The economics of the use of numerically controlled machine tools and program development

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THE ECONOMICS OF THE USE OF NUMERICALLY CONTROLLED MACHINE TOOLS AND PROGRAM DEVELOPMENT

by

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A B S T R A C T

Brief History

The introduction of numerically controlled machine tools into the manufacturing industries and design considerations for their technological progress.

Classification

Considered from three aspects: type of control, the machine tools with which they are combined and the procedure involved in machining.

Programming

The preparatory work which must be carried out before components can be machined in an N.C. machine tool. This includes planning and encoding the information into the input medium, using manual or computer assisted methods.

N.C. Economics

The number and type of N.C. machines in use in the U.K. are shown, plus an indication of their cost. This emphasises the fact that justification must be on economic grounds.

Cost Analysis

Comparison of N.C. and conventional methods. Examination of justification calculations shows the danger of using short cut methods.

The method of discounting estimated future returns is used to show that accurate forecasting and alternative methods of investment must be considered before a decision can be made.

Consideration of Batch Size

A rational method of assessing batch size and component complexity is shown. Graphical results of several methods of manufacture are used to indicate the economic advantages and disadvantages of each process.

Economic Considerations of Programming

Analysed under two headings: planning and programming, the latter being considered under the headings of manual and computer assisted.

The cost of preparing a control tape ready for prove out is examined and an analysis of special and general purpose systems has been carried out.

Comparison of Methods

The relative merits of in-house or computer bureau service have been analysed and a decision process outlined to assist in the correct system selection.

Program Development

Cost and levels of tape verification are considered, plus the essential facts of producing an accurate control tape.

Methods of eliminating setting errors are considered.

Program format is illustrated and an error checking program developed, using Fortran.

Appendix	A	Fortran program description (T.E.S.P.)
"	B	Module table calibration chart
"	C	Graph plotter output.

ACKNOWLEDGMENTS

The author wishes to express his sincere thanks to Professor G.R. Higginson of The University of Durham, for initially providing the opportunity to submit this thesis and for his valued help and guidance thereafter,

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CONTENTS

Except where specific acknowledgement is made to other works, the content of this thesis is entirely the work of the author.

GLOSSARY OF TERMS

ACCESS TIME

The time required to locate and retrieve a unit quantity of data from a store.

ACCURACY

The accuracy of a numerical-control system is measured by the difference between the actual position taken up by the machine slide and the position demanded. This difference will not be identical every time the same position is demanded and, like repeatability or reproducibility, accuracy is expressed in statistical terms. It is clear that the accuracy of a system can never be better than the repeatability.

ADAPT

Air Material Command Developed APT. A development of APT with a limited vocabulary, which can be employed on some small-to-medium sizes of American computers.

ADDRESS

In numerical-control programming, a symbol which indicates the significance of the information immediately following. For example, in the instruction X 1575, X is the address signifying the word 1575 as a co-ordinate on the X axis.

APT

Automatically Programmed Tools. A universal computer-assisted program system for multi-axis contouring work. Needs a large computer. The current version, APT III, is administered by the Illinois Institute of Technology Research Institute.

AUXILIARY FUNCTIONS

The functions, other than positioning controls, which have to be set to ensure correct operation of a machine tool. These functions include stop, start, selection of the machining cycle, tool selection, feeds and speeds, coolant on or off etc. They also include the visual display of information on the state of the machine.

BIT

An abbreviation for a binary digit.

BLOCK

A group of words containing all the instructions for one operation. In a positioning system, a block will include the co-ordinates of the position, together with all the instructions for auxiliary functions necessary to complete an operation. One block is distinguished from the next by an end-of-block character.

2 CL

2 Continuous, 1 Linear control axes. A language developed at the National Engineering Laboratory, East Kilbride, and mainly used in Great Britain. In many respects similar to EXAPT.

COMPILER

A program for a computer to translate an autocode program into its own machine code.

CONTOURING SYSTEM

A system in which motion has to be controlled on more than one axis continuously and simultaneously. This system, which is also known as a continuous-path system, is typically used in milling, turning, die-sinking, grinding and draughting machines.

DATA-PROCESSING

The performing of a systematic series of calculations or other logical operations or information, in order to extract further information from them, or to put them into a form suitable for controlling a numerically controlled machine or other equipment.

DATUM

The reference position of the machine members when the measuring system indicates zero.

DOWNTIME

Time during which equipment is out of action because of faults.

EIA

The Electronic Industries Association in U.S.A. A trade association representing manufacturers of electronic equipment which issues standards documents. Address: 2001 Eye Street NW, Washington DC.

END-OF-BLOCK CODE

An agreed code which indicates the completion of a block of input information on punched tape. This code usually also causes a line feed operation on a tape-operated typewriter. Thus one block of information is printed on one line by the typewriter.

FEEDRATE

The rate, in mm/min or in./min, at which the cutting tool is advanced into the workpiece. For milling and drilling, the feedrate applies to the reference point on the end of the axis of the tool. For turning, it applies to an agreed reference point on the tool.

FORMAT

An agreed order in which the various types of words will appear within a block, and thus also along the length of a magnetic or punched tape.

FORTRAN

FORmula TRANslation. A universal computing language or autocode developed by I.B.M. and used for describing numerical processes in such a way that they can be understood both by human beings and by computers. For computers to accept programs in FORTRAN, it has to have a compiler to translate FORTRAN programs into machine code. In the APT system, mathematical or logical calculations not catered for in the APT program can be programmed in FORTRAN.

INTERPOLATION

The joining up of programmed points to make a smooth curve by computation. If the segments joining the points are straight lines, the process is called linear interpolation; if they are arcs of circles or parabolas, it is known as circular or parabolic interpolation respectively.

ISO CODE

Like the EIA standard code, the ISO (International Standards Organization) code is also an 8-hole tape system.

LEAD TIME

The time between the issue of a drawing from the drawing office and the start of actual machining.

MANUSCRIPT

A planning chart of part-program containing all the information about the geometry of the part and the machining conditions (feeds, speeds, etc.) necessary to make it, written in correct order, and ready for transfer to an input medium.

PARITY CHECK

A means of minimizing errors in coding on tape, etc. All characters in a code are made either odd or even. In the EIA Standard Code for eight-track tape, for example, all characters are represented by an odd number of holes. This is ensured by using one of the eight tracks for a parity digit, the presence of a character with an even number of holes causing the parity check to fail and indicate an error in punching. The incorporation of a parity-check feature makes it possible to stop the machine automatically when a program error is detected.

PART-PROGRAMMER

The person responsible for the preparation of the manuscript.

PICNIC

Pera Instructional Code for Numerical Control. Intended to fill the gap between simple manual programming and complex computer programming. PICNIC has been designed expressly for programming point-to-point machines for such operations as drilling, boring, tapping and milling.

SOFTWARE

The information fed to a computer or control system, as distinct from their hardware.

SUB-ROUTINE

A discrete part of a computer program which carries out a particular function and can be used at any time in conjunction with information generated in another part of the program.

TAB SEQUENTIAL

A tape-programming method for positioning systems, in which the instructions are always punched in the same sequence, butthe TAB character is punched at the beginning of each word. If the particular instruction(word) remains unchanged, it need not be punched, and the TAB character is punched again to begin the next word.

VERIFIER

A feature of tape-preparation equipment specially designed for checking the accuracy of a punched card or punched tape by producing a second card or tape from the original data. The two versions are then compared in the equipment and, if there is any lack of agreement between the second punching and the first, indicating an error, the equipment automatically stops.

WORD

A group of characters referring to a unit of information. In numerical control, words include characters specifying co-ordinate positions and also such auxiliary functions as feeds, speeds, and coolant on or off.

CHAPTER 1 NUMERICALLY CONTROLLED MACHINES

INTRODUCTION

The first NC machine tools were designed and developed in response to a definite user demand in the early 1950's for the machining of complex shapes. During the following fifteen years most of the NC development work was undertaken by machine tool manufacturers in advance of a known market requirement and, therefore, without particular reference to the needs of the user.

The first generation of NC machines followed, in the main, conventional machine tool design. In most cases they were in effect adaptations of existing machine tools and, because of this, suffered from a variety of inherent defects, including:-

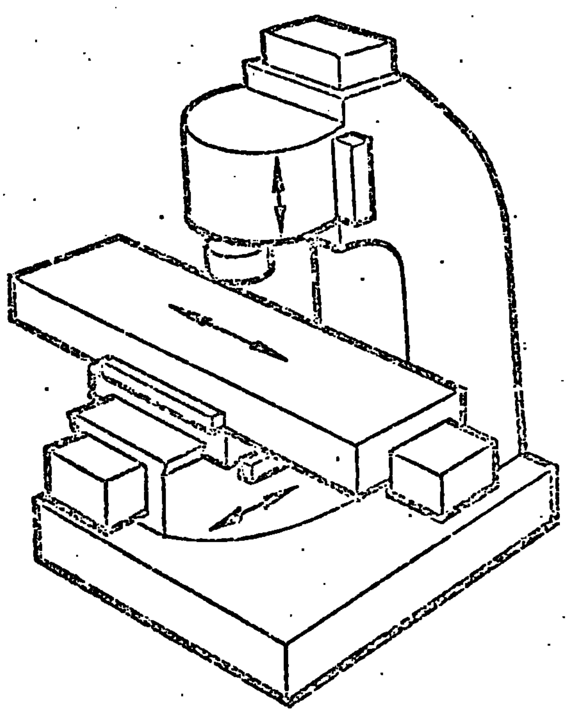
- short life of bearing surfaces due to more intensive utilization;
- accuracy limited by "stick-slip";
- little or no attention to positioning drive dynamics leading to limited drive response;
- spindle position and spindle axis orientation suitable for manual operation, but not necessarily most suitable for NC;
- the position of the feed-back transducers could introduce dimensional errors and often made them liable to interference by dirt and swarf.

Fig. 1 shows a diagrammatic representation of a typical first generation machine. Early in the 1960's machines of the second generation were produced, fig. 2. These were machine tools designed from the outset for NC and included one or more of the following features:-

- horizontal spindle permitting greater machine rigidity and easier clearance of swarf. (It was no longer necessary for the operator to have a continuous view of the cutting tool);
- wearing parts were given special attention, e.g. hydrostatic slideway fig. 3, lubrication and recirculating ball screws were commonly utilised fig. 4;

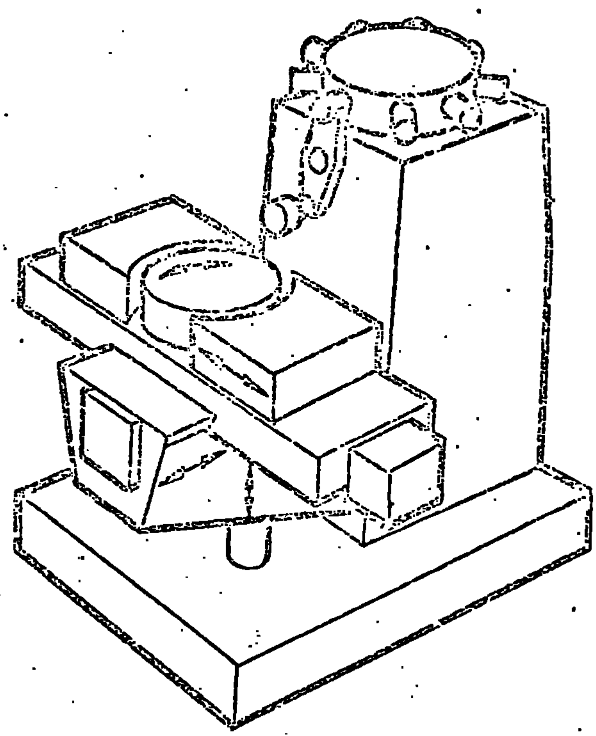
- programmed selection of spindle speed;
- feedback transducers integral with the machine;
- automatic tool-changing;
- pallet loading;
- programmed work-table indexing.

Some of these second generation machines were described as "Machining Centres" and introduced a new concept in batch-production metal-working. By having a machine capable of undertaking a range of operations from simple drilling to complex milling and by providing automatic changing of pre-set tools, automatic work-table indexing and pallet loading, it has become possible to carry out a large number of operations at a single



