air is supplied by a fan and is preheated through the recuperators by hot flue gas to approximately 800<sup>o</sup>F to 1,000<sup>o</sup>F. The preheated air is fed to burners through common headers for each zone. Air flows to each zone are measured by orifice plates in the hot air headers to each zone, and are compensated for temperature variations before being used. Air to fuel ratios are manually selected on the air flow controllers which automatically control the combustion air flows.

Furnace pressure is sometimes measured in the soak zone and sometimes in the tonnage zone. It is controlled automatically by dampers on the flue gas stacks. The operators generally favour the soak zone for pressure measurement because the

soak zone is the most sensitive zone to pressure fluctuations. When pressure is too high, flame leaks out through the many holes and doors of the soak zone. When pressure is too low, cold air is sucked in through the holes and door to cool the ends and edges of the slabs. This cold air inrush is particularly severe when the discharge door is opened to discharge a slab. However, the actuation of the flue stack dampers also affects the pressure profile throughout the furnace. As a result, the pressure set point in soak zones ideally should be re-adjusted regularly to maintain a proper balance of furnace pressures throughout the furnace. But this is difficult to do and is rarely carried out.

In most furnaces in the world, temperature control is effected through thermocouple measurement of furnace temperature. This method has the drawback of very slow response to changes in pushing rate and slab thickness. To overcome this many furnaces, including all Australian furnaces, have changed over to the use of radiation pyrometers sighted directly on the slab surface. This method does not measure slab temperature accurately in the primary zone where the slab temperature is much lower than that of the furnace surroundings. But

in the tonnage zone and soak zone where the temperature of slab surface is much closer to the corresponding furnace surroundings, the error is small and is tolerable. The zone temperature controllers regulate air and fuel to get the required slab temperatures. Air to fuel ratios are generally set by the combustion engineers between once per month to once per year.

Oxygen analysers are provided on some furnaces to measure the oxygen content in the flue gas. But the poor reliability of these analysers have so far prevented more widespread use of them for adjusting air to fuel ratios.

The recuperators are used to preheat the combustion air, but the air also performs the function of keeping the recuperators colder so that there is no excessive expansion of the metallic recuperators. In case the hot air requirement is too low and the recuperator temperature rises too high a blow-off valve in the hot air header opens to bleed off some hot air in order to increase the air flow through the recuperators and prevent over-expansion. The larger furnaces generally have fairly elaborate safety interlock systems to protect the recuperators, the furnace and the slabs.

The fuel firing system has to be correctly interlocked to prevent explosive mixtures from forming.

Because of the constantly changing furnace firing conditions, the fuel calorific value, ambient condition and flame characteristics, etc., it has been impossible for the furnace operators to adjust the settings in order to obtain maximum efficiency. Hence furnace efficiency has never been of much significance to the operators although the fuel cost per year is of such high magnitude (see Section 2.4).

Since only the slab surface temperatures are known, only the mill operator can tell whether a slab is sufficiently heated in the centre and on the bottom surface of the slab and whether the skid marks are soaked out. When the mill operator discovers that a slab is cold, the whole soak zone would be full of inadequately heated slabs. The soak zone does not have a large heating capacity, hence the resulting heat delay will be quite long. If the centre temperature of the slab can be determined, the cold slabs can be halted (or slowed down) in the tonnage zone where the large heating capacity burners can rapidly heat up the slabs from both top and bottom surfaces of the slabs. This,

however, cannot be done with the conventional instrumentation.

### 2.3 INSTRUMENTATION FOR COMPUTER CONTROL

When the reheat furnace operates semi-automatically using conventional instruments, some human judgment by the operators is used. Hence if there are inaccuracies or failures of signals, the operators can usually detect them and take remedial action. Also, provided the temperature measurements are accurate, inaccuracies in the other metering devices are unimportant to the operators. These would only result in poor air to fuel ratios, etc. and generally low efficiency, but do not affect pushing rate.

With the computer on-line, efficiencies and heat balances will be calculated from signals received and used for control. Fairly elaborate signal credibility checking programs have to be prepared to take care of possible signal failures and inaccuracies. (See Appendix 5). Without the experience and overall plant knowledge of the operators, the computer cannot tell that a signal

is obviously wrong or inaccurate. Hence, although the same type of conventional instruments can be used for computer controlled furnaces, they require much greater care in maintaining a higher degree of accuracy. If the computer makes obvious mistakes due to inaccurate signals, it will quickly lose the confidence of the operators.

Response time of the instruments need not be much faster than before, but fast response optical temperature sensors are required to detect the slabs as they are pushed out of the furnace. The slabs fall down a ramp on to the table rolls which transport every slab to the rolling mills. The sensors have to detect the slabs as they fall past the sighting path and measure the slab temperatures as well. Temperature of the slab can be measured more accurately outside the furnace by optical pyrometers as it is not affected by the furnace temperature and flame temperature, etc. This temperature measurement is used as a final check of the slab temperature. The slab drop out signals are used by the slab tracking program to reconcile the slabs pushed out against those pushed in.

Conventional systems using pneumatic

instruments have no noise or interference problems. Even those using electronic instruments are not bothered by noise pick-up and interference because of the inherently long time constants of most industrial processes. But a computer controlled system requires reasonably noise free signals as it samples the signals at high speed. With the system at 140" Mill, screened and twisted-pair cables are used throughout. A high noise rejection preamplifier is used before the analog to digital converter. Before each input signal is used, it is averaged with the previous value to reduce the errors from picking up a "spike" or a "valley". Surprisingly, in the implementation process it is found that the largest source of problem comes in the internally generated noise from many instruments. These instruments have noise of the order of 1 - 2 kHz which is usually unimportant and has not been noticed until now. Some A.C. ripples on electronic instruments are picked up by the computer as signal variations. These are overcome by providing more damping and smoothing of the signals before feeding to the computer.

Ideally, all input signals should be isolated from one another and from the computer.

This must be done if the input multiplexer is of the solid state type. If it is the relay type, theoretically it does not matter, but in practice it still gives trouble. The only foolproof solution is to ensure that in complicated cascade control loops, the individual instruments are either isolated or carefully arranged and connected to ensure common ground potential. When the relay input system is functioning correctly, there is no problem, but if some relays fail and result in two or more relays being closed at the same time, interaction will occur through the relays. An isolated preamplifier before the A.D.C. would protect the computer from this problem but would not protect the conventional control loops. The flying capacitor type of input multiplexer will protect the conventional control loops but the signal to the computer would not be affected. This method is the safest but is expensive and is not included in our system.

As the computer controlled furnace will result in less operator attention, more safety interlocks and alarms are provided.

The pushing rate can be measured automatically as described in Section 9.8 but has not been completed. At present it is calculated from



the time of slabs pushed out and the width of each slab. The time is given by the slab drop out detector and slab tracking program. The widths of slabs are manually entered through the pusher input station.

Slab dimensions can also be determined continuously as described in Section 9.8 but is not implemented yet. At present all the slab data are entered manually via the pusher input station. The manual input station has been designed using thumbwheel switches and pushbuttons. Appendix 6 gives details of the input station. The unit described in Appendix 6 is the original version. When this unit was commissioned, it was found to be taking up too much of the pusher operator's time. As a result, some of the data are deleted. Only the essential slab dimensions are entered. Even then it has been found to be impossible to provide the computer with error free information. For thermal efficiency control, small amounts of slab data errors can be tolerated because the control system is basically self-correcting. It is continuously searching for the optimum efficiency. If due to data entry error the efficiency is calculated incorrectly the system will still continue in trying

to search for the optimum efficiency whatever physical value the efficiency now has. But when the final stage of the temperature profile control is implemented, the slab data becomes critical. Even small errors can result in erroneous heating times being calculated. Hence, while the thumbwheel station is at present used for the efficiency control, a new system utilising automatic card readers obtaining slab data from punched cards is being considered in conjunction with another project team working on mill "drafting".

The furnace roof and floor occupy the largest area from which heat is radiated back to the slabs. It is difficult to measure the roof temperature. If the thermocouple is pushed through the furnace roof, it is affected by radiation from flame and slabs, etc. If the thermocouple hole in the roof brick is not drilled through, it is not certain how far to drill because of wear in the roof. Roof thickness does not remain constant for long. Ambient wind velocity alters the roof heat loss pattern from free convection and radiation to forced convection when the wind velocity is high. Fortunately the roof temperature is not needed, as a coefficient of heat transfer is available for the

"furnace temperature" as measured by the thermocouple inserted through the roof into the furnace.

Furnace thermal efficiency cannot be measured directly. It is calculated from the heat input to the furnace and heat contained in slabs discharged. The latter is calculated from the slab temperature and the slab data manually entered. Section 4.3 and Appendix 9 describes this in more detail.

One information which only the mill operator can provide is whether the slab is correctly heated. At present this is provided by pushbuttons operated by the furnace operator. This depends on the slab mean temperature after the sizing pass, the load on the rolls, and the degree of roll bending, etc. When the mill computer is fully controlling the rolling operation, it is planned to determine this automatically with the mill computer which provides the signal to the furnace computer as a feedback. For hot strip mills, the strip temperature after the roughing stands is generally used as feedback signal to the furnace computer. But in plate mills, the conditions are determined after the sizing pass. It has been observed that if the soak zone temperature has dropped by more than

30°F and is continuing to drop in spite of full firing, then the slabs in the soak zone are too cold. This method can be used as a feedback to the furnace control system, but is not definite enough for use as yet, except as a double check.

Information regarding impending delays, their duration, etc. are also provided by the furnace and mill operators via pushbutton switches.

#### 2.4 ECONOMIC CONSIDERATIONS

Furnace thermal efficiency has never been seriously considered by any furnace operators as a performance index. One reason for this is because there is a more important and more demanding performance index, "the rapidity of supplying correctly heated slabs as demanded by the mill". The other reason is that the operators do not know what the furnace efficiency is at any particular time, except about one week later when the weekly report is issued. By then the information is of little use for short term control of efficiency.

Every experienced furnace operator has his own set of rules-of-thumb for operating the

furnace. These are sometimes different from operator to operator. Also, these rules are generally orientated towards faster pushing rate and do not consider furnace efficiency.

Regression analysis described in Chapter 5 shows significant correlation between efficiency and air to fuel ratios, steam to oil ratios and furnace pressure. For small furnaces with mixed fuels, the fuel ratios (BF gas to CO gas) are also important.

A study of the furnace weekly reports show that the weekly mean efficiency, for similar tonnages and delays, vary by  $\pm 15\%$ . There is no other explanation for this fluctuation apart from variations in firing efficiency and furnace pressure. If the furnace efficiency can be calculated and displayed to the operators regularly, say once per 15 - 30 minutes, the operators can become efficiency conscious and start improving combustion efficiency as well. For large multizone furnaces, the number of variables are too large. Automatic optimising control of efficiency is required in order to obtain the best results. It can be reasonably assumed that the hour-by-hour furnace efficiency can be improved by approximately 15%.

For a typical 4-zone furnace heating approximately 500,000 tons of steel a year, the fuel consumption is of the order of \$800,000 per year. An increase in efficiency of 15% would result in a yearly saving of \$120,000 in fuel consumption. A side effect of efficiency control is reduction in scale loss. Metal loss due to scale formation while the slabs travel through the slab furnaces vary from 0.5% to 3%. Optimum efficiency means perfect combustion condition in the furnace. Hence formation of scale will be reduced to a minimum. If 1% reduction in scale formation is assumed, this amounts to 5,000 tons of metal saving per year. This represents a potential saving of \$400,000 per year. The total potential savings per year from efficiency control is approximately \$520,000 per furnace.

The temperature control also increases the efficiency by changing temperature profile during delays and thus saving fuel. It also minimises heating time and heat delays. It shortens heating time by altering furnace temperature profiles to bring the slabs to target temperature at the right time, eliminating wastage of time due to uncertainty of whether the slabs are heated

sufficiently. It reduces and shortens heat delays by being able to call for a delay (whenever necessary) before the slabs enter the soak zone hearth. A survey indicates that this type of temperature control can increase the production rate by approximately 10 - 15%. However, this is only realisable when the furnaces are operating at peak capacity all the time. At present, the second stand of the 140" Plate Mill has just been commissioned, and it will be some time before it can operate at full capacity. Hence, the two reheat furnaces are only operating at approximately 60% capacity. The temperature control program is not yet required. Plants are usually designed not to operate at maximum capacity continuously. When they are operating at maximum capacity for more than 50% of the operating time, plant extension or new plants have to be considered. This reduces the possible return from increased production. As a result of these, it becomes difficult to determine the possible savings obtainable from increasing production by temperature control. Better and more even heating of the slabs reduces rolling time, improves product quality and reduces the percentage of rejects. The potential saving is large, but

considerable investigation has to be carried out to determine the actual value.

However, the potential savings from the efficiency control is so large that the equipment can easily be justified without the production increases, etc. from the temperature control. Also, the work involved in the implementation of efficiency control is much less than that for temperature control. The return versus investment ratio is heavily in favour of the efficiency control. Hence, it was concluded that although minor hardware provisions will be made for temperature control, the costly computer bulk memory required for temperature control will be left out initially. The case will be prepared entirely on efficiency control and all effort will be made to place the furnace under computer control of efficiency as quickly as possible. When the efficiency control is fully implemented, then efforts can be diverted to implement the temperature control.

The total cost of the computer system for implementing the efficiency control is approximately \$100,000. The bulk memory required for implementing the temperature control will increase the cost by approximately \$40,000.



## CHAPTER 3

ON-LINE COMPUTER SYSTEM FOR CONTROL

### 3.1 GENERAL

The criterion of selection of the computer hardware is unfortunately "cost". There is just no large amount of funds available for a project which has no successful example to show. Uncertainty of its eventual functions and inexperience make the task of computer selection even harder. The trend in the world seems to be to refrain from one large computer system controlling a large number of processes and performing multiple functions. As small computers are becoming more and more powerful while the prices are dropping dramatically, the tendency is to use small computers to perform simple limited tasks. The type of computers used for on-line control work is quite different from the type used for commercial and data processing work. For the latter, as a large amount of the work involves manipulation of numbers and characters, etc., the machine structure is "character-oriented" while the control computers are "word-oriented" for faster operation. Some character-oriented computers have been used for process control in the early days but they have all been superseded by "word-oriented" computers.

The computer itself is only a small part of the consideration in the selection of an on-line computer system. The major part of the consideration lies in the interface equipment with the plant and the field and panel instruments. Many suppliers make good computers, but only a few of them have sufficient interface equipment and conventional instruments knowledge to build a good complete control system.

The trend in the world for small on-line computers is to use low level assembler-type language for programming. This saves a great deal of computer memory and allows the full power of the machine to be utilised. The high level languages, such as Fortran IV, because of conformity to standard, usually bypass some very useful features of the computer. That is, features which are not useful in commercial work but important in on-line control work. But, if complicated manipulation or calculations are involved, the programming effort becomes large and high level programming is required.

The computer system selected for this project is one that uses PDP-9 as the central processor. It consists of basically 16K words of core memory, 64 channels of analog inputs, 16

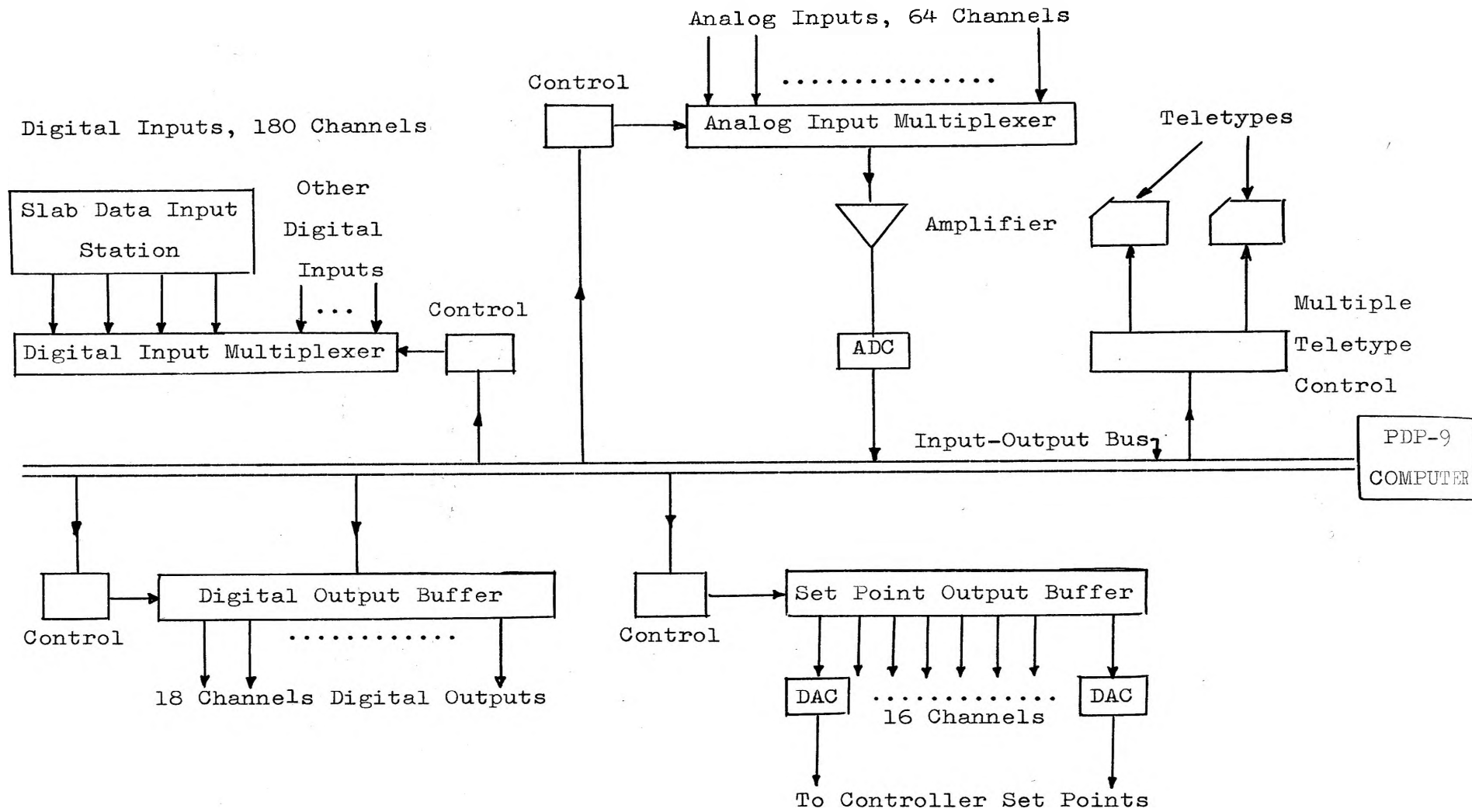


Fig.3.1 Simplified Diagram of Computer System for On-line Control

channels of analog outputs, 180 channels of digital inputs and 18 channels of digital outputs. Fig.3.1 shows a simplified diagram of the system. Ideally, a bulk memory storage unit such as a disc or a drum should be included, but it is left out due to cost considerations. Appendix 1 gives the complete lists of analog and digital inputs and outputs.

### 3.2 THE COMPUTER CENTRAL PROCESSOR

The PDP-9 central processor consists of the following:

- (i) Basic core memory of 8,192 words of 18 bit words;
- (ii) Memory parity option;
- (iii) Memory extension control;
- (iv) Additional 8,192 words of core memory plus parity;
- (v) Basic teletype unit KSR-33;
- (vi) High speed paper tape reader, 300 characters per second;
- (vii) High speed paper tape punch, 50 characters

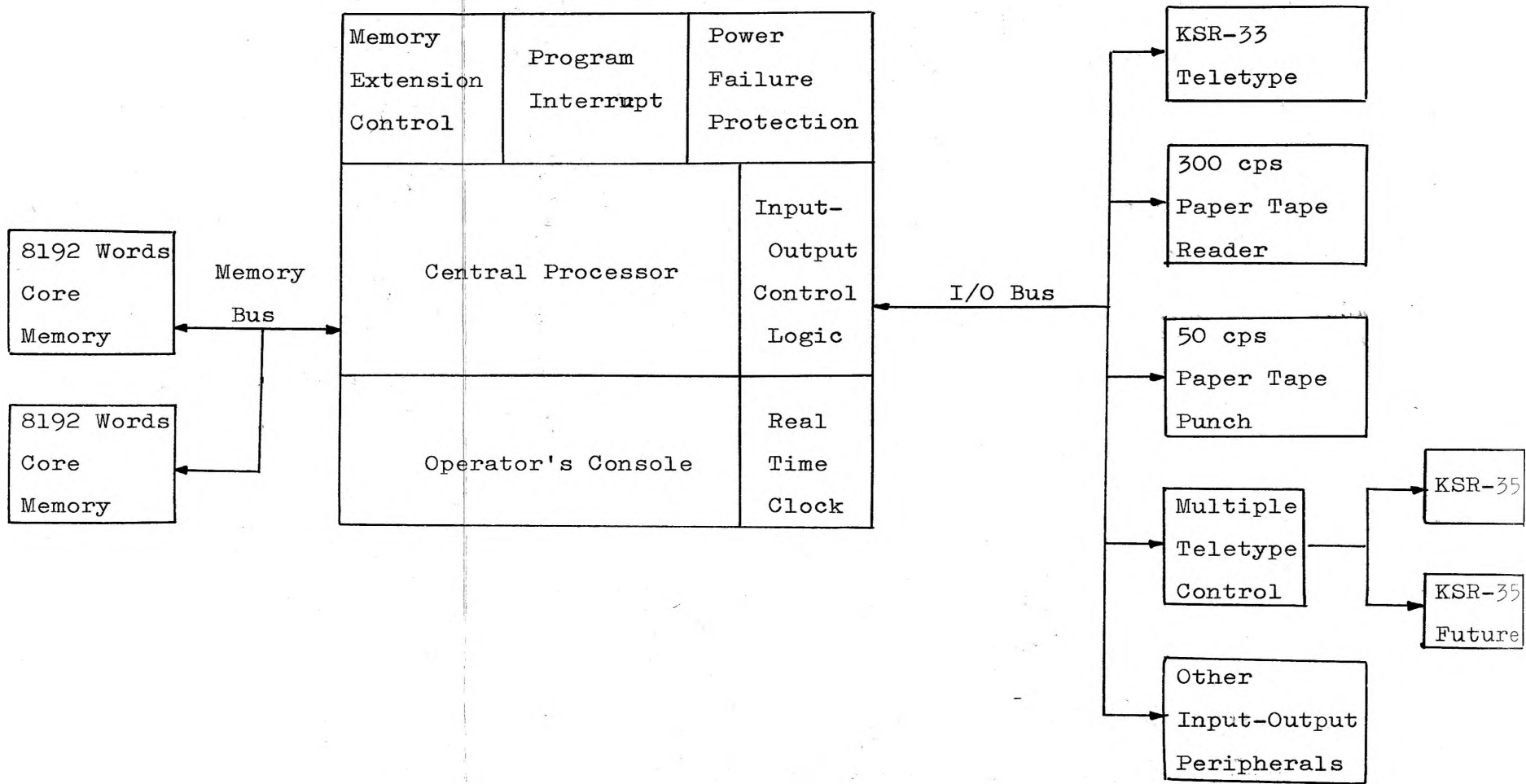


Fig.3.2. Block Diagram of PDP-9 Computer System

- per second;
- (viii) Real time clock;
- (ix) Power failure protection unit;
- (x) Program interrupt.

Fig.3.2 shows a block diagram of the PDP-9 system. The memory cycle time of the central processor is  $1 \mu\text{s}$ . A real time clock operating from the 50 Hz line frequency is provided to give a pulse every 20 ms and automatically increment one particular memory word by one. This unit is essential for real-time operation by the computer. The power failure protection unit holds the power for 25 ms upon a mains power failure, during which time the current instruction is completed and the contents of the active registers are saved. When power is restored, it automatically restarts the system where it was stopped before.

Automatic priority interrupt system is ideally required for this system, but due to budget considerations it is left out. A program interrupt system is used in its place. This provides only one hard wired interrupt channel where all the interrupting devices are connected. The computer continues execution of a program until an interrupt

signal appears. At that time the program is interrupted and control is transferred to an interrupt service program which allocates priorities to all the devices and organises a queue.

### 3.3 INPUT-OUTPUT PERIPHERALS

Special input-output peripherals added to the computer for on-line control are as follows:

- (i) Analog input multiplexer with 64 channels;
- (ii) High noise rejection input amplifier;
- (iii) High speed analog to digital converter;
- (iv) Digital input scanner with 180 channels;
- (v) Digital output unit with 18 channels;
- (vi) Analog output control with 16 channels, each with one buffered digital to analog converter;
- (vii) Multiple teletype output control unit;
- (viii) Heavy duty logging teletype KSR-35.

Fig.3.1 shows the simplified block diagram of the system.

All analog input signals are reduced to



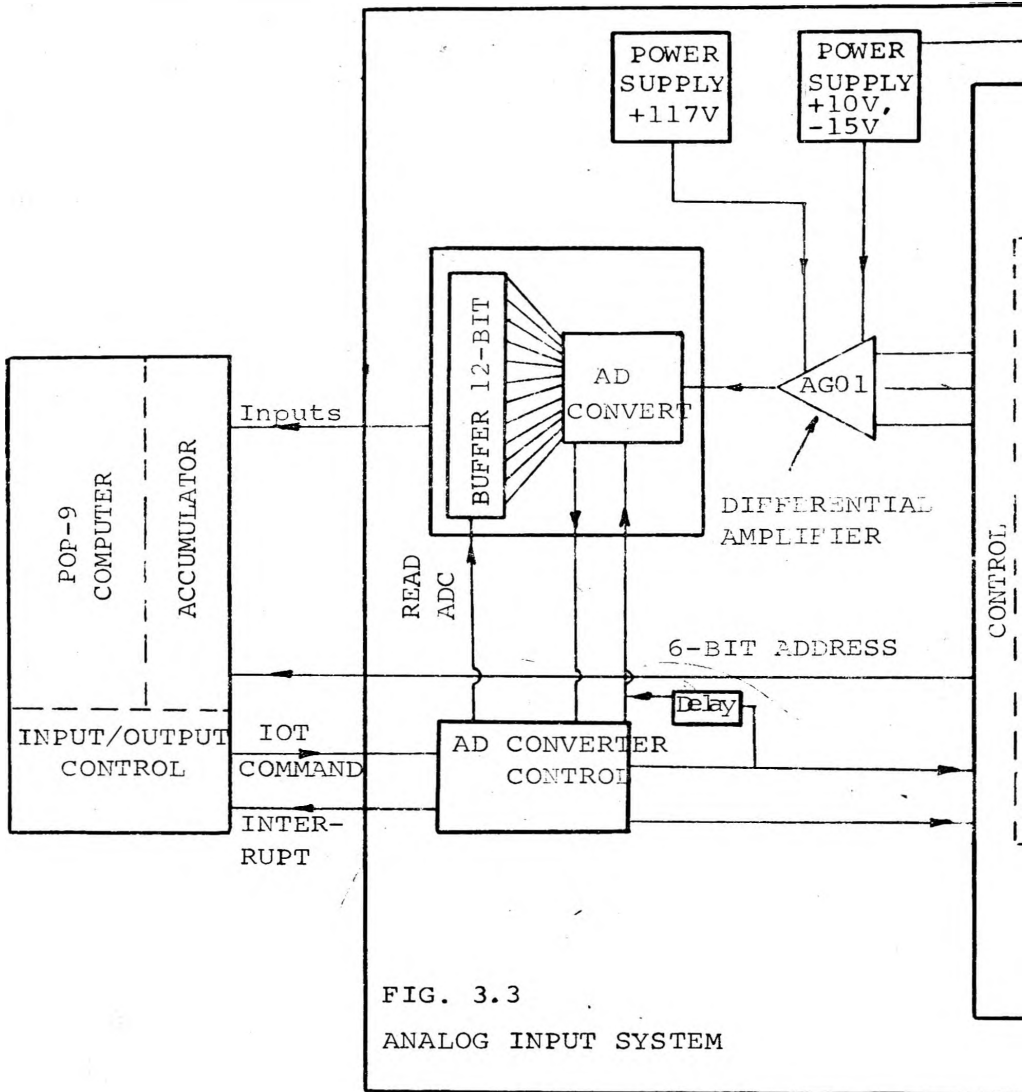
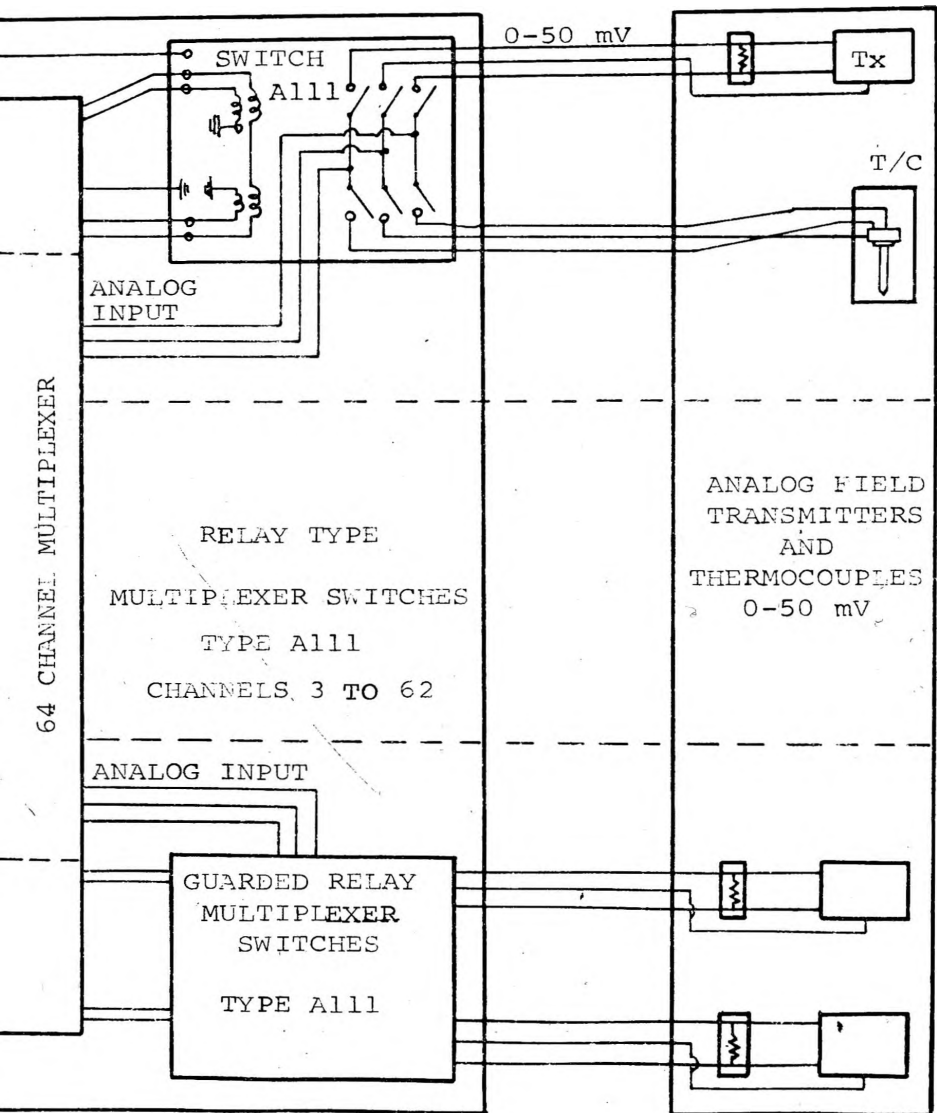


FIG. 3.3

ANALOG INPUT SYSTEM



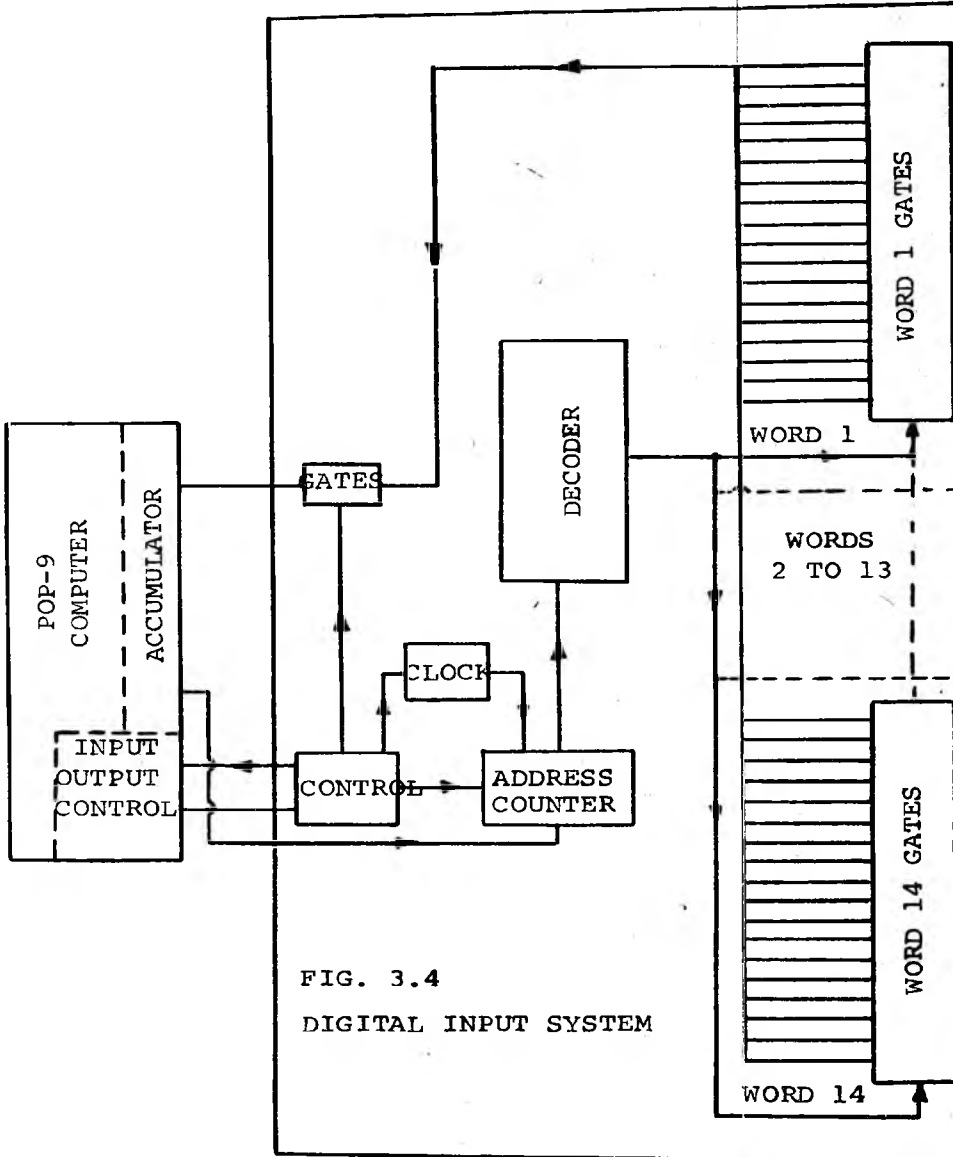
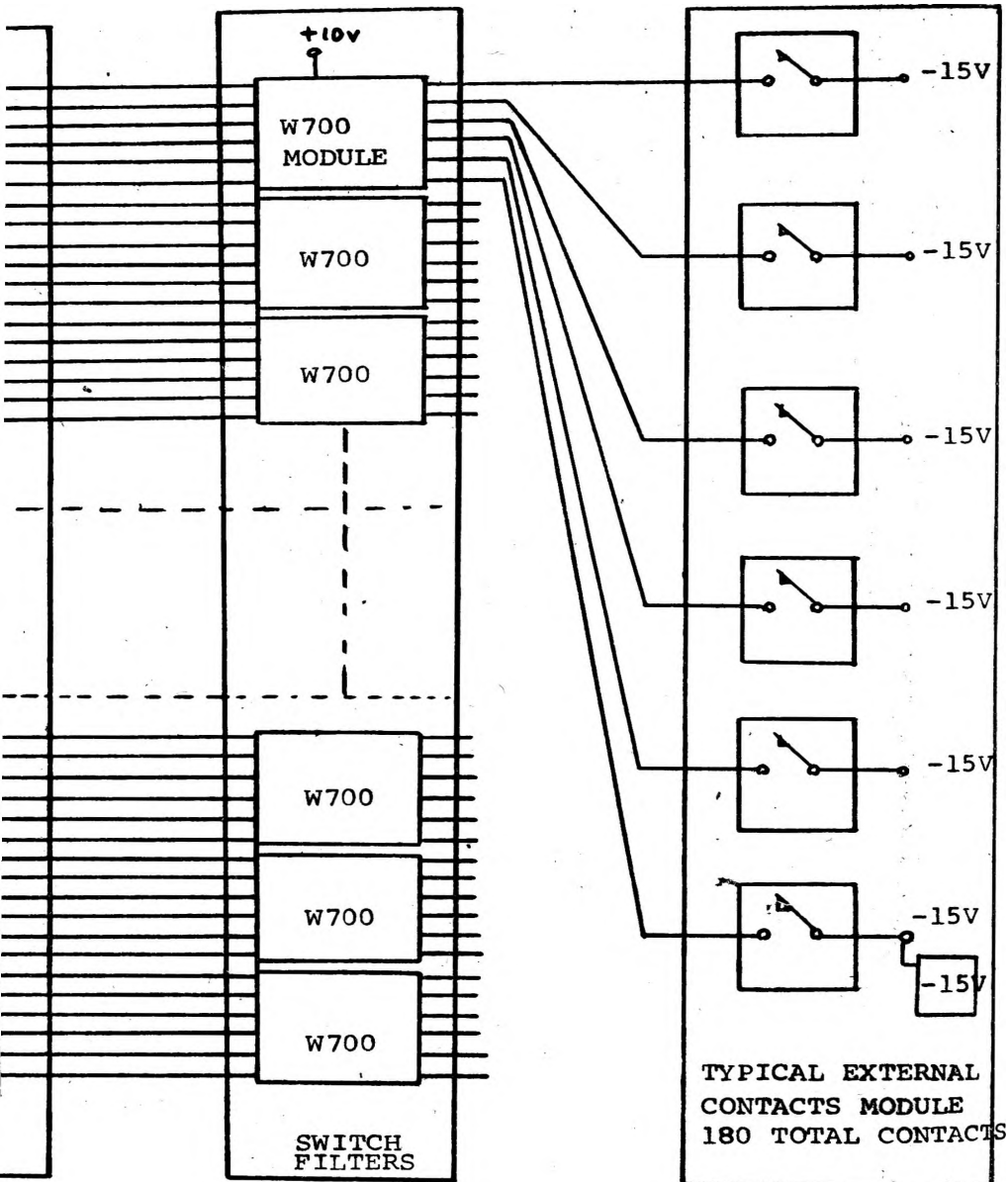


FIG. 3.4  
DIGITAL INPUT SYSTEM



within the span of 0 - 50 mV and switched through high quality shielded relays. The input multiplexer is controlled by program addressing. All inputs, when selected, are amplified by one amplifier with high noise rejection into high level signals of 0 - 10 V. These are then converted to 12 bit digital signals by an analog-to-digital converter. The 12 bit digital signal is connected directly to the computer accumulator through the input-output bus. Fig.3.3 gives the details of the analog input system.

Digital input signals are all converted to contact closure type signals. The 180 inputs are divided into 10 words of 18 bits each, and are scanned one word at a time into the core memory. The signals can be randomly addressed or sequentially addressed. But, for simplicity, the program is prepared to scan through the whole batch sequentially once per 50 ms. That is, it scans fast enough to detect the momentary depression of a pushbutton by an operator. Fig.3.4 shows the details of the digital input system.

A manual data input station, as described in Section 2.3, accounts for most of the digital inputs.

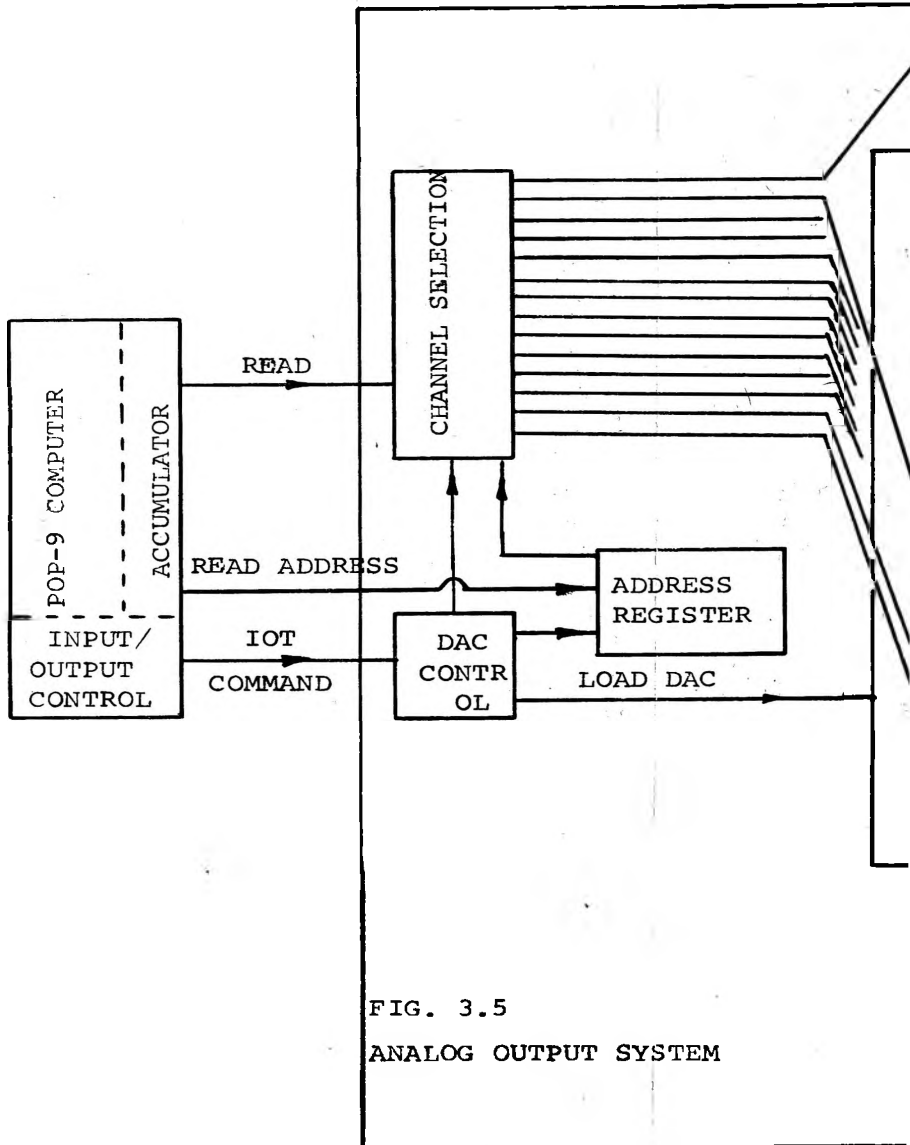
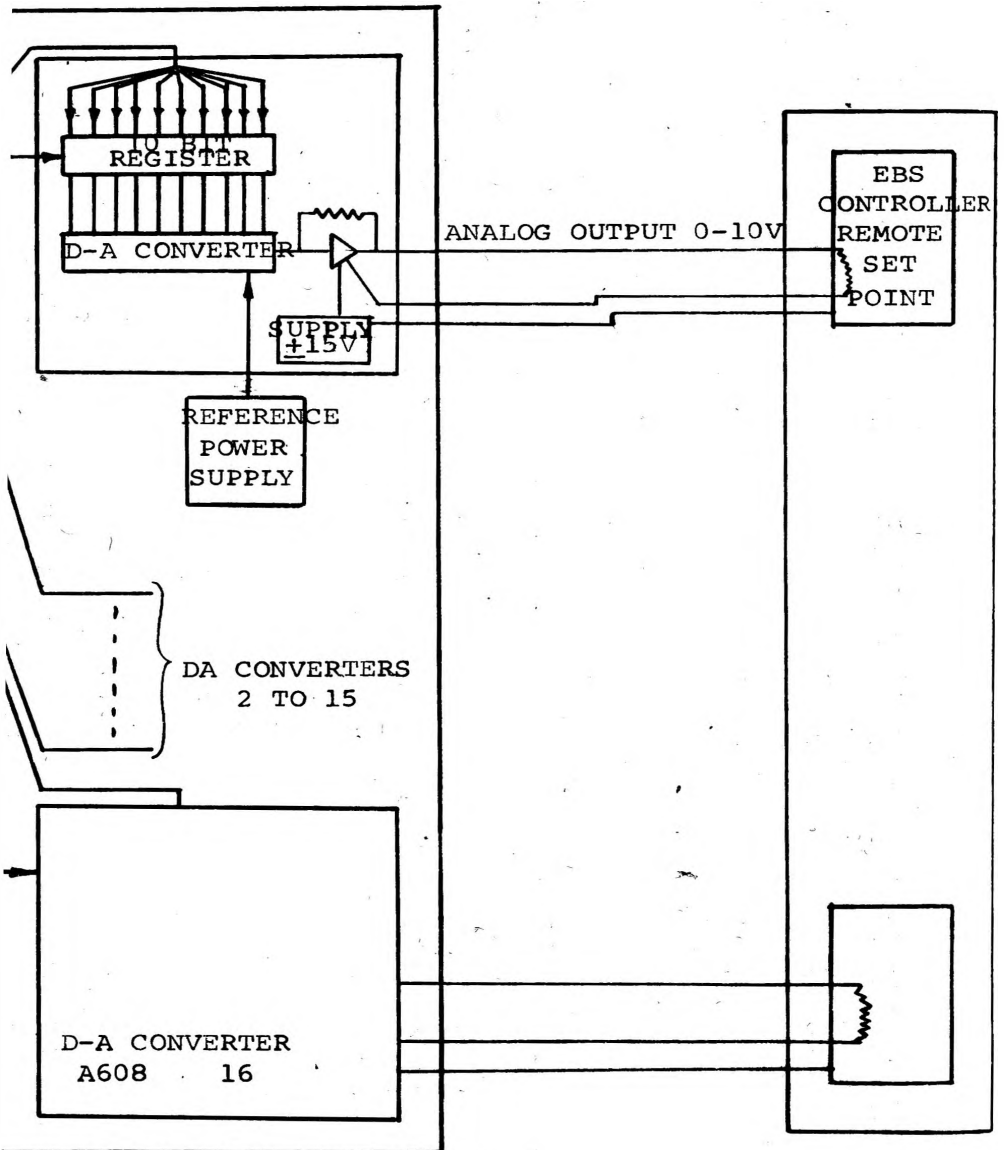


FIG. 3.5

ANALOG OUTPUT SYSTEM



Analog outputs are channelled by an output multiplexer into 16 individual buffered digital-to-analog (DA) converters. Fig.3.5 shows the details of the analog output system. Sixteen words in the core memory are used as output registers and values of the registers are updated regularly by other subroutines. Once every 10 seconds, an analog output subroutine enables each channel of the output multiplexer in turn and deposits each value into the corresponding DA converter. Ten second intervals are adequate for this application since only supervisory control is implemented. When implementation is extended to include DDC, this time has to be changed to about 50 ms. This would involve more programming work with the timing chain and program interrupt subroutines. Appendix 8 describes a PDP-8 computer program for DDC prepared before PDP-9 was selected.

An output system using a single DA converter can be used with an analog multiplexer after it. The output subroutine addresses each output channel in turn and deposits the converted analog signal on to a sample and hold amplifier. However, with the cost of DA converters very close to that of sample and hold amplifiers, there is



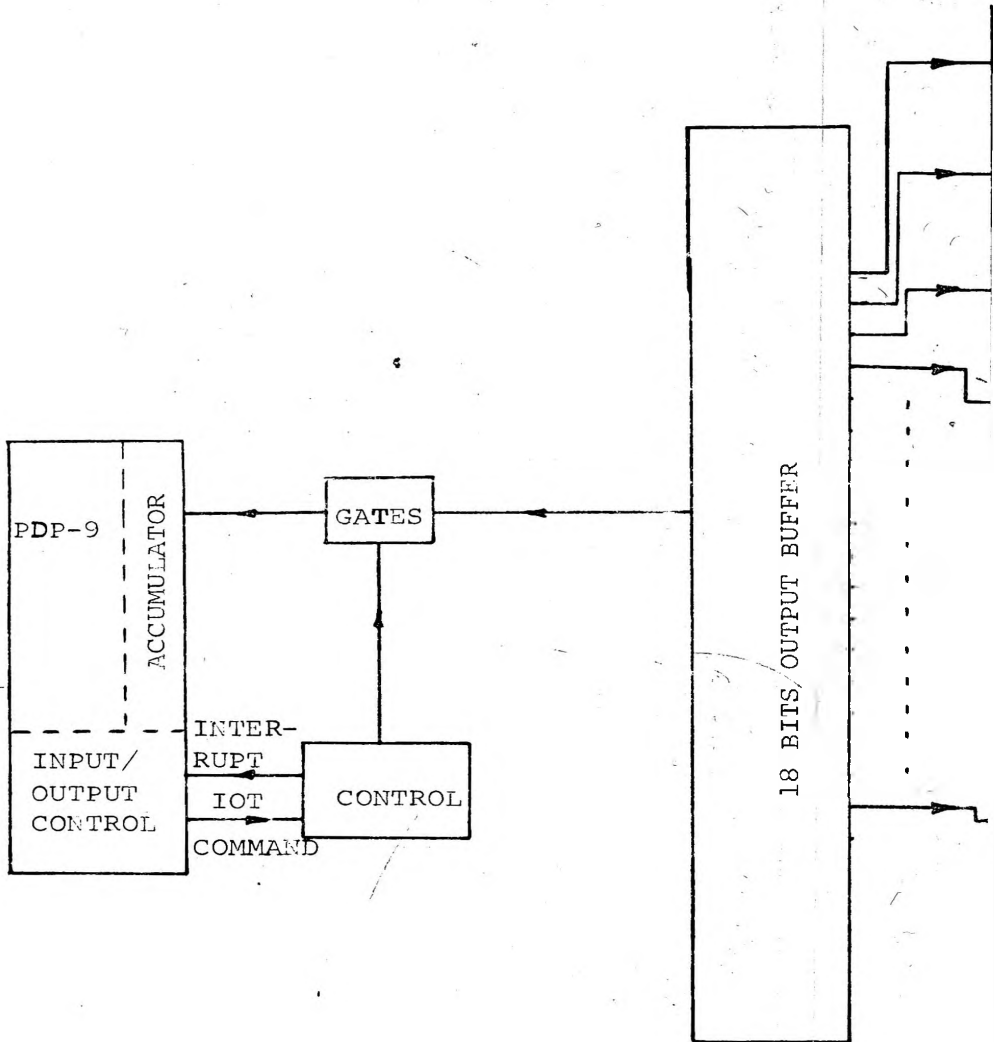
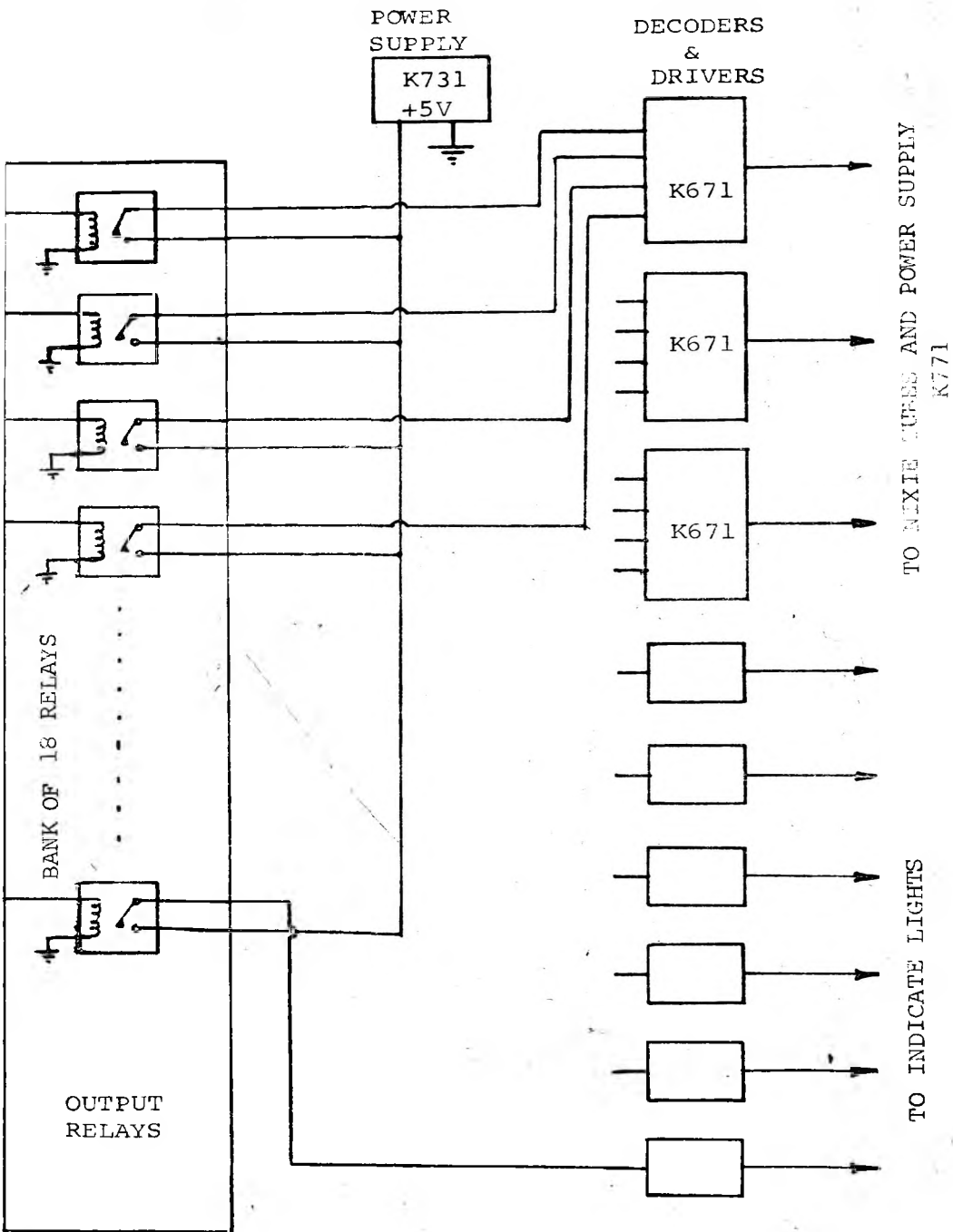


FIG. 3.6

DIGITAL OUTPUT SYSTEM



little gain in savings. The individual DA converter system provides the added feature of not losing everything when one DA converter fails.

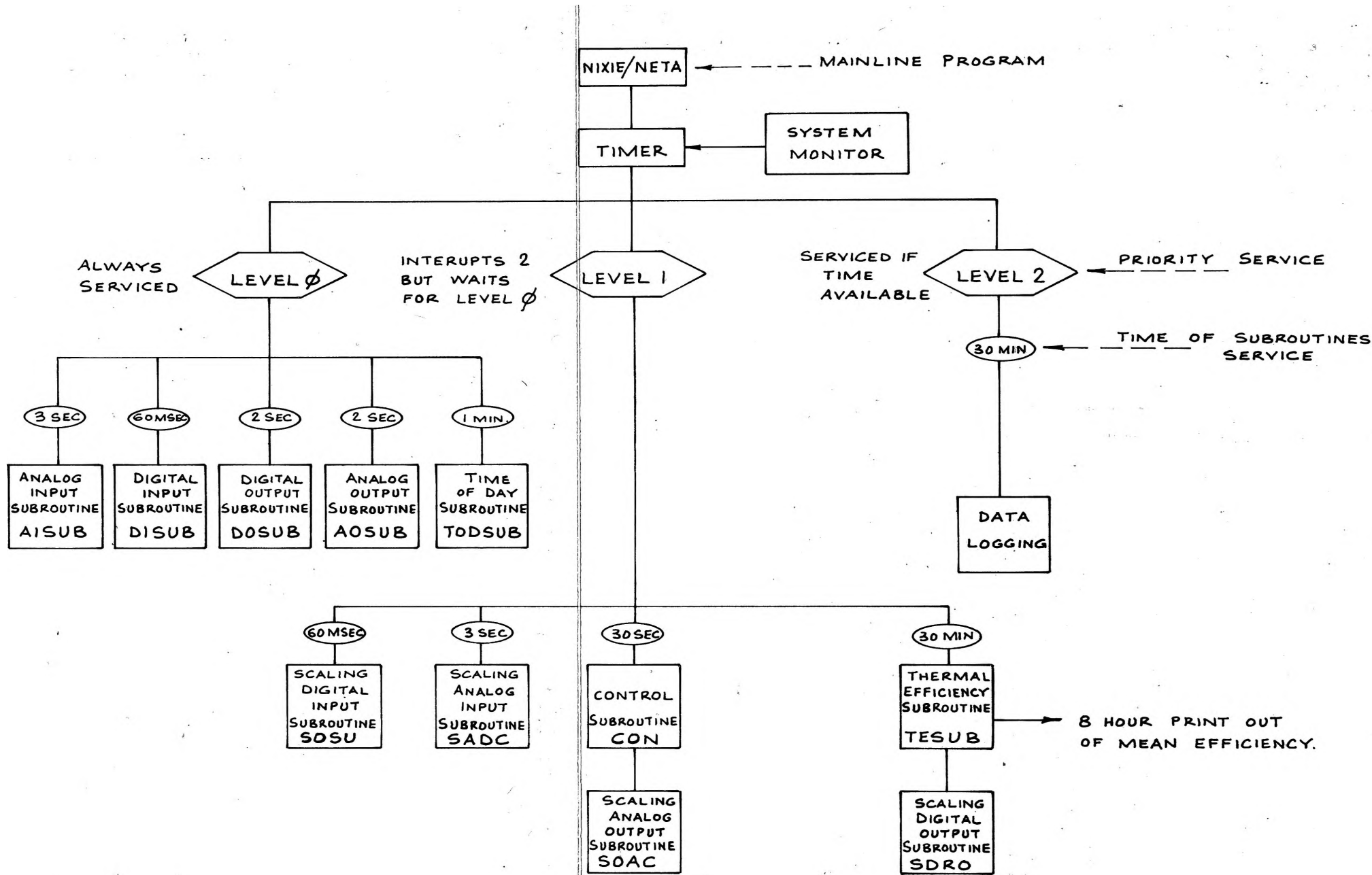
Analog outputs are all program scaled to 1 - 5 V signals feeding directly into the analog controllers as set points. There is a master switch on the control panel which can switch the control of all set points back to the operator in an emergency.

Digital output systems are basically the same as analog output systems. A number of words (in this case only one) are used as registers which are updated regularly by other subroutines. Once every 50 ms a digital output subroutine enables a digital output buffer and deposits the word into it. The output buffers hold the signals in registers and convert them into contact-closure outputs. Each output buffer contains 18 bits of digital outputs and occupies a distinct output address. Fig.3.6 shows the details of the digital output system. Some digital outputs are used to drive Nixie tubes for indicating thermal efficiency, and some to drive indicating lights and pushbutton lights as messages to operators.

### 3.4 PROGRAMMING REQUIREMENTS

Originally, due to the limited amount of core memory available, it was intended to use the assembler language for all the programming work. However, due to the shortage of time and the complexity of the computations to be carried out, it was decided to use Fortran IV language wherever possible. The PDP-9 computer, when purchased, has no software for on-line control application. But it has a resident monitor system which allows assembler or Fortran IV operation of basic peripheral devices such as teletypes, high speed papertape reader and punch, magnetic tape, line printers, etc.

It was decided to modify the monitor to include all the special input-output peripherals, and to allow multi-level timer operation and interrupt operation. Fortunately, the monitor system is written in a sectional manner to allow for easy modification and addition without rewriting the entire program. Hence a system initialisation program SYSINI was written in assembler language to modify a portion of the monitor system and set up multi-level timer operation and multi-level



**FIG. 3-7**  
**FURNACE CONTROL SYSTEM PROGRAMME BLOCK DIAGRAM SHOWING PRIORITY LEVELS AND TIMING LEVELS OF SUBROUTINES**

priority operation. A timer set up subroutine was prepared to add time setting instructions to the Fortran IV compiler and Macro 9 assembler. A power failure subroutine was added to handle the added power failure protection hardware KP09A and to automatically shut down the computer on power failure, save all register information and flag status, then restart and reinitialise device flags when power is restored. A digital device handler was prepared to read and write data to and from the digital input and output devices DSU-9 and DRO-9. An analog device handler was also prepared for the analog input and output devices AF03B and AA05. All these programs are written in assembler language and are given in Appendix 2.

With the monitor system modified, the overall system program can be organised fairly easily on a priority and time basis. Fig.3.7 shows the overall system. The subroutines are grouped into four priority levels, 0, 1, 2 and 3. Level 0 being the highest priority includes all the digital and analog input-output subroutines and time-of-day subroutine. Level 1 covers the data input station signal scaling and slab identification. Level 2 includes all the system computation and control

programs. The lowest level, 3 takes care of the data logging. The diagram shows the system monitor which includes all the modifications and added device handlers, etc. The rest are all functional programs controlled by the monitor. Details of the functional programs are given in Appendix 4.

One program which is not shown in Fig.3.7 is the program to take care of both computer failures and instrument failures. Major breakdowns, such as power failures, are easy to take care of. But minor or slow failures can escape detection until serious damage has been done. Hence, a program that carries out continuous credibility checks is required. This program is described in Appendix 5.

