Optimisation of steel plate production : the statement of the problem

Author:
Lawrance, Anthony Bohun

Publication Date:
1966

DOI:
https://doi.org/10.26190/unsworks/11997

A. B. LAWRANCE

M.B.A.
1966

U.
N.S.W.

Form 2
RETENTION

THE UNIVERSITY OF NEW SOUTH WALES

DECLARATION RELATING TO DISPOSITION OF THESIS

This is to certify that I ANTHONY BOHUN LAWRANCE being a candidate for the degree of MASTER OF BUSINESS ADMINISTRATION am fully aware of the policy of the University relating to the retention and use of higher degree theses, namely that the University retains the copies of any thesis submitted for examination, "and is free to allow the thesis to be consulted or borrowed. Subject to the provisions of the Copyright Act (1912-1950) the University may issue the thesis in whole or in part, in photostat or microfilm or other copying medium."

In the light of these provisions I declare that I wish to retain my full privileges of copyright in my thesis and request that neither the whole nor any portion of the thesis may be published by the University Librarian nor may he authorise the publication of the whole or any part of the thesis, and I further declare that this preservation of my copyright privileges in the thesis shall lapse from the 1st day of Jan 1968 unless it shall previously have been extended or revoked in writing over my hand.

Signature ....

Witness ....

Date 21/12/66

"OPTIMISATION OF STEEL PLATE PRODUCTION -

THE STATEMENT OF THE PROBLEM".

THESIS FOR MASTER OF BUSINESS ADMINISTRATION

SCHOOL OF BUSINESS ADMINISTRATION

UNIVERSITY OF NEW SOUTH WALES.

ANTHONY B. LAWRANCE B.Sc (Hons.)

DECEMBER, 1966

This has not been previously submitted to any other University of institution for any degree or award

21/12/06

TABLE OF CONTENTS

* * * * * * * * * * * *

SUMMARY OF THE PAPER

This paper looks at the problem of optimising plate production from a wide plate mill and associated shearlines. The boundaries of the problem are taken as the input to the re-heating furnace and the output from the shearlines.

By approaching the problem from an operations research point of view mathematical models of each section of the operations may be constructed.

The technical problems encountered in heating and rolling steel are considerable and the paper describes various approachs to the model building. The control of slab feed dimensions is found to be of prime importance and method of determining a suitable rationalisation of sizes is suggested.

The shearlines introduce a study of queuing characteristics for which the best approach to solution is a process of simulation.

Mill programmes should be controlled, with furnace, mill and shearline parameters to be considered.

Despite the technical nature of the plate rolling operations, most decisions which materially affect the production can be considered to be "management" decisions. It is in this area of management control that it is considered the greatest gains can be made by modern analytical techniques; rather than in applications of automation to the physical process.

I INTRODUCTION

The market for steel plates in Australia has been growing rapidly and received considerable impetus with the commissioning of the 86" plate mill at the Australian Iron & Steel Pty. Ltd. works at Port Kembla in 1954. In 1963 the advent of the 140" plate mill at the same plant provided the plate market with a range of plate products previously unavailable in Australia.

In 1966 a drop in local plate demand forced the B.H.P. Co. Ltd. to seek export markets in plate and other steel products[1]. This drop in demand may be a short term economic fluctuation, but it is evident that local steel is being subject to considerable competition from aluminium, plastics and concrete as well as from overseas steel manufacturers. An example of the loss of a traditional steel plate market to aluminium is the building of 100 bulk wheat hoppers for the Victorian Government. It is claimed that "because of the hopper's quicker loading and unloading ability one aluminium waggon will do the work of five of the steel hoppers now in use"[2].

Increasing technological advances in many industries are driving the manufacturer to increased competition in the form of reduced tolerances, improved quality, reduced delivery times as well as reduced prices. The trend towards customers demanding all the above advantages in steel plates is noticeable. The primary counter to this trend in the highly capitalised industry of steel will be in improved efficiencies in production.

The purpose of this paper is to show how existing equipment for the production of steel plate can be more efficiently utilised by the application of scientific management techniques. With a modern

---

1. Directors' Report B.H.P. Co. Ltd., 31st May, 1966.

2. Australian Financial Review, 10th February, 1966.

plate mill, which represents a major capital outlay, it is economically important to schedule optimally. Failure to utilise both the maximum rolling time possible, and the maximum degree of quality control necessary, will result in substantial opportunity loss on return on capital. More critical reasons are also clear. Failure to roll to best quality and maximum tonnage will result in longer lead-times to customers. This in itself is major cause of dissatisfaction to a consumer and can result in reduced market penetration by the steel supplier.

With the development of automation, cybernetics, and particularly with the trend of digital computers for use in managerial decisions, there is a hard core of thinking that more centralised management control is desirable. The Managing Director of the Steel Company of Wales Ltd. recommends that "every single part of the plant and every single operation (should be) gradually committed in writing to a Standard Practice Book" [3].

However, this in itself cannot be sufficient. Standard practices may be laid down, but these must be fully quantified for effective managerial control. To achieve a more centralised control of the critical aspects of the steel manufacturing industry, some type of model should be formulated for each process. Referring to the more particular aspect of plate rolling, the cost of product, the manufacturing lead times and the quantity supplied are all variables. To effectively plan operations on a plate mill then, it is essential to know the effect that product specifications will have on the above areas. Further, it is important to group and organise the products to be rolled to achieve maximum efficiency. If no managerial control is placed, for example, on the slab size provided or the arrangement of a rolling schedule, then no effective control is being placed on output or costs.

3. W.F. Cartwright "The Future of Automation in the Iron & Steel Industry", Australian Machinery & Production Engineering Dec., 1964.

If a model can be determined for each process of the manufacture of steel plates then the following two functions can be achieved:-

(a) Routine operations will have well defined guides and so can more closely approach optimum levels.

(b) Performance can be regularly checked against a standard and so control can be maintained.

The latter is frequently attempted in the use of flexible standard costing procedures. The usefulness of these depends greatly on the method used for calculation of the standard. Frequently, the standard does not effectively follow the optimum level due to lack of detailed investigation into the area concerned.

OPERATIONS RESEARCH

This writer feels that the solutionto optimisation problems in manufacturing enterprises can only be achieved through the application of Operations Research techniques. Therefore it is considered to be worth while at this stage to digress a little to examine briefly the history of Operations Research. An understanding of the essential characteristics of O.R. is required before its techniques can be intelligently applied. Knowledge of the development of this field of endeavour will assist in supplying this understanding.

When, in 1911, Fredrick Taylor published his "Principles of Scientific Management", it was the start of the application of scientific methods to modern business operations. He was followed closely by Frank Gilbreth with his detailed study of time and motion, but "Scientific Management" became the subject of much criticism in the United States and abroad.

Prior to the second world war the service chiefs in the United Kingdom became increasingly alarmed at the rate of re-armament of Nazi Germany, and in December, 1934 a Committee for Scientific

Survey of Air Defence was established [4]. In 1936 the Bawdsey Research Station was established and has been called the "birthplace of operational research" [5]. From this research team was developed the radar which is such an important feature of war and peace-time air and sea operations.

With the outbreak of war, this research work was accelerated and by 1943 all branches of the services had their own Operational Research teams. The United States was quick to follow the lead and in 1942 an Operations Analysis Section, trained by the Bomber Command Operational Research Section, was formed at the Headquarters of the Eighth U.S. Air Force [6].

After the war, the British service groups were largely disbanded and the trained scientists moved into industry. An Operational Research group was set up by the National Coal Board and this pattern was followed by many private industries [7]. It was not until 1950 that American industry took an interest in the new science. By 1960 it was claimed that more than a third of the 500 largest corporations in the U.S.A. were using Operations Research [8].

Thus modern "Operations Research", as it is known in the United States, cannot be considered as springing from Taylor's Scientific Management. Its birth was in the second world war and is the result of attempts to apply the science of probability to decision making.

---

4. Air Ministry "Operational Research in the R.A.F." H.M. Stationery Office, London, 1963, P.1X.
5. Ibid - P.5
6. Ibid - P.X
7. R.L. Ackoff and P. Rivett "A Manager's Guide to Operations Research Wiley, London, 1963 - P.6.
8. Ibid - P.9

THE NATURE OF OPERATIONS RESEARCH.

The first substantial book on O.R. to be produced outside the military services, that of Churchman, Ackoff and Arnoff in 1957, states that an object of O.R. is to "provide managers of the organisation with a scientific basis for solving problems involving the interaction of components of the organisation in the best interest of the organisation as a whole" [9].

A more recent publication details the Management Science approach to a decision-making problem as follows:- [10]

(a) Identify the decision variables.
(b) Specify the objective.
(c) Identify the parameters.
(d) Develop the model which expresses the objective as a function of the decision variables and the parameters.
(e) Solve the model for the value of the decision variables which optimises the objective.

In this, the essential nature of O.R. appears in the last two steps. Developing a mathematical model of the decision area removes subjectivity as much as possible and introduces the rigid logic of mathematics. Mathematics, as one author puts it, is simply a systematised way of preventing illogical thinking. The final step, the solving of the problem, is to "make the <u>best</u> choice from among the available courses of action". [11.]

---

9. C.W. Churchman, R.L. Ackoff & E.L.Arnoff - "Introduction to Operations Research" Wiley N.Y., 1957 - P.6.

10. J.E. Howell & D. Teichroew - "Mathematical Analysis for Business Decisions" Irwin, Illinois, 1963 - P.286.

11. R.L. Ackoff - "Scientific Method - Optimising Applied Research Decisions", Wiley N.Y. 1962 - P.31.

Many sophisticated mathematical techniques have been developed for analysing and optimising these problems but a basic weakness is still apparent. There is no generalised theoretical approach to a problem and publications deal, in the main, with examples of applications to specific types of problems.

THE OPERATIONS RESEARCH APPROACH.

Another definition of O.R. which admirably expresses the concept of this paper is "the application of scientific methods, techniques, and tools to problems involving the operations of the system so as to provide those in control of the system with optimum solutions to the problems". In this paper the problem is to develop conditions for optimum production of plate through a wide plate mill.

Frequently the most difficult aspect of the process of developing a solution to the problems associated with complex manufacturing techniques is a true statement of the problem. Hence this becomes the first and probably the most important step.

a) Formulation of the Problem.

This can also be broken down into two specific areas. The first being the managerial problem. In this step it is necessary to clearly define the management objectives in terms which can be related to the specific problem. Having defined the objectives, the second stage, namely, the operation problem, can be stated.

This function of defining the problem cannot be dismissed lightly. An executive may think he knows what he wants, but when asked to clearly quantify his wishes in concise terms, is frequently at a loss. Not only must the problem be stated clearly, but it must be given definite boundaries. It is not sufficient, for example, to ask a researcher to solve the general problem of transient heat flow, when the solution is to be applied to a specific furnace for a specific range of slabs. The classic Operations Research text book of Churchman, Ackoff and Arnoff claims various components of a problem.[12] These are as follows:-

(i) The decision maker

It is necessary to identify the decision maker so that the solution to the problem may be presented to him in a comprehensible manner. It must be presented in the language he understands.

(ii) The decision maker's objectives.

In formulating the problem it is necessary to ensure that the decision maker's objectives are consistant with the defined objective of the enterprise. Failure to ensure this can lead to costly sub-optimisation.

(iii) The system or environment.

In the particular type of manufacturing problems being discussed, this will usually mean the interaction of other physical components of the production process on the problem area in question. It can, also mean the personal environment of the decisionmaker, or the total environment of the enterprise in its market area.

These however, will principally affect the objectives and will not be considered in this paper.

(iv) Alternative courses of action

A problem does not exist unless there are at least two courses of action. Not all the possible courses may be apparent to the decision maker and may in fact be presented as part of the solution to the problem.

The management problem need is to state objectives clearly so that measures of effectiveness of the solution may be determined. The operation problem is then concerned with the environment and alternative courses of action. Where the problem can be stated in precise terms and, all factors in it can be quantified, the most satisfactory solution is frequently determined by constructing a mathematical model.

12. C.W. Churchman et. al. op. cit. - P.107.

b) The Model.

In the preface to their book on "Executive Decisions and Operations Research", Miller and Starr [13] state:- "We reject the approach that identifies operations research with a heterogeneous assortment of mathematical techniques. .....O.R. is a continuum of methods resulting from a fundamental programme of model building within the decision frame work".

When the relationship values of all factors in the problem are established, a mathematical model may be built which can be used to simulate conditions of the operations. The great advantage of this is that various factors may be varied and the results predicted experimentally before they are committed to actual practice. A true model of a plate mill will amongst other things, determine the range of orders and which can be accepted for a desired output, will establish the cost of new products for pricing and will determine the cut-off points of operations within the mill. The maximum tonnage to be rolled off one set of mill rolls would be such a point.

Due to the large number of variables and the difficulties of measuring parameters, any practicable model for plate rolling operations will of necessity contain approximations. Thus the model must be tested exhaustively to establish the degree of its reliability over a wide range of variables. The construction of such a model is complex and much of this paper is devoted to possible approaches to the model building. The derivation of a solution to the model must then be undertaken and the complexity of this will vary with the complexity of the model developed.

Thus the approach should be in four basic steps:

a) Formulation of the problem.

b) Construction of a model.

---

13. D.W. Miller & M.K. Starr "Executive Decisions & Operations Research" Prentice Hall N.J. 1960, preface.

c) Testing the model.

d). Derivation of a solution from the model.

The aim of this paper is not so much to find the optimum solution to the problem as to define the problems and determine possible approaches. Hence, when a numerical solution is given it must be considered to be indicative of the true solution only.

The aspect of model testing, with the necessary adjustment to the model, must be part of a second phase. There are two final steps to follow the above in a practical solution:-

e) The solution must be tested.

f) The solution must be implemented.

A further necessity for the development of mathematical models of operations within the steel industry is to allow improvement in the process control field. Sophisticated process logic devices are available formany applications, from furnace fuel control to automatic mill operation. Frequently the installation of this instrumentation is very costly and the economic gains could be marginal or even nonexistant. Collection of data and its analysis must provide the basic data for reasonable assessment of the feasibility of improved process control.

There are a number of papers on this approach, and one by C.W. Dunn[14] provides helpful insight into the application of process control technology to steel plant facilities by a logical step by step evaluation.

FEED BACK CONTROL.

With greater information available fromoperations and with the more highly developed tools and techniques for handling this information, it is felt that management must tend towards "feed back control". This is a control engineering term and is a very useful analogy when examining management control systems.

14. C.W. Dunn "Applying Computers to Existing Steel Plant Facilities" Industrial Heating, 1966 - P.1085.

Essentially, feed back control is "closed loop" control, in contrast to an "open loop" control in which no information is fed back from the output.

If a model is constructed for every operation, feed back will show the deviation of practice from that required (i.e. the desirable optimum).

Feed back without a model of the system, will serve no useful function. In practice, most operations have been reduced to a crude model at least, possibly subconsciously, by the programmers and operators. The aim is to formalise this model and make it deterministic where possible.

The advantages of any feed back control are:-[15]

a) Less dependence on the characteristics of the system components. For example, less initiative is necessary from plate mill providers if a rationalised slab and plate schedule is given to them.

b) Less sensitivity to load disturbances. The system is more able to cope with varying conditions if it has been pre-planned. Adjustment can be made for varying load conditions because the feed back presents the knowledge of the conditions.

c) Faster response to command signals. The manager can achieve a desired result more rapidly in the closed loop system.

d) Extreme modification of the systems behaviour is possible. The system can be guided towards a new goal by an iterative process even where the full model is not available. The feed back provides the guide for each successive modifying change by presenting the effect of the last change.

---

15. "Handbook of Automation, Computation & Control" E.M. Grabbe et. al. editors Vol. 1, Wiley N.Y., 1958 - P.19-12.

SUMMARY.

To summarise, this paper will be dealing with the formulation of the problem and will show the need for the derivation of mathematical models of the processes. This is what one writer calls the "judgment phase".[16] The "research and synthesis phase" will be discussed sufficiently to determine the depth and scope of the problem, but will fall short of the actual model building. The "action phase" or implementation will not be considered at all.

---

16. L. Hurni "Basic Processes of Operations Research & Synthesis" in A. Schuchman ed. "Scientific Decision Making in Business" Holt, Rinehart & Winston N.Y., 1963, - P.43.

4 ZONE SLAB REHEAT FURNACE

LONG SECTION

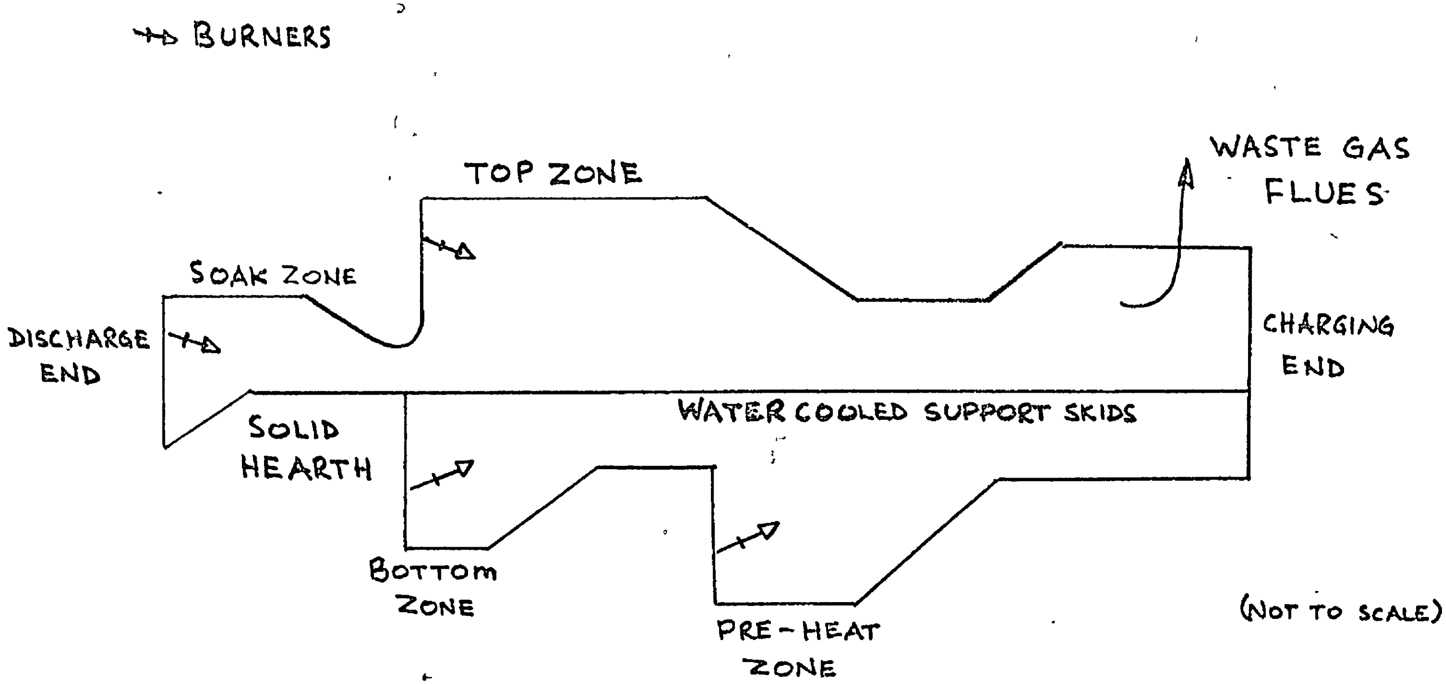


FIGURE 1

II THE FURNACE

It is considered essential that an analysis of the furnace characteristics be made in any attempt to optimise mill operations. In a great many aspects, the furnace must follow the dictates of slab yard, the providers and the mill. Yet the situation arises where the "tail wags the dog", for the mill production is inextricably tied to furnace production. Of course, more furnaces may be added to increase mill production. Although this unit is a much lower capital cost than the mill itself, it still represents a very substantial outlay and the aim must be to optimally programme existing equipment, or to design future equipment for optimum performance at minimum cost outlay.

Although operators have for many decades, used rules of thumb in furnace operation, and although the mechanics and mathematics of general heat transfer are largely understood, an analysis of furnace operations remains a complex undertaking. This is principally because of the difficulty in measuring the necessary factors prevailing in the furnace under operating conditions. A prime example is the difficulty of determining the thermal properties of the steel charge.

The purpose of this section is to analyse the problems and to lay down a line of approach to their solution. A solution has been attempted using various sources of empirical data but no attempt has been made to justify this as a general solution.

DESCRIPTION OF THE FURNACE:

The type of furnace under consideration is the four zone, continuous, re-heating slab furnace. The heating zones of the furnace consist of one row of burners firing above the charge of slabs and two rows of burners firing below the slabs. (Fig.1).

The slabs are supported on four rows of water cooled skids. As the slabs considered in this exercise are all under 12 feet 6 inches long, each slab rests on two skids and thus two parallel rows of slabs are formed through the furnace.

The water cooled support skids create cold spots on the bottom of the slabs and so the final "soaking" zone is provided. This consists of a solid brick hearth carrying the slabs, with a single row of burners firing above the slabs. The function of the soaking zone is to dissipate the cold spots and it thus tends to produce a slab with uniform temperature distribution.

The furnace may be fired by fuel, oil or coal gas with flow counter to the slab movement.