1st Generation N.C. Machine

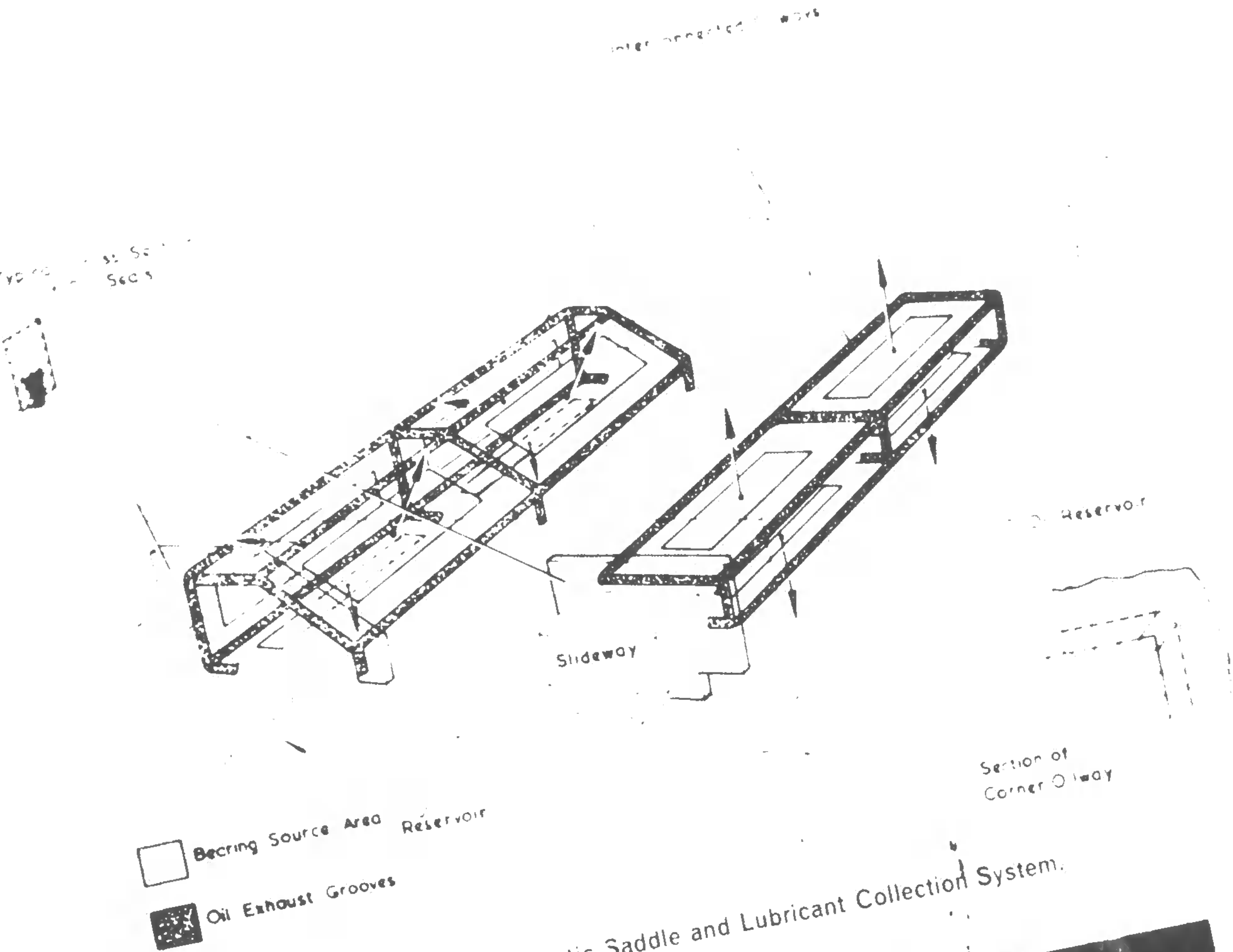
Fig. 1



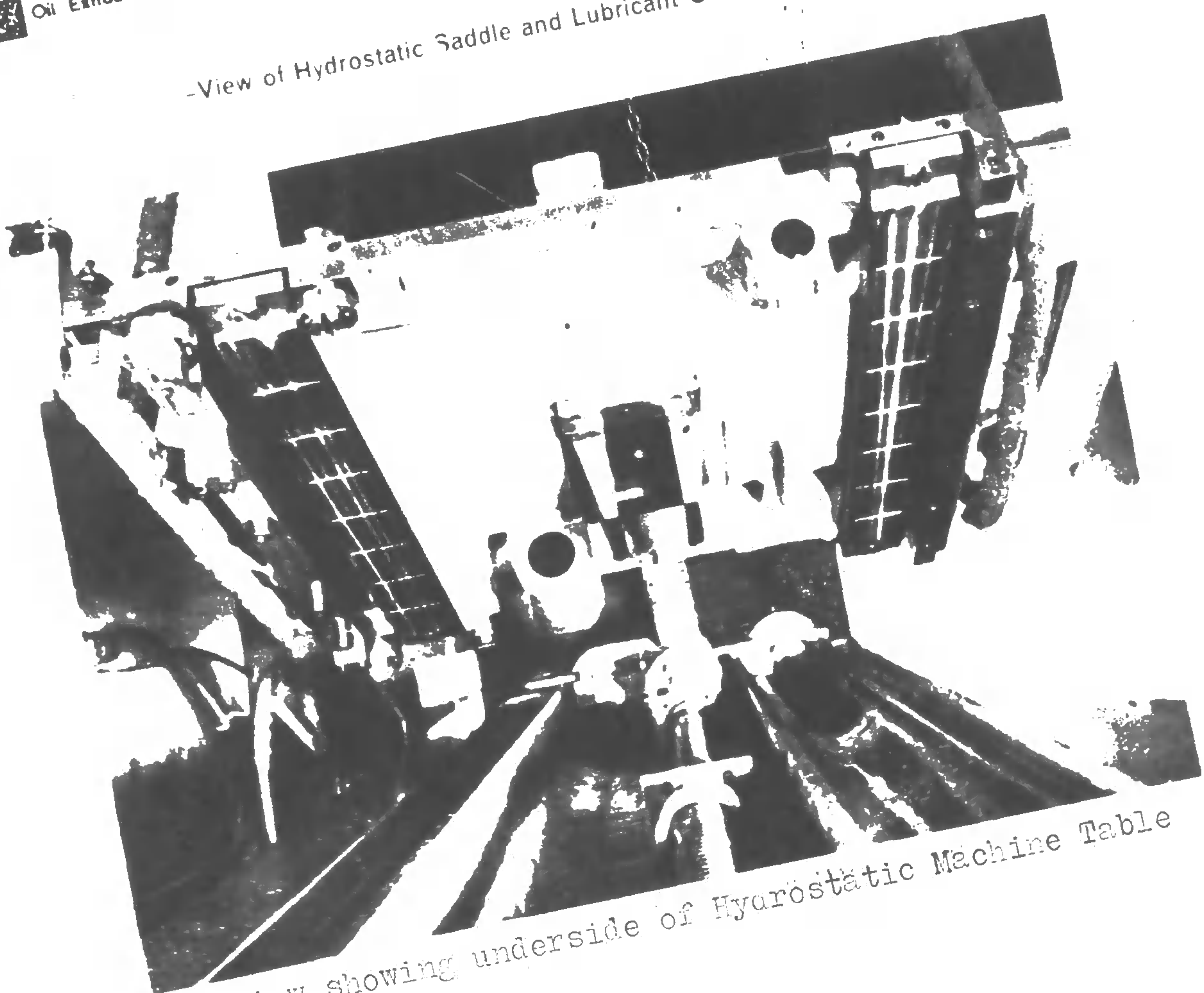
2nd Generation N.C. Machine

Fig. 2

setting of the piece-part. This has permitted much higher utilisation of the machine and considerably shorter lead times and lower work in progress. In many cases these factors have given economic advantages which have offset the much higher capital cost of the machine. An important advantage as the basis for justifying the purchase of NC machine tools must be, in broad terms, an economic one.

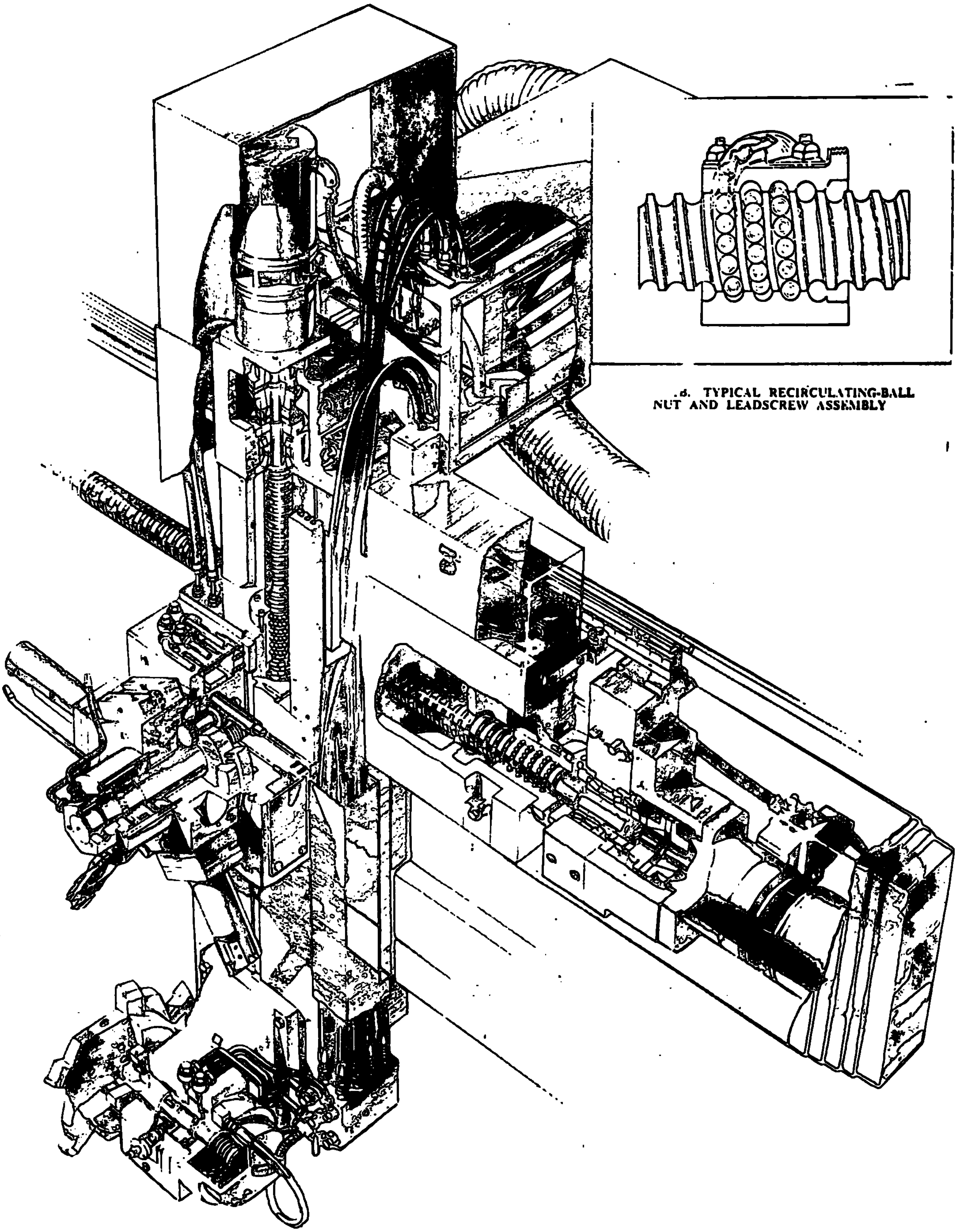


-View of Hydrostatic Saddle and Lubricant Collection System.



View showing underside of Hydrostatic Machine Table

Fig.3



Indexing and Clamping System

Fig 4

CHAPTER 2 CLASSIFICATION OF NUMERICALLY CONTROLLED MACHINE TOOLS

This can be considered from three aspects.

1. The degree and type of control systems which are available.
2. The type of machine tools with which they are combined.
3. The procedure involved in continuous path machining and in co-ordinate setting operations.

(1) Control Systems

These can be divided into two main categories,

a) positional control, and b) continuous contour control.

a) Positional Control

The machining and positioning functions are performed separately. The control system provides the position at which one or more machining operations are to be carried out. Thus operations which may be performed are dependent upon the available tooling. The cutter path during the positioning (non-machining) part of the cycle is immaterial, although the shortest distance would be desirable to minimise time for positioning.

Positional control can include the facility for machining whilst traversing on one of the controlled axes. This facility, usually employed in the form of straight-line milling, necessitates positioning the component so that the faces to be so machined lie parallel with the slideway axis of the machine. This is termed "paraxial" control. As a further refinement, the diagonal or "zig-zag" control facility enables machining to take place under power feed on more than one axis, and hence at an angle to the slideway axis of the machine. However, both paraxial and diagonal machining control are still basically positional, but with the incorporation of suitable power feeds.

b) Continuous Contour Control

During the machining operation the cutter is controlled in more than one axis simultaneously, thus providing relative movement in any desired direction. With three-axis control any workpiece shape may be readily and accurately produced (observing certain restrictions due to finite cutter diameter, work-holding devices, etc.).

Three-dimensional shapes may also be produced with a somewhat less costly system, having two axes with continuous contour control and one with positional control. Thus with the cutter set at discrete heights on the third axis, the form is generated by continuous control of the other two.

The continuous contour control systems possess a complexity, and cost, considerably higher than positional control. One of the first considerations therefore, must be to investigate the range and extent of the work to be performed in order to decide which type of control is needed.

The basic difference between positioning and contouring control systems can be seen, at least in part from the arrangements for feedback of the necessary information. Fig. 5 shows a positioning system in which position feedback is all that is required. For contouring, however, both position and velocity must be under control, and hence feedback of both is required, as shown in Fig. 6.

(2) Machine Tool Systems

Most basic forms of machine tool, such as the drill, mill, borer, lathe, etc. are now available with one or more types of control. It has been shown by Marshall (1) that the drill with positional control is the most commonly used of all, and milling machines with paraxial or continuous contour control, are a close second. These two general types together still account for something like two-thirds of numerically controlled machine tools in use today.

Machine tools with positional or paraxial control may be broadly categorised in order of increasing sophistication and cost as follows:-

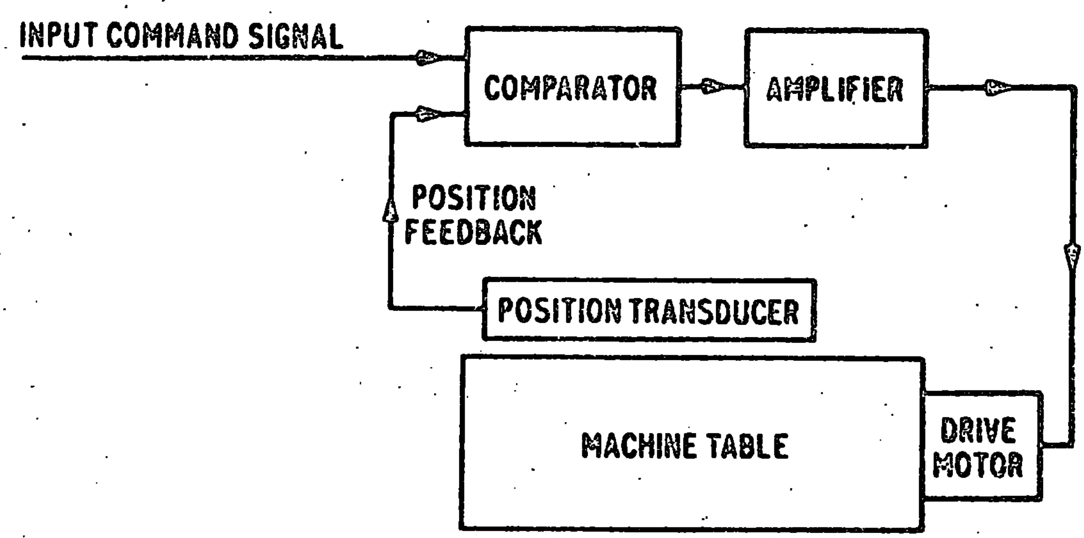


Fig. 5 Positioning System

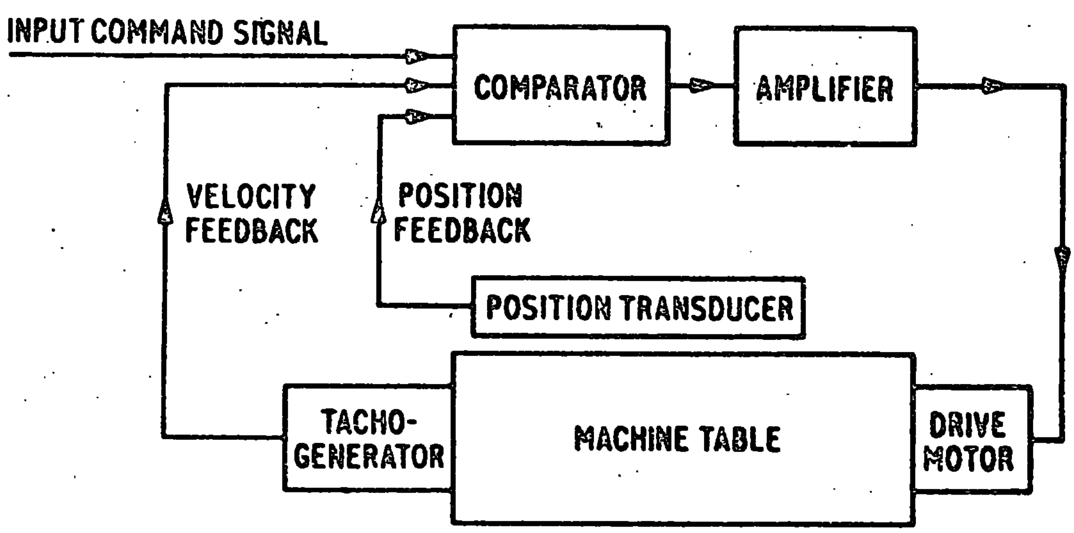


Fig. 6 Contouring System

a) Converted conventional machines fitted with a two-axis positioning table. Feed and speed changing and other machine operations remain the duty of the operator, who would, therefore, be hard pressed to handle an additional machine. The control system merely takes over the responsibility for positioning.

b) Single spindle with two-axis positional control. Usually the basic machine functions also (spindle speed, feed, etc.) may be programmed; simple machining cycles may thus be made automatic. Tool changing, however, must be performed by an operator. Depth of penetration (in the third axis) may usually be set by adjustable trips, but the number of these is limited.

c) Turret drills with two-axis positional control permits a fully automatic cycle, depending upon the maximum number of turret stations provided, possibly up to six or more. The operator's principal concern is now the loading of the machine, and he should be capable of handling more than one.

d) Boring and milling machines. Here accuracy and consistency of working are of great importance, and the potentialities of numercial control offer considerable advantages. Cutting times are inclined to be lengthy, so that positioning speeds, already favourable compared with an operator, proceeding cautiously, are not a critical factor. The third axis may be controlled, or may be semi-automatic; this is a matter of balancing utility against cost.