## CHAPTER 4

FORMULATION OF CONTROL ALGORITHM FOR A REHEAT FURNACE



#### 4.1 INTRODUCTION

In the past, emphasis has always been on the temperature control because, in a rolling mill, the mill is of primary importance. The furnace is only to provide hot steel slabs for the mill as fast as the mill requires them. Since very little work has been successfully carried out in optimising rolling mill operation itself, even less has been done on the furnace. Work done so far has been on minimising the error between the set point and actual temperature of the heated slabs. No one appears to have seriously considered that the thermal efficiency of the furnace could also be optimised with considerable savings.

This thesis considers all aspects of furnace characteristics as required for automatic control. The criteria of control can be summarised as follows:

- a. Maximization of thermal efficiency;
- b. Maximization of slab temperature uniformity and consistency;
- c. Maximization of pushing rate.

Thermal efficiency optimisation may be achieved as a side effect of pushing rate control by air-fuel ratio control and by furnace pressure and recuperation control. Slab temperature control and pushing rate control are difficult to separate as they are heavily dependent on each other.

Slab temperature control is the primary requirement and it must be controlled independently. When it has been fulfilled, then the slab pushing rate can be increased, and finally the thermal efficiency can be optimised within the constraints governing the slab temperature and pushing rate. That is, after satisfying the slab temperature requirements, an overall control strategy must be worked out to meet the highly variable pushing rates required by a plate rolling mill. Then thermal efficiency can be optimised provided the slab temperature and pushing rate are not affected.

Hence, in this treatment we have considered pushing rate as the ultimate controlled variable. The set point is determined by the mill roller, and the most important constraint is the slab temperature uniformity. Thermal efficiency control is considered completely separately, after the pushing rate and slab temperature requirements

are met.

Considerable work was already done on the billet furnace and thin slab model when the decision was made to install a computer on the large slab furnace. Hence, the treatment covers both the thin slab and thick slab cases while the actual implementation concerns the thick slab case only.

## 4.2 LITERATURE SURVEY

There is not a great deal of literature on actual furnace control, although there are quite a number of papers on parameter estimation, plant identification and optimal control. It appears that a great deal of effort has been spent in developing identification and control theories, while actual implementation has been sadly neglected. Only recently did people like Bricmont, Lerner, Kodz and Hollander try to apply the theory to the control of slab heating.

Lerner designed an analog optimal control system to control the final strip temperature at the finishing mill roll stands, in lieu of the slab temperature at furnace exit. It is a closed loop

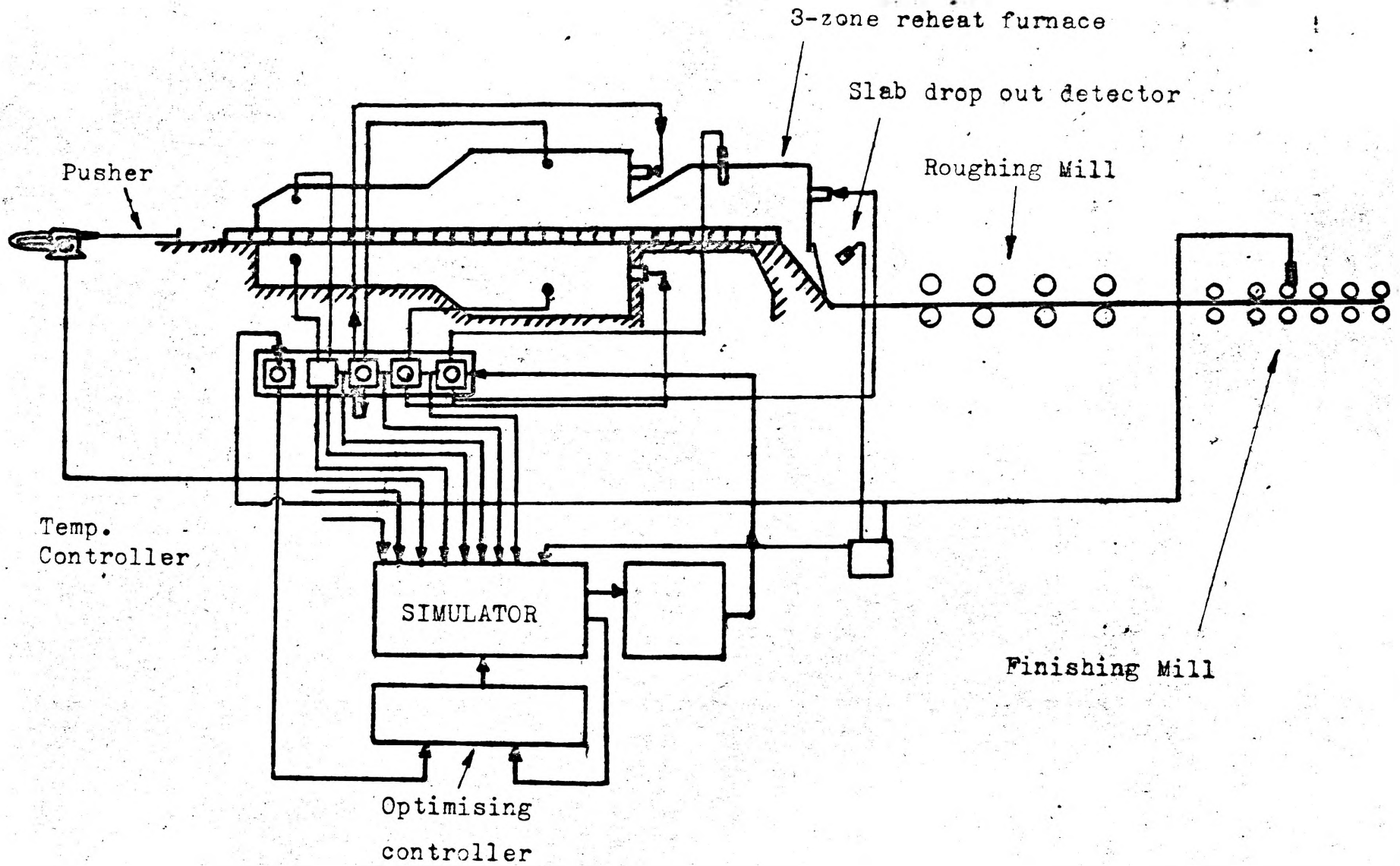


Fig. 4. 1 Optimal control system used by Lerner.

feedback control system, but the loop is very large. The paper deals mainly with optimal control theory using slab heating as an example of implementation. The heating model is assumed to be

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial t^2} - v \frac{\partial T}{\partial y}$$

Fig.4.1 shows a block diagram of Lerner's control system.

Between the point of corrective action and the measured temperature, there are the scale breakers and roughing mill roll stands. The control system should work but should have the criterion that the mill is processing strip, and is very smooth running with no disturbance between furnace and finishing mill rolls. On a plate mill, where slab dimensions and plate dimensions both change rapidly causing great variations in slab transit times, this control system is bound to run into trouble.

This system considers temperature control only, and uses one control variable "furnace temperature". This variable is a rather ambiguous one, measured by a thermocouple inserted into the furnace through the roof. This temperature represents neither the roof temperature nor the hot gas

or flame temperature. It is impossible to calculate a representative coefficient of heat transfer.

(23)  
Lerner did not mention how he obtained the coefficient of heat transfer he used. He merely mentioned that it was approximate, "with an insufficient degree of accuracy".

The great disadvantage of this controlled variable is that the response time is so long. It is suitable only for mills where slab thickness and pushing rates change very slowly.

The simplifying assumptions that the thermal properties of steel are constants seem to be adequate for his control system, but will not be adequate for plate mills.

(20)  
Bricmont (1966) made an elementary analysis of the heating problem. No information was given to indicate the form of the equations used in the calculations carried out. However, the shape of the curves showed no sign of the steel transformation point and closely resembled the curves obtained from Equation 4.16 (Page 77), assuming constant thermal properties of steel. The claim of having taken into account the temperature dependence of the thermal properties of steel was not adequately supported by the results presented.

Several unrealistic assumptions were made, restricting the work to a small range of ideal cases only. For example, the cold skid marks problem was completely ignored; the pushing rate and slab thickness were considered as constants and it was assumed that preheat zone temperature can be maintained at the constant temperature of 2,700°F along the full length of the zone. However, the work did shed some light on the general requirements of slab heating, and the results could be used as an aid in the rule-of-thumb method of operating reheat furnaces, when heating large batches of slabs with constant thicknesses.

(11)

Kodz claimed to have derived full equations describing the heat transfer of slab heating, confirmed by datalogging on the furnace. But no clue at all was given in his paper as to what the equations are and how he solved them. However, he mentioned Bricmont as reference, indicating that his equations may be similar to the simple approximation worked out by Bricmont. He seemed to have a clear understanding of furnace operation. He defined the control criteria and manipulated variables adequately. He is the only one of several workers in this field to appreciate that

(20)

furnace thermal efficiency can be and should be controlled. Unfortunately, the efficiency representation that he used is fuel consumption per ton of steel, a value that is found to be too cumbersome for use in optimising control as noted in Section 4.3. Using this value, the efficiency optimization must be very slow, too slow to cope with the disturbances to the combustion process. As a result, his efficiency control was reduced to simply increasing the pushing rate. In a later article presented jointly by Kodz and Bailey (19) dealing solely with the heating model, it was erroneously claimed that the simplified classical heat conduction equation

$$\frac{\partial T}{\partial t} = \frac{K}{\rho C_p} \frac{\partial^2 T}{\partial x^2}$$

was derived with the assumption that K and Cp depend on temperature. Experimental verification was claimed but no information was provided. Apparently the experiments were carried out by a separate team. One graph was provided to show comparison between calculated and measured "internal slab temperatures", but no absolute values were given for the temperatures and times. This makes it impossible to compare results. However, the



general shape of the calculated curve is identical to results in this thesis obtained from Equation 4.17 (Page 77), leaving out the  $\frac{\partial K}{\partial T}$  term. These results showed that this curve does not coincide exactly with experimental results and that the addition of the  $\frac{\partial K}{\partial T}$  term makes it considerably closer to the experimental results.

(9)  
Massey, Pattison and Ray carried out an interesting investigation into the performance of one particular 5-zone furnace at Spencer Works (RTB). They carried out experiments to measure slab internal temperatures, etc. The object apparently was to provide data for Kodz and Bailey. (19) No attempt was made at developing the mathematical model for heating.

(14)  
Dinneen pointed out the inadequacies of present methods of control and realised that the two main disturbances to the control system are slab thickness and pushing rate. He suggested that the furnace temperature set points be determined by a new variable which is the product of pushing rate and slab thickness. However, the study was superficial; no other theoretical analysis or experiments were carried out.

(21)  
Hollander and Huisman recently published

a paper on a computer control system installed on two 5-zone furnaces in Holland, operating in conjunction with a fully computer controlled hot strip mill. No detailed analysis appears to have been carried out regarding the heating model, and no experimental work was carried out. They simply made use of the basic equation

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2}$$

presumably calculating  $\alpha$  for different temperatures. That is, they used the same equations as Kodz and Bailey in the U.K. However, they have a system installed and operational. Results of long term operation are still being studied but short term tests showed significant improvements in the final strip temperature after roughing stands.

#### 4.3 THERMAL EFFICIENCY CONTROL

As can be seen from the literature survey above, practically no work was done to control the thermal efficiency of the furnace. The present practice of furnace operation does not take into account the control of thermal efficiency except

perhaps on a weekly or monthly basis. Charts and production records are collected and processed and efficiency figures produced for each week. These weekly figures only tend to show up long term fluctuations and permanent conditions such as excessive leakages, roof wear, and severe instrument malfunction, etc. They tend to smooth out low efficiency peaks caused by transient disturbances and malpractices. Any form of on-line calculation and indication of efficiency to the furnace operator should result in improved efficiency. With optimising control applied, efficiency could be greatly improved.

The thermal efficiency of the furnace is defined as the ratio of heat output contained in hot slabs to heat contained in fuel injected into the furnace. Or, as customarily used, it is defined as the amount of heat in fuel required to heat one ton of steel.

Both methods of representing efficiency are awkward to use. When the slab pushing rate is zero during say a short delay, the efficiency is also shown to be zero, irrespective of the amount of fuel used during the period to heat up slabs in the furnace and the furnace itself.

Initially, for consistency with operator usage, we selected the latter definition. The fuel injected into the furnace in a 20 minute period was calculated, as well as the heat contained in slabs pushed out in the same period. From these, the efficiency in terms of heat required per ton of steel was calculated.

$$\eta = \frac{\text{heat in fuel injected in 20 min}}{\text{tons of steel slabs pushed out in 20 min}}$$

$$= \text{BTU/ton of steel} \quad (4.1)$$

After the computer was installed on line and this efficiency had been calculated and logged for some time, it was compared with actual furnace efficiency figures obtained from heat balance checks on the furnace. It was found that the 20 minute periods used were not long enough to give a close enough representation of the efficiency, because the slab residence time in the furnace is of the order of 1½ to 2 hours. The period was increased to 30 minutes, and this proved to be adequately accurate during the extended period in which this program was tested.

In an initial trial period of static

control, where it was endeavoured to maintain a stable air/fuel ratio throughout the furnace without actually attempting to optimise the efficiency, this efficiency representation was also found to be good. The weekly mean efficiency was increased by about 20% during the test period.

However, after correlation analysis was carried out on furnace variables (see Chapter 5), it was found that five variables can be manipulated to control the efficiency. These variables can all affect the efficiency within a matter of  $\frac{1}{2}$  to 1 minute. To implement the simplest hill-climbing optimising technique with efficiency calculated only once per  $\frac{1}{2}$  hour would mean that the optimising search process can only be performed at  $2\frac{1}{2}$  hourly intervals. This is too long even for long term efficiency control.

Hence, a new method of representing efficiency was derived. This new index is the rate of heat absorption by the slabs and the furnace, and is calculated every 3 minutes. To obtain this a great deal more computation is required by the computer, and in the absence of much more instrumentation several approximations have to be made.

$$\eta_R = \frac{H_{\text{Fuel}} - H_{\text{Flue}} - H_w - H_{\text{wa}}}{H_{\text{Fuel}}} \quad (4.2)$$

where  $\eta_R$  = efficiency in terms of rate of heat absorption by slabs and furnace in 3 minute intervals

$H_{\text{Fuel}}$  = heat contained in fuel injected in 3 minute intervals

$$= C_p X$$

$X$  = gas flow or oil flow

$H_{\text{Flue}}$  = total heat contained in flue gas produced in 3 minute intervals

$H_w$  = total heat loss through cooling water in skids

$H_{\text{wa}}$  = total heat loss through radiation from furnace external walls and roof

The details of calculating  $H_{\text{Fuel}}$ , etc. and the approximations made are all described in Appendix 6.

It is easier to obtain optimum efficiency for small single zone furnaces. The number of manipulated variables are smaller and it is fairly easy to find a stable air/fuel ratio and furnace pressure which give optimum efficiency. However, for some small furnaces such as typical billet

furnaces, both high and low calorific value gases are fired. In these cases, another very important variable is introduced, the BF gas/CO gas ratio. BF gas is low in calorific value and gives a long gentle blue flame. CO gas is high in calorific value and gives a shorter and more luminous flame. The heat transfer characteristics are very different, and hence changes in the ratio of the two gases result in changes in flame shape, and affect efficiency considerably.

Flame theory at present is still more an art than a science. It is possible to derive theoretical heat transfer coefficients for different flame mixtures, but the anticipated accuracy obtainable is very low and does not warrant the effort. In this treatment, the BF gas/CO gas ratio is treated as an independent variable manipulated to optimise efficiency. Experiments and correlation analysis are carried out on these variables as described in Chapter 5.

The variables which are to be used in controlling efficiency of a billet reheat furnace are the following three:

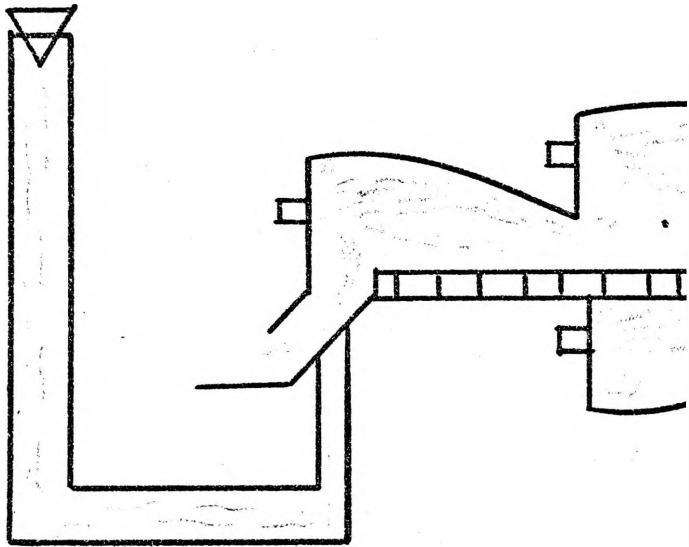
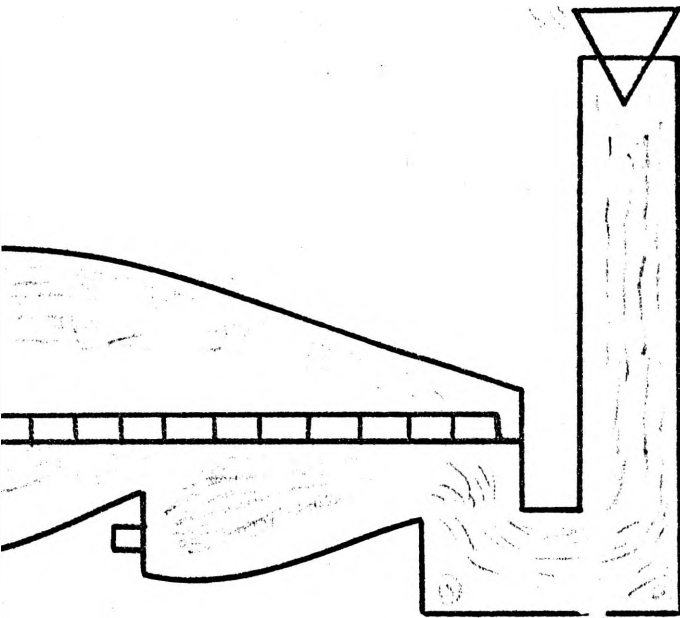


Fig. 4.2





Typical aerodynamic pattern inside a 4-zone reheat furnace showing vertical distribution only.

- (a) Air/fuel Ratio,  $R_f$
- (b) Furnace Pressure,  $P$
- (c) BF Gas/CO Gas Ratio,  $R_g$

Simple hill-climbing technique is used to optimise the efficiency using these three manipulated variables. The control program is described in Section 4.4. The flow diagram of the program is prepared but the detailed program is not yet written as it is not certain when a computer would be installed on these small furnaces.

For large multizone furnaces such as the A.I.S. slab reheat furnaces, it is much harder to obtain an optimal set of air/fuel ratios because of all the aerodynamics and fuel mixing problems of a large and long furnace with multiple zones for injection of fuel. The non-symmetrical 4-zone furnace at A.I.S. complicates the matter further. Fig.4.2 shows a typical aerodynamic pattern of a 4-zone furnace. When firing oil, the difficulty multiplies because steam must be injected to atomise the liquid oil, and the steam/oil ratio affects the flame shape and luminosity. There is an optimum steam/oil ratio for each pushing ratio. Hence four more variables are introduced.

From tests and observations carried out on the slab furnace (see Chapter 5), it is found that the air/fuel ratios (mean value for whole furnace) for optimum efficiency actually shifts about from 4.6 to 5.6 while theoretical air/fuel ratio for complete combustion is 4.2. Major factors affecting efficiency are found to be:

1. Waste flue gas temperature
2. Fuel calorific value
3. Furnace pressure profile
4. Frequency of discharge door opening
5. Slab thickness and length
6. Pushing rate
7. Steel grade
8. Changes in operators

The effects of these factors are investigated and described in Chapter 5. Some of these factors are easily compensated by simple on-line calculation by the computer. For example, the fuel calorific value changes can be taken care of by simply using heat content values calculated from the up-to-date calorific values. Effects due to changes in operating technique will not exist when

the computer is on line.

Some factors do not have clear cut manipulated variables which can be used to compensate them. For example, the changes in slab thickness, length and grade.

The other factors which are pushing rate, waste flue gas temperature, frequency of discharge door opening and furnace pressure profile can be compensated by furnace pressure setting and air/fuel ratios for each zone. Hence, for purely efficiency control, five manipulated variables are used, and if oil firing is used, four more are included. They are:

- (a) Furnace Pressure
- (b) Air/Fuel Ratio for Soak Zone
- (c) Air/Fuel Ratio for Upper Tonnage Zone
- (d) Air/Fuel Ratio for Lower Tonnage Zone
- (e) Air/Fuel Ratio for Preheat Zone
- (f) Steam/Oil Ratio for Soak Zone
- (g) Steam/Oil Ratio for Upper Tonnage Zone
- (h) Steam/Oil Ratio for Lower Tonnage Zone
- (i) Steam/Oil Ratio for Preheat Zone

However, scaling of slab surfaces is a severe problem and normal operation requires soak

zone air/fuel ratio to be very low, so that the excess fuel would burn all the oxygen in the continuously fluctuating leakage air resulting from pressure disturbances while opening discharge doors. Hence, this soak zone air/fuel ratio is fixed at a very low value of about 20% deficiency, eliminating it as a manipulated variable.

During initial stages of implementing the efficiency control, furnace operation is limited to gas firing as much as possible. When oil firing must be used for any zone, the steam/oil ratio is fixed at a predetermined value. Hence, the manipulated variables are reduced to four, simplifying the optimising program. The full efficiency optimising program using all eight manipulated variables has not yet been tried.

Simple hill-climbing type optimising technique is used for this also. The details of the program are given in Section 4.4.

#### 4.4 EFFICIENCY OPTIMISING TECHNIQUE

Experiments and observations on the furnaces, described in Chapter 5, show that all the

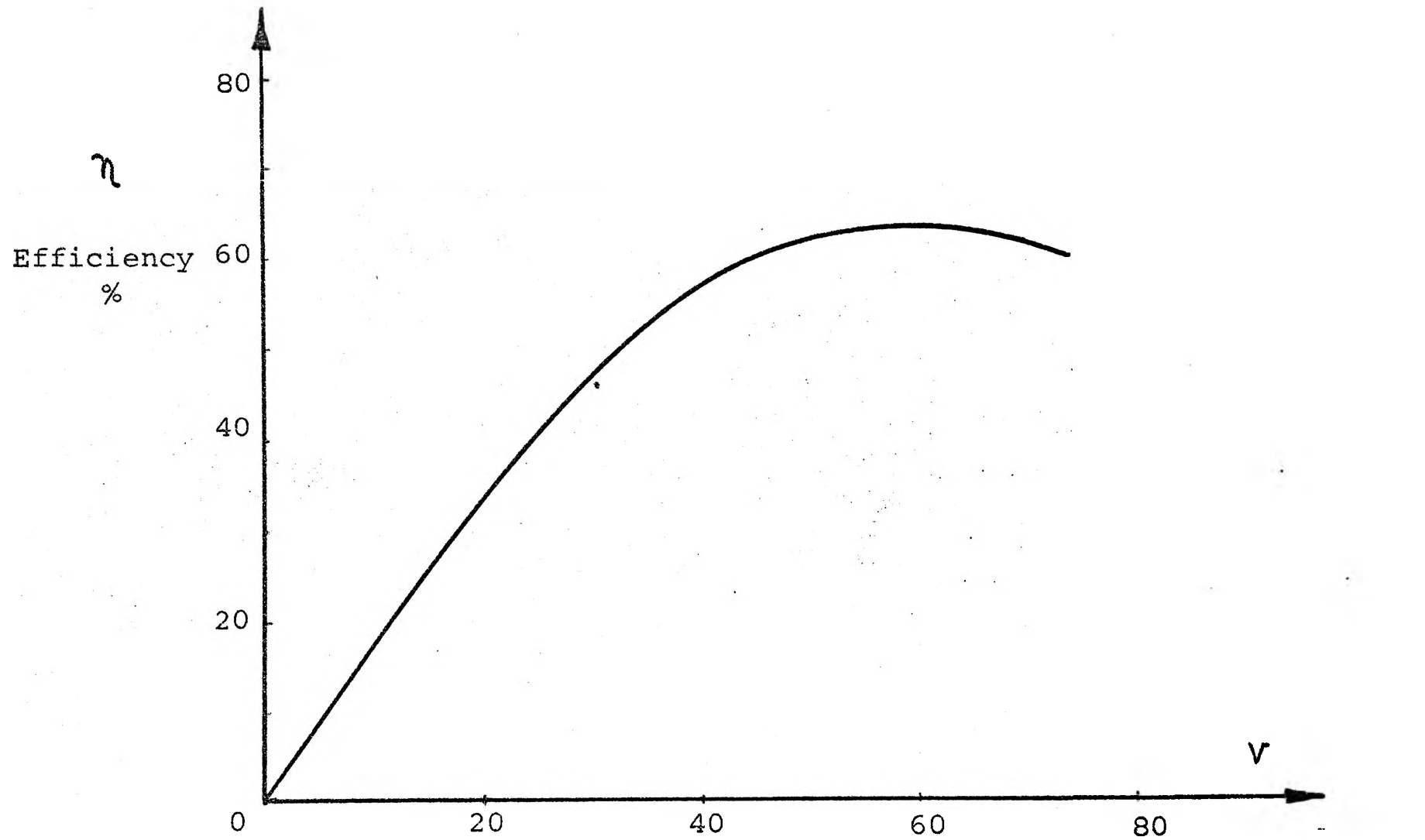


Fig. 4.3 Graph showing efficiency changes due to changes in pushing rate. Results obtained from tests on small billet reheat furnace.

independent variables manipulated to control efficiency are either linearly or fairly linearly related to the efficiency. This enables the simple hill-climbing type optimising technique to be applied in controlling furnace efficiency.

The same technique is used for both the small single zone furnace and the large multizone furnace. Only the number of variables are different.

For the small furnace, the number of independent process variables is smaller (only three), and the billet pushing rate is much faster at approximately two to three billets per minute average. Hence the original definition of efficiency is used, which is

$$\eta = \frac{\text{Heat in billets pushed in 10 min}}{\text{Heat in fuel injected in 10 min}}$$

Before each efficiency value is used it is compensated for changes due to changes in pushing rate in accordance to Fig.4.3. Fig.4.3 is a plot of efficiency changes due to pushing rate changes for one billet reheat furnace at A.I.S. obtained from experiments carried out on the furnace. This line

is a line of best fit obtained from the experimental data. It is used to indicate a trend only. When the previously calculated efficiency does not fit on the line, say if it is above this line, then the increase in efficiency due to the pushing rate increase (obtained from the line) is added to the present efficiency to obtain the corrected efficiency.

### Hill-Climbing Technique<sup>(66)</sup>

For a plant where efficiency is related to all the independent process variables by linear functions, linear programming can be used to find the set of values of the variables for optimum efficiency. However, if the functions are unknown and are not all perfectly linear, this method cannot be used. Another method, the "hill-climbing technique" or sometimes called the "non-linear programming" can be used to obtain the optimum solution. This method can be used for furnace efficiency control provided the efficiency can be calculated for any given set of the independent process variables, and the time required to calculate each efficiency value is much smaller than the time constant involved in the shifting of the



efficiency peak with time.

For small furnaces it is described in Sections 4.3 and 5.2 that air/fuel ratio  $R_f$ , furnace pressure  $P$ , and BF gas/CO gas ratio  $R_g$  are the three independent variables having significant effects on efficiency. Correlation analysis shows the approximate relationship, but the exact relationship is hard to determine because of other factors such as pushing rate. Experiments show that if all other factors remain constant, the efficiency changes very slowly with time. Hence this is ideally suited for hill-climbing technique.

The efficiency equation and the constraints are as follows:

$$\begin{aligned}\eta_1 &= f(R_f, P, R_g) \\ 7 &\leq R_f \leq 12 \\ 0.05 &\leq P \leq 0.25 \\ 0 &\leq R_g \leq 10\end{aligned}$$

where  $\eta_1$  = efficiency compensated for pushing rate, %

$R_f$  = air/fuel ratio, cu.ft. air per BTU fuel

$P$  = furnace pressure, "WG

$R_g$  = BF gas/CO gas ratio, cu.ft. per cu.ft.

At the start of the "climb" we set the values of  $R_f$ ,  $P$  and  $R_g$  at the best value we can guess. In this case  $R_{f0} = 8.4$ ,  $P_0 = 0.1$  and  $R_{g0} = 0.5$  give point (0). Then three other points (1), (2) and (3) are tried. These four points form a tetrahedron (called a simplex) and the worst point is determined. If point (2) is the worst point, then a new point (4) is formed by reflecting the worst point in the opposite face of the simplex. The equations as determined from the geometry of the tetrahedron are as follows:

$$R_{f4} = \frac{2}{3}(R_{f0} + R_{f1} + R_{f2} + R_{f3}) - \frac{5}{3}R_{f2}$$

$$P_4 = \frac{2}{3}(P_0 + P_1 + P_2 + P_3) - \frac{5}{3}P_2$$

$$R_{g4} = \frac{2}{3}(R_{g0} + R_{g1} + R_{g2} + R_{g3}) - \frac{5}{3}R_{g2}$$

The worst point, point (2) is then dropped and a new simplex is formed using points (0), (1), (3) and (4). The worst point of the new simplex is then determined and the process is repeated continuously. The optimum is reached when the new point is also the worst point. This indicates that the optimum is within the new simplex. Then the process will oscillate between the new point and

its projection until the optimum has been shifted out of the simplex by some other factors.

For the large multizone furnace, the basic principle remains the same, but the number of variables has increased. Instead of the 3-dimensional case we had before, now we have a 4-dimensional case, or, if considering oil firing, we have an 8-dimensional case.

If we consider a general case of  $N$  dimensions, we have

$$\eta_1 = f(a_1, a_2, a_3, \dots, a_N)$$

where  $a_1$  to  $a_N$  are the independent variables such as furnace pressure  $P$ , air/fuel ratio  $R_f$ , etc. The general equations to calculate the new point are as follows:

$$a_1 = \frac{2}{N} \sum_0^N a_{1i} - \left(1 + \frac{2}{N}\right) a^*_1$$

$$a_2 = \frac{2}{N} \sum_0^N a_{2i} - \left(1 + \frac{2}{N}\right) a^*_2$$

⋮

$$a_N = \frac{2}{N} \sum_0^N a_{Ni} - \left(1 + \frac{2}{N}\right) a^*_N$$

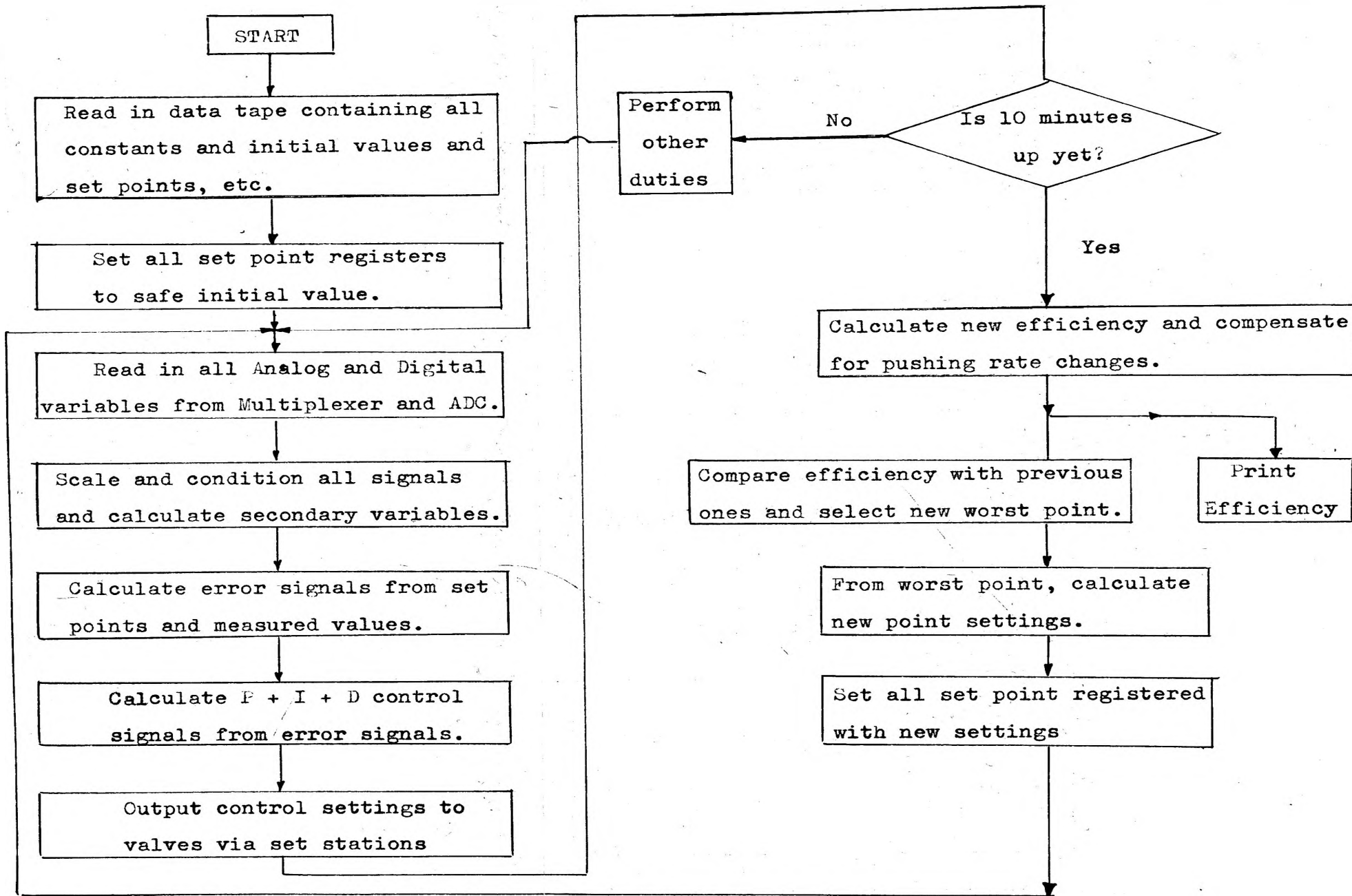


Fig.4.4 Simplified Block Diagram of Efficiency Control Program for Small Billet Reheat Furnace

where  $(a_1, \dots, a_N)$  is the new point while  $(a^*_1, \dots, a^*_N)$  is the worst point of the original simplex, and

$a_1$  = Furnace Pressure

$a_2$  = Air/Fuel Ratio for Soak Zone

$a_3$  = Air/Fuel Ratio for Upper Tonnage Zone

$a_4$  = Air/Fuel Ratio for Lower Tonnage Zone

$a_5$  = Air/Fuel Ratio for Preheat Zone

$a_6$  = Steam/Oil Ratio for Soak Zone

$a_7$  = Steam/Oil Ratio for Upper Tonnage Zone

$a_8$  = Steam/Oil Ratio for Lower Tonnage Zone

$a_9$  = Steam/Oil Ratio for Preheat Zone

Fig.4.4 shows a very much simplified block diagram of the control program for the small billet reheat furnace. A more detailed block diagram is shown in Appendix 12.

The program for efficiency control of the multizone furnace is a great deal more complicated. The details are given in Appendix 11.

#### 4.5 SLAB TEMPERATURE AND THROUGHPUT RATE CONTROL

In strip mills, pushing rate is fairly fast and steady at between 60 and 80 tons per hour for 3-zone furnaces. But for plate mills, requirements fluctuate drastically during operation, changing from 30 to 120 tons per hour. Normally more slabs than the furnace can heat are required, but sometimes half as much (when rolling to close tolerance or into fairly thin plates) and sometimes none at all (during mill delays). The thickness and steel quality of the slabs vary considerably also. Hence a control system is required to control the heating such that the slabs may be heated to required rolling temperature in the shortest possible time, subject to various constraints, such as maximum furnace roof temperature, minimum soaking time, etc.

The theoretical model approach was chosen for this. That is, the theoretical model is fairly accurately worked out, then tests carried out to verify and modify the model. There are two reasons for selecting this approach. The first is the fact that it is possible to derive the model from heat transfer laws, no complication being anticipated

initially. The second arises from the fact that the equations involved are known even from the start to be fairly complex non-linear partial differential equations. The design of test signals and analysis of data for empirical model building are formidable tasks.

For slabs up to 4" thick, the temperature difference between centre and surface is not so great and a reasonable amount of error in model accuracy and control can be tolerated. But, for slabs 4" thick and above, the difference becomes prominent and difficult to estimate.

Originally when work on this thesis was concerned with the small billet furnaces, only the thin slab case was considered, most billets being less than 4" thick and thickness changes infrequent. A thin slab heating model is determined and the criterion of control used is the minimisation of mean squared error between the desired exit slab surface temperature and actual slab surface temperature. The control of this is relatively easy and the mathematical model of the heating process is determined as described in Sections 6.3 and 6.4. Due to the purchase of an on-line control computer for the slab furnace, which only heats thick slabs,

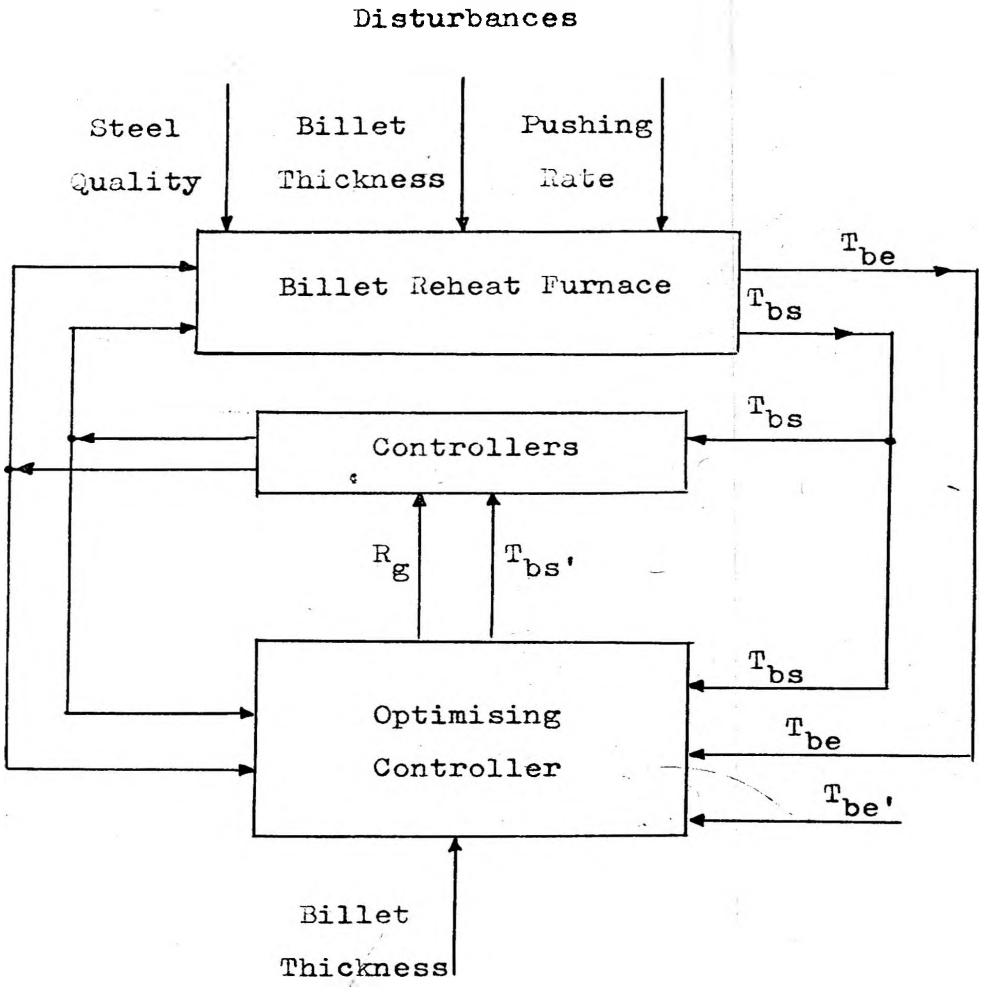


Fig 4.5 Thin Slab Temperature Control Block Diagram



$T_{be}$  = billet temperature at exit. (This temperature will be measured at the outlet of the furnace door from a horizontal position. Hence it is a good representation of the mean billet temperature.)

$T_{be}'$  = required billet temperature at exit.

$T_{bs}$  = billet surface temperature inside furnace near exit door. Actual measured temperature.

$R_g$  = BF gas/CO gas ratio.

$T_{bs}'$  = required billet surface temperature inside furnace near exit door, i.e., set point for  $T_{bs}$ .

work on the thin slab model has discontinued. Fig.4.5 shows a block diagram of the thin slab control system. Fig.2.1 shows an overall scheme of instrumentation for computer control of billet furnaces.

From Fig.4.5 it can be seen that the overall control strategy of the billet furnace is quite simple. The ultimate control criterion is

$$E = \text{Min} \int_0^{\tau} (T_{be'} - T_{be})^2 dt \quad (4.3)$$

The optimising controller (in this case, the digital computer) receives  $T_{be}$  and  $T_{be'}$  signals and calculates  $T_{bs'}$ , which goes out as a set point for conventional 3-term controller.  $R_1$ , the gas ratio index, which represents flame shape and luminosity, is generally not altered by this controller and left to the efficiency controller. However, when there is drastic change of billet thickness or pushing rate,  $R_1$  has to be overridden by the temperature optimising controller.

For example, if pushing rate suddenly increases significantly,  $R_1$  has to be reduced

considerably to increase the proportion of CO gas so that the flame becomes much shorter, more luminous and more violent, giving more heat to the billets near the burners (near exit door) which are waiting to be pushed out. If there is a mill delay,  $R_1$  must be increased to give more BF gas, so that the gentle long flame can provide a small amount of heat for billets near exit door, and also provide heat for heating up the cold billets further back in the furnace. If  $R_1$  is too low, the fuel firing will oscillate as a small amount of CO gas is enough to make significant change in  $T_{bs}$ . This effect would tend to cool the back of the furnace.

The disturbances are pushing rate, billet thickness and steel quality in order of significance. The pushing rate is dependent upon mill delays and other factors in the mill and is completely unpredictable. But, as data of billet is entered as it is charged into the furnace, billet thickness and steel quality are known. Hence, some feedforward control action can be applied to take care of billet thickness changes and steel quality changes.

For thick slabs, the criterion of control is the minimisation of mean squared error between the desired exit slab temperature, and the average

of slab cross-sectional temperature. An additional constraint has to be added. This is the maximum temperature difference between surface and centre of slab.

At present, only the slab surface temperature is known and controlled. It is up to the operator to estimate how long the slabs should stay in the furnace. Often this estimate is wrong because of difficulty in remembering the time slabs have stayed in the furnace. Cold or unevenly heated slabs are not discovered until the mill roller has experienced difficulties in rolling a slab. By that time, one slab may have been ruined and the whole soak zone would have all insufficiently heated slabs. As soak zone has a solid hearth and is only used for soaking and not heating, the heating capacity is small. A whole zone full of cold slabs will result in long delays.

The same three disturbances are present as for the billet furnace, i.e., pushing rate, slab thickness and steel quality. The first two are more prominent here than in either billet furnaces or slab furnaces feeding strip mills. Because of large variations in products in the plate mill, slab thickness and pushing rate vary frequently.

The large fluctuations in slab thickness and pushing rate complicate the optimising control system. Fortunately, slab thickness is known as soon as the slab is charged. Hence, some feedforward control action can be incorporated. Pushing rate so far has been completely independent. But an effort is made to even out the fluctuation and to inform the computer of the current pushing rate and the most likely pushing rate for the next several slabs. This is done by a cyclic timer which is set by the mill operator. The timer automatically calls for slabs on a cyclic basis. Another dial is set by the mill operator to indicate the current and anticipated pushing rates. These are described in more detail in Section 2.3.

As mentioned earlier, the soak zone has very limited heating capacity and heats only from one side. Hence, the tonnage zone mean slab temperature is used as the control criterion and the difference between surface and centre temperature is used as the constraint. Minimum times in the soak zone for slabs of various thicknesses are also used as constraints. Thus, if the temperature difference constraint is exceeded, a furnace delay can be immediately initiated and the large heating

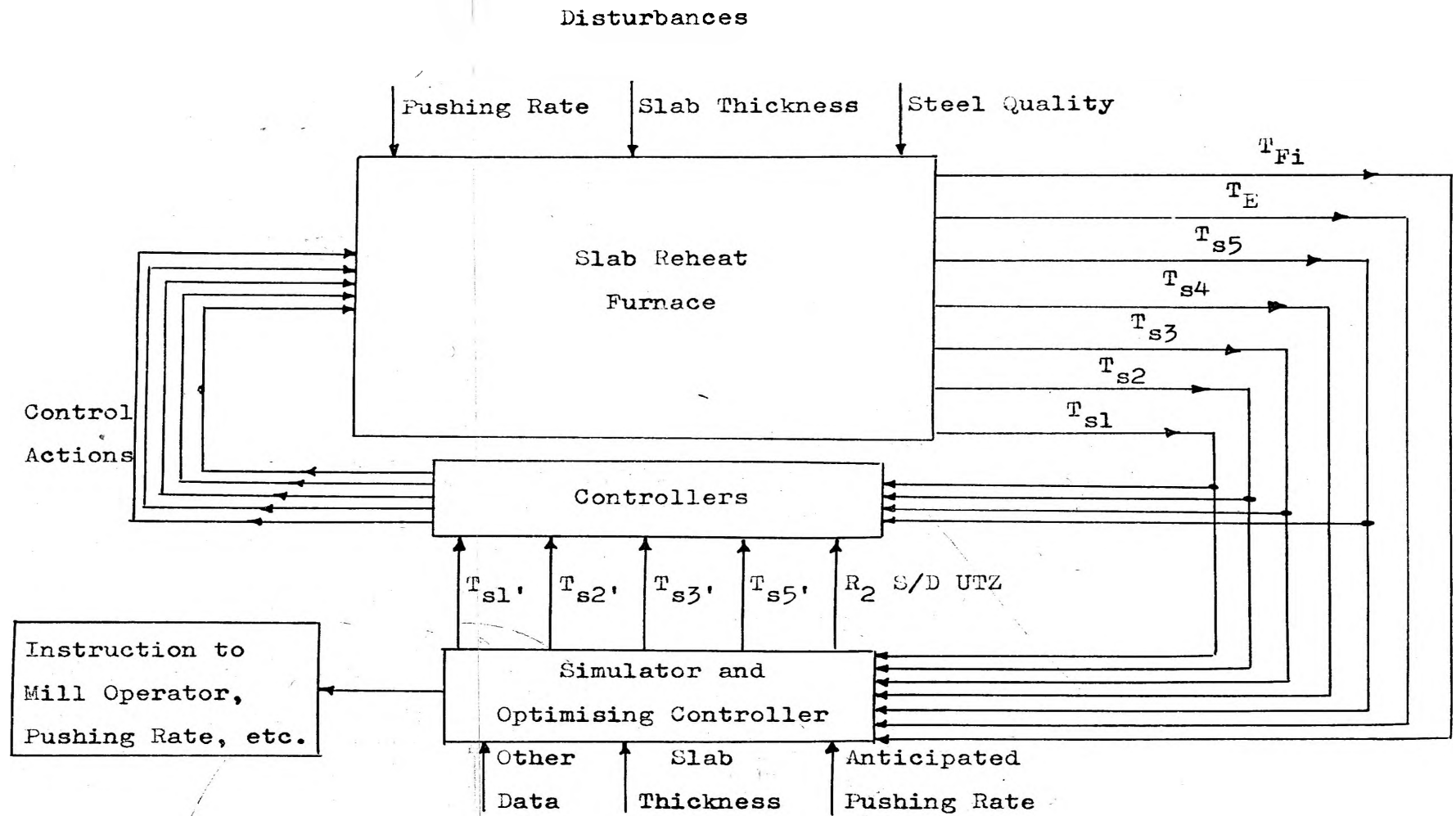


Fig.4.6 Thick Slab Temperature Control System Block Diagram

$T_E$  = Temperature of slab surface just after pushed out of furnace.

$T_{Fi}$  = Temperature of slab surface just after roughing stand.

$T_{s1}$  = Temperature of slab surface in soak zone.

$T_{s2}$  = Temperature of slab surface in UTZ.

$T_{s3}$  = Temperature of slab surface in LTZ.

$T_{s4}$  = Temperature of slab surface in UPZ.

$T_{s5}$  = Temperature of slab surface in LPZ.

capacity in the tonnage zones will bring the temperature up very quickly.

Fig.4.6 shows a block diagram of the temperature control system.

As shown in Fig.2.2, there are no burners in the Upper Primary Zone, as this is a 4-zone furnace. Hence, in this zone the top surfaces of slabs are heated by hot gas from the soak zone and Upper Tonnage Zone. The shape of the flame in the Upper Tonnage Zone affects this temperature significantly. When firing gas, little can be done with regard to flame shape, but when firing oil, the steam to oil ratio (i.e., the degree of atomisation) can be altered to change the shape of the flame. So the optimising controller determines the set points  $T_{s1}'$ ,  $T_{s2}'$ ,  $T_{s3}'$ ,  $T_{s5}'$  of zone slab temperatures and  $R_2$  the steam/oil ratio (of UTZ) to control the five zone temperatures  $T_{s1}$ ,  $T_{s2}$ ,  $T_{s3}$ ,  $T_{s5}$  and  $T_{s4}$  respectively.

The criterion of control for thick slabs is then defined as follows:

$$E_1 = \text{Min} \int_0^z (T_r - T_m)^2 dt \quad (4.4)$$

where  $T_r$  = required mean slab temperature at UTZ exit

$T_m$  = actual mean slab temperature at UTZ exit

$$= \frac{1}{s} \int_0^s T_{xy} dx \quad (4.5)$$

$$= \frac{T_{s2} + T_{s3} + 4T_c}{6} \quad (4.6)$$

where  $T_c$  = temperature of slab centre at UTZ exit  
calculated from mathematical model of  
heating process

with constraints

$$T_{s3} - T_c < 100^\circ\text{F} \quad (4.7)$$

$$T_{E'} - T_E < 25^\circ\text{F} \quad (4.8)$$

$$T_{F'} - T_F < 15^\circ\text{F} \quad (4.9)$$

$$\tau_1 > t_{1x} \quad (4.10)$$

where  $\tau_1$  = residence time of each slab in the soak  
zone

$t_{1x}$  = minimum soak time required for each  
slab, calculated in accordance with its  
thickness  $x$ .



Values of  $t_{lx}$  are contained in a table in the computer memory. These are precalculated off-line for each half inch increment in slab thickness. More detailed treatment of the calculations involved is given in Chapter 7 when dealing with the problem of skid marks.

$T_{xy}$  is the temperature profile of the slab in the x-direction (through its thickness) while travelling along the y-direction (along furnace). At the exit of UTZ,  $y = L_1$ , the distance from furnace entry point to UTZ exit. Hence

$$T_m = \frac{1}{s} \int_0^s T_{xL_1} dx$$

where  $s$  = thickness of slab.

In order to save computing time, an approximation is arrived at from the general shape of the  $T_{xL_1}$  curves. This is used in the on-line control program instead, so that

$$T_m = \frac{T_{s2} + T_{s3} + 4T_c}{6}$$

To calculate  $T_{xy}$ , mathematical models of the heating process were developed as detailed in Section 6.

These models all involve physical properties of steel. For some alloy steels such as 18-8 stainless steel, etc. the thermal properties are nearly constant within the required temperature range. The models are much simpler for these steels and are as follows:

#### Thin Slabs

$$v \frac{\partial T(y, t)}{\partial y} + \frac{\partial T(y, t)}{\partial t} = \frac{h_1}{s \rho C_p} [T_F(y, t) - T(y, t)]$$

(4.11)

#### Thick Slabs

$$v \frac{\partial T(x, y, t)}{\partial y} + \frac{\partial T(x, y, t)}{\partial t} = \frac{k}{\rho C_p} \frac{\partial^2 T(x, y, t)}{\partial x^2}$$

(4.12)

However, for most carbon steels, the specific heat and thermal conductivity are not constant as shown in Fig.6.2 and 6.3. This introduces considerable complexity to the models. These become as follows:

Thin Slabs

$$\begin{aligned}
v \frac{\partial T(y, t)}{\partial y} + \frac{\partial T(y, t)}{\partial t} + \frac{v T}{c_p} \frac{\partial c_p}{\partial T(y, t)} \frac{\partial T(y, t)}{\partial y} \\
= \frac{h_1}{s \rho c_p} \left[ T_F(y, t) - T(y, t) \right] \quad (4.13)
\end{aligned}$$

Thick Slabs

$$v \frac{\partial T}{\partial y} + \frac{\partial T}{\partial t} + \frac{v T}{c_p} \frac{\partial c_p}{\partial T} \frac{\partial T}{\partial y} = \frac{K}{\rho c_p} \frac{\partial^2 T}{\partial x^2} + \frac{1}{\rho c_p} \frac{\partial K}{\partial T} \left( \frac{\partial T}{\partial x} \right)^2 \quad (4.14)$$

Details of the derivations are given in Chapter 6. These equations are far too complicated to solve, and an attempt is made to simplify them. For Equation 4.14, the velocity terms are eliminated first. This is done by considering that the slabs remain stationary and the environment moves past them. The environment can be represented by the furnace temperature profile  $T_F(y, t)$  resulting from various control actions by the zone burners. The profile  $T_F(y)$  changes with time as the control of each zone varies. This complicates the boundary

conditions a little but it greatly simplifies the solution of the heating models.

Equation 4.11 becomes

$$\frac{\partial T}{\partial t} = \frac{h_1}{s \rho c_p} [T_F(y, t) - T] \quad (4.15)$$

Equation 4.12 becomes

$$\frac{\partial T}{\partial t} = \frac{K}{\rho c_p} \frac{\partial^2 T}{\partial x^2} \quad (4.16)$$

Equation 4.13 becomes

$$\frac{\partial T}{\partial t} = \frac{h_1}{s \rho c_p} [T_F(y, t) - T] \quad (4.14)$$

Equation 4.14 becomes

$$\frac{\partial T}{\partial t} = \frac{K}{\rho c_p} \frac{\partial^2 T}{\partial x^2} + \frac{1}{\rho c_p} \frac{\partial K}{\partial T} \left(\frac{\partial T}{\partial x}\right)^2 \quad (4.17)$$

Equation 4.15 is fairly straightforward and is solved in Section 6.5. Equation 4.16 is

fairly simple also, and it is solved with both analog and digital computers as described in Section 6.8.

Equation 4.17 is more complex and is solved as described in Section 6.8 with limited success. However, although the calculated profile of centre temperatures does not correspond to the experimental results exactly, the results from Equation 4.17 are much closer to the real case than those from Equation 4.16. Equation 4.16 is the classical equation used by Kodz, Hollander, Lerner and others. Since Lerner and Hollander claimed some degree of success using Equation 4.16, then it follows that Equation 4.17 must give better results. Hence Equation 4.17 is adopted as the final slab heating model for use in the control program.

CHAPTER 5

DETERMINATION OF PARAMETERS OF REHEAT

FURNACE PERFORMANCE

## 5.1 INTRODUCTION

A series of observations and experiments were carried out on both the single zone billet reheat furnace and the 4-zone slab reheat furnace, in order to determine the parameters of the furnaces.

For the small furnace, experiments were carried out and data collected on seven variables. Multiple correlation and regression analysis was carried out on the data. Four variables are found to have significant correlation to the efficiency. Pushing rate is found to be the most significant, but this is due to the way furnace efficiency is represented. Eliminating this, we are left with three manipulatable variables for efficiency control, BF gas to CO gas ratio, furnace pressure, and air to fuel ratio, in order of importance.

For temperature and throughput rate control of the single zone furnace, it is found that only furnace temperature can be used as the manipulated variable. But fortunately, the mixed fuel firing of BF gas and CO gas provides another manipulated variable as the gas ratio varies the length and shape of the flame, thus giving a

different furnace temperature profile along the furnace. Hence two manipulated variables are used for controlling temperature and throughput rates, the furnace temperature (measured value of the temperature at the point of measurement), and the BF gas/CO gas ratio.

For large furnace efficiency control, experiments and observations were also carried out. Eight major factors are found to affect efficiency. Some of these factors can easily be compensated for when on-line computer control is used, for example, fuel calorific value changes, changes due to changes in operators, and pushing rate changes. The other factors are more difficult to define. They either act indirectly or are interrelated to one another. The only independent process variables that can be manipulated are the furnace pressure, the air/fuel ratio of each zone and the steam/oil ratio of each zone if firing oil.

For multizone furnace temperature control and throughput rate control, it is found that the only manipulated variables are the zone temperatures, which determine the furnace temperature profile. As this is a non-symmetrical 4-zone furnace, the Upper Tonnage Zone is very long, and its temperature



profile is controlled solely by the UTZ temperature setting, except when this zone is firing oil. Then the steam/oil ratio for this zone becomes a manipulated variable as it varies the flame length and hence varies the temperature profile in the UTZ.

The experiments and observations carried out on the furnaces generally improved the understanding of furnace behaviour and characteristics. This has resulted in better and more efficient operation even before the computer was controlling the furnace.

## 5.2 THIN SLAB FURNACE EFFICIENCY CONTROL PARAMETERS

The single zone billet reheat furnace is described in Section 2.2. The instrumentation on this furnace is very poor, and there is no automatic control on the furnace at all. This makes it difficult to keep any variable constant while studying the effect of some other variable on efficiency. The lack of instrumentation also made the experiments difficult as most of the measurements have to be taken manually using portable test instruments, or calculated by hand. Hence a series

Furnace Temperature

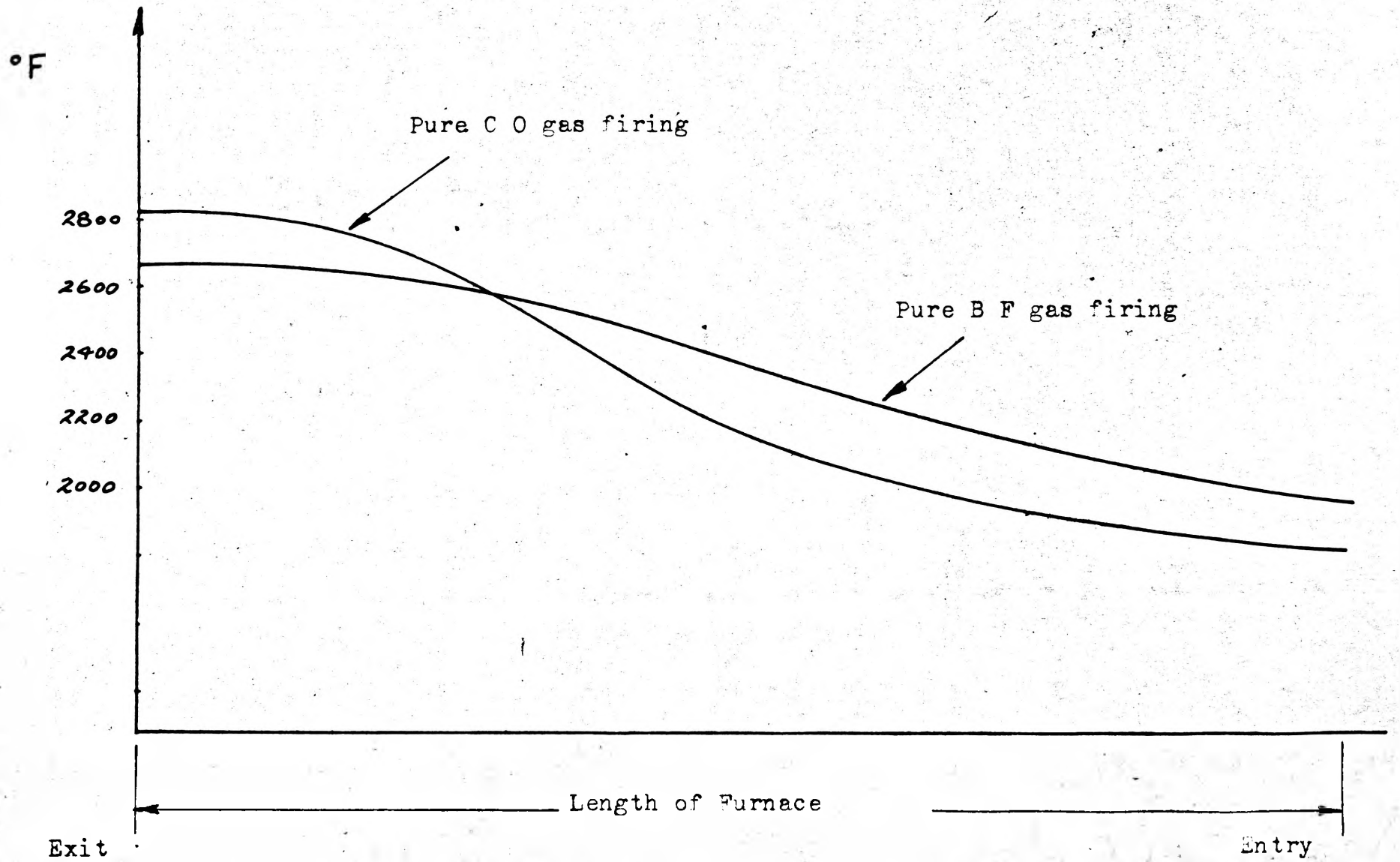


Fig. 5. 1 Billet furnace temperature profiles from purely BF gas firing and from purely CO gas firing.

of experiments were carried out monitoring all the variables that may affect efficiency. A digital computer program was then used to carry out multiple correlation and regression analysis on the results.