The slabs are charged by double pushers and each slab charged causes a slab to be discharged. The elements of the furnace may then be summarised as follows:-

a) The heating chamber, which is an enclosure to contain the slabs and retain the heat;

b) The hearth and skid supports to carry the slabs through the furnace;

c) Facilities to develop heat, to raise and maintain the temperature of the slabs;

d) Means to distribute the heat and remove the waste gasses;

e) Facilities to charge and withdraw the slabs.

THE HEATING FUNCTION:

The fuel is mixed with combustion air and ignited almost immediately on entering the furnace chamber. The air/fuel ratio is adjusted to give a long flame and still retain adequate combustion. This lowers the flame temperature and so prevents localised overheating and also provides better distribution of the heat. The heat may be transmitted to the slabs in three main ways:-

a) Radiation from the luminous flame.

b) Radiation from the hot refractory brick walls, roof and floor.

c) Convection of the hot gasses.

Since refractory bricks and steel both have an emissivity of approximately 0.9 at elevated temperatures, the radiation between the walls and the slabs is given by:[17]

$$Q = 0.173 \times 0.9A\left[\left(\frac{\theta_1}{100}\right)^4 - \left(\frac{\theta_2}{100}\right)^4\right]t$$

where Q - heat transferred in B.T.U.

A - Area of the steel charge (surrounded by radiating walls)

θ_1 - temperature of walls ^oF.

θ_2 - surface temperature of slab ^oF.

t - exposure time in hours.

Analysis of this equation shows two important features. Firstly, the expression $\theta_1^4 - \theta_2^4$ is expanded to $(\theta_1 - \theta_2)(\theta_1^3 - \theta_1^2\theta_2^2 + \theta_1\theta_2^2 + \theta_2^3)$ which becomes approximately equal to $2(\theta_1 - \theta_2)(\theta_1 + \theta_2)^3$. This shows that even small differences in temperatures result in high rates of heat transfer at elevated temperatures. The wall temperature in the furnace under consideration is of the order of 2700^oF.

Secondly, the heat radiation is shown to be a linear function of the exposure time. This however is only true if the emissivity of steel is not a function of temperature.

The radiation laws of luminous flames are exceedingly complex and will not be expanded here. The luminosity, and so the radiation, can be increased by various practical ways. An increase in combustion air will increase flame temperature but lower the luminosity, while the addition of a carboniferous fuel, such as bunker oil, will greatly increase the luminosity.

Heat transfer can also be effected by convection, expecially at the lower temperatures but again the heat transfer laws become complex. It was considered by F.S. Bloom in 1955[18] that the total

---

17. W. Trinks & M.H. Mawhinney "Industrial Furnaces", Vol. 1 5th ed. Wiley N.Y. 1961 - P.33.

18. F.S. Bloom "Rate of Heat Absorption of Steel" Iron & Steel Engineer May, 1955 - P.64

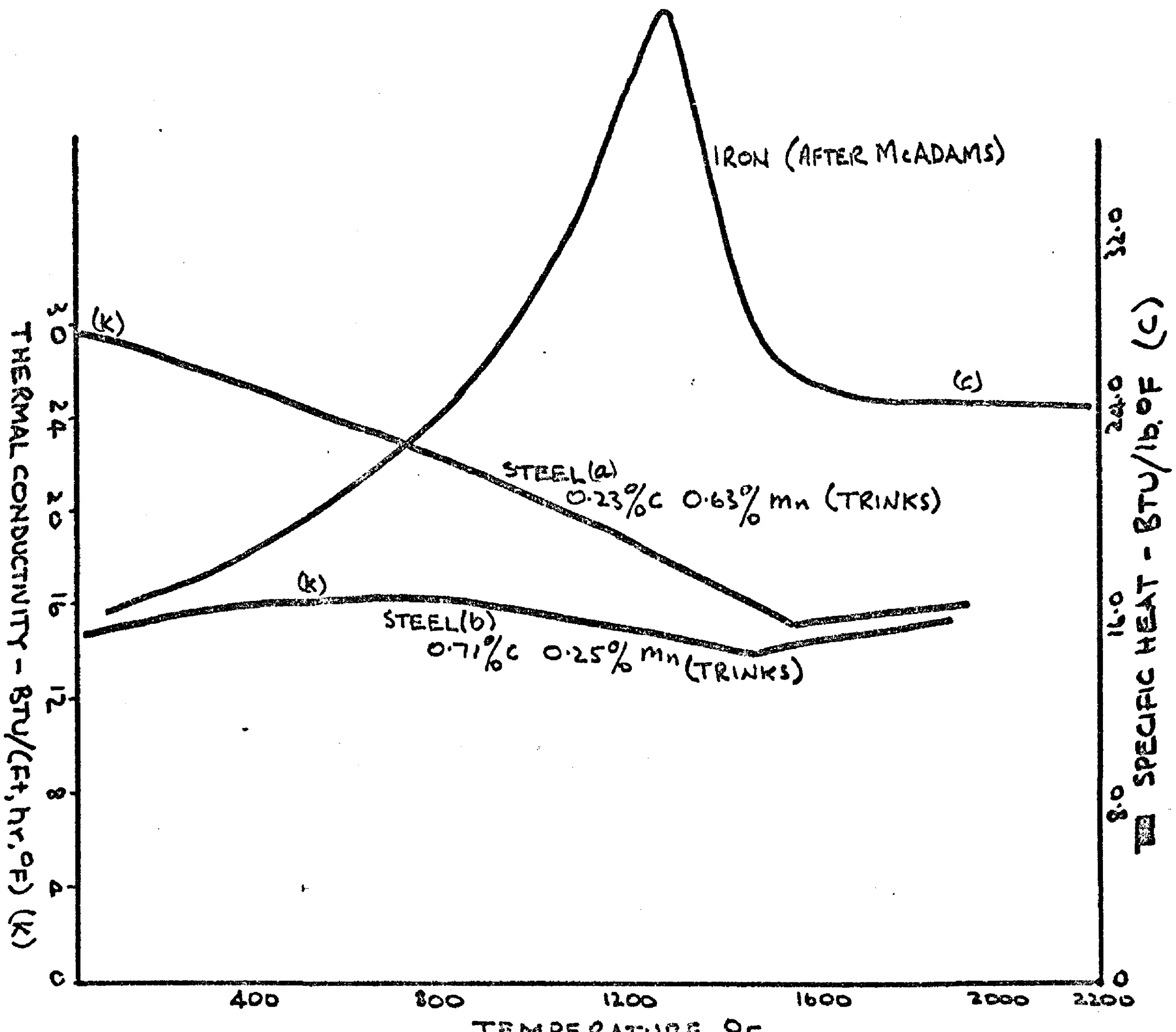

IRON (AFTER McADAMS)
(k)
(c)
STEEL (a)
0.23%C 0.63% mn (TRINKS)
(k)
STEEL (b)
0.71%C 0.25% mn (TRINKS)
THERMAL CONDUCTIVITY - BTU/(Ft, hr, °F) (K)
SPECIFIC HEAT - BTU/lb, °F (C)
0
4
8
12
16
20
24
30
8.0
16.0
24.0
32.0
400
800
1200
1600
2000
2200
TEMPERATURE °F

FIGURE 2

heat transfer whether by radiation from walls and gas or by convection can be considered to approximately follow the Stefan-Boltzmann law, viz. $Q \propto (\theta_1^4 - \theta_2^4)$.

The major difficulty at this stage is the variation of the emissivity of steel with temperature, and the progressive formation of surface scale which again has different thermal properties to the steel base. This concept is developed further in a later section.

The first aim of the furnace is then to transmit heat to the steel charge and so raise the temperature of the surface.

The second consideration is to transmit the heat from the surface to the centre of the slab by conduction. The expression for the steady state condition is:-

$$Q = \frac{kA\ (\theta_2 - \theta_3)}{S}\ t$$

Q - heat flow in B.T.U.

k - conductivity in B.T.U./ (ft/hour/^{o}F.)

A - slab area in sq. ft.

θ_2 - temperature of outside of slab ^{o}F.

θ_3 - temperature of centre of slab ^{o}F.

S - thickness of slab in feet.

t - time in hours.

For our purpose, the significant features of this expression are that the heat transfer varies directly as the surface area and the time, but varies inversely as the thickness.

However, the conductivity of steel is a function of its temperature as shown in figure 2 as well as depending on steel analysis. High carbon slabs curve (b) are always charged hot due to the detrimental effects of thermal shock on cooling. This tends to compensate for the lower thermal conductivity at lower temperatures.

As a result, it is possible to operate the furnace under normal conditions with both low carbon and high carbon slabs in the charge.

The above equation is applicable only in the steady state conditions. Under normal operating conditions the heat flow is transient. That is to say, the temperature at a given point in the steel slab varies with time. The above simple equation is replaced by a differential equation, each term of which holds for one of the three space co-ordinates.

$$\frac{\partial^2 \theta}{\partial x^2} + \frac{\partial^2 \theta}{\partial y^2} + \frac{\partial^2 \theta}{\partial z^2} - \frac{1}{\alpha}\frac{\partial \theta}{\partial t} = 0$$

where θ is the temperature at point (x,y,z) and α is the thermal diffusivity ($= \frac{k}{\rho c}$).

However, the thermal properties of conductivity, specific heat and density are not constant, but vary with temperature (but not with position in an isotropic solid) and the equation becomes:-[19]

$$\rho c \frac{\partial \theta}{\partial t} = k\nabla^2\theta + \frac{\partial k}{\partial \theta}\left[\left(\frac{\partial \theta}{\partial x}\right)^2 + \left(\frac{\partial \theta}{\partial y}\right)^2 + \left(\frac{\partial \theta}{\partial z}\right)^2\right]$$

where ∇^2 is the laplace operator, $\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}\right)$

In the opinion of Trinks [20] the solution of this equation is "usually impossible". Never-the-less the calculation of the distribution of heat within slabs has been made by a number of people. El-Waziri has used an iterative method, dividing the slab into a network and calculating heat flows from nodal points[21]. It is necessary to use an electronic computer in this method due to the large number of calculations involved.

---

19. H.S. Carslaw & J.C. Jaeger "Conduction of Heat in Solids" Oxford London, 1947.

20. W. Trinks op. cit. - P.22.

21. A.H. El-Waziri "The Transient Temperature Distribution Within Slabs "Iron & Steel Engineer March, 1961 - P.132.

Mirsepassi[22] has compiled tables for the use in heat transfer problems which enables simple problems to be done by hand, but his tables do not include allowances of changes of thermal properties with temperature. A valuable article by Jackson and others in 1944[23] gives calculated time lags between surface and centre temperature for different temperatures which are claimed to relate closely to practice.

It is clearly a difficult proposition to incorporate the above differential equation in a furnace model. To obtain the solution it is necessary to determine the mathematical relationships between the thermal properties and temperature. To apply the data a computer programme is required to carry out iterative calculations through the slab thickness at various stages through the furnace.

Thus a detailed practical investigation is required followed by analysis by a competant mathematician. These are most necessary steps in the derivation of a reliable model. In the interim the writer attempts in the following section to derive a simple model from data already available.

THE EFFECT OF SLAB THICKNESS - A SIMPLE MODEL:

To transmit the radiant heat from the flame and walls, the heat must penetrate the surface barrier of the slab. This has an oxide layer which exhibits an insulating effect which varies with composition and temperature. The measurements of the thermal properties of the surface are very difficult, but the effective emissivity is the key factor for any transfer of heat to be calculated.

---

22. T.J. Mirsepassi "Heat Transfer Tables for Time - Variable Boundary Temperatures in a Slab" British Chemical Engineering Vol.10 No.11, November, 1965.

23. R. Jackson et.al. Variable Heat Flow in Steel" Journal of Iron & Steel Institute C.L. page 211, 1944.

Trinks gives some values of heat transfer co-efficients for steel[24] however it must be realised that these are indicative only and the co-efficient will vary with the following parameters:- chemical composition of the steel, the steel temperature, the wall temperatures, the flame temperature, the type of fuel, the percentage of combustion air and the degree of combustion, the thickness of the gas blanket, the areas of the steel stock, hearth, walls and roof, the type of furnace refractory, the thickness of and composition of the oxide layer.

Having determined the heat transfer from the furnace to the surface of the stock, it is necessary to determine the rate of heat transfer through the slab.

The criterion of optimum rolling temperature is principally the temperature of the centre of the slab.

The conduction heat in the steady state is given by:

$$\frac{Q}{t} = \frac{k \times A \times (\theta_2 - \theta_3)}{S}$$ as stated on page (18)

However, as explained previously, the heat flow in the case under consideration is transient and the above expression cannot be applied.

The following logic was attempted to determine the order of magnitude of the effect of slab thickness on the time required in the furnace, and ultimately on the tonnage throughput.

a) Constant Thermal Properties.

Assume the steel charge is divided into a number of thin laminae and that within each lamina the thermal properties are constant. Suppose a resistance to heat flow from the centre of one lamina to the next of Rn and a heat capacity of each lamina of Cn. These properties

---

24. W. Trinks op. cit. - P.48.

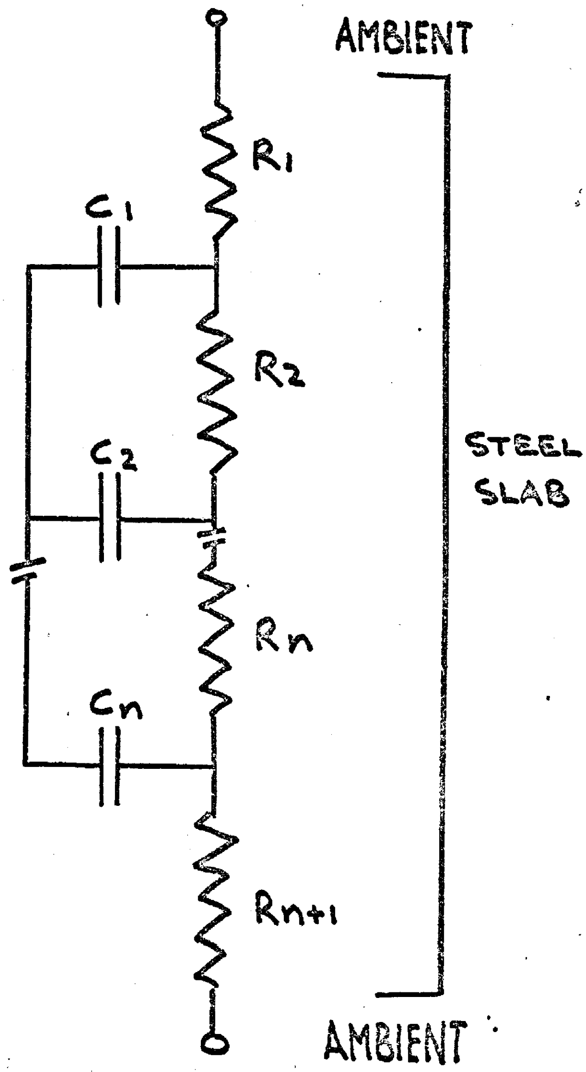


FIGURE 3

can be represented by an electrical circuit analogue as in figure 3.[25a] Note that R1 and Rn + 1 in this figure are the resistances to heat transfer from the furnace to the slab. This value will depend on the fourth power radiation law while the others will depend on the single power conduction law.

If the slab is isotropic and the two ambient temperatures are equal, then it will be sufficient to consider heat travelling in one direction only, from one surface to the centre. The purpose of the exercise is to determine how much longer it will take for the centre of a thick slab to reach a desired temperature, compared to the time for a thin slab to reach the same temperature.

Considering that the thermal properties are independent of temperature and position, then it is apparent that a slab of thickness 2s will have twice the resistance to heat flow (if R1 and Rn + 1 are ignored) and twice the heat capacity of a slab of thickness s. This means that the time for the temperature in the centre to reach a certain temperature will vary directly at S^2.

This result was also concluded by Williamson & Adams in 1919[25] who considered that the time lag between the surface and centre temperatures passing through any particular value is ultimately $\frac{S^2}{8\alpha}$ where α is the thermal diffusivity, (considered constant). It appears logical to assume an average value for α if this property varies with the temperature distribution through the slab, although this value will itself be a function of time.

As the heating rate will be proportional to $\frac{1}{S}2$ and the tonnage of slab is proportional to S the total tons/hour heating rate will be proportional to $\frac{1}{S}$. This strongly favours the thinnest slab as being the best slab for highest tonnage output.

---

25. E.D. Williamson & L.H. Adams, Physical Review Vol.14, 1919 - P.99.

25a J. Cole Private communication

However, the resistances R1 and Rn + 1 cannot be ignored. As these are surface resistances only, it is apparent that if these resistances are substantial they will tend to favour the thicker slab as a better slab for tonnage output. Practice has shown that the surface resistance is indeed substantial and the scale layer formed in the furnace has an insulating effect. The following analysis will consider this variation of thermal properties

b) <u>Variable Thermal Properties</u>:

The writer has not been able to locate suitable data which will directly give the variation of all the thermal properties of steel with temperature. Fig.2 shows the magnitude of variations possible, but such values must, in general, be established for the particular operating conditions under consideration.

It is frequently useful to go straight to operating practices and attempt to analyse them. The U.S. Steel publication "Making, Shaping and Treating of Steel" gives a curve relating the average rate of heat absorption to the thickness of steel in re-heating furnaces.[26] This shows a linear relationship over the thicknesses of interest of the form:-

$$Q = b - a \cdot s$$

where a & b are constants, Q = heat transfer in B.T.U. sq.ft.hour.
s = thickness of slab in feet.

An analysis of this curve gave rough values to a & b as follows:-

$$Q = 31{,}00 - 7820s$$

Thring (11) shows that the average temperature of a slab in a furnace of temperature θ_1 after time t is given by:-

$$\underline{\theta} = \theta_1 - (\theta_1 - \theta_o)\, e^{-(Qt)/gc}$$

26. "The Making, Shaping & Treating of Steel" United States Steel, Pittsburgh 7th edition - P.400 fig. 21-2.

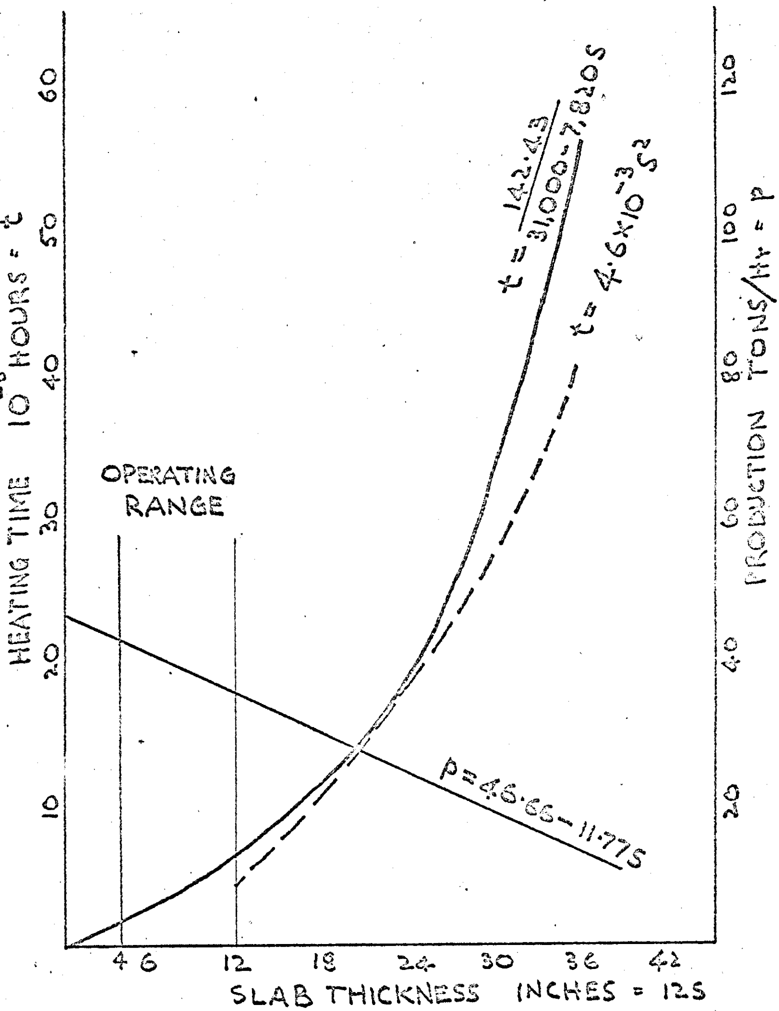

HEATING TIME 10^{-3} HOURS = t
10
20
30
40
50
60
OPERATING RANGE
$t = \frac{142.43}{31,000 - 7,820S}$
$t = 4.6 \times 10^{-3} S^2$
$p = 46.66 - 11.77S$
20
40
60
80
100
120
PRODUCTION TONS/Hr = P
4
6
12
18
24
30
36
42
SLAB THICKNESS INCHES = 12S

FIGURE 4

where θ_o is the initial slab temperature in ^oR, g is the weight of the body in lb/sq.ft. of exposed surface, and c is the specific heat. If ρ is the density and the above expression and the following values are substituted....

$$Q = 31{,}000 - 7820s \quad \text{B.T.U./sq.ft.hour } ^oF.$$
$$g = \rho S = 480 \text{ lb/cubic ft.} \times S$$
$$\theta_o = 70^oF = 562 \; ^oR$$
$$c = 0.168 \text{ B.T.U./hour ft. } ^oF.$$
$$\theta = 2250^oF = 2742 \; ^oR \text{ (as a desired temp.)}$$
$$\theta_1 = 2700^oF = 3192 \; ^oR.$$
$$S = \text{slab thickness.}$$

$$e^{Qt/\rho Sc} = \frac{\theta_1 - \theta_o}{\theta_1 - \theta} \qquad t = \frac{S\rho c}{Q} \ln\left[\frac{\theta_1 - \theta_o}{\theta_1 - \theta}\right] \text{ hours}$$

$$t = \frac{S}{Q} 480 \times 0.168 \ln 5.845 = \frac{142.4S}{31{,}000 - 7{,}820S} \text{ hours}$$

This gives a heating rate of 43 tons/hour for a 4" slab. Observed practice on one furnace gives tonnage rates of 50-80 tons per hour on 4" slabs and considering that none of the parameters have been measured on that furnace the correlation is better than expected. It is interesting to note that an 8" slab, using the same equation gives a tonnage rate of 39 tons/hour. The significant feature is that there is not as great a difference if the previous law of $\propto \frac{1}{S^2}$ held. It is apparent then, that the surface resistance is significant (as was anticipated) and, as stated before, this favours the thicker slab.