Various types of control system are available with this class of machine. Many have paraxial, as well as positional control facilities.

Machines with continuous contour control employ the control system for the primary form generation process; the form of the cutter used for such operations, although fulfilling the requirements of practical convenience, is quite secondary. These machines will normally also perform the positioning role, and can be used for drilling, boring, etc., with normal tooling. Whilst it would be obviously uneconomic to employ

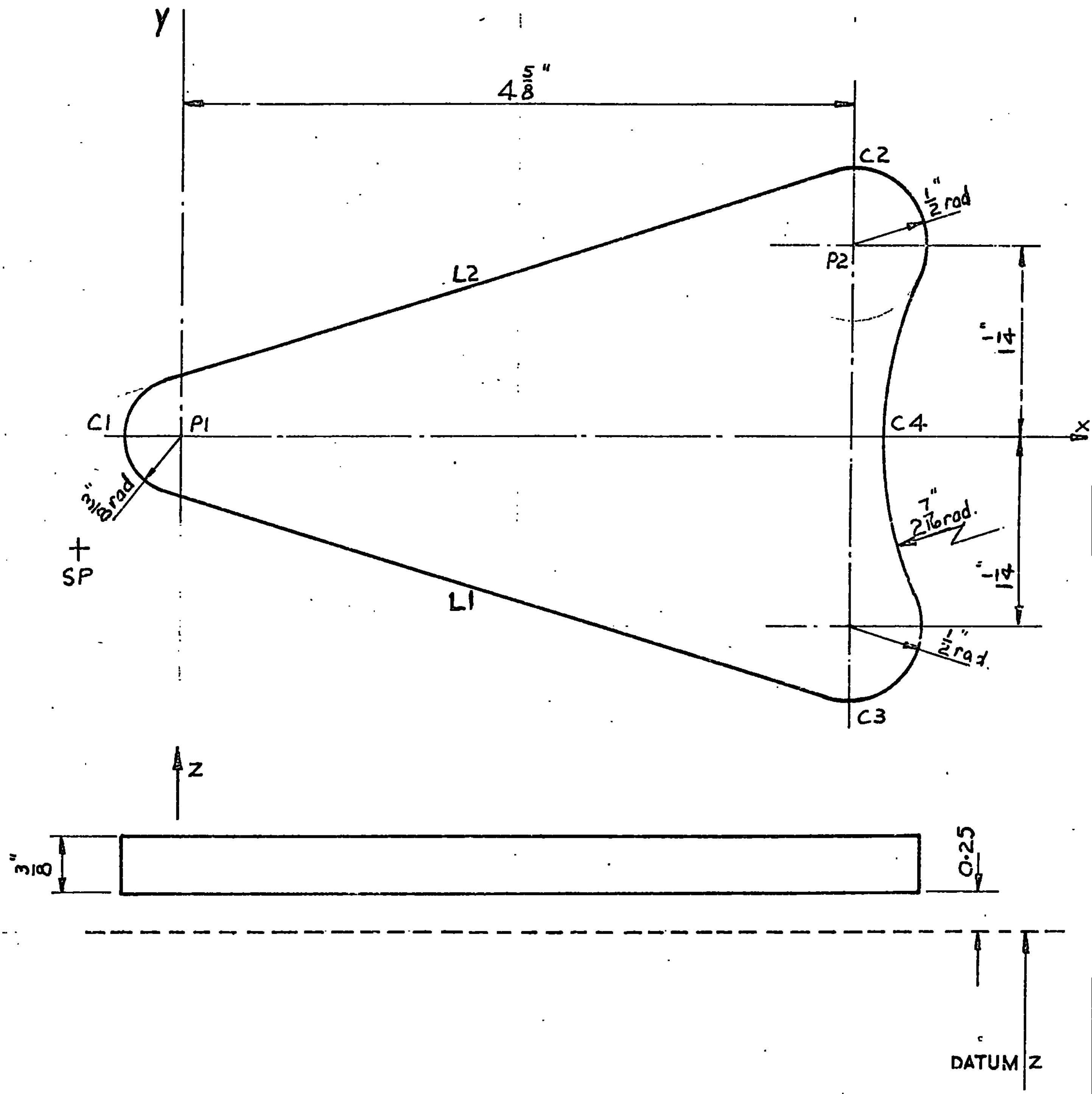


Fig. 7 STOP PLATE

such machines excessively upon work that could equally well be carried out by the positional or paraxial control types, the great versatility of these machines is evident.

3. Procedure Continuous Path Machining

The procedure involved in machining, on a vertical milling machine, the outer contour of a workpiece such as that shown in Fig. 7 is as follows:

The shape of the workpiece is adequately defined in its simplest form on a drawing. This is achieved by using a suitable datum point, Polar and Cartesian co-ordinates and by specifying non-linear shapes in mathematical terms. (Fig. 12).

The cutter path is computed, either manually or automatically, in conjunction with auxiliary information such as cutter diameter, feed rates, etc., and recorded in numerical form on a suitable data storage medium such as punch paper tape or magnetic tape.

The tape is fed into the control equipment, situated alongside the machine tool, which translates the "language" on the tape into a form acceptable to the servomechanisms controlling the movements of the machine slides. The machining proceeds without operator intervention until the operation is completed.

Procedure Co-ordinate Setting Operations

For producing the holes in a workpiece such as that shown in Fig. 8 the procedure involved is given below.

The position of the holes are suitably specified on a drawing, usually in the form of Cartesian co-ordinates from a suitable datum point.

Generally, there are two methods of operation in the control unit, by decade switches, or encoded punched cards; or punched paper tape. The decade switches would be set by the machine operator to correspond with the hole positions.

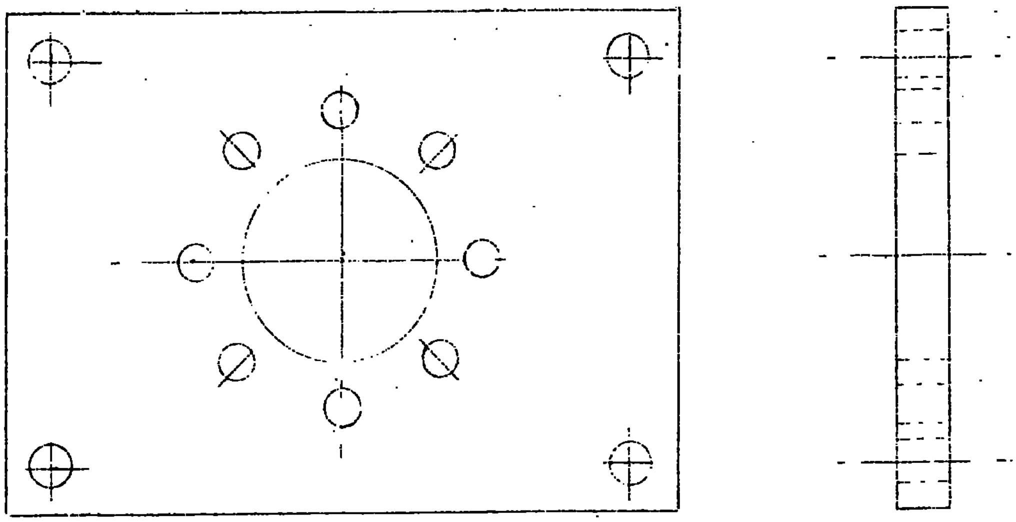


Fig. 8 Component drilled with co-ordinate setting equipment

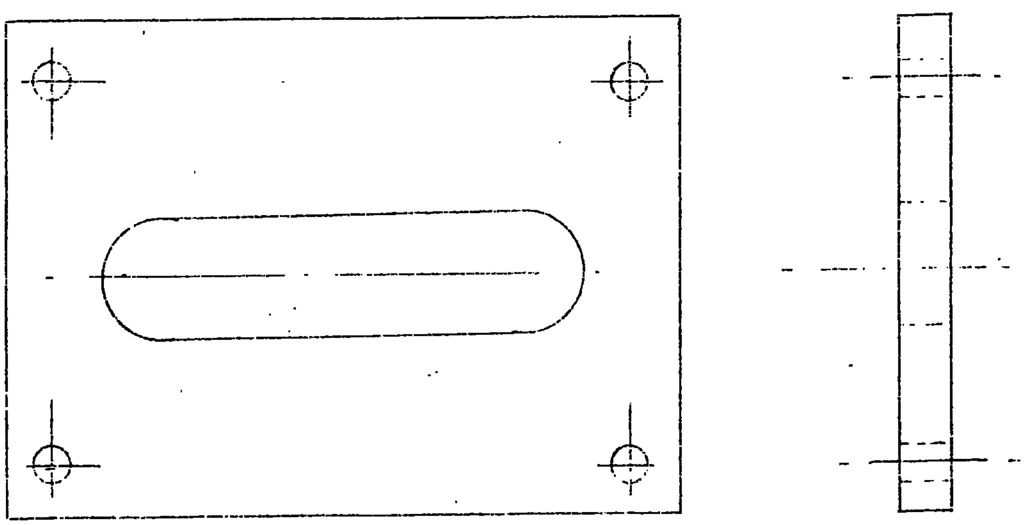


Fig. 9 Component machined with paraxial control equipment

Using punched cards or paper tape the co-ordinates would be encoded onto these. The cards or tape would then be inserted into the control unit.

When decade switches are used the procedure (that of setting the switches) is repeated for each individual machine setting. A facility that is economically very useful for one-off jobs, due to the cost savings in tape preparation and machine setting time. For a machine tool coupled to a positional control system with the facility for paraxial control, the operation procedure is the same as that for co-ordinate setting operations, with the exception that coding will need to include the facility for bringing in the suitable power feeds. The type of component produced is shown in Fig. 9.

Information Transfer and Coding

It has been shown by Brewer (2) that machine command information will comprise both the numerical specification of co-ordinate positions and machines functional commands, such as "start of operation" and "change of tooling". The machine responds to suitably coded information, normally in binary form. Non-numerical information must also be coded, such as alphabetical letters and other symbols for delete and end of block codes. These are required for the machine function command, according to the instructions which a particular machine may require.

For positional (point-to-point) control systems, such instructions would refer to the initiation of machining operations, and specification of speeds and feeds to be used, change of tooling, etc.

In continuous control (contouring) applications the paper tape normally constitutes the implicit instructions, i.e. the shorthand specification of contours by centre locations and radii of curves, intersections with straight lines, etc. The tape thus contains data on co-ordinates and instructions on cutter path sequence, the precise speci -

fication of cutter path subsequently being computed in terms of a large number of individual points.

Irrespective of programming languages, the tape codes have become standardised, broadly into two systems, both of which employ eight hole punched paper tape. The E.I.A. (Electronics Industries Association) and I.S.O. (International Standards Organisation) (See Fig. 10).

An advantage of the I.S.O. code is its compatability with computer codes, particularly when the latter are used for contouring control which require certain symbols not available in the E.I.A. code.