The following five factors were considered:

(i) Mill Delays

The billet furnace regularly has short mill delays of several minutes each. As the furnace firing must continue during these delays to maintain the billet temperature and make up for heat losses, it is thought that this would affect efficiency.

(ii) BF Gas/CO Gas Ratio

The BF gas is the by-product of the blast furnace and the calorific value is very low, between about 75 - 130 BTU/cu.ft. Its flame is pale blue in colour, and is long in shape. The CO gas is the by-product from the coke ovens. Its calorific value is much higher at between 460 - 540 BTU/cu.ft. The flame is orange to white in colour and is short and violent. The furnace temperature profiles resulting from the two gases are different as shown in Fig.5.1. As the gases are mixed when fired, the furnace temperature profile varies in

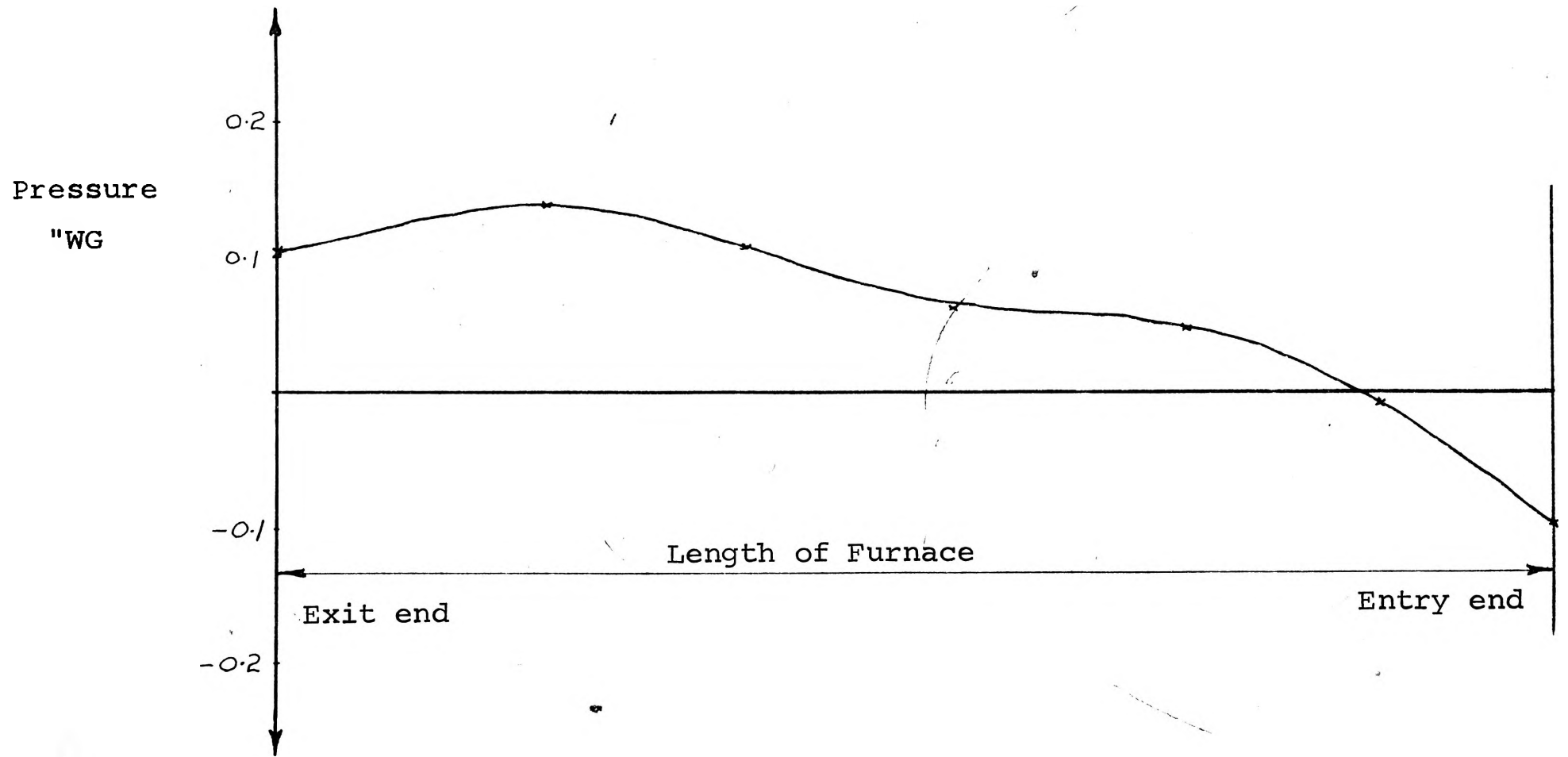


Fig.5.2 Typical pressure profile of billet reheat furnace

accordance to the ratio of the two gases.

(iii) Furnace Pressure

As described in Section 2.1 and Fig.2.1 the furnace is 62 feet long with doors along the full length of the furnace. The doors, the roof and various cracks and openings all tend to leak.

There is only one point where pressure can be varied, the dampers at the top of the stack.

Pressure is measured at one point along the furnace, and the dampers are adjusted to control the pressure at the measuring point at a selected set point.

However, the pressure profile along the furnace varies continuously depending on ambient conditions and fuel firing rate, etc. Fig.5.2 shows typical pressure profile of the billet furnace. Ideal pressure requirement is for most of the furnace to be slightly positive, approximately 0.05"WG, and the last short length at the entry end approximately 0"WG. This way, no cold air can leak in, and very little hot combustibles leak out. But because of the changing pressure distribution along the furnace, and the availability of only one manipulatable device, ideal furnace pressure profile cannot be achieved. The pressure set point has to be

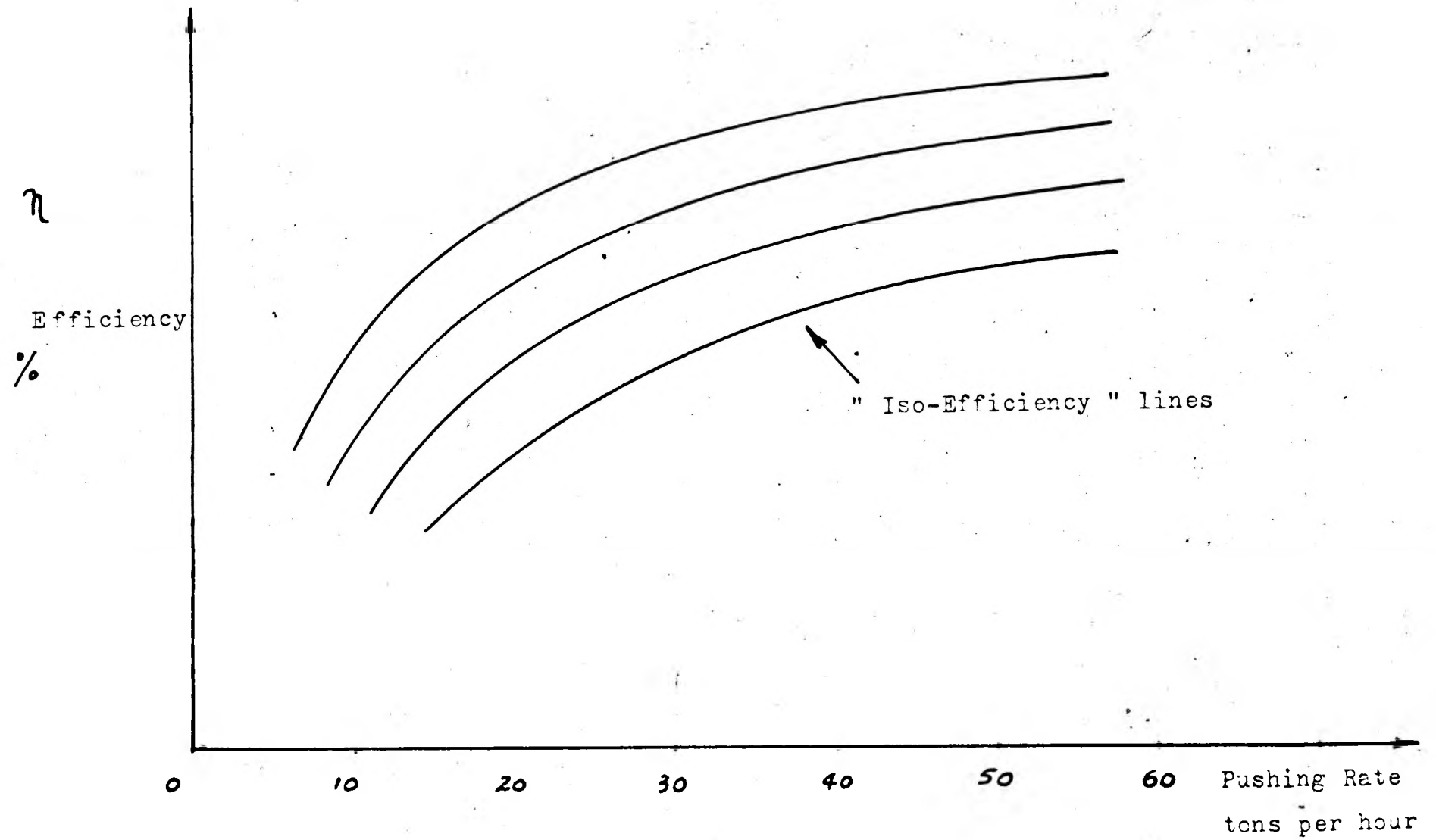


Fig.5.3 Billet furnace efficiency plotted against pushing rate.

adjusted regularly to compensate for the disturbances.

Negative furnace pressure results in cold air leaking in from doors and leaks in walls and roof. The cold air changes the flow pattern and mixing of the fuel and hot air. It also tends to cool the two ends of the billets, resulting in longer heating time being required for the billets, hence lower efficiency. Positive furnace pressure forces flame and hot combustibles out from doors and leaks. This also has the side effect of reducing the amount of hot flue gas to the recuperators and hence reducing the hot air temperature and flame characteristics.

(iv) Pushing Rate

Pushing rate does not in itself directly affect efficiency. Because of the definition of efficiency used for the billet furnaces (see Equation 4.1), efficiency is related to pushing rate in accordance to the graphs in Fig.5.3. Each of the lines on the graph represents the same effective furnace operation efficiency for different pushing rates, i.e., iso-efficiency lines. Every

efficiency calculation can be compensated for this effect of pushing rate by shifting it along the appropriate iso-efficiency line to a reference pushing rate of 50 tons per hour.

From the experiments it is observed that pushing rate has another effect. As pushing rate changes (particularly when increased) large changes in fuel firing rate result. It is found that the magnitude and frequency of pushing rate changes are both almost directly proportional to the compensated effective efficiency.

(v) Air/Fuel Ratio

Theoretically one fixed air/fuel ratio should give perfect combustion, and hence best efficiency. But, in practice, some excess air above the theoretical value is required, and the amount of excess air required is also not fixed. This is caused by a number of factors. For different burner design, different gas and air pressures, different firing rates, different gas and air preheat temperatures, different gas calorific values, signal drifts and different furnace pressure profiles, the amount of air required for complete



combustion of the fuel is different.

In the experiment, the flue gas at the entry end of the furnace is analysed to double check the effect of air/fuel ratio on efficiency. From previous tests on other billet furnaces, it is found that if ideal combustion occurred in the furnace, the flue gas should contain about 1 - 2% oxygen. This unfortunately is not successful due to contamination of the flue gas by cold air leakage and the inaccuracy of the method of gas analysis used.

The results of the analysis show that mill delays have no correlation with efficiency. This may be because the delays are very short and frequent. The variation in the total duration and frequency of the delays is small, and the fuel firing is automatically cut back to maintain the billet temperature near the exit.

The BF gas/CO gas ratio shows very strong correlation to efficiency. Apart from pushing rate, this is the most significant variable affecting efficiency.

Pushing rate shows the strongest correlation but this is mainly due to the definition of

efficiency used here. Magnitude and frequency of pushing rate changes are not included due to the difficulty in monitoring them.

Furnace pressure and air/fuel ratio both have significant correlation with efficiency, but not quite as strong as the BF gas/CO gas ratio.

Hence, it is concluded that there are three independent process variables which can be manipulated to control efficiency. These are BF gas/CO gas ratio, furnace pressure and air/fuel ratio.

The main disturbances are pushing rate, billet quality and dimensions, gas calorific values and furnace pressure profile.

### 5.3 THICK SLAB FURNACE EFFICIENCY CONTROL PARAMETERS

The 4-zone slab reheat furnace is also described in Section 2.1. Instrumentation on the older No.1 furnace is not sufficient to carry out extensive experimentations, but the new No.2 furnace is well instrumented. With the computer on line calculating and logging furnace performance

indices, such as efficiency and pushing rate, etc. experiments were carried out. Special care is taken to select test periods during which mill operation is smooth and most variables can be maintained constant.

The following observations and experiments were carried out:

(i) Waste Flue Gas Temperature

The experiments show that this is affected by a number of different factors such as air/fuel ratios, changes in temperature set point (hence firing rate, particularly in primary zone), thickness changes of slabs coming into primary zone, and sudden changes in pushing rate. These vary the temperature of the preheated combustion air, thus varying the flame characteristic and efficiency. Since temperature set points, slab thickness and pushing rate are all disturbances, air/fuel ratios are the only independent process variables which can be manipulated to change the waste flue gas temperature.

(ii) Fuel Calorific Value

When firing oil, the calorific value changes infrequently at about once per day or

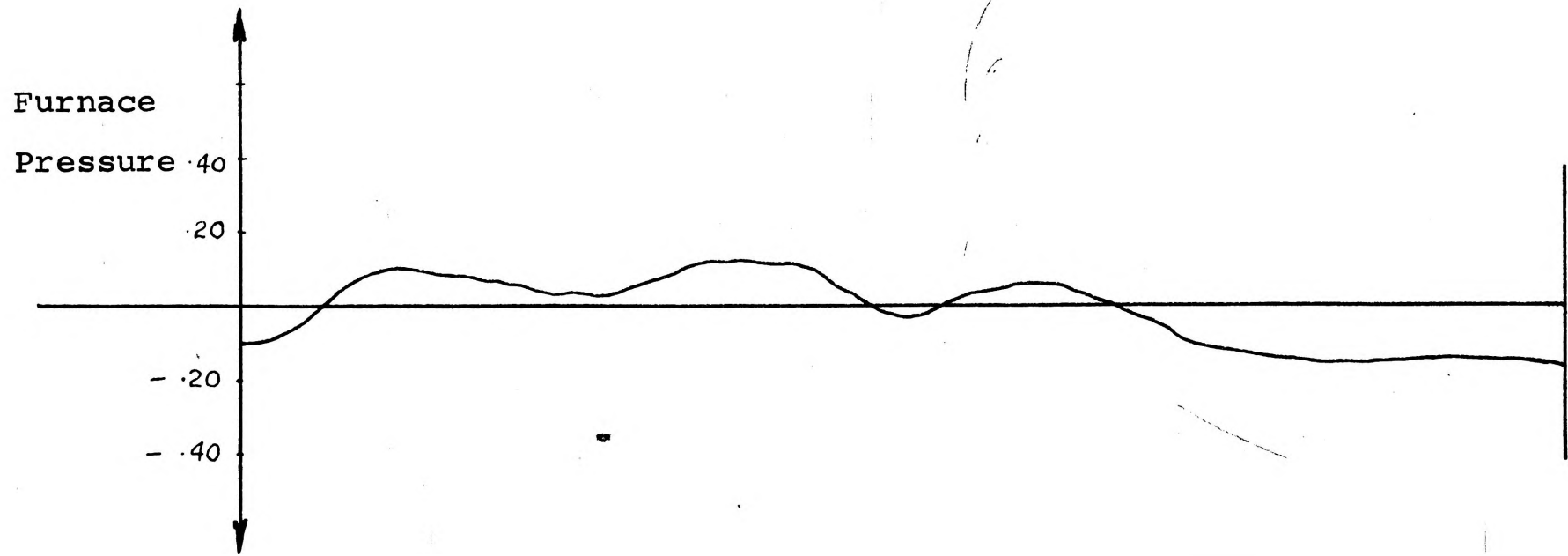
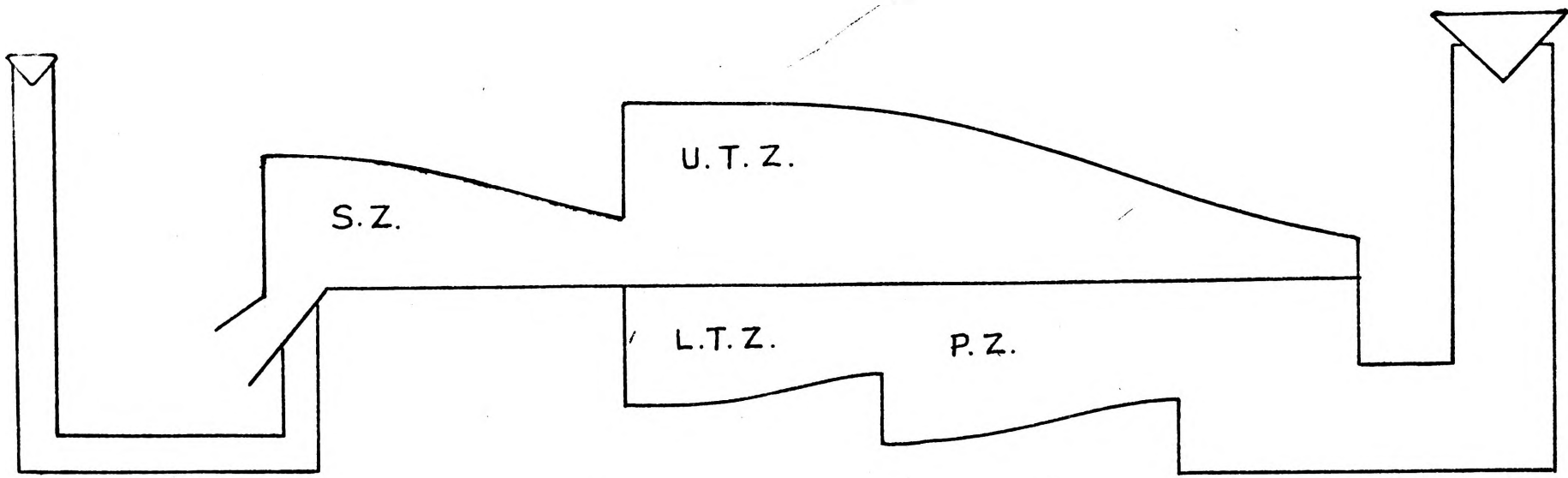


Fig. 5.4 Typical pressure distribution along a 4 zone slab reheat furnace.

longer. This depends on the variation in the batches of oil put into the temporary oil storage tanks. But when firing gas, which represents more than 70% of the fuel used, a greater variation in calorific value is encountered as the CO gas calorific value can change by up to  $\pm 10\%$  of mean value. The frequency of change is low, only about one cycle per hour, but the rate of change is faster, at about 10% per 10 minutes. With the computer on line, and the calorific value monitored continuously, this disturbance is easily eliminated by computing the correct heat content and adjusting the air/fuel ratios accordingly.

(iii) Furnace Pressure

The effect of furnace pressure on efficiency is similar to that described for the small billet reheat furnace in Section 5.2. However, the slab furnace is much longer at 88 feet, and the pressure profile is a great deal more complex. Fig.5.4 shows a typical furnace pressure profile along the furnace. Its effect on efficiency is also more complex. For the single zone furnace, it is found that the efficiency has a simple optimum with respect to furnace pressure, and this optimum

point moves about due to ambient conditions, firing rate, fuel mixture, etc. But for the large furnace, the experiments indicate that there may be two optimum points with a minima between the two.

During the test period, the two optima are at approximately 0.095 and 0.135"WG, and the minima at 0.110"WG. This phenomenon is confirmed by analysis of the flue gas in the soak zone. This shows that there is an abnormally high excess oxygen content of approximately 2% when pressure is at 0.110"WG. At 0.095 and 0.135"WG the oxygen contents are about 1.0% and 0.3% respectively. This occurs when the soak zone air/fuel ratio is maintained at 25% deficiency in air.

The maxima at 0.135"WG is the normal maxima, as the flame starts to leak out of the furnace at 0.140"WG. The second maxima at 0.095"WG is not prominent and is obviously the result of the minima at 0.110"WG. The existence of a minima at 0.110"WG is difficult to explain. It appears that at 0.110"WG, the combined effect of cold air leakage, furnace design, and burner design results in very poor combustion.

The discovery of this minima is very useful in the optimising control program. The program

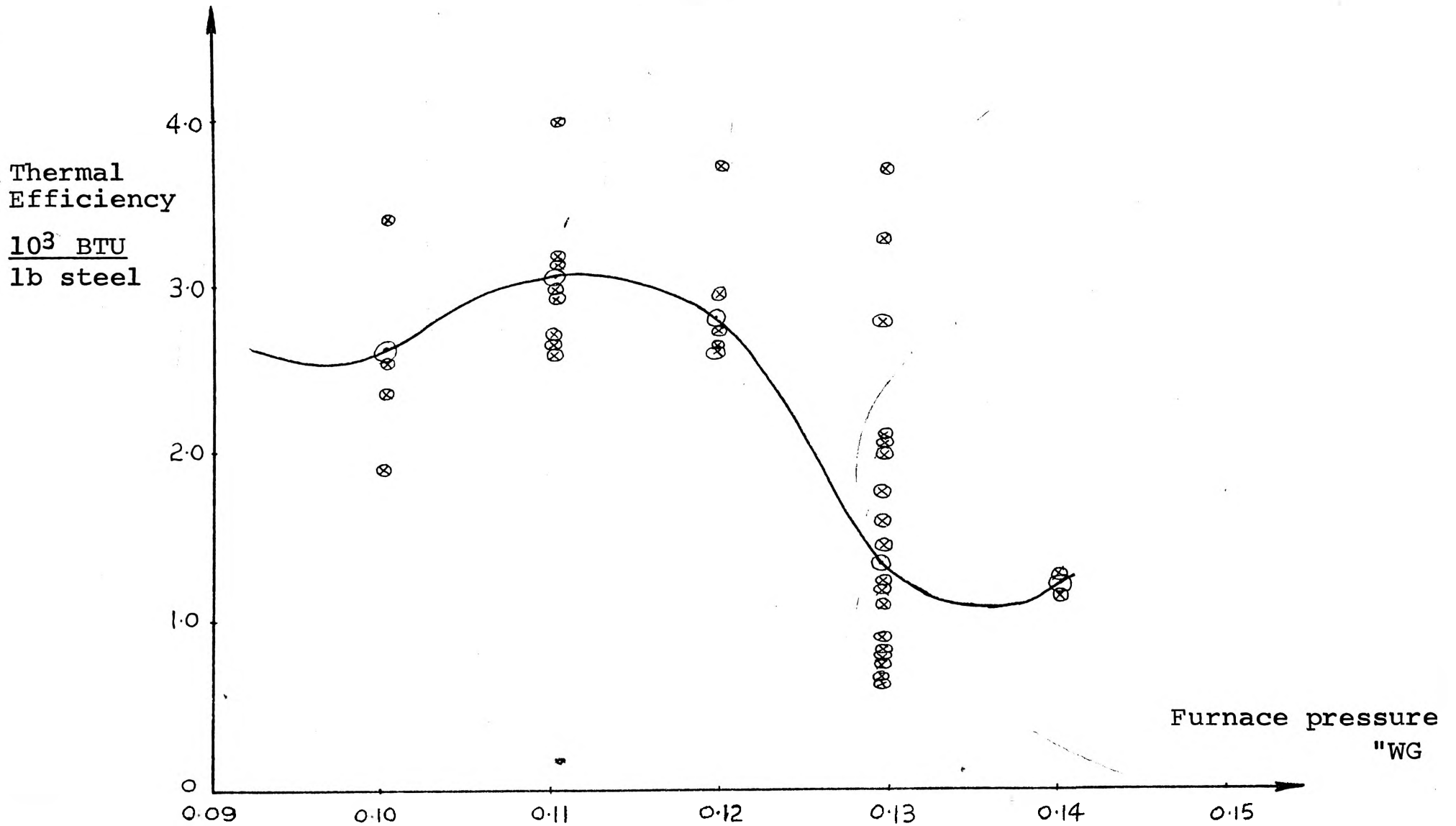


Fig. 5.5 Furnace thermal efficiency plotted against furnace pressure

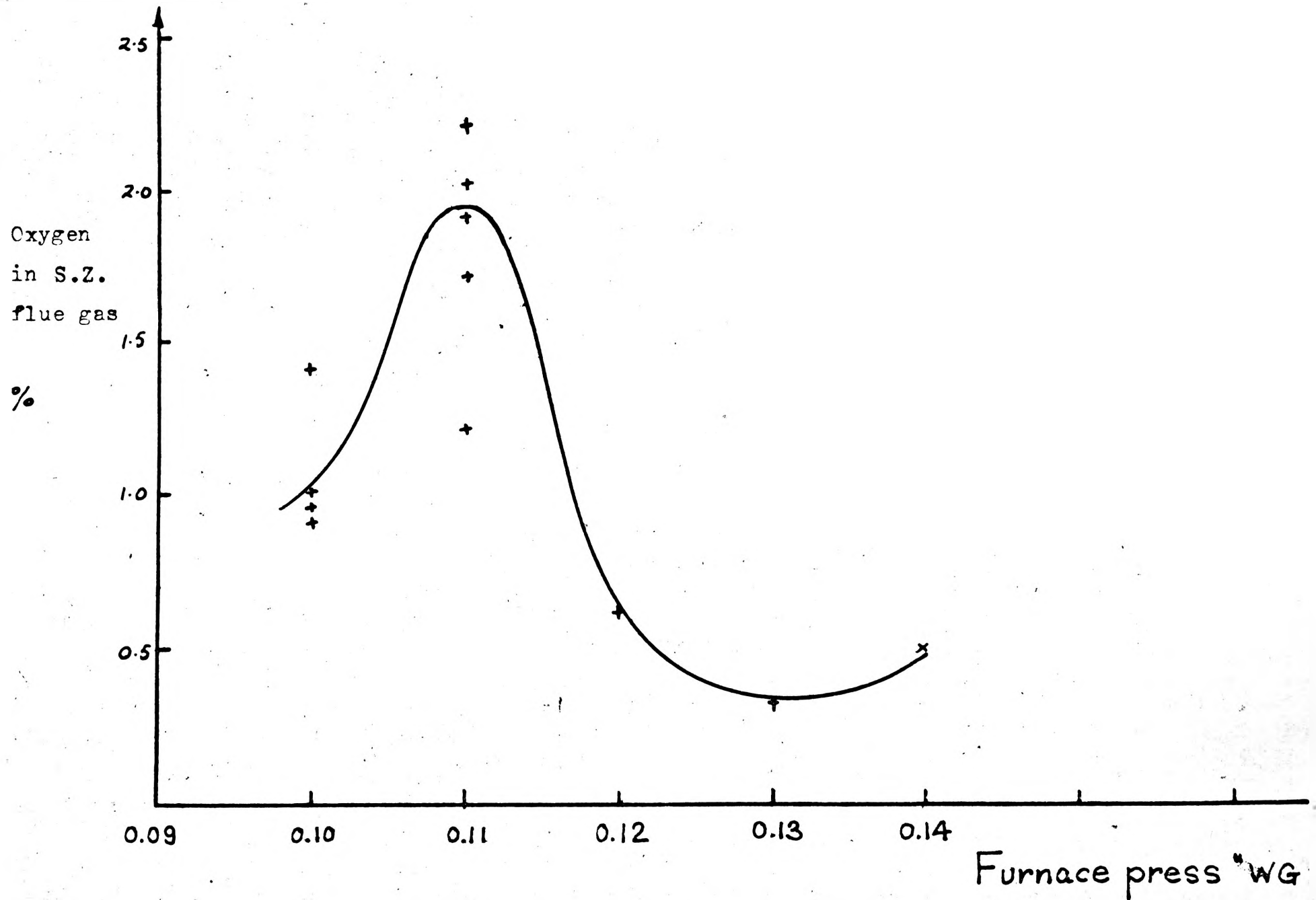


Fig. 5.6 Furnace thermal efficiency plotted against oxygen in flue gas.



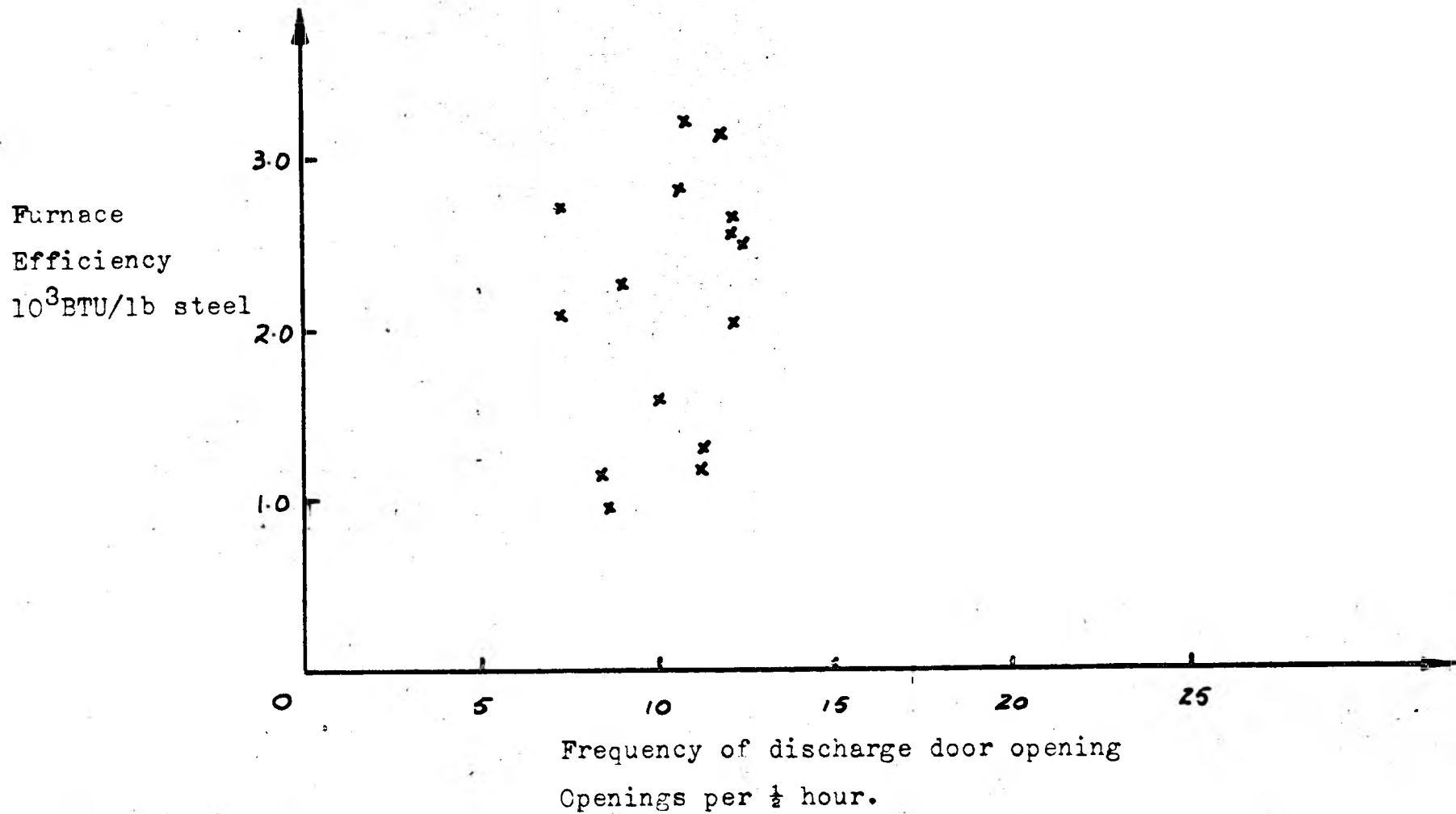


Fig. 5.7 Thermal efficiency plotted against frequency of door openings.

will now be told to search for the optimum pressure at between 0.120 and 0.140"WG.

Fig.5.5 and Fig.5.6 show furnace efficiency plotted against furnace pressure and oxygen content respectively. The experiments were carried out with pressure controlled at fixed values and efficiency calculated once per half hour. Other factors such as pushing rate, slab thickness and temperature set points and air/fuel ratios were kept relatively constant during the test periods. One mean value was calculated for each pressure setting and a line drawn through the mean value points. The experiment was restricted between 0.090 and 0.140"WG, because at 0.140"WG excessive flame starts to leak out from the furnace, and at 0.090"WG the slabs begin to have cold ends and edges due to excessive leakage of cold air.

(iv) Frequency of Discharge Door Opening

Theoretically this should affect furnace efficiency as it causes considerable pressure disturbances in the furnace. Unfortunately, the experiments do not support this theory. Fig.5.7 shows widely scattered efficiency for each frequency. This may be due to the limited range of

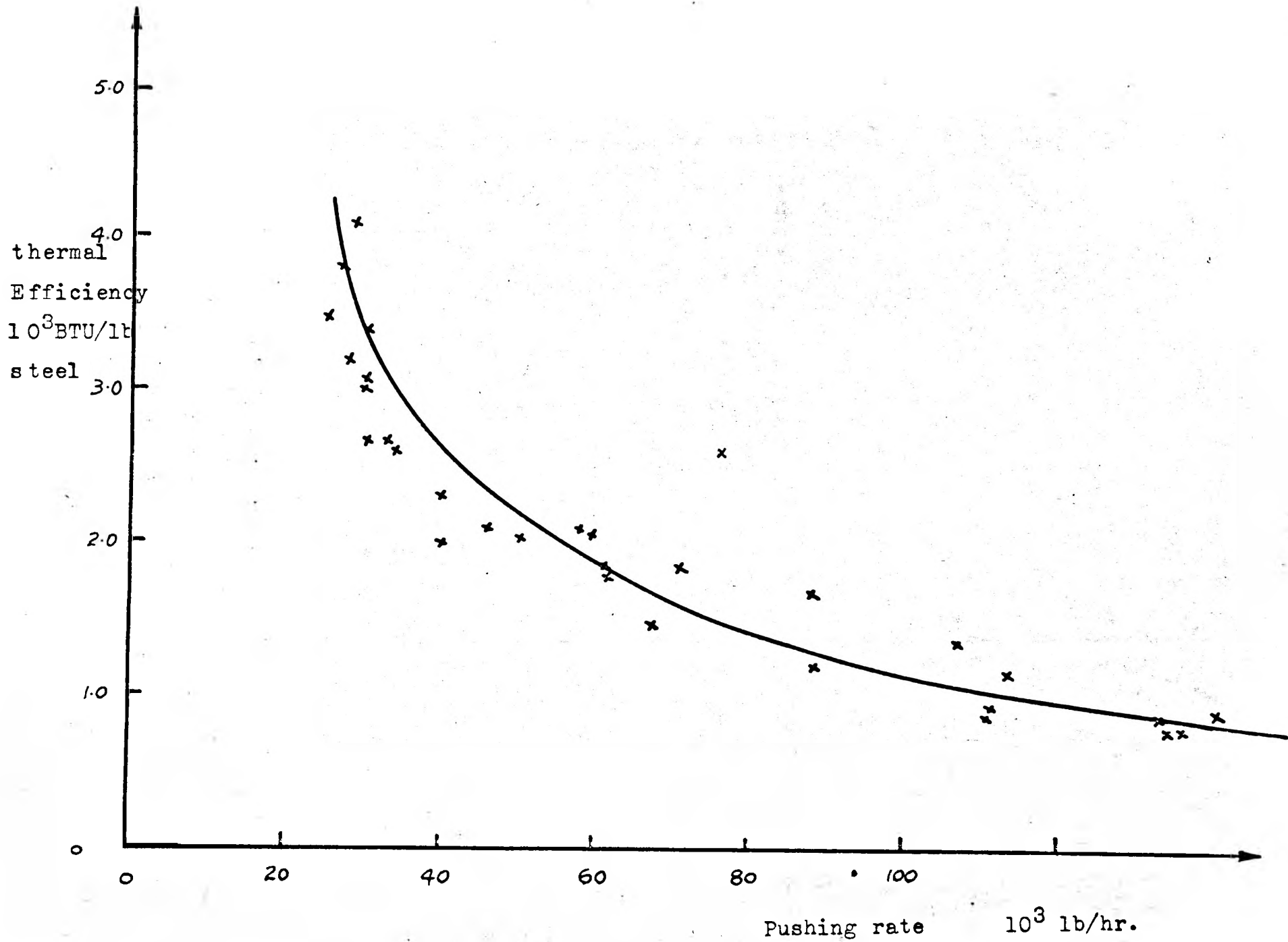


Fig. 5.8 Thermal efficiency plotted against pushing rate.

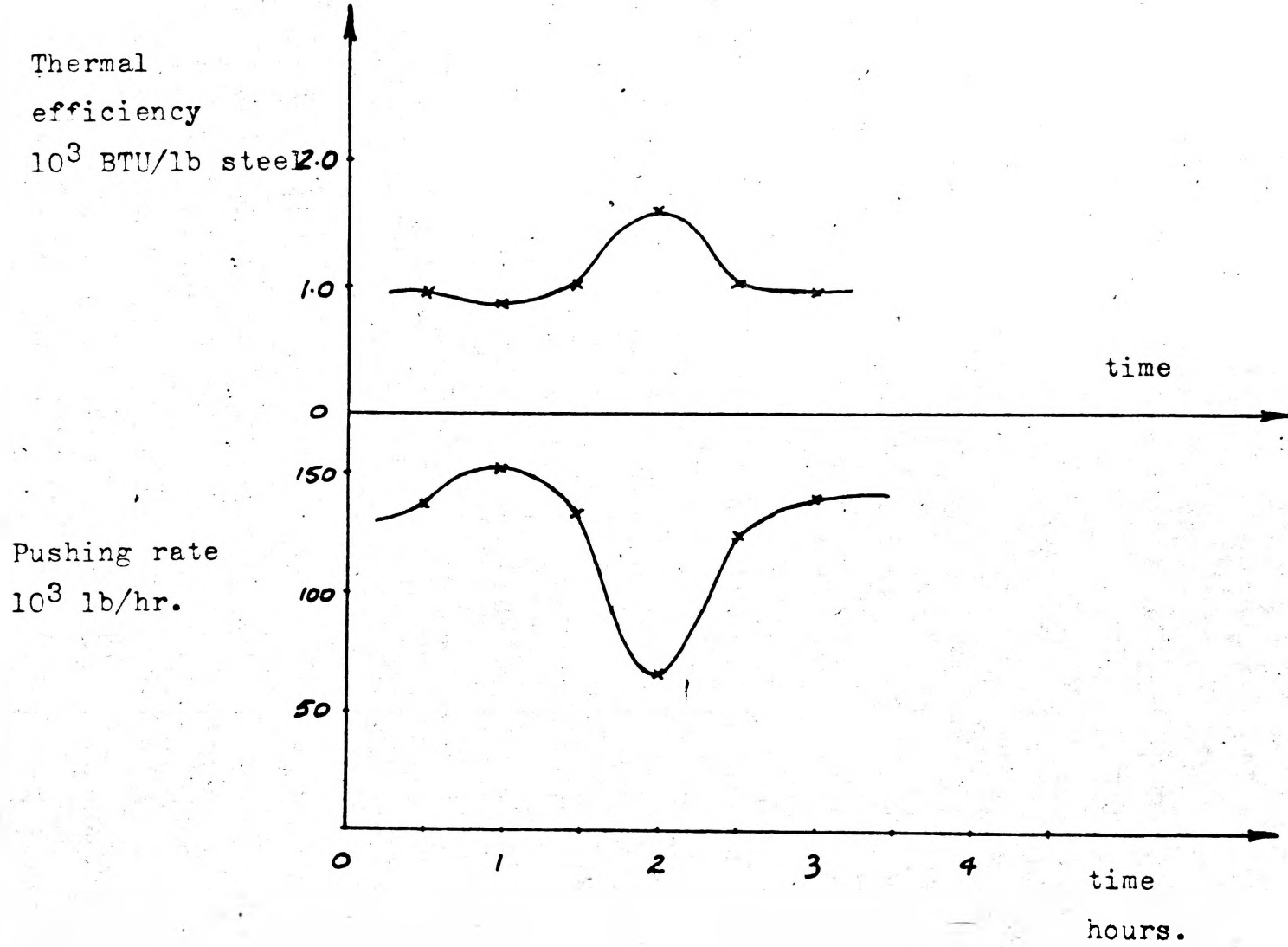


Fig. 5.9 Correlation between efficiency and pushing rate.

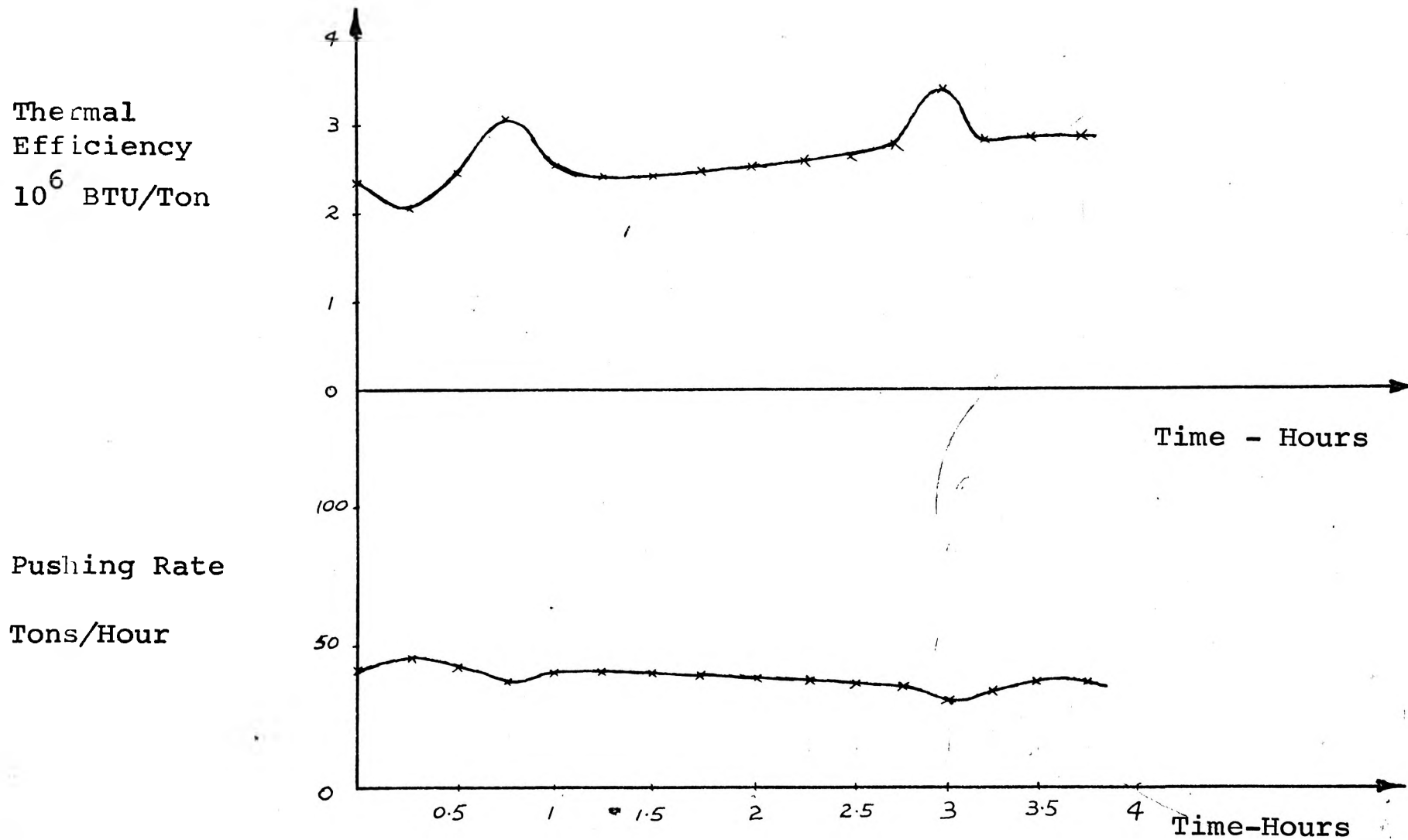


Fig 5.10 Correlation between efficiency and pushing rate

frequencies available during the test period and effects due to other factors.

(v) Pushing Rate

Experiments show that pushing rate has two effects on efficiency. The first one is due to the definition of efficiency, BTU/ton of steel. Fig.5.8 shows that for steady state conditions, that is, taking periods when there is no change in pushing rate and other conditions, efficiency is almost directly proportional to the inverse of pushing rate. Fig.5.9 and 5.10 show the definite relationship between pushing rate and thermal efficiency. On analysing the points in Fig.5.8, it is found that all the points obtained from test periods which contain a step change in pushing rate or are immediately after a step change in pushing rate are points with lower thermal efficiency (points with circles). This points to the fact that efficiency drops with the increase in frequency of pushing rate changes.

(vi) Temperature Set Points

With the discovery that the frequency of pushing rate changes affect efficiency, it was

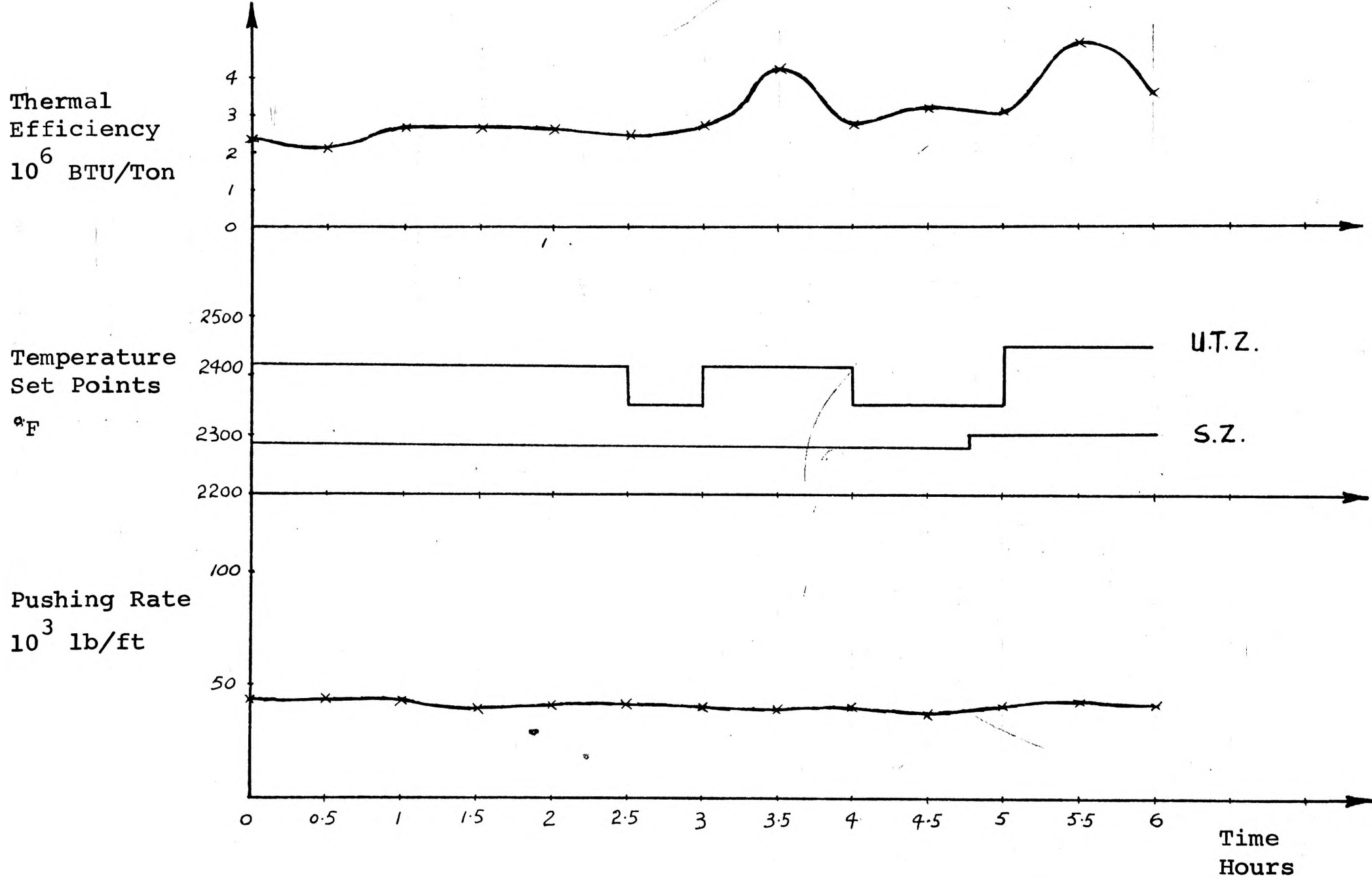


Fig. 5.11 Effect of temperature set point changes on thermal efficiency

thought that this must be due to the changes in firing rate accompanying the pushing rate changes. Hence experiments were carried out to test the effect of temperature set point changes on efficiency. The results are plotted on Fig.5.11, which shows that efficiency is not affected by the lowering of temperature set points, but is drastically affected by the increase of temperature set points. Raising the UTZ temperature set point by  $40^{\circ}\text{F}$  (from  $2,340^{\circ}\text{F}$  to  $2,380^{\circ}\text{F}$ ) can reduce the thermal efficiency by about 60% for a period of half an hour. But, after the half hour period, the efficiency generally settles back to its normal value.

Unfortunately, to the efficiency control program, the temperature set point is, like pushing rate and slab thickness, a disturbance. No independent process variable can be adjusted to compensate for them. The only thing that can be done is to restrict the frequency and amplitude of the changes by improved rolling techniques and scheduling techniques.

(vii) Slab Thickness

Observations are made to determine the



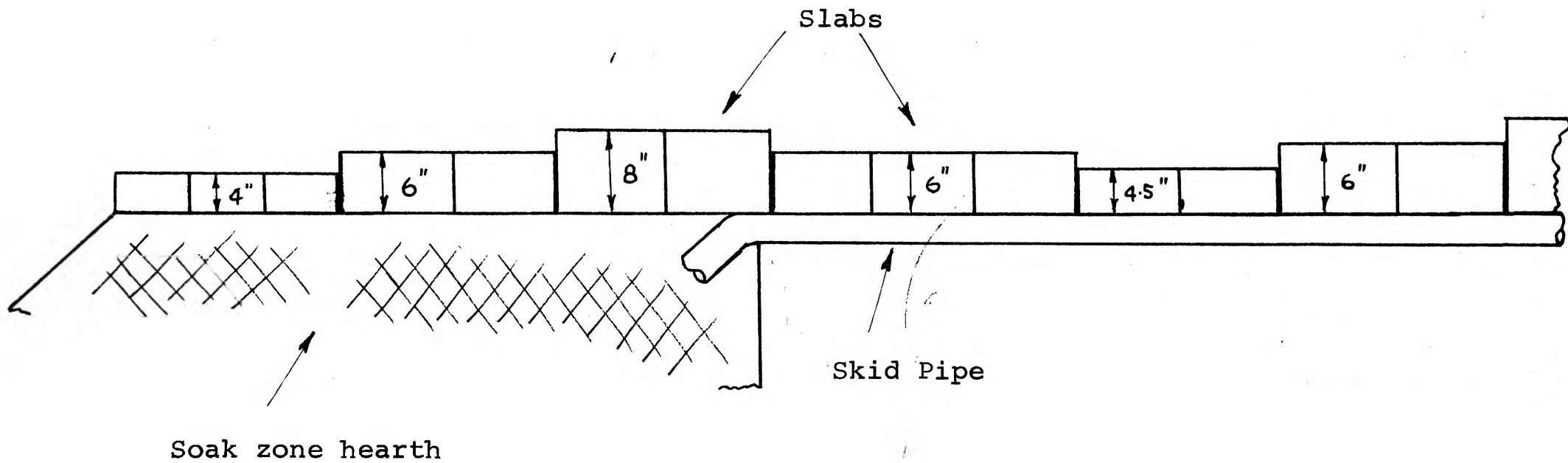


Fig. 5.12 Typical slab thickness patterns in a slab furnace supplying a plate mill

effect of slab thickness on efficiency. It is immediately obvious that the effect is identical to that caused by pushing rate. As slab thickness changes it causes large changes in fuel firing rate, causing disturbances in the flow patterns and the steady state condition established for optimum efficiency. Furnace pressure and air/fuel ratios have to be re-established. For a plate mill, slab thickness changes very frequently. Fig. 5.12 shows the worst case of slab thickness distribution in a typical furnace.

(viii) Slab Length

Slab length changes cause changes in effective steel surface area for heat transfer. They also change the amount of mixing between upper and lower zones. Observations are made confirming this, but no planned experiment was carried out.

(ix) Steel Quality

As the grade of steel changes, the coefficient of heat transfer between furnace and steel changes. At present, there is no simple way to compensate for this effect. Theoretical calculation to determine this is too tedious and is not assured

of clearcut results. This effect is neglected in this instance.

(x) Air/Fuel Ratios

A series of long and tedious experiments were carried out to determine the effects of air/fuel ratios on efficiency. The result, unfortunately, is not as conclusive as originally hoped for. When efficiency is plotted against the overall air/fuel ratio, a large amount of scatter is encountered. After screening the results for points of similar temperature, pushing rate and slab thickness conditions, a trend appears. Furnace pressure is maintained constant throughout the experiment. This shows that optimum efficiency lies somewhere around an air/fuel ratio of 5.6. This result is peculiar because the theoretical air/fuel ratio for CO gas is 4.2. Allowing 10% excess air for imperfect mixing, this still only comes to 4.6. Air/fuel ratio of 5.6 represents excess air of 35%. Previous experiments on the single zone billet reheat furnace show that best efficiency occurs at between 4.5 and 4.7. Experiments on the older slab reheat furnace show that best efficiency occurs at an air/fuel ratio of

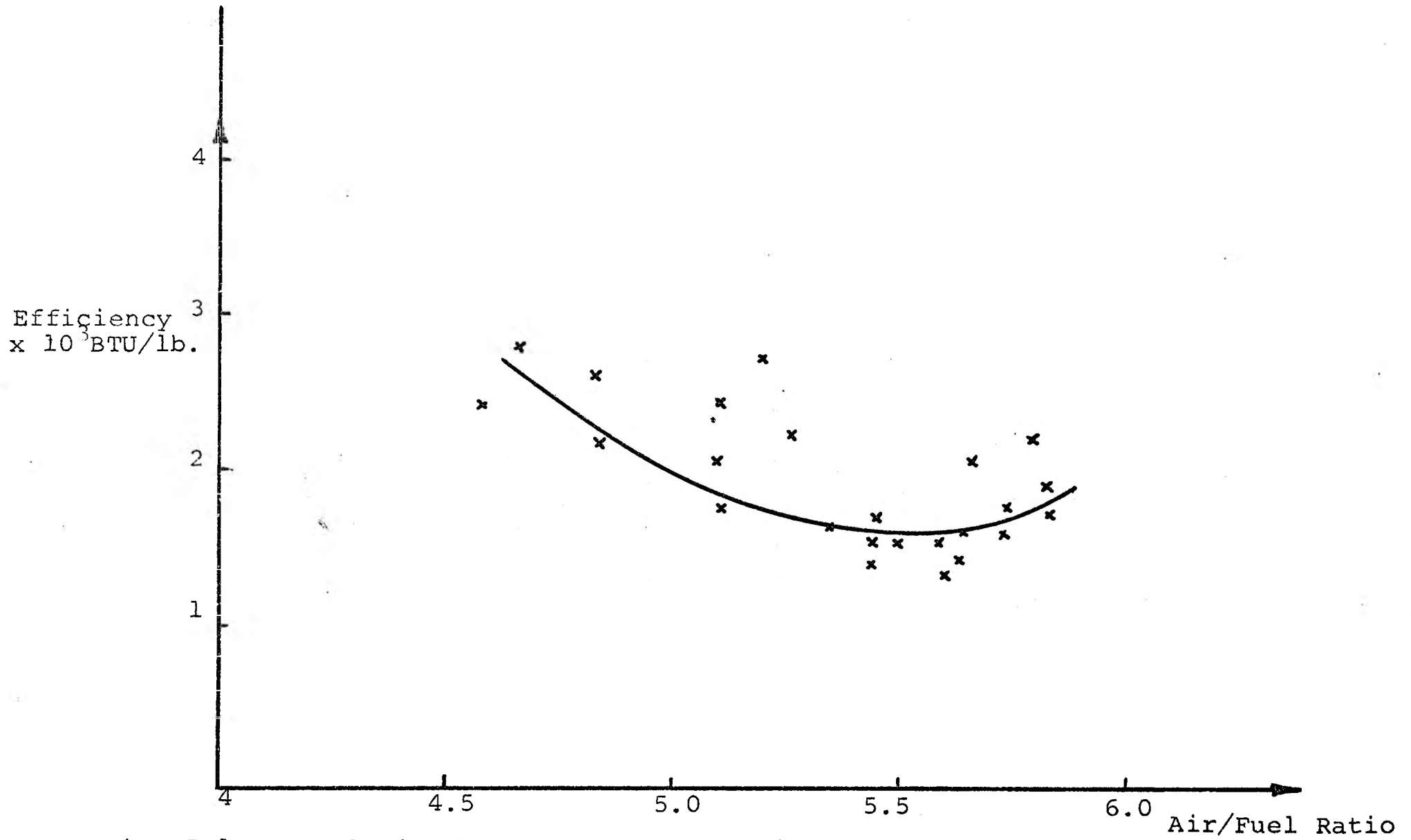


Fig. 5.13 correlation between overall air/fuel ratio and thermal efficiency.

about 5.0. This peculiar result shows that it is not possible to predict the best air/fuel ratio for any furnace. For any furnace at one particular time, the furnace design, the burner design, the gas and air pressure, the gas composition, ambient wind velocity and direction, orifice plate errors, hot air compensation errors, instrument fault and signal drifts, etc. can all combine and result in an optimum air/fuel ratio which is completely unpredictable. Fig.5.13 shows the results (screened) plotted against air/fuel ratio.

(xi) Steam/Oil Ratios

When oil firing is used, steam is used to atomise the oil as it is injected into the furnace. The steam/oil ratio determines the degree of atomisation. When this ratio is high, the oil is atomised to a very fine mist which produces a short flame similar to CO gas flame, but more luminous. When the ratio is lower, the flame becomes longer as the oil particles are larger and combustion takes longer to complete. When the ratio is too low, the oil particles are too large to be burnt in the furnace, and a black smoke is formed at the end of the flame. Between the extremes of wasting steam

and producing smokey flames, the ratio can be adjusted to give different shapes of flames, and hence different heat transfer coefficients and different efficiencies. Experiments were carried out to establish the adjustability of flame length by steam/oil ratio. These establish the adjustability at between 3 and 5. At a ratio of about 2.5 black smoke starts to appear. More experiments are being arranged to determine the relationship of these ratios with efficiency.

(xii) Other Factors

While carrying out experiments and observations on the furnace, it is observed that the changing of operators from shift to shift causes a significant change of efficiency. Investigation shows that each operator has his own methods and rules-of-thumb in operating the furnace. With the computer on line and controlling the operation, this factor would be eliminated as is proven in the initial trial period of steady state control.

From these experiments, it is concluded that the independent manipulated variables to be used for controlling furnace thermal efficiency are

the following:

- (a) Furnace pressure;
- (b) Air/fuel ratio in each zone;
- (c) Steam/oil ratio in each zone.

#### 5.4 THIN SLAB TEMPERATURE CONTROL PARAMETERS

For the single zone furnace, parameters for temperature control and throughput rate control are very limited. Experiments carried out on the BF gas/CO gas ratio show that it varies the furnace temperature profile. Fig.5.1 shows the temperature profile inside the billet furnace as measured by a thermocouple probe for different gas ratios. The same experiment shows that the time constant for furnace temperature profile to change on changing the gas ratio is approximately 5 minutes, for a gas ratio change of 1. Hence, BF gas/CO gas ratio can be used as a manipulated variable for temperature and throughput rate control.

It was originally intended to use the flame, roof and wall temperatures as the other manipulated variables, but after work done on the large furnace

as described in Section 5.5, it was decided to use the furnace temperature instead. This, together with the BF gas/CO gas ratio, become the only two manipulated variables. One varies the temperature profile along the furnace while the other varies the amplitude of the profile.

As the furnace can be considered as entirely single-sided heating, the boundary conditions are fairly easy to define. The solid hearth is considered as an insulating medium. Heat conduction through it is small comparatively and is neglected in the temperature control problem. Slab temperature at entry to the furnace is ambient.

$$T(0, 0) = T_a = \text{Ambient Temperature} \quad (5.1)$$

Temperature gradient of billets at the exit door is zero, therefore

$$\frac{\partial T(L, t)}{\partial y} = 0 \quad (5.2)$$

As derived in Sections 6.3 and 6.4, the thin slab heating equations are

$$s \rho v C_p \frac{\partial T}{\partial y} + s \rho C_p \frac{\partial T}{\partial y} = h_1 (T_F - T) \quad (5.3)$$



and

$$\begin{aligned} s \rho C_p \frac{\partial T}{\partial t} + s \rho v T \frac{\partial C_p}{\partial T} \frac{\partial T}{\partial y} + s \rho C_p v \frac{\partial T}{\partial y} \\ = h_1 (T_F - T) \end{aligned} \quad (5.4)$$

$T_F$  represents both the manipulated variables, and is  $T_F(y, t)$ , the mean furnace temperature as measured by a thermocouple inserted into the furnace;  $h_1$  is the effective coefficient of heat transfer and is determined experimentally. This is treated in more detail in the following Section 5.5 on large slab furnaces.