The curve of the time - thickness equation is shown in Fig.4. This has no maxima; $t = 0$ at $S = 0$ and $t = \infty$ at $S = 3.9$ ft., where t is the time to heat a slab of thickness S to the desired temperature. This latter statement is obviously impossible but it is not intended to use the graph beyond 12 inches. At greater thicknesses the surface barrier effect is obviously far less important that the conduction effect.

The expression $t = a\,S^2$ is then assumed where a is a constant. This is also plotted in figure 4. Taking $a = 4.6 \times 10^{-3}$ the square curve takes over from the other curve at 2 ft. as shown. The form of this expression has been justified to some extent earlier if the barrier effect is negligible.

As t is the time in hours to heat one square foot of steel, thickness S ft., to an average temperature of 2250°F. the tonnage heated in t hours will be

$$S \times \frac{480}{2240} \times \frac{1}{t} \quad \text{tons/hour.}$$

where density of steel = 480 lb./cubic ft.
Therefore, the total tonnage equation becomes:

$$\frac{(31{,}000 - 7820S)}{142.4} \times \frac{480}{2240} = 46.66 - 11.77\,S \text{ tons/hour} \quad \text{(S in feet.)}$$

This is also plotted on figure 4 and shows clearly in the significant range 4" - 12" that the thinnest slab gives the best heating rate.

This is, of course, an over simplified model of the heating process. It is however, of the right order as verified by practice. It is important that some mathematical relationship between thickness of slab and tonnage rate be supplied to a mill manager to enable optimum conditions on the furnace to be approached.

A true model will, almost certainly, have the finished plate thickness as a parameter. Heavier plate requiring less heat than lighter plate.

A further important operating feature to be considered is the rate of variation in thickness in the furnace. If an 8" thick slab is placed next to a 4" thick slab, the obvious result is that the time required to heat the thick slab will overheat the thin slab. This results in poor operation and loss of furnace efficiency. It is difficult to mathematically arrive at a maximum difference in thickness for best operations, but practical observations set this figure at

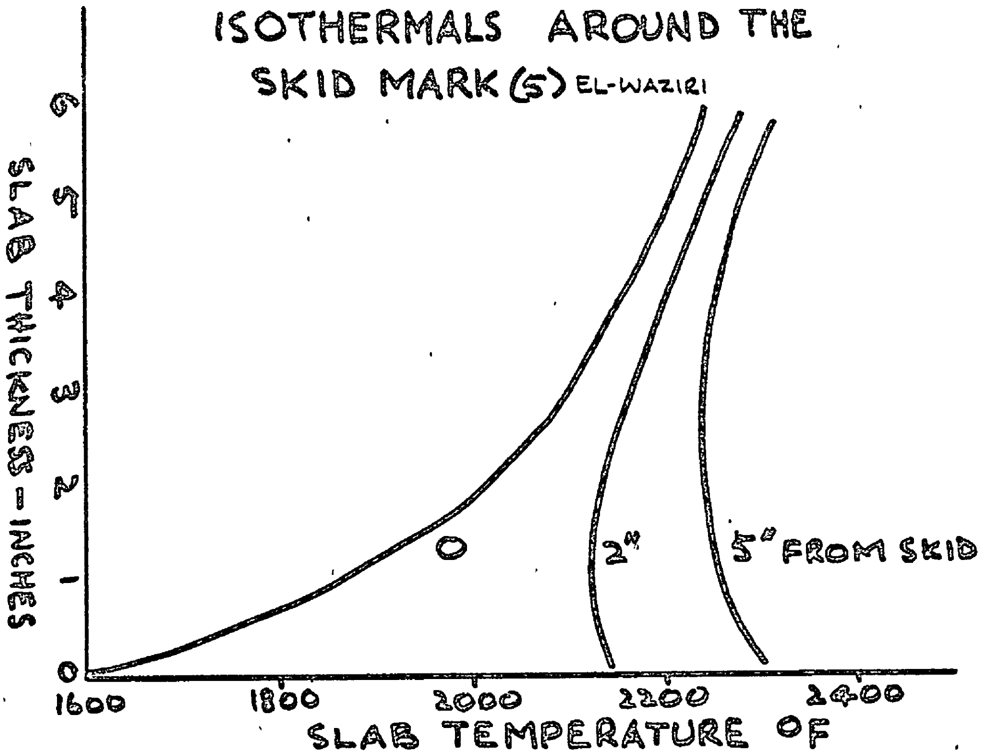


FIGURE 5

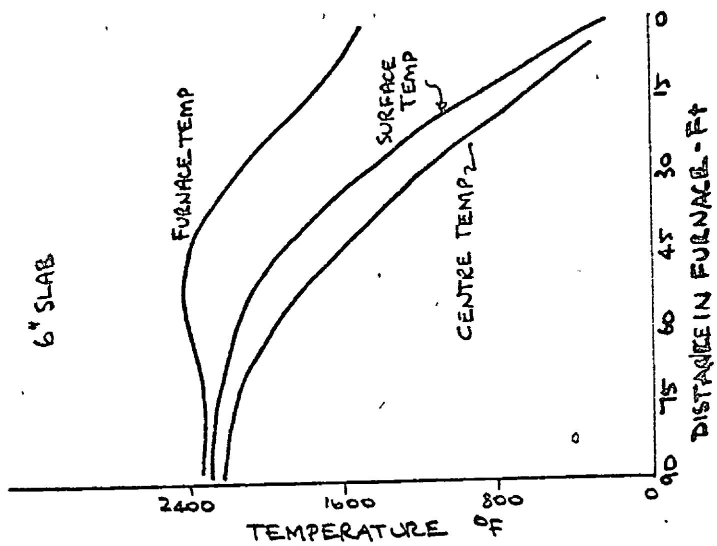


FIGURE 6

about 25% maximum increase, with a desirable figure of 12½%. These figures give maximum variation of one inch at 4" & 2" at 8" thick slabs. When considering programming for the mill, this condition can frequently be difficult to maintain.

THE EFFECT OF THE SUPPORT SKIDS:

The water cooled support skids, which are necessary to allow bottom firing, absorb the heat from the slab. It is attempted to remove these "skid marks" by equalising the slab temperature in the soaking zone. This is seldom fully effected and the increase in gauge on a finished plate due to these cold spots must be reckoned with. It is frequently the presence of these skid marks which place the limitation on the furnace heating rate. Figure 5 shows the isothermals in a typical slab before soaking.

As the cooling effect of the water cooled skids is mainly by simple conduction (there is also an effect of shielding from the flame, but this is less significant) the heat flow from the slab is given by:

$$Q = k\, k_1 A\, (\theta_2 - \theta_4)\, t/d$$

Q - heat transferred to the water.
k - thermal conductivity of slab.
k_1 - thermal conductivity of skid runner.
A - contact area.
θ_2 - slab temperature ^{o}F.
θ_4 - water temperature ^{o}F.
d - distance from slab surface to water.

This shows that the heat loss and so the intensity of the skid mark varies directly as the slab temperature and the time of contact.

It may be possible to evaluate the effect of skid marks in the general tonnage equation given previously and further work in this direction would be justified.

SCALING OF THE SLABS:

Due to the reaction of hot steel with the products of combustion and available oxygen, a surface oxide (scale) is formed. This scale does not exhibit the properties of plastic deformation as does steel and must be removed before rolling.

The composition of the atmosphere has a pronounced effect on the characteristics of the oxide layers formed. An atmosphere of carbon monoxide and hydrogen produces a scale which is loose and friable. On the other hand, oxide layers produced in atmospheres containing excess oxygen are quite adherent and heavy. Also the rate of formation of oxides produced by incompletely combusted atmospheres is much slower than the oxides produced when oxygen is present.[27.] However if oxygen IS present then the rate of formation varies very little with the oxygen percentage of the gasses.[28]

Under "average conditions" the weight of scale formed is given by:-[29]

$$\text{lbs. of scale/sq.foot} = 0.4 \left(\frac{\theta_2}{2200}\right)^5 t$$

θ_2 - slab surface temperature $^{\circ}$F.

t - exposure time in hours.

Trinks points out that this equation has an accuracy of $\pm 25\%$ depending on the composition of steel and the furnace atmosphere.

Scale is undesirable in the furnace as well as on the finished product. A yield loss of the order of 2% due to scale becomes a most important cost factor. Additionally scale is an insulator and

27. M.W. Trink "The Science of Flames & Furnaces" 2nd edition Chapman, London, 1962 - P.383

28. W. Trinks op cit. P.22.

29. Ibid - P.96.

slows the heat transfer process in the furnace. Scale on heavy slabs may be melted, due to the higher atmosphere temperatures used to speed up heat transfer to the slab, as the melting point of ~~scale~~ scale is less than that of steel. This molten scale then causes severe operational difficulties on the solid hearthes of furnaces as well as making a mushy scale which is more difficult to remove on rolling.

The percentage of scale formed will be found by combining the general tonnage equation with the equation above, noting that the slab temperature is a function of the distance through the furnace as shown in figure 6.

It is interesting to note that a significant increase in scale occurs after the value of 2200°F. of furnace temperature.

THE EFFECT OF SLAB LENGTH:

Furnaces are designed to heat a certain amount of steel per unit area of hearth surface. If this available heating surface is not fully utilised the effectiveness of the furnace will drop. Slab width will have little significant bearing as the slabs can be considered to form two continuous lines of steel in the furnace.

Slab length is important and the effectiveness of the furnace is generally given as:-

Heating rate in lbs/sq.ft. of hearth = $\frac{L}{L_1} \times H_1$

H_1 the max. heating rate in lbs/sq.ft of hearth.

L actual length of slabs.

L_1 max. length of slabs.

However, it cannot be assumed that the heating capacity varies directly as length. It is apparent that for very short slabs furnace efficiency will suffer, but is by no means apparent for smaller variations in lengths near the maximum. As shown by Trinks, the heat transfer factor varies as the ratio of furnace wall surface to steel charge area.[30] As the steel charge area decreases, the tonnage decreases but the heating rate will increase. It is expected that only empirical results on a particular furnace will demonstrate the actual relationship for that furnace.

As shown in the section on slab rationalisation, it is necessary to vary the slab length to provide the necessary plate length range for customers' orders.

The difficulties in developing mathematical models of a furnace control are great and M.G. Shortland of B.I.S.R.A. considers that "the reheating furnace still defies computer control. Satisfactory continuous measurement of slab surface temperatures within the furnace have not yet been developed. This situation presents great difficulty in establishing equations by experiment to describe the rate of slab heating even under steady conditions. It also completely excludes the possibility of a continuous temperature feed back to any controller adjusting furnace heat release pattern".[31]

The writer disagrees with such a strongly worded statement which implies the virtual impossibility of solutions being determined.

Professor Lerner of the U.S.S.R. has developed the principles of automatic process control for a continuous reheating furnace[32]. In this paper he describes a method of simulation of the heat process which is ideally handled on a hybrid digital/analogue computer. Furnace control by a computer system is further developed in a restricted paper from the British Iron & Steel Research Assoc.[33]

---

30. Ibid - P.48.

31. M.G. Shortland 'Models of Good Measurement" Iron & Steel, 26th May, 1965 - P.279

32. A.Y. Lerner "Optimum Control for Continuous Processes" I.F.A.C. paper 501/1 Basle, 1963.

33. W.T. Kodz "Computer Control of the Continuous Slab Reheating Furnace". Restricted B.I.S.R.A. report PE/B/20/6J, London, 1965.

A digital computer installed on a slab re-heating furnace would perform the functions of conventional recorders and would have the following advantages from a management view point:-[34]

a) Log all data to enable the mathematical model to be improved and to be altered for changed conditions.

b) Perform dynamic optimisation of the controlable variables such as fuel and air flow, furnace pressure and pushing rate. Recent work on soaking pits[35] which is currently being verified on operating pits in Australia indicates that with detailed analysis of all variables, considerably reduced heating times can be achieved. It can be anticipated that increased pushing rates in slab furnaces may also be achieved by full analysis of the relevant data (although the problem is somewhat different).

SUMMARY:

To understand what is actually happening in the furnace, to be able to quantify conditions and so exercise control, a model of the furnace must be developed. This must take account of the significant modes of heat transfer to the slab such as convection, conduction and radiation, although it has been suggested that the radiation law is the over-riding factor.

The mode of heat transfer within the slab must be developed, together with the heat losses to the water cooled skid supports. This aspect must make allowance for the varying thicknesses of the slab feed and for the rate of change of thickness.

The effect of slab length and the loss due to scaling do not appear to be primary aspects for control. The length is dictated by providing requirements and scaling is affected by the heat transfer rates. These aspects should be quantified however for a complete model.

---

34. T. Suing Yang private communication.

35. F. Hollander comments on Centralised Information System on Soaking pits and Slabbing Mill" paper E.103 Verein Deutscher Eisenhuttenleute Dusseldorf, 1965.

One useful approach appears to be[36] to use the partial differential equation of page (19). The slab feed can be considered to be infinitely long and wide so that all effective heat transfer occurs through the top and bottom surfaces. This eliminates the y and z co-ordinates, however a velocity factor must be introduced to consider various velocities of slabs through the furnace. This equation can then be simulated on an analogue computer. The output from the model can be compared to the actual output and the model adjusted until its fit is reasonable.

A second approach is the iterative method of dividing the slab into laminae, considering constant thermal properties within each lamina, and utilising the digital computer. Once again the results of the model must be compared to actual and the model adjusted.

In using the digital computer, a table of values for the temperature curves in figure 6 is all that is required. For the analogue computer, however, analytical expressions are necessary. A standard curve fitting programme on a digital computer was applied to the wall temperature curve in fig.6 with the following results:-

$$\text{Temperature} = 1200 + 33.01x - 0.1037x^2 + 0.015541x^3 - 0.00051946x^4 + 0.0000391220x^5$$

where x = distance through the furnace in feet.

This equation, with a standard error of 7.15°F., gives 95% confidence limits of $\pm$ 14.3°F. This is about the accuracy of standard furnace temperature measuring devices.

The data for the centre and surface temperatures will be the check against the output of the model. Only the furnace temperature, which is the forcing function, needs to be analysed as above. The output from the analogue computer can in fact, be a set of curves for temperature distribution which can be checked directly against those obtained in practice.

---

36. T. Suing Yang - private communication.

To complete the model of the furnace, to determine what range of temperature distributions are required within the slab and what centre temperature is desirable, the mill itself must be studied. This aspect is investigated in the next section.

III THE PLATE MILL

DESCRIPTION OF THE MILL:

The plate mill on which trials were conducted was a 4-high mill with 39" diameter iron work rolls at 144" barrel length and 63" diameter steel back-up rolls.

Slabs are heated to a temperature of approximately 2300°F. in the furnace at which temperature plastic deformation will occur in the rolling operation. After descaling, with high pressure water jets, the slabs are edge worked in an edging mill situated before the main mill stand. Slabs are then rolled in a forward and reverse direction through a successively smaller mill gap until the desired thickness is achieved.

The reduced thickness produces a corresponding increase in length with very little lateral spread. Consequently, to roll a plate wider than the incoming slab width, the slab must be "broadsided". This consists of turning the slab through 90°, rolling in the mill so that the width is increased by the desired amount, then turning back through 90° for the "straight" passes.

The work rolls must be kept cool by water to retain their surface finish. This results in cooling of the slab being rolled and contributes towards the mill limitation of the minimum thickness which can be produced.

As the slab enters the mill and is reduced in thickness, the rolls flatten and bend, and the mill housing stretches. This is mill "spring" and results in the rolls being set closer than the required finished thickness. The spring is frequently of the order of 0.1 inches or more.

The product off the mill from one slab is termed a "pattern". From this pattern, several customer plates may be cut. As the width increases and the thickness decreases, so shorter patterns are rolled due to difficulties in the operation. A limit on the length for increasing thickness is provided by the physical layout of the mill and by the maximum slab weight which can be produced by the Slabbing Mill. This latter limitation comes from the slab shears which have a maximum capacity of 640 sq. inches of slab cross section.

OPTIMISING MILL DRAFTING:

The aim is to get maximum tonnage through the mill with the following restrictions:-

a) Control the gauge within the allowable tolerance. This aim tolerance is usually considerably less than the total allowable in order to get a greater yield from slab to plate.

b) Control the shape so the plate will be flat when cold. This becomes more difficult with wider and thinner plate and is essentially a function of the temperature variation and heat losses in the plate. It results in the last few passes in a drafting schedule becoming "ironing" passes with a drafting very much less than the maximum possible.

c) Control the width within the tolerance allowed. In particular, plates which require excessive widening or "broadsiding", that is where the finished plate width/initial slab width ratio is of the order of 1.5 and more, the plate width tends to "run off" or become narrow on the back and front ends.

d) Control the finishing temperature, and frequently the temperature at intermediate passes, to achieve the desired internal metallurgical structure of the plate.

e) The plates should be produced at the maximum mill speed and the minimum number of passes, consistant with the above criteria, to achieve maximum mill loading and maximum production.

Knowledge of the roll separating force encountered during rolling is desirable for two reasons. Firstly, the mill should be loaded as much as possible during the early passes, without exceeding design limitations, to obtain maximum mill utilisation. Secondly, the final passes must be rolled at pre-determined roll separating forces to produce a flat plate.

a) Roll Separating Force:

Schultz & Smith[37] developed an empirical relationship to describe roll separating force as given below:-

$$F = \left[\frac{a_1 \times 10^{a_2 R/h_1}}{10^{a_3 \theta}} \frac{(h_1 - h_2)}{h_1} + (a_4 - a_5 \theta) \right] W \left[R(h_1 - h_2) \right]^{1/2}$$

where a_1 to a_5 are constants.

h_1 = incoming thickness in inches.

h_2 = delivery thickness in inches.

F = roll separating force, 10^3 lbs.

θ = average pattern temperature, ^{o}F.

W = plate width, inches.

R = work roll radius, inches.

and $\left[R(h_1 - h_2)\right]^{\frac{1}{2}}$ becomes the arc of contact between the work roll and the slab, in inches.

This shows that:-

F = function $(\theta, D, h_1, w, \text{chemistry})$

where D is the draft = $(h_1 - h_2)$

In this equation all values except the temperature are readily measured. The same researchers[37] developed an empirical relationship of temperature drop with time as follows:-

$$\Delta\theta_p = \sigma \bar{e} K_x (\theta_p)^4 A \Delta t / K_k - \frac{E_w}{E_k}$$

$$\text{and } E_w = V I K_m K_v \Delta t$$

37. R.G. Schultz and A.W. Smith - "Determination of a Mathematical Model for Rolling Mill Control", Iron & Steel Engineer, May 1965.

where θ_p = temperature drop in time interval t

E_w = energy input to the slab, watt-sec.

V = drive motor voltage, volts.

I = drive motor current, amp.

Km = Motor efficiency, unitless.

Kv = per unit energy put into slab, unitless.

Kx = conversion factor 17.5.

Δt = time interval seconds.

Kk = $C \rho V_s K_x$ watt-sec./^{o}R.

$\bar{e}$ = effective emissivity, unitless

σ = Stefan-Boltzman constant.

A = surface area of plate, sq.ft.

θ_p = mean plate temperature ^{o}R.

C = mean specific heat of plate B.T.U./lb./^{o}R

ρ = density, lb.cub.ft.

V_s = volume of slab cu./ft.