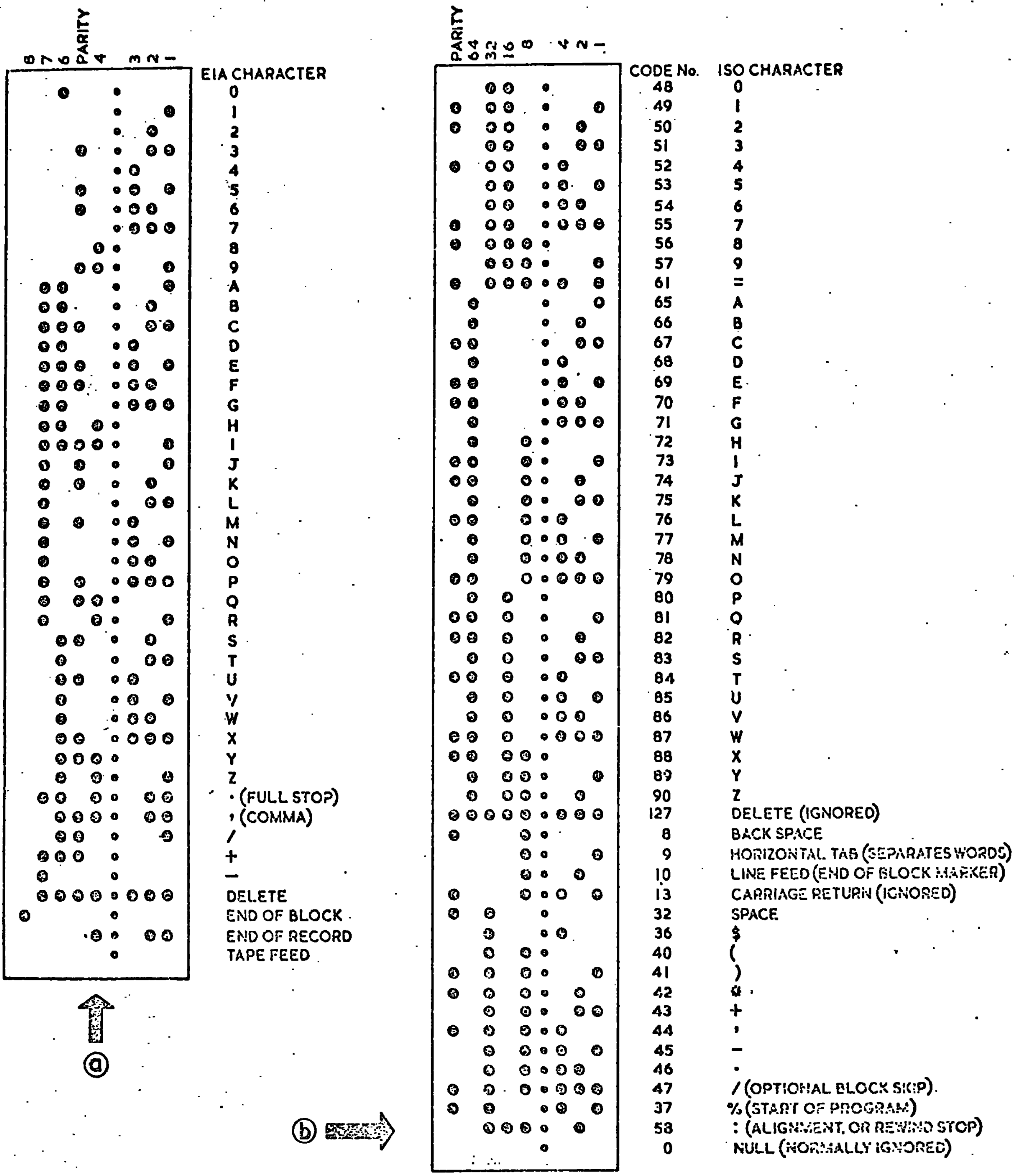
It was this limitation which led to the development in the U.S.A. of the ASC11 code, from which the I.S.O. code was derived. A further advantage of the I.S.O. code will arise when the international teletypewriter network becomes available, which will be based upon the I.S.O. code.

Information can be stored (when coded in the manner mentioned above) in the form of punched cards, magnetic tape, or punched paper tape. Other methods are known, but the present trend towards standardisation has consolidated the former three systems of storage.

CHAPTER 3 Program Preparation

The preparatory work which must be carried out before components can be machined on a Numerical Control machine tool can be divided into a number of separate tasks:

1) Selection of a suitable method of mounting the unmachined component on the worktable of the NC machine, including the design of any required jigs and fixtures.
2) Selection of the tools and cutters required to machine the component to the specified final condition.
3) Selection of suitable cutting speeds and feed rates for these tools, taking into account both the workpiece material and also any



Codes for 8-Hole, 1 inch wide punched paper tape, showing (a) the standard EIA code and (b) the ISO code. In the ISO code, the functions specific to numerical control are given in brackets.

Fig. 10

special features such as thin sections in castings etc. which may make it necessary to reduce the normal values of speed and feed.

4) Writing a description of the movements operations and functions which the machine tool must carry out, in the order it must perform them, to machine the component to the required finished condition. And, where programming is carried out manually, this set of instructions must be written in the special language used by the machine tool control system.

5) Encoding this set of instructions onto the input medium used by the control system.

These tasks, with the exception of item 5, which is usually carried out on a tape typewriter are all inter-related and all require, as a pre-requisite, a detailed study of both the unmachined and finished component drawings, and are all, therefore, usually carried out by the same man and collectively referred to as "programming". However, the first three of these tasks are no different from those normally carried out in the planning office for manufacture on conventional machines were detailed production planning is applied. Thus, task 4 alone is correctly described as programming an NC machine tool.

If we now consider the two main classes of NC machine tools mentioned previously.

1) Continuous Path Machines, which can be used for cutting complex shapes such as aerofoil sections, dies, etc.

2) Point to Point Machines, which are intended to move to a predetermined point and there carry out some specified task such as drilling a hole.

Due to the need to calculate vast numbers of intermediate points round the curved paths to be machined, most continuous path NC machines are programmed with the assistance of a computer using a programming system such as APT, ADAPT or 2C,L. But currently the majority of point machines are programmed by manual methods.

However, with the increased versatility of point to point NC machines - many of which can do boring, tapping and milling parallel to the machine axis, in addition to drilling and also the machining of more complex components, manual programming becomes a laborious and lengthy task.

It will be realised from the statements above that programming can be an expensive process and will be referred to in the section dealing with economics.

Programming Procedure

It is evident that the two major alternative roles, i.e. positioning and contouring, are differentiated most particularly by the requirements for the specification of machining operations. For positional control, only the locations at which operations are to be performed, and the instructions for the auxiliary functions of the machine, are required to carry out even very complex cycles and sequences of machining. The information needed is thus not basically complex, and programming can be performed manually.

By comparison, a contouring operation may require a great number of co-ordinate values to define adequately the relative cutter path. Thus, the amount of information needed by the machine is very considerable and is virtually outside the scope of an unaided manual programmer.

Manual Programming

The illustrations in Fig. 11 show the process involved in manual programming. Details of feed, speed and tools to be used and cuts to be taken are first established by the programmer. A programme sheet is then prepared in accordance with them. Using a tape punch, the information on the programme sheet is typed onto this tape (which is the control medium for the machine) to the previously determined code. This method of

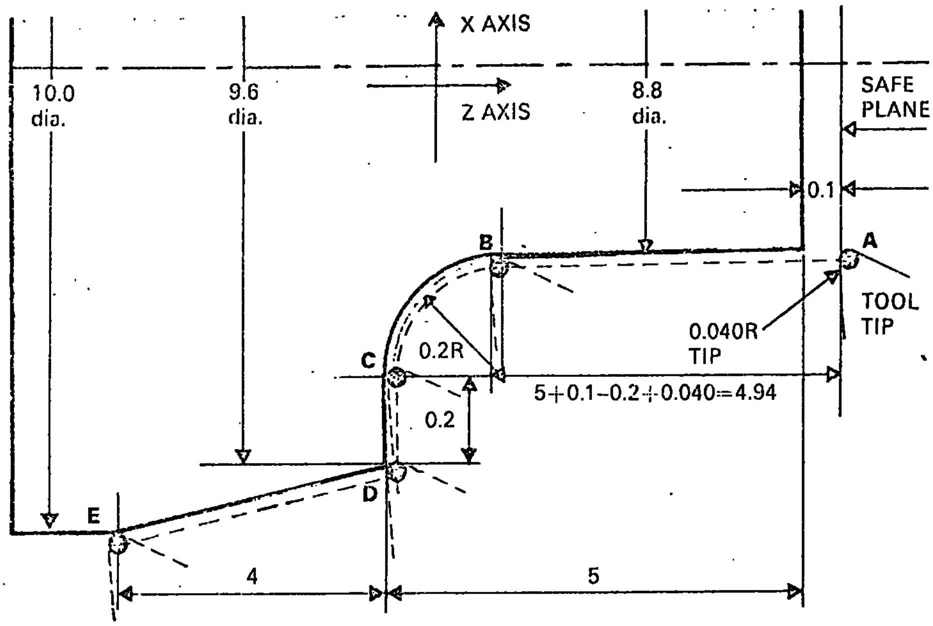


Fig. 11

The portion of the Programme Sheet corresponding to the above cut.

	N	G	X	Z	I	K	F	T	S	M	EOB
Select 679 rev/min	N014	G04	X02						S30	M04	
Turn A to B	N015	G01		Z-49 4			F02				
B to C	N016	G03	X-016	Z-016	1016		F4				
C to D	N017	G01	X-024				F4				
D to E	N018		X-02	Z-404			F025				

N block number
G preparatory function
X movement in X axis
Z movement in Z axis
I auxiliary function of X (e.g. distance of centre of arc to starting point in X direction)
K auxiliary function of
F feed rate

T tool number
S spindle speed number
M miscellaneous functions
EOB end of block

programming is particularly suited to small batch production using point to point machines, and can offer considerable economic advantage over conventional methods, particularly to the smaller user.

Computer Aided Programming

Computer aided programming was originally developed to assist in the problems involved in preparing control tapes for making parts having very complex geometry. The eventual outcome of this being the APT programme, now widely used in the U.S.A. It soon became evident that a computer could be used not only to make geometrical calculations but, given tooling and material data, to calculate speeds, feeds, roughing cuts required, repositioning movements etc. as well. This is known as "technology".

Though the computer can be used to assist in point to point programming, where it can be economically justified (see Programming Economic Considerations), the greatest advantage is in contour control and multi axis machines.

The following example is a typical computer aided part-programme using National 2CL language. For the component shown in Fig. 7 instructions written into the part-programme comprises several different types, e.g.:-

a) Heading statements

b) Geometric statements

c) Motion statements

d) Machine function statements

e) Arithmetic statements

f) Special facility statements, such as "area clearance" for cutting pockets and recesses.

```
Partno    Stop Plate (Drg. No.AJ001X5)
Remark    Heading Statements Follow
          Machin/Nelmil
          Cutter/1
          Spindl/350
          Toler/0.003
          Fedrat/5
Remark    Geometric Statements Follow
  P1      Point/0,0,0.25
  P2      Point/4.625,1.25,0.25
  P3      Point/4.625,-1.25,0.25
  C1      Circle/Center,P1,Radius,0.375
  C2      Circle/Center,P2,Radius,0.5
  C3      Circle/Center,P3,Radius,0.5
  L1      Line/Right,Tanto,C1,Right,
          Tanto, C3
  L2      Line/Left,Tanto,C1,Left,Tanto
          C2
  C4      Circle/XLarge,Out,C2,Out,C3,
          Radius,2.4375
  SP      Point/-1,-1,1
  PL1     Plane/P1,P2,P3
Remark    Motion Statements Follow
          From/SP
          GO/TO,L1,TO,PL1
          GORGT/L1,Tanto,C3
          GOFWD/C3,Tanto,C4
          GOFWD/C4,Tanto,C2
          GOFWD/C2,Tanto,L2
          GOFWD/L2,Tanto,C1
          GOFWD/C1,Tanto,L1
```

```
GOTO/SP

STOP

FINI
```

PROGRAMME WRITTEN IN 2 C.L.

In the part programme the cutter is instructed to move from a convenient start point (SP) clear of the workpiece, and proceed to line L1. Line L1 is defined as being tangential to (TANTO) circles C1 and C3, which, in turn, have been respectively defined as being centred as points P1 and P3, with the appropriate radii. The MOTION STATEMENT then instructs GORGT/L1, TANTO, C3, i.e. go right along L1 to the point of tangency (blend point) with circle C3. In effect L1 has been specified by its common tangency to C1 and C3. This is not yet a complete specification, as four possibilities exist, as shown in Fig. 12. Hence the modifiers RIGHT in the GEOMETRIC STATEMENT L1 = LINE/RIGHT, TANTO, C1, RIGHT, TANTO, C3 eliminate all but the desired common tangent, i.e. tangent I.

The mathematical programming implications can be seen from Fig. 12. These are intended to illustrate the general principles, rather than specifically to represent any particular programming language. All four possible common tangents (I to IV) can be defined by their respective blend points with C1 and C3. The blend point co-ordinates are given below, in which suffices 0 and b refer to the co-ordinates of the circle centres and blend points respectively, and suffices 1 and 3 to the circles C1 and C3 respectively. Hence,

$$\text{Tangent I} \quad \left\{ \begin{aligned} X_{b1} &= X_{01} + r_1 \cos(\alpha + \beta) \\ Y_{b1} &= Y_{01} - r_1 \sin(\alpha + \beta) \\ X_{b3} &= X_{03} + r_3 \cos(\alpha + \beta) \\ Y_{b3} &= Y_{03} - r_3 \sin(\alpha + \beta) \end{aligned} \right.$$

$$\text{Tangent II} \quad \left\{ \begin{aligned} X_{b1} &= X_{01} + r_1 \cos(\beta - \alpha) \\ Y_{b1} &= Y_{01} + r_1 \sin(\beta - \alpha) \\ X_{b3} &= X_{03} + r_3 \cos(\beta - \alpha) \\ Y_{b3} &= Y_{03} + r_3 \sin(\beta - \alpha) \end{aligned} \right.$$

$$\text{Tangent III} \quad \left\{ \begin{aligned} X_{b1} &= X_{01} + r_1 \cos(\alpha + \gamma) \\ Y_{b1} &= Y_{01} - r_1 \sin(\alpha + \gamma) \\ X_{b3} &= X_{03} + r_3 \cos(\alpha + \gamma) \\ Y_{b3} &= Y_{03} + r_3 \sin(\alpha + \gamma) \end{aligned} \right.$$

$$\text{Tangent IV} \quad \begin{cases} X_{b1} = X_{01} + r_1 \cos (\gamma - \alpha) \\ Y_{b1} = Y_{01} + r_1 \sin (\gamma - \alpha) \\ X_{b3} = X_{03} + r_3 \cos (\gamma - \alpha) \\ Y_{b3} = Y_{03} - r_3 \sin (\gamma - \alpha) \end{cases}$$

$$\text{where } \alpha = \tan^{-1} \frac{Y_{03} - Y_{01}}{X_{03} - X_{01}}$$

$$\beta = \frac{\pi}{2} + \sin^{-1} \frac{r_3 - r_1}{(Y_{01} - Y_{03})^2 + (X_{03} - X_{01})^2}$$

$$\gamma = \cos^{-1} \frac{r_3 + r_1}{(Y_{01} - Y_{03})^2 + (X_{03} - X_{01})^2}$$

It will be noted that the co-ordinates of the blend points are all given by expressions of the general form:

$$X_b = X_0 + r \cos \theta$$

$$Y_b = Y_0 + r \sin \theta$$

The blend points appropriate to any of the common tangents could be specified by the appropriate signs, and by values of θ, such as those given in Table I, for the common tangents I to IV shown in Fig. 12. Thus, each "sign-and-angle" convention would be allotted an appropriate modifier code in the part-programming language, so that the form of common tangent required by the programmer would be unambiguously specified as the cutter path.

The blend points of line L1 with circles C1 and C3 now establish its position; it is now possible to evaluate any required number of co-ordinate points along its length from the equation:-

$$Y = \left(\frac{Y_{b3} - Y_{b1}}{X_{b3} - X_{b1}}\right) X + \frac{Y_{b1}\, Y_{b3} - Y_{b3}\, Y_{b1}}{X_{b3} - X_{b1}}$$

However, the blending of circles C3 & C2 with circle C4 involves eight possibilities, as shown in Fig. 13. Thus, in the line:-

C4 = CIRCLE/X LARGE, OUT, C2, OUT, C3,
RADIUS 2.4375

the modifier X LARGE eliminates possibilities (1) to (4), and OUT, C2, OUT, C3 eliminates possibilities (5) to (7), leaving the desired form (8).