The temperature of billets at the exit of the furnace is measured as a check against the accuracy of the control.

As described in Section 5.5, the control system adjusts the set point of slab surface temperature as measured by the radiation pyrometer sighted on the billets, rather than furnace temperature. This has the same final effect as changing the furnace temperature set point but it has the added advantage of faster response and safeguard against the danger of overheating the billet surface.

## 5.5 THICK SLAB TEMPERATURE CONTROL PARAMETERS

For the large 4-zone furnace, no provision is made for mixed fuel firing. Either oil or CO gas is fired from each zone, but the number of zones on oil or gas can be randomly chosen depending on the availability of gas. If CO gas is available it must be used as it is a by-product gas and there is limited storage space. Due to a deficiency in gas, about 25 - 30% of the fuel used is oil.

Hence, when firing gas, the only manipulatable variable available for controlling temperature of slab and throughput rate is the furnace temperature profile. In this case this variable is divided into four, as the furnace is divided into four zones and the furnace temperature of each zone can be separately controlled. Soak zone does not have much heating capacity, so the main control criterion is the mean slab temperature just before the slabs enter the soak zone hearth. However, the lower half of the furnace has two heating zones, while the top only has the UTZ. Hence, if the pushing rate is very fast, the two lower zones would tend to make the bottom of the slab hotter, The soak zone temperature set point has to be raised so that the

top and bottom temperatures are more even.

When firing oil, the condition is almost exactly the same. Steam/oil ratios can affect efficiency, but the LTZ and PZ are too short for flame shape to affect temperature control. The soak zone does not usually fire oil because of excessive scaling. The only place where steam/oil ratio can have some effect is in UTZ. So, when oil firing is necessary, one more manipulated variable is added: the steam/oil ratio for UTZ.

Initially, it was intended to analyse the heat transfer problem by considering the actual ways by which heat is transferred, i.e.,

- (a) Convection from hot gas,
- (b) Radiation from roof and walls,
- (c) Radiation from the luminous flame.

The boundary conditions for the heating Equations 4.16 and 4.17 are the following:

$$T(x, 0, 0) = T_a = \text{Ambient Temperature} \quad (5.5)$$

$$\frac{\partial T(x, L, t)}{\partial y} = 0 \quad (5.6)$$

$$\frac{\partial T(s/2, y, t)}{\partial x} = 0, \text{ for } y < 68 \text{ ft} \quad (5.7)$$

$$\frac{\partial T(0, y, t)}{\partial x} = 0, \text{ for } y > 68 \text{ ft} \quad (5.8)$$

$$\begin{aligned} & \frac{\partial T(s, y, t)}{\partial x} \\ &= \frac{\partial T(0, y, t)}{\partial x} \\ &= \beta_1 h(T_g - T) + \beta_2 \sigma E' (T_w^4 - T^4) + \beta_3 \sigma E'_1 (T_{Fl}^4 - T^4), \\ & \qquad \qquad \qquad \text{for } y < 68 \text{ ft} \quad (5.9) \end{aligned}$$

$$\begin{aligned} & \frac{\partial T(s, y, t)}{\partial x} \\ &= \beta_1 h(T_g - T) + \beta_2 \sigma E' (T_w^4 - T^4) + \beta_3 \sigma E'_1 (T_{Fl}^4 - T^4), \\ & \qquad \qquad \qquad \text{for } y > 68 \text{ ft} \quad (5.10) \end{aligned}$$

where  $T_g$  = hot non-luminous gas temperature

$T_w$  = wall and roof temperature

$T_{Fl}$  = flame temperature

An oxide film always exists on the slab surface as it moves along the furnace, and this affects the heat transfer, so it has to be taken into account. The boundary conditions Equations 5.9 and 5.10 then become:

$$\begin{aligned} & \frac{\partial T(s, y, t)}{\partial x} \\ &= \frac{\partial T(0, y, t)}{\partial x} \\ &= \frac{\beta_1}{\left(\frac{1}{h}\right) + \left(\frac{d}{K'}\right)} (T_g - T) + \beta_2 \sigma E' (T_w^4 - T^4) + \beta_3 \sigma E'_1 (T_{F1}^4 - T^4), \end{aligned}$$

for  $y < 68$  ft      (5.11)

and

$$\begin{aligned} & \frac{\partial T(s, y, t)}{\partial x} \\ &= \frac{\beta_1}{\left(\frac{1}{h}\right) + \left(\frac{d}{K'}\right)} (T_g - T) + \beta_2 \sigma E' (T_w^4 - T^4) + \beta_3 \sigma E'_1 (T_{F1}^4 - T^4), \end{aligned}$$

for  $y > 68$  ft      (5.12)

where  $d$  = thickness of oxide

$K'$  = thermal conductivity of oxide

These boundary condition equations become exceedingly difficult to solve for the following reasons:

- (i) Oxide thickness,  $d$ , is a variable starting from about zero at entry to furnace and becomes thicker as it approaches the exit of the furnace. The final thickness is dependent on air/fuel ratios, type of fuel, type of steel, etc.
- (ii) Oxide thermal conductivity,  $K'$ , is different for different types of steel.
- (iii) The hot gas temperature  $T_g$  is very difficult and costly to measure continuously. A gas temperature probe is designed and made for this purpose. Unfortunately, it fails at  $2,000^{\circ}\text{F}$ . More details of the experiment and the probe are given in Appendix 10.
- (iv) The wall and roof temperature,  $T_w$ , can be

obtained, but with considerable difficulty as special roof bricks would have to be made so that the thermocouples do not protrude into the furnace and become affected by radiation from the flame, etc.

- (v) Flame temperature,  $T_{F1}$ , can be measured, but only by a manually operated optical pyrometer. No continuous measurement can be obtained due to difficulty in focusing.
- (vi)  $\beta_1, \beta_2, \beta_3$  have to be obtained experimentally. Design of the experiments to obtain these is a major task beyond the scope of this thesis.

Hence, it was decided to use an approximation by simplifying the right hand side of the Equation 5.12. That is, let

$$\frac{\beta_1}{\left(\frac{1}{h}\right) + \left(\frac{d}{K}\right)}(T_g - T) + \beta_2 \sigma E (T_w^4 - T^4) + \beta_3 \sigma E'_1 (T_{F1}^4 - T^4) = h_1 (T_F - T) \quad (5.13)$$

where  $h_1$  is the overall coefficient of heat transfer, and  $T_F$  is the furnace temperature as measured by a thermocouple inserted into the furnace. This thermocouple should measure the mean temperature of the furnace, as it is affected by the hot gas, flame, roof, wall, as well as the steel slabs.

Experiments to determine  $h_1$  are also quite time consuming and costly. Fortunately, literature survey shows that work has previously been done on this heat transfer coefficient in reheat furnaces. Schack (4) and Heiligenstadt (5) work out the coefficient to be as follows:

$$h_1 = 10.25 + 0.03416 (T_F - 1,292) \quad (5.14)$$

Gray and Brooks (3) tested the equation of Schack and Heiligenstadt and suggest a modified equation which is

$$h_1 = 10.25 + 0.0416 (T_F - 1,292) \quad (5.15)$$

As described in Section 6.8, the equation of Gray and Brooks is tried but proves to be inadequate, while Heiligenstadt's equation (5.14) reproduces slab surface temperature profiles from furnace



temperature profiles which is almost exactly the same as the experimentally obtained profile.

Hence, the boundary Equations 5.9 and 5.10 become the following:

$$\frac{\partial T(s, y, t)}{\partial x} = \frac{\partial T(0, y, t)}{\partial x} = h_1(T_F - T)$$

for  $y < 68$  ft      (5.16)

and

$$\frac{\partial T(s, y, t)}{\partial x} = h_1(T_F - T)$$

for  $y > 68$  ft      (5.17)

With furnace temperatures  $T_F$  as the manipulated variables, the slab surface temperatures must be measured or calculated and used as a constraint in case the steel surface is overheated. Theoretically, the only way to measure slab surface temperature accurately is by inserting a thermocouple into the slab just below the surface, or by using a hemispherical pyrometer placed on the slab surface to obtain block body condition. These two

methods are obviously difficult to use for continuous control. Literature survey shows that no one has successfully devised a continuous method of measurement. At BISRA, a pyrometer is lowered through the furnace roof to 6" above the slab surface in a water-cooled probe. This is costly to construct and difficult to maintain, and is still affected by flame and roof temperature reflected from the slab surface.

Experiments were carried out at AIS, Port Kembla on radiation pyrometers sighted on slab surfaces through furnace side walls. The results show that radiation pyrometer readings in SZ and tonnage zones are quite good. They differ from actual temperatures by about  $+20^{\circ}\text{F}$  to  $+40^{\circ}\text{F}$ , and are always on the positive side. However, the temperature in preheated zones where the temperature difference between slab and furnace walls and roofs is large, the pyrometer readings are much higher than the actual temperature. It is generally between  $200^{\circ}\text{F}$  to  $300^{\circ}\text{F}$  higher than the actual temperature. But as the pyrometers are sighted on the slab surfaces, the most significant factor is the slab temperature, and the measurements do vary in accordance to the actual slab temperatures. The

response of the pyrometer is also found to be much better than the thermocouple measuring furnace temperature. Experiments show that when fuel firing is increased, the slab surface temperature actually rises faster than the temperature of the sheath housing the furnace temperature thermocouple. Hence, if the fuel is not controlled by the slab surface temperature pyrometer, the slab surface is likely to melt before the furnace temperature thermocouple can detect the temperature rise. This measurement can also indicate the thickness changes in the slabs, as the temperatures of slabs of different thicknesses are different. Hence, it was decided that although the furnace temperatures  $T_F$  are the manipulated variables, the actual set points adjusted are the slab surface temperatures as measured by side-wall radiation pyrometers. This has the same effect as adjusting the furnace temperatures, but has the advantage of faster response and elimination of the danger of overheating slab surface.

The furnace temperatures  $T_F$  will still be measured and used to calculate the correct surface temperature profile and centre temperatures of slabs. Temperature of the slab as it comes out of

the furnace is measured and used as a check against the accuracy of the control of surface temperature. A feedback signal is fed directly from the mill operator to the computer indicating whether the slab is adequately heated at the centre.

Details of experiments are given in Appendix 10.

## CHAPTER 6

DEVELOPMENT AND SOLUTION OF THE THEORETICAL MODEL  
FOR SLAB HEATING

## 6.1 INTRODUCTION

In the control of thick slab heating, one of the critical factors is the temperature difference between centre and surface of the slab. Generally a slab is considered sufficiently heated for good rolling when its surface temperature is about  $2,200^{\circ}\text{F}$ , and its centre temperature is no more than  $50^{\circ}\text{F}$  below this value. As it is difficult even to measure slab surface temperature accurately, it is almost completely impossible to continuously measure the distribution of temperature inside the slab in the x, y and z planes. To achieve this, it is necessary to determine the mathematical model of the heating process.

When considering thin slabs, the problem is simpler as the temperature distribution in the x, y-plane can be neglected. But a mathematical model for the heating process is still needed for control purposes.

As the properties of some slabs heated are constant while others are dependent on temperature, models for both cases are necessary. Variations in steel properties are considered. All the mathematical models are solved and results verified

against experimental data. Equipment are designed and experiments carried out to verify the models.

Lerner (23) is the only one who has treated the thin slab case but the thick slab case has been studied by various people with different degrees of success.

The solution of the simplified Equation 4.16 was first solved by Jackson et al (7) using the analog computer and assuming  $K$  and  $C_p$  constant.

O'Brien et al (1) solved the same equation later using numerical methods and different equations. Douglas and Peacemen (53) solved the two-dimensional equation of

$$\frac{\partial T}{\partial t} = \alpha \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \quad (6.1)$$

Then Gay et al (41) and Brian (51) both solved the three-dimensional equation of

$$\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \quad (6.2)$$

Although they had heat conduction application in mind, their treatments are purely mathematical and

do not consider the problem of temperature dependence of  $K$  and  $C_p$  or the boundary condition and coefficients of heat transfer.

Chu et al (50) use Equation 4.16 to solve heat conduction in a rod of finite length, assuming  $\alpha$  is dependent on temperature. Kodz et al (19) and Hollander et al (21) use exactly the same equation on reheat furnaces and claim some success. Lerner uses the same equation but assumes  $\alpha$  constant and adds a velocity term to the equation.

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} - v(t) \frac{\partial T}{\partial y} \quad (6.3)$$

Scharbrough et al (22) derive a different equation which seems to be incorrect.

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial T}{\partial x} \quad (6.4)$$

Hollander (21) derives an equation of the form

$$(T_1 - T_2) + (T_3 - T_2) = \frac{\Delta x^2}{\alpha_2 \Delta t} (T'_2 - T_2) \quad (6.5)$$



where  $T_i$  = temperature of slice  $i$  at time  $t$

$T'_i$  = temperature of slice  $i$  at time  $t + \Delta t$

$\alpha_2$  = value of  $\alpha$  at  $T_2$

He claims some success. However, in a later article he uses Equation 4.16 in lieu of this.

Several other people such as Butkovskii (59) and Sakawa (61) who worked on optimal control theory merely treat the Equation 4.16 with constant coefficients.

At the start of the project, the only person who had tried anything on a real plant was Lerner. He used Equation 4.16 with constant coefficients. His results are not very impressive, although he claims some success in reducing the strip end point temperature scatter.

When Equation 4.16 with constant coefficients is solved on an analog computer, the results do not appear to correspond to the experimental results. Hence a more accurate set of equations are derived and solved.

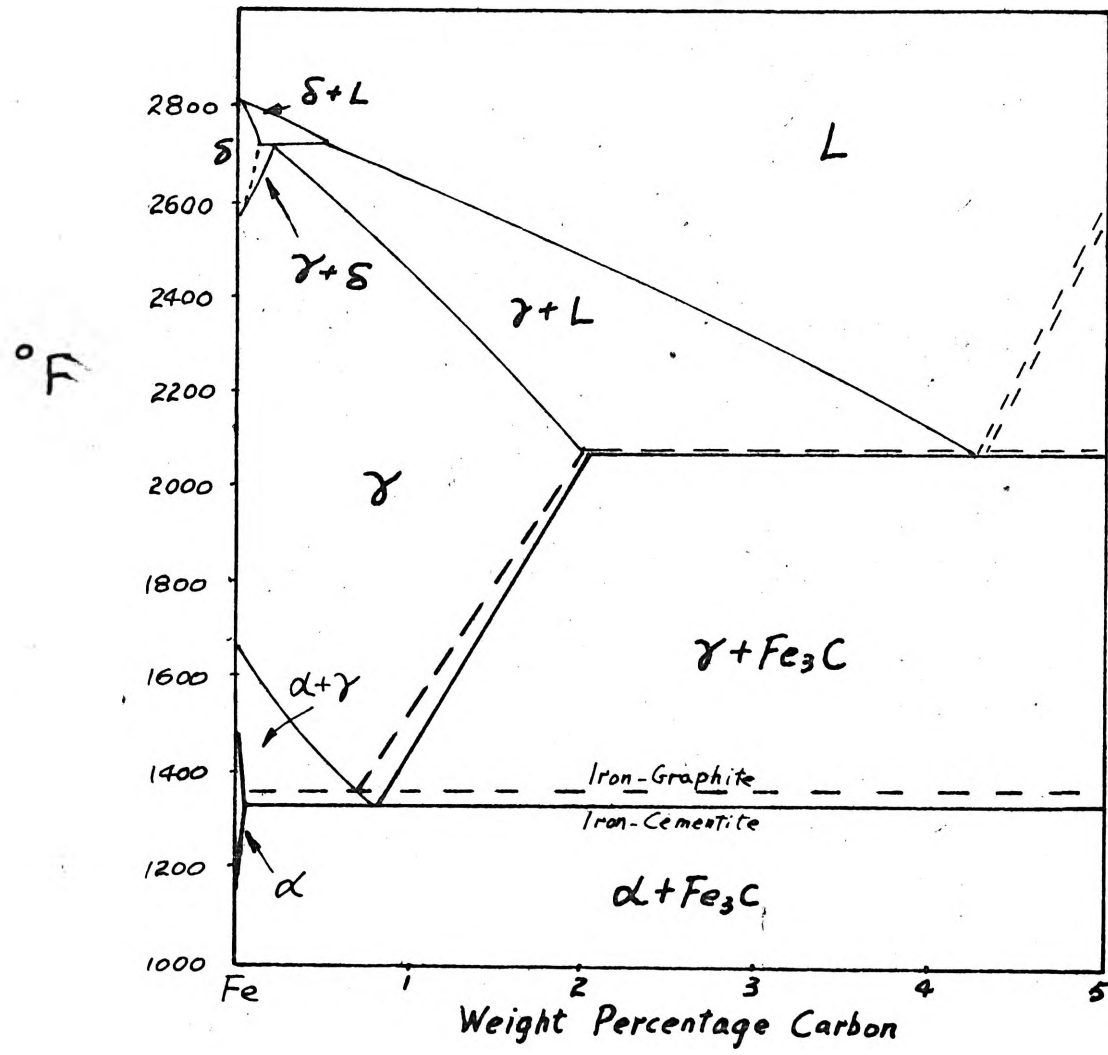


Fig. 6.1 Iron - Carbon Phase Diagram

## 6.2 PHYSICAL PROPERTIES OF STEELS

Generally strip mill furnaces get more constant feed of slab types as compared to plate mill furnaces which are likely to be required to heat slabs of widely differing types of steels.

Of the three properties  $\rho$ ,  $K$  and  $C_p$  that appear in heat conduction equations,  $\rho$  is the only one which changes very little with temperature and has a linear relationship with temperature.  $K$  and  $C_p$  are widely different from steel to steel, particularly for carbon steels which undergo phase transformation as temperature changes (see Fig.6.1).

Literature survey of the subject reveals a very acute shortage of information on thermal properties of steels. Unimo (31) measured the specific heat of some carbon steels in 1926. His results on pure iron seem to be very good but results on other steels do not seem to agree with results by others. Shelton (27) worked out the thermal conductivity of some irons and steels below 932°F. A team led by Griffiths (63) carried out a series of tests on twenty-two steels in 1945. Since then there have only been a few papers published on the subject such as Hogan et al (25), Fulkerson

Thermal Conductivity  
BTU/hr. ft.<sup>2</sup> ( °F/ft. )

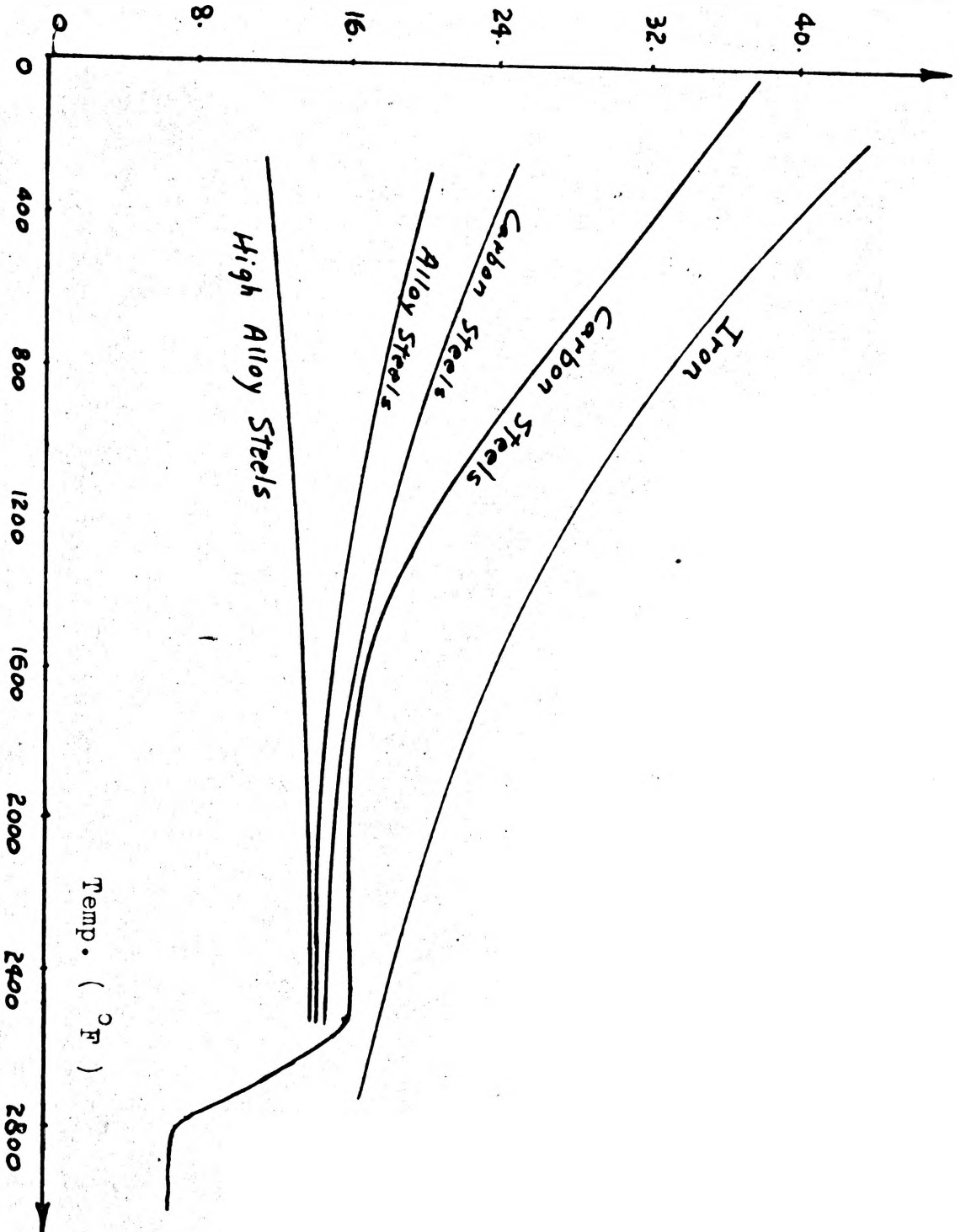


Fig. 6.2 Thermal Conductivity of Iron & Steels

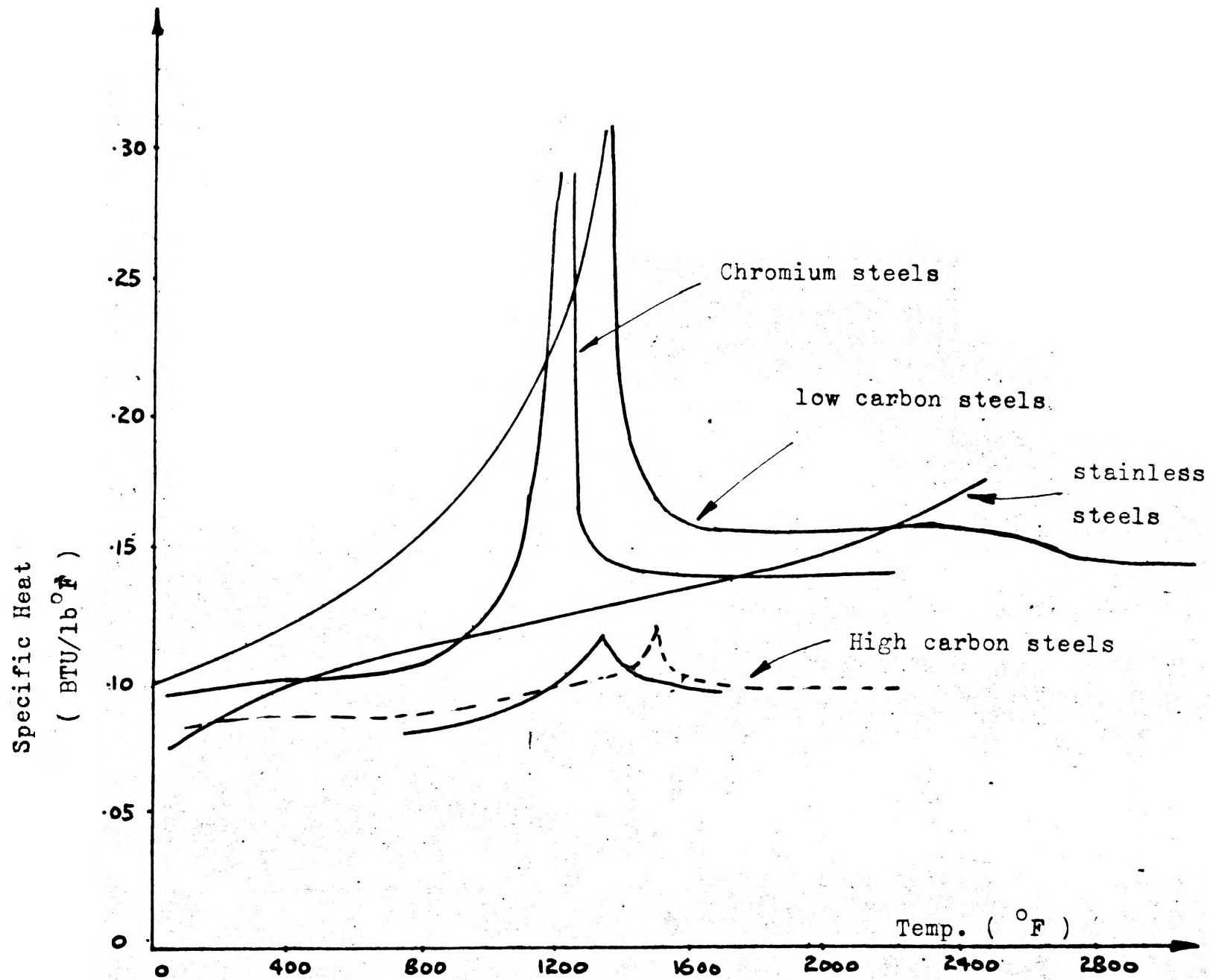


Fig. 6.3 Specific Heat of Steels.

et al (26), Butler et al (28) and these deal with limited ranges only. A newly published book by Goldsmith (29) summarises most of the work done on this subject.

Fig.6.2 shows typical thermal conductivity graphs for different types of steels. Fig.6.3 shows typical specific heat graphs for different types of steels. From Fig.6.3 it can be seen that the specific heats are greatly influenced by the phase transformation and the occurrence of the discontinuity due to transformation vary between  $1,300^{\circ}\text{F}$  and  $1,600^{\circ}\text{F}$  depending on the type of alloying materials used.

Fig.6.2 shows that variation in thermal conductivity is very large, varying from positive gradient to negative gradient. Pure iron has a thermal conductivity curve with a negative gradient but most alloying metals such as Tungsten (W), Nickel (Ni) and Chromium (Cr) have positive gradients. Hence the alloyed steels all have varying thermal conductivity curves between the extremes of pure iron and very high alloy steels. The curves generally become very peculiar from about  $2,500^{\circ}\text{F}$  upwards. Fortunately that is beyond our range of interest.

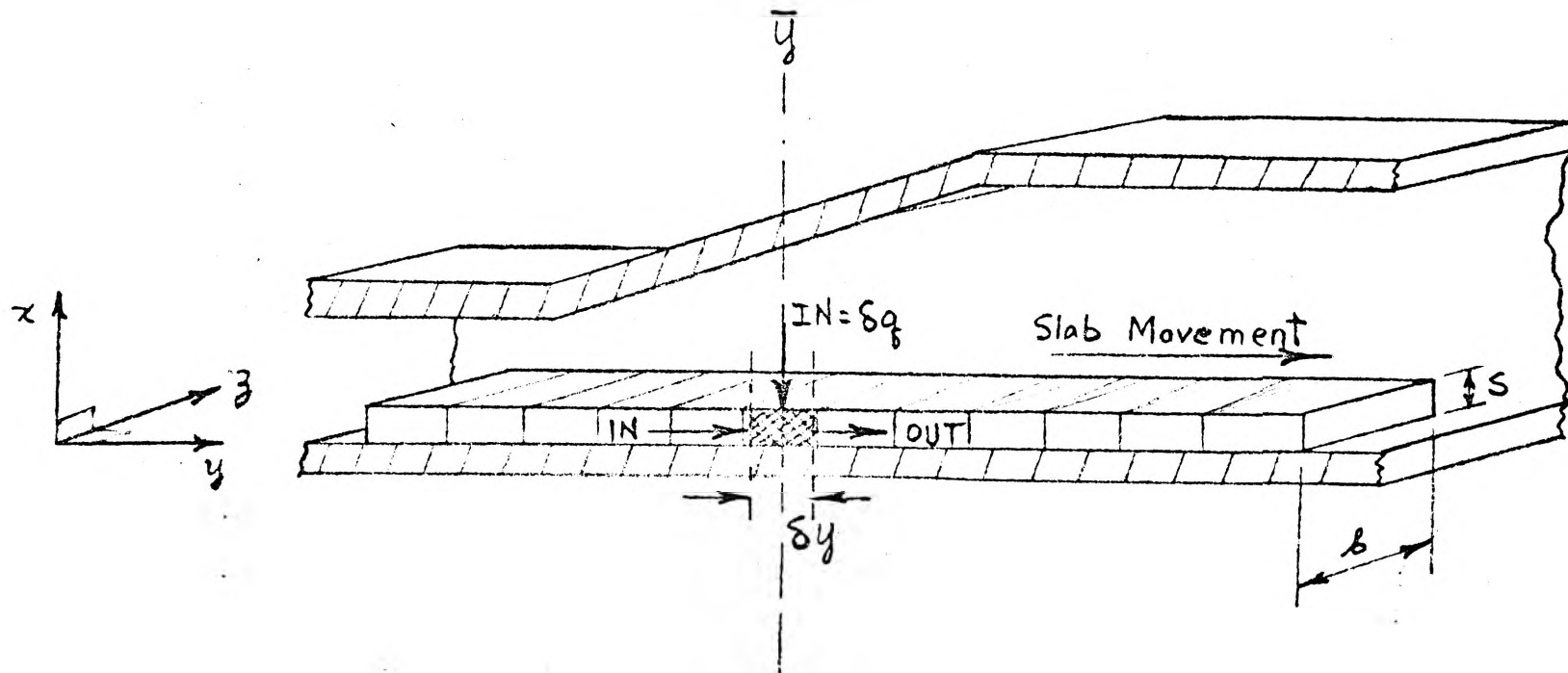


Fig. 6.4 Thin slab heat balance.

### 6.3 SLAB HEATING MODELS WITH CONSTANT THERMAL PROPERTIES

#### (a) Thin Slab Model

The equation for thin slab heating can be derived easily from heat balance on a small strip of metal of width  $\delta y$  (see Fig.6.4).

$$\text{Heat Input} = \text{Heat Output} + \text{Accumulation} \quad (6.6)$$

$$\begin{aligned} \therefore M C_p T(y, t) + \delta q \\ = M C_p T(y + \delta y, t) + s b \rho \delta y C_p \frac{\partial T(\bar{y}, t)}{\partial t} \quad (6.7) \end{aligned}$$

where  $M$  = rate of steel flow, lb/min

$T(y, t)$  = temperature of metal surface, assuming slab is thin and temperature at centre of slab follows this temperature closely.

$\delta q$  = heat input to steel from furnace, BTU

$f_x$  = heat flux to steel in x-direction from furnace, BTU/ft<sup>2</sup>

$b$  = width of slabs, ft

$s$  = thickness of slab, ft

$v$  = velocity of slab in y-direction, ft/min  
 $= \frac{\partial y}{\partial t}$



Expanding M, Equation 6.7 becomes

$$\begin{aligned}
 & s b v \rho C_p T(y, t) + \delta q \\
 & = s b v \rho C_p T(y + \delta y, t) + s b \delta y \rho C_p \frac{\partial T(\bar{y}, t)}{\partial t} \\
 & s b v \rho C_p [T(y + \delta y, t) - T(y, t)] + s b \delta y \rho C_p \frac{\partial T(\bar{y}, t)}{\partial t} \\
 & = \delta q = - \frac{\delta f_x b \delta y}{\delta y} \quad (6.9)
 \end{aligned}$$

Now let  $\delta y \rightarrow 0$ , then

$$s v \rho C_p \frac{\partial T(y, t)}{\partial y} + s \rho C_p \frac{\partial T(y, t)}{\partial t} = - \delta f_x \quad (6.10)$$

For pure forced convection heat transfer

$$- \delta f_x = h [T_g - T(y, t)] \quad (6.11)$$

where  $h$  = coefficient of forced convection heat transfer between hot gas and slab

$T_g$  = temperature of hot gas

For pure radiation heat transfer from roof and walls, assuming the furnace is a black body furnace,

$$- \delta f_x = \sigma E' (T_w^4 - T^4) \quad (6.12)$$

where  $\sigma$  = Stephan-Boltzmann constant

$E'$  = emissivity

= 0.79 to 0.95 depending on temperature  
and scale condition of slab surface

$T_w$  = temperature of roof and walls

For pure radiation heat transfer from flame assuming the furnace is a black body furnace,

$$- \delta f_x = \sigma E'_1 (T_{F1}^4 - T^4) \quad (6.13)$$

where  $T_{F1}$  = flame temperature

It is obvious that for good accuracy Equations 6.11, 6.12 and 6.13 must all be taken into account. However, continuous and accurate measurement of  $T_g$ ,  $T_w$  and  $T_{F1}$  are difficult to obtain and an approximation is often used. This is based on a temperature  $T_F$  defined as the furnace temperature. It is measured simply by inserting a thermocouple into the furnace through the roof. This thermocouple would register a temperature somewhat higher than  $T_g$  and  $T_w$  but lower than  $T_{F1}$ , since it lies in the hot gas stream but is also subjected to heat radiation from the roof and the walls.

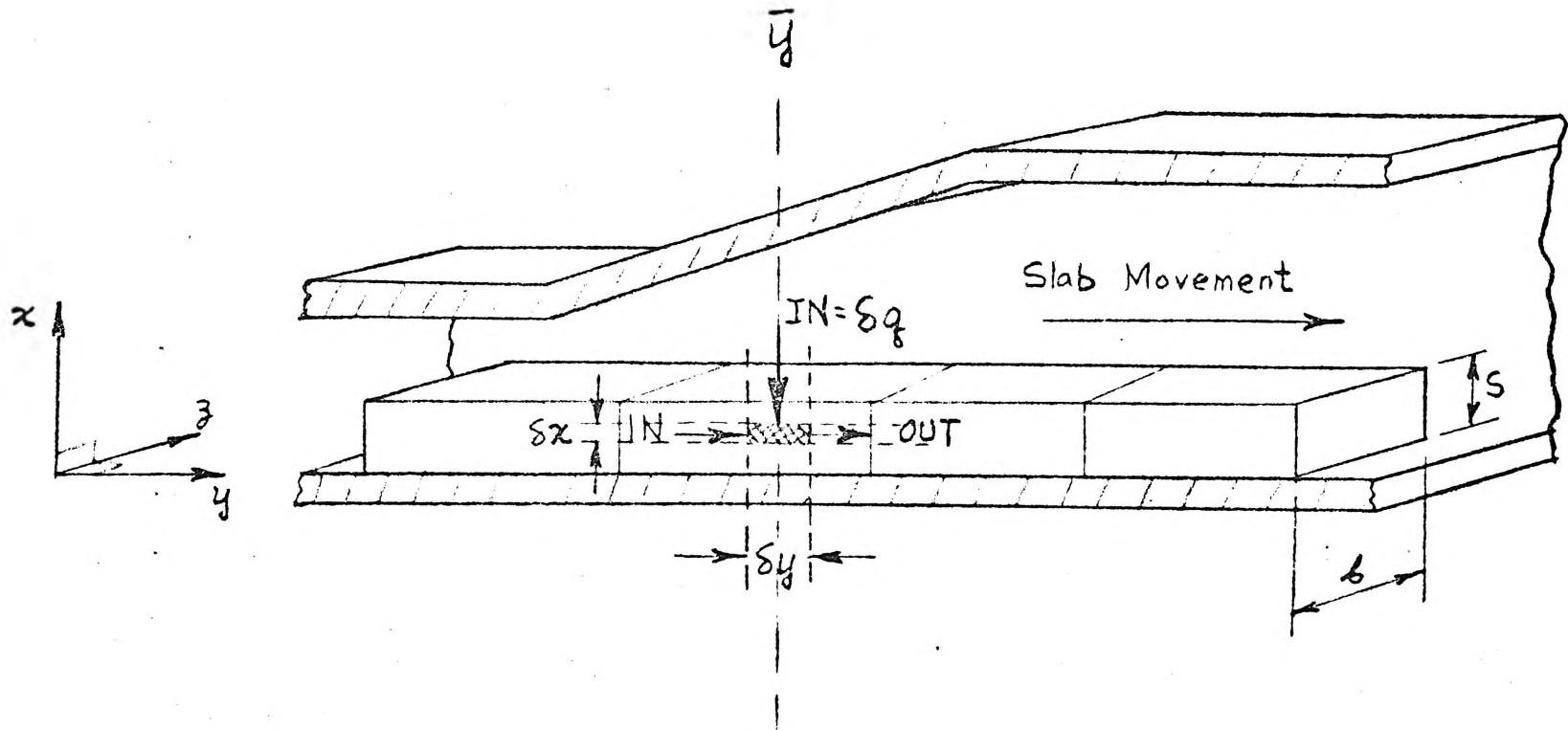


Fig. 6.5 Thick slab heat balance.

Hence, we have,

$$-\delta f_x = h_1(T_F - T) \quad (6.14)$$

where  $h_1$  = an arbitrary coefficient of heat transfer  
obtained experimentally

$$= 10.25 + 0.03416(T_F - 1,292), \text{ Equation 5.1}$$

as described in Section 5.5

Hence, Equation 6.10 becomes

$$\begin{aligned} s v \rho C_p \frac{\partial T(y, t)}{\partial y} + s \rho C_p \frac{\partial T(y, t)}{\partial t} \\ = h_1(T_F - T) \end{aligned} \quad (6.15)$$

(b) Thick Slab Model

The derivation of thick slab equations can be on similar lines as that for thin slabs, but in this case the small strip of slab of width  $\delta y$  and thickness  $s$  becomes a small strip of a thin slice of slab of width  $\delta y$  and thickness  $\delta x$  and the total slab thickness being  $s$  (see Fig.6.5).

In this case, Equation 6.10 becomes

$$\delta x v \rho C_p \frac{\partial T(x, y, t)}{\partial y} + \delta x \rho C_p \frac{\partial T(x, y, t)}{\partial t} = -\delta f_x \quad (6.16)$$

$$\therefore v \rho C_p \frac{\partial T}{\partial y} + \rho C_p \frac{\partial T}{\partial t} = - \frac{\delta f_x}{\delta x} \quad (6.17)$$

As  $\delta x \rightarrow 0$ , Equation 6.17 becomes

$$v \rho C_p \frac{\partial T}{\partial y} + \rho C_p \frac{\partial T}{\partial t} = - \frac{\delta f_x}{\delta x} \quad (6.18)$$

But the heat flux  $f_x = -K \frac{\partial T}{\partial x}$  (6.19)

$$\therefore v \rho C_p \frac{\partial T}{\partial y} + \rho C_p \frac{\partial T}{\partial t} = K \frac{\partial^2 T}{\partial x^2} \quad (6.20)$$

if K is assumed constant.

The heat transfer with the furnace becomes boundary conditions at  $x = s$  and  $x = 0$  for two-sided heating, i.e.,

$$- f_x = K \left( \frac{\partial T}{\partial x} \right)_{\substack{x = s \\ x = 0}} = h_1 (T_F - T) \quad (6.21)$$

For single-sided heating, the boundary  $x = 0$  is considered as insulated, as the heat loss through this boundary is negligible compared to heat input at  $x = s$  boundary.

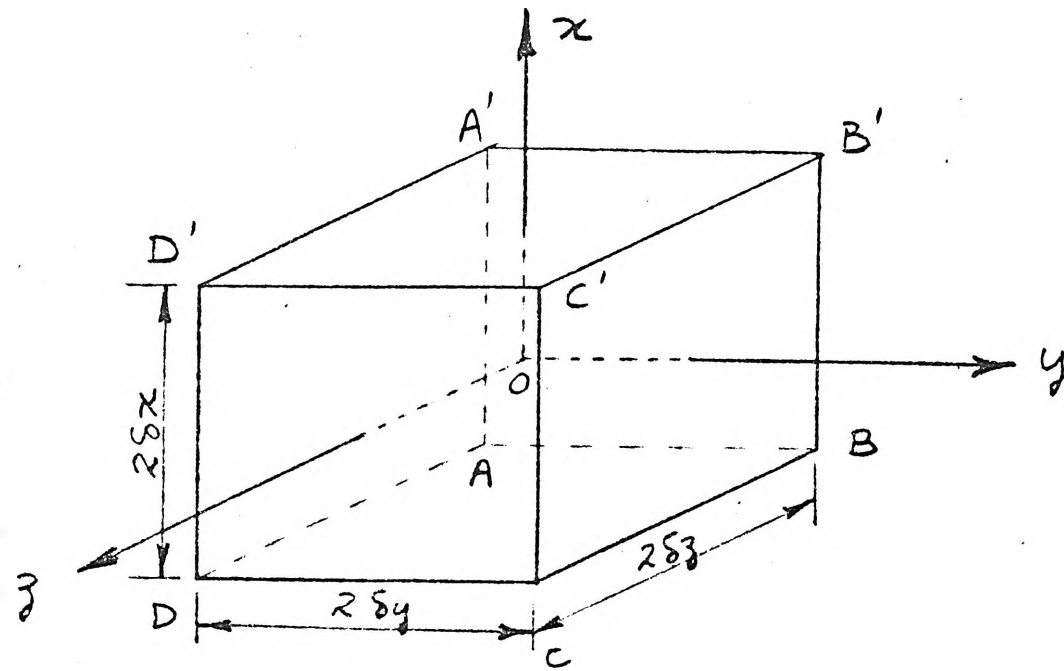


Fig. 6. 6 Rectangular parallelepiped for heat balance.

#### 6.4 SLAB HEATING MODELS WITH TEMPERATURE DEPENDENT THERMAL PROPERTIES

For the case with variable thermal properties, it is easier to derive a generalised equation from the classical method of deriving heat conduction equations. Most equations used for this type of work are derived with some simplifying assumptions which are not applicable to the most commonly used material, the carbon steel.

Consider a rectangular parallelepiped of sides  $2\delta x$ ,  $2\delta y$  and  $2\delta z$ , (see Fig.6.6). This represents a small section of slab subjected to heat conduction from all directions. Heat balance of this parallelepiped is as follows:

$$\text{Heat accumulated} = 8 \delta x \delta y \delta z \rho C_p \frac{\partial T}{\partial t} \quad (6.22)$$

Heat flow into y, z face (ABCD)

$$= 4 \delta y \delta z \left( f_x - \frac{\partial f_x}{\partial x} \delta x \right) \quad (6.23)$$

Heat flow out of y, z face ( $A^1 B^1 C^1 D^1$ )

$$= 4 \delta y \delta z \left( f_x + \frac{\partial f_x}{\partial x} \delta x \right) \quad (6.24)$$

Therefore, from Equations 6.23 and 6.24, heat accumulated in y, z face

$$= - 8 \delta x \delta y \delta z \frac{\partial f_x}{\partial x} \quad (6.25)$$

Similarly, for x, z and x, y faces, we have the following equations:

Heat accumulated in x, z face

$$= - 8 \delta x \delta y \delta z \frac{\partial f_y}{\partial y} \quad (6.26)$$

Heat accumulated in x, y face

$$= - 8 \delta x \delta y \delta z \frac{\partial f_z}{\partial z} \quad (6.27)$$

Since,

Heat Input = Heat Output + Accumulation

we have,

$$\rho C_p \frac{\partial T}{\partial t} + \left( \frac{\partial f_x}{\partial x} + \frac{\partial f_y}{\partial y} + \frac{\partial f_z}{\partial z} \right) = 0 \quad (6.28)$$

where  $f_x$ ,  $f_y$ ,  $f_z$  are heat fluxes in x, y and z directions respectively.



of unit width, unit thickness & unit height,

For a body/moving with velocity  $U_x, U_y, U_z$  where  $U_x, U_y, U_z$  are velocity components in x, y and z directions respectively, we have

$$f_x = -K(T) \frac{\partial T}{\partial x} + \rho C_p(T) T U_x \quad (6.29)$$

$$f_y = -K(T) \frac{\partial T}{\partial y} + \rho C_p(T) T U_y \quad (6.30)$$

$$f_z = -K(T) \frac{\partial T}{\partial z} + \rho C_p(T) T U_z \quad (6.31)$$

#### (1) Thin Slab Model

For a thin slab of thickness  $s$ , Equation 6.28 becomes

$$\rho C_p(T) \frac{\partial T}{\partial t} + \left( \frac{\partial f_x}{s} + \frac{\partial f_y}{\partial y} + \frac{\partial f_z}{\partial z} \right) = 0 \quad (6.32)$$

and Equations 6.29, 6.30, 6.31 become

$$f_x = -K(T) \frac{\partial T}{\partial x} \quad (6.33)$$

$$f_y = -K(T) \frac{\partial T}{\partial y} + \rho C_p(T) T U_y \quad (6.34)$$

$$f_z = 0 \quad (6.35)$$

Then Equation 6.32 is

$$\rho C_p(T) \frac{\partial T}{\partial t} + \frac{\delta f_x}{s} + \frac{\partial}{\partial y} \left[ -K(T) \frac{\partial T}{\partial y} + \rho C_p(T) T U_y \right] = 0 \quad (6.36)$$

Expanded it becomes

$$\begin{aligned} \rho C_p \frac{\partial T}{\partial t} - K \frac{\partial^2 T}{\partial y^2} - \frac{\partial K}{\partial T} \left( \frac{\partial T}{\partial y} \right)^2 + \rho T U_y \frac{\partial C_p}{\partial T} \frac{\partial T}{\partial y} + \rho C_p U_y \frac{\partial T}{\partial y} \\ = - \frac{\delta f_x}{s} \end{aligned} \quad (6.37)$$

In Equation 6.34 the first term on the right hand side is much smaller than the second term, and hence may be omitted to simplify Equation 6.37, that is,

$$f_y = \rho C_p(T) T U_y \quad (6.38)$$

Hence, Equation 6.36 becomes

$$\rho C_p \frac{\partial T}{\partial t} + \frac{\delta f_x}{s} + \frac{\partial}{\partial y} (\rho C_p T U_y) = 0 \quad (6.39)$$

$$\begin{aligned} \rho C_p \frac{\partial T}{\partial t} + \rho T C_p \frac{\partial U_y}{\partial y} + \rho T U_y \frac{\partial C_p}{\partial T} \frac{\partial T}{\partial y} + \rho C_p U_y \frac{\partial T}{\partial y} \\ = - \frac{\delta f_x}{s} \end{aligned} \quad (6.40)$$

But  $\frac{\partial U}{\partial y} = 0$ , as the velocity is considered fairly constant throughout the  $y$ -direction at any particular time. Hence, Equation 6.40 reduces to

$$s\rho C_p \frac{\partial T}{\partial t} + s\rho T v \frac{\partial C_p}{\partial T} \frac{\partial T}{\partial y} + s\rho C_p v \frac{\partial T}{\partial y} = - \mathcal{f}_x \quad (6.41)$$

letting  $U_y = v$

For constant  $C_p$ , Equation 6.41 reduces to

$$s\rho C_p v \frac{\partial T}{\partial y} + s\rho C_p \frac{\partial T}{\partial t} = - \mathcal{f}_x$$

which is identical to Equation 6.10, proving the validity of the derivation.

Applying Equation 6.14, Equation 6.41 becomes

$$s\rho C_p \frac{\partial T}{\partial t} + s\rho T v \frac{\partial C_p}{\partial T} \frac{\partial T}{\partial y} + s\rho C_p v \frac{\partial T}{\partial y} = h_1(T_F - T) \quad (6.42)$$

## (2) Thick Slab Model

For the thick slab,  $f_x$ ,  $f_y$  and  $f_z$  are given by Equations 6.33, 6.38 and 6.35 respectively and Equation 6.28 becomes

$$\rho C_p(T) \frac{\partial T}{\partial t} + \frac{\partial}{\partial x} (-K(T) \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y} (\rho C_p(T) U_y) = 0 \quad (6.43)$$

Expanding and manipulating as before, we have

$$\begin{aligned} \rho C_p \frac{\partial T}{\partial t} + \rho C_p v \frac{\partial T}{\partial y} + \rho T v \frac{\partial C_p}{\partial T} \frac{\partial T}{\partial y} \\ = K(T) \frac{\partial^2 T}{\partial x^2} + \frac{\partial K(T)}{\partial T} \left(\frac{\partial T}{\partial x}\right)^2 \end{aligned} \quad (6.44)$$

For constant  $C_p$  and  $K$ , Equation 6.44 reduces to

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p v \frac{\partial T}{\partial y} = K \frac{\partial^2 T}{\partial x^2}$$

which is identical to Equation 6.20, proving the validity of this equation also.

The boundary condition for Equation 6.44 can either be Equation 6.21, i.e.,

$$K \frac{\partial T}{\partial x} = h_1 (T_F - T)$$

or

$$K \frac{\partial T}{\partial x} = \beta_1 h (T_g - T) + \beta_2 \sigma E' (T_w^4 - T^4) \quad (6.45)$$

where  $\beta_1$  and  $\beta_2$  are constants to take care of uncertainties and variations in  $h$  and  $E'$  and also the omission of radiation from flame. They must be found experimentally and corrected periodically when used.

Equation 6.44 is thus the general equation for slab heating where all other equations representing the various conditions are obtained by deleting appropriate terms from it.

## 6.5 SOLUTION OF SLAB HEATING EQUATIONS

Solution of the slab heating problem hinges on the solution of the four equations 6.15, 6.20, 6.42 and 6.44. Equations 6.15 and 6.42 are one-dimensional heat flow problems which can be readily solved by either analytical or numerical methods.

Equations 6.20 and 6.44 are two-dimensional heat problems which are much harder to solve. The solution of each of these equations would be a major project for applied mathematicians and is not really an engineering problem. Hence it is decided to view the problem from a different approach, that

is, to eliminate the  $y$  terms and reduce the equations to one-dimensional equations. This can be done if the problem is viewed as a stationary section of steel subjected to a constantly varying furnace temperature  $T_F$ , which depends on velocity  $v$ . When  $v$  changes, the  $T_F$  profile becomes compressed or extended. As changes in  $v$  are relatively infrequent, this method does not introduce significant error. This would reduce Equations 6.20 and 6.44 to

$$\rho c_p \frac{\partial T}{\partial t} = K \frac{\partial^2 T}{\partial x^2} \quad (6.46)$$

and

$$\rho c_p \frac{\partial T}{\partial t} = K(T) \frac{\partial^2 T}{\partial x^2} + \frac{\partial K(T)}{\partial T} \left( \frac{\partial T}{\partial x} \right)^2 \quad (6.47)$$

respectively.

As a numerical method is the only possible means of solving these equations, it was decided to attempt a solution on an IBM 360/30 digital computer. Since different numerical methods are required to solve steady state and transient equations, the relaxation method for the former and finite difference method for the latter, the one-dimensional transient equation would seem most suitable for solution by the finite difference

method. By using time dependent boundary conditions the furnace effect on the slabs could be simulated and both shut-down and continuous operation easily handled.

(1) Using Constant Coefficients

If the slab is divided into a grid or mesh the partial derivatives may be replaced by difference equations at any point. Three types of difference equations may be used - forward, backward, and central differences. O'Brien, Morton, Hyman and Kaplan (1) have shown that for parabolic partial differential equations, selecting a central difference representation leads to an unstable solution. It was decided therefore to use a forward notation and initially to attempt a solution of the most simple case, Equation 6.46 above, which in difference notation, becomes:

$$\frac{T_j^{t+1} - T_j^t}{\Delta t} = \frac{K}{\rho C_p} \frac{T_{j+1}^t - 2T_j^t + T_{j-1}^t}{(\Delta x)^2} \quad (6.48)$$

where  $T_j^t$  = temperature at time  $t$ , at a reference point  $j$  of the mesh

$T_j^{t+1}$  = temperature at that point,  $\Delta t$  later

Rearranging to obtain the "future temperature in terms of "present" known temperature,

$$T_j^{t+1} = T_j^t \left(1 - \frac{2}{M}\right) + \left(\frac{T_{j+1}^t + T_{j-1}^t}{M}\right) \quad (6.49)$$

$$\text{where } M = \frac{\rho c_p \Delta x^2}{K \Delta t} \quad (6.50)$$

Equation 6.49 may be solved for all  $j$  to obtain the distribution within the slab at finite time intervals ahead of the initially assumed distribution. O'Brien et al also showed that to obtain a stable solution of Equation 6.49,  $M$  must be greater than 2. This restriction severely limits the selection of a mesh to solve Equation 6.49, as a fine grid will involve a very small time increment and hence involve a very large number of computer cycles to obtain a solution.

To test this method on the digital computer, a heat flow example in Kreith (2) is solved. The Equation 6.49 is solved for a steel slab of thickness 4.8" and constant thermal diffusivity of  $0.25 \text{ ft}^2/\text{hr}$ . The slab is initially at a uniform temperature of  $100^\circ\text{F}$  and the surface temperature raised to  $500^\circ\text{F}$  at  $t = 0$ . Using a mesh with



$\Delta x = 0.6''$  and  $\Delta t = 0.02$  min, gives  $M$  a value of 3. The suggestion of Kreith to use the average of the surface at  $t < 0$ , i.e.,  $100^\circ\text{F}$ , and  $t > 0$ , i.e.,  $500^\circ\text{F}$ , as the boundary conditions for the first iteration is followed. The boundary conditions used in conjunction with Equation 6.49 are:

$$\begin{aligned} T(0, t) = 100, & \text{ for } t < 0 \\ & 300, \text{ for } 0 < t < \Delta t \\ & 500, \text{ for } t > \Delta t \end{aligned} \quad (6.51)$$

$$\frac{\partial T}{\partial x}(L, t) = 0 \quad (6.52)$$

where  $L = 2.4''$ , i.e., centre of slab

The solution is plotted by computer for the first three minutes and the characteristic parabolic profile obtained, thus vindicating the applied numerical method. By cross-plotting, the table by Kreith is reproduced. This result is shown by him to coincide with the analytical solution.

## (2) Using Temperature Dependent Coefficients

As previously mentioned, the physical

properties of most steels cannot be assumed constant. The variation with temperature is further complicated by the phase transformation of ferrite ( $\alpha$ -phase) and austenite ( $\gamma$ -phase) which occurs in the range  $1,000^{\circ}\text{F} - 1,600^{\circ}\text{F}$ , depending on the exact composition, (see Fig.6.1, 6.2 and 6.3). Accurate data on the variation of the specific heat and conductivity of the steel is unfortunately not readily available. The values given by Goldsmith (29) are used in this computation.

By replacing the curves with mathematical expressions - polynomial correlations and straight lines - variations in physical properties could be followed with temperature. A basis of five minutes is chosen initially for the adjustment of the steel properties.

The properties are calculated on the average temperature of the steel, obtained by averaging surface and centre temperatures, at the beginning of each interval, based on the temperature at the end of the preceeding five minutes. A five minute basis is chosen to save computation time and it is considered that such a basis will not greatly affect the accuracy of the result.

The aim of this calculation is to

reproduce a set of experimental results. Thermocouples have been attached at various depths below the surface of a slab and the readings recorded as the slab is pushed through the furnace. It is hoped to use the experimentally obtained surface temperatures in predicting the variation of the centre temperature. The ultimate aim is, however, to use a furnace profile to predict both surface and centre temperatures. (See Appendix 10 for details of the experiments).

The results obtained are plotted against the experimental curves. Two points become evident: (1) the displacement of centre temperature below surface temperature is too small; and, (2) the transformation occurs at  $1,000^{\circ}\text{F}$  instead of  $1,300^{\circ}\text{F}$ . The first discrepancy seems to indicate that at any point in the slab the assumed specific heat is too low and the conductivity too high. This can be rectified by using a higher temperature as the basis for calculating  $C_p$  and  $K$ ; this is done by selecting the surface temperature as the basis. The displacement of the transformation points and the fact that its effect is less prominent than in the tested slab indicates that the physical properties used may be erroneous. From Fig.6.3 it seems that the transfor-

mation can affect the distribution in the range 1,000°F to 1,600°F, as is in fact experienced. The actual  $C_p$  curve of the tested slab is probably displaced and encloses a greater area under the peak to account for the more pronounced temperature dip.

The program is then modified. The temperature on which the properties are based is altered to the surface temperature and the term concerning  $\frac{\partial K}{\partial T}$  is introduced. That is, to solve

$$\rho C_p \frac{\partial T}{\partial t} = K \frac{\partial^2 T}{\partial x^2} + \frac{\partial K}{\partial T} \left( \frac{\partial T}{\partial x} \right)^2 \quad (6.47)$$

with the previous boundary conditions.

In difference notation, after rearranging, this is

$$T_j^{t+1} = T_j^t \left(1 - \frac{2}{M}\right) + \left(\frac{T_{j+1}^t + T_{j-1}^t}{M}\right) + M_2 (T_{j+1}^t - T_j^t)^2 \quad (6.53)$$

where,

$$M = \frac{\rho C_p \Delta x^2}{K \Delta t} \quad (6.54)$$

$$M_2 = \frac{\partial K}{\partial T} \frac{\Delta t}{\rho C_p \Delta x^2} \quad (6.55)$$

The net effect of these two measures is to displace the centre temperature by about 20°F at each point. Although an improvement in the results has been obtained the complete solution has not been found.

With the uncertainty of the accuracy of steel properties data used, it was decided to proceed to the next step, viz., the prediction of the surface temperature of the slab from a given furnace profile. If computer control of the furnace is to be as successful as hoped for, then this would be the most versatile method of predicting the profile as stoppages as well as continuous running could easily be catered for.

The approximate coefficient of heat transfer,  $h_1$ , from Gray and Brooks (3), as described in Section 5.5, is used initially.

$$h_1 = 10.25 + 0.0416(T_F - 1,292) \text{ BTU/ft}^2 \text{ hr } ^\circ\text{F} \quad (5.15)$$

Using an overall heat transfer coefficient, the boundary condition Equation 6.21 becomes

$$\left( K \frac{\partial T}{\partial x} \right)_{x=0} = h_1 (T_F - T)_{x=0} \quad (6.56)$$

By using an overall coefficient, an error is introduced by approximating the radiative term which involves  $T^4$ . This error, however, is found to be negligible.

The boundary condition equation when transformed to difference form must account for the finite thickness of the assumed boundary. Thus the boundary condition equation becomes

$$\rho c_p \frac{\Delta x}{2} \frac{\partial T}{\partial x} = h_1 (T_F - T) + K \frac{\partial T}{\partial x} \quad (6.57)$$

or

$$T_1^{t+1} = T_1^t (1 - G_1 - G_2) + T_F G_2 + T_2^t G_1 \quad (6.58)$$

where  $T_1$  = surface temperature

$T_2$  = temperature  $\Delta x$  from the surface

$$G_1 = \frac{2 \alpha \Delta t}{\Delta x^2}$$

$$\alpha = \frac{K}{\rho c_p}$$

$$G_2 = \frac{2 \Delta t h_1}{\rho c_p \Delta x}$$

Various pushing rates  $v$  can be accommodated by varying the rate of alteration of the furnace temperature above the slab.

It is found that using  $h_1$  by Gray and Brooks (3) the calculated surface temperature increases too rapidly. It was decided to use the slightly lower coefficient of Heiligenstadt, i.e.,

$$h_1 = 10.25 + 0.03416(T_F - 1,292) \quad (5.14)$$

At the same time, the program is altered to allow a continuous variation of furnace profile and steel properties. Instead of altering these values in a stepwise fashion at five minute intervals they are calculated every hundredth of a minute, i.e., virtually continuously. The basis for calculating the physical properties is also changed. For the boundary condition (6.57) the weighted mean temperature of the first strip thickness  $\frac{\Delta x}{2}$  is used, viz.,

$$\text{Average Temperature} = \frac{3T_1^t + T_2^t}{4} \quad (6.59)$$

At each point within the solid, the properties are based on the average temperature about that point.

$$\text{Average Temperature} = \frac{T_{j-1}^t + T_j^t + T_{j+1}^t}{3} \quad (6.60)$$

A marked improvement in results is obtained. Although the experimental surface temperature is not exactly reproduced, the greatest discrepancy is 10%. Again the centre temperature is too high although it has been reduced from the stepwise result.

## 6.6 EXPERIMENTAL VERIFICATION

Because of the difficulty in deriving theoretical models, it was decided to obtain a set of experimental readings of slab temperatures and then find equations that would fit them. Experiments were planned and carried out mainly to measure temperatures and to find methods of measuring them accurately. The temperatures involved are furnace roof temperatures, hot gas temperatures, flame temperatures and slab temperatures in the x, y and z directions.