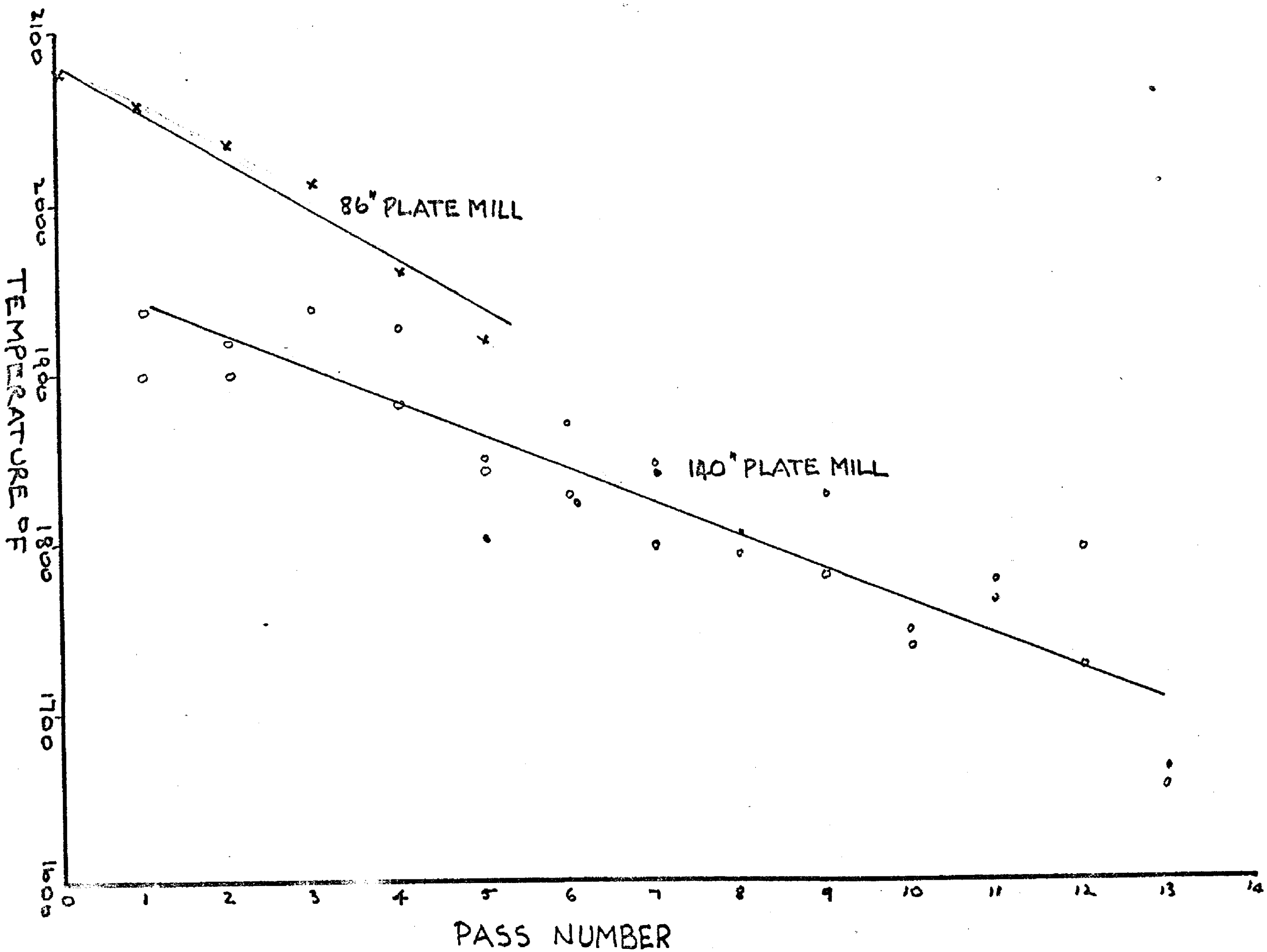
This shows that the drop in temperature varies as below:

θ_p = function (Δt, h, θ_p^{4}, Ew).

The emissivity of steel varies with the temperature, as shown earlier in the furnace section, and also varies with chemical composition. The fourth power relationship comes from the Stefan-Boltzman radiation law and does not include the very significant conduction heat loss of the plate to the table rolls, the work rolls and the roll cooling water. This is allowed for by using an 'effective' emissivity which is determined from experiment.

In addition, the rise in temperature of the plate by the energy input must be allowed for by the inclusion of the appropriate energy values as shown.

While the solution of this expression is available froma digital computer it becomes a major problem to measure all variables and so programme the computer. Once again, a simpler interim solution is being sought. Plate surface temperatures are very difficult to



2100
2000
1900
1800
1700
1600
TEMPERATURE °F
86" PLATE MILL
140" PLATE MILL
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
PASS NUMBER

FIGURE 7

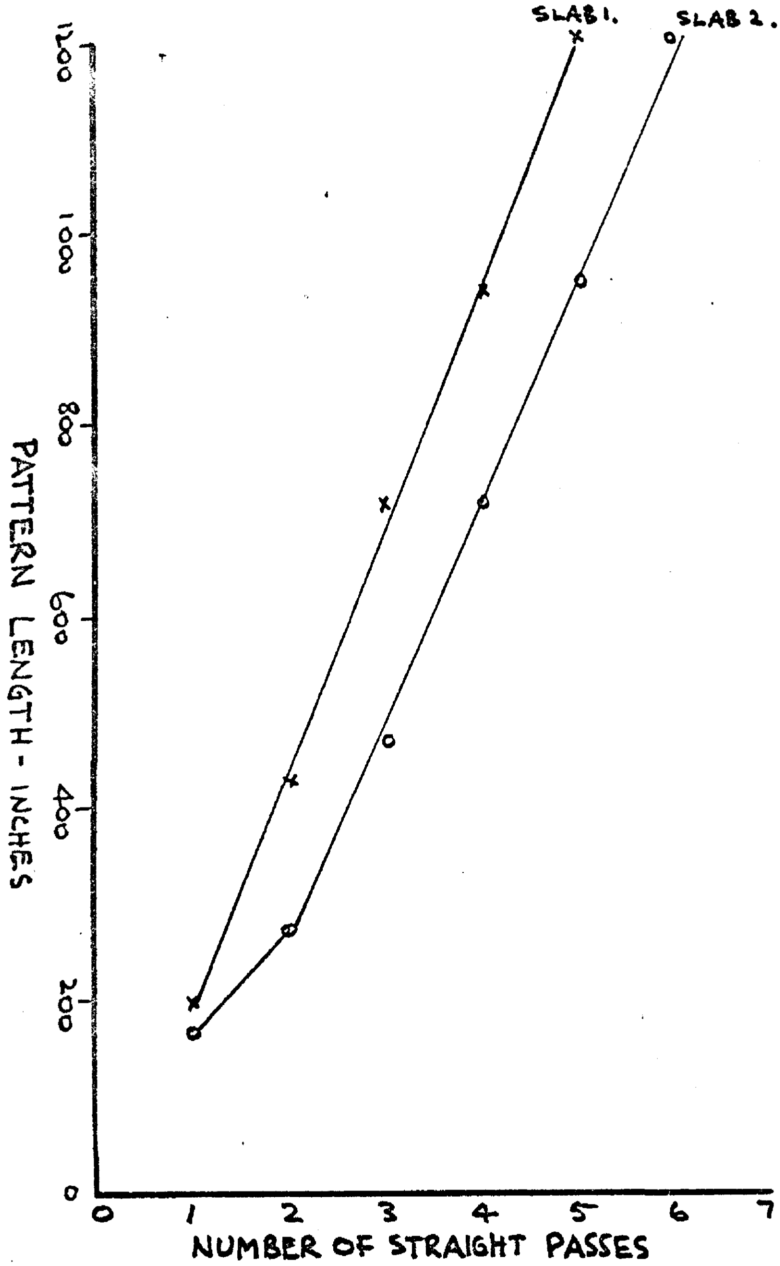

SLAB 1.
SLAB 2.
PATTERN LENGTH - INCHES
0
200
400
600
800
1000
1200
0
1
2
3
4
5
6
7
NUMBER OF STRAIGHT PASSES

FIGURE 8

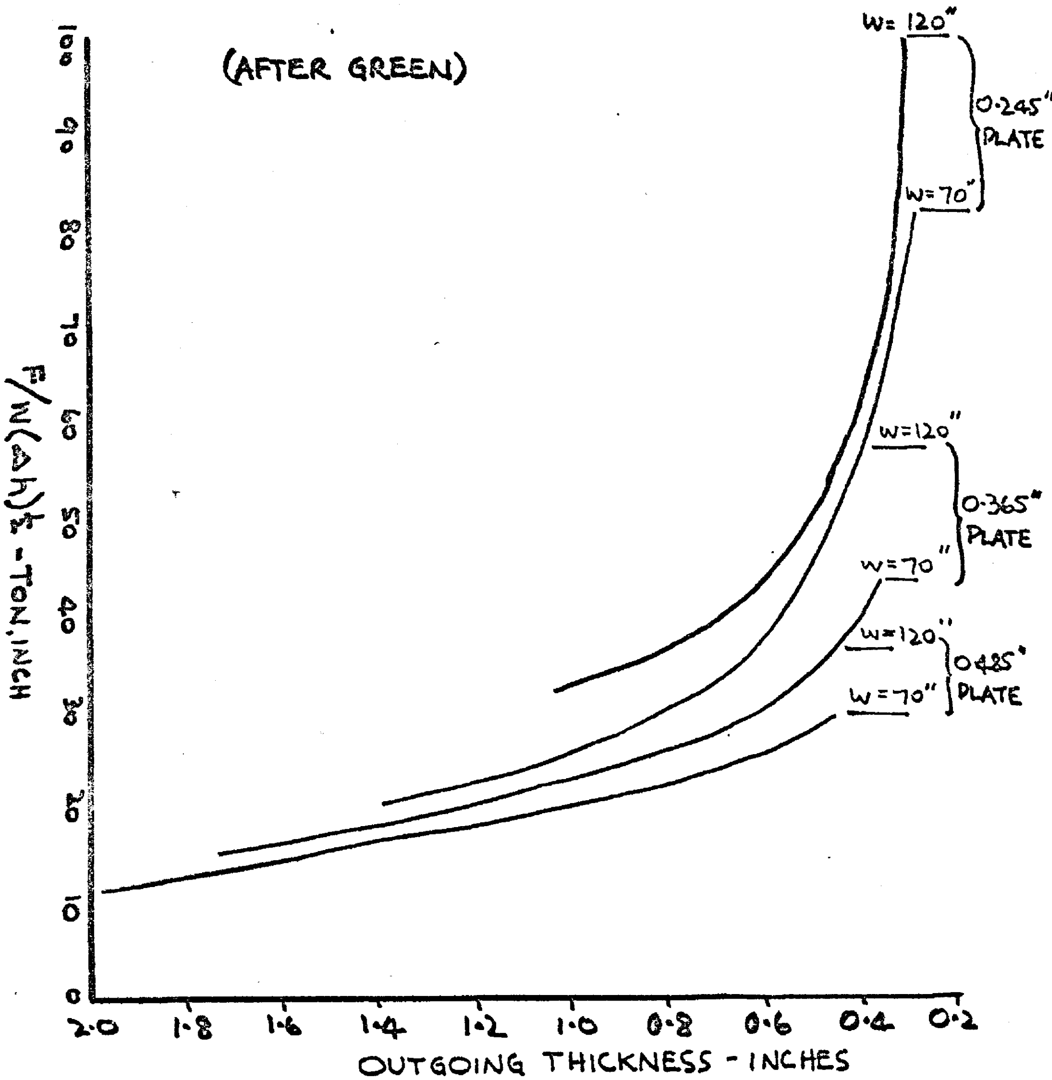

(AFTER GREEN)
W= 120"
W=70"
0·245" PLATE
W=120"
W=70"
0·365" PLATE
W=120"
W=70"
0·485" PLATE
0
10
20
30
40
50
60
70
80
90
100
F/W(Δh)½ - TON/INCH
2·0
1·8
1·6
1·4
1·2
1·0
0·8
0·6
0·4
0·2
OUTGOING THICKNESS - INCHES

FIGURE 9

measure accurately and the whole solution depends greatly on empirical relationships.

A plot of temperatures on successive passes for a plate mill was made (see figure 7). Although there is a reasonably large scatter, a crude approximation would give the linear relation shown. Similarly, a plot of pattern lengths shows a roughly linear increase (see figure 8). As length is directly related to thickness, an operational approximation is that the temperature of the pattern varies as thickness.

Green[38] reduces the load formula to a basic expression:-

$$F = W(R \Delta h \quad y \quad Q)^{\frac{1}{2}}$$

F - roll separating force.

W - plate width. R- roll radius

Δh - drafting.

y - the yield stress in plain strain.

Q - a factor of relating plain strength to roll gap.

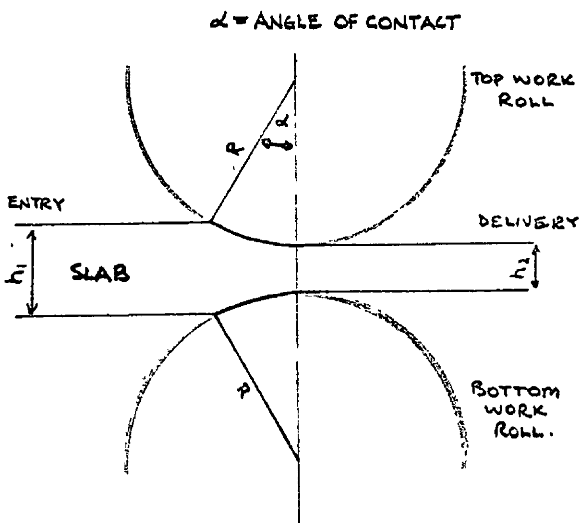
so $\frac{F}{W(\Delta h)^{\frac{1}{2}}} = (R \ y \ Q)^{\frac{1}{2}}$

The quantities on the left hand side of the equation are measurable (F can be measured by the standard procedures of press-ductors, strain gauges etc.) Thus the left hand side can be evaluated to give a measure of $(R\ y\ Q)^{\frac{1}{2}}$ which is proportional to the rolling resistance of the plate. By making several simplifying assumptions, including the approximation that in a mill with fixed rolling practice it is likely that the temperature is proportional to the thickness (as previously observed), this resolves to

$$\frac{F}{W(\Delta h)^{\frac{1}{2}}} \propto h$$

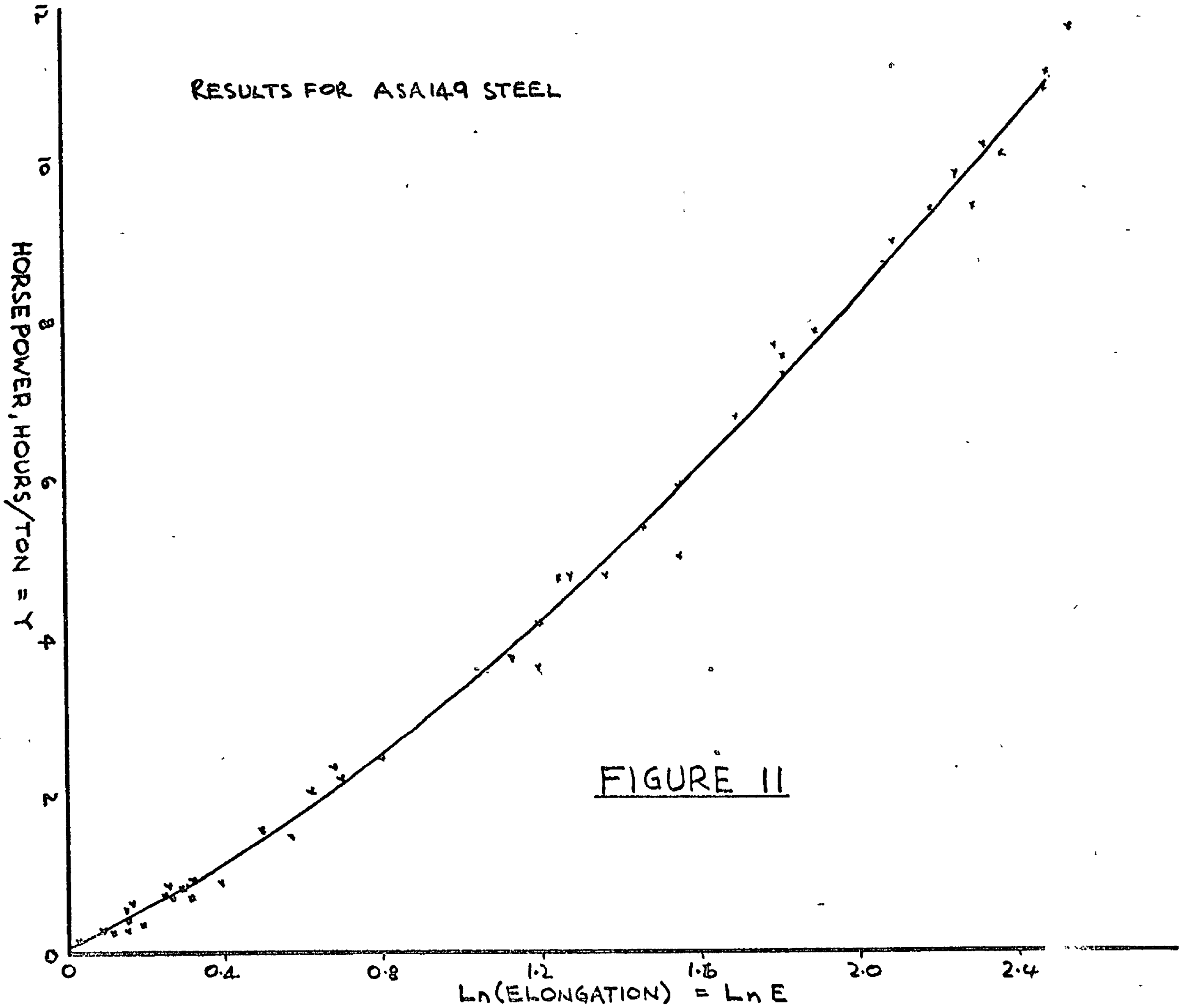
This can be plotted for groups of widths and thicknesses as shown on figure 9 and used for establishing rolling schedules.

38. R. Green, Discussion on Hot Rolling Mills. Journal of Iron & Steel Inst. March, 1963 - P.2.



α = ANGLE OF CONTACT
TOP WORK ROLL
R
α
ENTRY
DELIVERY
SLAB
h
h1
R
BOTTOM WORK ROLL.

FIGURE 10



RESULTS FOR ASA149 STEEL
HORSEPOWER, HOURS/TON = Y
0
2
4
6
8
10
12
0
0.4
0.8
1.2
1.6
2.0
2.4
Ln(ELONGATION) = Ln E

FIGURE 11

The desirable maximum roll separating force is specified by the mill designers. This, however, is not sufficient to schedule the draftings for a mill.

The limitations for drafting are roll separating force for wide/thin entry sizes; absolute draft for thick/narrow; percentage draft for thin/narrow; and roll torque for wide/thick entry sizes.

b) <u>Drafting Limitations</u>:

The maximum draft on thick/narrow entry sizes is limited by the "bite angle". This is the limiting value of the angle of contact (see figure 10) and is of the order of $22\frac{1}{2}^{\circ}$ to 24° [39]. For rolls of 39" diameter this limits the maximum draft to $39(1-\cos 24^{\circ})$, by the geometry of figure 10, = 3.4 inches.

However, considerations of roll separating force and torque will show that this drafting cannot be taken on normal slab thicknesses. It can be taken on ingot thickness of the order of 20 inches.

c) <u>Rolling Torque</u>:

After the above two limitations, the maximum torque which can be supplied by the drive motors is the limiting factor for draft.

A useful method of determining rolling torque is to use a curve of horse-power-hours/ton plotted against the natural logarithm of the elongation.[40] This relationship depends strongly on rolling temperature and as mentioned previously, a crude approximation can be made, that with reproduceable conditions in the mill, the temperature varies directly as the thickness of the plate. The scatter of the points on the curve figure 11 can be partly explained by the error of this approximation. This is an experimental curve obtained from a 140"

---

39. "Roll Pass Design", United Steel Coys. Ltd., Sheffield, 1960.

40. A.J. Winchester "How to Select the Size of a Rolling Mill Drive Motor". Blast Furnace & Steel Plant, January, 1955.

wide plate mill[41] and has been used as a basis for torque calculations.

It was considered that although a polynomial expression could be found to describe this curve it could not be adapted to linear programming techniques, nor was it useful for a ready manual check of mill drafting programmes. A series of straight lines were imposed on the curve to give a minimum of error and to give limiting values of LnE which were easily used values of E (elongation). The HP-hour/ton curve can then be represented by the following linear relationships:-

a)	$Y = 3.0 \ln E - 0.05$	$1 < E \leq 1.5$
b)	$Y = 3.28 \ln E - 0.162$	$1.5 < E \leq 2.0$
c)	$Y = 4.02 \ln E - 0.67$	$2.0 < E \leq 3.0$
d)	$Y = 4.8 \ln E - 1.53$	$3.0 < E \leq 5.0$
e)	$Y = 5.44 \ln E - 2.55$	$5.0 < E$

Where Y is the horse power-hours/ton.

Assuming a roll diameter of 39 inches and a mill speed of 50 revs/min., the through-put per pass is given by

$$\frac{W \times h_2 \times 39 \times \pi \times 50 \times 0.283 \times 60}{2,240} \quad \text{tons/hour}$$

0.283 lbs/cubic inch = density of steel.

W = plate width in inches.

h_2 = exit thickness in inches.

This gives a through=put of $46Wh_2$ tons/hour. Note that the exit speed of the plate from the rolls is, for all practical purposes equal to the surface speed of the rolls.