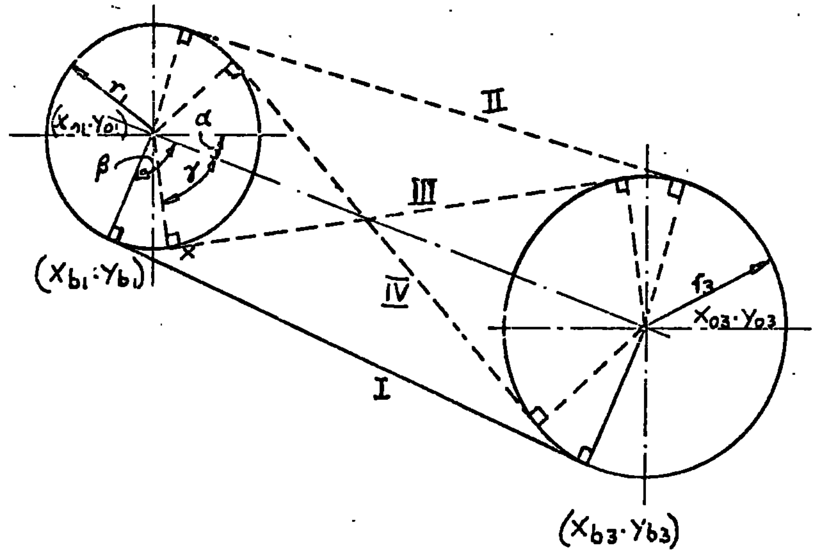


FIG.12 THE FOUR POSSIBLE COMMON TANGENTS TO TWO CIRCLES

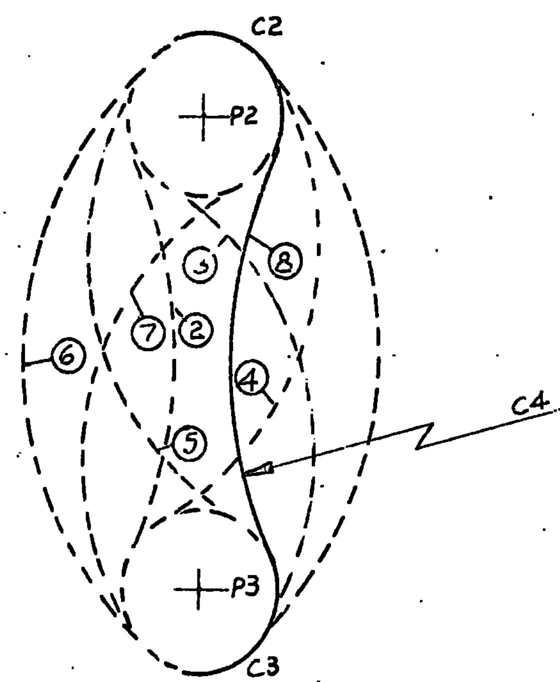


FIG.13 THE EIGHT POSSIBILITIES OF BLENDING THREE CIRCULAR ARCS

As has already been mentioned, once the component profile has been established, the computer must now calculate the cutter path, taking into account the radius of the cutter to be used. When cutting at point P (see Fig. 14) i.e. at co-ordinates (x,y), the centre of the cutter axis will be at Q, with co-ordinates ($x \pm \delta x$, $y \pm \delta y$), where $\delta x = R\sin\phi$, $\delta y = R\cos\phi$, R = cutter radius and $\tan\phi = dy/dx$ at P. Hence, when cutting a straight line such as L1 in Fig. 7, the cutter path is also a straight line (Fig. 14) and can be computed from an expression of the general form

$$y = mx + c \pm R\sqrt{1 + \tan^2\phi}$$

When cutting a circular arc, the cutter axis also moved around a circle of radius r + R, and so that the general equation for its path is

$$(x - xo)^2 + (y - yo)^2 = (r \pm R)^2$$

In each case the alternative signs ± are resolved by a modifier which conveys the sense of the cutter path, e.g. whether it is an external or internal shape which is being machined.

Performed manually, these calculations, if not particularly difficult, are lengthy and tedious, and are subject to the inevitable occasional errors which, however low the level of incidence with a careful programmer, are bound to arise. Not least among the benefits of using a computer is the lead time saved in obtaining the machine control tape. It is therefore generally considered to be virtually essential to use a computer for the programming of contouring operations

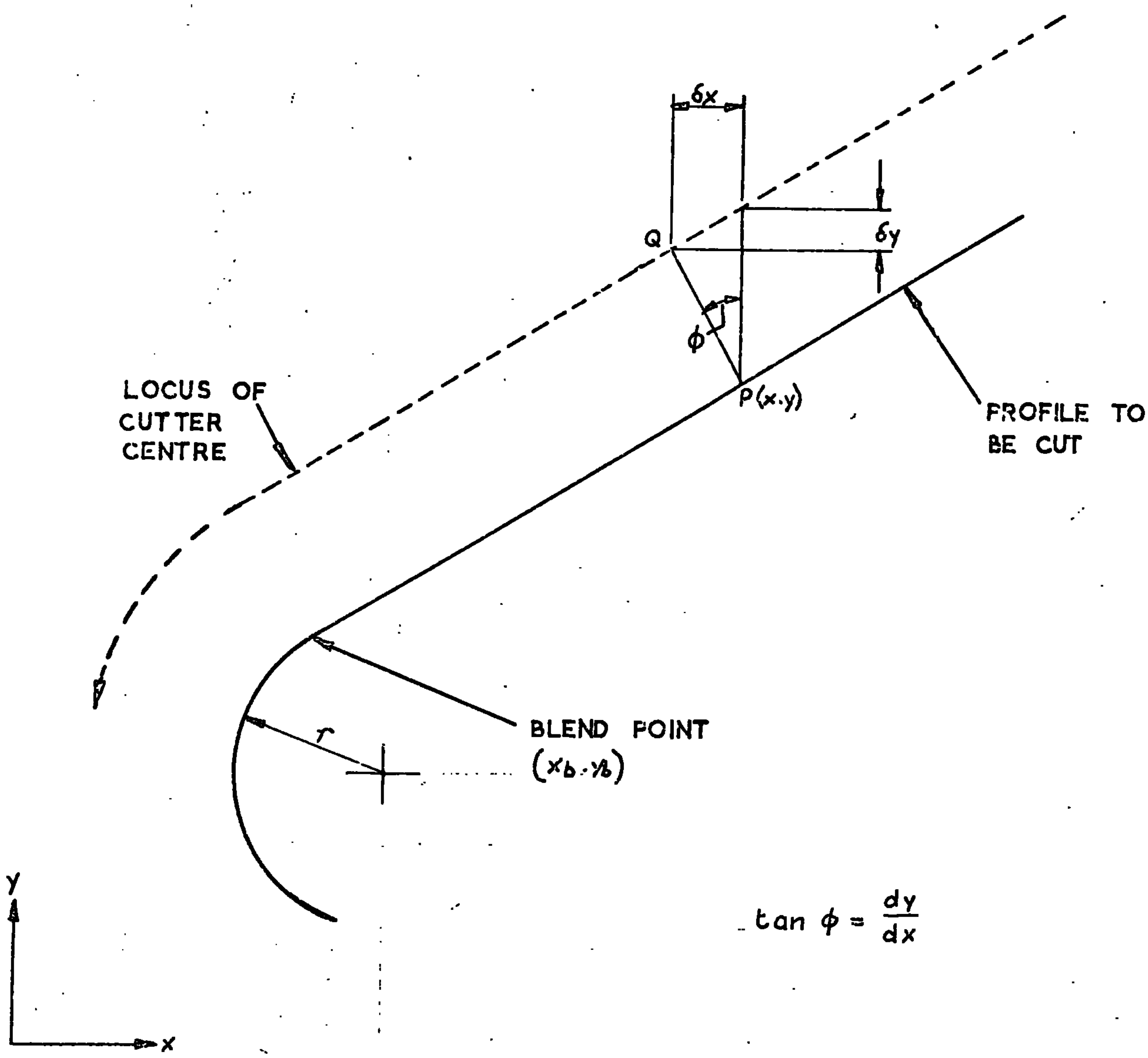


Fig. 14 Derivation of Locus of Cutter Centre

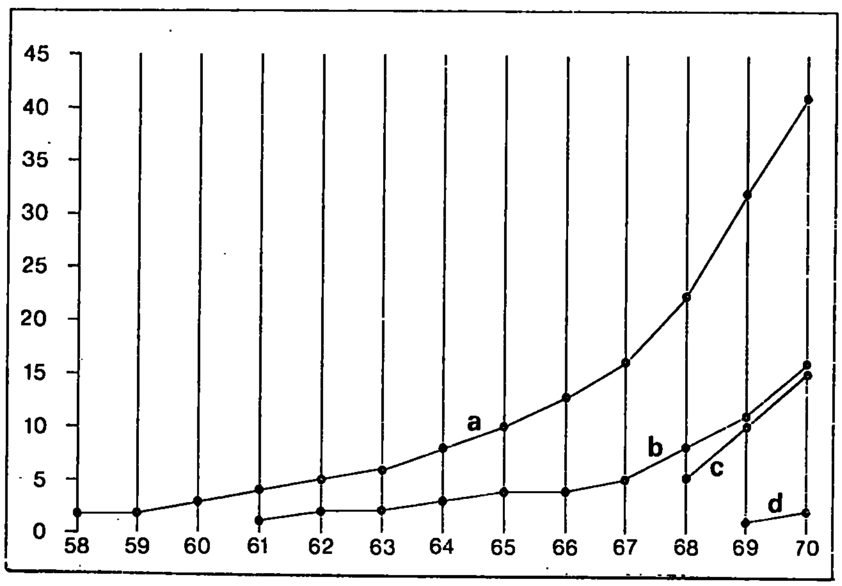
TABLE I SIGNS AND ANGLE CONVENTIONS

	Tangent Type / Circle No.	I	II	III	IV
Angle θ	C1 and C3	$\alpha + \beta$	$\beta + \alpha$	$\alpha + \gamma$	$\gamma - \alpha$
x co-ordinates	C1	+	+	+	+
	C3	+	+	+	+
y co-ordinates	C1	−	+	−	+
	C3	−	+	+	−

CHAPTER 4 Numerical Control Economics

The number of NC machine tools in use in U.K. industry is now approaching 2,500 and although this number is still only about 0.2% of the total, (about $1\frac{1}{4}$ million) NC is now an accepted part of the manufacturing scene. The major problems of marrying mechanical and electronic systems together to form a satisfactory working unit have now been generally overcome - although standards of reliability still show considerable scope for improvement - and the potential NC machine user can make his choice from a total of some 500 machine/system combinations. The following graph shows the number of NC machines being used by a typical advanced engineering company.

Installation of numerically controlled machine tools 1958/70



A point to point B continuous path C turning D machining centres

It would seem that the technological step forward which numerical control represents is now fully appreciated, and the main stumbling block to the more widespread use of NC over the past few years has concerned the selection and economic justification of the 'right' machine to meet the needs of individual users. The basic cost of NC hardware, i.e. the machine tools, is undoubtedly high by comparison with conventional machines, and this fact coupled with the general lack of techniques which enable a would-be-user to evaluate the advantages of NC in terms of pounds, shillings and pence has proved a fairly severe deterrent to many companies.

Numerically controlled machines cost approximately $1\frac{1}{4}$ to 4 times as such as their conventional counterparts, and therefore to justify their use a manufacturer must first satisfy himself that some overall saving, either direct or indirect, is going to result.

When considering the purchase of a numerically controlled machine as opposed to a conventional machine, the following factors need to be considered.

Direct Charges

Capital cost of machine including installation charges,

Power Consumption,

Maintenance Charges (Labour and Spares),

Tooling Costs,

Programming and Tape Preparation, Planning,

Factory Overheads (Supervision, Labouring, Inspection,

Building depreciation, Lighting, Heating, Rent, Rates and Insurance),

Machining Costs.

Indirect Costs and Factors

Jigs, Fixtures and Special Tooling:-

These can often be eliminated completely by the use of NC machines with the resultant liberation of design, storage, handling and maintenance facilities.

Against this we have the cost of storing the data input media, i.e. Punched Cards and/or Tapes.

Operations:-

Reductions. Marking out can be dispensed with completely and, as confidence grows, inspection will decrease substantially.

Increases Time is taken proving tapes, by common practice, on the machine.

Consistency of performance

Once input data has been verified as "correct", scrap, resulting from those operations removed from operator control, will be eliminated.

Assembly considerations

In order to avoid incurring the cost of complicated jigs, assemblies are often planned on the basis of "Holes transferred on assembly". Other advantages to be considered under this heading are:-

1. Machining time which is much easier to control than fitting time.
2. Interchangeability between parts because of machining accuracy.
3. Modifications quickly introduced by simple editing of the master tape.
4. Due to more operations being carried out on NC machines, material handling is sharply cut, thus making valuable floor space available

Positioning times

By NC these are dramatically decreased and will be reflected as a substantial part of the saving of machining time. Assuming that rapid traverse rates are equal and considering final positioning only, it is not uncommon for allowances of 1-2 minutes to be made per hole for this operation on Non-NC machines, whereas the NC machine will steer itself into position in something in the order of $1\frac{1}{2}$ seconds.

In addition, rapid traverse is often faster on NC machines in that the control is tailored to the transmission inertias such that acceleration and deceleration, relative to the final position, are automatically programmed with regard to the rapid traverse rate, to avoid damage. On Non-NC machines one often finds that low "rapid traverse" rates are used to avoid troubles.

Work in Progress

The elimination, combination and shortening of operations reduces Lead time and consequently reduces the volume of work in progress. This related to Bank Charges alone will show tangible savings, there are savings in Labouring, (transportation of parts between operations), Progressing, Inspection and Storage.

Reduction in operator involvement

NC releases the operator from direct involvement with the operation for longer periods and his time can be directed to tasks such as:-

Controlling a number of machines,

Setting up a second component during machining of the first

Tool organisation/maintenance

Inspection duties.

The above factors can be used to compile a balance sheet for relative costs of manufacture by NC as opposed to Non-NC, but the following factors, at least equally significant in benefits, are difficult to allocate convincing costs to.

Intangibles

Operator Fatigue

There is no doubt that NC takes a lot from the shoulders of the operator particularly with accurate and intricate work and this can show itself as reduction of scrap from those functions which he still controls.