Furnace roof temperatures, wall temperatures and flame temperatures are easily measurable by



optical pyrometers, but cannot be continuously monitored without very large expense. The hot gas temperature is also difficult to measure. A suction pyrometer is designed and fabricated to measure the gas temperature without the radiation effect from furnace roof and flame. The details are described in Appendix 10. Only limited success is achieved with this apparatus. An improved design was prepared but was never fabricated because the difficulties in measuring roof and flame temperatures continuously have necessitated the use of "furnace temperature"  $T_F$  in the boundary equations, as described in Section 6.3.

$T_F$  is a temperature affected by all the walls, roof, hot gas and flame temperatures, and is measured by inserting a thermocouple into the furnace from the roof, protruding about 6" inside the furnace. The furnace temperature profile is obtained by placing seven of these roof thermocouples along the length of the furnace.

For measuring slab temperatures accurately, it is found that a thermocouple in close contact with the slab is the only way, particularly for slab temperatures below the surface. The temperature distribution in the x and z directions is measured

by inconel sheathed chromel-aluminal thermocouples trailing through the furnace, with junctions imbedded in the parts of the slab where temperature measurements are required. Temperature in the y-direction is measured by continuously feeding thermocouple leadwires to the furnace as the test slab with the imbedded thermocouples is pushed through the furnace with the other slabs. The slab centre temperature is checked by inserting a thermocouple probe through the furnace side doors into a hole drilled in the side of the test slab to the point where one of the trailing thermocouples is imbedded.

This method proves to be very accurate and reliable, but unfortunately the furnace atmosphere is very corrosive, particularly when firing oil containing sulphur. Unsheathed heavy gauge chromel-aluminal thermocouples fail within half an hour and inconel sheathed thermocouples break down within 1½ to 2 hours. The thermocouples generally fail at about 2,400°F. Hence, for very thick slabs of residence time longer than 2 hours the tests are unsuccessful. But for a test slab of 6" thickness a good set of results is obtained. This test involves a specially prepared carbon steel slab of known quality and dimensions. Small holes are

drilled on the surface to various depths at two locations. One location is remote from the skid contact points and the other location is directly above the skid contact points. Into each hole is inserted a  $\frac{1}{8}$ " diameter inconel sheathed thermocouple in close contact with the metal at the bottom of each hole. The thermocouples trail along the furnace as the test slab is pushed, and the signals are recorded on a multipoint recorder as well as a magnetic tape recorder through a reed relay scanner and an amplifier.

The results show that near the centre of the slab, the effect of the temperature dependent thermal conductivity  $K$  and specific heat  $C_p$  becomes more prominent. The  $y$  temperature profile has a pronounced dip around the transformation point.

This set of results is the one used for checking the theoretical results. The results do not have complete agreement, but they do show that Equation 6.47 is considerably more accurate than Equation 6.46 which is the one commonly assumed to be correct. They also show that the boundary condition Equation 6.57 is correct while the coefficient of heat transfer by Heiligenstadt, Equation 5.14, is the more accurate one.

## CHAPTER 7

SKID MARKS PROBLEM

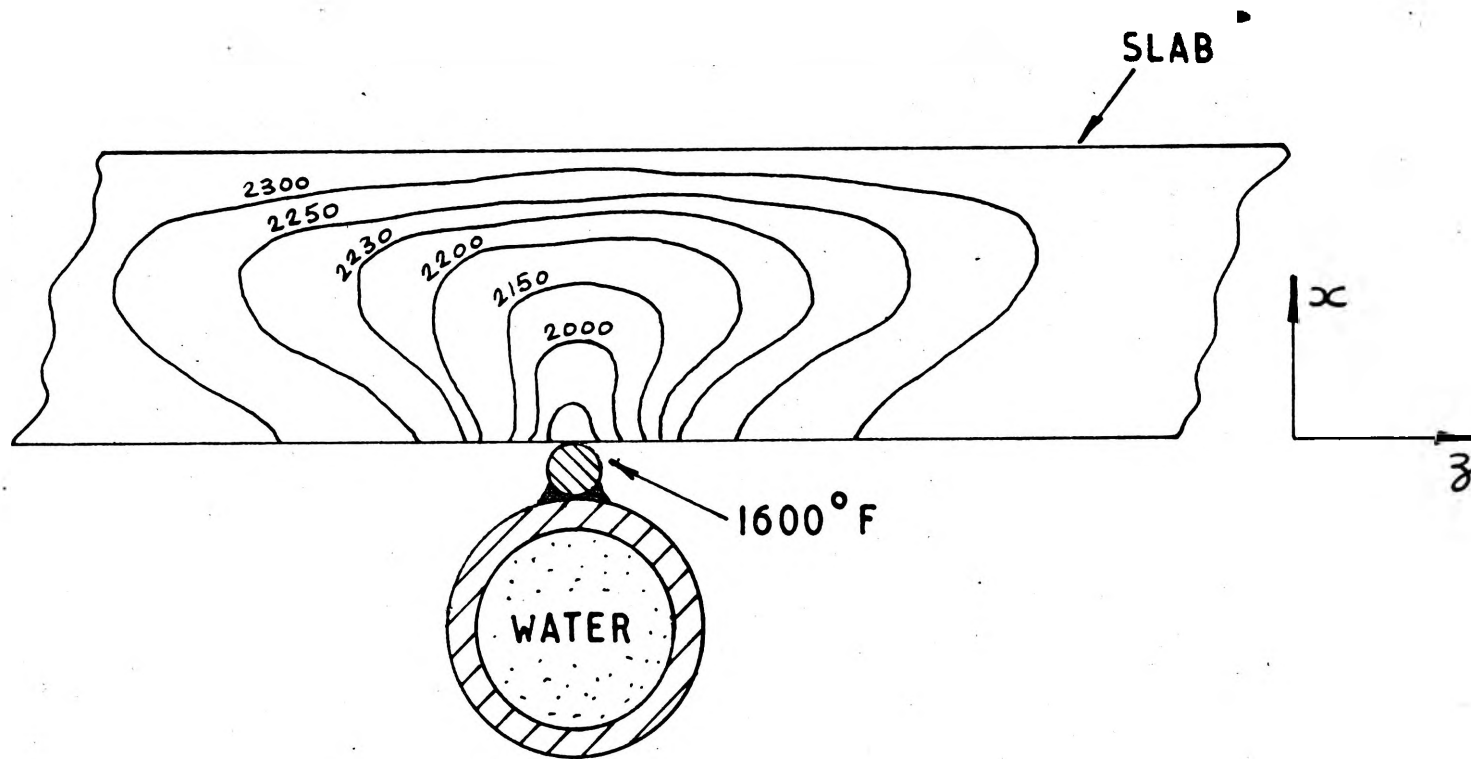


FIG. 7-1 SKID MARK TEMPERATURE DISTRIBUTION  
 CROSS SECTION OF SLAB AND SKID IN THE  
 TONNAGE ZONE BEFORE ENTERING THE SOAK  
 ZONE HEARTH SHOWING TYPICAL ISOTHERMAL  
 LINES.

## 7.1 INTRODUCTION

Skid marks problem is a major problem requiring some concentrated investigation. No detailed treatment is intended in this thesis, but, as it is an important constraint in the temperature control problem, it is briefly treated here.

Small furnaces for small billets are generally single-sided firing type. But for thick slabs and large blooms, double-sided heating is required. The slabs are supported on four longitudinal skid pipes which are water cooled (see Fig.7.1). The longitudinal skids are supported by cross skids which are in turn supported by vertical standpipes, all water cooled. The contact points between the slabs and the skids leave cold patches of "skid marks" on the bottom side of the slabs. If these skid marks are not removed before rolling, the finished plates or strips will be uneven.

Hence, a soaking zone is provided to soak out these skid marks. When a slab enters the solid hearth of the soaking zone, the skid contact points come into contact with either stainless steel solid skids or magnesite fillings. It has been found that just before entering the soaking zone, the

temperature at the skid contact point can be as low as  $1,600^{\circ}\text{F}$  compared to  $2,300^{\circ}\text{F}$  surface temperature away from the skids.

The length of the soaking zone is fixed and limited. Hence, in the temperature control problem, the optimum pushing rate for any condition is always constrained by the minimum soaking time required for the slabs.

Calculation of this minimum soaking time for each different type and thickness of slabs is the main task here. Fortunately, the analysis is a great deal simpler than the temperature control problem, because the thermal properties above  $1,600^{\circ}\text{F}$  are fairly constant for most steels. Hence the simpler treatment using thermal diffusivity value  $\alpha$  can be used. Also, the temperature in the soaking zone is fairly constant and hence it is not necessary to consider actual physical location of the slabs with respect to the furnace temperature profile. As the rate of heat loss through the soak zone hearth is very small compared to the rate of heat input to the slab, the skid marks heat transfer can be closely approximated by pure conduction of heat from surrounding steel (of the slab) to a cold spot in the  $x, z$  plane.

Another serious problem introduced by the water cooled skid pipes and standpipes is the shielding effect. The maze of water cooled pipes in the lower tonnage and primary zones form a fairly extensive heat absorbing dark shield between the bottom steel surface and the flame and furnace environ. This introduces inaccuracy in the assumptions of Chapter 6 that furnace temperature  $T_F$  is a good representation of the temperature of the heat-emitting furnace environ. As the skid pipes and standpipes are much darker and colder than the slabs (generally about 500 to 600°F), they absorb heat at a much faster rate than the slabs. However, this makes the problem far too complicated and is not treated in this thesis.

During experiments and observations carried out on the furnace, it is observed that this constraint is very severe. During at least 50% of the test periods, the limitation to pushing rate is constrained by this soaking time.

This indicates that there is a severe shortcoming in the design of the furnace itself, and is not really a control problem. But once the furnace has been built, all problems become part of the control problem, and have to be overcome by



the control system.

The real solution to the skid mark problem is in eliminating or minimising it before it is formed. Several methods have been tried to eliminate the problem. The walking-beam type furnace is designed to produce no skid marks, but is not in wide use because of higher cost of construction and operation. Staggered skids are tried by Hollander (21) but with no success. Skid insulation has been tried very widely, but with only limited success. The insulations generally stay on for a maximum of several months before crumbling due to high temperature and hot gas impingement. Two methods of reducing skid marks and saving considerable amount of fuel are proposed and described in this chapter and Chapter 9.

## 7.2. LITERATURE SURVEY

Very little previous work has been done on this subject, compared to the large amount of papers written on automatic gauge control of the hot rolling mill to overcome the same problem. This is another example of trying to develop complicated

control techniques to overcome a problem and not carrying out some simpler and more fundamental work in curing it at the source.

El-Waziri (65) pioneered the work in 1961 by publishing a theoretical study of the problem and the effect of staggering the skids. He concludes that by laterally displacing the longitudinal skids by 6" over the last 106" of the skids run, the maximum temperature difference can be reduced by about 80%. However, no experimental work was carried out to support the claim, and too many simplifying assumptions are made. He assumes that only radiation heat transfer is involved, hence using the incorrect coefficient of heat transfer. He does not consider the shielding effect the skids have on the bottom surface of the slabs, and that the slab surface does not lose heat by radiation to the much colder skid pipes. He also assumes that  $K$  and  $C_p$  of the slabs are independent of temperature. This introduces considerable inaccuracies. But his work is an interesting introduction to the problem.

No follow-up work appears to have been done until 1968 when Hollander (21) carried out some experiments to test El-Waziri's claims, but

found that no improvement was noticeable until the lateral displacement reached about 12". This large displacement is not acceptable because it would introduce difficulties in the determination of slab lengths to prevent it bending in the middle or falling off the skids. Hollander's work proves that staggered skids are impractical to implement, but does not propose any alternative solution.

The only other significant work done on the skid marks problem is by Salter (64) in 1968. Salter theoretically analyses the problem and studies the effects of skid pipe diameters, skid rail materials and whether the skid pipes are insulated or not. His analysis is quantitative but he has used it in a strictly qualitative manner, possibly because of the inaccuracies introduced by the assumptions. He treats the two extremes only for each case. The thermal conductivity of the skid rails is considered to be either that of mild steel or zero. The skid pipe diameter is considered to be either 4" or 16". The skid pipe is considered to be either absorbing all incident radiation and emitting none, or is in perfect equilibrium with the slab surface. From this analysis he concludes that:

1. The most significant of the three factors is the shielding and shadowing effect of the skid pipes. The smaller the skid pipe diameter the smaller is the effect on the slab.
2. An insulated skid pipe results in less skid marks.
3. The thermal conductivity and contact resistance of skid rails only results in small variations of the skid marks and localised in a small region around the contact point.

The second conclusion is a well known fact, but the first and third conclusions have not been very obvious. It has been the common belief that heat loss by conduction is the main cause of skid marks rather than the shielding effect.

### 7.3 FORMULATION AND SOLUTION OF EQUATIONS

To calculate the detailed temperature distributions around a skid mark involves lengthy calculations such as those carried out by El-Waziri

and Salter. But these would only be needed for evaluation of skid performances and for design of new types of skids. In a control problem, the furnace and skids are generally already in existence. Hence there is only one condition of skid diameter, insulating material and skid rail material. Small variations in pushing rate do not significantly affect the temperature distribution around the skid marks. The problem can be reduced to one of calculating the time required to soak out skid marks of known temperature distribution before entering the soak zone. The variation in slab thickness can be dealt with by varying the soaking time in proportion with the total heating time required for each slab thickness. That is, consider the soaking time as a fixed percentage of the total heating time of each slab. This is an approximation, but can be checked and corrected by actual measurement of skid marks temperatures for various thicknesses of slabs. It can also be double checked by actual rolling experience of the rolling mill operators.

Following the same derivation procedure as in Section 6.4, and disregarding the slab velocity term as the temperature in the soak zone is

fairly uniform, we arrive at the following equation:

$$\rho c_p \frac{\delta T(x, z, t)}{\delta t} = K \frac{\delta^2 T(x, z, t)}{\delta x^2} + K \frac{\delta^2 T(x, z, t)}{\delta z^2} \quad (7.1)$$

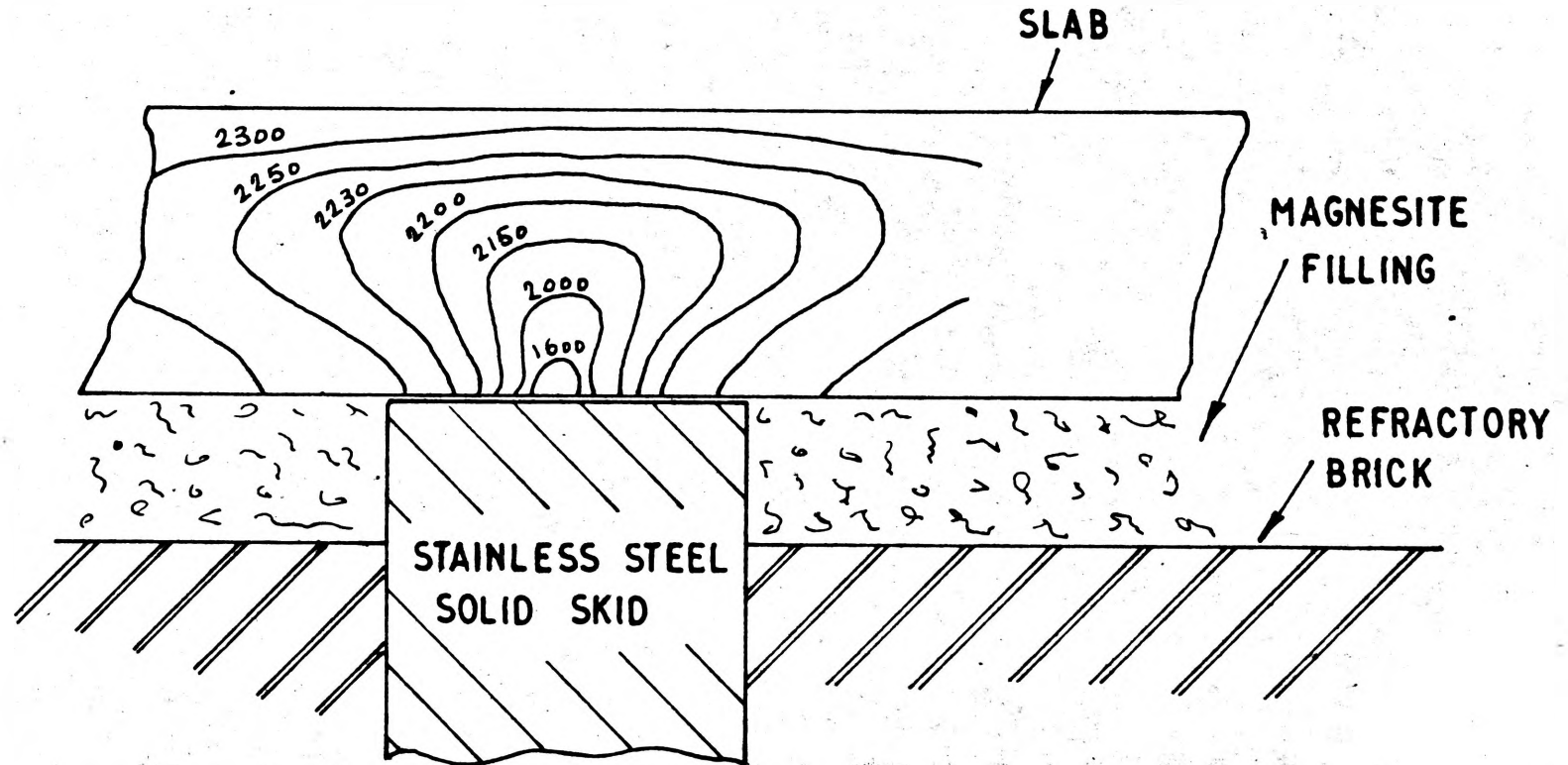
From Section 6.2 it is apparent that thermal properties of nearly all steels above 1,600°F are fairly constant. As the coldest point of the skid marks has been found to be above 1,600°F, constant thermal properties can be assumed and Equation 7.1 becomes

$$\frac{\delta T(x, z, t)}{\delta t} = \alpha_1 \left[ \frac{\delta^2 T(x, z, t)}{\delta x^2} + \frac{\delta^2 T(x, z, t)}{\delta z^2} \right] \quad (7.2)$$

where  $\alpha_1$  is mean thermal diffusivity for each type of steel between 1,600°F and 2,540°F.

Thus, the problem reduces to that of solving a simple two-dimensional heat conduction equation with constant thermal diffusivity and without the complications of velocity terms. No solution of Equation 7.2 will be given here as it has already been solved by Douglas and Peacemen (53).

Fig.7.1 shows a typical skid mark temperature distribution just before the slab enters the



**FIG. 7.2** SKID MARK TEMPERATURE DISTRIBUTION  
IMEDIATELY AFTER THE SLAB HAS  
ENTERED THE SOAK ZONE HEARTH.

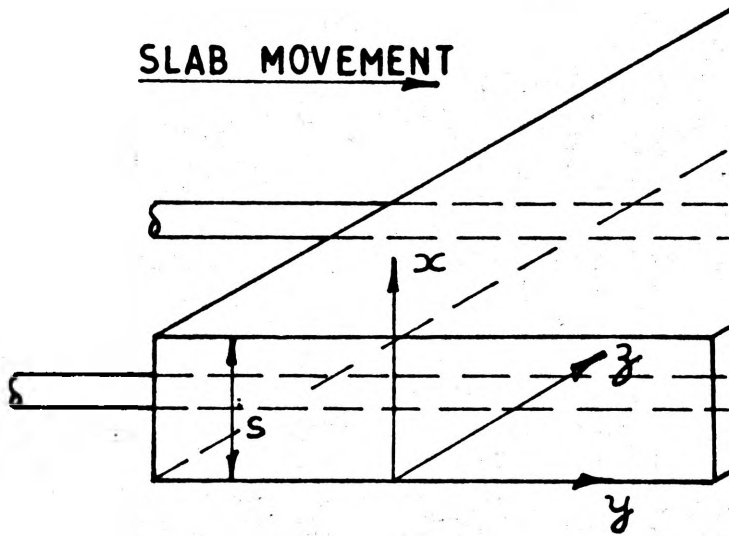
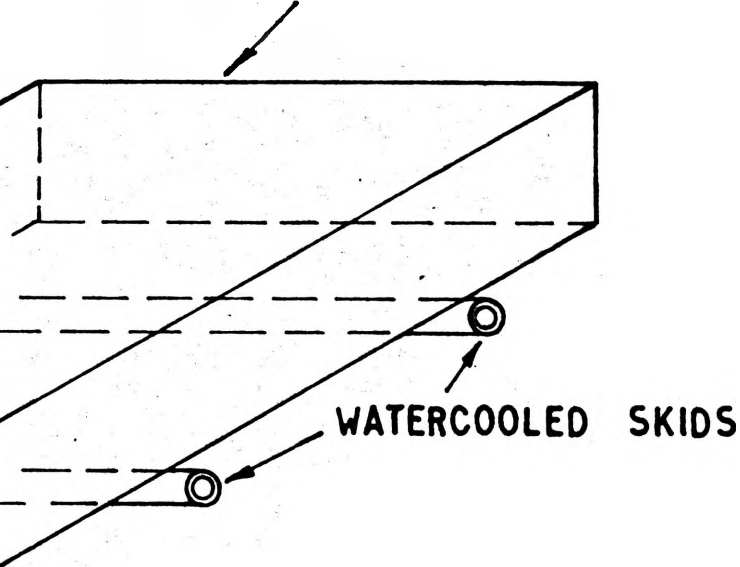


FIG. 7.3 LONGITUDINAL SKIDS  
IN TONNAGE ZONE.



STEEL SLAB



WATERCOOLED SKIDS

SHOWN SUPPORTING A SLAB

soak zone, as determined by Salter. Fig.7.2 shows the same slab just after it has entered the soak zone. Fig.7.3 shows the general arrangement of longitudinal skids supporting a slab.

The boundary condition for the top surface of the slab is still the same as before. That is, Equation 5.17. But  $T_F$  in this case is almost completely independent of time. As there is no heat source in the hearth, and the stainless steel solid skids are also supported by insulating brickwork, the lower boundary condition can be considered as an insulating medium.

#### 7.4 METHODS TO MINIMISE SKID MARKS

Various methods have been tried to minimise the skid mark problem but so far none have been completely successful.

As described in Section 7.2, El-Waziri's conclusion on staggered skids has been found to be in error by Hollander's experiments which show that a displacement of 6.7" over the last 200" of the skid length does not produce noticeable improvement. This may be due to the numerous simplifying assump-

tions used, as described in Section 7.2. Also, in order that the slabs can still be adequately supported by the skids, at least one additional longitudinal skid has to be added. To give the skids sufficient strength to withstand the longitudinal frictional force when slabs are being pushed, larger cross skids with larger and more numerous stand pipes have to be provided. This introduces more shielding and thus results in more skid marks, cancelling the benefits of staggering the skids. Hence, even if the staggered skid method had been theoretically sound, it is not possible to achieve the benefit in practice due to the difficulty of mechanically providing support. Conventional longitudinal skids are supported by the soak zone hearth where they terminate. The staggered skids have to be supported by the cross skids.

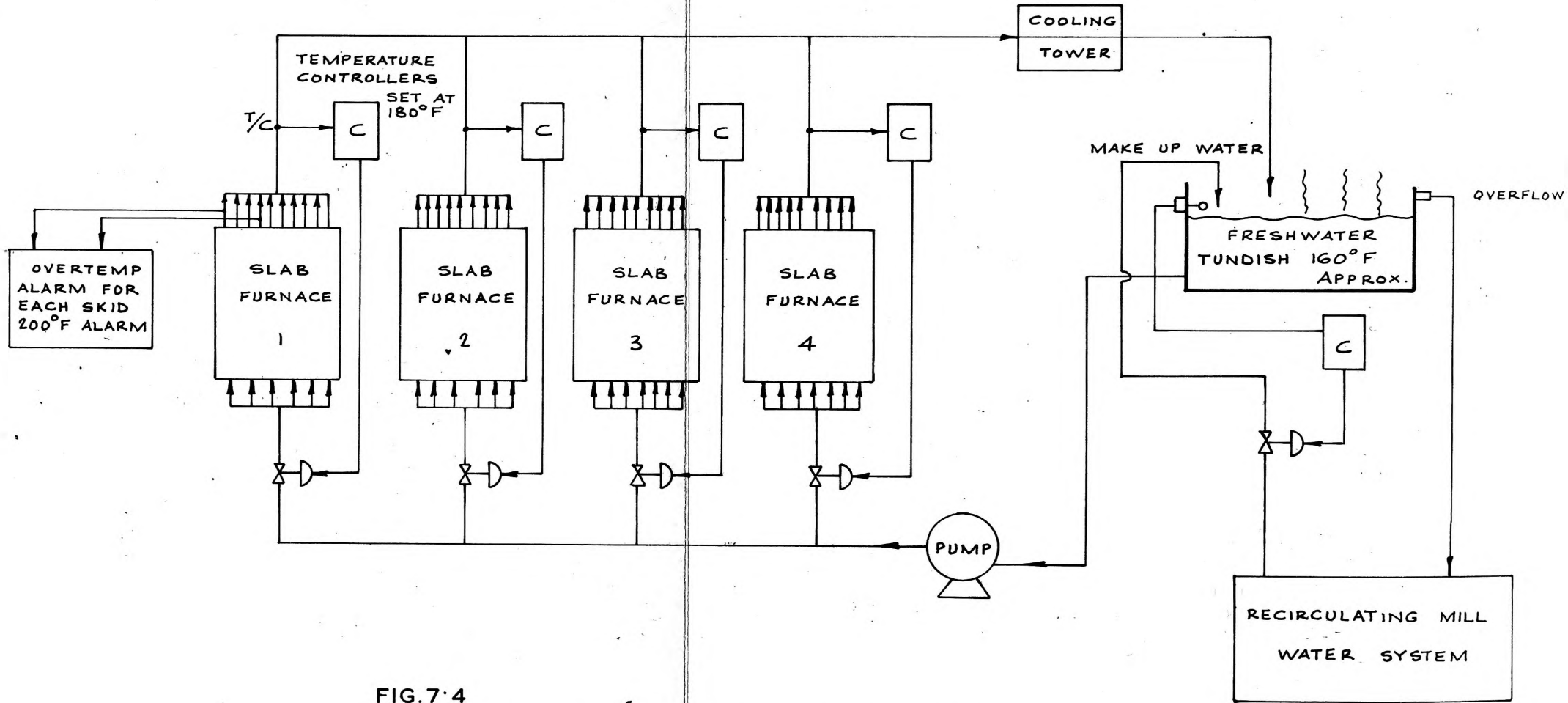
One method which has had limited success is the insulation of the skids with insulating materials. Stand pipes are insulated by brickwork. Cross skids and long skids are generally insulated with reinforced asbestos type materials. Apart from parts of cross skids where they do not make contact with longitudinal skids and stand pipes, the insulating materials cannot completely encircle

the skid pipes. Hence, although reinforced, it still lacks clinging power, particularly in the Lower Tonnage Zone where the temperature is very high and it is subjected to severe flame impingement. The life of the insulating material in the tonnage zone where it is most needed is generally from several days to a maximum of four months. Because of the high cost of stopping production once the insulation falls off, it is not replaced until the furnace is stopped for other major repairs.

Increasing the temperature of the skid coolant has been considered by El-Waziri (65) in his theoretical study. He concludes that the maximum temperature difference of the skid marks will decrease by 10% for every 200<sup>o</sup>F increase in coolant temperature. This result has not been tested experimentally, but as he does not consider the shielding and shadowing effect of the skids, it is likely to be inaccurate. Nevertheless, the increase in coolant temperature must increase the external surface temperature of the skids and the temperature of the skid rails. Hence it can still be reasonably assumed that considerable advantage can be derived from increasing skid coolant temperature. The practical implementation of this is not

simple. Saltwater is the most frequently used coolant, and its temperature is limited to  $130^{\circ}\text{F}$  as the rate of saltwater attack on mild steel increases sharply at temperatures above  $140^{\circ}\text{F}$ . Freshwater can be used for up to  $180^{\circ}\text{F}$ , and treated boiler quality water can be used up to boiling temperature. Air cooling can bring the temperature possibly to  $1000^{\circ}\text{F}$ , but this may reduce the physical strength of the skids. Further work has to be done to determine the temperature limit of the coolant before the physical strength of the skids is reduced requiring larger skid diameter.

Freshwater cooling has so far not been contemplated where saltwater is available because freshwater is costly, and it would require a recirculation system with cooling tower, filtration circuit, etc. Initial cost of implementation is high and the benefit has not been clear so far. However, even though the benefit to skid marks reduction is uncertain, the benefit from reduced heat loss through cooling water is very large. The normal 4 or 5-zone furnace loses approximately 20 to 30% of its total heat input through the cooling water. The fuel consumption is of the order of \$1,000,000 per annum per furnace. In Section 9.4



**FIG. 7.4**  
**PROPOSED FRESH WATER COOLING SYSTEM**  
**SLAB FURNACES.**

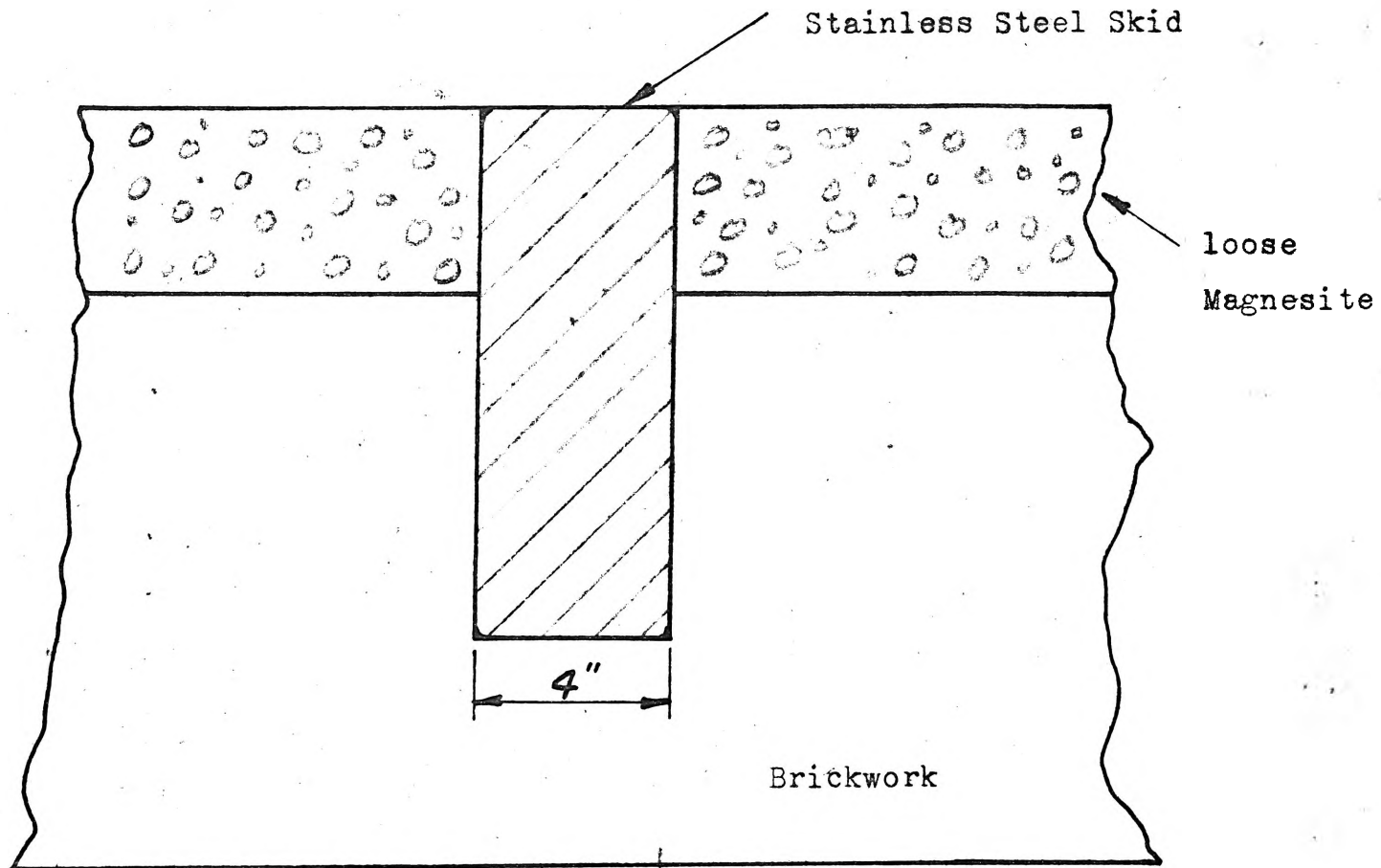


Fig. 7.5 Cross-section of present arrangement of Solid Skid in Soak Zone Hearth.

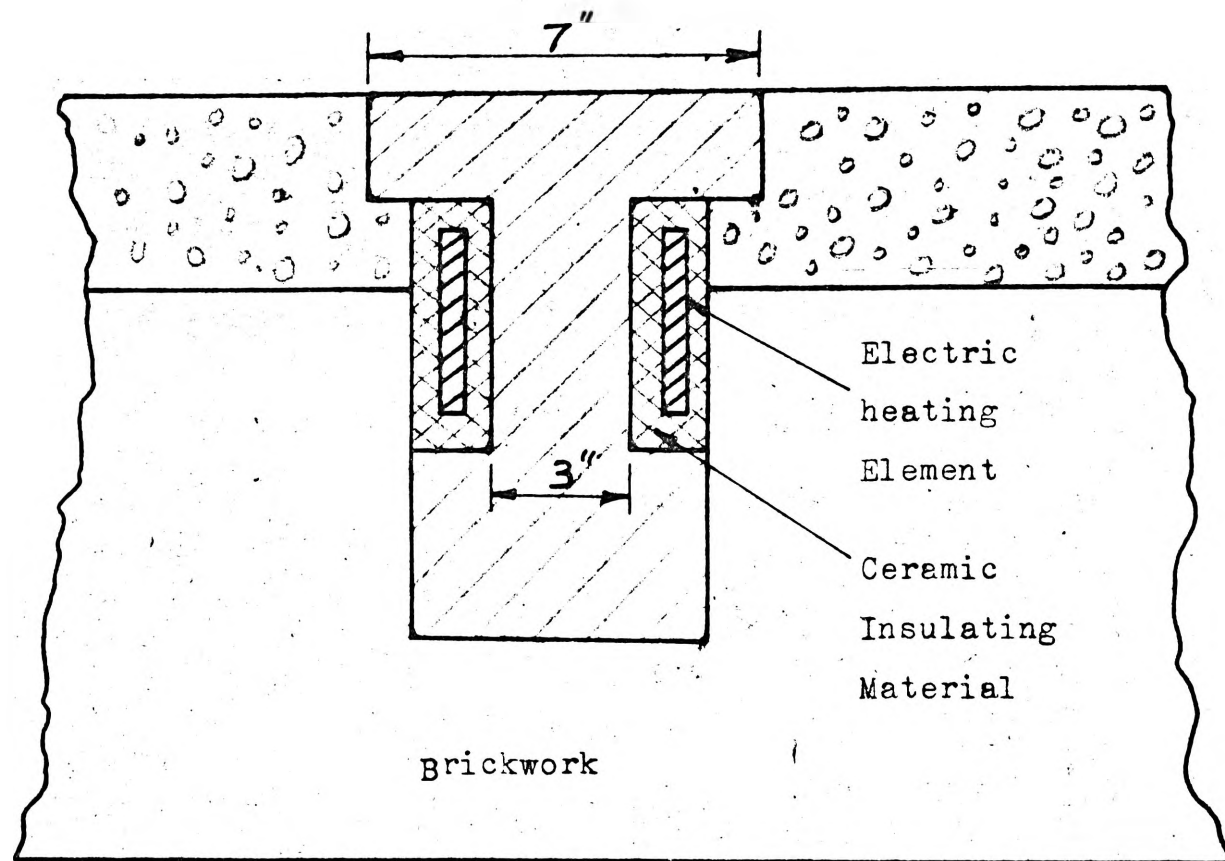


Fig.7.6 Proposed heated Solid Skid arrangement showing Heating Elements and wider Contact Surface.



a proposal is put forward to install a multi-furnace freshwater cooling system that has the potential of reducing heat loss through water by 50%. Fig.7.4 shows a simplified system applied to the four furnaces of the hot strip mill.

Although the soak zone hearth is assumed to be an insulating medium, this is not strictly true because the solid skids are conductive and conduct heat away from the slabs. The present practice is to stagger the solid skids so that they come into contact with skid marks as little as possible. Underhearth burners have been tried but found to be impractical due to the costly design of the hearth and difficulty of maintenance.

One simple method that has not been considered is to leave the solid skids unstaggered and exactly in line with the water cooled longitudinal skids. They are converted from heat sinks to heat sources by the addition of electric heating elements. Fig.7.5 shows the cross-section of a conventional solid skid arrangement. Fig.7.6 shows the cross-section of proposed heated and unstaggered solid skids with heating elements and wider contact surface. The amount of heat required is very small as it is only required to compensate for a small

amount of heat loss through the hearth brickwork and to supply some heat to the skid marks.

Maintenance will be minimal as the skids no longer require to be narrow. They can be made much larger and be firmly fixed in the hearth. They can be made into one piece, instead of three or four short sections for the purpose of staggering.

## CHAPTER 8

IMPLEMENTATION OF CONTROL ALGORITHMS

Due to inexperience with this type of on-line computer control work and the incompleteness of some parts of the investigation, the implementation has been planned in several stages. As each stage is completed, it is used for a period to familiarise the operators and to ensure that all possible contingencies have been covered. This is necessary as the computer communicates with the operators and receive some manually entered data.

The different stages are as follows:

Stage 1. Datalogging Stage

No control action is taken by the computer initially. A simplified version of the data input station is used so that the operator only has to enter the weight of each slab discharged. This and the analog input signals are used by the computer to calculate the thermal efficiency and other performance indices. These are logged on the typewriter together with all the analog inputs. The latter are used to observe the computer and instrumentation hardware performance.

Stage 2. Datalogging and Slab Tracking Stage

When the operators are familiar with the

simple data input station, the complete data input station is introduced. The program is modified to include the full slab tracking program with the necessary operator communication functions.

### Stage 3. Predetermined Set Point Operation

Stage 2 has ensured that the operators are familiar with the computer system and that the computer has available all the information required for control. The next stage is to ensure that the computer system as a whole operates sufficiently reliably to permit continuous on-line control of the furnace. Predetermined air/fuel ratios, steam/oil ratios, furnace pressure and zone temperatures for different levels of pushing rate and slab dimensions and types are prepared in a table and used by the computer in setting all the controller set points. This is a relatively safe method of operating the furnace. During this period all the safety precautions, shut-down and start-up safety procedures, etc. are evaluated and modified if necessary. Even though the efficiency is not optimised, steady operation is achieved and some benefit in fuel saving should be obtained.

#### Stage 4. Heat Balance

While Stage 3 is in operation and showing little problem, a further function is added to the computer system. The computer monitor system is extended to carry out simultaneous multiple teletype operation, and a complete heat balance calculation program is added. The continuous heat balance log enables work on the cooling water system to progress as described in Section 9.4. Work on optimum slab length determination can also be carried out as described in Section 9.7.

#### Stage 5. Thermal Efficiency Control

When the operators' acceptance and the reliability of the computer system and instrumentation have been proven by prolonged operation of Stage 4, the final thermal efficiency optimising control can be implemented. This efficiency program is briefly described in Section 3.4 and detailed in Appendix 9. The datalogging and heat balance calculation program is still incorporated. During this stage, the operators still have to determine and set the zone temperature set points, but all the others will be set by the computer.

### Stage 6. Efficiency and Simple Temperature Control

While prolonged trial of Stage 5 is under way, work can proceed on off-line calculation of heating times required for different slabs, and also the minimum soaking times. In conjunction with furnace operators and combustion engineers, a strategy for temperature profile setting can be determined for various slab thicknesses. Using all this information, a simple temperature control program can be prepared without a great deal of time and computer memory capacity. This program functions on the basis of searching through prepared tables for information, then using the information to set the temperature profile and advise the operators whether or not the slab to be discharged is ready.

### Stage 7. Efficiency and Temperature Optimising Control

This final stage of the implementation program includes everything in Stage 6, but the predetermined temperature profile setpoint table is replaced by a table constantly updated by an optimising control program.

During the implementation, many more difficulties were encountered than initially anticipated. Most of the problems occur in providing the computer with accurate and reliable information, and also in the long term reliability of the computer itself. It is easy to develop a system to operate for a few weeks in a laboratory but a system that has to operate continuously becomes more complicated as all sorts of precautionary measures must be included in case the computer receives erroneous signals or there is some computer hardware failure causing mistakes in the calculations, etc. Some of these difficulties are described in Sections 2.3 and 3.4, but others will not be elaborated in this thesis.

At present, implementation has reached Stage 5. Completely reliable long term operation has not yet been obtained due to frequent computer hardware difficulties. Proper assessment of the benefits obtained by computer control cannot be made until more long term on-line control by the computer has been achieved. However, the present indications show that when the two slab furnaces No.1 and No.2 are operated in parallel with the same loading, the computer controlled No.2 furnace



is more efficient by a margin of up to 21%.

Work on Stage 6 has commenced, but it is proceeding very slowly and is considered a low priority job. The Plate Mill, having just obtained another furnace, does not as yet have heating capacity problems. Hence, the optimising temperature control will not have significant effect. Other work with much larger return/effort ratio, such as the freshwater skid cooling system, efficiency control of soaking pits, etc. are rating higher priority. Also, Stage 6 may require more memory capacity as there are only about 3K words left after implementing Stage 5.

Stage 7 is still in the conceptual stage. Its implementation will certainly require additional memory for the computer. When the second stage of the Plate Mill is fully commissioned and the mill is operating at full capacity, Stages 6 and 7 will be implemented as the furnaces will again become the bottleneck.

## CHAPTER 9

RECOMMENDATIONS FOR FURTHER WORK

## 9.1 THERMAL PROPERTIES OF STEEL

As described in Section 6.2, very little work seems to have been done on the thermal properties of steels. This may be due to the low glamour profile of the subject. Most research workers prefer the glamorous topics such as "optimal control", "pseudorandom signals", etc. The more basic but more urgently required work such as the thermal properties of various steels have been sadly neglected.

A great deal of systematic work, such as the work done by Unimo (31) in 1926 on some carbon steels, has to be done on a whole range of new types of carbon steels and low alloy steels which have come into wider use since the 1950's.

## 9.2 SOLUTION OF THICK SLAB EQUATION

The solution of the thick slab equation with temperature dependent thermal properties as described in Section 6.5.1 still needs improving as there are still discrepancies between the theoretical solution and experimental results. This is not

carried out here due to the limited scope of the thesis. This thesis is an exercise in furnace control while the more accurate solution of the equations is strictly speaking an Applied Mathematician's project.

It is therefore recommended that control engineers concentrate on some of the more useful and down-to-earth control problems and let the Applied Mathematicians help in the use of complex mathematical techniques for solving some of the complicated equations.

### 9.3 SKID MARKS CALCULATION

The skid marks problem has been described in Chapter 7 and the skid marks calculation equation presented but not solved. The solution of the equation is simple and has been described by Douglas and Peaceman (53). However, a great deal of hard work is still needed to solve the problem using various boundary conditions and for different types and sizes of slabs, skid rail materials, skid diameters, etc. A comprehensive table needs to be prepared showing the minimum soaking time for each

type and size of slabs for each furnace. This table can then be stored in the control computer's memory as the skid marks constraint.

#### 9.4 FRESHWATER SKID COOLING SYSTEM

Nearly all known reheat furnaces near coastal areas use saltwater for skid cooling because of the apparent economy of saltwater. But the rate of saltwater attack on steel pipes increases rapidly above the water temperature of 140°F. So the saltwater outlet temperature is usually kept below 120°F. Also, the saltwater often carries with it marine life and plants, causing blockages in the pipes. Hence the water flow must be maintained at a fairly fast rate. For these reasons, most saltwater skid cooling systems are devoid of any instrumentation and the valve in each skid pipe is just fully opened to allow full water flow. The average temperature rise is about 15°F with a total water consumption of about 6,000 gallons per minute.

The present plate mill slab reheat furnaces are losing approximately 20 to 30% of their total

heat input through cooling water. At the present fuel consumption rate of approximately \$1,000,000 per furnace per annum, this represents a loss of \$200,000 to \$300,000 per annum plus a cost of \$50,000 per annum for the cost of pumping the saltwater.

The proposal shown previously in Fig.7.4 suggests the use of freshwater in a recirculation loop with water temperature up to about 180°F. The capital expenditure is high at about \$150,000 for four furnaces, but the potential saving is extremely attractive. It is estimated that this system would reduce heat loss by up to 50% and also reduce the operating cost by 50%. That is a possible total saving of approximately \$150,000 per annum per furnace.

The freshwater can be heated up to a maximum of 180°F without any adverse effect on the steel pipes, and being clean and filtered can tolerate much lower rate of flow. The increase in water temperature will increase the external skin temperature and reduce heat absorption. The lower water velocity will reduce the coefficient of heat transfer between steel pipe and water and further reduce the heat absorbed by the water.

Equation 9.1 gives the coefficient of heat transfer between steel pipe and water for turbulent flow.

$$h_s = \frac{0.023 K_w}{D} \left[ \frac{D V \rho_w}{\mu_w} \right]^{0.8} \left[ \frac{C_{p_w} \mu_w}{K} \right]^{1/3} \quad (9.1)$$

where  $K_w$  = thermal conductivity of water,  
BTU/ft<sup>2</sup> hr °F

$D$  = pipe internal diameter, ft

$V$  = water velocity, ft/hr

$\rho_w$  = water density, lb/ft<sup>3</sup>

$\mu_w$  = water viscosity, lb/ft hr

$C_{p_w}$  = water specific heat, BTU/lb °F

$h_s$  = heat transfer coefficient, BTU/ft<sup>2</sup> hr °F

It can be seen that changes in water velocity produce almost the same proportion (0.8 times) of changes in the  $h_s$ .

The system in Fig.7.4 shows the system as applied to the four furnaces at the hot strip mill. Similar systems can be designed for the two furnaces at the plate mill. The system provides temperature alarms on each skid pipe water outlet to enable flow in each to be manually adjusted to correct values. The total water flow to each

furnace is controlled to give a constant mean water temperature.

A further advantage of this system is the possibility of increasing the life of skid pipe insulating material giving more savings and less skid marks. The main reason for insulation failure is flame impingement and thermal fatigue. When the furnace varies between fast and slow pushing, the amount of flame and heat produced vary accordingly. Hence the insulation is subjected to varying intensities of heat. But the saltwater flow rate remains unchanged, so the water temperature changes, absorbing more or less heat. If the water flow rates are altered to maintain the temperature constant, the temperature fluctuation experienced by the insulation will be reduced.

With the computer on line it will be easy to check this theory. First the computer should be switched to performing heat balance calculations only, giving regular print-outs of heat loss through cooling water. Then, with a team of experimenters watching the tundish where all the skid pipes terminate, the skid pipe valves are throttled back one by one to an average temperature of about 150°F. This temperature is maintained for one hour and then



returned to the original condition. Comparison of the water heat loss during high temperature and low flow period with normal period will reveal the extent of savings. High temperatures of 150°F for short terms should not damage the skid pipes.

#### 9.5 HEATING OF UNSTAGGERED SOLID SKIDS

Heating of unstaggered solid skids has been described in Section 7.4. While the freshwater cooling system reduces the skid marks slightly and saves large amounts of fuel, the heating of solid skids does not save fuel but has great potential in completely deleting skid marks as a constraint. Further experimental and theoretical work should be carried out to check the validity of the proposal before actual implementation. The following work is recommended:

- (a) Experimentally measure the solid skid temperature gradient from top to bottom for various conditions of slab thicknesses and pushing rates;
- (b) Calculate heat loss through solid skids;

- (c) Assuming the skid marks are directly in contact with an infinite heat source at  $2,200^{\circ}\text{F}$ , solve Equation 7.2 again and see how much improvement is obtained in the required soaking time;
- (d) Calculate the required heating capacity of the heating element;
- (e) Design solid skids construction details and make two for trial.

#### 9.6 OPTIMUM SLAB THICKNESS DETERMINATION

The control problem is considerably complicated by the enormous variety of slabs supplied to the furnace. The slab thickness changes from 4" to 12". There are also two major reasons for this. The first is that the plate mill is the only wide plate rolling mill in Australia. There are large numbers of different plates to be rolled. The second is that there is no clear idea of what relationship slab thickness has with pushing rate (i.e., heating rate) and with thermal efficiency. If this relationship can be found and the optimum slab thickness (or a range of thicknesses) determined, the variation in slab thickness will decrease

and the control will be easier.

By solving the slab heating models on a large off-line computer, (i.e., Equations 6.46 and 6.47) it is possible to calculate the times required for slabs of different thicknesses to be heated to target, taking into account all the constraints such as zone temperature limits, mill rolling speed limits, skid mark soaking time, etc. If these are plotted against slab thickness the plot will reveal whether an optimum slab thickness exists.

Another way of determining optimum slab thickness is to gather large amounts of half-hourly computer print-outs of slab thicknesses and efficiency. Then carry out a correlation analysis which should reveal the optimum thickness if there is one.

## 9.7 OPTIMUM SLAB LENGTH DETERMINATION

Slab length does not affect pushing rate, but affects thermal efficiency. Slab length is actually a measure of the effective coverage of the furnace area by the slabs. For short slabs, there is a smaller steel surface area for receiving heat.

The flame and hot flue gas tend to heat up the walls and recuperators, thus reducing efficiency. For longer slabs, there is more steel surface area and hence better heat transfer rate and better efficiency. But if the slabs are too long and the ends become too close to the furnace walls, there will be detrimental effects of the ends not being sufficiently heated.

Experiments should be carried out to determine the optimum slab length. With the computer on line, switch to efficiency and heat balance calculation and datalogging only. Arrange for slabs to be scheduled such that different lengths of slabs are charge in different batches. Plot slab lengths against thermal efficiency and carry out correlation analysis if necessary. Thus optimum slab length can be determined.

## 9.8 CONTINUOUS SLAB THICKNESS AND PUSHING RATE MEASUREMENTS

Slab thickness and pushing rate are the most important variables for the heating control. Continuous methods must be found to measure them

and eliminate the present operator-dependent manual data input station which is the main source of error. Possible methods of measurement are as follows:

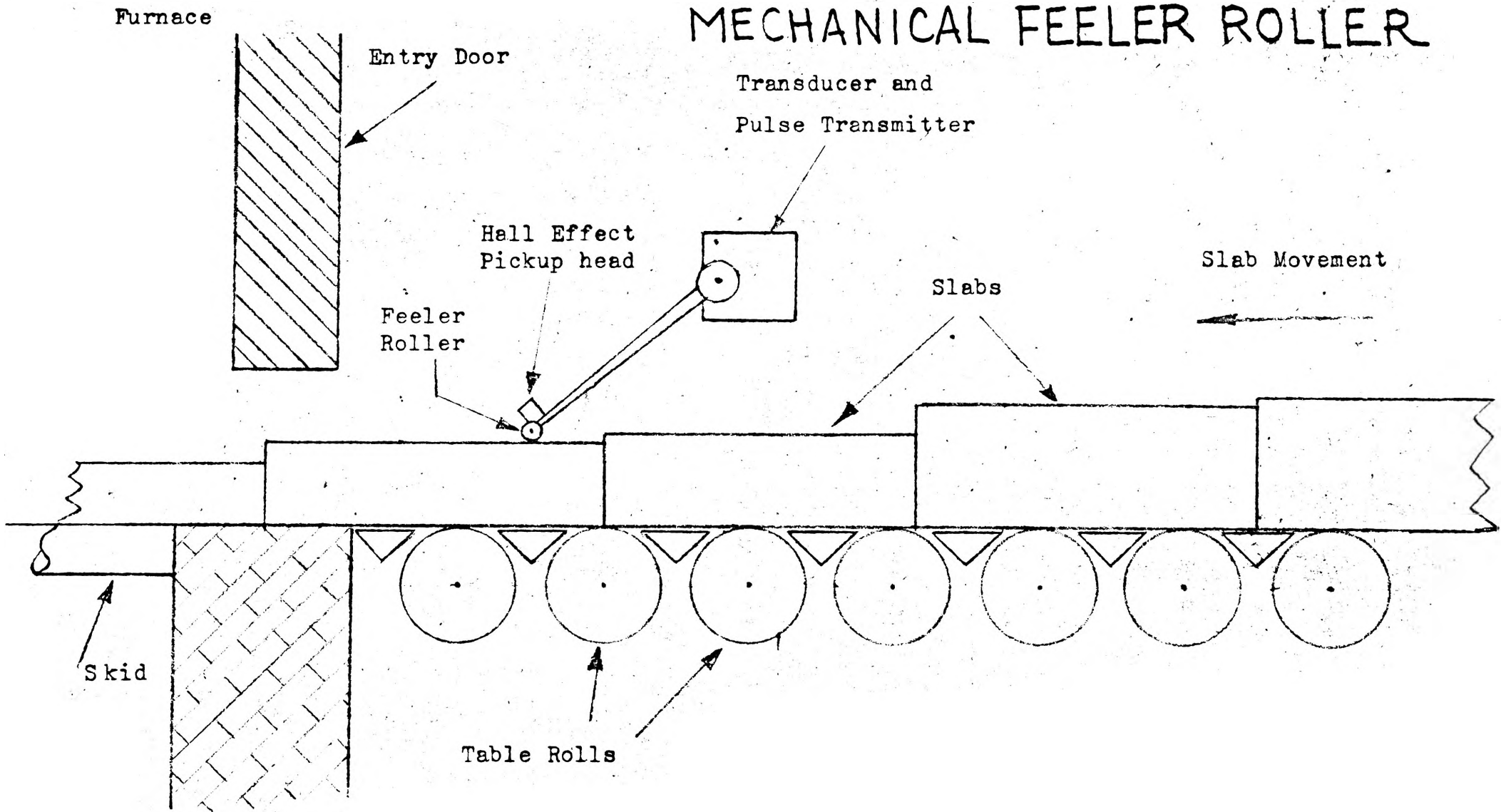
(a) Ultrasonic Detector

This method has been used successfully for gauging the depth of holes drilled from the side of the test slab during the experiment on slab temperature distribution. It is also used by the Metallurgists to detect hollow air pockets in slabs. The existing available equipment is unfortunately not for continuous measurement. The results displayed on the oscilloscope have to be manually interpreted. However, modification of the unit for continuous measurement should be possible.

(b) Laser

Used with a closed-circuit television camera, a method has been developed to use Laser for measuring the slab thicknesses continuously. Unfortunately, the price of the equipment at present is prohibitive.

# MECHANICAL FEELER ROLLER



• Fig. 9.1 Slab thickness and pushing rate measuring device •

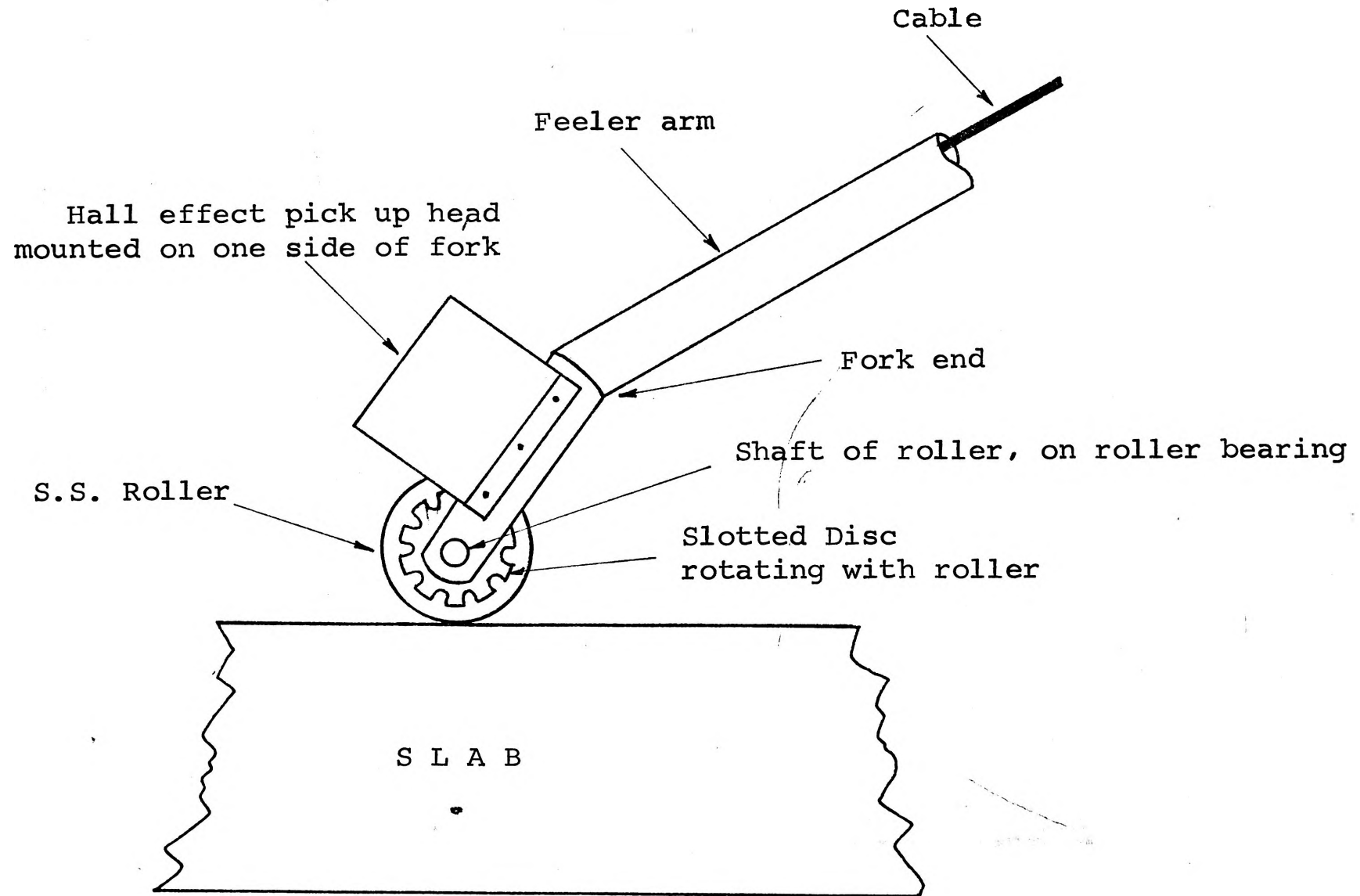


Fig. 9.2 Mechanical feeler roller close up view

(c) Mechanical Feeler

A mechanical feeler arm slanted in the direction of slab movement can be used to measure slab thickness continuously. See Fig.9.1 for general diagrammatic arrangement and Fig.9.2 for more detail of the roller at the contact point. The unit can be mounted near the furnace entry door. The rotational movement of the rod can indicate the slab thickness. The small wheel at the end of the rod rolls on the slab surface as the slab is being pushed. A slotted disc rotates in parallel with the wheel and a Hall-Effect magnetic pick-up head transmits the slab travel in terms of pulses. The computer can then easily calculate the pushing rate, and determine the slab thickness profile in the furnace. This method seems crude and has not yet been constructed and tried, but it may be the only economical way of obtaining continuously the slab thickness and pushing rate.

(d) Slab Weighing

Some overseas slab reheat furnaces have load cells on the entry charging table so that the weight of each slab can be measured and the signal used. This can give the computer weight accumulation



in the furnace and the approximate weight distribution in the furnace, but it does not give slab thickness information. The cost of implementation is also high, and suitable mainly for new plants.

(e) Slab Pusher Movement

The slab pushers are operated either to position the slabs on the charging table or to push a slab out through the discharge door. The two types of operations can be distinguished by the load on the pusher motor. Much larger current is used when pushing a slab out. Hence, if the pusher travel during this large current flow period is monitored, it gives the actual slab travel through the furnace. However, this method may prove to be unsatisfactory regarding accuracy.

9.9 TEMPERATURE DIFFERENCE BETWEEN SLAB ENDS

Slabs are rolled one end first. By the time the other end reaches the rolls, the slab temperature may have dropped. This problem is not so severe in plate mills, but can be quite significant in the hot strip mill where the time between

the front end the rear end entering the rolls can be quite significant. One possible solution is to adjust the furnace burners so that one end of the slab is hotter than the other end. Another possible solution is to screw down the rolls further to overcome the extra "spring" due to lower temperature.

It is desirable to carry out the following work:

- (a) Determine the temperature difference between two ends of each slab of different thickness and finished plate thickness;
- (b) Determine whether it is easier to correct the problem by burner adjustment or gauge control.

#### 9.10 OPTIMUM SCALE THICKNESS

If the air/fuel ratios and furnace pressure settings are incorrect, excessive scale formation occurs on the slab surface. This results in metal loss of the order of 0.5 - 3%. For a furnace heating approximately 400,000 tons of steel per year, this amounts to a loss of between 2,000

and 12,000 tons of steel per year. That is, approximately \$160,000 - \$960,000 per year.

With the efficiency optimising control, this scale loss will be considerably reduced. But the amount this can be reduced to is uncertain, and hence the savings from this cannot be calculated. Also, there is a minimum thickness of scale that is required. Below this thickness, the scale becomes difficult to remove and increases the danger of being rolled into the plate. This problem is particularly acute when the furnace heating is poorly controlled and the slab surface becomes overheated. This minimum scale thickness has so far not been determined.

Experiments need to be carried out to determine this minimum scale thickness, and to determine the amount of scale loss reduction resulting from furnace efficiency control. Determination of this reduction can strengthen the case for rapid implementation of computer control on all the other reheat furnaces and soaking pits.