So now the maximum possible draft can be calculated as follows:-

Consider passes n and n + 1:-

The change in horsepower hours/ton = $Y_{(n+1)} - Y_n$

Where Y_n is the <u>total</u> horsepower expended in getting to pass n.

41. D.J.H. Lewis, unpublished work.

With elongations E_n and $E_{(n+1)}$ and the thickness entry to pass $n + 1 = h_n$, the thickness delivery from pass $n + 1 = h_{(n+1)}$.

Therefore:- $E_{(n+1)} = \frac{h_n}{h_{(n+1)}}$ this is the <u>total</u> elongation.

Also:- $dY = Y_{(n+1)} - Y_n$, the incremental change in horse power-hours per ton.

Now the tons through-put/pass at 50 revs/min. is:-

$$W \times h \times 39 \times \pi \times 50 \times \frac{0.283}{2,240} \times 60 \text{ tons/hour}$$

= Wh 46 where h is the delivery thickness. Therefore:- H.P. = dYi x Wh 46 for the i th pass.

$$HP_{n+1} = Wh_{n+1} 46\left[(a_{n+1} \ln E_{n+1} - b_{n+1}) - Y_n\right] \text{ — (a)}$$

The maximum H.P. for a 6,000 H.P. motor at 70% duty cycle =

$$\frac{6,000}{\sqrt{0.7}} = 7170 \text{ H.P.}$$

So for maximum draft the right hand side of equation "(a)" = 7,170 H.P.

(Note that $a_{(n+1)}$ and $b_{(n+1)}$ are the constants given earlier for different values of E).

As this is an iterative process Y_n has already been calculated ($Y_o = 0$), therefore Y_n can be considered a constant.

Also:- $$\frac{h_n}{h_{(n+1)}} = E_{(n+1)}$$

$$h_{n+1} = \frac{h_n}{E_{(n+1)}}$$

As h_n has also been calculated, it can be considered to be a constant. The equation "(a)" then resolves to

$$\frac{7170}{W\,46\,h_{n+1}} = (a_{n+1} \ln E_{n+1} - b_{n+1} - Y_n)/E_{n+1}$$

This is of the form $WE = v\ln E - u$, where w, v and u are constants. An analytical solution to this form of equation has yet to be determined.

Two methods of ariving at the final solution of $E_{(n+1)}$ and so $h_{(n+1)}$ which gives the draft to maximise the torque are given below:-

(i) Trial and error method converging on the solution.

Suppose a value of h_{n+1}. A reasoned guess is possible here after the first calculation, by taking a slightly smaller percentage drafting.

If this gives a torque which is far from the maximum value choose another value of $h_{(n+1)}$.

Progressively do this until an acceptable answer is reached. (This would be in the order of maximum horse power $\pm 5\%$). A high speed digital computer would be very applicable to this approach.

(ii) Graphical method.

Draw the curve ln E for the various limiting values of E. Draw a series of curves of the form.

$$Y = u\,E + v, \quad u, v, \text{ constants, with different values of } u \;\&\; v.$$

Solve for the two equations at the points of intersection.

(iii) The Newtonian method of determination of roots may also be used.

This then is a method of optimising the drafting schedule of any given slab size. The general principles for determining the optimum slab size for maximum rolling rates in the mill is a simple exercise. If the slab is wide, less broadside passes will need to be taken.

As a certain weight is required to provide sufficient length plate for customers requirements, the slab weight is a feature which cannot be controlled other than to require the maximum slab weight within the mill limitations. It follows then that if the widest slab is provided, it will also be the thinnest. This also is desirable for it reduces the number of straight passes required.

It remains now to fully specify all mill limitations. These will vary between mills and the following are illustrative of a 140" wide plate mill.

INITIAL DRAFTING:

It is considered desirable that all slabs have an initial "sizing pass". This produces a definite thickness slab for subsequent passes, eliminating any small variations in the incoming slab thickness. This has been set by mill operation at 0.5 inches for all slab sizes and is incorporated in the slab rationalisation section which follows.

Where the slab then has to be turned 90° for further broadsiding, the length of the slab after the sizing pass must not exceed 134" to allow it to fit safely in between the mill housings.

Considering Ls and Ts as initial slab length and thickness then:-

$$\text{Max. } L_s = \frac{130\ (T_s - 0.5)}{T_s.} \qquad \text{in inches}$$

BROADSIDE DRAFTING:

To produce a plate wider than the initial slab, the slab is drafted at 90° to its long axis. This produces all the elongation on the width. Thus the total drafting D for broadsiding will be:-

$$D = h_1 \left(1 - \frac{W_s}{W_p}\right) = \frac{h_1}{h_2}$$

where h_1 = thickness before broadsiding ($h_1 = T_s - 0.5$)

Ws = slab width

Wp = desired pattern width

h_2 = thickness after all broadside passes or

$$h_2 = h_1 \frac{Ws}{Wp}$$

Mill design imposes maximum draftings for each pass as detailed earlier. As the width across the mill can be considered to be reasonably constant at 130 inches (this at least is the maximum and so creates conditions for maximum torque) standard draftings can be laid down. For a 140" Mill with 63" diameter back-ups and 39" diameter work rolls driven by two 6000 H.P. motors the following maximum draftings are found by practice:-

(a) If $D \leq 1.25$", a single broadside pass is possible.

(b) If $1.25 < D \leq 2.25$", two passes are necessary.

(c) If $2.25 < D \leq 3.0$", three passes are necessary.

(d) If $3.0 < D \leq 3.75$, four passes are necessary.

This can be expanded to more broadside passes, but is sufficient illustration.

The plate must always be finished on the last pass heading away from the furnace or an "idle" pass is required. This means that an odd number of total passes (broadside plus straight passes) must always be taken. Thus it is not necessarily an optimum solution to load the mill to maximum torque if it results in an even number of passes.

<u>MILL SPRING</u>:

When a slab enters the bite of the mill work rolls, the rolls are forced apart by the roll separating force already mentioned. The separating force bends the rolls, stretches the housing and takes up any slack in the head screw assembly. The result of this is that the thickness of the bar delivering from the mill is greater than the initial roll gap by an amount known as the "spring."

It is considered to be reasonably accurate to assume a stretch co-efficient for a mill and to calculate mill spring as follows:-

$$g_1 = \frac{F}{M}$$

F = roll separating force

M = stretch co-efficient

This is the basis of the B.I.S.R.A. gaugemeter principle.[42]

The roll bending is dependant on the load and the plate width and can be expected to be of the form:-

$$g_2 \propto W(l - W)F$$

where l = roll length

W = plate width.

The total spring which is the sum of mill stretch and roll deflection, becomes:-

$$g = g_1 + g_2 = (a_1 + a_2 W + a_3 W^2) F$$

where a_1, a_2, a_3 are constants.

A first order approximation would be to ignore the effect of roll bending on plate gauge and assume the simple form:-

$$g = \frac{F}{M}$$

Justification of this approximation can be verified empirically but observation of an operating mill does support the contention.

ROLL FLATTENING:

The roll separating force is dependent on the area of contact between the slab and the work rolls. This is given by:-[43]

$$\text{area} = W \left[R (h_1 - h_2)\right]^{\frac{1}{2}}$$

42. E. Downs, P. Shipp and B.W. Smith "Plate Mill Automation" British Iron & Steel Research Association, London, report PE/B/76/63, December, 1963.

43. E.C. Larke "The Rolling of Strip, Sheet and Plate", Chapman & Hall, London, 1957 - P.324.

However, the roll separating force is found in practice to be significantly greater than if computed from this expression due to the elastic flattening of the rolls.

The deformed radius is given by:-[44]

$\cancel{R_1 = R(1 + 2\ aF/d)}$ $R_1 = R(1 + 2\ aF/\Delta h)$

R_1 = deformed roll radius.

R - original roll radius

F - roll separating force

a - $2.9 + 10^{-4}$ sq. inches/ton for chilled iron rolls.[45]

Δh - mill drafting.

Thus all previous calculations must be ammended to include this deformed roll radius in place of the nominal radius.

THE PROCEDURE OF OPTIMISING:

The following section outlines a basic method for utilising the proceding mill parameters for optimising the roll schedule.

It is considered that a certain slab size is presented to the mill and the exercise is to roll the slab to a plate so as to achieve maximum output in tons/hour consistant with plate quality.

Having taken a sizing pass, as considered desirable for mill practice, the minimum number of broadside passes must be calculated to achieve the required plate width. The maximum drafting which may be taken on broadside passes can be established on a simple rule as mentioned previously. The load can be considered to vary only as the entry thickness and the drafting. The width (the length after sizing) and the temperature can be assumed to be constant for standard practice. Shorter initial slab lengths will certainly give less load but this effect is ignored in the interests of simplicity.

---

44. P.M. Cook & A.W. McCrum "The Calculation of Load & Torque in Hot Flat Rolling", British Iron & Steel Research Association London, 1958 - P.9.

45. E.C. Larke, op. cit. - P.326.

The problem then becomes the need to reduce the slabfrom a thickness delivered from the broadside pass to the desired plate size in the minimum number of passes. Practice will establish that certain sections require one or two "ironing" passes. These are the final passes in which very little draft is taken to ensure a flat plate is achieved by eliminating the effect of previous roll bending.

Observation can establish a predetermined roll separating force required to produce the correct drafting for ironing passes. Other passes should be the maximum draft to achieve the maximum roll separating force or the maximum torque, which ever is reached first.

SUMMARY:

Equations giving the roll separating force and the rolling torque must be checked against operating results to derive suitable parameters for the mill in question. Values for the constants in the spring equation must be found. These equations can then be used considering reproduceable or standard temperature conditions, or an attempt can be made to further refine the model by calculation of temperature drop.

By making due allowance for certain rolling requirements, such as broadsiding and ironing passes, the drafts can be maximised for roll separating force or rolling torque.

The full model, as described previously, will most certainly require an electronic computer for its solution. This will have application where the mill is controlled by a computer or when computer time is immediately available to an operator who wishes to vary his drafting schedule. The model may also be used off-line to calculate all drafting schedules in advance.

There is still a strong need for a simplified model for use by an operator (who does <u>not</u> have access to the computer). This could complement his rolling experience in producing optimum mill scheduling. In the years past, rolling operators served a long apprenticeship and built up a great fund of practical experience. In a rapidly developing industry, there is no time for such experience to be developed. The experience which is held by a few of the senior men must be quantified and presented to the younger man so it can be readily used. This experience can be incorporated in the model in the form of temperature and rolling load requirements for various plate sections.

In the case of temperature, it must be determined what constitutes the "right" temperature for a certain section. All mill operators have experienced the circumstances where the section just "won't roll" - the finished shape may be poor or the bar may "chew up" in the mill. All this can occur even when conditions appear to be the same as on a previously successful rolling. If it were practicable to measure the temperature distribution through the slab from the furnace, most of the difficulties would probably vanish. It is not practicable to do this and this fact emphasises the need for an adequate furnace model which can predict temperature distributions.

Other aspects, such as the temperature distribution and the surface roughness on the work rolls, also materially affect the rolling. This latter point is discussed in section VI.

IV SLAB RATIONALISATION

In modern plate mills, the actual mill draftings are pre-programmed, so that it is important that any one plate section be consistantly rolled from the same slab size. Failure to do this can result in the necessity of building an immense library of pre-programmed rolling schedules with a subsequent high cost due to the lack of flexibility in up-dating schedules to improve practice; apart from the physical difficulty of building up such a library. More important is that there will be an optimum slab size for each section rolled, and this optimum size should always be programmed.

Standard sizes also allow concentration on the rolling practices of one section from one slab to permit improvements in practice. It is considered that in any progressive mill the "optimum' slab rationalisation will not stay static, but will have to be varied to meet changes in practice.

To be able to predict mill through-puts and so design schedules and programmes for optimum conditions, it is necessary to know the slab sizes for each section to be rolled. A further need for slab rationalisation is in decreased size variations in the slab yard which facilitates storage.

From the furnace viewpoint, the thinnest slab provides the greatest output. From the mill viewpoint, allowing that a pre-determined weight slab has to be rolled, then maximum throughput will also be achieved by the thinnest slab for this will require less reductions. Within the standard slab lengths, reducing the slab thickness will increase the slab width. This again increases mill through-put by decreasing the broadside drafting required to achieve the desired plate width.

It is then apparent that for optimum conditions in the plate mill, the slab should be as thin and as wide as possible. This may well prove to be a sub-optimisation in some cases when considering the Slabbing Mill and Steelmaking Shop. In the Slabbing Mill, the principle time in rolling is in reducing the ingot width to slab width. The universal principle of the widest slab cannot then be far from an optimum here. The major problem comes from variability of the ingot feed, which is generated from the steelmaking side of the problem.

Assume a 64" x 35" ingot has been programmed to a certain quality, and to a slab size of 58 inches wide by 4 inches thick. The steel making shop may produce an off-programme heat and the orders in this quality made may call for 70" wide by 6" thick slabs. It is impossible to roll a 70" x 6" slab from a 64" x 35" ingot.

On the other hand, one advantage which can acrue from standard slab sizes is the greater possibility to roll to stock sizes against future orders in the above circumstances. This would tend to give greater flexibility to the Slabbing Mill.

LIMITATIONS:

The following are restrictions which must be placed on slab feed in a plate mill. These restrictions will vary from mill to mill and so can be indicative for a 140" wide mill.

i) The maximum practicable slab width which can be rolled on a slabbing mill with a 76" bull-head is 70". The minimum desired width is around 38" but this lower level will only depend on the smallest size ingot mould available. Such small ingots are not favoured in the slabbing mill as the handling time gives low tonnage rates. Narrow slabs will also tend to give lower tonnage throughput in the plate mill. The minimum width will naturally be governed by the narrowest plate rolled.

ii) It is considered desirable for the plate mill to take a "sizing pass" before broadsiding the slab. This results in a known thickness being presented to the broadside passes, eliminating variations in the slab due to slabbing mill practice and losses on deseaming in the slab yard.

A feasible operating figure is 0.5 inches for a sizing pass.

Increased sizing passes can be taken if the slab length permits to decrease the drafting required for broadside passes.

On a 140" mill the widest pattern which can be rolled is of the order of 134". Thus for broadsiding, the slab length (which becomes the width on being turned 90^{o}) must not exceed 134". Slab thickness and length may well vary by 1% so it is unwise to programme a slab longer than 130" for broadsiding.

Thus to allow for at least an 0.5" drafting for sizing and to achieve not more than 130" length for broadsiding, the initial slab length must not exceed 130 x (S - 0.5)/S, where S = slab thickness in inches. The minimum desirable length for safe furnace operation is 90".

iii) The minimum slab weight required must be determined. From practice this is shown to be of the order of 4,000 lbs. on a 140" Mill. This is the weight required to produce the shortest length of the thinnest section at the narrowest width and must be derived from the plate market requirements.

iv) All weights from 4,000 lbs. up to the maximum weight possible must be covered by slab sizes with weight gaps of no more than approximately 1%. This is to ensure a minimum of yield loss within practical limits.

v) The minimum slab thickness is 4" as dictated by furnace operations. Increments of slab thickness should be no greater than 30% to ensure reasonable heating in the furnace.

vi) Integral slab dimensions are desirable for recording purposes, but this is not an over-riding consideration.

vii) It is undesirable to produce a slab wider than 6" less than the widest dimension of an ingot. The widest 4" slab which can be rolled on the Slabbing Mill is 64" while 5" may be rolled to 70" wide.

viii) The ingots available for the production of slabs are all below:-

SIZE	YIELD SLAB WEIGHT Maximum	Minimum
80" x 30"	44,707 lbs.	34,240 lbs.
70" x 34"	40,877 lbs.	30,816 lbs.
64" x 35"	37,343 lbs.	28,118 lbs.
53" x 34"	33,414 lbs.	25,098 lbs.
50" x 27"	25,264 lbs.	19,474 lbs.

The parameters for slab providing may be summarised as follows:-

a) Weight 4,000 lb. minimum.
44,000 lb. maximum.

b) Weight increments 1.12% $_{max}$ (1 inch in 90 inches)

c) Width in even integrals and $\leq$ 70"

d) Length and thickness integral.

e) Length $\leq \dfrac{130\ (S - 0.5)}{S}$, $\geq$ 90"

f) Thickness (S) $\geq$ 4", $\leq$ 12"

g) Width to be a maximum) - for any weight.
Thickness to be a minimum)

h) Cross section $\leq$ 640 sq. inches.

FIRST RATIONALISATION:

The approach was to produce complete tables of slab weights as print outs from a digital computer. These were arranged as follows:-

a) Thickness groups:- Within each group, the weights of all integral slab lengths for each double integral width from 38" to 70". Each thickness group contained the integral thickness plus three ¼" increments. This was to prevent sub-optimisation on the restriction of integral thicknesses. There were seven groups from 4" to 10" inclusive.

b) Increasing weights:- This enabled the various slab sizes which could produce each weight (within 1.12%) to be determined.

c) Increasing weight for each thickness:- This enabled the maximum slab width to be readily found.

A rationalisation with all the previous conditions, but with the aim of the minimum number of sizes, was then compiled as below. Two slab sizes were considered "given", namely the 40" x 4" which produced the lightest slab for broadsiding, and the 70" x 5" which was the thinnest, of the widest slabs:

SIZE	WEIGHT	INGOT SIZE.
40 x 4 x 90	4,080	53 x 34 or 50 x 27
40 x 4 x 114	5,158	
50 x 4 x 90	5,100	64 x 35 or 70 x 34
50 x 4 x 114	6,460	
64 x 4 x 90	6,528	70 x 34 or 80 x 30
64 x 4 x 114	8,268	
64 x 5 x 90	8,160	70 x 34 or 80 x 30
64 x 5 x 117	10,608	
70 x 5 x 90	8,925	80 x 30
70 x 5 x 117	11,602	
70 x 7 x 90	12,495	80 x 30
70 x 7 x 121	16,798	
70 x 9 x 90	16,065	80 x 30
70 x 9 x 123	21,955	

It was not possible to get from 40 x 4 to 70 x 5 in less than 5 sizes therefore the widest at each point were chosen, rather than giving a uniform weight overlap between slab sizes. The 64 x 5 slab has, therefore, only to cover a weight range of 657 lbs.

Some further desirable conditions now became apparent. One standard customer width is 48". This width should be rolled from a slab which gives the desired width off the mill (before shearing) without broadsiding or edging other than required for shape considerations.

Thus a 52" slab is required for 48" product so the first two sizes became.

40 x 4 x 90	4,080
40 x 4 x 116	5,258
52 x 4 x 90	5,304
52 x 4 x 114	6,718

where some length safety in the 40 x 4 was sacrificed to go from 114" to 116" to cover the weight gap to 52 x 4 x 90.

This rationalisation will allow one section (width and thickness) to be rolled from one of several slab sizes according to the length required of the mill. This will result in several rolling schedules for drafting for each section but this number is well within practicable limits.

The danger now is that this is an optimisation in regard to the number of slab sizes but may prove to be far from an optimum for mill production. The optimum slab size for mill production will be the one which produces the greatest tonnage per hour. This will be the product of the number of slabs rolled each hour, and the weight of each slab.

It is the practice for mill providers to schedule a certain slab weight to produce the length from the mill which will best suit the customers' orders. The mill sets an upper limit on length for each section which is governed by the section and the characteristics of the mill. It is considered desirable to always roll the maximum length possible from the mill. Although this may not necessarily produce the highest tonnage it will produce the least scrap. This scrap, or yield loss, which is of the order of 15%, is critical in the cost structure and must be minimised.

Thus the slab weight may be considered to be an independent variable.

The whole problem of optimisation of slab sizes may be tackled from a linear programming approach as formulated below:-

LINEAR PROGRAMMING APPROACH TO OPTIMISATION

Symbols
- L_s slab length
- L_p plate length
- L_i intermediate length during rolling.
- T time to roll a slab in seconds.
- Q mill through-put in tons/hour
- t time to roll each pass, secs.
- n the total number of passes
- b the number of broadside passes
- W_s slab width
- W_p plate width (as rolled)
- S slab thickness.
- P plate thickness
- B total broadside drafting
- d density of steel lb/inch^2 $\times$ ft. = 3.4
- M_1 M_2 minimum and maximum slab weights in lbs to roll the required length range of the section.

The objective function, which is required to be maximised, is the expression for tons/hour for each slab rolled:-

$$Q = \frac{M}{T} \quad \times \quad \frac{3600}{2240} \text{ tons/hour.}$$

As M is an independant variable Ti is the only dependant variable. Thus the aim is to minimise $T = \sum^{n} t_i$ for each slab.

a) Sizing and Broadsiding:

Assume one sizing pass of 0.5" which is a standard time for all slabs of t_1 seconds. Similarly the time to turn and turn back for broadsiding can be uniform for all slabs at t_2 seconds. The time for each broadside pass can be considered uniform at t_3 for all slabs. It is reasonable to make these assumptions for the length of the slab at this stage has little effect on the time taken for the pass.