Cutting Tools

Retrospective analysis of Cutting Tool costs will show that a reduction has occurred due to the disciplined use of Tools under NC.

Production Flow

Constant speeds, feeds and a smooth production flow are ensured with NC. These should improve as more optimisation of speeds is introduced into computer programming.

Modifications

A modification to a tape or the replacement of some punched cards simplifies this need as compared to the physical alteration of a jig.

Flexibility

NC methods and facilities allow production to be switched, between machines or even factories with only the inconvenience of transferring tapes, cards and planning layouts and with the assurance of consistency or productivity and accuracy. The alternative to the transfer of tapes would be the costly and complex removal of machines.

There are no hard and fast rules to determine when numerical control should be used, but consideration of the factors discussed and the justification examples to follow, should give useful guidance to potential users.

These factors may be classified into four sections as follows:-

1. A cost analysis of the factors discussed.

2. Typical component cost comparison.

3. Systematic method to calculate the justification of Numerical Control.

4. Programme cost considerations.

CHAPTER 5 Cost Analysis Example I

Cost analysis of a numerically controlled Turret Lathe having a dimensional continuous path control operating from punched paper tape. The machine having - 24 in diameter swing; 30 H.P. motor; hydraulic chuck; two four positions automatically indexing turrets; pre-set tooling; 24 speeds from 36 R.P.M. to 2400 R.P.M. in either direction; and a rapid feed rate of 200 inches per minute.

Instead of the purchase of:-

A No. 7 combination Turret lathe.

The study is carried out on a basis of preparation (set up) and operation time for average batch size of 25 components. (Data supplied by Newall Engineering Co. Peterborough).

Preparation: Set-up time

This includes selection and setting of tools and equipment and a contingency for starting and finishing a batch. The study shows that for the purchase of one NC machine

$$\frac{\text{Preparation Time for NC machine}}{\text{Preparation Time for manual machine}} = \frac{8}{10}$$

This ratio could drop to 4/10 if several NC machines were purchased to justify a man being employed to preset tools and prepare following batches.

N.B. The average manual preparation time per batch was found to be three times the average operation time.
(These factors were obtained by averaging the details of a number of studies).

Operation Time

Floor to floor time (including contingencies) shows the NC machine 2.4 times as fast as the manual machine.

Lost Time NC machine

Electronic breakdown = $1\frac{1}{2}\%$ of total operating time

Mechanical " = $2\frac{1}{2}\%$ " " " "

Tape proving time	= 4% of total operating time.
Shortage of operators	= 2% " " " "
	10% of total operating time

Lost Time - Manual Machine

Shortage of operators = 2% of total operating time.

Labour

One man per machine.

Operator rate - NC.	= 10/2 per hour
Operator rate - Manual	= 11/3 per hour

Alternative methods of working

40 hours + 4½ hours overtime at 1.1/3

or

40 hours nights at 1.1/3 + 4 hours overtime at 1½ plus 40 hours + 4½ hours overtime at 1.1/3

or

Three equal shifts of 38 hours but each paid for 45 hours.

N.B. 1 year = 48 working weeks.

Fixed Charges	NC Machine	No. 7 Comb. Lathe
Capital cost of machine	£20,600	£4,500
Installation charge	140	20
Programming and tape preparation costs	1,000 p.a.	-
Power consumption	130 p.a.	44 p.a.
Indirect Labour charge (Supervision, Inspection, Labouring, etc.)	700 p.a.	640 p.a.
Maintenance engineers salaries etc.	220 p.a.)	80 p.a.
Including Spares	150 p.a.)	
Tooling	250 p.a.	250 p.a.
General overheads based on floor area:-		
Building depreciation & maintenance	130 p.a.	90 p.a.
Light and heat	25 p.a.	18 p.a.
Rent, rates and Insurance.	180 p.a.	126 p.a.

Calculation of Fixed Charges

NC Machine £		Manual Machine £
20,600	Capital cost of machine	4,500
140	Installation Charges	20
20,740		4,520
2,074	Written down over 10 years	452
1,000	Tape preparation	-
130	Power	44
700	Indirect Labour	640
220	Maintenance)	80
150	Spares)	-
250	Tooling	250
130	General overheads - Building	90
25	Light and heat	18
180	Rent, Rates and Insurance	126
4,859		1,700
4,859	Wages - total per annum:-	1,700
	Total weekly hours x weeks/year x hourly rate.	
	40	
	$4\frac{1}{2}$ x 1.33 105.33 x 48 x 10/2 NC, 11/3 Manual	
	40 x 1.33	
	4 x 1.5 = 2576 NC	
2,576	TOTAL = 105.33 hrs. 2848 Manual	2,848
7,435	Total expenses per annum.	4,548

∴ Cost ratio = $\dfrac{\text{Total expenses/annum NC}}{\text{" " Manual}} = \dfrac{£7,435}{£4,548}$

Cost Ratio = 1.64

Two Shift Working   Productivity Ratio

	NC	Manual
Possible Weekly Hours	$88\frac{1}{2}$	$88\frac{1}{2}$
Lost time	10% = 8.85	2% = 1.77
Actual hours available	79.7	86.7
Average Batch size	25	25
No. of components lost due to preparation 3 x 0·8 =	2.4	3
Effective Batch size for productivity purposes	27.4	28

Production time lost to Preparation per week:-

$$\frac{\text{actual hours available x no. of components lost due to preparation}}{\text{Effective batch size}}$$

$= \frac{79.7}{27.4} \times 2.4 \quad = \quad 7 \qquad \frac{86.7}{28} \times 3 = 9.6$

Actual hours spent machining

$79.7 - 7 \quad = \quad 72.7 \qquad 86.7 - 9.6 = 77.1$

Machining hours available

$72.7 \times 2.4 \quad = \quad 174.4 \qquad 77.1$

Productivity Ratio $\doteq \frac{\text{NC(Effect.) Hours available}}{\text{Manual hours available}} = \frac{174.4}{77.1}$

Comparison of effective machining hours assuming that the capital invested in NC had been spent on Manual machinery:-

NC - Effective machining hours available = 174.4

Manual - Effective machining hours x Cost Ratio

$77.1 \times 1.64 \quad = \quad 126.3$

Therefore, extra hours available due to investment in NC per week = 48.1

Related to Operator Wages at 10/2 per hour annual saving 48.1 x 10/2 x 48 = £1172

Related to annual expense savings

$\frac{48.1}{77.1} \times$ £4,548 = £2830

Single Shift Working

Repeating the above calculations for single shift

Hours.

NC Effective machining hours available	= 87.6
Manual - Effective machining hours x Cost Ratio	
39 x 2.04	= 78.1
Extra hours available due to investment in NC per week.	= 9.5
Annual Savings 9.5 x 10/2 x 48	= £232
plus $\frac{9.5}{77.1}$ x £4,548	= £559

The following list compares conventional machining time, with those taken on a 3 axis continuously Controlled Milling Machine data supplied by Messrs. Rolls Royce, Derby.

	Quantity/ Annum	Average Machining Time Contimatic	Conventional
Glass plates for Inspection	460	$1\frac{1}{4}$ hours	5 hours
Profile and former plates	143	9 hours	30 hours
Electrodes	244	5 hours	20 hours
Blade Forms (for Foundry dies)	23)	15 hours	70 hours
(for Production dies)	22)		
(for Experimental dies)	17)		
Cam Plates	97	3 hours	10 hours

From the details shown above:-

Total hours on Conventional machine = 16,780

Saving (Hours) = 12,477

Example II By employing NC Messrs. Rolls Royce have cut the lead time for Turbine Blade Production from 12 weeks to 72 hours and reaped a "significant intangible". A retrospective modification was required to the compressor of an engine already in production. Engines were being produced at the rate of 2 per week and, as production could not be halted, the modification had to be applied to all engines already produced - at a cost of £5,000 per engine to Rolls Royce.

The shortened Lead Time for the introduction of the modification saved 23 x £5,000 = £115,000.

The original purchase price for the machine was £43,000.

Details of old and new procedures employed:-

Blade Forms

Conventional Method

Blade design

Die block design

Conventional machining (4 stages) of Master Die Block

Proof Inspection of master die block

Production of Blades

With the installation of the Contimatic and the computerisation of blade design, the technique at present is:-

Blade Forms

Contimatic Method

Blade design and automatic generation of magnetic tapes, for master die block and inspection profile plate

NC machining of master die block

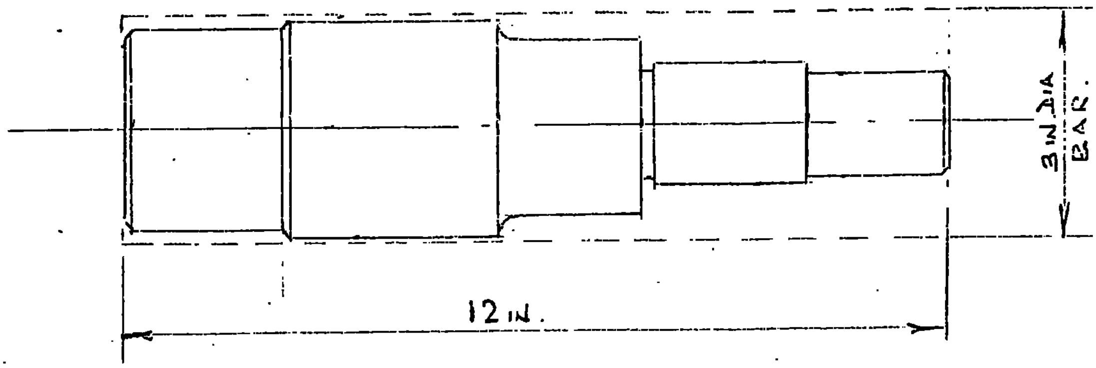
Simplified inspection of die block

Production die manufacture

Production of Blades.

Cost comparison of component produced on a centre lathe and on the N.C. P5 lathe.

Cost values and production times for figs. supplied by Churchill Redman Ltd. (4)



EXPERIMENTAL COMPONENT

	SETTING		CUTTING		PLANNING	
	C.L.	N.C.	C.L.	N.C.	C.L.	N.C.
TIME COST	25 mins. 12/6	10 mins. 10/-	80 mins. 40/-	4½ mins. 4/6	30 mins. 15/-	90 mins. 45/-

Costs Planning 30/- per hour
Centre Lathe 30/- per hour
N.C. P5 Lathe 60/- per hour

	BATCH SIZE		
Average Production Time Per Component	1	6	10
Centre Lathe N.C. Lathe	105 mins. 14½ mins.	84 1/6 mins. 6 1/6 mins.	82½ mins. 5½ mins.
Saving per component	90½ mins.	78 mins.	77 mins.
% Saving	86.2 %	92.8 %	93.3 %

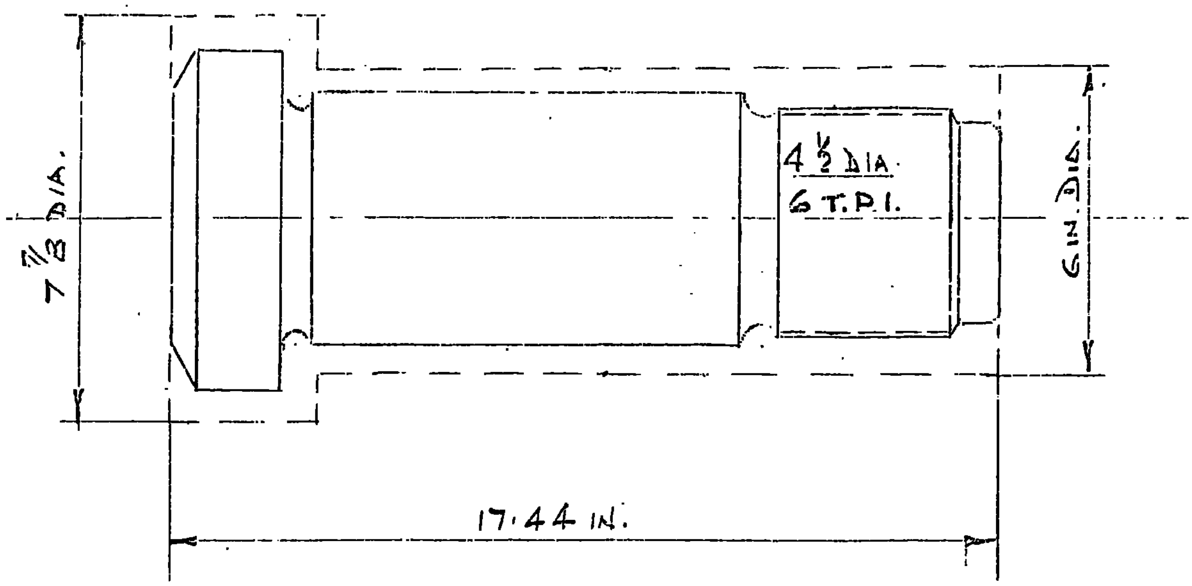
COST PER COMPONENT

	1st Batch			Repeat Batch		
Batch Size	1	6	10	1	6	10
Centre Lathe N.C. Lathe	67/6 59/6	44/7 13/8	42/9 10/-	52/6 14/6	42/1 6/4	41/3 5/6
Saving per Comp.	8/-	30/11	32/9	38/-	35/9	35/9
% Saving	11.8%	69.6%	76.7%	72.3%	85.2%	86.7%

NOTE. The centre lathe cutting time shown for this component is an estimated one assuming cutting in 2 operations.

The N.C. cutting is for end driving the component, eliminating one set up.

Cost comparison of component produced on a centre lathe and on the N.C. P5 Lathe.