CHAPTER 10

CONCLUSIONS

The problem of reheat furnace control has been studied from the angles of combustion efficiency of the furnace and temperature distribution of the slabs. Furnace parameters for efficiency control have been determined and experimentally verified for both small billet reheat furnaces and large slab reheat furnaces.

Mathematical models have been determined for the heating of billets and slabs of constant thermal properties as well as temperature dependent properties. These models are solved on a digital computer using numerical methods. Experiments were carried out to measure the temperature distribution in a thick slab travelling through the furnace. The theoretical solution corresponds fairly closely to the experimental results considering the lack of data on steel properties.

An on-line computer control system has been designed and installed on one slab reheat furnace. Implementation of control functions has reached the stage of optimising control of furnace efficiency. Economic justification for the system is based on resultant fuel saving and reduction in metal loss through scaling. At present the computer controlled furnace is operating at approximately

20% higher efficiency than the No.1 furnace alongside it, and the metal loss through scaling has been reduced from a usual 1 - 2% to 0.8%. It appears that sound economic return has been achieved by the system.

The whole question of reheat furnace control has been examined in the light of using an on-line computer system. It is found that a great deal of work needs to be done to overcome the problems encountered. Only some of this work can be considered as within the scope of this thesis. Nevertheless, a thorough understanding of furnace operation and control has been obtained, and all the necessary work to be done is described and recommended for future projects. A corollary of this investigation is the realization that a great deal can be done to improve the furnace operation and performance without the complication of mathematical model development and optimal control theories. Some simpler control techniques and sound practical engineering can give much larger benefits in a comparatively shorter time.

The computer can be used most successfully in controlling a reheat furnace, but care must be taken to provide sufficient safeguards as the

computer cannot intuitively detect faults as a human operator would. Some special interfacing equipment also has to be designed and built.

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## APPENDIX 1

ANALOG AND DIGITAL INPUTS AND OUTPUTS

ANALOG INPUT TABLE

ANALOG INPUT	DESCRIPTION	INPUT SIGNAL	INPUT EQUIVALENT	SCALE TYPE
ADC 1	S.Z. Slab Temp. - Left Hand Side	10 - 50 mV	1100 - 2600°F	4th Root
ADC 2	S.Z. Slab Temp. - Right Hand Side	10 - 50 mV	1100 - 2600°F	4th Root
ADC 3	U.T.Z. Slab Temperature	10 - 50 mV	1100 - 2600°F	4th Root
ADC 4	L.T.Z. Slab Temperature	10 - 50 mV	1100 - 2600°F	4th Root
ADC 5	P.Z. Slab Temperature	10 - 50 mV	1100 - 2600°F	4th Root
ADC 6	"Upper" P.Z. Slab Temperature	10 - 50 mV	1100 - 2600°F	4th Root
ADC 7	No.1 Furnace Slab Out, Door A	0.079 - 50 mV	1300 - 2545°F	9th - 18th Root
ADC 8	No.1 Furnace Slab Out, Door B	0.079 - 50 mV	1300 - 2545°F	9th - 18th Root
ADC 9	No.2 Furnace Slab Out, Door C	0.079 - 50 mV	1300 - 2545°F	9th - 18th Root
ADC 10	No.2 Furnace Slab Out, Door D	0.079 - 50 mV	1300 - 2545°F	9th - 18th Root
ADC 11	S.Z. Furnace Pressure	10 - 50 mV	-0.25" W.G. to +0.25" W.G.	Linear
ADC 12	P.Z. Furnace Pressure	10 - 50 mV	-0.25" W.G. to +0.25" W.G.	Linear
ADC 13	S.Z. Oxygen Analyser	10 - 50 mV	0 - 10% O <sub>2</sub>	Linear
ADC 14	"Upper" P.Z. Oxygen Analyser	10 - 50 mV	0 - 10% O <sub>2</sub>	Linear
ADC 15	Main Recuperator Stack Oxygen Analyser	10 - 50 mV	0 - 10% O <sub>2</sub>	Linear
ADC 16	S.Z. Air Flow	10 - 50 mV	0 - 400000 C.F.H.	Sq. Rt. d. p.
ADC 17	U.T.Z. Air Flow	10 - 50 mV	0 - 1600000 C.F.H.	Sq. Rt. d. p.
ADC 18	L.T.Z. Air Flow	10 - 50 mV	0 - 800000 C.F.H.	Sq. Rt. d. p.
ADC 19	P.Z. Air Flow	10 - 50 mV	0 - 1200000 C.F.H.	Sq. Rt. d. p.
ADC 20	S.Z. Oil Flow	10 - 50 mV	0 - 200 I.G.P.M.	Sq. Rt. Target
ADC 21	U.T.Z. Oil Flow	10 - 50 mV	0 - 800 I.G.P.M.	Sq. Rt. Target
ADC 22	L.T.Z. Oil Flow	10 - 50 mV	0 - 400 I.G.P.M.	Sq. Rt. Target
ADC 23	P.Z. Oil Flow	10 - 50 mV	0 - 600 I.G.P.M.	Sq. Rt. Target



ANALOG INPUT	DESCRIPTION	INPUT SIGNAL	INPUT EQUIVALENT	SCALE TYPE
ADC 24	S.Z. Gas Flow	10 - 50 mV	0 - 70000 C.F.H.	Sq. Rt. d. p.
ADC 25	U.T.Z. Gas Flow	10 - 50 mV	0 - 280000 C.F.H.	Sq. Rt. d. p.
ADC 26	L.T.Z. Gas Flow	10 - 50 mV	0 - 150000 C.F.H.	Sq. Rt. d. p.
ADC 27	P.Z. Gas Flow	10 - 50 mV	0 - 210000 C.F.H.	Sq. Rt. d. p.
ADC 28	S.Z. Steam Flow	10 - 50 mV	0 - 700 lb/hr	Sq. Rt. d. p.
ADC 29	U.T.Z. Steam Flow	10 - 50 mV	0 - 2800 lb/hr	Sq. Rt. d. p.
ADC 30	L.T.Z. Steam Flow	10 - 50 mV	0 - 1500 lb/hr	Sq. Rt. d. p.
ADC 31	P.Z. Steam Flow	10 - 50 mV	0 - 2000 lb/hr	Sq. Rt. d. p.
ADC 32	Total Oil Flow	10 - 50 mV	0 - 2000 I.G.P.M.	Sq. Rt. Target
ADC 33	Total Gas Flow	10 - 50 mV	0 - 710000 C.F.H.	Sq. Rt. d. p.
ADC 34	Total Steam Flow	10 - 50 mV	0 - 7000 lb/hr	Sq. Rt. d. p.
ADC 35	Gas Supply Pressure	10 - 50 mV	0 - 20" W.G.	Linear
ADC 36	Oil Inlet Temperature	0 - 4.91 mV	32 - 200°F	T/C Curve
ADC 37	Gas Inlet Temperature	0 - 2.52 mV	32 - 120°F	T/C Curve
ADC 38	Hot Air Header Pressure	10 - 50 mV	0 - 20" W.G.	Linear
ADC 39	Hot Air Header Temperature	0 - 29.52 mV	32 - 1000°F	T/C Curve
ADC 40	Hot Air Temp., Outlet of Main Recup.	0 - 29.52 mV	32 - 1000°F	T/C Curve
ADC 41	Hot Air Temp., Outlet of S.Z. Recup.	0 - 29.52 mV	32 - 1000°F	T/C Curve
ADC 42	S.Z. Combustion Air Temperature	0 - 29.52 mV	32 - 1000°F	T/C Curve
ADC 43	U.T.Z. Combustion Air Temperature	0 - 29.52 mV	32 - 1000°F	T/C Curve
ADC 44	L.T.Z. Combustion Air Temperature	0 - 29.52 mV	32 - 1000°F	T/C Curve
ADC 45	P.Z. Combustion Air Temperature	0 - 29.52 mV	32 - 1000°F	T/C Curve
ADC 46	Supply Gas B.T.U. Analyser	10 - 50 mV	360 - 540 BTU/SCF	Linear
ADC 47	Cold Junction Thermocouple T/C	10 - 50 mV	32 - 200°F	Linear

ANALOG INPUT	DESCRIPTION	INPUT SIGNAL	INPUT EQUIVALENT	SCALE TYPE
ADC 48	Cooling Water Inlet Temperature	0 - 2.52 mV	32 - 120°F	T/C Curve
ADC 49	Cooling Water Outlet Temperature	0 - 6.42 mV	32 - 250°F	T/C Curve
ADC 50	Total Cooling Water Flow	10 - 50 mV	0 - 240000 IGPH	Sq. Rt. d. p.
ADC 51	S.Z. Roof Brick Temperature Left	0 - 19.39 mV	32 - 3000°F	T/C Curve
ADC 52	S.Z. Roof Brick Temperature Right	0 - 19.39 mV	32 - 3000°F	T/C Curve
ADC 53	S.Z. Hearth Brick Surface Temp. Middle	0 - 19.39 mV	32 - 3000°F	T/C Curve
ADC 54	S.Z. Rear Roof Brick Temp. Middle	0 - 19.39 mV	32 - 3000°F	T/C Curve
ADC 55	U.T.Z. Burner Wall Brick Temp. Middle	0 - 19.39 mV	32 - 3000°F	T/C Curve
ADC 56	L.T.Z. Burner Wall Brick Temp. Middle	0 - 19.39 mV	32 - 3000°F	T/C Curve
ADC 57	U.T.Z. Roof Brick Temp. Middle Front	0 - 19.39 mV	32 - 3000°F	T/C Curve
ADC 58	U.T.Z. Roof Brick Temp. Middle	0 - 19.39 mV	32 - 3000°F	T/C Curve
ADC 59	U.T.Z. Roof Brick Temp. Middle Back	0 - 19.39 mV	32 - 3000°F	T/C Curve
ADC 60	L.T.Z. Floor Brick Temp. Middle Back	0 - 19.39 mV	32 - 3000°F	T/C Curve
ADC 61	P.Z. Floor Brick Temp. Middle Back	0 - 19.39 mV	32 - 3000°F	T/C Curve
ADC 62	Furnace Charging End Roof Brick Temp. Middle	0 - 19.39 mV	32 - 3000°F	T/C Curve
ADC 63	Main Recup. Flue Gas Inlet Temp. (Flue Gas ex. Furnace)	0 - 14.79 mV	32 - 2400°F	T/C Curve
ADC 64	S.Z. Recup. Flue Gas Inlet Temp. (Flue Gas ex. Furnace)	0 - 44.91mV	32 - 2000°F	T/C Curve

ANALOG OUTPUT TABLE

ANALOG OUTPUT	DESCRIPTION	INPUT EQUIVALENT	SCALE TYPE
DAC 1	S.Z. Temp. Controller Set Point	1100 - 2600 <sup>o</sup> F	4th Root
DAC 2	S.Z. Air/Fuel Ratio Controller Set Point	0.6 - 1.7	Linear
DAC 3	S.Z. Steam/Oil Ratio Controller Set Point	0.6 - 1.7	Linear
DAC 4	U.T.Z. Temp. Controller Set Point	1100 - 2600 <sup>o</sup> F	4th Root
DAC 5	U.T.Z. Air/Fuel Ratio Controller Set Point	0.6 - 1.7	Linear
DAC 6	U.T.Z. Steam/Oil Ratio Controller Set Point	0.6 - 1.7	Linear
DAC 7	L.T.Z. Air/Fuel Ratio Controller Set Point	0.6 - 1.7	Linear
DAC 8	L.T.Z. Steam/Oil Ratio Controller Set Point	0.6 - 1.7	Linear
DAC 9	P.Z. Temp. Controller Set Point	1100 - 2600 <sup>o</sup> F	4th Root
DAC 10	P.Z. Air/Fuel Ratio Controller set Point	0.6 - 1.7	Linear
DAC 11	P.Z. Steam/Oil Ratio Controller Set Point	0.6 - 1.7	Linear
DAC 12	Furnace Pressure Controller Set Point	-0.25 to +0.25" W.G.	Linear
DAC 13	L.T.Z. Bias Station Set Point	1100 - 2600 <sup>o</sup> F	4th Root
DAC 14	Spare		
DAC 15	Spare		
DAC 16	Spare		

DIGITAL INPUT TABLE

BIT NO.	WORD NO.	DESCRIPTION	INPUT TYPE
D1-1	1	Slab Data Set	Push Button
D1-2		Slab Entry	Push Button
D1-3		Slab Not Charged	Push Button
D1-4		Last Slab Data Incorrect	Push Button
D1-5		Cancel (Pusher's)	Push Button
D1-6		Print Output Data	Push Button
D1-7		Output Data Set	Push Button
D1-8		Fast Pushing	Push Button
D1-9		Normal Pushing	Push Button
D1-10		Slow Pushing	Push Button
D1-11		Slab Too Hot	Push Button
D1-12		Slab Too Cold	Push Button
D1-13		Long Delay	Push Button
D1-14		Short Delay	Push Button
D1-15		Five Minutes Before Delay Ends	Push Button
D1-16		End Delay	Push Button
D1-17		Cancel (Operator's)	Push Button
D1-18		Spare Point	Push Button
D1-19	2	Computer Off	Switch SW708
D1-20		Computer Logging	Switch SW708
D1-21		Computer Control	Switch SW708

BIT NO.	WORD NO.	DESCRIPTION	INPUT TYPE
D1-22	2	Furnace Pressure Control Point 1 S.Z.	Switch SW705
D1-23		Furnace Pressure Control Point 2 U.T.Z.	Switch SW705
D1-24		Soak Zone Fuel Oil	Switch SW701
D1-25		Soak Zone Fuel Gas	Switch SW701
D1-26		Soak Zone Fuel Off	Switch SW701
D1-27		U.T.Z. Fuel Oil	Switch SW702
D1-28		U.T.Z. Fuel Gas	Switch SW702
D1-29		U.T.Z. Fuel Off	Switch SW702
D1-30		L.T.Z. Fuel Oil	Switch SW703
D1-31		L.T.Z. Fuel Gas	Switch SW703
D1-32		L.T.Z. Fuel Off	Switch SW703
D1-33		L.P.Z. Fuel Oil	Switch SW704
D1-34		L.P.Z. Fuel Gas	Switch SW704
D1-35		L.P.Z. Fuel Off	Switch SW704
D1-36		Spare Point	
D1-37		3	
D1-38	On Demand Printout		Thumbwheel
D1-39	Switch 1st Digit		Switch
D1-40			
D1-41	On Demand Printout		Thumbwheel
D1-42	Switch 1st Digit	Switch	

BIT NO.	WORD NO.	DESCRIPTION	INPUT TYPE
D1-43	3	On Demand Printout	Thumbwheel
D1-44		Switch 2nd Digit	Switch
D1-45		S.Z. Temp. Controller Output on Manual	Switch SW710
D1-46		U.T.Z. Temp. Controller Output on Manual	Switch SW711
D1-47		L.T.Z. Temp. Controller Output on Manual	Switch SW712
D1-48		P.Z. Temp. Controller Output on Manual	Switch SW713
D1-49		U.T.Z. Radiamatics North Wall or South Wall	Switch SW709
D1-50		F.D. Air Fan On	Switch SW706
D1-51		Dilution Air Fan On	Switch SW707
D1-52		Main Recuperator Smoke Density High	
D1-53		Spare Point	
D1-54		Spare Point	
D1-55		4	Slab Door Position (1BCD Digit)
D1-56	Switch		
D1-57			
D1-58			

BIT NO.	WORD NO.	DESCRIPTION	INPUT TYPE
D1-59	4	Slab Width 1st Digit	Thumbwheel Switch
D1-60			
D1-61			
D1-62			
D1-63		Slab Width 2nd Digit	Thumbwheel Swtich
D1-64			
D1-65			
D1-66			
D1-67		Slab Width 3rd Digit	Thumbwheel Switch
D1-68			
D1-69			
D1-70			
D1-71		Spare Point	
D1-72		Spare Point	
D1-73	5	Slab Thickness 1st Digit	Thumbwheel Switch
D1-74			
D1-75			
D1-76			
D1-77		Slab Thickness 2nd Digit	Thumbwheel Switch
D1-78			
D1-79			
D1-80			

BIT NO.	WORD NO.	DESCRIPTION	INPUT TYPE		
D1-81	5	Slab Thickness 3rd Digit	Thumbwheel Switch		
D1-82					
D1-83					
D1-84					
D1-85		Slab Length 1st Digit	Thumbwheel Switch		
D1-86					
D1-87					
D1-88					
D1-89				Spare Point	
D1-90				Spare Point	
D1-91	6	Slab Length 2nd Digit	Thumbwheel Switch		
D1-92					
D1-93					
D1-94					
D1-95		Slab Length 3rd Digit	Thumbwheel Switch		
D1-96					
D1-97					
D1-98					
D1-99		Spare Point			
D1-100		Spare Point			
D1-101		Slab Serial No. 1st Digit	Thumbwheel Switch		
D1-102					
D1-103					
D1-104					



BIT NO.	WORD NO.	DESCRIPTION	INPUT TYPE
D1-105	6	Slab Serial No.2nd Digit	Thumbwheel Switch
D1-106			
D1-107			
D1-108			
D1-109	7	Slab Serial No.3rd Digit	Thumbwheel Switch
D1-110			
D1-111			
D1-112			
D1-113		Slab Serial No. 4th Digit	Thumbwheel Switch
D1-114			
D1-115			
D1-116			
D1-117		Slab Serial No. 5th Digit	Thumbwheel Switch
D1-118			
D1-119			
D1-120			
D1-121		Slab Serial No. 6th Digit	Thumbwheel Switch
D1-122			
D1-123			
D1-124			
D1-125	Spare Point		
D1-126	Spare Point		

BIT NO.	WORD NO.	DESCRIPTION	INPUT TYPE
D1-127	8	Slab Serial No. 7th Digit	Thumbwheel Switch
D1-128			
D1-129			
D1-130			
D1-131		Slab Serial No. 8th Digit	Thumbwheel Switch
D1-132			
D1-133			
D1-134			
D1-135		Slab Serial No. 9th Digit	Thumbwheel Switch
D1-136			
D1-137			
D1-138			
D1-139		Slab Serial No. 10th Digit	Thumbwheel Switch
D1-140			
D1-141			
D1-142			
D1-143		Spare Point	
D1-144		Spare Point	
D1-145	9	Slab Serial No. 11th Digit	Thumbwheel Switch
D1-146			
D1-147			
D1-148			

BIT NO.	WORD NO.	DESCRIPTION	INPUT TYPE	
D1-149	9	Slab Serial No. 12th Digit	Thumbwheel Switch	
D1-150				
D1-151				
D1-152				
D1-153		Spare Point		
D1-154		Spare Point		
D1-155		Grade 1st Digit	Thumbwheel Switch	
D1-156				
D1-157				
D1-158				
D1-159		10	Grade 2nd Digit	Thumbwheel Switch
D1-160				
D1-161				
D1-162				
D1-163	Grade 3rd Digit			
D1-164				
D1-165				
D1-166				
D1-167	Grade 4th Digit	Thumbwheel Switch		
D1-168				
D1-169				
D1-170				

BIT NO.	WORD NO.	DESCRIPTION	INPUT TYPE
D1-171	10	Grade 5th Digit	Thumbwheel Switch
D1-172			
D1-173			
D1-174			
D1-175		Spare Point	
D1-176		Spare Point	
D1-177		Spare Point	
D1-178		Spare Point	
D1-179		Spare Point	
D1-180		Spare Point	

DIGITAL OUTPUT TABLE

BIT NO.	DESCRIPTION	OUTPUT DEVICE
DO - 1	First BCD digit of efficiency display	BCD to decimal decoder and Nixie tube
DO - 2		
DO - 3		
DO - 4		
DO - 5	Second BCD digit of efficiency display	BCD to decimal decoder and Nixie tube
DO - 6		
DO - 7		
DO - 8		
DO - 9	Third BCD digit of efficiency display	BCD to decimal decoder and Nixie tube
DO - 10		
DO - 11		
DO - 12		
DO - 13	Instrument malfunction	Display light
DO - 14	Computer malfunction	Display light
DO - 15	Next slab ready	Display light
DO - 16	Second next slab ready	Display light
DO - 17	Slab data correct	Display light
DO - 18	Slab entry	Display light

## APPENDIX 2

SUBROUTINES TO CONVERT THE PDP-9 MONITOR  
TO ON-LINE REAL-TIME OPERATION

```

        .TITLE SYSINI
/SYSTEM INITIALISATION
/MODIFIES PORTION OF THE RESIDENT MONITOR
-AND SETS UP MULTI LEVEL TIMER OPERATIONS
/CALLING SEQUENCE:
/      JMS SYSINI
/      RETURN
/OR    CALL SYSINI
/      RETURN    FOR FORTRAN PROGS
/
        .GLOBL SYSINI ,TIMADR,TIMINT,TIMTEM
/
/
CLON=700044
CLSF=700001
SYSINI    CAL
/      LAC .TAL  PUT THESE IN WHEN LOGGING TYPEWRITER
/      DAC* (144  IS IMPLEMENTED. DAT SLOT 7
        LAC (PDLST
        DAC PDP#
        LAC (Q3
D      DAC POINT#
        LAC (Q3-TIMINT    /CLEAR QUES
        DAC COUNTI#
        DZM* POINT
        ISZ POINT
        ISZ COUNT1
        JMP .-3
        CAL
        16
        CLSF
        TIMSER
        LAC (-1
        DAC* (7
        CLON
        JMP* SYSINI
/
TIMSER    DAC* PDP  /STORE AC AND PD
          ISZ PDP  /ON PDLIST FOR
          LAC* (0  /MULTIPLE ENTRANCY
          DAC* PDP
          ISZ PDP
          LAC (-1  /RESET CLOCK
          DAC* (7  AND DISMIS
          CLON
SEARCH    LAC (Q1+1-TIMINT
          DAC COUNT#
          LAC (Q1+1 /INIT FOR SEARCH
          DAC POINT /OF ENABLED SUBROUTINES
          DZM BASE#

```

```

LOOKA    LAC* POINT
          SZA
          JMS FOUND /FOUND ENABLED SUBROT.
          ISZ POINT /GO INCREMENT HIS CLOCK
          ISZ BASE
          ISZ COUNT
          JMP LOOKA
SUBENT   JMS SRCH  /ALL CLOCKS UPDATED.
          DAC DSPTCH#           /GO SEARCH FOR THOSE
          ION
          JMS* DSPTCH           /BECOME ACTIVE
          IOF
          LAC Q1    /GO TO SUBROT.
          SMA           /THIS TORESET ACTIVE BIT
          JMP .+4    /IN HEADER
          XOR (400000
          DAC Q1
          JMP SUBENT
          LAC Q2
          SMA
          JMP .+4
          XOR (400000
          DAC Q2
          JMP SUBENT
          LAC Q3
          XOR (400000
          DAC Q3
          JMP SUBENT
SRCH     O           /SEARCH FOR JOB TO RUN
          LAW -3
          DAC CNTR#
          LAC (Q1
          DAC QPTR#
NEXTQ    LAC* QPTR
          SPA           /JOB ACTIVE ON THIS Q
          JMP DISMIS           /YES - COME BACK LATER
          AND (17 /NO
          SZA           /IS Q EMPTY
          JMP EXTRCT           /NO, GET FIRST JOB
          LAW -1
          TAD QPTR /GO TO NEXT Q
          DAC QPTR
          ISZ CNTR
          JMP NEXTQ
          JMP DISMIS           /ALL Q'S EMPTY.
EXTRCT   TAD (Q1
          DAC TEMP# /JOB POINTER ADDR
          LAC* TEMP
          AND (17 /SET ACTIVE BIT IN
          XOR (400000 /HEADER

```



```

DAC* QPTR
LAC* TEMP /GET DISPATCH ADDRESS
AND (777760
CLL!RTR
RTR
JMP*SRCH
FOUND O /INCREMENT CLOCK
LAC (TIMTEM /FOR THIS JOB
TAD BASE
DAC TEMP
ISZ* TEMP
JMP* FOUND
LAC (TIMINT /OVERFLOW, RESET CLOCK
TAD BASE
DAC TEMPER#
LAC* TEMPER
DAC* TEMP
LAC BASE
TAD (1
JMS NEWJOB
JMP* FOUND
NEWJOB O /ADD THIS JOB TO Q
DAC JOBNUM# /WHICH Q HEADER
LAC (Q3
DAC QUE#
LAC JOBNUM
TAD (-20
SMA
JMP* NEWJOB
TAD (5
SMA
JMP .+5
TAD (5
SPA
ISZ QUE
ISZ QUE
LAC* QUE
AND (17
SNA /IS Q EMPTY
JMP INSRT /YES
NXT TAD (Q1
DAC TEMP
LAC* TEMP
AND (17
SZA /IS THIS LAST ENTRY?
JMP NXT
LAC JOBNUM /YES, STORE THIS ITEM
TAD* TEMP /ON THE LIST
DAC* TEMP
SETEND LAC JOBNUM /MAKE SURE Q END
TAD (Q1 /IS ZERO JOB

```

```
DAC TEMP
LAC* TEMP
AND (777760
DAC* TEMP
JMP* NEWJOB
INSRT  LAC* QUE
TAD JOBNUM
DAC* QUE
JMP SETEND
DISMIS LAC PDP
TAD (-1
DAC PDP
LAC* PDP
DAC POINT
LAC PDP
TAD (-1
DAC PDP
LAC* PDP
ION
DBR
JMP* POINT
Q3      0
Q2      0
Q1      0
TIMADR  .BLOCK 20
TIMINT  .BLOCK 17
TIMTEM  .BLOCK 17
PDLST   .BLOCK 30
        .END
END OF BUFFER REACHED BY:
P 9000
>
```

```

/          POWER FAILURE WITH AUTOMATIC RESTART
          .TITLE PFAIL
/HANDLER FOR POWER FAILURE OPTION KPO9A
/MAINTENANCE PANEL SWITCH IN "LOCK" POSITION FOR AUTO RESTART.
/IF NOT IN LOCK - ADDR SWITCHES TO ZERO & PRESS START TO RESTART MANUAL
/DEVICE INSTRUCTIONS.
          .ABS          /ABSOLUTE ADDRESS
SPFAL=703201
CLON=700044
/PROGRAMME IS ABSOLUTE ADDRESSED .LOC 46
          .LOC 46      /PFAIL LOADING ADDRESS IS
          .DSA PFAIL      /CONTAINED IN LOC 46
          .LOC 2650
/POWER FAILURE PROGRAMME
/MACHINE SHUT-DOWN
PFAIL      DAC ACSAVE          /SAVE ACCUMULATOR
           LAC 00000          /CONTENTS OF LOC 0 IN AC
           DAC RETADR        /RETURN ADDRESS ON RESTART
           LAC (JMP RSTART
           DAC 00000 /LOC 0 CONTAINS RESTART ADDR.
/CHECK CLOCK & FLAG STATUS BEFORE MACHINE SHUT-DOWN
IORS      /READ FLAG STATUS
DAC CLKSTS          /CLOCK STATUS
HLT      /MACHINE PROGRAMME STOP
/MACHINE RESTART
RSTART    LAC CLKSTS          /LOAD FLAG STATUS
          RTL      /ROTATE CLOCK FLAG BIT TO LINK
          RTL
          RTL
          SPL      /SKIP IF LINK 0
          CLON     /IF NOT PUT CLOCK ON
/REINITIALISE ADC & DAC DEVICE FLAGS
          LAC (0
          DAC (2061 /ZERO VALUE IN ADUND
          DAC (545      /ZERO TTY -TTIOSW VALUE
/.ADC+61 IS ADUND OR ADC UNDERWAY
/.TTA-1 IS TTY IO UNDERWAY SKIP
/
/PREPARE TO RESTART
          LAC ACSAVE          /RESTORE AC
          ION      /TURN PIE ON
          DBR
          JMP* RETADR
RETADR    0
ACSAVE    0
CLKSTS    0

```

```

      .TITLE TIMER SET UP
/CALLING SEQUENCE:
/MACRO: JMS TIME
/
      JMP .+4
/
      .DSA A
/
      .DSA B
/
      .DSA C
/
      RETURN
/FORTRAN:   CALL TIME (A,B,C,)
/
      RETURN
/WHERE C (A) = TIME INTERVAL IN 1/50 SEC

/      B =      SUBROUTINE NAME TO BE CALLED
/      C (C) = PRIORITY LEVEL (0,1, OR 2.)

      .GLOBL TIME, TIMADR, TIMINT, .DA, TIMTEM.

TIME          CAL
              JMS* .DA
              JMP .+4
TIMI          .DSA O
TIMAD         .DSA O
TIMP          .DSA O
              LAC* TIMP
              SNA
              JMP .+5
              TAD (4
              SAD (5
              SKP
              TAD (5
              TAD* (TIMADR
              DAC      POINT#
              LAW -5
              DAC COUNT1#
              DZM BASE#
              LAC* TIMI
              SZA
              JMP NEWTIM
              LAC TIMAD
              AND (37777
              CLL RTL
              RTI
              DAC TEMP#
NXT          TAD (01          /NO, FIND END OF Q
              DAC TEMP
              LAC* TEMP
              AND (17
              SZA          /IS THIS LAST ENTRY?

```

```

                JMP NXT
                LAC JOBNUM           /YES, STORE THIS ITEM
                TAD* TEMP             /ON THE LIST
                DAC* TEMP
SETEND          LAC JOBNUM           /MAKE SURE Q END
                TAD (01              /IS ZERO JOB
                DAC TEMP
                LAC* TEMP
                AND (777760
                DAC* TEMP
                JMP* NEWJOB

INSRT          LAC* QUE
                TAD JOBNUM
                DAC* QUE
                JMP SETEND

DISMIS

                LAC PDP
                TAD (-1
                DAC POINT
                TAD (-1
                DAC PDP
                LAC* PDP
                JMP* POINT

Q3            0
Q2            0
Q1            0
TIMADR       .BLOCK 20
TIMINT       .BLOCK 17
TIMTEM       .BLOCK 17
PDLST        .BLOCK 10
.END

```

```

        .TITLE DIGITAL DEVICE HANDLER
/HANDLER TO READ AND WRITE DATA TO AND FROM THE DSU-9 AND DRO-9
/DEVICES.DATA IS PACKED INTO BUFFERS IN LOGICAL
/FORMAT.
/
/DEVICE INSTRUCTIONS
        .ABS
/
SDF=705001          /SKIP ON FLAG
CDF=705002          /CLEAR FLAG
RDW1=705014        /READ WDO 1 ETC
RDW2=705031
RDW3=705032
RDW4=705034
RDW5=705051
RDW6=705052
RDW7=705054
RDW8=705071
RDW9=705072
RDW10=705074
/INSTRUCTIONS FOR THE DRO-9 OUTPUT
ORC=702101         /CLEAR OUTPUT BUFFER
ORS=702104         /LOAD OUTPUT BUFFER 1
ORC2=702121        /CLEAR OUTPUT BUFFER 2
ORS2=702124        /LOAD OUTPUT BUFFER 2
/
/
/
/MACRO INSTRUCTIONS
/ .INIT A,F,R
/A=.DAT SLOT
/ F=0 OUTPUT FILE; F<1 INPUT FILE
/ R=NO EFFECT,BUT MUST BE SET
/
/
/
/ .READ A,M,L,W
/ A=.DAT SLOT
/ M=0 IOPS BINARY
/ L=LINE BUFFER ADDRESS
/W=NUMBER OF WORDS TO BE READ+2
/
/.WRITE A,M,L,W
/ A=.DAT SLOT
/ M=MODE (IOPS BINARY=0)
/ L=LINE BUFFER ADDRESS
/ W= WORD COUNT OF BUFFER INCLUDING HEADER
/ #OF WORDS TO BE TRANSFERED IS DETERMINED BY WPC IN HEADER

```

```

/
/ .WAIT A
/ A=.DAT SLOT
/
/.CLOSE A
/A=.DAT SLOT
/OR ALL THE ABOVE MAY BE CALLED DIRECTLY, AND NOT THROUGH THE CAL
/HANDLER BY PLACING A JMS* .DSUI BEFORE THE MACRO CAL
/
.MED=3
/
        .LOC 41
        .DSA .DSUI
        .LOC 2300
.DSUI   CAL
        LAC .DSUI
.DSU    DAC ADCALP#
        DAC ADARG#
        ISZ ADARG
        LAC* ADARG
        ISZ ADARG
        TAD (JMP DTABLE-1
        DAC .+1
        HLT
DTABLE  JMP DSIN /INIT
        JMP IODERR /DELETE
        JMP IODERR /SEEK
        JMP IODERR /ENTER
        JMP IODERR /CLERA
        JMP DSCLOSE /CLOSE
        JMP IODERR /MTAPE
        JMP DSREAD /READ
        JMP DSWRITE /WRITE
        JMP DSWAIT /WAIT
        JMP IODERR /TRAN
        JMP IODERR /TIMER
        JMP IODERR /EXIT
IODERR  LAW 6
        JMP* (.MED+1
/
/INITIALISE
DSIN    ISZ ADARG
        LAC* ADCALP
        AND (3000
        SNA!CLA
        TAD (330
        TAD (46
        DAC* ADARG
        ISZ ADARG

```

```

        DZM DSUND#
        DBR
        JMP* ADARG
/
/
/READ ROUTINE
/
DSREAD  LAC* ADARG
        DAC DSBP#
        DAC DSLBHP#
        ISZADARG
        LAC* ADARG
        TAD (2
        DAC DSWC#
        ISZ ADARG
        DZM DSWPCT#
        DZM DSCKSM#
        ISZ DSBP
        ISZ DSBP
        ISZ DSBP
        RDW1
        JMS LOGICI
        RDW2
        JMS LOGICI
        RDW3
        JMS LOGICI
        RDW4
        JMS LOGICI
        RDW5
        JMS LOGICI
        RDW6
        JMS LOGICI
        RDW7
        JMS LOGICI
        RDW8
        JMS LOGICI
        RDW9
        JMS LOGICI
        RDW10
        JMS LOGICI
        CLA
        LAC DSWPCT
        TAD (3
        RTL; RTL; RTL; RTL;
        AND (377000
        DAC* DSLBHP
        ISZ DSLBHP
        LAC (400000
        DAC* DSLBHP
        ISZ DSLBHP

```

DEND



```

TAD DSCKSM
CMA
TAD (1
DAC* DSLBHP
DBR
JMP* ADARG

/
/
/
LOGICI 0
DAC TEMP#
LAW -22
DAC COUNT#
AGIN LAC TEMP
RCL
DAC TEMP
SZLCLA
CLC
DAC* DSBP
TAD DSCKSM
DAC DSCKSM
ISZ DSBP
ISZ DSWPCT
ISZ DSWC
SKP
JMP DEND
ISZ COUNT
JMP AGIN
JMP* LOGICI

/ .WAIT ROUTINE
DSWAIT NOP
DSCLOSE DBR
JMP* ADARG

/
/
/. WRITE ROUTINE
/
DSWRITE LAC* ADARG
DAC DSBP
DAC DSLBHP
ISZ ADARG
ISZ ADARG
LAC* DSLBHP
CLL
RTR; RTR; RTR; RTR;
AND (776
TAD (-2
CMA
DAC DSWC
DZM DSCKSM

```

```

DZM DSWPCT
ISZ DSBP
ISZ DSBP
ISZ DSBP
JMS LOGICO
LAC TEMP
ORC!ORS
LAC DSWC
SMA
JMP .+5
JMS LOGICO
LAC TEMP
ORC2!ORS2
LAC DSWPCT
TAD (3
RTL; RTL; RTL; RTL;
AND (377000
DAC* DSLBHP
ISZ DSLBHP
DZM* DSLBHP
DBR
JMP* ADARG

/
LOGICO 0
LAW -22
DAC COUNT
DZM TEMP
LAC (LAC* DSBP
DAC .+1
AGIN2 LAC* DSBP
ISZ DSBP
RCL
LAC TEMP
RAL
DAC TEMP
ISZ DSWPCT
ISZ DSWC
SKP
JMP X1
Y1 ISZ COUNT
JMP AGIN2
JMP* LOGICO
X1 LAC (CLA
DAC AGIN2
JMP Y1
.END

```

.TITLE ANALOG DEVICE HANDLER  
 /HANDLER FOR THE AFO3 ADC AND THE AA05 DAC.  
 /DEVICE INSTRUCTIONS

.ABS

CLER=701401           /CLEAR REGS AND EOS  
 RCA=701412           /READ CA  
 LCA=701404           /LOAD CA  
 EOSK=701421          /SKIP ON END OF SCAN  
 IXCA=701422          /INDEX CA  
 LFA=701424           /LOAD FA  
 ADSF=701301          /SKIP ON AD FLAG  
 ADRB=701312          /READ ADC  
 ADCV=701304          /START CONVERT  
 CDAR=705101          /CLR DAC ADDRESS  
 LDAR=705102          /LOAD DAC RDG  
                       /ADDRESS 0-5 DATA 8-17  
 DACC=705104          /DOUBLE BUFFERED

/

/

.MED=3  
 AD=0           /57 FOR API  
               .LOC 40  
               .DSA .ADCl  
               .LOC 2000

/

.ADCl           CAL  
               LAC ADUND  
               SNA!CLA  
               JMP .+5  
               LAC .ADCl  
               TAD (-1  
               DAC .ADCl  
               JMP\*.ADCl  
               LAC .ADCl  
 .ADC           DAC ADCALP#  
               DAC ADARG#  
               ISZ ADARG  
               LAC\* ADARG  
               ISZ ADARG  
               TAD (JMP DTABLE-1  
               DAC .+1  
               HLT  
 DTABLE        JMP ADIN  
               JMP IODERR  
               JMP IODERR  
               JMP IODERR  
               JMP IODERR  
               JMP ADOK  
               JMP IODERR

```

JMP ADRD
JMP ADWRT
JMP ADWAIT
IODERR LAW 6
JMP* (.MED+1
/
/
/
ADIN LAC (ADSF
DAC* (475
ISZ ADARG
LAC* ADCALP
AND (3000
SNA!CLA
TAD (60
TAD (22
DAC* ADARG
ISZ ADARG
CALAD CAL AD
16
ADSF
ADINT
LAC (JMP ONCE
DAC CALAD
ONCE DZM ADUND
DBR
JMP* ADARG
ADUND .DSA 0
/READ ROUTINE
/
ADRD LAC ADUND
SZA!CMA
JMP ADBUSM
DAC ADUND
LAC* ADARG
DAC ADLBHP#
TAD (3
DAC ADDBP#
ISZ ADARG
LAC* ADARG
DAC ADRWC#
ISZ ADARG
CLER
DZM ADWPCT#
DZM ADCKSM#
DZM ADUND
CLA
LCA
DBR

```

```

                JMP* ADARG
/
/
/INTERRUPT ROUTINE
/
ADINT          DAC ADSAVE#
                LAC* (0
                DAC INSAV#
                ADRB
                CLL
                RTR; RTR; RTR;
                DAC* ADDBP
                ISZ ADDBP
                ISZ ADWPCT
                TAD ADCKSM
                DAC ADCKSM
                LAC ADRWC
                TAD (1
                DAC ADRWC
                SPA
                JMP ADCONT
                LAC ADWPCT
                TAD (3
                RTL; RTL; RTL; RTL;
                AND (377000
                DAC* ADLBHP
                ISZ ADLBHP
                TAD ADCKSM
                DAC* ADLBHP
                ISZ ADLBHP
                LAC (400000
                DAC* ADLBHP
                SKP
ADCONT         IXCA
                LAC ADSAVE
ADSWCH         ION
                DBR
                JMP* INSAV
/
/
/
/
ADWAIT         LAC ADUND
                SNA
                JMP ADOK
ADBUSY        DBR
                JMP* ADCALP
ADOK          DBR
                JMP* ADARG

```

```

/
/
/
ADWRT      LAC* ADARG
           DAC ADDBP1#
           DAC ADLBH1#
           LAC* ADLBH1
           CLL
           RTR; RTR; RTR; RTR;
           AND (776
           TAD (-2
           CMA
           DAC ADRWC1#
           ISZ ADARG
           ISZ ADARG
           DZM ADWPC1#
           DZM CHAN#
           ISZ ADDBP1
           ISZ ADDBP1
           ISZ ADDBP1
AGIN       LAC* ADDBP1
           ISZ ADDBP1
           RTL
           AND (7774
           TAD CHAN
           CDAR!LDAR
           ISZ ADWPC1
           LAC CHAN
           TAD (10000
           DAC CHAN
           ISZ ADRWC1
           JMP AGIN
           ISZ ADLBH1
           DZM* ADLBH1
           DBR
           JMP* ADARG

/

.END

```

APPENDIX 3

SUBROUTINES USED FOR ON-LINE COMPUTER

CONTROL OF REHEAT FURNACES

### A3.1 Analog Scan Routine

This determines the Sequence, Frequency and Speed of scanning each variable, e.g., flows need to be scanned more frequently than the temperatures.

### A3.2 Digital Scan Routine

This decodes the digital signals coming in and interprets them into steel data, furnace conditions and operator requests, etc., and stores them in pre-allocated locations.

### A3.3 Signal Filtering and Conditioning Routine

This provides digital filtering of all input signals to smooth out the noise (e.g., peaks). Consult Chapter 17, Vol. I, Handbook of Automation Computer & Control.

### A3.4 Thermocouples Scaling Routine

This is for direct thermocouple inputs. It contains the mV/Temp. equations for each type of thermocouple used. At the beginning of every scanning cycle, the cold junction temperature is read first, scaled and stored in a fixed location. This then is subtracted



from all the temperature readings in this scanning cycle, before they are finally stored in the memory.

### A3.5 Transmitter Signals Scalling Routine

This converts all transmitted signals to engineering units. It eliminates the 20% elevated zero, extracts square root and fourth root and applies temperature compensation to combustion air flows. Orifice, venturi, pressure, oxygen and radiamatic, etc. scale ranges are stored and used in this routine.

### A3.6 Totalising and Averaging Routine

This subroutine integrates flows, totalises steel throughput, computes mean values of temperature and pressure flows, etc. and stores them for periodic print-out as demanded by the Executive Program or on demand by the operator.

### A3.7 Logging Routine

This contains the predetermined logging format. It picks out the values to be logged

from various locations and outputs them in accordance to the format to the teleprinters or highspeed punch. It logs all set points alongside the variables.

### A3.8 Alarm Conditions Logging Routine

This contains a set of alarm limit values. It compares all measured and calculated variables with their limits and if any exceed the limit, it stores the value together with time of occurrence, code number of variable and the limit value. The print-out of this information will be in red on the input-output teleprinter. It may be arranged to print out immediately or on demand or at certain intervals of time. The recommended corrective action for each alarm condition will also be printed out alongside.

If no corrective action is taken and any significant variable remains in alarm condition for more than 5 minutes, alarm condition, time, set point, etc. will be printed out again. A red warning light will also be switched on automatically. When the alarm condition is corrected it prints out the

message that alarm No. -- is cleared and time of clearance.

### A3.9 Furnace Pressure Control Routine

This retains a value of required furnace pressure set point which is updated by the optimal control subroutines. It also contains upper and lower limits for furnace pressure. Before it accepts the updating, it checks the limits and if exceeded, will reject updating and use the old value. If it checks out correctly, it updates the set point of the furnace pressure controller with the new value.

### A3.10 Control Signal Output Routine

This contains the addresses of all control signals, their required values and the present positions of all the DAC's. It checks and increments or decrements the DAC values according to requirement.

It also outputs the digital signals.

### A3.11 Program Interrupt Routine

This contains the priorities of the various functions. Whenever an interrupt

occurs, this subroutine checks the priority and services it accordingly. This is incorporated in the modified monitor.

#### A3.12 Slab Tracking Routine

This identifies and tracks every slab from entering to leaving the furnace. It keeps serial numbers of slabs in the furnace. It may send this out directly or through Subroutine No.10. The estimated time before the slab is ready is updated every time the furnace condition is changed. This will be done for every slab if storage permits.

#### A3.13 Temperature Calculation Routine

This solves the slab heating equations and calculates the temperature profiles of slab cross-sections as it travels through the furnace.

#### A3.14 Skid Marks Calculation Routine

This solves the skid mark equation and determines the minimum time for the skid marks of each slab to be soaked to a tolerable level. These minimum soaking times are used

as the major constraint in the temperature control system.

#### A3.15 Slab Temperature Optimising Control Routine

This solves the optimal control equations and sets up control signal values for sub-routine No.10. It determines optimal steel surface temperature as slabs pass through the furnace.

#### A3.16 Thermal Efficiency Calculation Routine

This calculates the gross thermal efficiencies at 15 minute intervals and 8 hour intervals. The mean of the last two periods will be used. This will be replaced by the more complete heat balance calculation routine as described in A3.18.

#### A3.17 Thermal Efficiency Optimising Routine

This solves the optimal control equations and determines optimal values for the air/fuel ratio for each zone, furnace pressure and steam/oil ratio. The hill-climbing method is used for this initially. More sophisticated methods will be tried later if necessary.

### A3.18 Heat Balance Calculation Routine

This calculates the heat balance of the furnace, works out the actual thermal efficiency, heat losses, etc., and checks and updates all the approximate values used in the control equations.

### A3.19 Credibility Check Routine

This stores latest mean values of all variables and checks rate of rise and fall of signals against the expected rates. It contains standard warnings and comments for typing on the teleprinter.

### A3.20 Watchdog Routine

This contains all the safety interlock sequences and requirements. It also makes sure the operator does not switch anything to manual control. If he does, this will print out precautions and alarm conditions.

## APPENDIX 4

FUNCTIONAL SUBROUTINES FOR REHEAT FURNACE CONTROL

```
C      TITLE NIXIE
C      NIXIE TUBE DISPLAY OF GROSS THERMAL EFFICIENCY
      EXTERNAL AISUB,DISUB,DOSUB,SADC,SDSU,TESUB,NIXLOG,TODSUB
      LOGICAL DUMB1(3),DLGIBU(25),DUMB2(3),DIGOBU(8)
      INTEGER DUMB3(3),ANIBUF(64),SADCB(64),XSADCB(5),NETA
      INTEGER DAY,HOUR,MIN
      REAL THCOIL,THCGAS,TSLABW
      REAL TOILHC,TGASHC,TWLABW,EFFY
      COMMON/BUF1/DUMB1,DIGIBU/BUF2/DUMB2,DIGOBU/BUF3/DUMB3,ANIBUF
      COMMON/BUF4/SADCB,XSADCB/BUF5/THCOIL,THCGAS,TSLABW/BUF6/NETA
      COMMON/BUF7/DAY,HOUR,MIN
      COMMON/BUF8/TOILHC,TGASHC,TWLABW,EFFY
      CALL SYSINI
      CALL TIME (3,DISUB,0)
      CALL TIME (50,AISUB,0)
      CALL TIME (100,DOSUB,0)
      CALL TIME (3,SDSU,1)
      CALL TIME (50,SADC,1)
      CALL TIME (3000,TODSUB,1)
      CALL TIME (90000,TESUB,1)
      CALL TIME (90000,NIXLOG,1)
200   GO TO 200
      STOP
      END
```



```
.TITLE AISUB
.GLOBL AISUB, BUF3
AISUB  O
      LAC BUF3
      DAC RREAD+2
      JMS* (2000
      .INIT 6,0,AISUB+1
      JMS* (2000
RREAD .READ 6,0,0,66
      JMP* AISUB
      .END
```

```
.TITLE DISUB
.GLOBL DISUB,BUF1
DISUB  O
      LAC BUF1
      DAC RD+2
      JMS* (2300
      .INIT 4,0,DISUB+1
      JMS* (2300
RD     .READ 4,0,0,27
      JMP* DISUB
      .END
```

```
.TITLE DOSUB
.GLOBL DOSUB,BUF2
DOSUB  O
      LAC BUF2
      DAC RDD+2
      LAC DOWPC
      DAC* RDD+2
      JMS* (2300
      .INIT 4,0,DOSUB+1
      JMS* (2300
RDD    .WRITE 4,0,0,10
      JMP* DOSUB
DOWPC  005000
      .END
```

```

C      ROUTINE TO TEST SPECIAL DEVICES
      EXTERNAL ANAI, ANAO, DIGI, DIGO, DLOG, ALOG
      INTEGER ANOBUF(16), ANIBUF(64)
      LOGICAL DIGOBU(18), DIGIBU(72)
      COMMON/BUF/ANIBUF, ANOBUF, DIGOBU, DIGIBU

C
      CALL SYSINI
      DO 50 I=1,17,2
50     DIGOBU(I) = .TRUE.
      CONTINUE
      DO 51 I=2,18,2
51     DIGOBU(I)=.FALSE.
      CONTINUE
      K=0
      DO 52 I=1,16
52     ANOBUF(I)=-500+K
      K=K+50
      CONTINUE
      WRITE (1,3)
3      FORMAT (26H ANALOG INPUT SCAN (SECS)=)
      READ (2,4)A
4      FORMAT (F10.2)
      J=A*50.
      CALL TIME (J,ANAI)
      WRITE (1,5)
5      FORMAT (27H ANALOG OUTPUT SCAN (SECS)=)
      READ (2,6)B
6      FORMAT (F10.2)
      K=B*50
      CALL TIME (K,ANAO)
      WRITE (1,7)
7      FORMAT (27H DIGITAL INPUT SCAN (SECS)=)
      READ (2,8)A
8      FORMAT (F10.2)
      J=A*50.
      CALL TIME (J,DIGI)
      WRITE (1,9)
9      FORMAT (28H DIGITAL OUTPUT SCAN (SECS)=)
      READ (2,10)B
10     FORMAT (F10.2)
      K=B*50.
      CALL TIME (K,DIGO)
      WRITE (1,11)
11     FORMAT (26H DIGITAL LOGGING PERICDS =)
      READ (2,12)A
12     FORMAT (F10.2)
      J=A*50.
      CALL TIME (J,DLOG)
      WRITE (1,13)
13     FORMAT (24H ANALOG LOGGING PERIOD =)
      READ (2,14)B
14     FORMAT (F10.2)
      K=B*50.
      CALL TIME (K,ALOG)
200    GO TO 200

```

```
SUBROUTINE SDSU
LOGICAL DUMB1(3),DIGIBU(25)
REAL THCOIL,THCGAS,TSLABW
INTEGER DICV(5),SLABTW,PUSH
REAL SLABW
COMMON/BUF1/DUMB1,DIGIBU/BUF5/THCOIL,THCGAS,TSLABW
IF(.NOT.DIGIBU(4))GO TO 6
GO TO 7
6  PUSH=0
   RETURN
7  PUSH=PUSH+1
   IF(PUSH-1)8,9,8
8  RETURN
9  L=0
   II=0
   M=6
   N=25
5  II=II+1
   DO 10 I=M,N,4
   L=L+1
   DICV(L)=0
   DO 10 K=1,4
   J=I+K-1
   IF(DIGIBU(J))DICV(L)=DICV(L)+2**(4-K)
10 CONTINUE
   SLABW=DICV(1)*10000+DICV(2)*1000+DICV(3)*100+DICV(4)*10+DICV(25)
   TSLABW=(SLABW/2240.)+TSLABW
   SLABTW=TSLABW
   RETURN
END.
```

## SUBROUTINE SADC

INTEGER DUMB3(3), ANIBUF(64), SADCB(64), XSADCB(5)

REAL THCOIL, THCGAS, TSLABW

REAL SADC!(64), FXADCB(2), RXADCB(2)

COMMON/BUF3/DUMB3, ANIBUF

COMMON/BUF4/SADCB, XSADCB/BUF5/THCOIL, THCGAS, TSLABW

DO 98 IX=1,64

SADC1 (IX)=ANIBUF (IX)

SADC1 (IX)=SADC1 (IX)\*1.221

98 SADCB (IX)=SADC1 (IX)

C ALL SADCB (IX) ARE IN INPUT ADC MILLIVOLTS DC

IF(1000.GE.SADCB(32))GO TO 4

RSADC3=SADCB(32)

RXADCB(1)=2000.\*((RSADC3-999.)/(4000.))\*0.5

C RXADCB(1) IS OIL FLOW 0-2000 I.G.P.H

GO TO 5

4 SADCB(32)=1000

RXADCB(1)=0

5 XSADCB(1)=RXADCB(1)2000

C 2000 IS DESIGN MAX. OIL FLOW (IGPH)

IF(1000.GE.SADCB(33))GO TO 7

RSADC4=SADCB(33)

RXADCB(2)=71000.\*((RSADC4-999.)/(4000.))\*0.5

GO TO 8

7 SADCB(33)=1000

RXADCB(2)=0.

8 XSADCB(2)=RXADCB(2)

C XSADCB(2) IS TOTAL FUEL GAS FLOW X 10\*\*-1(S.C.F.H)

C 710000 IS DESIGN MAX. GAS FLOW (SCFH)

IF(1000.GE.SADCB(46))GO TO 9

XSADCB(3)=((SADCB(46)-999)\*18)/400)+360

C XSADCB(3) IS GAS CALORIFIC VALUE B.T.U'S PER CU.FT.

GO TO 10

9 SADCB(46)=1000

XSADCB(3)=500

10 XSADCB(4)=((XSADCB(1)\*19)/(36))\*94

C XSADCB(4) IS HEAT CONTENT OF OIL B.T.U'S PER SECOND(0-94000)

C 19000 IS CALORIFIC VALUE OF FUEL OIL IN B.T.U'S PER LB.WEIGHT

C 9.4 IS SPECIFIC GRAVITY OF FUEL OIL LBS/IMP. GALLON

XSADCB(5)=((XSADCB(2)/1000)\*XSADCB(3))/36

C XSADCB(5)- HEAT CONTENT OF GAS IN B.T.U'S PER SECOND X 10\*\*-2

C 3600 IS CONVERSION FROM SCFH TO CU. FEET PER SECOND

C 1000 IS INTEGER SCALING FACTOR

FXADCB(1)=XSADCB(4)/1000

C FXADCB(1) IS HEAT CONTENT OF OIL X 10\*\*-2

THCOIL=FXADCB(1)+THCOIL

C THCOIL IS TOTAL HEAT INPUT OF FUEL OIL

FXADCB(2)=(XSADCB(5)/10)

C FXADCB(2) IS HEAT CONTENT OF GAS X 10\*\*-2

THCGAS=FXADCB(2)+THCGAS

C THCGAS IS TOTAL HEAT INPUT OF C.O.GAS

RETURN

END

```
C      SUBROUTINE SDRO
      SCALING OF "NETA" INTO B.C.D. FOR NIXIE TUBE DISPLAY
      LOGICAL DUMB2(3),DIGOBU(8)
      INTEGER NETA
      COMMON/BUF2/DUMB2,DIGOBU/BUF6/NETA
      IF999.LE.NETA)NETA=99
      NO=NETA/10
      NO=6*NO+NETA
      DO 50 K=1,8
      DIGOBU(K)=.FALSE.
      I=2**(8-K)
      IF(NO-I)50,20,20
20     DIGOBU(K)=.TRUE.
      NO=NO-I
50     CONTINUE
      RETURN
      END
```

```
      SUBROUTINE TODSUB
C      TIME OF DAY CALCULATION
      INTEGER DAY , HOUR , MIN , NETA
      COMMON / BUF 7 / DAY , HOUR , MIN
      MIN = MIN + 1
      IF ( MIN - 60 ) 20 , 1 , 1
1     HOUR = HOUR + 1
      MIN = 0
      IF ( HOUR - 24 ) 20 , 2 , 2
2     DAY = DAY + 1
      HOUR = 0
      IF ( DAY - 365 ) 20 , 3 , 3
3     DAY = 1
20    RETURN
      END
```



```

SUBROUTINE TESUB
EXTERNAL SDRO
INTEGER NETA
INTEGER NETA8, HOUR3
REAL THCOIL, THCGAS, TSLABW
REAL THOIL8, THGAS8, THSLB8
REAL TOILBC, TGASHC, TWSLAB, EFFY
COMMON/BUF5/THCOIL, THCGAS, TSLABW/BUF6/NETA
COMMON/BUF8/TOILHC, TGASHC, TWSLAB, EFFY
NETA = ((THCOIL+THCGAS)/TSLABW)/100.
C NETA IS GROSS EFFICIENCY IN BTU./TON OF STEEL PUSHED (10**-6)
TOILHC=THCOIL
TGASHC=THCGAS
TWSLAB=TSLABW
EFFY=NETA
EFFY=EFFY/10.
HOUR8=HOUR3+1
THOIL8=(THCOIL/20.)+THOIL8
THGAS8=(THCGAS/20.)+THGAS8
THSLB8=(TSLABW/20.)+THSLB8
IF (HOUR8-16) 4, 5, 5
5 NETA8 = ((THOIL8+THGAS8)/THSLB8)/100.
THOIL8=0
THGAS8=0
THSLB8=0
HOUR8=0
WRITE (1, 7) NETA8
7 FORMAT (40H LAST 8 HOURS GROSS THERMAL EFFICIENCY =, I5)
4 CONTINUE
THCOIL=0
THCGAS=0
TSLABW=0
C HEAT CONTENT OF FUEL & TONS PUSHED ARE RESET TO ZERO
CALL SDRO
RETURN
END

```

```

SUBROUTINE NIXLOG
C DATA LOGGING OF NIXIE INPUT VARIABLES
INTEGER SADCB(64),XSADCB(5)
INTEGER DAY,HOUR,MIN
REAL TOILHC,TGASHC,TWLAB,EFFY
COMMON/BUF4/SADCB,XSADCB
COMMON/BUF7/DAY,HOUR,MIN
COMMON/BUF8/TOILHC,TGASHC,TWLAB,EFFY
WRITE(1,70) DAY,HOUR,MIN
70 FORMAT(7H DAY.,I3,11H HOUR.,I2,10H MIN.,I2/)
WRITE(1,71)XSADCB(1),XSADCB(2),XSADCB(3)
71 FORMAT(23H TCTAL OIL (IGPH) =,I6/23H TOTAL GAS (SCFH X10
2)=,I6/23H GAS BTU =,I6
WRITE(1,72)EFFY
72 FORMAT(51H GROSS TH. EFF. BTU)TON X10**6 FOR LAST 30 MIN =
2,F8.1)
WRITE(1,74)TOILHC,TGASHC,TWLAB
74 FORMAT(51H HEAT CONTENT OF OIL (BTU X10**6) =
2,F8.1/51H HEAT CONTENT OF GAS (BTU X10**6) =
3,F8.1/51H TOTAL STEEL PUSHED (TONS CURRENT 30MIN) =
4,F8.1//)
WRITE(1,77)
77 FORMAT(1H )
WRITE(1,78)
78 FORMAT(16H -----//))
RETURN
END

```

```

SUBROUTINE CON
EXTERNAL UTZAF,SDAC
C   CON IS SIMPLIFIED U.T.Z. AIR/FUEL RATIO CONTROL
C   UTZAF IS AIR FUEL RATIO -GAS ONLY ON U.T.ZONE
C   GAS FIRING ONLY
LOGICAL ZONEF(4)
INTEGER CONTRL,AUTO,SAFE
REAL SDACB(13)
COMMON/BUF9/SMOKE,CONTRL,AUTO,SAFE/BUF11/SDACB/BUF13/ZONEF
IF (CONTRL-1) 3,4,4
C   CONTRL=1 IS COMPUTER CONTROL SWITCH ON
C   EXIT IF NOT SO; "SWITCH TO AUTO CONTROL" LIGHT OFF
3   SAFE=0
    AUTO=0
    RETURN
4   SAFE=SAFE+1
    IF (SAFE-1) 5,5,6
C   INITIALISE ALL ANALOG OUTPUTS TO SAFE VALUES
C   ZONEF ( ) IS TRUE -OIL & FALSE -GAS
C   SDACB (2) IS ACTUAL AIR SIG./GAS SIG. RATIO
C   2.89 IS 1.7 ON DIAL SQUARED
5   SDACB (1)=2300.
    SDACB (2)=2.89
    SDACB (3)=0.77
    SDACB (4)=2400
    SDACB (5)=1.44
    SDACB (6)=0.77
    SDACB (7)=1.21
    SDACB (8)=0.84
    SDACB (9)=1500
    SDACB (10)=1.44
    SDACB (11)=0.77
    SDACB (12)=0.13
    SDACB (13)=-20.
C   IS OIL OR GAS BEING FIRED?
C   OF NO REAL INTEREST SINCE OIL GAS A/F RATIOS ARE SAME
16  RETURN
C   RETURN WHEN SAFE<2 INITIALISES ON FIRST ENTRY ONLY
C   SETTING SAFE=0 CAUSES REINITIALISATION
6   IF (SAFE-130000) 7,7,8
C   DONT LET "SAFE" OVERFLOW
8   SAFE=2
C   RESET SAFE > 1
7   CALL UTZAF
    CALL SDAC
    RETURN
END

```

```

SUBROUTINE UTZAF
C AIR FUEL RATIO CONTROL FOR GAS ONLY OF ALL ZONES
LOGICAL ZONEF(4)
INTEGER CONTRL,AUTOC,SAFE
REAL SDACB(13)
REAL RXADCB(25),THE20A(8),THE10A(8),NEWAFR(24),CAIRFR(24)
COMMON/BUF9/SMOKE,CONTRL,AUTOC,SAFE/BUF11/SDACB/BUF13/ZONEF
COMMON/CONLNK/RXADCB,NEWAFR,CAIRFR,THE20A,THE10A,THECA,STH2A,
2STH1A,STHOA
N=0
IA=0
24 IA=IA+1
IF(IA-5) 20,21,21
21 RETURN
20 NB=2
IF(IA-(IA/2)*2) 22,23,22
23 NB=3
22 N=N+NB
DA2UTZ=(RXADCB(IA+5)-THE20A(IA+4))
IF(DA2UTZ) 30,30,31
C DA2UTZ IS DIFFERENCE BETWEEN RXADCB(7)-UTZ AIR AND
C THE20A(6)-UTZ 20% EXCESS AIR : 30=NO,31=YES
30 DIFF20=(DA2UTZ/RXADCB(IA+5)-(RXADCB(IA+5)/100.))
IF(DIFF20) 33,33,34
C 34 1%; 33 1%
34 NEWAFR(IA+20)=((11./12.)*NEWAFR(IA+20)*(1.+(DA2UTZ/RXADCB(IA+
25))))
33 SDACB(N)=NEWAFR(IA+20)
GO TO 24
31 DALUTZ=(RXADCB(IA+5)-THE10A(IA+4))
C COMBUSTION 20% EXCESS AIR
IF(DALUTZ) 36,36,37
36 DIFF10=((DALUTZ/RXADCB(IA+5))-(RXADCB(IA+5)/100.))
IF(DIFF10) 38,38,39
39 NEWAFR(IA+12)=((11./12.)*NEWAFR(IA+12)*(1.+(DALUTZ/RXADCB(IA+
25))))
38 SDACB(N)=NEWAFR(IA+12)
GO TO 24
37 SDACB(N)=CAIRFR(IA+4)
GO TO 24
END

```

## APPENDIX 5

DESCRIPTION OF PROGRAM TO TAKE CARE OF INSTRUMENT

FAILURES AND COMPUTER FAILURES

Description of Program to Take Care of Instrument  
Failures and Computer Failures

This program has not been completed. The following is a list of guide lines along which the program is being prepared.