The aim now becomes to minimise the number of broadside passes (b). The total drafting required on broadsiding (B) is the spread necessary to get the final plate width:-

$$\frac{S - 0.5}{S - 0.5 - B} = \frac{W_p}{W_s}$$

$$B = (S - 0.5)\frac{W_s}{W_p} - (S - 0.5)$$

$$= \left(\frac{W_s}{W_p} - 1\right)(S - 0.5)$$

The maximum draftings possible on broadside passes are laid down in section III. Thus the number of passes (which must integral) is found as follows:-

i)	If	$B \leq 1.25$	$b = 1$
ii)	If	$1.25 \leq B \leq 2.25$	$b = 2$
iii)	If	$2.25 < B \leq 3.00$	$b = 3$
iv)	If	$3.00 < B \leq 3.75$	$b = 4$
v)	If	$3.75 < B \leq 4.25$	$b = 5$

To eliminate one pass from a 4 pass schedule it is obvious that the total broadside drafting required must be reduced by 0.75"

The dependent variables are W_s and S, and may now be varied to achieve minimum b at maximum drafting utilisation. This will be done by achieving minimum B and then increasing B to achieve the minimum b at maximum drafting for each pass.

W_s will be increased until it reaches 70", with a slab thickness of 4" for up to 64" and 5" over 64, until $W_s \times S \times 90 \times \frac{3.4}{12}$ $\not> M_1$. and $W_s \times S \left(\frac{130\ (S - 0.5)}{S}\right) = 130\ W_s\ (S - 0.5) \not< M_2$.

If the latter condition is not met then S must be increased until it is met. If it is not possible to achieve this by varying S then W_s must be reduced and the exercise again worked through.

This will eventually produce the thinnest slab to minimise the number of broadside passes while still fully loading the mill.

The time to broadside will then be:-

$$t_2 + b\, t_3 \text{ seconds.}$$

b) Straight Passes:

The number of straight passes required to reduce the slab from the broadsided thickness to the required plate thickness must now be calculated. This is a complex undertaking and is described in section III.

The time taken for each straight pass can be considered to be:-

$$t_4 + \frac{L_i}{v}$$

where t_4 is a standard time to enter a bar in the mill, L_i is the length of the bar in feet on the pass in question and v is the surface speed of the rolls in feet per second. The length L_i will depend on the thickness at each pass. A number of mill draftings were examined and it was found that L can be considered to increase roughly linearly with the draftings currently used. So for m - straight passes the length at pass m_i will be:-

$$\left(\frac{S}{S-0.5}\right) L_s \times \frac{(S - 0.5 - B)}{P} \times \frac{m_i}{m} \quad \text{where} \quad \sum^{\wedge} m_i = m$$

The time for m straight passes is then:-

$$mt_4 + \frac{1}{m} \sum^{\wedge} \frac{S\, L_s\, (S - 0.5 - B)\, m_i}{(S - 0.5)\, P_i v} \quad \text{seconds.}$$

$$P_i = \text{thickness at } i^{th} \text{ pass } (P_m = P)$$

Having already provided the thinnest slab to meet the providing requirement it is not possible to reduce this time any further.

c) Total Time:

The total time for the rolling of the plate then becomes:-

$$T = t_1 + t_2 + bt_3 + mt_4 + \frac{1}{m} \sum_{i}^{m} \frac{S\, L_s\, (S - 0.5 - B)\, m_i}{(S - 0.5)\, P_i\, v}$$

This should be an optimum because 'b' is optimised by varying slab size and the remainder is optimised by maximising load on the motor.

However if the total number of passes $1 + b + m$ is an even number then the plate will finish on the wrong side of the mill, requiring an additional idle, unproductive pass. In this case, the slab thickness should be increased until an additional straight pass or broadside pass (which ever is the shorter time) is introduced.

The calculation of the number of straight passes is described in the mill section. The equations used can be linear however, as mentioned previously, the calculation of each pass on the mill involves a series of calculations converging on the desired result. A preferred approach to this problem is the dynamic programming described below.

DYNAMIC PROGRAMMING APPROACH:

To fully control mill operations, as mentioned earlier, it is necessary to nominate one slab size for each section. As there are a great range of plate sizes to be considered this becomes a major undertaking. The following approach is then computer oriented which should allow for easy re-assessment if conditions change. A change which could occur is surplus capacity in the plate mill with difficulties in the slab mill or slab yard. Different measures of effectiveness would then be applied to the problem.

A brief statement of the essential points of dynamic programming is considered desirable as an introduction to this approach.

Dynamic programming is a conceptual frame work for analysing multi-stage decision making problems. That is, problems in which the sequence of decisions is vital, in which one decision will affect following decisions. Yet the maximum value a function can attain, depends only on the constraints on the maximisation and not on the procedure used to determine the maximum value.

Further characteristics are:-[46]

a) The existance of state variables whose values completely specify the instantaneous situation of the process. Relatively few variables must be known in order to describe the problem.

b) A decision is the opportunity to change the state variables. This decision will not change the number of variables relevant to the problem, but will merely transform a state variable.

c) The past history of the system is of no importance in determining future actions.

d) The purpose of the process is to maximise some function of the state variable.

One standard analytic approach to the Dynamic Programming problem is by the backwards algorithm[47] which is based on the Bellman's principle of optimality[48]. "An optimal policy has the property that whatever the initial state and initial decisions are, the remaining decisions must constitute an optimum policy with regard to the state resulting from the first decision".

The approach would then be made as laid out in the following steps:-

a) Determine the range of pattern lengths for any one section which require to be rolled. The top limit will be set by mill limitations and the bottom limit by customer orders. This will give the range of slab weight required for the particular plate section (width and thickness).

b) Determine the widest and thinnest slab which will give the required weight range over the slab lengths 90" to 130 (S - 0.5)/S.

---

46. R. Bellman "Dynamic Programming", Princeton N.J., 1957, P.81.

47. D. Teichroew "An Introduction to Management Science", Wiley N.Y., 1964, P.610

48. R. Bellman op.cit. P.83.

c) By the method described in the linear programming section, determine the number of broadside passes, maximising slab size within the limitation of (b) above.

Determine the thickness delivered from the final broadside pass and whether this will result from an odd or even total number of passes.

d) Working backwards from the required plate dimensions, maximise mill drafting in each case (except where a predetermined mill loading for an "ironing" pass is required).

e) Arrive at a thickness which should be delivered from the last broadside pass and determine whether this results in an odd or even number of passes.

f) When the thickness from (e) does not equate the thickness from (c) vary the initial forward approach, within the stated limitations, to converge on the thickness from (e).

If the two thicknesses are still incompatible vary the backwards dynamic approach until they are.

g) The final test should ensure that the total number of all passes is an odd number. The cost of further compromising to achieve the pattern delivering on the correct side of the mill should then be determined. This cost will be the increased time to roll and will assist in the decision of which course to take.

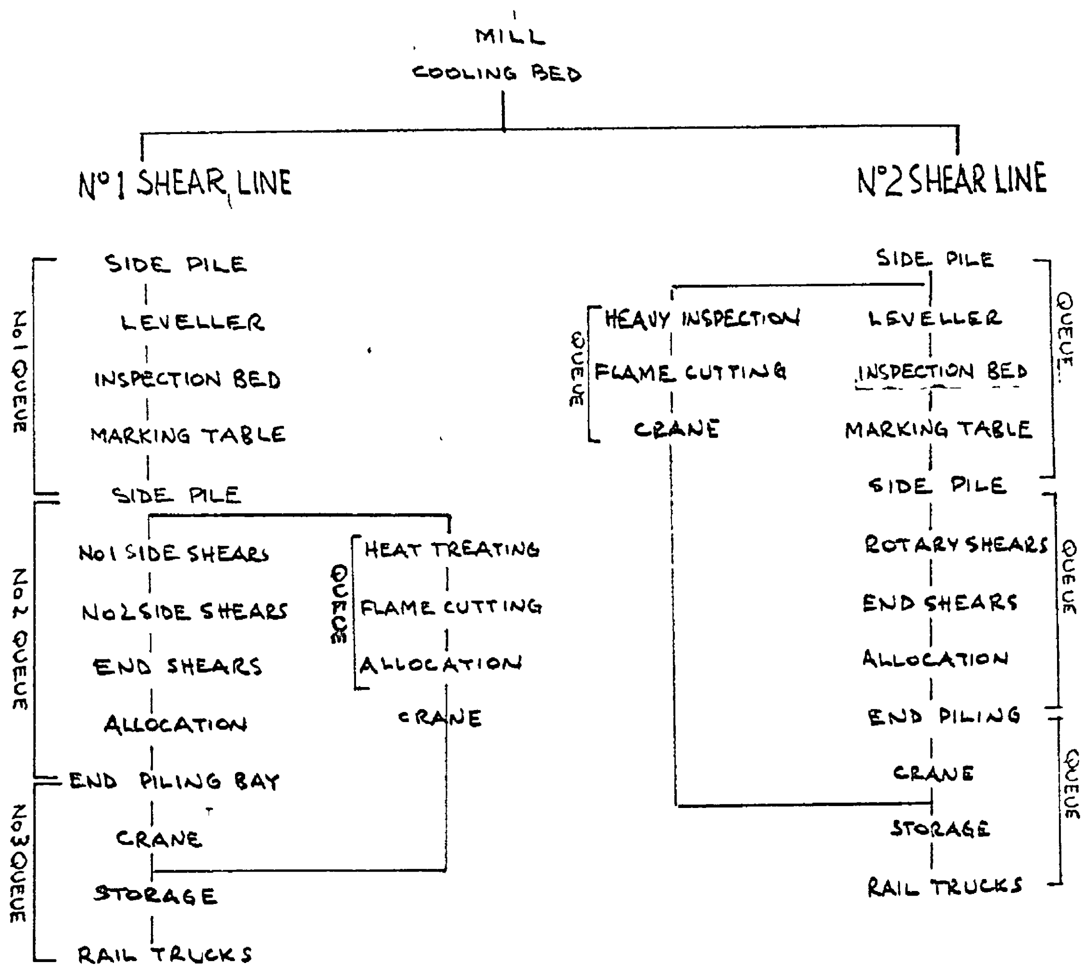
This approach would be exceedingly tedious by hand and the high speed digital computer is an ideal tool for the solution.

SUMMARY:

To achieve optimum rolling conditions the optimum slab size must be programmed for each finished plate size. The slab cross section only should be specified, variations in the slab length being used to produce variations in the plate length to give the best fit for customers' orders.

Using the heating model for the furnace and the rolling model for the mill the slab size which maximises produce for each plate size can be found.

From this list of slab sizes the final rationalisation can be made by considering the less deterministic problems of slab storage in the slab yard and the diversions due to steelmaking problems.


MILL
COOLING BED
No 1 SHEAR LINE
No 2 SHEAR LINE
SIDE PILE
LEVELLER
INSPECTION BED
MARKING TABLE
SIDE PILE
No 1 QUEUE
No 1 SIDE SHEARS
No 2 SIDE SHEARS
END SHEARS
ALLOCATION
END PILING BAY
No 2 QUEUE
HEAT TREATING
FLAME CUTTING
ALLOCATION
CRANE
QUEUE
CRANE
STORAGE
RAIL TRUCKS
No 3 QUEUE
SIDE PILE
HEAVY INSPECTION
FLAME CUTTING
CRANE
QUEUE
LEVELLER
INSPECTION BED
MARKING TABLE
SIDE PILE
QUEUE
ROTARY SHEARS
END SHEARS
ALLOCATION
END PILING
QUEUE
CRANE
STORAGE
RAIL TRUCKS
QUEUE

FLOW SHEET 1

V THE SHEARLINES

The problem of optimum plate production cannot stop at the plate mill itself. The shearlines which handle product from the mill must be considered as an integral part of the manufacturing process. The mill may "over-roll" the shearlines for short periods but, in general, it is apparent that the output from the mill can only equal the sum of the outputs from the shearlines (after allowances for scrap, rejects etc.).

The analysis of optimum conditions for production on the shearlines presents quite different problems to that of the preceeding analysis. It is less of a technical study and more of a statistical analysis.

The process is basically a series of queues, the first queue being the leveller, inspection and marking. This queue is fed by the mill, which is the "waiting line", and the output from this queue provides the input or waiting line for the next queue. These queues are shown in the flow sheet 1.

As all the handling equipment in each queue is in tandem, with surge points only before or after the queue, all the processes in each queue can be considered as one service facility.

Thus in the No.1 Line, levelling, inspection and marking is one service and the queue can move only as fast as the slowest unit. The side pile area ahead of the leveller is part of the waiting line and the side pile area after the marking table is part of the waiting line for the shearing queue. (Queue 2).

The end piling becomes the waiting line for the queue of placing in storage. The storage is the waiting line for the despatch process. This is the point at which the problem under investigation is considered to end.

THE QUEUEING PROBLEM IN GENERAL:

The queues under consideration must be identified by the following characteristics.

a) Input:- This is the manner in which the units arrive and become part of the waiting line.

b) Queue discipline:- The order in which units are served.

c) Output:- This includes the type of service and its duration.

Most of the queues will have only one possible servicing unit. However, in deciding whether the plates will go to one line or the other, or to the flame cutter, where will arise the choice of alternative action and so this must be introduced as below:-

d) Channels:- The number of alternative service units which may perform the work on the product.

The characteristic of "service policy", mentioned in most queueing theory, is not relevant there. The service facility must process the plate in the manner required by the customer and this cannot be considered a controlable variable.

The main variable is the time to service an item and it is this variability which raises the problem of the behaviour of the system. This factor determines the maximum queue length which will develop in a given period. It becomes a figure of great interest for space has to be provided for the waiting items.

The probability of a queue having a length n is given by:-[49]

$$P_n = (\lambda/u)^n (1 - \lambda/u) \quad \text{if } \lambda/u < 1$$

where λ = Mean arrival rate.

u = mean service rate.

n = length of the queue.

---

49. C.W. Churchman, R.L. Ackoff & E.L. Arnoff "Introduction to operations Research", Wiley N.Y. 1957, P.6

and assuming that Pn does not vary with time. Note that if $\lambda \geq$ u, the queue becomes infinitely long.

Following on the above, the mean length of the queue becomes:-

$$\bar{n} = \frac{\lambda/u}{1-\lambda/u} \qquad \lambda/u < 1$$

APPLICATION TO THE SHEARLINES.

There is little point in doing this analysis unless there are controllable variables. The aim of the exercise then becomes to:-

a) Control the rolling rate of the mill to approach optimum processing in the shearlines. This 'optimum' can be considered to be the rolling rate at which there is no nett increase in the waiting line ahead of the leveller over a period of, say, 48-hours. This is then controls the 'input'. Although this will tend to decrease mill output it will still be optimising total plate output because holding plate at the leveller more than 48-hours creates considerable difficulties.

b) Decide which shearline will handle each particular plate to get maximum production. This is a 'chanel' decision.

c) Control the order of product being rolled on the mill. That is, to arrange mill programmes to best suit the shearlines. This must, however, be an optimisation for both the mill and shearlines, not a sub-optimisation for the shearlines alone. This becomes a problem of 'queue discipline' (considering customer's orders as the waiting line).

d) Control the amount of labour or any other variable in the basic operating equipment such as side-loading trucks, mobile cranes etc., which can result in decreased service time. This is a problem of 'output'.

Thus it can be seen that the four basic characteristics of queues mentioned previously can be varied to approach the optimum.

To apply data for the above considerations, the rolling rate for each section on the mill must be determined. Then, the processing times for each queues measured. Maximum and minimum desirable levels

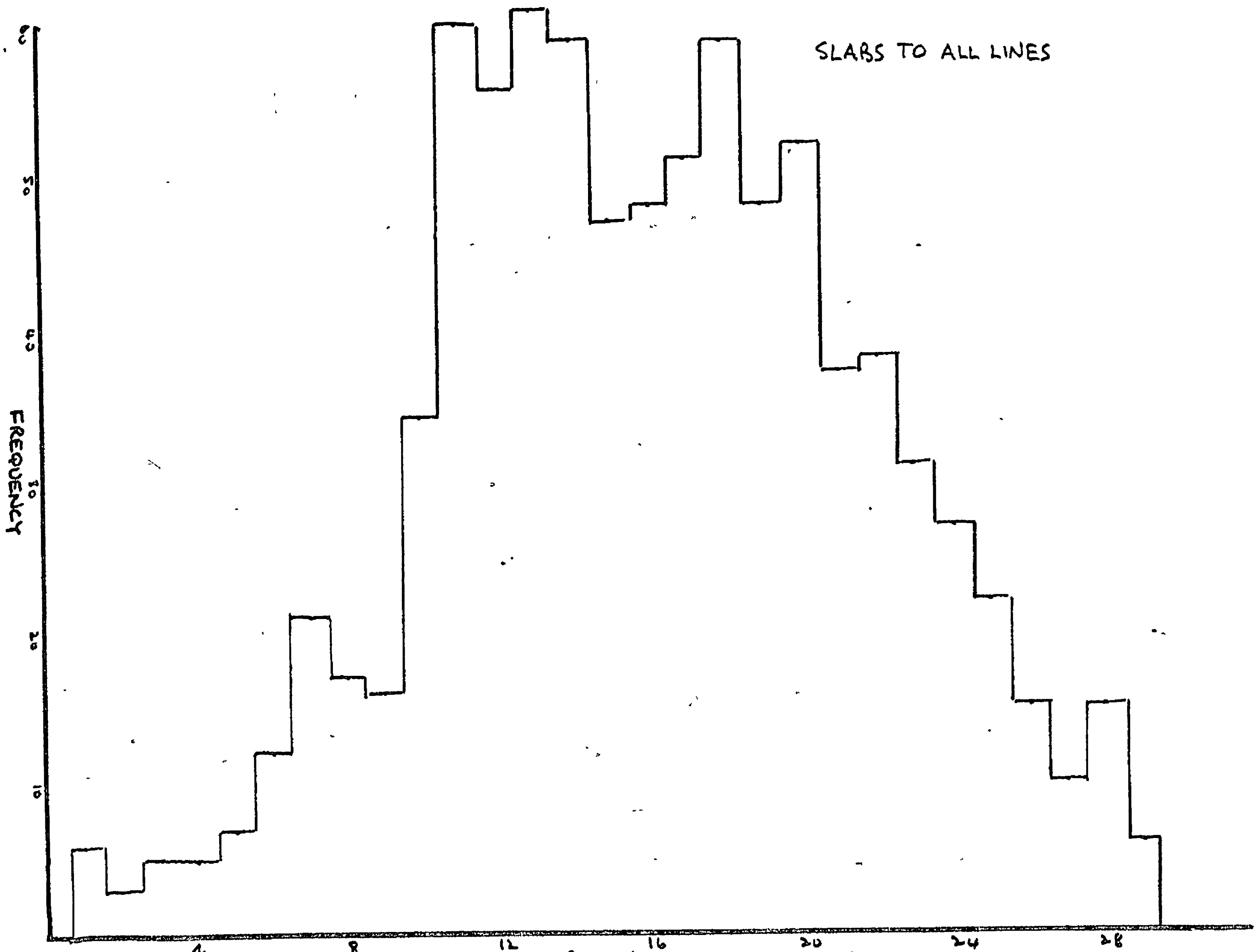


FIGURE 12a

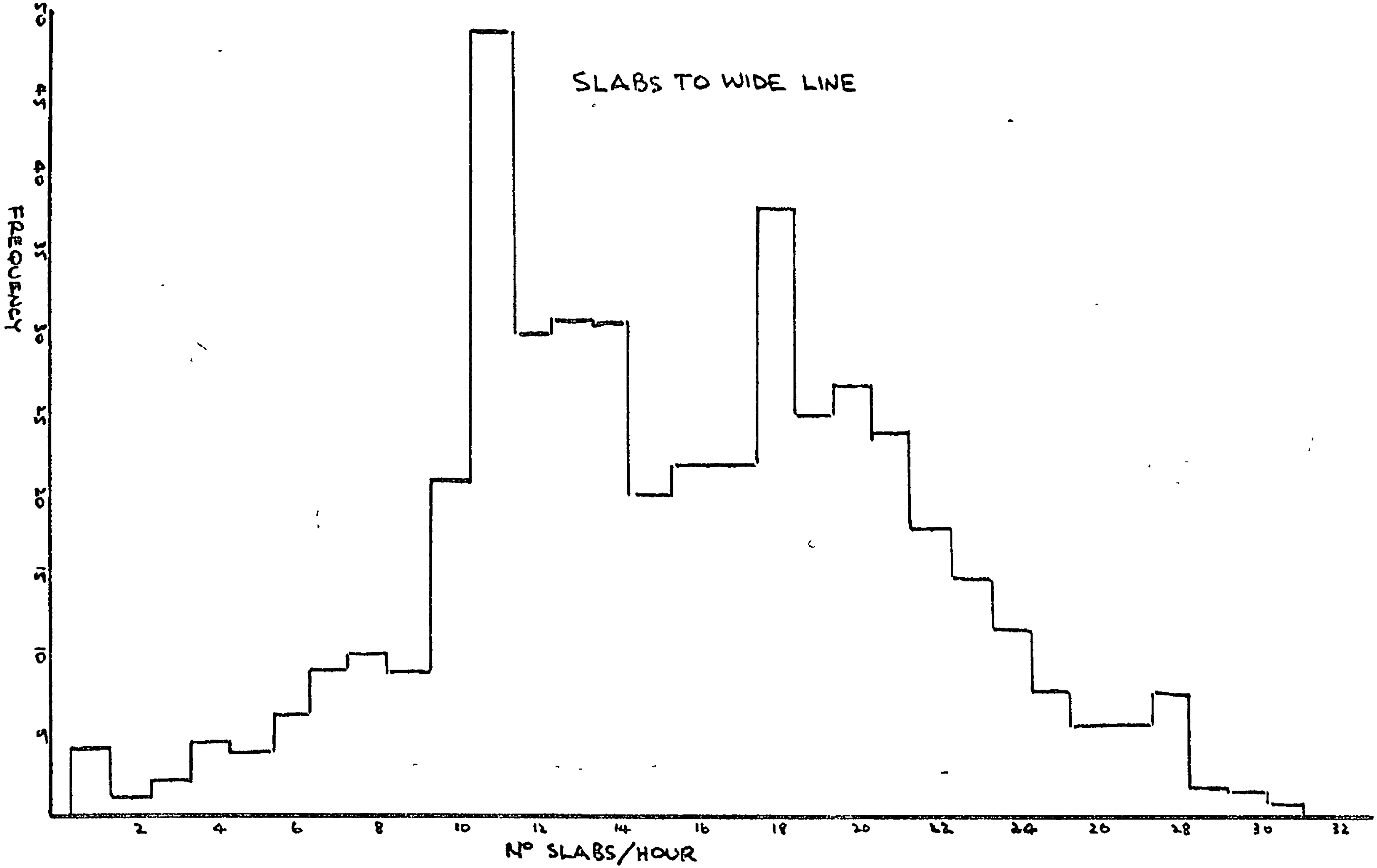

SLABS TO WIDE LINE
FREQUENCY
2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32
Nº SLABS/HOUR