COUPLING BOLT

	SETTING		CUTTING		PLANNING	
	C.L.	N.C.	C.L.	N.C.	C.L.	N.C.
TIME COST	40 mins. 20/-	15 mins. 15/-	52 mins. 26/-	15 mins. 15/-	60 mins. 30/-	180 mins. 90/-

Costs Planning 30/- per hour

Centre Lathe 30/- per hour

N.C. P5 Lathe 60/- per hour

Average Production Time Per Component

	BATCH SIZE		
	1	6	10
Centre Lathe N.C. Lathe	92 mins. 30 mins.	58 2/3 mins. 17 1/3 mins.	56 mins. 37 1/2 mins.
Savings per Comp.	62 mins.	41 1/6 mins	39 1/2 mins.
% Saving	67.3%	70%	70.5%

COST PER COMPONENT

	1st Batch			Repeat Batch		
Batch Size	1	6	10	1	6	10
Centre Lathe N.C. Lathe	76/- 120/-	34/4 32/6	31/- 25/-	46/- 30/-	29/4 17/6	28/- 16/6
Saving per Comp.	Loss of 44/-	1/10	5/6	16/-	11/10	11/6
% Saving	- 57.8%	5.4%	17.7%	34.8%	40.4%	41.2%

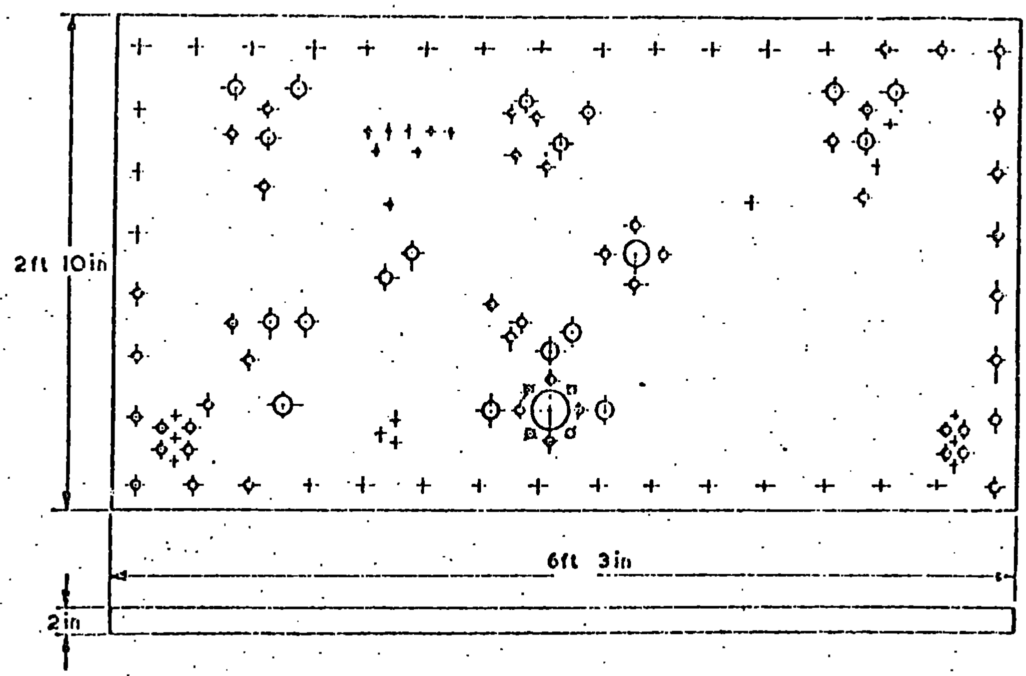
NOTE: This component is in fact normally produced on a copy turning lathe and not a centre lathe. No account has been taken in costing out the first batch of the cost involved in producing the template. The machine hour rate would also be higher when using a copy turning lathe.

In this example a detailed study has been carried out into the complete proposed machine load as follows. Initial data was obtained from the Newall Engineering Co. (5).

Machine Hour Rate

	Conventional M/C.	N/C Machine
Capital Cost	£10,000	£18,000
Floor Area	100 sq. ft.	150 sq. ft.
Labour	£ 1,000	£ 1,000
Depreciation at 20%	£ 2,000	£ 3,600
Insurance at 1%	£ 20	£ 36
Power	£ 20	£ 50
Maintenance	£ 50	£ 150
Factory Overheads allocated to shop: (a) Material (b) Engineering Services (c) General Maintenance (d) Shop Expenses (e) Personal Services (f) Admin. Expenses	£ 1,500	£ 1,500
Total Yearly Expenses	£ 4,590	£ 6,336
Machine utilisation	90%	80%
Utilisation hours/year	1,800	1,600
Machine hour rate	51. 0d.	79. 3d.

Piece-part Cost Analysis.



Workpiece	Material
Steel Door	Mild Steel
Numerically Controlled Method	Portal frame drilling machine
Conventional Method	Radial drilling machine
Operations	Drill, tap & C'bore 3/16 - $1\frac{3}{4}$ in dia. 137 holes
Production Quantity	60 per batch; 12 batches per year

	Numerical Control					Conventional				
	Time		Cost			Time		Cost		
Production Details	hr.	min.	£.	s.	d.	hr.	min.	£.	s.	d.
Programming/Planning	8	0	6.	0.	0.	-		-		
Data Preparation										
Jig & Tool Design & Manf.	20	0	15.	0.	0.	220	0	250.	0.	0.
Pre-Production Time/Cost	28	0	21.	0.	0.	220	0	250.	0.	0.
Marking-off & Setting Up	3	15	12.	18.	0.	2	45	7.	0.	0.
Machining										
Inspection	Similar for both methods									
Handling	-		-			-		-		
Fitting and Assembly	24	0	24.	0.	0.	40	0	40.	0.	0.
Processing Time/Cost	27	15	36.	18.	0.	42	45	47.	0.	0.
Total for 720	19648	0	26568.	0.	0.	31000	0	33840.	0.	0.

Examples of actual savings incurred by using N.C.

Part No. 38211-250 Spindle Drive Pulley FIG 15

Average Batch Size 12

Average Time taken on Conventional Machine - 1 hour 33 min. each.

Average Time taken N.C. - 52 min. each.

Part No. 31861-541 Gear Change Bracket FIG 16

Average Batch Size 6

Average Time taken on Conventional Machine - 3 hours 56 min. each.

Average Time taken N.C. - 1 hour each.

Part No. 38861-314 - holes in front and rear faces. FIG 17

Average Batch Size 6

Average Time taken - Manual Jig Borer - 10 hours 10 mins.

Average Time taken - N.C. Borer - 2 hours 45 mins.

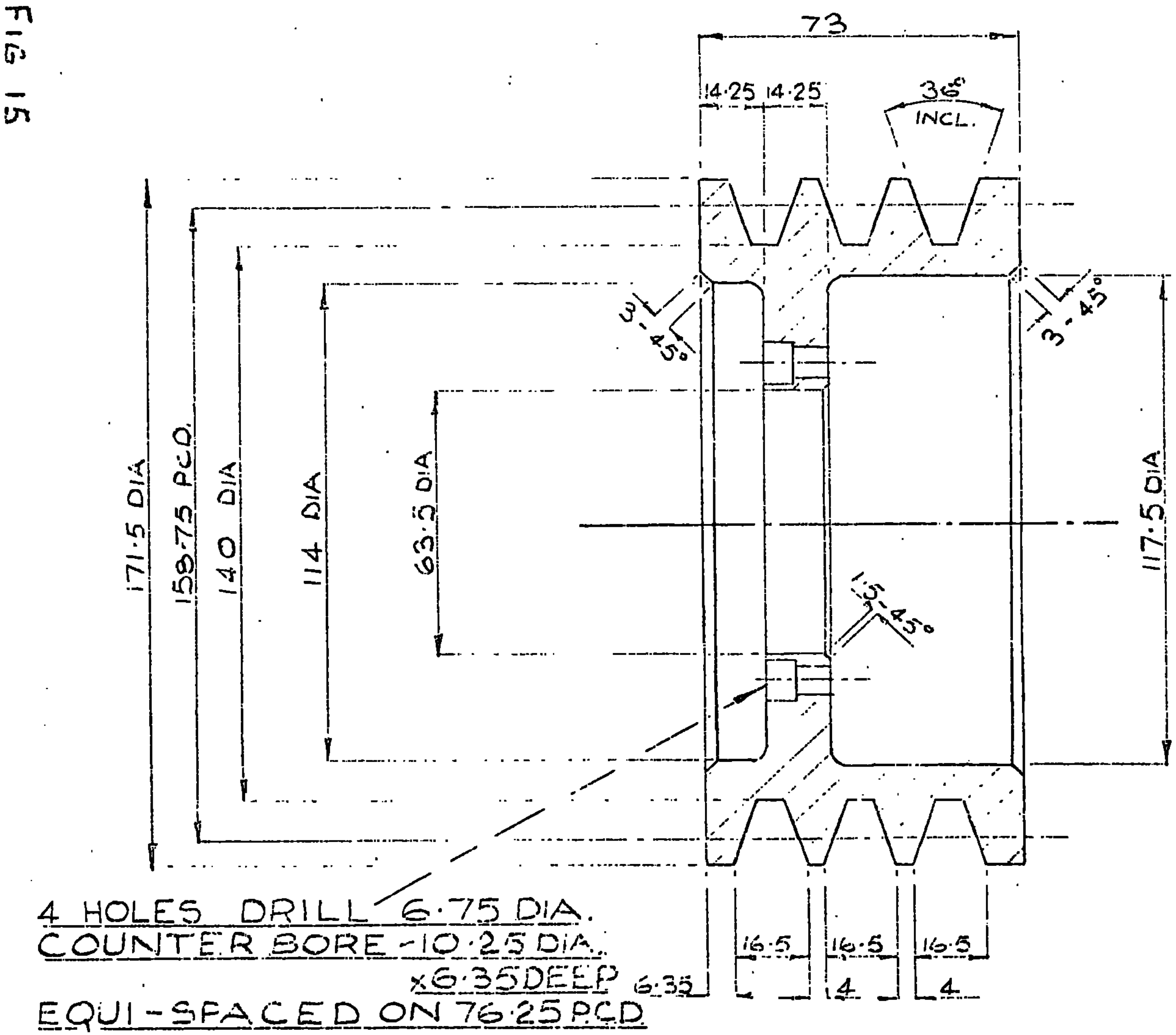


FIG 15

ALL DIMENSIONS SHOWN IN MILLIMETERS

MACHINE ALL OVER

TO BE STATICALLY AND DYNAMICALLY BALANCED

PART Nº 38211-250

SPINDLE DRIVE PULLEY

SCALE :- FULL SIZE

H.Y.

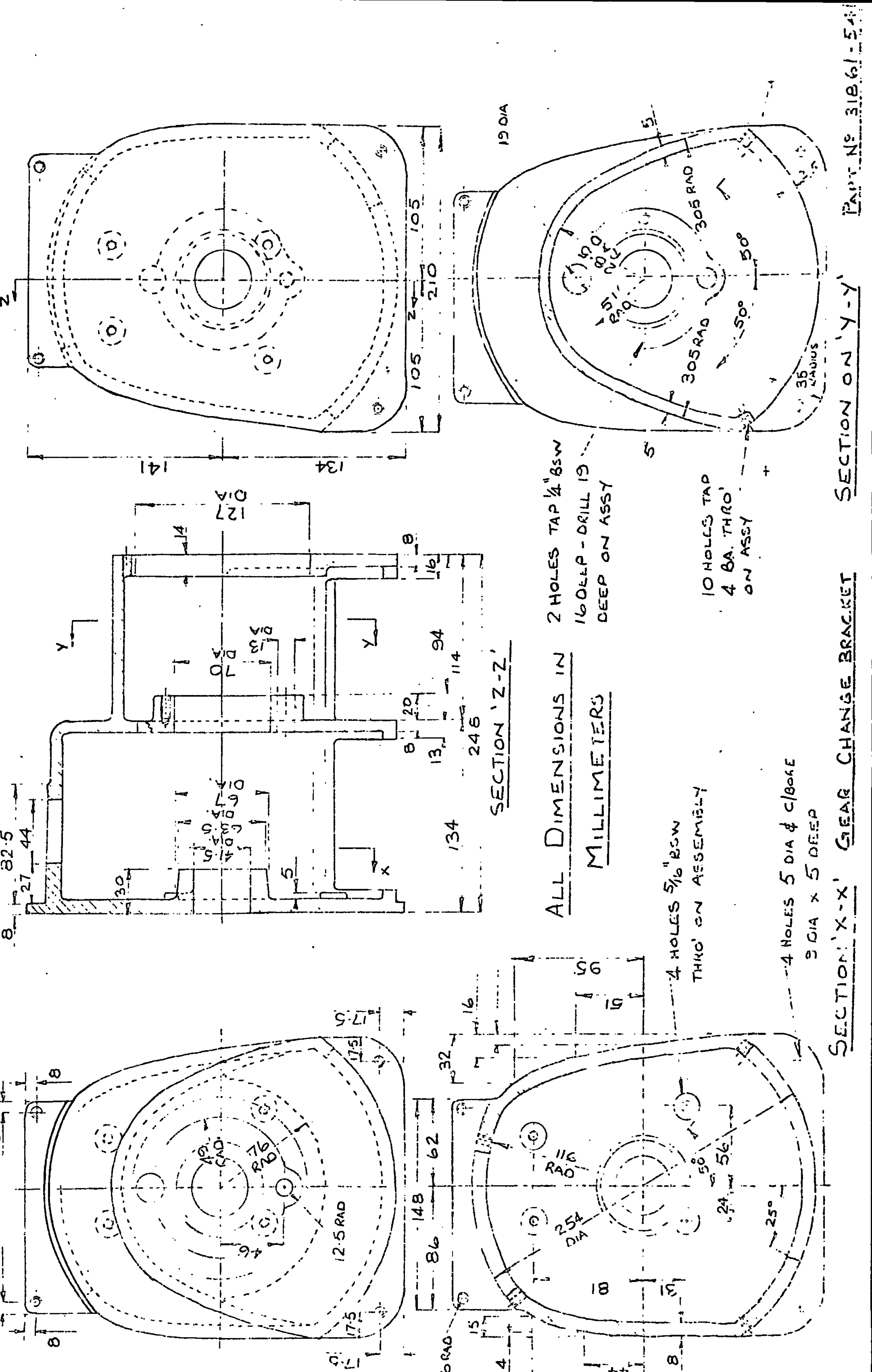
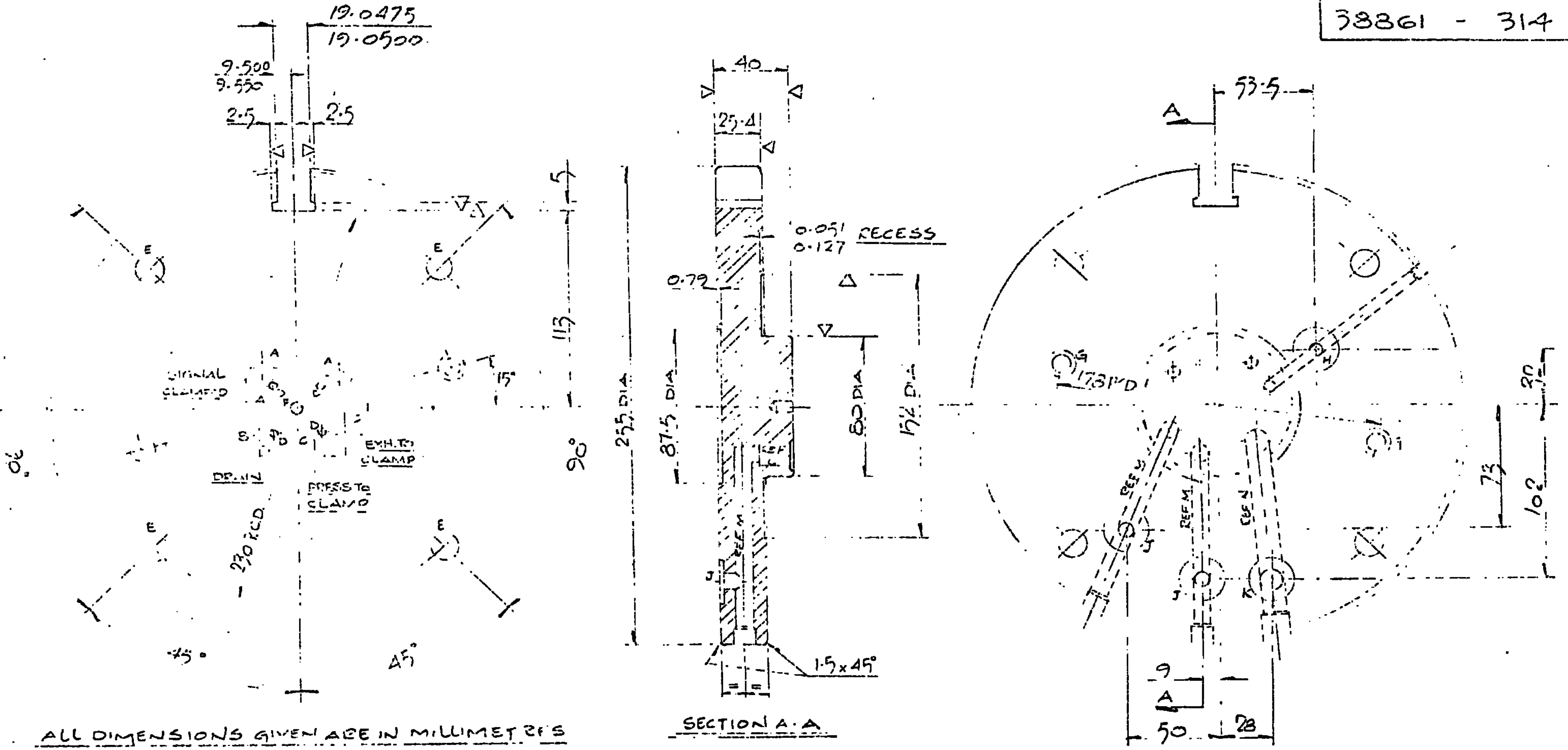