1. Sudden Instrument Failures

These can be detected by storing high and low limit values on all signals in the core memory and carrying out periodical checks for alarm conditions. When alarm conditions are detected, an alarm message is printed out and the computer disregards the suspected signal and uses a prestored emergency value.

2. Gradual Instrument Failures

These gradual failures are much harder to take care of. The only possible way of detecting them is the provision of a table of reasonable signal levels and rates of level changes. For example, the computer may check the rate of temperature rise for a given slab thickness and fuel flow rates. If it is much slower than the usual rate, an alarm message will be printed out, and the computer will disregard

the suspected signal and use a prestored safe value.

### 3. Complete Computer Failure

When the computer fails completely, a master control relay will automatically put all controllers back to the local set point control. The master relay is held in by a computer pulse signal which updates once per 50 ms. Hence, when the computer stops functioning, the relay drops out within 50 ms.

### 4. Partial Computer Failures

These types of failures are the most troublesome and are difficult to take care of. A great deal of effort and core memory are needed to develop a foolproof program to guard against partial computer failures. At present, the simple method of checking parity is used. Whenever a parity error occurs, an alarm message is printed out and the master relay dropped out.

## APPENDIX 6

SLAB DATA MANUAL INPUT STATION



OPERATING INSTRUCTIONS  
PUSHER'S DATA INPUT STATION

I. FUNCTION

To supply slab details to the computer.

II. EQUIPMENT DESCRIPTION

A. Top row of 5 indicating lights:

- (i) Power ON.
- (ii) Computer Malfunction.
- (iii) Slab not ready.
- (iv) Next slab ready.
- (v) Second row slab ready.

B. Middle row of 27 thumbwheel switches:

- (i) Door (1 off 0 - 9)
- (ii) Slab width (3 off 0 - 9)
- (iii) Slab thickness (3 off 0 - 9)
- (iv) Slab length (3 off 0 - 9)
- (v) Slab identification (2 off A - Z  
3 off 0 - 9  
5 off 0 - 9)
- (vi) Steel grade (5 off 0 - 9)

C. Bottom row of 6 indicating push-buttons:

- (i) Slab not charged.
- (ii) Test (lamps).

- (iii) Cancel.
- (iv) Last slab data incorrect.
- (v) Slab data entry.
- (vi) Slab data set.

### III. SYSTEM DESCRIPTIONS

#### A. Charging door numbers:

Furnace 2, Door 1	Allocated No. - 1
Furnace 2, Door 2	Allocated No. - 2
Furnace 2, Doors 1 and 2	Allocated No. - 5
(i.e., long slabs)	
Furnace 1, Door 1	Allocated No. - 3
Furnace 1, Door 2	Allocated No. - 4
Furnace 1, Doors 1 and 2	Allocated No. - 6

#### B. Slab Identification Numbers

Represented by 2 alphabetic characters and 3 numeric numbers. The alphabet consists of only 8 characters split into 2 switches.

First switch contains:

A, B, C, D, F, H, K, L, M, -

Second switch contains:

N, P, R, S, T, W, X, Y, Z, -

e.g., /-Z/B-/9/9/9/ is a typical number.

#### C. Lamp Test

To test all lamps on the input station, press "Test" button. Ring Instrument Fitter

S792 for new lamps.

#### IV. OPERATING PROCEDURES

Four cases may be encountered:

- A. Normal loading of Slab Data.
- B. Loading of Slab Data. Computer questions the authenticity of the data, but data is "Correct".
- C. As in B but data is "Incorrect".
- D. Slab Not Charged Condition. Slab entered into computer but not yet in the furnace proper. It is removed from the charging table so that the associated Slab Data has to be cancelled.

##### A. Normal Loading of Slab Data

1. Pre-requisites: "Power On" - On  
"Computer Malfunction" - Off
2. Enter Slab Data on to the thumbwheel switches, when slab is positioned on the charging roll tables.
3. Press the "Slab Data Set" pushbutton.  
(Computer switches off light on "Slab Entry" and checks the data on the thumbwheel switches, then puts on light on the "Slab Data Set" pushbutton since data is correct.)

4. "Slab Data Set" pushbutton light is on.
5. When roller requests slab, press "Slab Entry" pushbutton, then push slab. (Pressing "Slab Entry" is to extinguish the lamps on the "Slab Data Set" pushbutton and also light the "Slab Entry" pushbutton.)
6. Computer switches off "Slab Data Set" lamps on sensing "Slab Entry" and tests if a slab has just left the furnace. If so, it switches on "Slab Entry" pushbutton lamps.

The next slab data is entered in the same manner.

(Note: Two slabs must not be discharged with one pusher without loading another one first.)

B. Loading of Slab Data. Computer questions authenticity of data, and slab data is found to be "Correct".

1. Pre-requisites: "Power On" - On  
"Computer Malfunction" - Off
2. Enter Slab Data on to the thumbwheel switches.
3. Press the "Slab Data Set" pushbutton. (Computer cancels "Slab Entry" light and checks the data on the thumbwheel switches and decides

that it is not satisfactory. Hence it switches on lights on the "Last Slab Data Incorrect" pushbutton. No light on "Slab Data Set".)

4. Computer switches on "Last Slab Data Incorrect" pushbutton lights. (Prints out on Teletype that Slab Data is incorrect.)
5. Operator checks Slab Data on thumbwheels. In this case the data is in fact correct, thus he presses the "Cancel" pushbutton.
6. On sensing "Cancel", the computer will cancel the "Last Slab Data Incorrect" light and accept the original Slab Data entered. Then the computer lights the "Slab Data Set" pushbutton light.
7. Press "Slab Entry" pushbutton, then push slab (when roller requests slab).
8. Computer switches off "Slab Data Set" lamps and switches on "Slab Entry" lamps.

C. Loading of Slab Data. Computer questions the authenticity of the data, and data found to be "Incorrect".

1. Pre-requisites: "Power On" - On  
"Computer Malfunction" = Off
2. Enter Slab Data on to the thumbwheel switches.

3. Press the "Slab Data Set" pushbutton.  
(Computer cancels "Slab Entry" light and checks the data on the thumbwheel switches and decides that it is not satisfactory. Hence it switches on lights on the "Last Slab Data Incorrect" pushbutton. No lights appear on the "Slab Data Set" pushbutton.)
4. Computer switches on "Last Slab Data Incorrect" pushbutton light.
5. Data is incorrect. Press "Last Slab Data Incorrect" pushbutton. (Computer then deletes the last slab data entered and switches off the "Last Slab Data Incorrect" pushbutton light.)
6. The data input station is now returned to its original state and will accept input information as usual.

D. Removal of Slab from the Furnace Charging Table after its associated Slab Data has been entered into the Computer.

1. Pre-requisites: "Power On" - On  
"Computer Malfunction" - Off
2. Enter Slab Data on thumbwheel switches.
3. Press the "Slab Data Set" pushbutton.
4. Computer switches on "Slab Data Set" pushbutton

light.

5. Press "Slab Entry" pushbutton.
6. Computer switches on "Slab Entry" pushbutton lights and switches off "Slab Data Set" pushbutton lights.
7. Push slab and repeat from 1.

Now it is decided that the slab previously entered cannot be rolled. Thus the Pusher operator is faced with the position that he has told the computer that this slab is coming and has to cancel this information. This slab may be two or three slabs "ago" as far as his slab entry station is concerned. The procedure to rectify this position is as follows:

8. Enter the data of the withdrawn slab on thumbwheels.
9. Press "Slab Data Set" pushbutton.
10. Computer checks and finds this slab is not consecutive to the last one, hence it switches on "Last Slab Data Incorrect".
11. Press "Slab Not Charged" pushbutton.  
(Computer searches for the serial number in the buffer which corresponds to this and wipes

it, then shifts all previous serial numbers by one place to fill in the blank space.)

12. When completed, computer switches on "Slab Not Charged" light, which is only switched off the next time the "Slab Data Set" push-button is pressed.



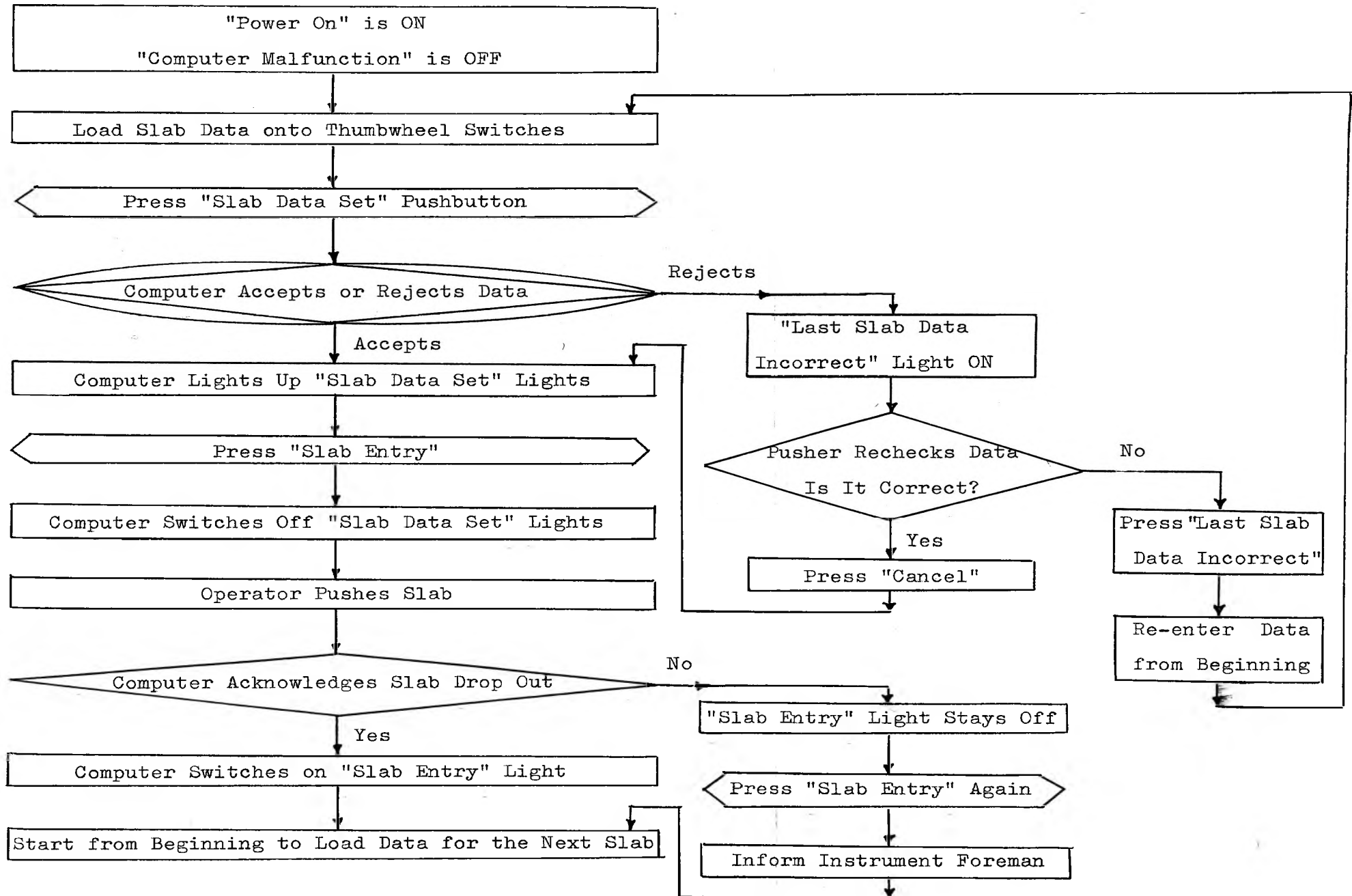


Fig. A6.1 Block Diagram of Pusher Input Station Operating Procedure

DATA INPUT STATIONCONVERSION OF LOGICAL INPUT SIGNALS TO USEABLE VALUES

## NOTES:

1. Total number of logical inputs = 180  
Named DIGIBU (I) where I = 1 to 180
2. These 180 inputs are divided into 2 Sections:  
Section (a) 1 to 54 are scanned once every 50 ms.  
Section (b) 55 to 180 are scanned only when  
DIGIBU ( ) is TRUE but tested once per 50 ms.
3. From the list it can be seen that the information  
to be converted is contained in No.55 to No.180.
4. This conversion will be treated as one indepen-  
dent subroutine, serviced once every 50 ms.
5. The start of the subroutine will test if  
DIGIBU ( ) is TRUE. If not, skip the rest and  
return to Timer control. If TRUE, then  
complete the whole subroutine.
6. DIGIBU (I) will be logical inputs, that is, it

will either be TRUE or FALSE.

7. Switch details are represented by the logic inputs. See table below.

<u>Door</u>	<u>Width</u>			<u>Thick- ness</u>			<u>Length</u>			<u>Serial No.</u>							<u>At present Not Used</u>			<u>Grade</u>					
	1	2	3	1	2	3	1	2	3	1	2	3	4	5	6	7				1	2	3	4	5	
A	6	2	5	1	0	5	1	0	8	A	-	-	R	9	8	9	9	9	9						

8. List of values each decade switch can take:

(See next page)

## 8. List of values each decade switch can take:

	0	1	2	3	4	5	6	7	8	9
Door	0	1	2	3	4	5	6	7	8	9
Width 1	0	1	2	3	4	5	6	7	8	9
Width 2	0	1	2	3	4	5	6	7	8	9
Width 3	0	1	2	3	4	5	6	7	8	9
Thickness 1	0	1	2	3	4	5	6	7	8	9
Thickness 2	0	1	2	3	4	5	6	7	8	9
Thickness 3	0	1	2	3	4	5	6	7	8	9
Length 1	0	1	2	3	4	5	6	7	8	9
Length 2	0	1	2	3	4	5	6	7	8	9
Length 3	0	1	2	3	4	5	6	7	8	9
Serial 1	A	B	C	D	F	H	K	L	M	-
Serial 2	N	P	R	S	T	W	X	Y	Z	-
Serial 3	A	B	C	D	F	H	K	L	M	-
Serial 4	N	P	R	S	T	W	X	Y	Z	-
Serial 5	0	1	2	3	4	5	6	7	8	9
Serial 6	0	1	2	3	4	5	6	7	8	9
Serial 7	0	1	2	3	4	5	6	7	8	9
Grade 1	0	1	2	3	4	5	6	7	8	9
Grade 2	0	1	2	3	4	5	6	7	8	9
Grade 3	0	1	2	3	4	5	6	7	8	9
Grade 4	0	1	2	3	4	5	6	7	8	9
Grade 5	0	1	2	3	4	5	6	7	8	9

9. Each decade is represented by 4 bits (BCD). The smallest number of the 4 bits always represents the least significant bit. For example,

DIGIBU (55)	1)	}	Door
" (56)	2)		
" (57)	4)		
" (58)	8)		
" (59)	1)	<hr/>	
" (60)	2)	}	Width first digit
" (61)	4)		
" (62)	8)		

10. In the case of numerics, work out what the decimal number is from the BCD, and then multiply by 100 if the first digit and multiply by 10 if the second digit. When 3 digits of, say, width is worked out, add them together to obtain the final value. For example,

DIGIBU (59)	FALSE)	}	First digit
" (60)	TRUE)		
" (61)	TRUE)		
" (62)	FALSE)		

DIGIBU (63)	FALSE)	} Second digit
" (64)	TRUE )	
" (65)	FALSE)	
" (66)	FALSE)	
" (67)	TRUE )	} Third digit
" (68)	FALSE)	
" (69)	TRUE )	
" (70)	FALSE)	

Then, 59 is false. Let it =  $0 \times 1 = 0$   
 60 is true. Let it =  $1 \times 2 = 2$   
 61 is true. Let it =  $1 \times 4 = 4$   
 62 is false. Let it =  $0 \times 8 = \underline{0}$

Sum	6
	=

And, since it is the first digit,  $6 \times 100 = 600$   
 and let WIDTH = 600.

Now, 63 is false, =  $0 \times 1 = 0$   
 64 is true, =  $1 \times 2 = 2$   
 65 is false, =  $0 \times 4 = 0$   
 66 is false, =  $0 \times 8 = \underline{0}$

Sum	2
	=

Since it is the second digit,  $2 \times 10 = 20$ .

Add 20 to WIDTH,  $20 + 600 = 620$ . Now WIDTH = 620.

Again, 67 is true,  $= 1 \times 1 = 1$

68 is false,  $= 0 \times 2 = 0$

69 is true,  $= 1 \times 4 = 4$

70 is false,  $= 0 \times 8 = \underline{0}$

Sum           5  
=

Since it is the third digit,  $5 \times 1 = 5$ . Add 5 to WIDTH,  $620 + 5 = 625$ . Now WIDTH = 625, which is the final value of WIDTH. Keep it in Integer form.

#### 11. Table of Units:

Width           0.1 inch

Thickness       0.1 inch

Length           1.0 inch

Other digits have no units.

#### 12. For Alphabetic Digits:

Use same method to work out what numerical value each digit is, then convert it to the appropriate alphabetic digit in accordance with the table.

This means storing of a table for serial numbers.

## APPENDIX 7

FURNACE OPERATING PROCEDURES UNDER COMPUTER  
CONTROL

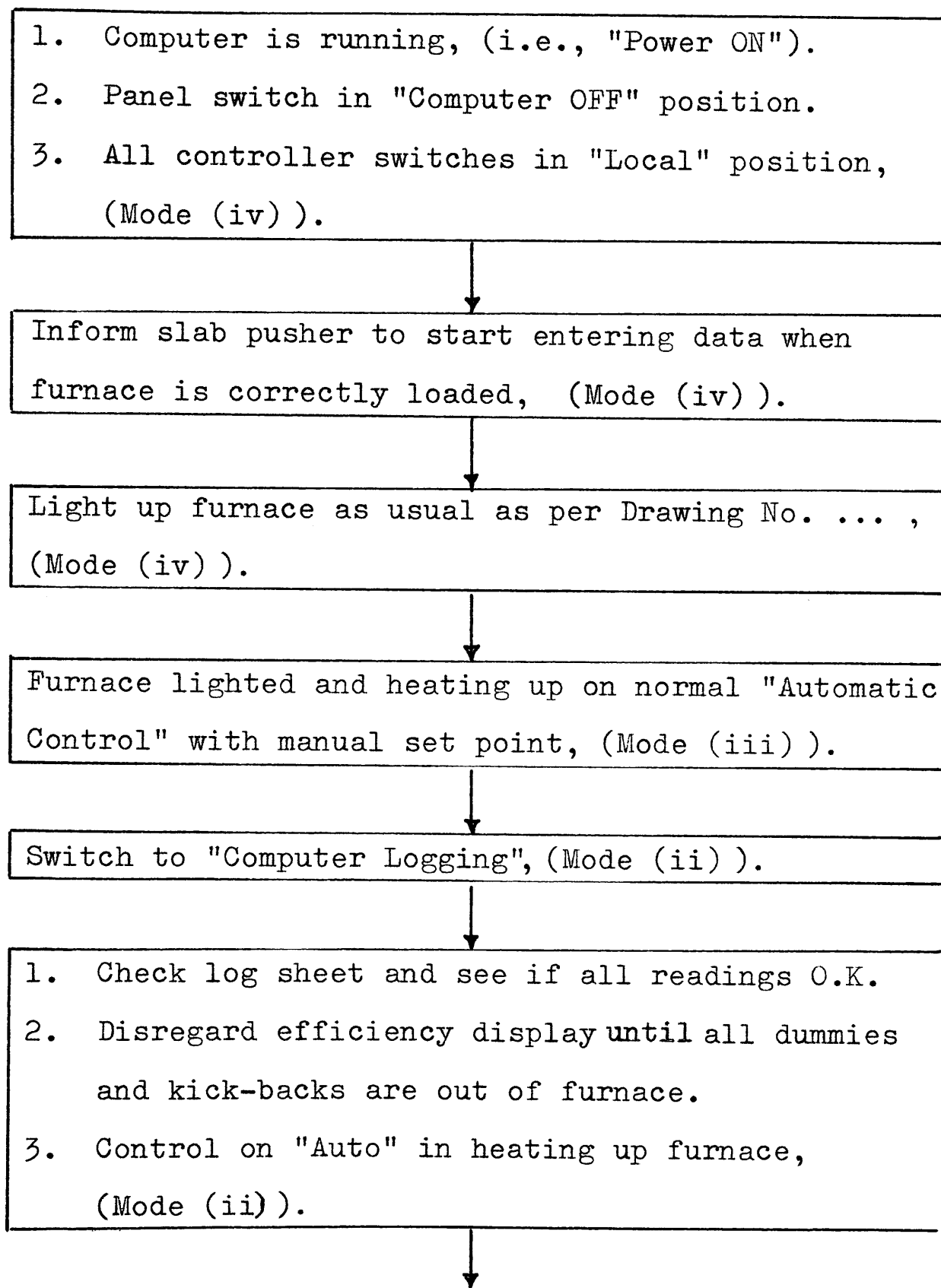


AUSTRALIAN IRON & STEEL PTY. LTD., PORT KEMBLANO.2 REHEAT FURNACE OPERATING PROCEDURES140"PLATE MILLMODES OF CONTROL

- (i) Complete Computer Control.
- (ii) Computer Logging Only, Instruments on Automatic Control. (Manual Set Point Adjustment).
- (iii) Computer OFF, Instruments on Automatic Control. (Manual Set Point Adjustment).
- (iv) Computer OFF, Instruments Control Off. Control from Manual Output Knob of Temperature Controllers.

TABLE OF OPERATING PROCEDURES

- Table 1. Start-up Procedure.
- Table 2. Normal Operating Procedures.
- Table 3. Changing from Mode (i) to Modes (ii) or (iii).
- Table 4. Changing from Mode (i) to Mode (iv).
- Table 5. Changing from Mode (iii) to Modes (ii) and (i).
- Table 6. Changing from Mode (iv) to Mode (iii).
- Table 7. On-demand Print-out.

TABLE 1. START-UP PROCEDURE - PRELIMINARY

1. Observe "Slab In", "Slab Out" log.
2. When "Slab Out", start printing slab number, check if it is the last slab pushed out. If so, computer now has all necessary data to take over control.

Switch to "Computer Control", (Mode (i)).

Observe log sheet and see if the "Measured Values" column is gradually approaching the "S.P." column. If so, then computer is correctly controlling.

See Table 2 for "Normal Operating Procedures".

TABLE 2. NORMAL OPERATING PROCEDURES1. "Next Slab Ready" Indicator

If "Next Slab Ready" light is not lighted, operator should ring Mill Roller and call for a heat delay. He should press the button "Slab Too Cold".

Note:

Do not press "Delay" button, which is only for delays not caused by furnace.

2. "Second Row Slab Ready" Indicator

If this indicator is not lighted consistently, operator should push the button "Fast Pushing" to let the computer change to a different strategy, which considers efficiency as low priority.

3. Pushing Rate Pushbuttons

"Fast Pushing", "Normal Pushing" and "Slow Pushing" pushbuttons are to be pressed by the operator as conditions require. Examples are as follows:

- (i) Say 6" slabs are normally pushed at the rate of about 1 ft per minute and is

suddenly sped up to 1.25 ft per minute. The "Fast Pushing" button should be pressed to allow the computer to change strategy to cop with this.

- (ii) Similarly, if pushing is suddenly slowed to 0.80 ft per minute, the "Slow Pushing" button should be pressed to enable the computer to adjust control strategy and also to prevent the computer seeing it as a "short delay".

4. "Computer Malfunction" Indicator

This light is normally off. If it lights up, follow Table 3 and change to Control Mode (ii). Then call Instrument Foreman.

5. "Instrument Malfunction" Indicator

If this lights up, check alarm logger and see what is the fault. If fault is unimportant, do not change mode of control and call Instrument Foreman. If a fault is serious, e.g., "S.Z. Pyrometer Burned Out", follow Table 3 and change to Mode (ii) control. Then call Instrument Foreman.

6. "Delay" Pushbuttons

These are the most important pieces of information which the computer cannot get from any other source. If there are to be delays, the operator should press the appropriate pushbuttons, so that the furnace temperature profile can be readjusted to suit.

7. On-demand Data Print-out

Tabulated data, such as "Slabs in the Furnace at Present", etc., can be printed out on the alarm logger on-demand from the operator. For procedure of requesting print-out, see Table 7, "On-demand Print-out".

8. Furnace Efficiency Display

This is primarily for furnace control. If efficiency is lower than usual and the furnace is on "Computer Control", the operator should check the furnace for excessive leakage in collection box, furnace recuperators, etc., and call for Instrument Foreman to check all instruments.

9. Fuel Switches

Operator can switch from gas to oil (or vice

versa) as requested by Gas Control Station. No other instruction needs to be provided to the computer as the switches are directly monitored by the computer.

10. Furnace Pressure Control Switch

This is normally on "Back End" (U. Tonnage Zone). The pressure in the back end of the furnace is controlled via the main stack damper. When desired, it may be switched to "Front End", and the front end pressure of the furnace will be controlled via the main stack damper as well. (It is normally controlled via the auxiliary stack damper).

TABLE 3. CHANGING FROM MODE (i) TO MODES (ii)  
OR (iii)

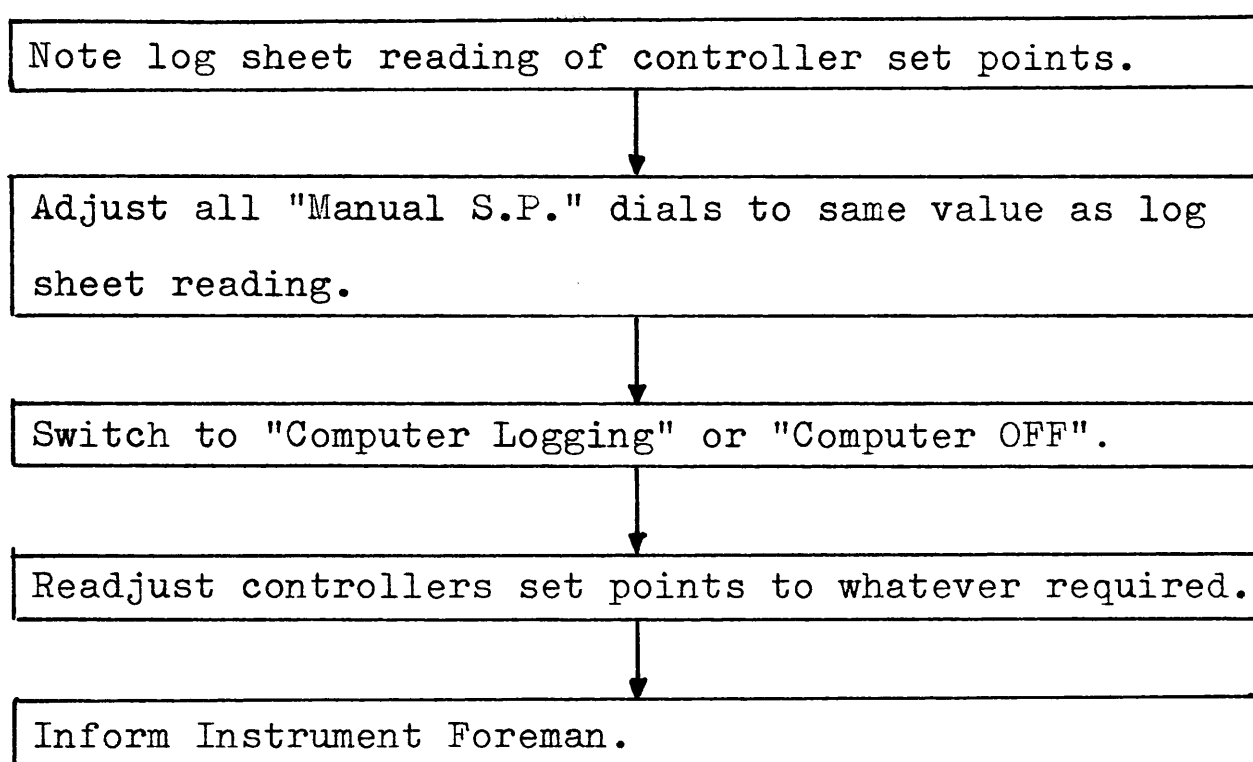




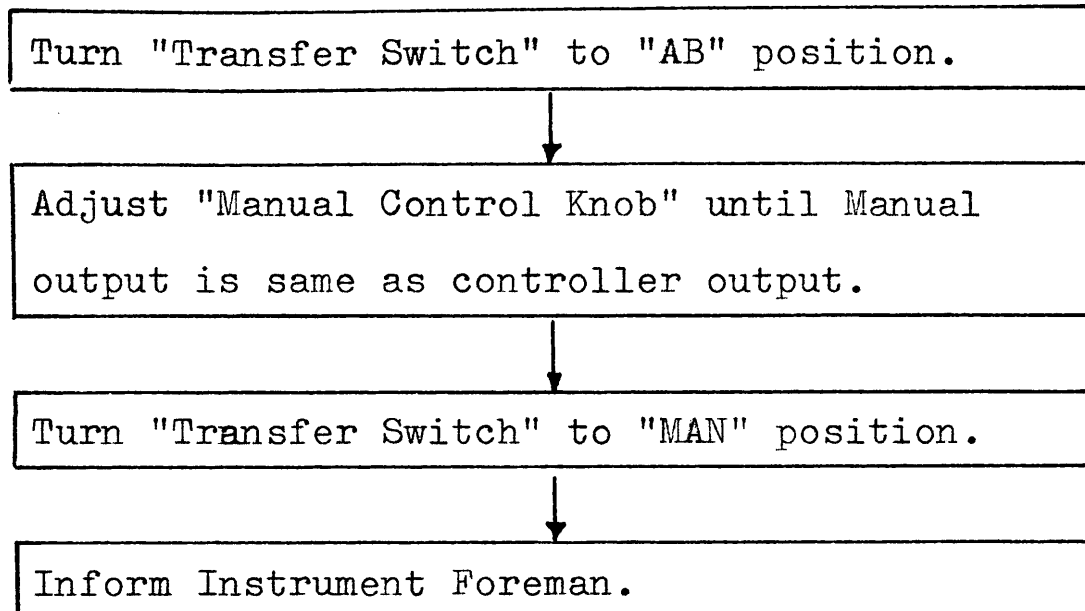
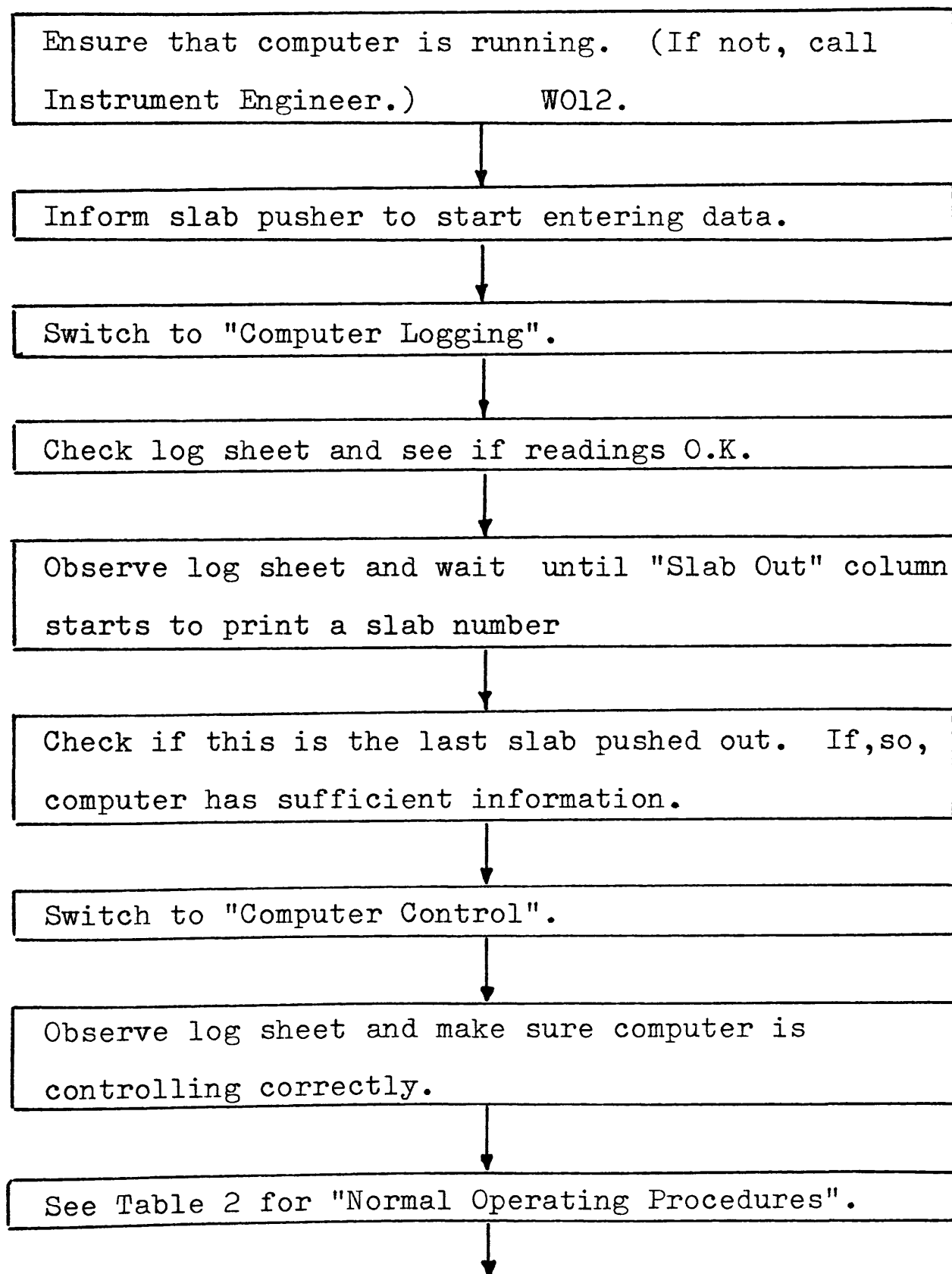
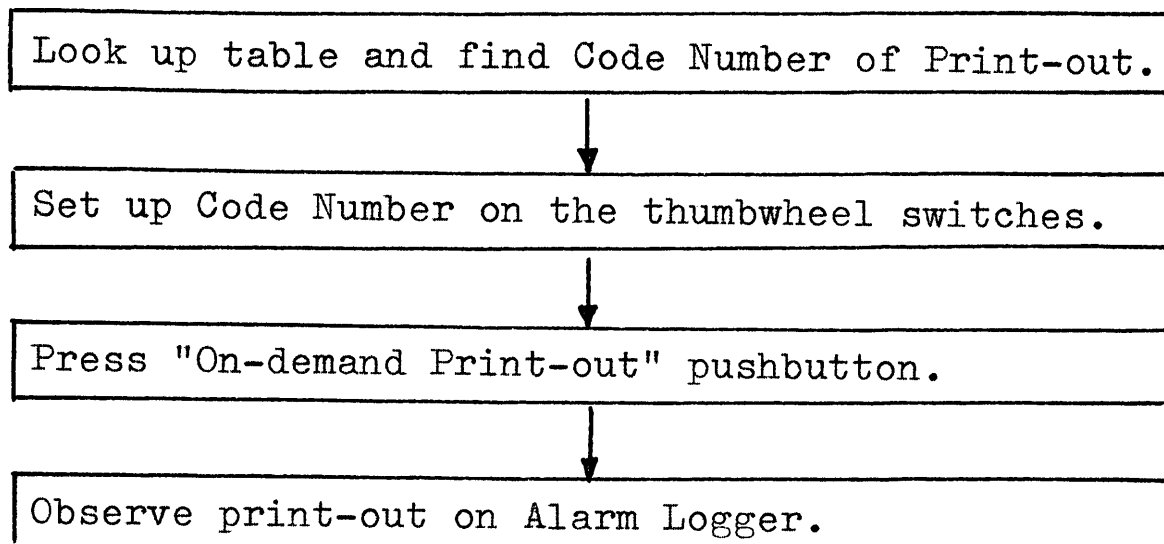
TABLE 4. CHANGING FROM MODE (i) TO MODE (iv)

TABLE 5. CHANGING FROM MODE (iii) TO MODE (ii)  
AND MODE (i)



Turn "Transfer Switch" directly from "MAN" position to "AUTO" position, on temperature controllers only.

TABLE 7. ON-DEMAND PRINT-OUTNote:

1. This input is not as closely interlocked as the Pusher Data Input Station.
2. Only one pushbutton operation is required.
3. In case the computer did not register the request, just press the pushbutton once more.
4. When the pushbutton is pressed, the lamp will light up for the duration the button is depressed.
5. As soon as the lamp is lighted, the computer should have acknowledged the request.

## APPENDIX 8

A COMPUTER PROGRAM FOR DDC OPERATION

## A Computer Program for DDC Operation

This program compares 18 set values with 18 measured values, calculates the differences, and stores three control words, C1, C2 and C3 for transmission to the stepping motors. This routine takes less than 1.01 milliseconds, and is obeyed once per second.

Note: Suggest storage as 18 words of set values, 18 words of measured values, 18 words of differences and 18 words of temporary controls as one block of 72 words. For this program to work, the temporary control block must immediately follow the differences block.

This program takes 3 control words, and updates them from 18 stored increments (or decrements). It requires 241.6 microseconds, and is obeyed once every 25 milliseconds.

Page Addr	Tag	Instn	I	Z	Address	Comments
0	setp,	cla				
1		tad			seta	/address of Set values -1
2		dca		z	nset	/nset is auto index register
3		tad			acta	/address of measured values -1
4		dca		z	nact	/nact is aut 2
5		tad			difa	/address of differences -1
6		dca		z	ndif	/ndif is aut 3
7		tad			cona	/address is temporary control words -1
10		dca		z	ncon	/ncon is auto index 4
11		tad			m 18	/count of -18
12		dca			cnt	/store loop counter
13	look,	tad	i	z	nset	
14		c11			cma iac	/ (- set value)
15		tad	i	z	nact	/ (measured - set value) = difference
16		sna				/skip if not zero
17		jmp			zero	
20		sma				/skip if minus (i.e. set > measured)
21		cml			cma iac	
22		dca		z	ndif	/always store negative difference
23		cla			ral	
24		c11			cml	
25		ral				
26	zeri,	dca	i	z	ncon	/unless difference = 0, store "move" bit and maybe "up" bit

Page Addr	Tag	Instn	I	Z	Address	Comments
27		isz			cnt	/stored 18 differences yet?
30		jmp			look	/go back to calculate next diffs, etc.
31		jms			cnvt	/convert first 6 temp controls to 1 word
32		dca			c1	
33		jms			cnvt	/convert second 6 temp controls to 1 word
34		dca			c2	
35		jms			cnvt	/convert third 6 temp controls to 1 word
36		dca			c3	
37		jmp			off	/finished
40	zero,	dca	i	z	ndif	
41		jmp			zeri	
42	cnvt,	Ø				
43		cla			c11 iac	/set AC <sub>11</sub> = 1
44		rtl				
45		tad	i	z	ndif	/add in temporary control
46		szl				/skip if have done less than 6
47		jmp	i		cnvt	/return
50		jmp			.-4	/get next temporary control
72	seta,	set-1				/set is address of first Set value
73	acta,	meas-1				/meas is address of first measured value
74	difa,	diff-1				/diff is address of first difference



Page Addr	Tag	Instn	I	Z	Address	Comments
75	cona,	contr-1				/contr is address of first control word.
76	m18,	0-22				/22 octal is 18 decimal
77	cnt,	0				
100	step,	cla				
101		tad			difa	/difa is address of decrements -1
102		dca		z	ndif	/ndif is auto index register 3
103		tad			C1	
104		jms			corr	
105		dca			C1	
106		tad			C2	
107		jms			corr	
110		dca			C2	
111		tad			C3	
112		jms			corr	
113		dca			C3	
114		jmp				/go to next routine or halt (END)
115	corr,	0				
116		rtl				
117		isz	i	z	ndif	
120		cml				
121		cml				/correct 1st controller
122		rtl				
123		isz	i	z	ndif	

Page Addr	Tag	Instn	I	Z	Address	Comments
124		cml				
125		cml				/correct 2nd controller
126		rtl				
127		isz	i	z	ndif	
130		cml				
131		cml				/correct 3rd controller
132		rtl				
133		isz	i	z	ndif	
134		cml				
135		cml				/correct 4th controller
136		rtl				
137		isz	i	z	ndif	
140		cml				
141		cml				/correct 5th controller
142		rtl				
143		isz	i	z	ndif	
144		cml				
145		cml				/correct 6th controller
146		ral				/allow for link
147		jmp	i		corr	
150	C1,	∅				
151	C2,	∅				
152	C3,	∅				

## APPENDIX 9

TERMINOLOGY USED IN ROLLING MILLS

AND REHEAT FURNACES

Terminology Used in Rolling Mills  
and Reheat Furnaces

1. Slab Reheat Furnace

A slab reheat furnace is used to reheat cold steel slabs to uniform rolling temperature for the rolling mills. It consists of a number of heating zones which may vary from one to five depending on the type and sizes of slabs to be heated. Each heating zone is fired by a row of burners which may fire either gas or oil, together with combustion air. Conventional reheat furnaces are counter-flow type where slabs are pushed along horizontally through the furnace in the reversed direction of the fuel flow.

2. Slab, Bloom, Billet

Reheat furnaces may be used to heat slabs, blooms or billets. Small ones used to roll merchant bars and rods, etc. are called billets. Medium sized ones used to roll billets or large RSJ's, etc. are called blooms. The large flat ones for rolling plates and strips are called slabs.

3. Plate, Strip

Plates are steel products of a minimum of  $\frac{1}{4}$ " thickness and widely varying widths and lengths. Strips are thin sections less than  $\frac{1}{4}$ " thick. They have fairly consistent width of about 60" and length up to several thousand feet.

#### 4. Roughing Stand

This is generally a reversing mill used to roll the large slabs to a size the finishing mill can cope with.

#### 5. Reversing Mill

This is generally a single stand DC motor operated mill, used to roll steel ingots into slabs or to roll slabs into plates. Some steam operated reversing mills are still in operations.

#### 6. Finishing Mill

This is generally a multi-stand mill operating in one direction only, but with variable speed. It is used to roll plates or pre-rolled slabs to coils of thin strips.

#### 7. Soak Zone

This is the last zone of a reheat furnace.

It is used to soak out the skid marks and allow the slab centre temperature to catch up with the surface temperature. It has solid hearth.

#### 8. Tonnage Zone

This is the zone where most heat is pumped into the slab. It is divided into Upper and Lower Tonnage Zones and has much larger burners than other zones. The slabs are supported in the middle of the Upper and Lower Zones by a row of water cooled skids.

#### 9. Preheat or Primary Zone

This is the first zone each slab enters. It has large heating capacity because temperature gradient between the cold slabs and flame is very high. But its operation is inefficient because it is too close to the exit. There is insufficient time for the flue gas to transfer the heat before it enters the recuperators.

#### 10. Hearth

The hearth in the soak zone is required to help eliminate the skid marks on slabs. It generally consists of solid skids with loose magnesite fillings.

### 11. Walking Beam Furnace

This is a new type of slab reheat furnace designed mainly to eliminate skid marks problems. Instead of the slabs being pushed through the furnace horizontally, they are placed vertically on their ends and lifted along the furnace periodically by the "walking beam". However, these furnaces are not widely used yet because of mechanical maintenance problems.

### 12. Skids, Watercooled

Where top and bottom of slabs are heated, the slabs are supported by water cooled skid pipes running longitudinally along the furnace in the direction of slab movement. There are generally four of these longitudinal skids which are in turn supported by cross skids and stand pipes, all water cooled. Where saltwater is available, it is generally used as the cooling water.

### 13. Skids, Solid

In the soak zone, solid stainless steel skids are set into the hearth brickwork. These skids are generally staggered to minimise the contact with skid marks caused by the water cooled

skids. The spaces between the skids are filled with loose magnesite fillings, and the slabs slide (when pushed) across the skids.

#### 14. Blast Furnace Gas

This is the by-product gas from the blast furnace. It contains mainly CO, CO<sub>2</sub>, H<sub>2</sub> and N<sub>2</sub> gases. The calorific value varies from 80 to 120 BTU/ft<sup>3</sup>. It is generally between 80 and 90 BTU/ft<sup>3</sup> for efficient furnaces. It burns with a pale blue non-luminous flame.

#### 15. Coke Ovens Gas

This is the by-product gas from the coke ovens. It contains some CO and CO<sub>2</sub> gases as well as various combinations of hydrocarbon gases. The calorific values are more constant and are generally between 480 to 520 BTU/ft<sup>3</sup>. It ignites more readily than the Blast Furnace Gas and burns with a bright orange luminous flame.

#### 16. Recuperators

Recuperators are counter-flow metallic heat exchangers used to recover some of the heat contained in the waste flue gas. Some are simple



concentric tubes type while others are more elaborate with various types of fins and checkers. Combustion air flows through the outer tube while the hot flue gas flows through the inner tube. For furnaces using BF gas, the recuperators are also used to preheat the BF gas.

#### 17. Heat Delays

These are delays on the entire rolling mill operation caused by the furnace. These could be due to incorrect furnace control procedures resulting in cold slabs or slabs with distinct skid marks. They could also be due to incorrect mill design resulting in rolling capacity exceeding heating capacity by a wide margin.

#### 18. Mill Delays

These are delays caused by other factors, not the furnace. These include delays caused by roll breaks, roll changes, finishing mill hold-ups, etc.

#### 19. Skid Marks

As slabs are pushed along the furnace on the watercooled skids, cold skid marks are formed on

the bottom side of the slabs where they come into contact with the skids. The main function of the soak zone is to soak out these skid marks. If not removed, these cold skid marks result in uneven thickness in the finished plates and strips.

Considerable work has been done in "Automatic Gauge Control" for the mill to overcome these fluctuations in temperature (thus hardness) along the slabs.

## 20. Scales

Scales are the oxidised outer surface (or skin) of a slab. Scale thickness varies, depending on the fuel/air ratios of the burners, and the length of time the slabs have stayed in the furnace. Thin, fragile scales are desirable, as they tend to remove minor surface imperfections and are easy to remove. Thick scales are undesirable as they represent unrecoverable loss of metal. However, it is also undesirable for scales to be too thin, as they tend to stick to the slab surface and become difficult to remove.

## 21. Pushing Rate

Pushing rate is the rate at which slabs are pushed through the furnace. It can be expressed

either in feet per minute or tons per hour.

## 22. Through-put Rate

Because pushing rate can be expressed in two ways, it is becoming customary to use the term "through-put rate" which only means tons per hour.

## 23. Blow-off Valve

This valve is situated in the hot air header for protection of the recuperators. If pressure of hot air is too high or if the temperature is too high, the blow-off valve is opened automatically to relieve the pressure in the hot air main and to increase the volume of cold air entering the recuperator.

## 24. Table Rolls

These are rows of motor-driven rollers used to receive and transport slabs and plates, etc.

## 25. Mill Drafting

This means the preparation of detailed rolling schedules for each slab. This sets out how many passes a particular slab needs to be rolled to the finished plate, and how much reduction per pass.

## APPENDIX 10

EXPERIMENTS ON SLAB TEMPERATURE MEASUREMENT

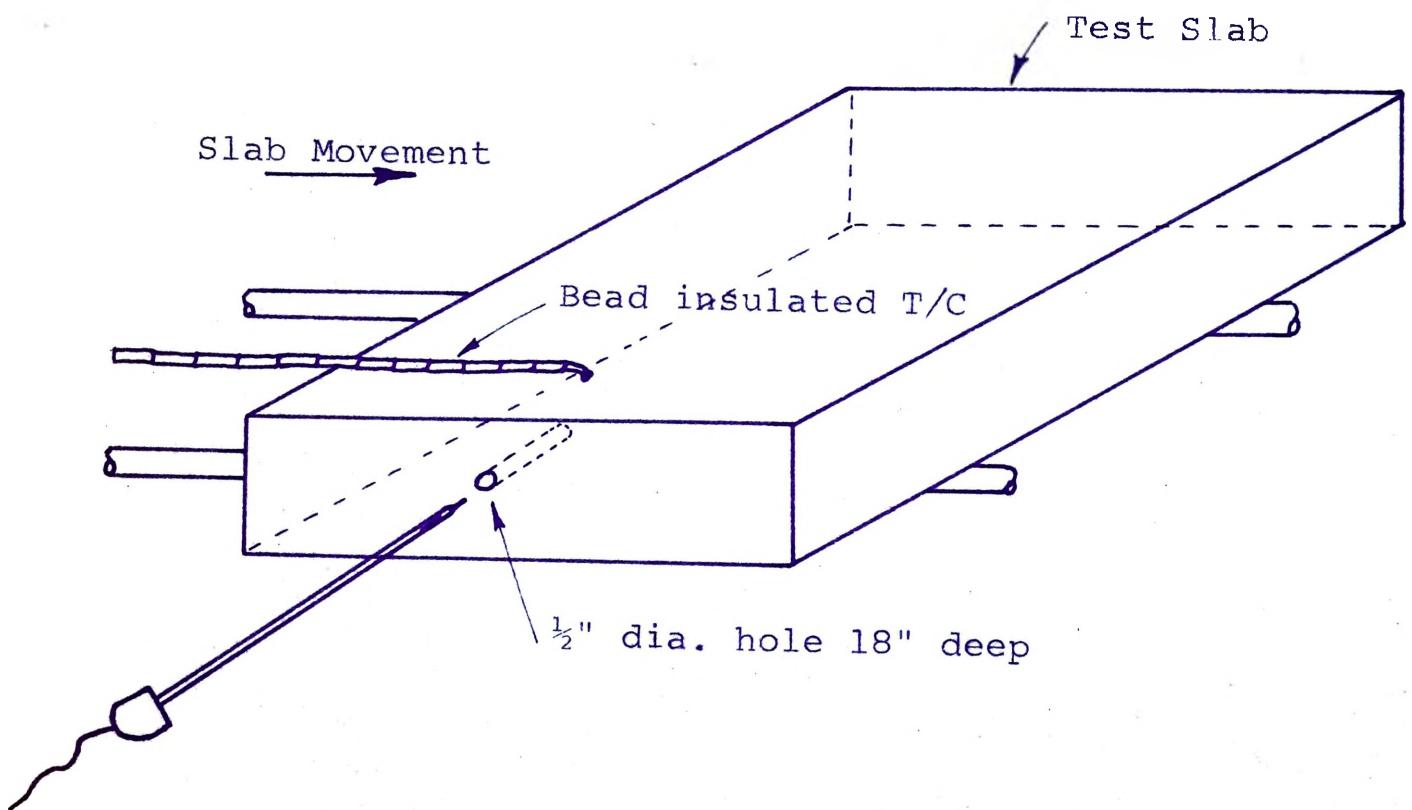


FIG. A1 - First experimental set-up for measuring slab surface temperature and slab centre temperature.

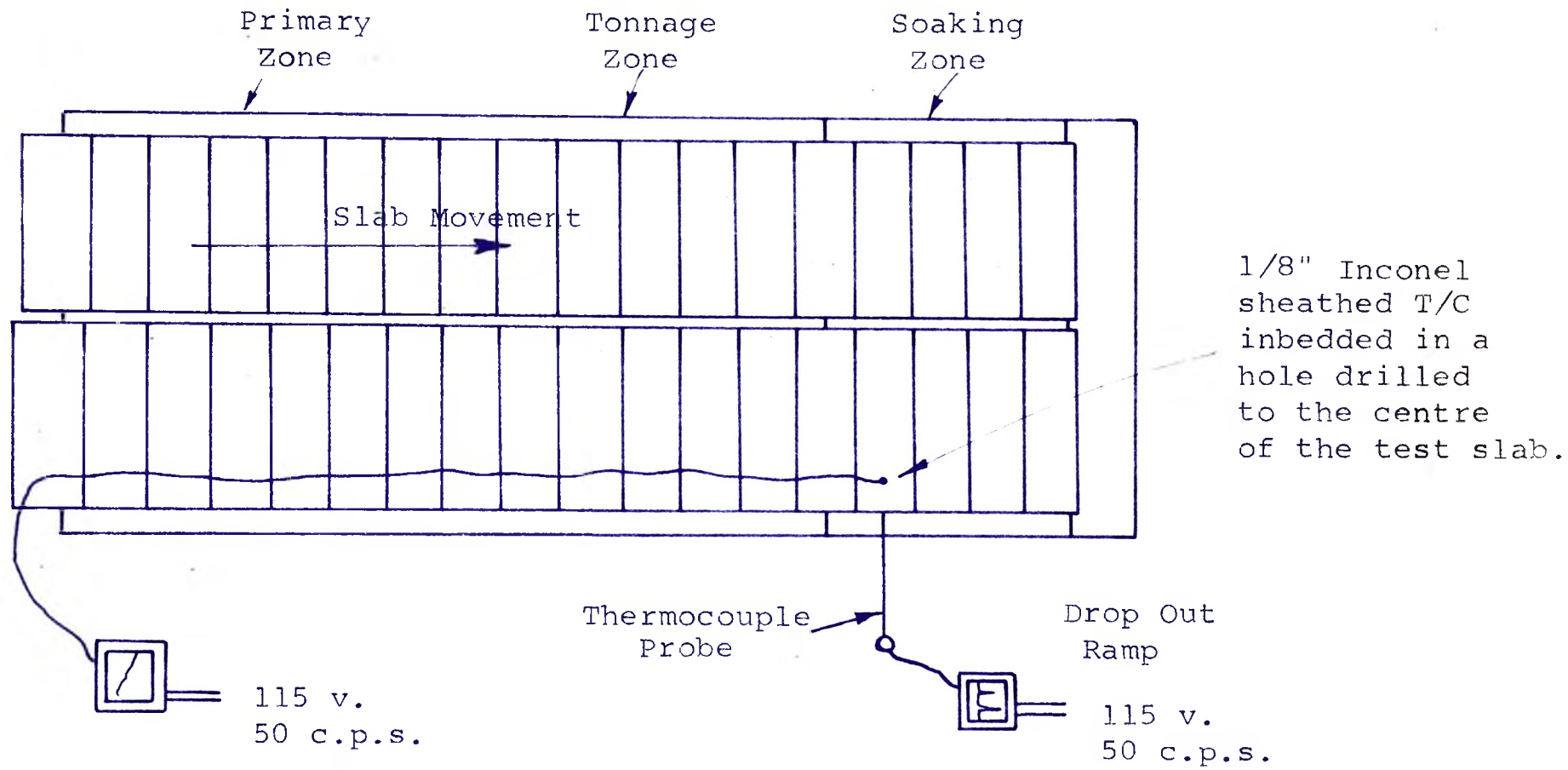
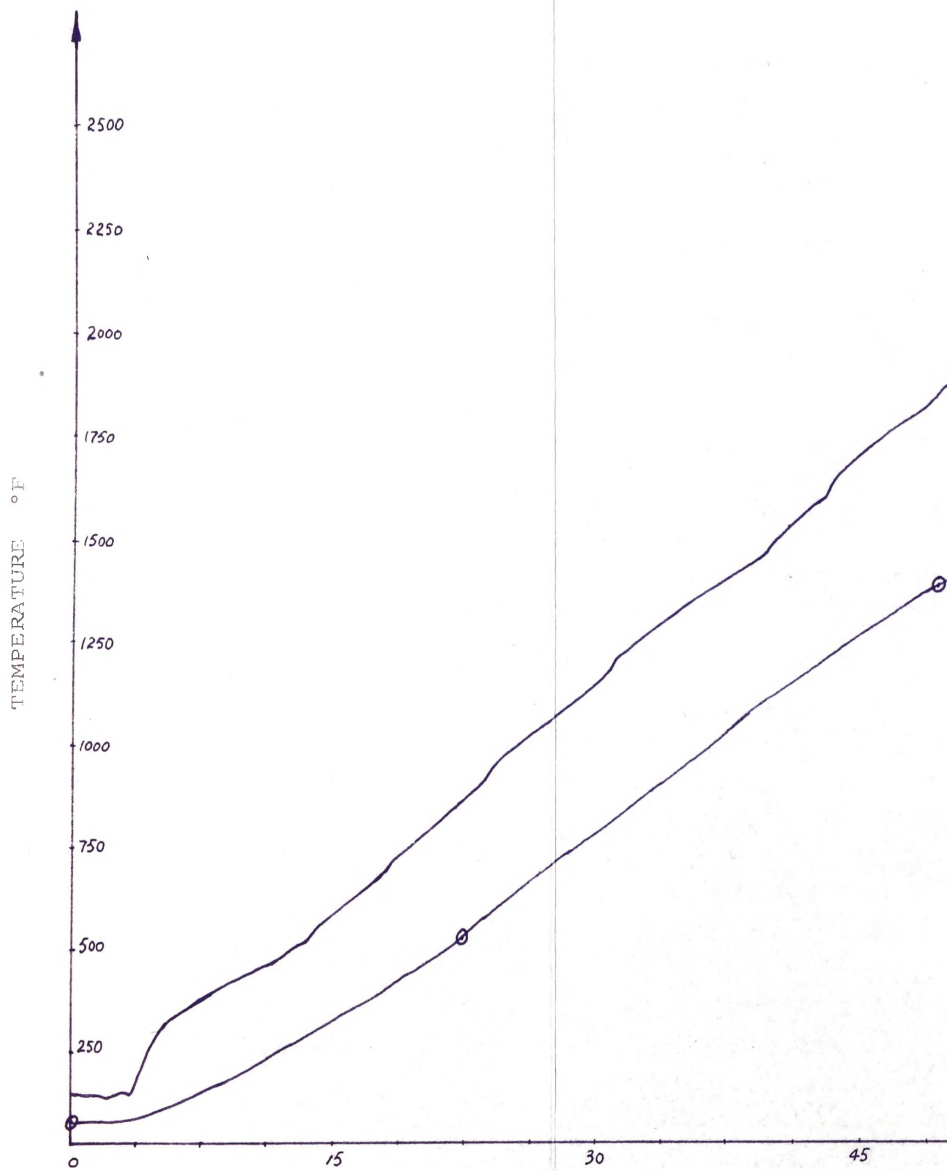


FIG. A2 - Plan view of furnace showing slabs and experimental set-up for testing suitability of inconel sheathed T/C for measuring centre temperature of a slab.