FIGURE 12 b

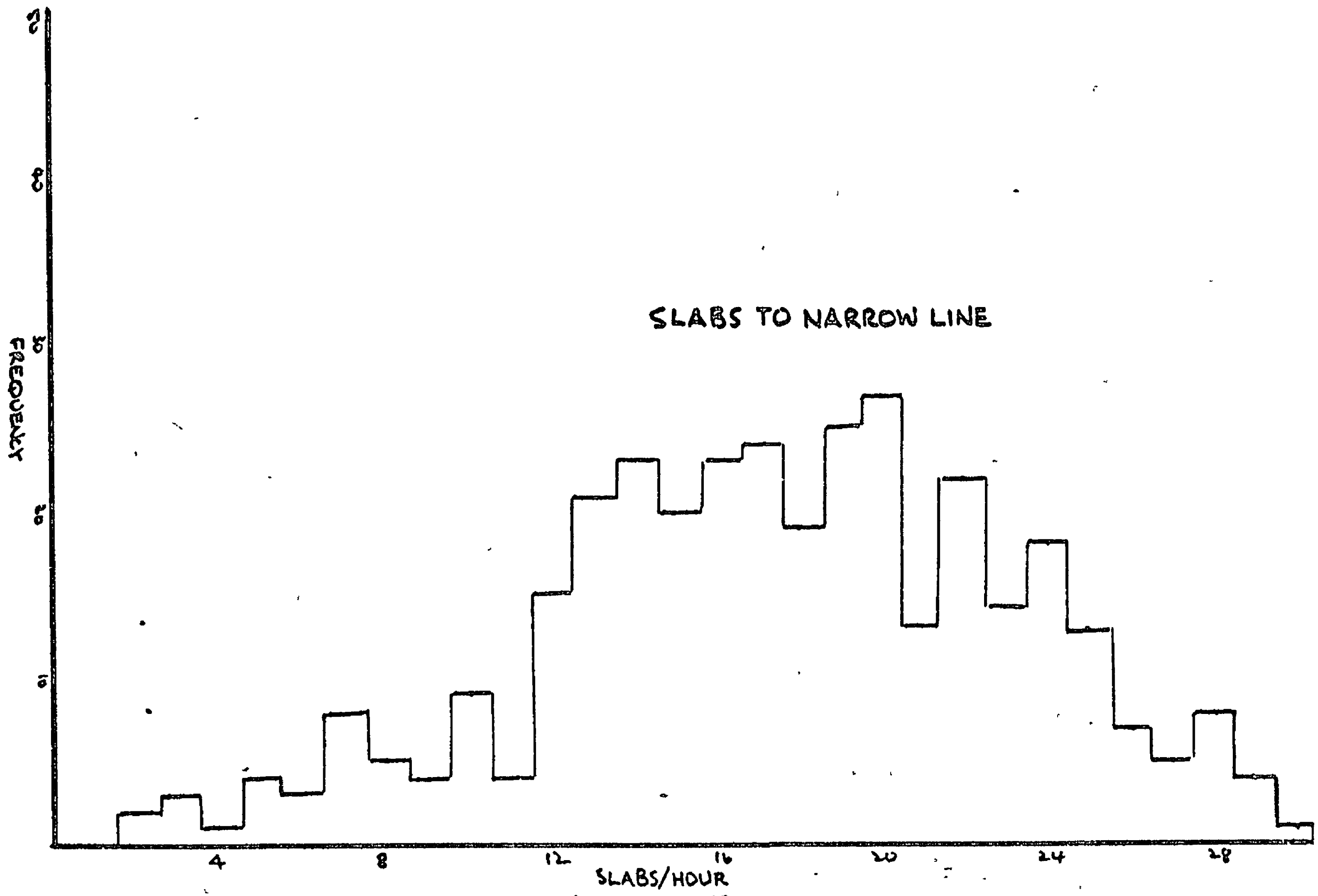


FIGURE 12C

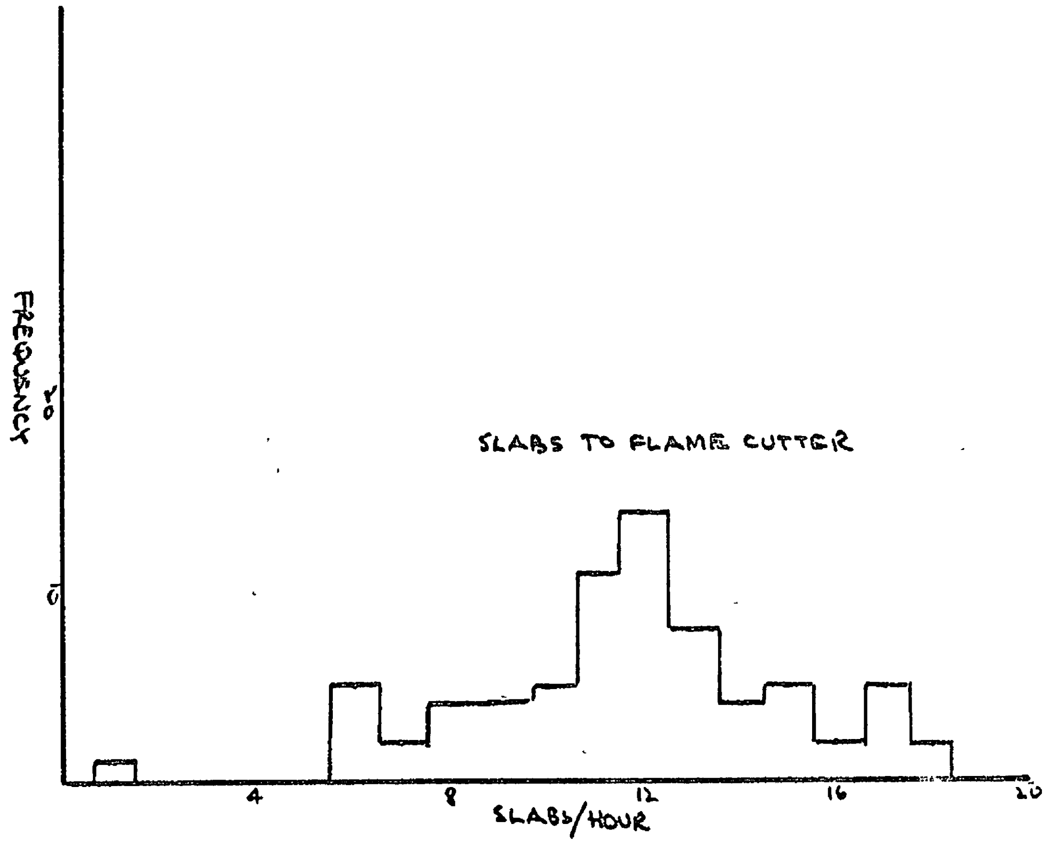


FIGURE 12d

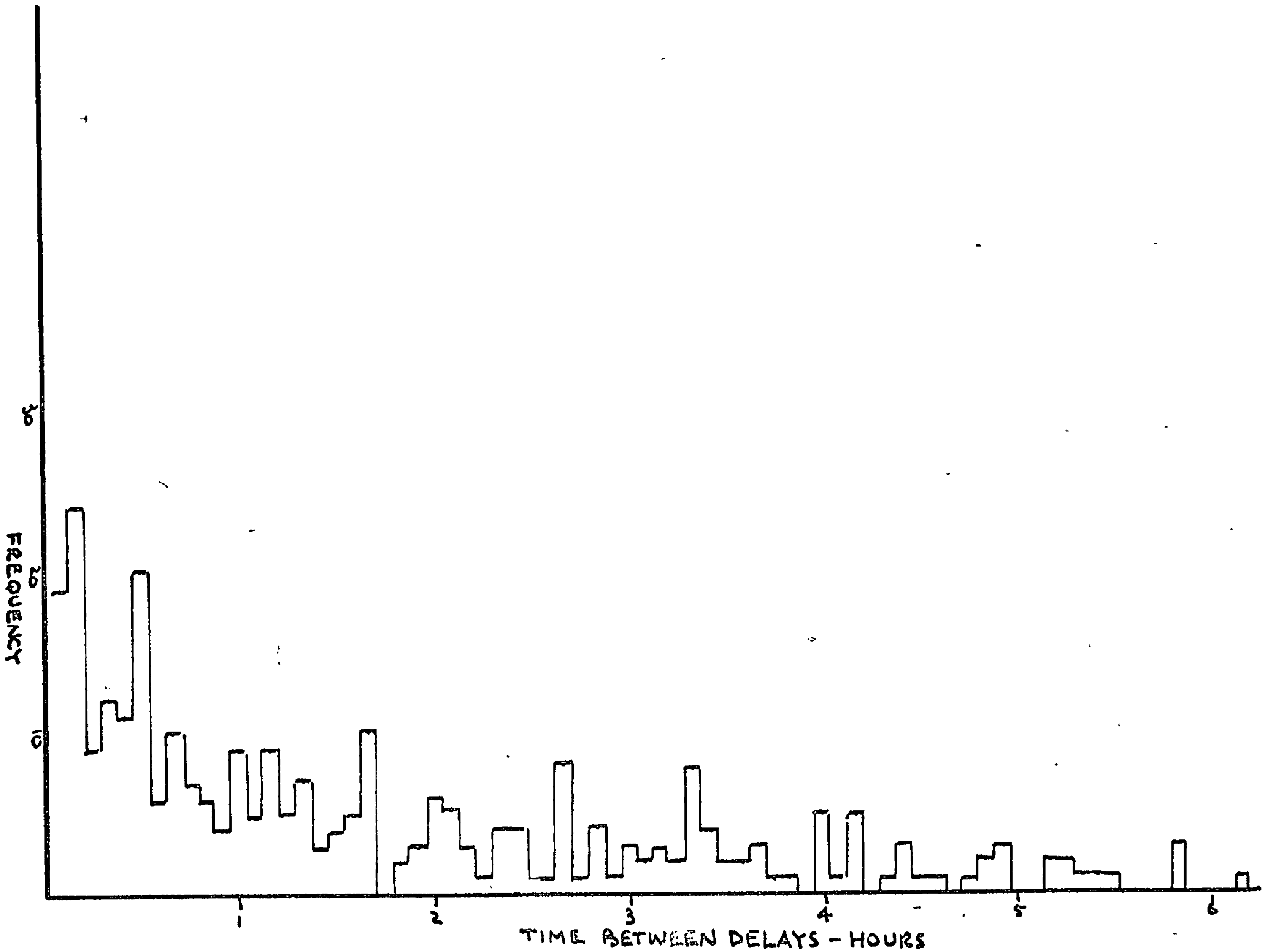
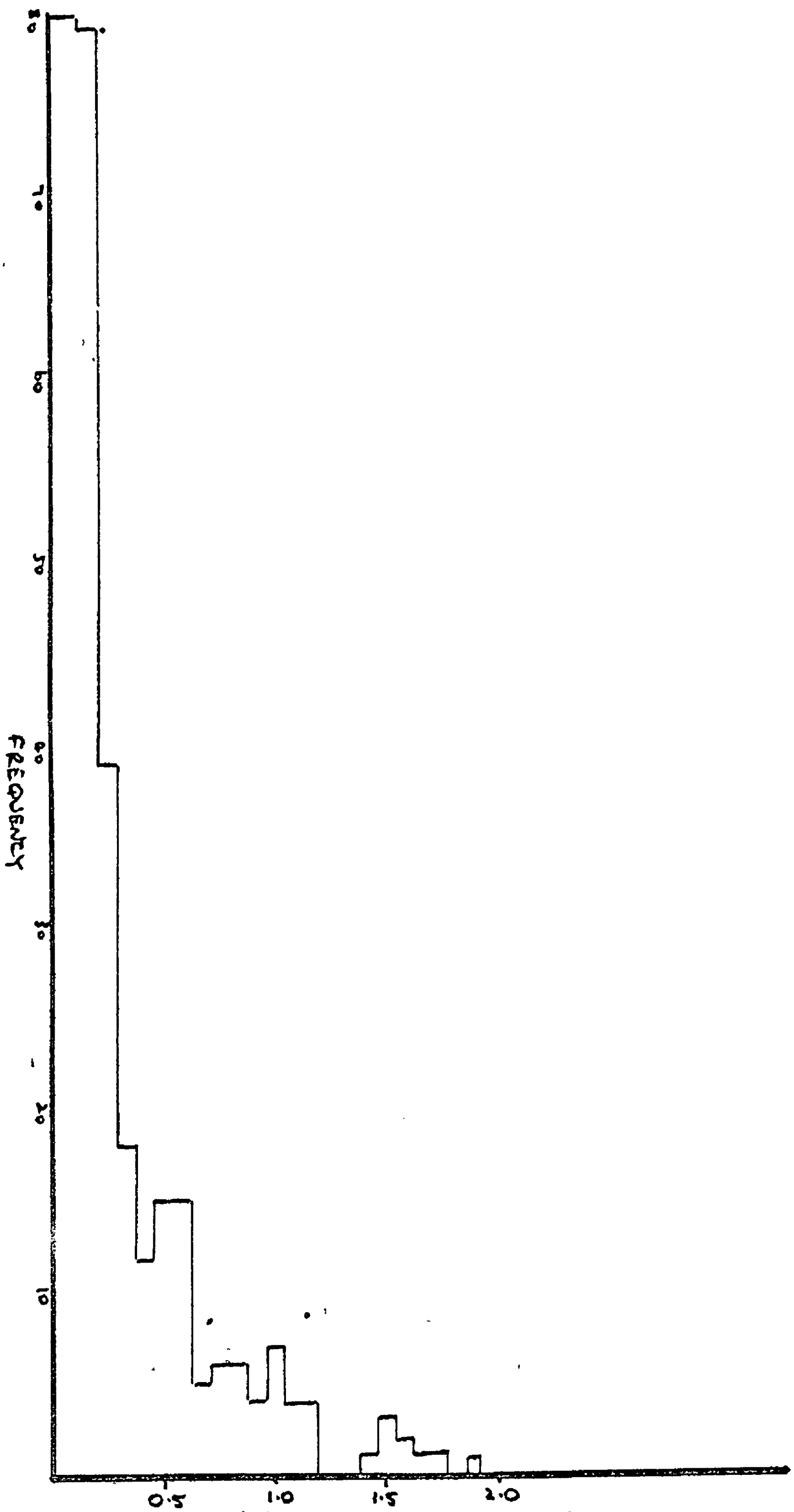


FIGURE 13a



LENGTH OF DELAY – HOURS

FIGURE 13b

in the surge areas must be set.

This can be applied in the following general manner.

a) Rolling Rate:

A frequency plot of the number of slabs rolled/hour on a mill was made for a period of one month. This gave normal type distribution as shown in fig. 12a. This will give a probability of arrival rates at the leveller of line 1 or the entry side piler of line 2.

A more accurate method may be to combine maximum rolling rates for each section with delays. To do this a two dimension chart should be compiled showing the maximum number of slabs which can be rolled for each width and thickness combination. Reasonable estimates should be obtainable from mill records. Probability estimates of delay occurence and delay time must be made to produce a probability versus rolling rates chart for each section.

Surveys on delay times and the times between delays were made on a mill for the same month period as for rolling rates. These are shown in figure 13a.

The service times by the various queues in the plate lines, and the allowable increase of stock in the surge areas, must be determined. This will give the maximum rate at which the shearlines can accept plates. This will vary very little with plate dimensions and so should produce a single figure of patterns per hour, modified by variations in branding practice and the number of plates to be cut from each pattern.

This must be determined for each queue.

The procedure sounds involved but once reasonable parameters are obtained, the whole system of queues can be simulated. This can be done most effectively on a digital computer which can handle a large number of trials in a short period.

b) Chanel Decision:

On many products no problem exists as only one of the chanels can physically cope with the requirements. On other products, where some flexibility is allowable, the proportion of product to each chanel can be varied to reduce the waiting times as determined by the analysis above.

c) Order of Rolling;

The order of rolling must be governed by quality considerations on the mill, but the quantity of each section can be varied according to the previous analysis. This will have to be balanced against the remainder of a schedule on the mill to prevent overall loss of production (see section VII on programming).

In addition to the shearing requirements of plates, the shearlines are affected greatly by such items as destination and metallurgical testing requirements. These aspects must be quantified to establish the number of patterns which can be handled. The actual relationships will vary according to such aspects as, the number of ships loading, or the quantity of rail trucks available, and must be continually updated.

d) Output:

The level of production under each condition of labour or equipment must be determined. Having firstly determined that it is an economic proposition to so vary the labour and equipment, then the shearline production should be lifted to meet optimum plate mill operation before the mill programme is modified.

e) Determining Parameters:

Data must be collected for the estimation of the number of arrivals and the servicing times under varying conditions. This data may then be grouped in time intervals after which statistical tests for independence of the means in successive time intervals may be found by such standard statistical tests as the variance ratio test.

If this is shown to be dependant, the data must be subdivided into time intervals within which a steady state is a reasonable approximation.

With the data which appears homogeneous, a further grouping is made and a frequency histogram constructed. The appearance of this histogram will suggest certain standard distributions such as the normal, Poisson, exponential or Erlangian. Parameters of the distribution are then estimated from the data.

The figure 12a, which shows the number of slabs rolled per hour from a mill, taken over a monthly period, was further divided into product for the wide shear line (fig. 12b); product for the narrow shearline (figure 12c); and thick plate for the flame cutters (figure 12d). This tended to give a more uniform distribution for the narrow line however there are still marked departures from a smooth curve on the wide line. It is felt that further analysis of the wide product would produce the reasons for this. It may then be desirable to use two or more distributions for the wide line - perhaps for thin product and for thick product. Note that thin, wide plate is more difficult to roll than thin narrow plate and this may be the reason for the smooth curve for the narrow product as distinct from the irregular curve for the wide product.

It appears that the distribution of arrivals at the head of each shearline would be Poissonian. Poisson arrivals are said to occur if the probability of an arrival between the time t and time t + Δ t is equal to $\lambda \Delta t$ (if Δt is small and where λ is a constant). The mean arrival rate is also λ as before and the probability of n arrivals in time t is given by:-[50]

$$(\lambda t)^n e^{-\lambda t} / n!$$

and the density function for $\tau = \quad e^{-\lambda t}$

50. M. Sasieni et.al "Operations Research - Methods & Problems", Wiley N.Y., 1959, P.127.

An examination of the time between delays on the mill (figure 13a) and the length of time of delays (figure 13b) show that these times appear to follow an exponential distribution. It is possible that examination of service times in the shearline queues will show that these are also distributed exponentially.

Where the probability of a unit being serviced in the time interval t to $t + \Delta t$ is given by $u \Delta t$ (u being a constant) the service times are distributed exponentially. If s is a random variable representing the time it takes the station to complete the service on a unit then the density function of s is given by:-[51]

$$g(s) = ue^{-us}$$

Note that u becomes the mean service time as before.

SIMULATION:

The mathematical theory of queues is a powerful tool for discovering the kind of phenomena that can arise, however all but the simplest queue systems defy analytic solutions.[52]

Once a complete description of the system is given it becomes possible to simulate it by sampling the appropriate distributions for process and inter-arrival time. This method of approach is described in a monograph by Dr. K.D. Tocher.[52]

The advantage of this simulation is that the effect of certain programmes can be predicted in advance of the rolling and corrective measures taken. Conversely, feed back from simulation studies can modify the approach to programming.

51. Ibid P.128.

52. K.D. Tocher, "The Art of Simulation" English Universities Press, London, 1963. P.120.

SUMMARY:

The first task is to identify the processing stages in the shearlines. These are seen to be a series of queues. Analysis of records may provide information to determine the parameters of the arrival and service time distribution. If records are not adequate a study on site must be made.

The theory of queues provides necessary insight into the problem, but it is felt that analytical solutions to a practical problem are very difficult to obtain. The method preferred is one of simulation, using such techniques as the Monte Carlo. This method is most effectively used on a digital computer.