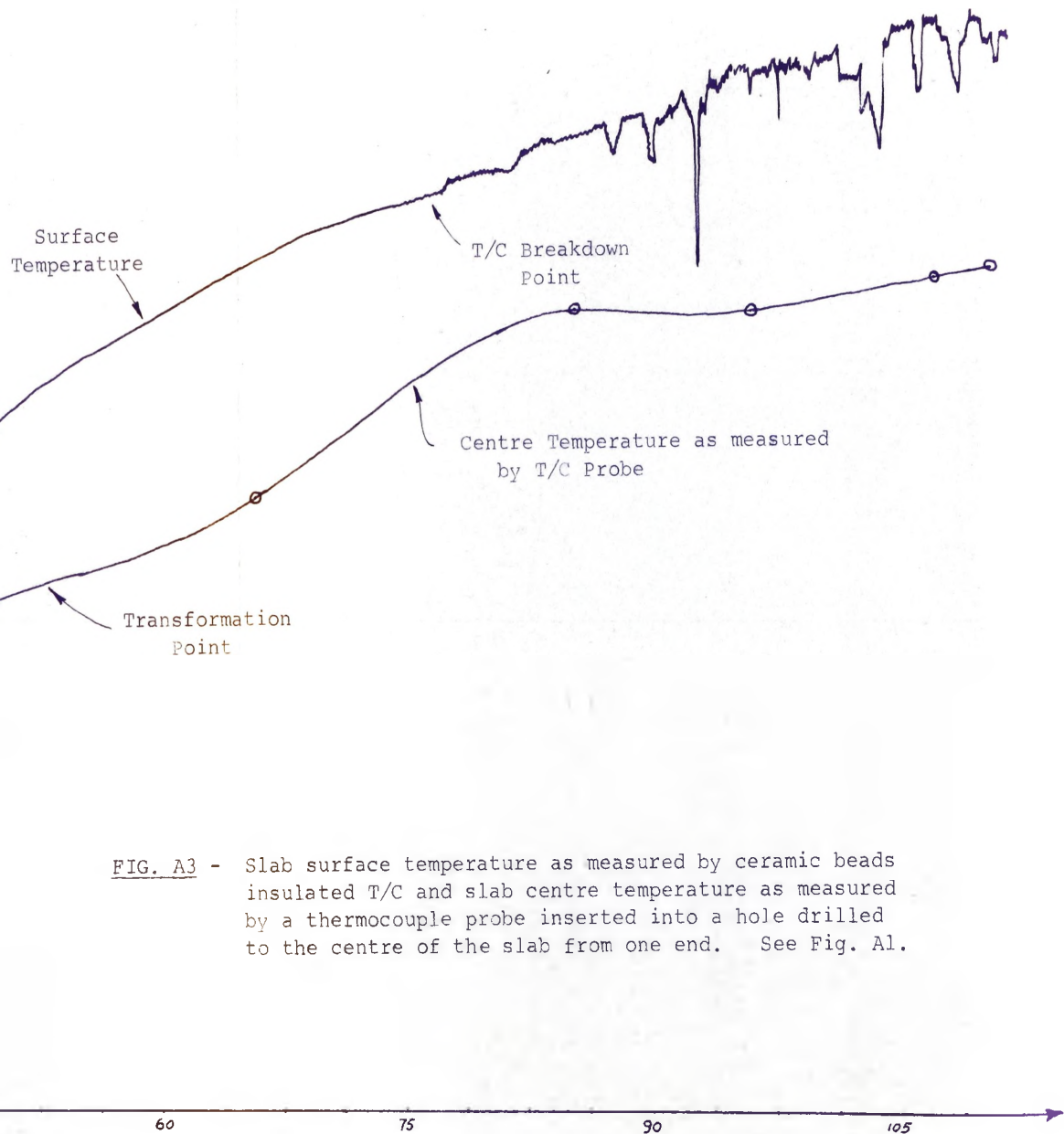


FIG. A3 - Slab surface temperature as measured by ceramic beads insulated T/C and slab centre temperature as measured by a thermocouple probe inserted into a hole drilled to the centre of the slab from one end. See Fig. A1.



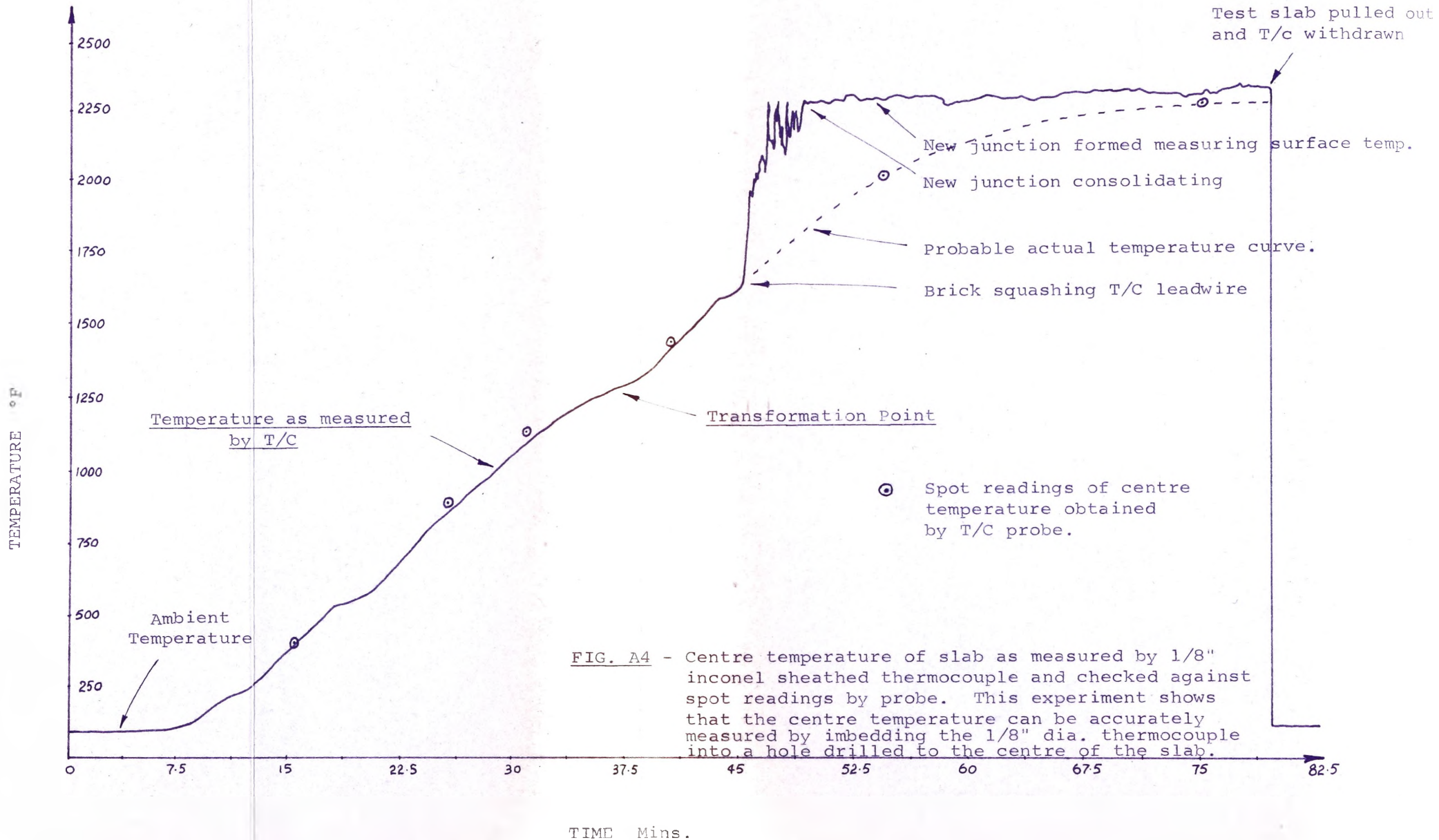


FIG. A4 - Centre temperature of slab as measured by 1/8" inconel sheathed thermocouple and checked against spot readings by probe. This experiment shows that the centre temperature can be accurately measured by imbedding the 1/8" dia. thermocouple into a hole drilled to the centre of the slab.

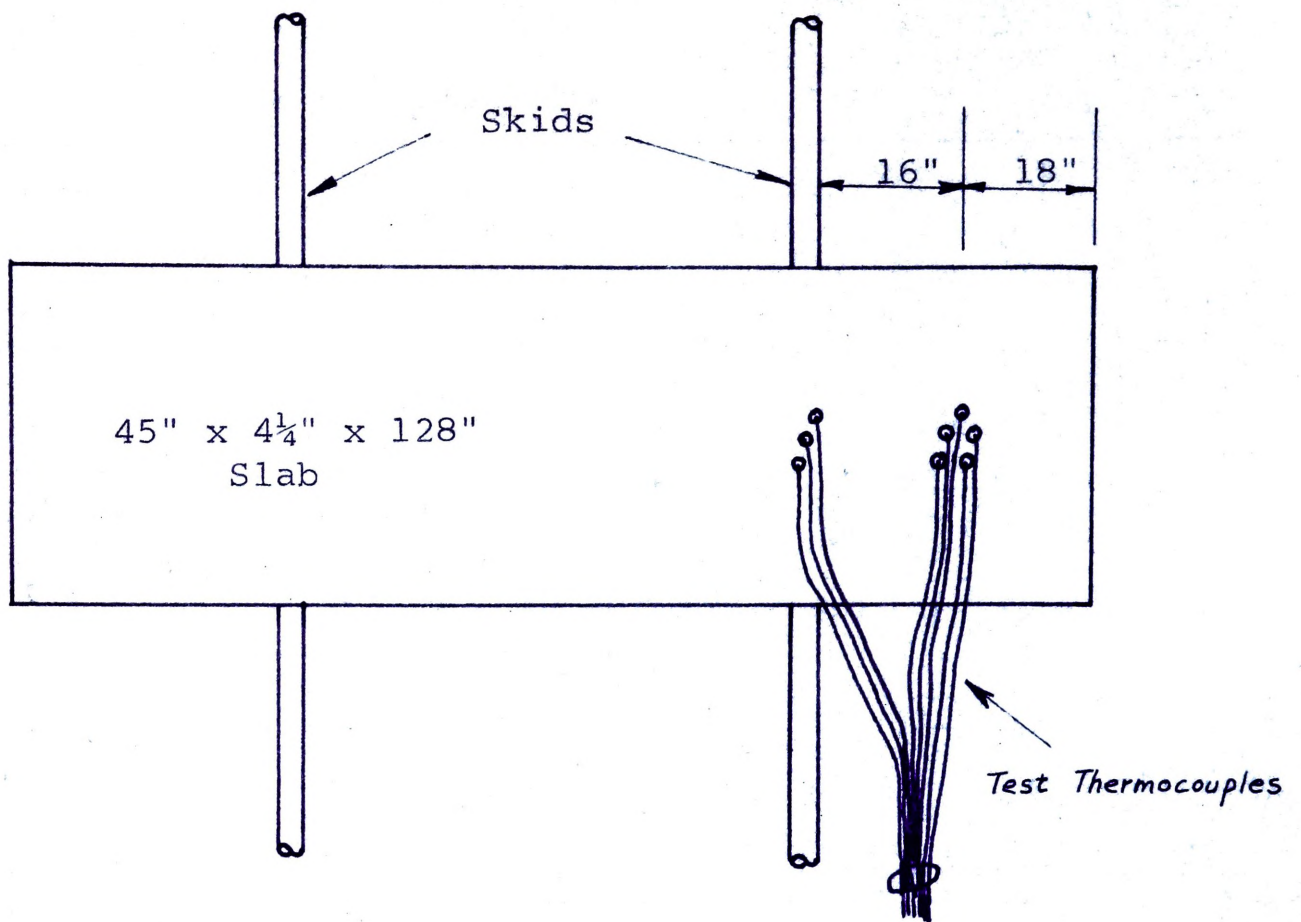
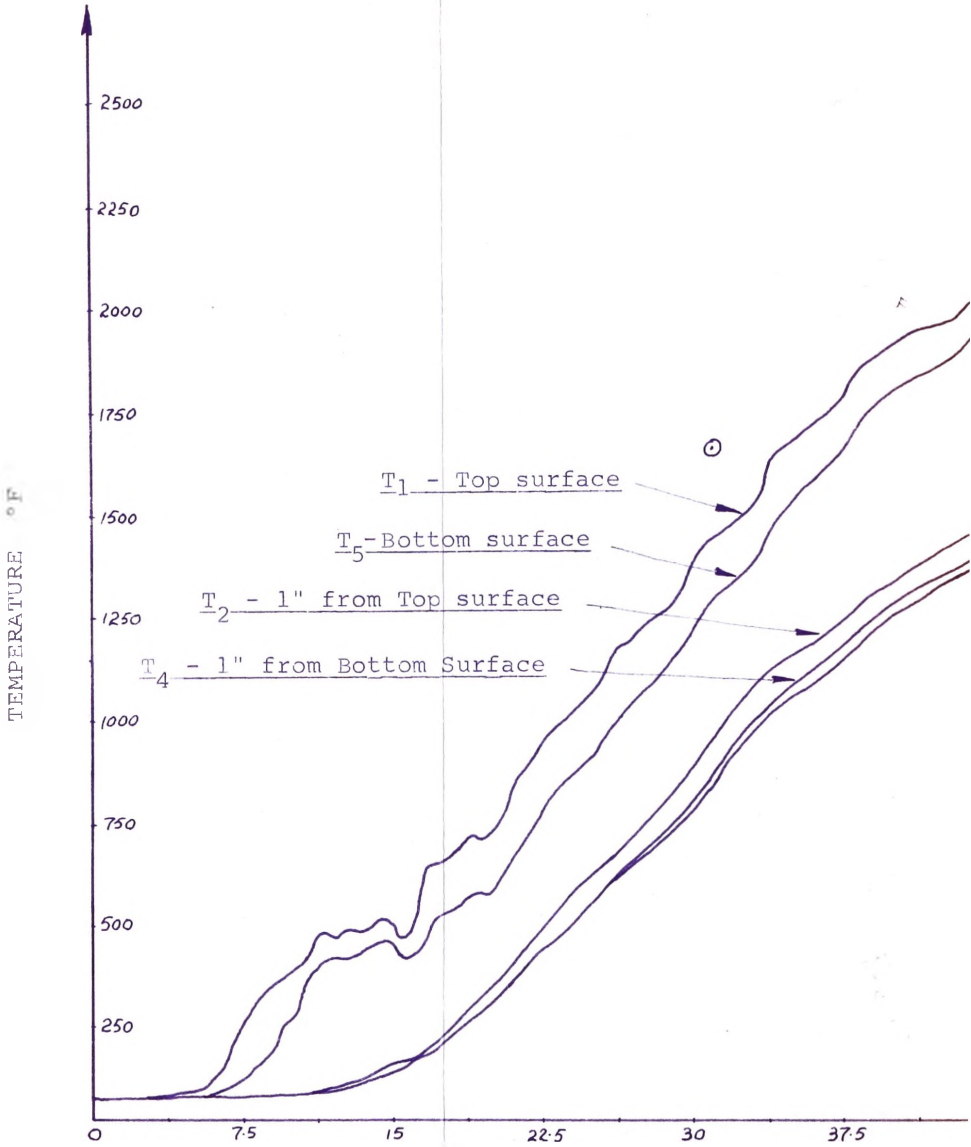
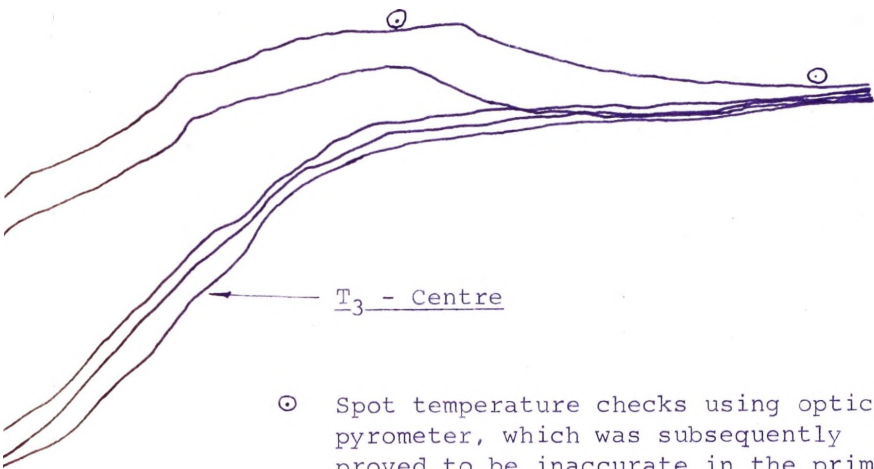


FIG. A5 - New test slab showing the 8 inconel sheathed 1/8" dia. thermocouples inserted in holes as shown. The holes are drilled to required depths for measuring the cross-sectional temperature profile of the slab. Three T/C's are located at the skid contact point and five are located remote from it.





- ⊙ Spot temperature checks using optical pyrometer, which was subsequently proved to be inaccurate in the primary zone where furnace temperature is much higher than slab surface temperature.

FIG. A6 - Temperature of Slab Cross-Section Remote from Skids.

45                      52.5                      60                      67.5                      75                      82.5                      90

TIME Mins.

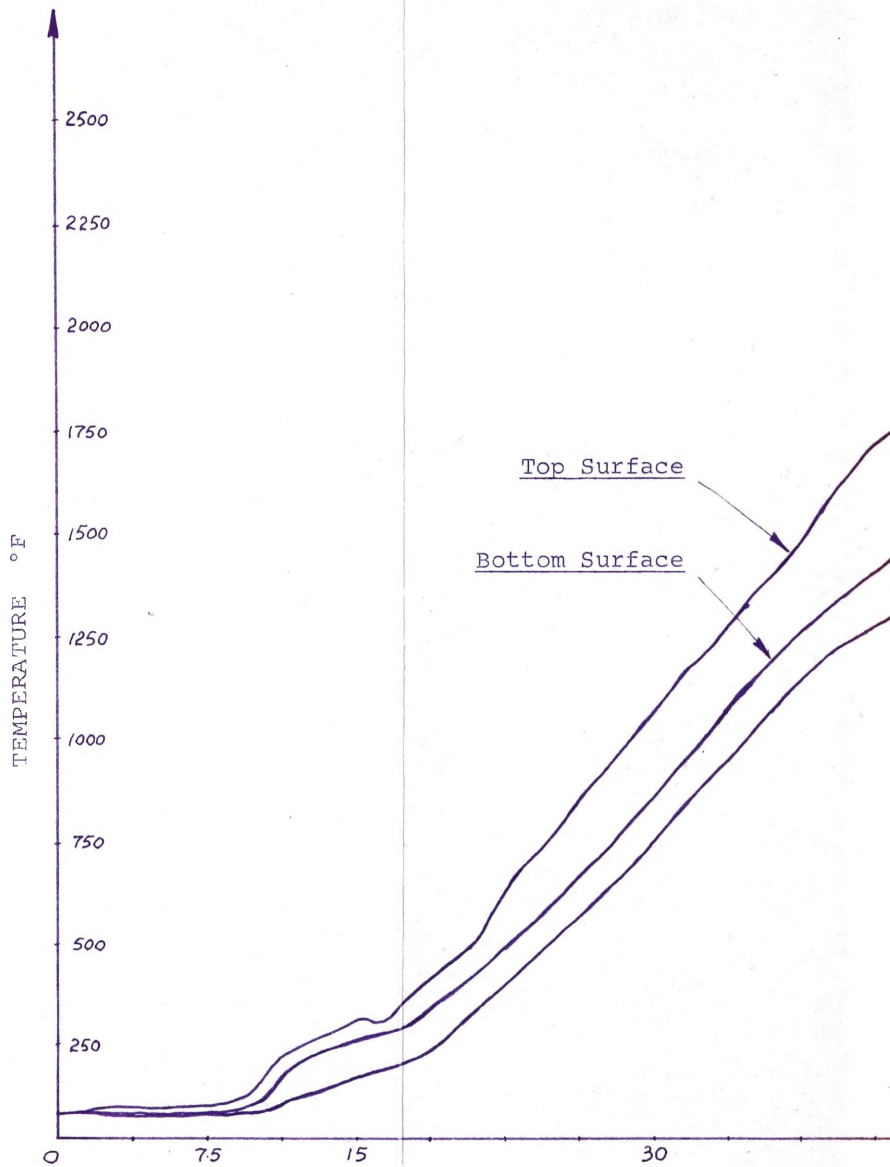




FIG. A7 - Temperature of Slab Cross-Section  
At Skid Contact Point.

Great care was taken to prevent this point from skewing off the skid. This, however, has not been successful as shown by the fact that bottom temperature is still higher than the centre temperature.

45

60

75

90

TIME Mins.

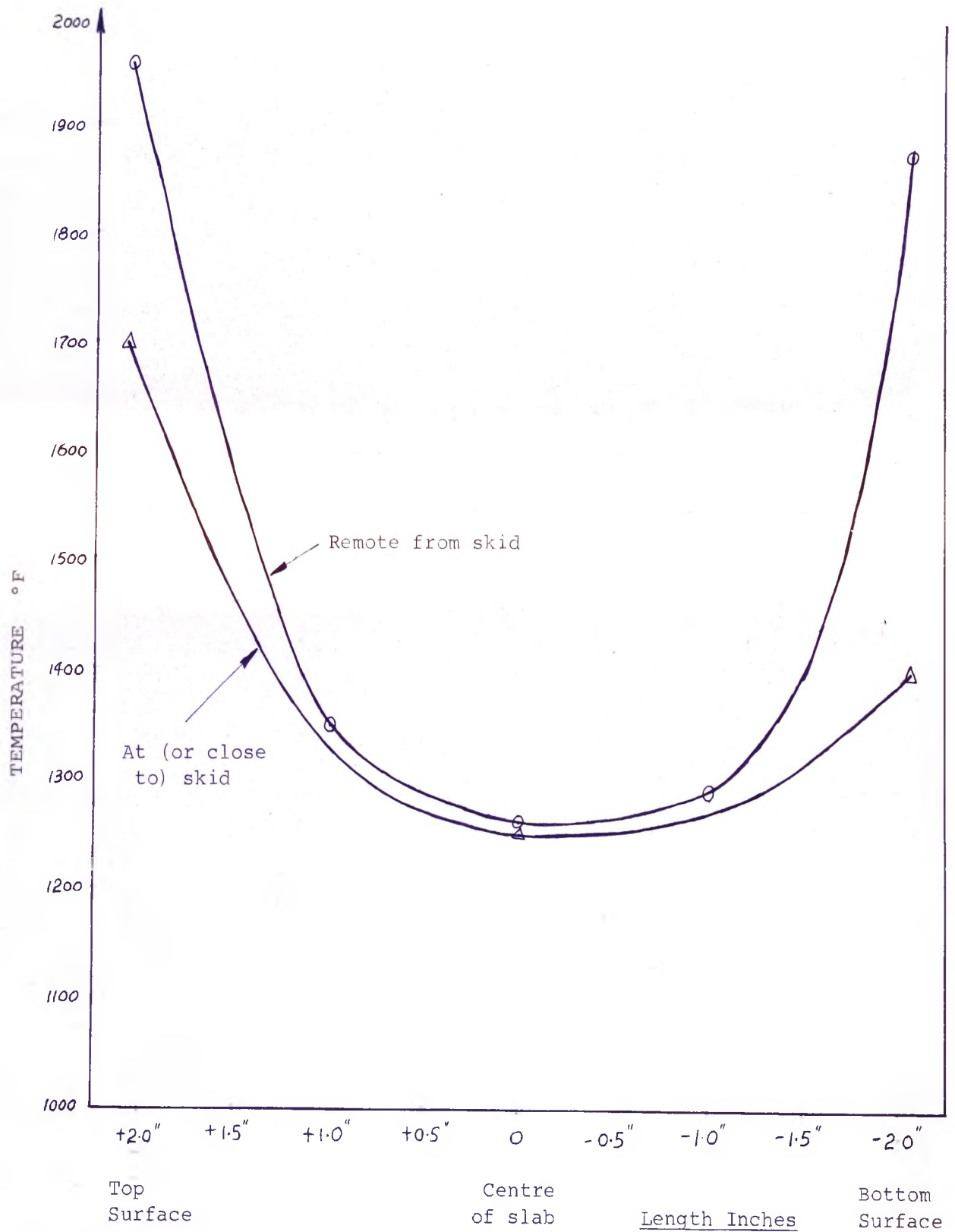


FIG. A8 - Cross-sectional temperature distribution of the test slab at locations remote from skid and close to skid, as it entered the tonnage zone and when the centre has reached the transformation point.

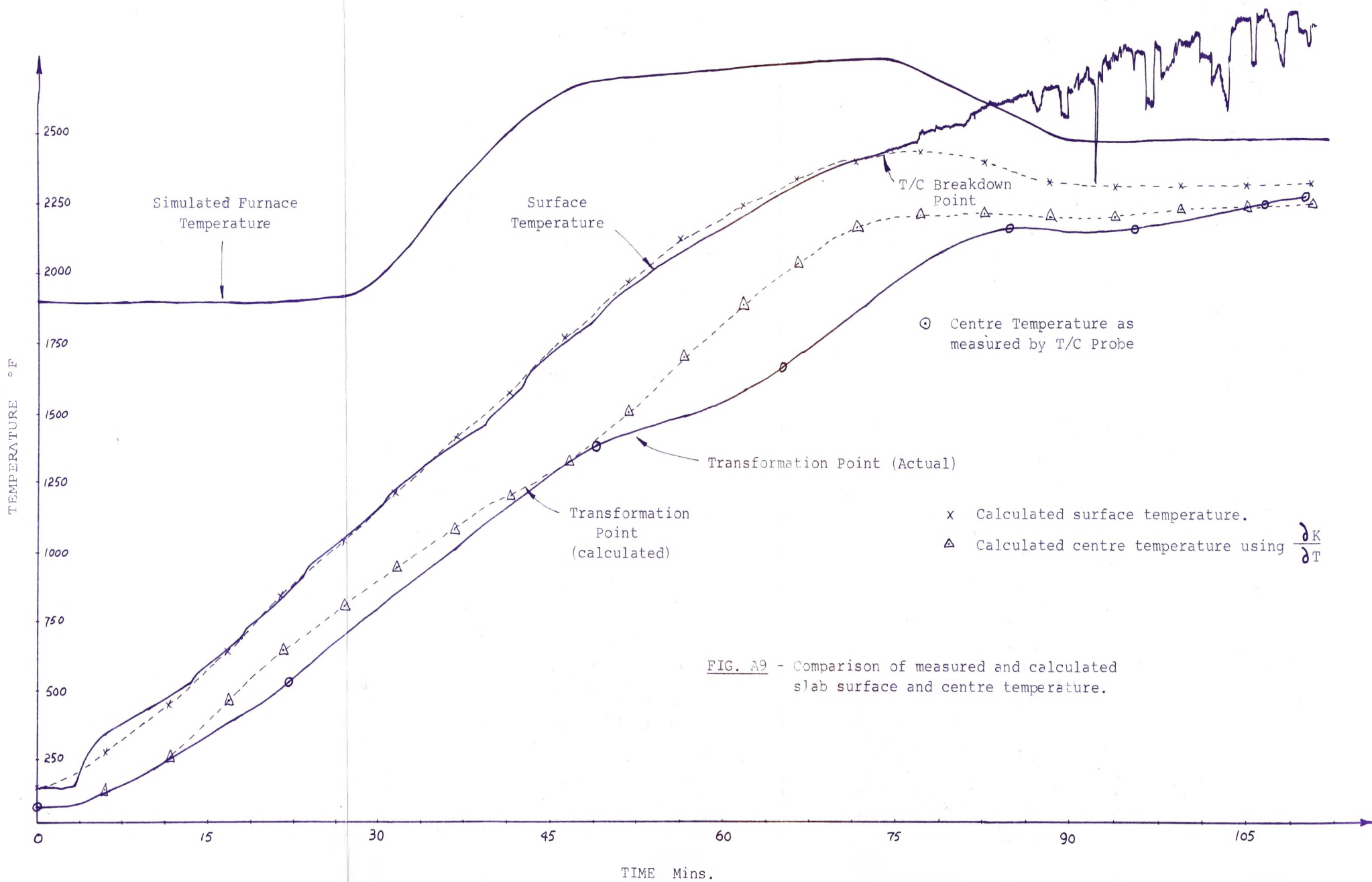
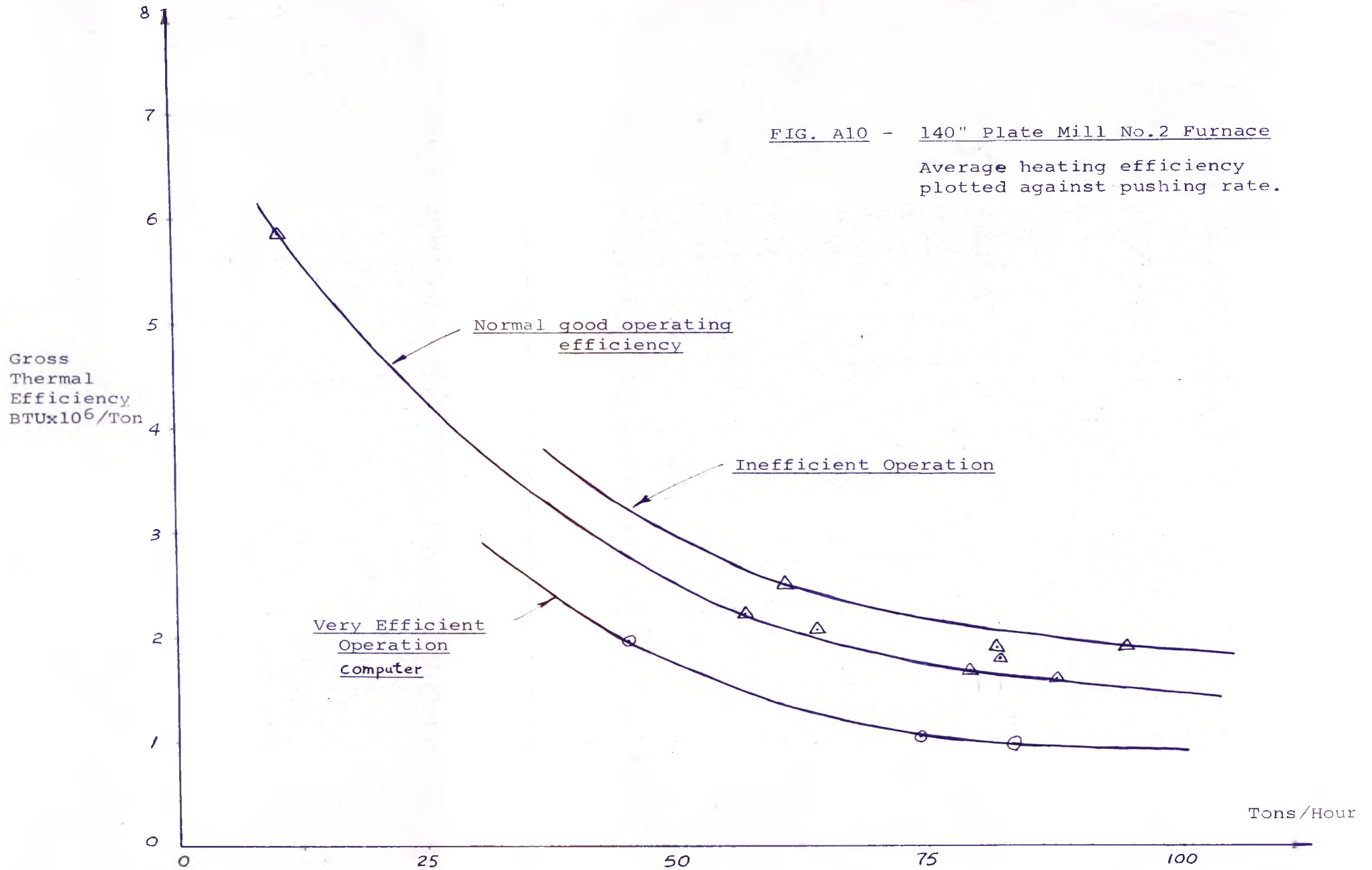




FIG. A10 - 140" Plate Mill No.2 Furnace

Average heating efficiency  
plotted against pushing rate.



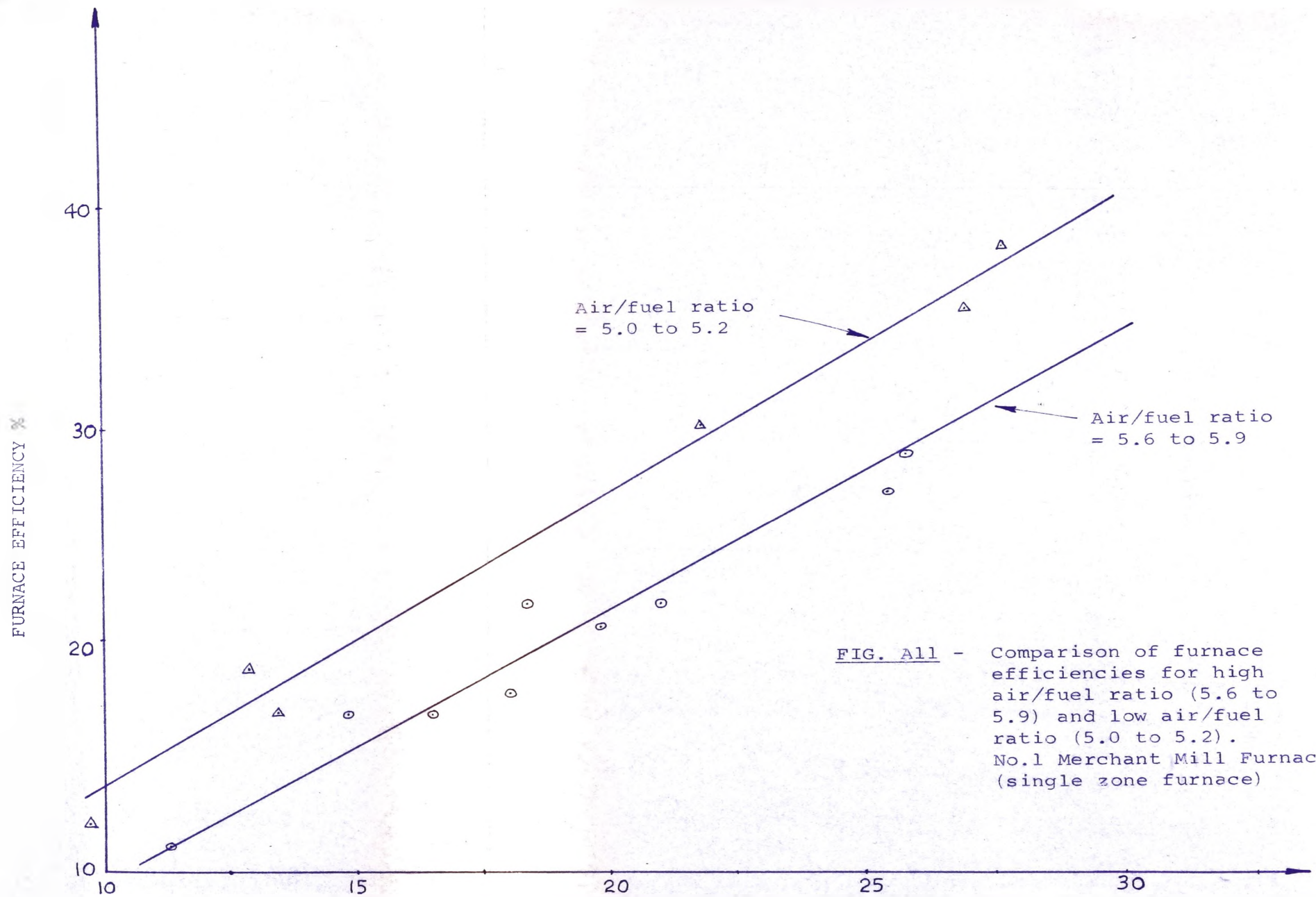


FIG. All - Comparison of furnace efficiencies for high air/fuel ratio (5.6 to 5.9) and low air/fuel ratio (5.0 to 5.2). No.1 Merchant Mill Furnace (single zone furnace)

PUSHING RATE TONS/15 MINUTES.

## Experiments on Slab Temperature Measurement

### 1. Introduction

In order to check the validity of and modify the theoretically worked out model for temperature control, it is necessary to measure the temperature profiles of the furnace, and the slabs in the x, y and z directions. Several methods were tried and a successful method was found for measuring the slab temperature in the y direction, the x direction and the z direction under carefully controlled furnace conditions. Flame temperature could only be measured manually. Furnace roof and wall temperatures were measured manually, but arrangements are being made to measure them continuously. Gas temperature could only be measured manually with a suction pyrometer. Even then there was only limited success.

### 2. Description of the Experiments and Results

Initially, an 8 gauge, 110 ft long Chromel-Alumel thermocouple, insulated by twin bore ceramic insulators, was used to measure the surface temperature of the test slab, and a thermocouple probe was used to measure the slab centre temperature

through a hole drilled to the centre of the slab directly beneath the location where the surface thermocouple was welded. The surface temperature and centre temperatures were correctly measured by the respective instruments, but both had considerable shortcomings. For the surface temperature, it was found that the bare and unsealed thermocouple wire was corroded by the furnace atmosphere. Its maximum life in the furnace was about one hour at  $2,250^{\circ}\text{F}$ , before it was completely corroded through and failed. The centre temperature had a dip in the gradient at about  $1,300^{\circ}\text{F}$ . It was thought at first that the measurement was faulty, but subsequent tests showed the same dip, and then it was realised that the transformation point for mild steel occurs at about  $1,300^{\circ}\text{F}$ , during which its specific heat had a discontinuity. However, there were also shortcomings in the experiments. The hole did not always stay long enough opposite a door for a measurement to be taken, and it is difficult to drill a long horizontal hole in a slab to exactly the right location. An ultrasonic detector was used to detect exact location of the hole.

To overcome these troubles, a number of sealed thermocouples were obtained and tested in

the furnace. These thermocouples were insulated by magnesium oxide and completely sealed with metal sheaths such as stainless steel, cupro-nickel alloys and Inconel. It was found that the Inconel sheathed one was the only one that did not completely fail. It did fail under severe furnace conditions, particularly when oil firing was used, but when the furnace was carefully controlled and gas firing was used throughout, it could last at least two hours in the furnace.

In order to find a better way of measuring slab centre temperature, a  $\frac{1}{8}$ " diameter Inconel sheathed thermocouple was imbedded to the bottom of a hole drilled vertically down to the centre of the slab from the top surface. The measurement was checked against spot readings measured by the thermocouple probe described above and was found to be correct within experimental accuracy.

A suction pyrometer was designed and fabricated to measure the gas temperature without effects of radiation from flame and roof. However, when used it failed at about 2,070°F because of silicon poisoning of the platinum—platinum + 13% rhodium thermocouple junction. The fire-cement used in the fabrication of the pyrometer contained silicon,

which melted at  $2,000^{\circ}\text{F}$  and dribbled over the thermocouple junction. Fire-cement which can withstand  $3,000^{\circ}\text{F}$  and contains no silicon was required but was not readily available. Hence, the pyrometer was reconstructed with no fire-cement used. Also, to prevent sulphur poisoning of the thermocouple wire, the exposed thermocouple junction was covered with an Inconel sheath. However, tests with this probe still failed at approximately  $2,500^{\circ}\text{F}$ , well below the flame temperature.

A much larger scale experiment was then conducted to obtain temperature profile down the slab (x direction), at the skid contact point, and remote from the skids. Five thermocouples were imbedded to varying depths at a position remote from the skid, and three above the skid contact point.

The furnace was maintained at very stable gas firing throughout the test. Tonnage zone temperature was maintained at  $2,400^{\circ}\text{F}$  and soak zone temperature was maintained at  $2,200^{\circ}\text{F}$ .

Two sets of temperature profiles, one at the skid contact point and one remote from it, were obtained. The experiment was not a complete success but a great deal of information was obtained from it.

## APPENDIX 11

COMPUTER PROGRAMS FOR EFFICIENCY OPTIMISING CONTROL  
AND HEAT BALANCE CALCULATION

The complete program for carrying out efficiency control and heat balancing is too long for inclusion in this thesis. Hence, only three subroutines directly dealing with efficiency control and heat balance calculation are described and listed here. The three subroutines are HILLCL, HTBAL and SORT, together with two BLOCK DATA subprograms.

Four furnace combustion variables, the three zone air-fuel ratios and the furnace pressure are used by the classical hillclimb technique to optimise furnace efficiency.

The principle of this technique is the systematic setting of values of the available variables and the noting of the effect that differing sets of these variables have on furnace efficiency. Safe limit values are set for each variable. New values of the variables are generated using results of previous trials, and a further trial is conducted on furnace performance using the new conditions. Repetition of this process will eventually lead to an optimum efficiency. The set of conditions for optimum efficiency are time variant due to changes in fuel firing rates, ambient temperature, throughput rate, inaccurate ratioing and grade of steel slabs. Hence, the system will continuously search



for and follow the shifting optimum efficiency.

This technique consists of two steps. Step 1 is to select, from furnace tests, an initial set of test points, followed by calculation of the resulting efficiency. The number of trial points is equal to the number of variables plus one. Step 2 is the selection of the worst set of furnace conditions from the set of trials from Step 1, (that is, the set of conditions which give the worst efficiency) and then generates a new set of furnace conditions to replace it. The furnace is then tested under the new set of conditions and the resulting efficiency is calculated. Continuous repetition of Step 2 results in the continuous optimisation of furnace efficiency.

The formula for calculating a new set of conditions is given by:

$$x' = \frac{2}{N} \sum x - (1 + \frac{2}{N})x^*$$

$$y' = \frac{2}{N} \sum y - (1 + \frac{2}{N})y^*$$

and so on for the number of variables  $N$ , where:

$x'$ ,  $y'$ , ... are the values of the variables in the new set of furnace conditions;

$x^*$ ,  $y^*$ , ... are the values of the variables in the worst set of furnace conditions;  
 $\sum x$ ,  $\sum y$ , ... are the sums of the values of the corresponding variables from the current sets of furnace conditions.

#### 1. Subroutine HILLCL

This carries out the basic hillclimbing operation. The four variables used are air-fuel ratios for all zones except soak zone and furnace pressure. Hence  $N = 4$  and the number of trial points is five.

Initially, the percentage limits of the above variables are used to modify the current values of furnace conditions to generate the four trial points. If a trial point lies outside the allowable safe range, the value of the offending variable is replaced by the current value of that variable. The sums of the values of corresponding variables are incremented on each pass with each new trial point, with the values of the corresponding variables of the replaced point being subtracted.

After the four trials are completed, a new point is generated from the simplex using the worst trial found by sorting the array of efficien

cies. This replaces the old point unless it lies outside the safe range, when the second worst point is used instead to generate a new trial point. If this point is also outside the boundary, then it is assumed that the point of optimum efficiency has been reached.

## 2. Subroutine SORT

This subroutine sorts the values of efficiency stored in PERFM (5.5) into descending order of magnitude so that PERFM (1, -) is the worst, with its actual value being the highest.

## 3. Subroutine HTBAL

This subroutine calculates an efficiency based on a heat balance using only heats of combustion, heat input from steam, and heat output with flue gases. Mean heat capacities between 32°F and 2,000°F are used. The amounts of flue gases are calculated on the basis of complete combustion of all fuels. The average values for flows calculated over the length of the trial period (5 minutes) are used.

HILLCL

```

C OPTIMISATION OF F'CE PERFORMANCE BY HILLCLIMB TECHNIQUES
C VARIABLES:UTZ,LTZ,+PZ AFR ; F'CE PRESSURE AT SZ
SUBROUTINE HILLCL
INTEGER CNTR 6
REAL PERFM(5,6),CAIRFR(4),SUMAFR(3),SDACB(13)
REAL XLIM(16),SADC(64),WAFR(3)
COMMON/CONLNK/SADC,NEWAFR,CAIRFR,THEOA,STHOA/CLIM/XLIM
COMMON/BUFL1/SDACB/EFF/THERM,PERFM/INIT/CNTR
CNTR=CNTR+1
C CNTR IS INCR. COUNTER SET EXTERNALLY
IF (CNTR-130000) 4,5,5
5CNTR=6
C RESET CNTR TO PREVENT OVERFLOW
4CALL HTBAL
IF (CNTR-5) 6,3,3
6PERFM(1,CNTR)=THERM
C HTBAL RETURNS EFF. AS THERM=HT OUT/GROSS HT IN
C SLAB HT IS IGNORED
C INITIALISE SUMS WITH CURR. AFR IF CNTR=1
IF (CNTR-1) 29,29,20
29DO 21 J=1,3
SUMAFR(J)=CAIRFR(J+1)
21PERFM(J+1,1)=CAIRFR(J+1)
C IF AVGD VARIABLES ARE AVAILABLE,USE INSTEAD OF SADC
SUMFCP=SADC(11)
PERFM(5,1)=SADC(11)
20DO 30 J=2,4
IA=4*J+CNTR-8
CC GENERATION OF SUBSCRIPTS IA FOR TRIAL PT LIMITS
TEMP=CAIRFR(J)*(1.+XLIM(IA)/100.)
IF (TEMP.GE.1.67.OR.TEMP.LE.0.30) TEMP=CAIRFR(J)
PERFM(J,CNTR)=TEMP.
30SUMAFR(J-1)=SUMAFR(J-1)+PERFM(J+1,CNTR)
PERFM(5,CNTR)=SADC(11)*(1.+XLIM(IA)/100.)
IF PERFM(5,CNTR).GT.0.25.OR.PERFM(5,CNTR).LT.(-.25) PERFM(5,CNTR)=SADC(11)
C IFS TEST FOR BOUNDARY CONDITIONS
C IF BDRY CONDS EXCEEDED,RESET TO CURR. VALS
C SETTING OF NEW LEVELS FOLLOWS
16N=0DO 25 K=1,3
NB=2
IF (K-(K/2)*2) 2,7.2
7NB=3
2N=N+NR
C ABOVE GETS N FOR SDACB(N)
IF (CNTR-5) 13,14,14
13SDACB(N)1.0/PERFM(K+1,CNTR)
SDACB(12)=PERFM(5,CNTR)

```

```
GO TO 25
14SDACB(N)=1.0/PERFM(K+1,L)
SDACB(12)=PERFM(5,CNTR)
25CONTINUE
17RETURN
C CNTR=5 HERE
3PERFM(1,CNTR)=THERM
11L=1
C SORT SORTS PERFM(5,6) INTO DESCENDING ORDER
C PERFM(1,1) WORST ETC,PERFM(1,2) NEXT WORST
12CALL SORT
GO TO 28
8PERFM(1,L)=THERM
GO TO 11
C WORST PT LAST TIME IS REPLACED BY NEW PT+SORTING OCCURS
28DO 24 I=1,3
WAFR(I)=PERFM(i+1,L)
PERFM(i+1,L)=0.5*SUMAFR(I)-1.5*WAFR(I)
C WAFR,WFCP ARE AFR, FCP CORRESPONDING TO WGRST PT
C HILLCLIMB TECH. GENERATES NEW PT IN SIMPLEX
C NO. OF DIM. = 4
C FOR FORMULA SEE WRITE-UP
C TEST FOR B'DRY COND.
IF(PERFM(i+1,L).GE.1.67.OR.PERFM(i+1,L).LE.0.30)GO TO 19
24CONTINUE
WFCP=PERFM(5,L)
PERFM(5,L)=0.5*SUMFCP-1.5*WFCP
IF PERFM(5,L).GE.0.25.OR.PERFM(5,L).LE.(-.25))GO TO 19
C CHANGE SUMS-REMOVE WORST POINT + ADD NEW POINT
DO 26 I=1,3
26SUMAFR(I)=SUMAFR(I)-WAFR(I)+PERFM(i+1,L)
SUMFCP=SUMFCP-WFCP+PERFM(5,L)
GO TO 16
19L=L+1
IF(L-2)12,12,15
15L=0
RETURN
END
```

BLOCK DATA FOR HILLCL

C BLOCK DATA FOR XLIM IN HILLCL

BLOCK DATA

REAL XLIM(16)

COMMON/CLIM/XLIM

DATA XLIM(1),XLIM(2),XLIM(3),XLIM(4)/-10.,-5.,0.,5./

DATA XLIM(5),XLIM(6),XLIM(7),XLIM(8)/5.,-5.,-10.,0./

DATA XLIM(9),XLIM(10),XLIM(11),XLIM(12)/0.,5.,-5.,-10./

DATA XLIM(13),XLIM(14),XLIM(15),XLIM(16)/-10.,-5.,5.,10./

C FIRST 12 ARE AFR% CHANGES FROM UTZ TO PZ

C LAST 4 ARE PRESSURE CHANGES

C ALL ARE % CHANGES

END

SORT

```
CSORTING SUBROUTINE -PART OF H.C. PCKGE
C SORTS PERFM(5,5) INTO DESCENDING ORDER
SUBROUTINE SORT
REAL PERFM(5,5)
COMMON/EFF/THERM,PERFM,IND,L
DO 6 I =1,4
DO 6 J=2,5
IF(PERFM(J-1,J-1)-PERFM(J,J))4,6,6
C DOUBLE SUBSCRIPTS ARE NECESSARY TO LOCATE ORIGINAL ORDER
4PERFM(J-1,J)=PERFM(J,J)
PERFM(J,J-1)=PERFM(J-1,J-1)
6CONTINUE
DO 9 IK=1,5
IF(PERFM(L,IK).GT.1.OE-7)IND=IK
C L ENGBLES 2ND WORST POINT TO BE FOUND
C IND =INDEX(ORIGINAL) OF WORST POINT
C 1.OE-7 ,NOT 0,AS REAL MODE IS BEING USED
9CONTINUE
RETURN
END
```

HTBAL

```

C CALCULATION OF GROSS THERMAL EFFICIENCY
C BASED ON HEATS OF COMBUSTION+HEAT ESCAPING IN FLUE GAS
C SIMPLIFIED+LESS ACCURATE VERSION OF HTBAL AS WRITTEN BY
C D.VAN HELDEN,1969-1970
C SYMBOLS USED ARE HIS,WITH SEVERAL ADDITIONS+OMISSIONS
SUBROUTINE HTBAL
REAL SADC(64)
COMMON/HTCAP/CPCO2,CPWV,CPSO2,CPN2,CPO2/EFF/THERM,PERFM,IND,L
COMMON/CONLNK/SADC,NEWAFR,CAIRFR,THEOA,STHOA
C HTCAP ARE IN BLOCK DATA.IF AVAILABLE,USE AV. VALS OF SADC
FUNHT(A,B,C)=A*B*C*3.59
HCOM=0
PMCOT=0
TOIL=0
PMAT=0
DO 12 IA=1,4
PMAT=PMAT+SADC(IA+15)/388.
TOIL=TOIL+SADC(IA+19)*9.1
PMCOT=PMCOT+SADC(IA+23)/388.
PMWST=SADC(IA+27)/18
12CONTINUE
C LB MOLES AS UNITS EXCEPT TOIL-LBS-ON HRLY BASIS
TEMDIF=SADC(57)-32.
C SADC(57)=TEMP OF FLUE GAS EX-F'CE
C PMAT-TOTAL AIR
C "COT-TOTAL GAS
C "WST-TOTAL H2O AS STEAM
C WV TOT H2O,HWV-ITS HT OUT
WV=(PMWST+1.108*PMCOT+0.02625*TOIL)/1000.
HWV=FUNHT(WV,TEMDIF,CPWV)
C HT UNITS-1000'S OF BTUS;1 LBMOLE:359 SCF
CO2=(0.388*PMCOT+0.0743*TOIL)/1000.
HCC2=FUNHT(CO2,TEMDIF,CPCO2)
N2=0.79*PMAT/1000.
HN2=FUNHT(N2,CPN2,TEMDIF)
O2=(0.21*PMAT-0.88*PMCOT-0.10066*TOIL)/1000.
HO2=FUNHT(O2,CPO2,TEMDIF)
SO2=0.00016*TOIL/1000.
HSO2=FUNHT(SO2,CPSO2,TEMDIF)
HS=PMWST*1202.*18./1000.
C INPUT ENTHALPIES ARE NEGLECTED
C HT CAPS ARE MEAN HT CAPS FROM 32F TO 2000F
C (BTU/DFG F SCFX100)
C HTS OF COMBUSTION
HCOM=PMCOT*SADC(46)/1000.+TOIL*19.*9.1
C OIL-19000 BTU/GAL
C HT BAL. NEGLECTING LOSSES,STEEL OUT,SKID COOLING ETC.
HOT=HWV+HN2+HCO2+HSO2-HS
THERM=HOT/HCOM
RETURN
END

```



BLOCK DATA FOR HTBAL

C BLOCK DATA SUBPROGRAM FOR HTBAL

C CPUNITS: BTU/DEG F SCF X 10(-2)

BLOCK DATA

COMMON/HTCAP/CPCO2,CPWV,CPSO2,CPN2,CPO2

DATA CPCO2,CPWV,CPSO2,CPN2,CPO2/3.35,2.59,3.37,2.1,2.21/

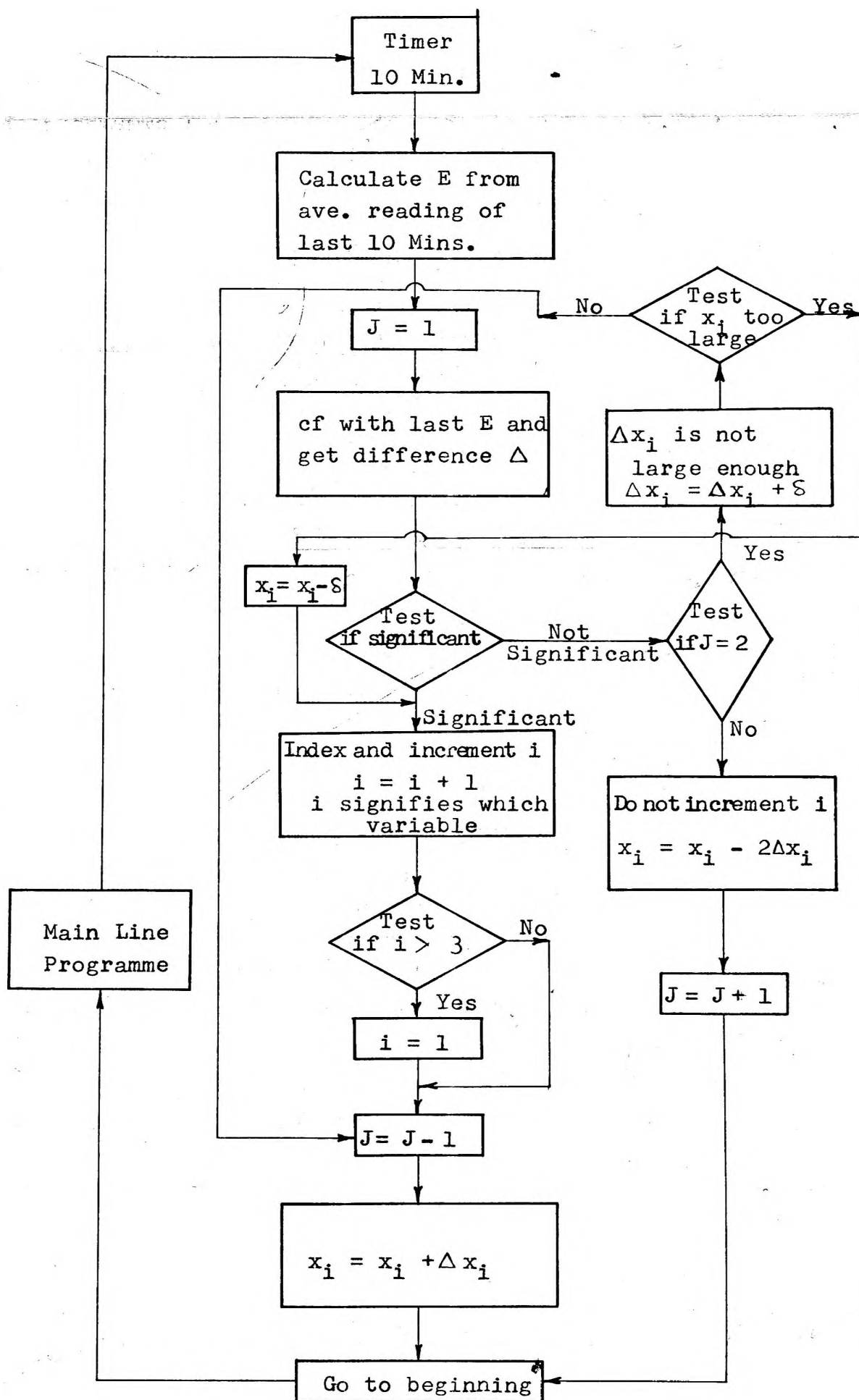
END

APPENDIX 12

BLOCK DIAGRAM OF COMPUTER PROGRAM

FOR EFFICIENCY OPTIMISING CONTROL

BLOCK DIAGRAM OF COMPUTER PROGRAMME FOR  
EFFICIENCY OPTIMISING CONTROL.



## APPENDIX 13

COMPUTER PROGRAM FOR THE SOLUTION OF THICK SLAB  
MODEL WITH CONSTANT THERMAL PROPERTIES

```

DIMENSION PRINT(121),T(102),W(102)
INTEGER S,U,V,X
REAL M
READ(1,3) CH,BL
3 FORMAT(2A1)
READ(1,15) PRINT
15 FORMAT(80A1/41A1)
M=2.0
DO 33 V=1,2
DO 1 I=1,6
1 T(I)=100.0
DO 16 I=1,15
IF(I-1)4,4,5
4 T(1)=300.0
GO TO 6
5 T(1)=500.0
6 U=I
WRITE(3,101)U
101 FORMAT(1H1,21H GRAPH OF TEMP. VS. X,5X,3H AT,I4,5H MIN.///)
DO 27 N=2,5
W(N)=(T(N+1)+T(N-1))/M+(1.-2./M)*T(N)
27 CONTINUE
DO 65 X=2,5
65 T(X)=W(X)
T(6)=T(40)
17 CONTINUE
DO 19 L=1,6
J=(T(L)-100.0)/4.0+1.25
PRINT(J)=CH
K=L-1
11 WRITE(3,12) K,PRINT
12 FORMAT(1H0,I4,'-*',120A1)
26 PRINT(J)=BL
19 CONTINUE
WRITE(3,18)
18 FORMAT(1H , ' *****
1*****
2*****
WRITE(3,31)
31 FORMAT(1H , ' I I I I I I I I I I
1 I I I I I I I I I I I I I I
2 I I')
WRITE(3,32)
32 FORMAT(1H ' 100 200
1300 400 500')
16 CONTINUE
M=3.0
33 CONTINUE
CALL EXIT
END

```

## APPENDIX 14

COMPUTER PROGRAM FOR THE SOLUTION OF THICK SLAB  
MODEL WITH TEMPERATURE DEPENDENT THERMAL PROPERTIES

```

C TEMP. OF SLAB USING VARIABLE CP AND K, WITH SLAB SURFACE TEMP.
  AS BOUNDARY
C CONDITION
  DIMENSION PRINT(121),T(102),W(102)
  .INTEGER S,U,V,X
  REAL M,M2
  DELX=0.2
  DELT=0.01
  DEL=0.5833
  READ(1,3) CH,BL
3  FORMAT(2A1)
  READ(1,15) PRINT
15  FORMAT(80A1/41A1)
  DO 1 I=1,21
1  T(I)=132.5
  T(1)=500.0
  DO 33 V=1,10
  U=5*V
  WRITE(3,101)U
101  FORMAT(1H1,24H GRAPH OF TEMP. VS. X AT,14,5H MIN.///)
  AT=T(1)/100.0
  IF(AT-13.3) 51,51,52
51  CP=9.99742E-2-1.10612E-3*AT+2.69509E-3*AT*AT-3.77209E-4*AT*AT*AT+
  11.93386E-5*AT*AT*AT*AT
  CK=37.9239-1.25268*AT-0.100382*AT*AT+9.43425E-3*AT*AT*AT-1.96102E-
  14*AT*AT*AT*AT
  DKDT=-1.25268-0.200764*AT+2.830275E-2*AT*AT-7.84408E-4*AT*AT*AT
  GO TO 57
52  IF(AT-17.0) 53,53,54
53  CP=4.35246-0.688843*AT+4.08463E-2*AT*AT-1.03176E-3*AT*AT*AT+9.2771
  11E-6*AT*AT*AT*AT
  CK=37.9239-1.25268*AT-0.100382*AT*AT+9.43425E-3*AT*AT*AT-1.96102E-
  14*AT*AT*AT*AT
  DKDT=-1.25268-0.200764*AT+2.830275E-2*AT*AT-7.84408E-4*AT*AT*AT
  GO TO 57
54  IF(AT-20.0) 55,55,56
55  CP=0.155
  CK=37.9239-1.25268*AT-0.100382*AT*AT+9.43425E-3*AT*AT*AT-1.96102E-
  14*AT*AT*AT*AT
  DKDT=-1.25268-0.200764*AT+2.830275E-2*AT*AT-7.84408E-4*AT*AT*AT
  GO TO 57
56  CP=0.155
  CK=16.8
  DKDT=0.0
57  A=CK*2.4/(7.7*62.4*CP)
  A2=DKDT*2.4/(7.7*62.4*CP)
  M=DELX/A*DELX/DELT
  M2=DELX/A2*DELX/DELT
  DO 17 S=1,500

```

```

DO 27 N=2,13
W(N)=(T(N+1)+T(N-1))/M=(1.-2./M)*T(N)+(T(N+1)*T(N+1)-2.*T(N)*T(N+1)+
T(N)*T(N))/M2
27 CONTINUE
DO 65 X=2,13
65 T(X)=W(X)
T(18)=T(16)
T(1)=T(1)+DEL
17 CONTINUE
DO 19 L=1,14
J=T(L)/20.+1.5
PRINT(J)=CH
K=L-1
IF(K-(K/5)*5)14,11,14
11 WRITE(3,12) K,PRINT
12 FORMAT(1H ,14,'-*'120A1)
GO TO 26
14 WRITE(3,25)PRINT
25 FORMAT(1H ,' *',120A1)
26 PRINT(J)=BL
19 CONTINUE
WRITE(3,18)
18 FORMAT(1H ,' *****
1*****
2*****')
WRITE(3,31)
31 FORMAT(1H ,' I I I I I I I I I I I I I I
1 I I I I I I I I I I I I I I
2I I')
WRITE(3,32)
32 FORMAT(1H ' 0 100 2000 300 400 500 600 700 800 900
11000 1100 1200 1300 1400 1500 1600 1700 1800 1900 2000 2100 2200
22300 2400')
WRITE(3,35)M
35 FORMAT(///' VALUE OF M:',F7.3,' M MUST BE GREATER THAN 2.0 OR
I THE NUMERICAL SOLUTION IS UNSTABLE.')
16 CONTINUE
IF(U-40)33,41,41
41 DEL=0.16667
33 CONTINUE
CALL EXIT
END

```



APPENDIX 15

COMPUTER PROGRAM FOR TRACKING  
SLABS THROUGH THE FURNACE

This program is far too long for inclusion in this thesis. Also, it is in the process of being rewritten. Hence, it has been decided not to include it here. It may be obtained from the author, if required.