To be of practical value, the analysis must show improvements in performance by variations of chanel decisions, order of rolling, (i.e. arrival distribution), and service facilities.

VI MILL PROGRAMME

Mill providers are issued with customer orders in groups according to required delivery periods. The problem of programming the plate mill is to be able to put out a series of programmes which produce the maximum tonnage of plate while completing the orders in the time allotted by the customer.

A programme is issued to cover the "life" of a set of rolls in the mill. At the completion of a programme, the rolls are withdrawn and the roll surface re-dressed ready for another run in the mill. Programmes must start on wide plates and then gradually come in to finish on narrow plates.

The tonnage which can be rolled at any particular width during a programme depends on the thickness range of that width and also on the tonnages and thicknesses already rolled at previous widths in the programme. Thus 500 tons of 3/8 thick plates at 90" wide may roll satisfactorily on one occasion, but not on another due to a large tonnage of 3/16 plate rolled before it at 96" wide. Similarly, 500 tons of 3/8" thick plate at a certain width may give good product while possibly only 300 tons of 3/16" plate may be rolled in place of it at the same width.

A relationship between the tonnages which can be rolled at any one width and the thickness, must be established. From observation of rolling mill practice the following effects on roll wear are apparent:-

a) The roll wear increases as the thickness being rolled decreases. This can be attributed to three reasons. Firstly, the thinner sections frequently require more passes but, more significantly, roll separating force is more dependent on percentage reduction than on actual reduction. The percentage reduction increases on thinner sections; on 3/16" plate, reductions rise to as high as 75% while on, say, 1" plate the reduction would seldom rise above 50%.

Thirdly, on lighter sections, the heat loss is greater.

Roll separating force and, as a result, roll wear, increases rapidly with decreasing temperature.

Assuming a slab rationalisation with pre-determined slab sizes for each finished plate cross section, as described earlier, it is conceivable that a constant factor could be found for each plate width/thickness combination. This factor, multiplied by the tonnage rolled in a width/thickness combination, would give "equivalent tons" which could be summed arithmetically over the whole schedule.

Applying the correct factor to each width/thickness combination, a total "equivalent tons" would be arrived at to give an estimate of roll wear at each plate width and also an estimate of the final roughness in the centre of the rolls. Both these effects are important. The roll wear (the roll "profile") determines the shape of the plate rolled. Excessive wear on one width will result in thick edges on the plate. Excessive total tonnage off the rolls will give a very rough surface to the plate which may be unacceptable in some cases.

b) As mentioned above, roll wear increases with decreased temperature of the slab being rolled. Considering the cross section of a slab, it is observed that the extreme edges are always considerably colder than the body of the slab.

This factor, plus the effect of the discontinuity of the edge of the slab, results in increased roll wear at the two outer edges of the slab or plate.

Thus, "equivalent tons" at each width must be considered. The excessive wear due to the edge effect reduces rapidly the further the distance from the edge. The tonnage that can be rolled at one width will then depend to a varying degree on the tonnage rolled at each preceeding width.

It is important to establish the above relationships to enable maximum tonnages to be programmed for each set of rolls and to prevent excessive tonnages being programmed which would result in poor

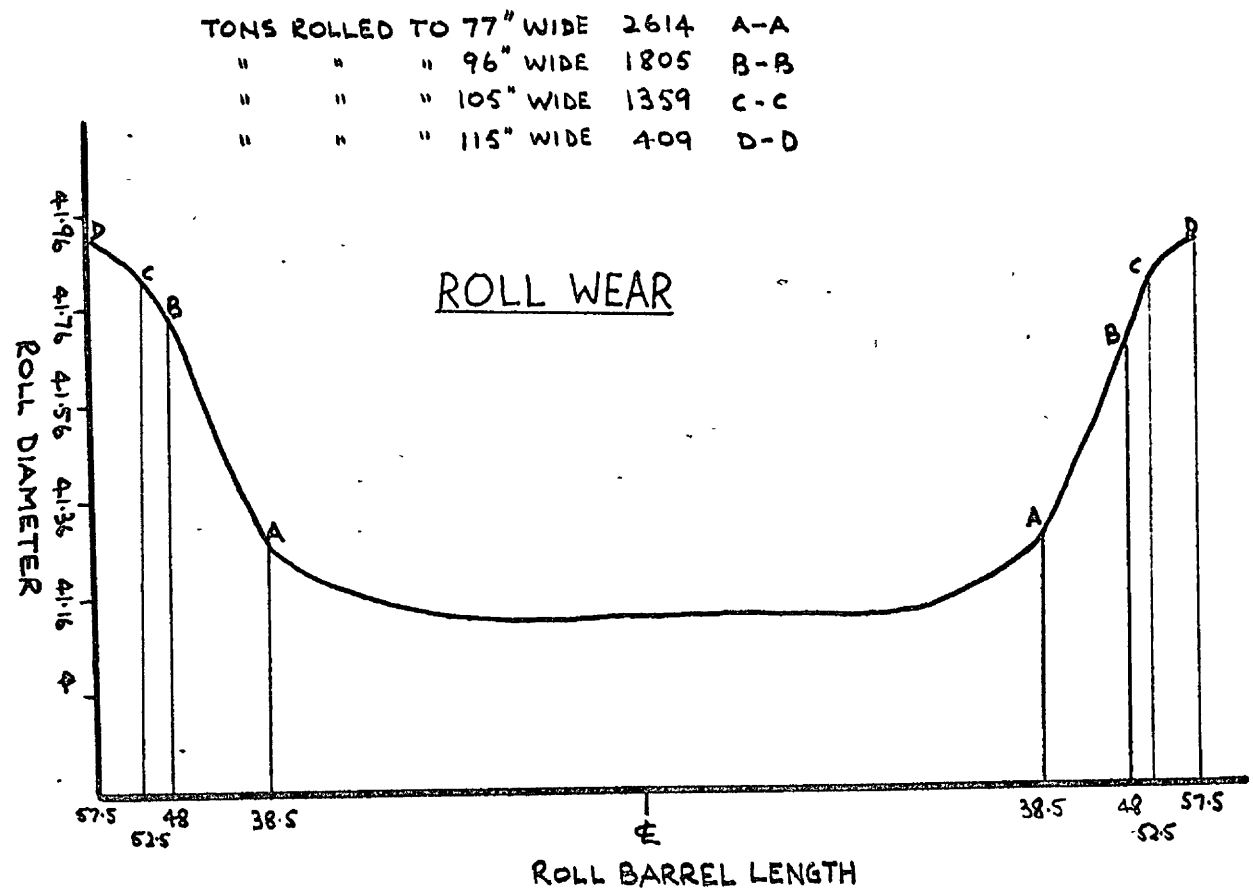

TONS ROLLED TO 77" WIDE 2614 A–A
" " " 96" WIDE 1805 B–B
" " " 105" WIDE 1359 C–C
" " " 115" WIDE 409 D–D
ROLL WEAR
ROLL DIAMETER
41.96
41.76
41.56
41.36
41.16
41
57.5
52.5
48
38.5
ROLL BARREL LENGTH

FIGURE 14

quality.

To establish the relationships described above, detailed surveys of roll wear and a measure of roll roughness must be made for each programme. The type of results obtained from such a survey is shown in figure 14.

Statistical analysis of sufficient data will enable a suitable method of determining roll wear to be established. By feeding the programme details into a digital computer the statistical model can be easily applied. This would then show the mill manager whether the safe limits at any section have been exceeded.

If real computer time is readily available the model could be constantly updated as the providers write the schedule. The model would continually show the provider how much more tonnage he could programme for each width band.

An approach to developing schedules for rolling mills by mathematical methods, is described for a bloom mill and structural mill in a Russian paper.[53] Although the problem has somewhat different parameters to the plate mill problem, the philosophy behind the approach is the same. The authors of the paper claim considerable improvement in operations over the previous manual method. This writer is also convinced that substantial gains can be made in plate programming by the mathematical approach.

The approach to programming outlined above considers the roll wear in the mill but the breadth of programming should be extended to cover all operations. That is, each programme placed on the mill, should be the optimum programme which can be selected from the order book as considered under the following classifications:- the required delivery dates; slab thickness increments for the furnace; the tonnage

---

53. N.S. Sachko, et.al."Development of Operating Schedules for Rolling Mills by Mathematical Models" - Stahl in English No.7, July, 1964. P.566.

at each width for roll wear, plus the total tonnage; the capacities of the shearlines according to the sections rolled; the shipping requirements of the shearlines according to destinations being rolled.

All these aspects, and several more, should be considered in detail, not only at the stage of compiling the schedule but at least a week before when the ingot feed is being ordered on the steel making shop.

SUMMARY:

The composition of the mill programme, that is, the assembly of a number of slabs to be rolled to plates over the life of one dressing of a set of rolls, is of the greatest importance to mill operations.

All aspects of operations which are affected by the programme should be quantified so a complete model of operations can be determined. A particular programme can then be tested on the model and alterations made to approach an optimum programme for the point of view of maximum plate production.

VII CONCLUSION

Operations research was developed as a scientific approach to wartime tactical and strategic problems. Following the war "the steel industry was among the first to take up operations research in a really big way. There are, however, wide discrepancies between countries, and in some the development is only just beginning and lags noticeably behind that in other industries".[54] The steel industry in Australia must be considered to follow the latter class although there is a growing awareness of the need of such an approach to the problems.

In the process control field, however, this statement is far from the truth. Sophisticated electrical and mechanical control systems have been installed with a considerable amount of the engineering design done in this country. This is particularly true in rolling mills such as the plate mills, cold rolling mills, temper mills and universal beam mills. The area where the development is lacking is the link between the production manager and the engineer. The most modern plate mill will not operate efficiently if the slab feed has not been planned adequately or the mill is not programmed correctly,

MODEL BUILDING:

In nearly all cases there is sufficient technical knowledge available to provide the data which describes the system under review. However, as Richard Bellman clearly points out,[55] "we have cart loads of data in many fields but we usually lack the equations that govern the data". Having the data and with the ability of the modern digital computer to make rapid calculations, a trial and error method of finding a solution may be possible. Bellman's "curse of dimensionality"[56] shows that in a problem of x variables in y combinations, this method may have to examine x^y separate problems.

54. Progress in Operations Research II - P.258.

55. R. Bellman "Adaptive Control Processes: A Guided Tour", Princeton N.Y., 1961 - P.335.

56. Ibid - P.94.

Even with a computer, this could be a lengthy and certainly a costly procedure because the problem could not be handled with the fast machine memory. Such problems could not be handled routinely by the computer because of the memory requirements. The formulation of a mathematical model reduces these calculations, it guides the process of optimisation along a definite, not a random, path towards its goal.

This mathematical model must be a representation of the system and can be used, simulate, or predict, the behaviour of the system. Three powerful properties of mathematical models are:-[57]

a) Generality:

The same mathematical model can apply not only to a whole range of values for any given system, but also to other, physically different, types of systems. As has been mentioned previously the engineering concept of feed-back control system can be applied to management systems.

b) Economy:

Given the equations and a small amount of data, the basic data can be generated. This avoids much of the costly process of information gathering. Further, it is relatively easy to adjust the basic data to suit new conditions and so maintain a dynamic model of a dynamic process. The use of computers allow mathematical models to be processed readily to provide rapid solutions.

c) Finality:

The mathematics of the model implies that rigorous logic has been applied to the analysis of the process. Allowing the rigorous analysis, attention can be focused on the more elementary problems of accuracy of input data and the validity of initial assumptions.

In solving these mathematical models analysts use three basic approaches:-[58]

---

57. C.H.J. Beaven and N.J. Maroudas "A Review of Mathematical Models", British Chemical Engineering Vol. 11, No.7, July, 1966 - P.715.

58. Ibid - P.716-7.

d) Hill Climbing:

Assuming an objective function of the form, $P = f(x,y,z)$ which is usually non-linear, the aim is to look for values of x,y and z which maximise P. Initial estimates of x,y and z are made and the value of P calculated. The values are then marginally changed and if the effect on P is favourable the change is reinforced; if not the step is reversed. This procedure drives the system to an optimum.

e) Linear Programming:

Where the objective function is of the form, C = a,x+b, Y+c, ...etc., the path to the optimum is not smooth and continuous. The optimum is assumed to be on the topmost vertex of the polygon formed by the mesh of intersecting straight lines defined by the above equation.

f) Dynamic Programming:

This has been described previously. The principle of optimality is applied to the policy which makes optimum use of the remaining stages of a multi stage process, no matter what has gone before.

FORMULATING THE PROBLEM:

The main task which faces the manager of a manufacturing enterprise is "which problems require solving?" and "how can I most efficiently use the available talent in solving these problems?" Only the manager himself knows which problems he wants solved and this stage cannot be delegated. A manager may ask a researcher to find which problem he should want solved first but this in itself is a basic decision ~~problem~~ and again must be first formulated by the manager.

There are many technical and managerial problems in producing steel plate from a wide plate mill. The main purpose of this paper is to formulate the major problems leading to an optimisation of plate production. These are summarised hereunder:-

a) Furnace:

Given a range of slab sizes to be heated for rolling to a range of plate sizes, the problem is to determine the optimum operating conditions to produce the maximum tonnage of plate. A further aim is the determination of optimum slab sizes for maximum furnace production.

b) Mill:

Given a plate section to be produced from a certain slab section, the optimum drafting schedule that produces maximum output, consistant with quality, must be determined.

c) Slab Feed:

Following the determination of optimum drafts the optimum slab size for each section can be determined. These slab sizes can then be grouped into an optimum rationalisation. The costs incurred by a compromise in slab sizes must be found to determine the optimum.

d) Shearlines:

An analysis of the various shearline queues will provide a basis for programming the mill for maximum production. Any necessary variations of production facilities in the shearlines must be readily determined in advance from the schedule.

e) Programming:

The requirement of the programme is that it must produce the maximum tonnage in the furnace/mill/shearline group. This programme must recognise all variables which affect production.

THE NEED FOR THE ANALYSIS:

A modern wide plate mill, with shearlines, represents a capital outlay of the order of $40,000,000 or more. It may produce half a million tons of plates a year and employ around 1,000 men. The factors which can affect the quality of the product or the production rates are many and varied. The problems which occur may be of a complex technical or organisational aspect.

It is apparent that seemingly small gains involve large amounts of money. An increase in production of 1% could mean an increase in sales of the order of $500,000 p.a. Losses in production, due to poor management decisions, involve the enterprise in correspondingly large costs.

At each stage in the operations, from compiling the programme to organising the order of despatch, judgement decisions are called for. The aim of the models is not to eliminate the judgment but enable more decisions to become routine so that the judgment can be concentrated on the vital points. Bellman makes this same point when discussing the merits of computers in handling complex problems. "Freed of the drudgery of these calculations, the human mind can contemplate problems of real conceptual difficulty...".[59]

Having made many of the decisions routine they can, of course, be handled automatically by a computer. There are some computer controlled plate mills[60] but it is not intended to imply in this paper that the step to automatic process control must be made in a hurry. Such installations are costly and suffer from a number of disadvantages. It is felt, rather, that the need to automate the management decisions making processes, rather than the actual operating equipment is more pressing and the area where the greatest cost savings can be made.

There are some serious inherent organisational risks in this step, however, which must be recognised in order to be overcome.

The quality of management personnel will need to be higher to take advantage of the release from routine. It must be emphasised that "managers" in this sence are not the chief executives but all men who are "getting things done with and through people".[61] This will include the mill roller, the furnace foreman, and the shearline foreman as well as the mill manager.

---

59. R. Bellman op. cit. - P.334.

60. R.B. McCullock "On-Line Computer Control of a Universal Plate Mill", Australasian Engineer, September, 1965 and R. Bazuro and L.A. Oliva "Plate Rolling with On-Line Computer Control", Journal of Metals, October, 1965.

61. L.F. Urwick "Management", Current Affairs Bulletin Vol.30 No.8, August 27, 1962 - University of Sydney.

It is felt that this paper could not be concluded better than by a statement from Alfred North Whitehead as quoted by David Teichroew.[62]

"It is a profoundly erroneous truism, repeated by all copy books and by eminent people when they are making speaches, that we should cultivate the habit of thinking of what we are doing. The precise opposite is the case. Civilisation advances by extending the number of important operations which we can perform without thinking about them".

---

62. D. Teichroew "An Introduction to Management Science", Wiley N.Y. 1964.

BIBLIOGRAPHY

BOOKS:

Air Ministry "Operational Research in the R.A.F." H.M. Stationery Office, London, 1963.

R.L. Ackoff and P. Rivett "A Manager's Guide to Operations Research" Wiley, London, 1963.

C.W. Churchman, R.L. Ackoff & E.L. Anoff "Introduction to Operations Research", Wiley N.Y., 1957.

J.E. Howell & D. Teichroew "Mathematical Analysis for Business Decisions" Irwin, Illinois, 1963.

R.L. Ackoff "Scientific Method - Optimising Applied Research Decisions" Wiley N.Y., 1962.

D.W. Miller & M.K. Starr "Executive Decisions & Operations Research", Prentice Hall N.J., 1960.

"Handbook of Automation, Computation & Control, E.M. Grabbe et. al. editors VOL. 1, Wiley N.Y., 1958.

W. Trinks & M.H. Mawhinney "Industrial Furnaces", Vol. 1 5th ed., Wiley N.Y., 1961.

H.S. Carslaw & J.C. Jaeger "Conduction of Heat in Solids" Oxford, London, 1947.

"The Making, Shaping & Treating of Steel" United States Steel, Pittsburgh 7th edition.

M.W. Tring "The Science of Flames & Furnaces", 2nd edition. Chapman, London, 1962.

"Roll Pass Design", United Steel Coys. Ltd., Sheffield, 1960.

E.C. Larke "The Rolling of Strip, Sheet & Plate", Chapman & Hall, London, 1957.

P.M. Cook & A.W. McCrum "The Calculation of Load & Torque in Hot Flat Rolling", British Iron & Steel Research Association London, 1958.

R. Bellman "Dynamic Programming", Princeton N.J., 1957.

D. Teichroew "An Introduction to Management Science", Wiley N.Y.,1964.

M. Sasieni et. al. "Operations Research - Methods & Problems", Wiley N.Y., 1959.

K.D. Tocher "The Art of Simulation" English Universities Press, London, 1963.

Progress in Operations Research II.

R. Bellman "Adaptive Control Processes: A Guided Tour", Princeton N.Y., 1961.

ARTICLES and OTHER SOURCES

Directors' Report B.H.P. Co. Ltd.

Australian Financial Review.

W.F. Cartwright "The Future of Automation in the Iron & Steel Industry" Australian Machinery & Production Engineering., December, 1964.

C.W. Dunn "Applying Computers to Existing Steel Plant Facilities" Industrial Heating, 1966.

L. Hurni "Basic Processes of Operations Research & Synthesis" in A. Schuchman ed. "Scientific Decision Making in Business", Holt, Rinehart and Winston N.Y., 1963.

F.S. Bloom "Rate of Heat Absorption of Steel" Iron & Steel Engineer, May, 1955.

A.H. El-Waziri "The Transient Temperature Distribution Within Slabs" Iron & Steel Engineer, March, 1961.

T.J. Mirsepassi "Heat Transfer Tables for Time - Variable Boundary Temperatures in a Slab", British Chemical Engineering Vol.10, No.11 November, 1965.

R. Jackson et. al. "Variable Heat Flow in Steel", Journal of Iron & Steel Institute C.L., 1944.

E.D. Williamson & L.H. Adams, Physical Review, Vol.14, 1919.

M.G. Shortland "Models of Good Measurement", Iron & Steel, 26th May, 1965.

A.Y. Lerner "Optimum Control for Continuous Processes", I.F.A.C. paper 501/1 Basle, 1963.

W.T. Kodz, "Computer Control of the Continuous Slab Reheating Furnace", Restricted B.I.S.R.A. report PE/B/20/6J., London, 1965.

T. Suing Yang private communication.

F. Hollander comments on Centralised Information System on Soaking Pits & Slabbing Mill", paper E.103 Verein Deutscher Eisenhuttenleute, Dusseldorf, 1965.

R.G. Schultz & A.W. Smith "Determination of a Mathematical Model for Rolling Mill Control", Iron & Steel Engineer, May, 1965.

R. Green, Discussion on Hot Rolling Mills. Journal of Iron & Steel Inst. March, 1963.

A.J. Winchester "How to Select the Size of a Rolling Mill Drive Motor". Blast Furnace & Steel Plant, January, 1955.

D.J.H. Lewis, unpublished work.

E. Downs, P. Shipp & B.W. Smith "Plate Mill Automation" British Iron & Steel Research Association, London, report PE/B/76/63, December, 1963.

N.S. Sachko, et. al. "Development of Operating Schedules for Rolling Mills by Mathematical Models", Stahl in English No.7 July, 1964.

C.H.J. Beaven & N.J. Maroudas "A Review of Mathematical Models" British Chemical Engineering Vol. 11, No.7, July, 1966.

R.B. McCullock "On-Line Computer Control of a Universal Plate Mill" Australasian Engineer September, 1965 and R. Bazuro and L.A. Oliva "Plate Rolling with On-Line Computer Control", Journal of Metals, October, 1965.

L.F. Urwick "Management", Current Affairs Bulletin Vol. 30, No.8, August 27, 1962 - University of Sydney.

LIST OF ILLUSTRATIONS