SECTION 'Z-Z'
SECTION ON 'Y-Y'
SECTION 'X-X'
GEAR CHANGE BRACKET
PART No 31861-54
ALL DIMENSIONS IN MILLIMETERS
2 HOLES TAP 1/4" BSW 16 DEEP - DRILL 19 DEEP ON ASSY
10 HOLES TAP 4 BA. THRO' ON ASSY
4 HOLES 5/16" BSW THRO' ON ASSEMBLY
4 HOLES 5 DIA & C/BORE 9 DIA x 5 DEEP
19 DIA
305 RAD
12·5 RAD
6 RAD
116 RAD
254 DIA
127 DIA
35 RADIUS

FIG 16

38861 - 314



ALL DIMENSIONS GIVEN ARE IN MILLIMETRES

HOLE REF	No OF HOLES	DRILL SIZE	DEPTH TO POINT	C'BORE SIZE	C'BORE DEPTH	RECESS DIA	RECESS DEPTH	REAMER SIZE	FULL DEPTH	TAP SIZE	THREAD DEPTH
A	3	6·35	34	9·525	19·05	12·446 12·5[illegible]	1·4224				
B	1	12·75	34								
C	2	9·525	34	12·7	19·05	15·621 16·129	1·4224				
D	4									2BA	12·7
E	4	14·275	THRO'								
F	1	6·07	12·5					6·35 A DIA	9·525		
G	2	10·03	THRO'	15	12·7						
H	1	6·35	17			25·1[illegible] 25·[illegible]	1·4224				

R.H. TRANSFER PLATE

FIG. 17

Justification Calculations

To determine whether N.C. or conventional methods are the more economic in given circumstances, the calculation made must take into account all the factors which have been discussed. Information supplied by machine tool manufacturers, of which the following example is typical, can be misleading. In addition, methods which have been shortened to make these calculations less tedious can prove to be inaccurate. If the following example is examined, this fact becomes evident.

Cost comparison with N.C. lathe.

Component P5.C.5328, shown in Fig. 19.

Existing Method Centre lathe (5 in rad. sphere not cut).

	Setting		Cutting		Pre-Production Planning	
	Existing Method	N.C.	Existing Method	N.C.	Existing Method	N.C.
Cost per hour	£1.75	£3.5	£1.75	£3.5	£1.75	£1.75
Time (Hrs.)	1.0	0.39	1.0	0.24	1.0	1.0
Cost	£1.75	£1.36	£1.75	£0.84	£1.75	£1.75

Average production time for each component when produced in batch sizes shown.

$$\frac{\text{Setting Time} + (\text{Cutting Time x Batch Size})}{\text{Batch Size}}$$

Batch Size	1	5	10	20
Existing Method	2.0	1.2	1.1	1.05
N.C.	0.63	0.32	0.8	0.24
Saving in Time	1.37	0.88	0.82	0.81
% Saving	69%	73%	75%	77%

Cost for each component when produced in batch sizes shown.

$$\text{1st Batch} = \frac{\text{Setting Cost + (Cutting Cost x Batch Size) + Planning Cost}}{\text{Batch Size}}$$

Repeat batch is without planning cost.

	1st Batch				Repeat Batch			
Batch Size	1	5	10	20	1	5	10	20
Existing Method	£5.25	£2.45	£2.10	£1.92	£3.5	£2.1	£1.93	£1.83
N.C.	£3.45	£1.46	£1.15	£1.0	£2.2	£1.1	£0.98	£0.91
Saving per component	£1.30	£0.99	£0.95	£0.92	£1.3	£1.0	£0.95	£0.92
% Saving	25%	40%	45%	48%	37%	48%	49%	50%

<u>Cost Saving in (1 year Single Shift)</u>

	Existing Method (1)	N.C. (2)
Batch Size	5	5
Total Production Time Setting and Cutting	6.0 hrs.	1.6 hrs.
Cost	£10.5	£5.6

Cost (1) £10.5 - Cost (2) £5.6 = £4.9 saving in 1.6 N.C. hours.

Saving in 2000 hours (1 year single shift) = £6,130 (3)

	Existing Method	N.C.
Capital Expenditure	£5,000	£30,000
20% grant	£1,000	£ 6,000
Total	£4,000	£24,000

N.C. - Existing Method = £20,000 (4)

Return on Investment of (4) £20,000 = £6,130 (3)

% Return Investment per year $= (\frac{3}{4}) \; \frac{£6,130}{£20,000} \times 100$

$= 30.5\%$

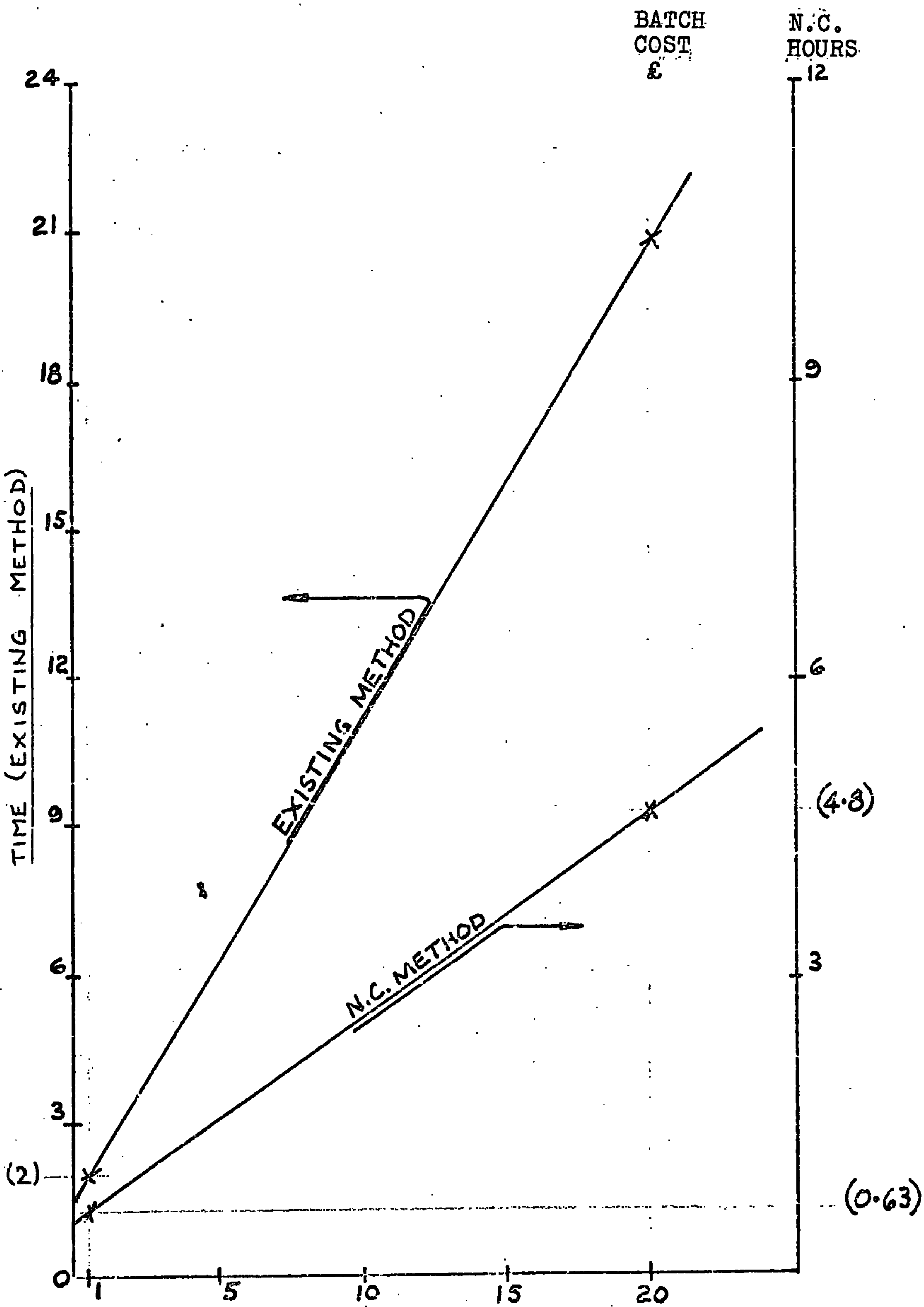
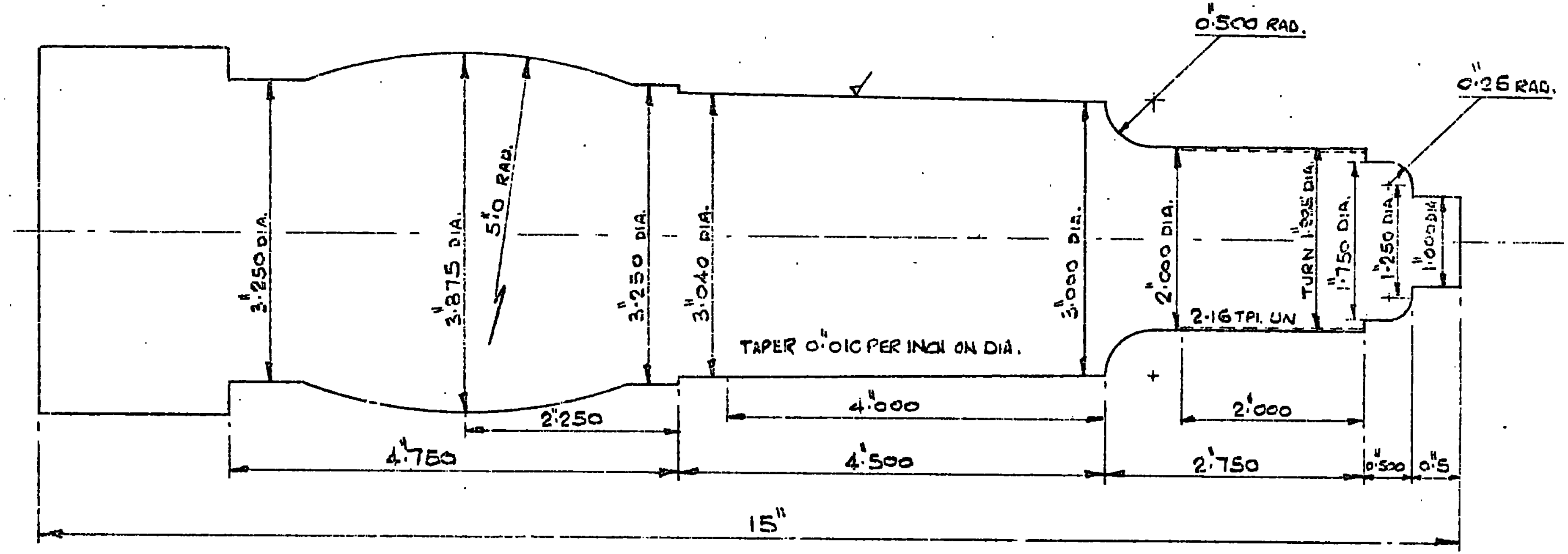


FIG.18

GRAPH OF BATCH COST AND TIME

FIG. 19



TEST COMPONENT.

MATERIAL :- 4" DIA EN.8.

MACHINING SYMBOL ✓

ALL DIMENSIONS TO 3 DECIMAL FIGURES TO BE ±0·001"

PS. C. 5328

H.Y.

There are instances where pre-production costs for both numerical control and conventional methods are equal,* therefore, if the data above is used in the calculation shown below then this method becomes void, and is therefore in opposition to Marshall (1).

* (see page 47).

Break-even Quantity q

The cost C for producing q components is given by

$$C = T + q(tM + A); \tag{1}$$

where T = pre-production cost, i.e. cost of programming, planning, design and manufacture of jigs and tools.

t = maching time (floor-to-floor).

M = machine hour rate (i.e. depreciation rate, plus labour rate plus overhead rate).

A = cost per component, of inspection (off the machine), fitting and assembly.

Let the suffixes $_c$ and $_n$ indicate conventional and numerically controlled methods respectively.

Then for conventional production:

$$C_c = T_c + q(t_c M_c + A_c); \tag{2}$$

and for production by numerically controlled methods

$$C_n = T_n + q(t_n M_n + A_n). \tag{3}$$

The break-even quantity is given by the value of q for which

$$C_c = C_n,$$

so

$$T_c + q(t_c M_c + A_c) = T_n + q(t_n M_n + A_n). \tag{4}$$

Therefore, q, the break-even quantity is given by:

$$q = \frac{T_c - T_n}{(t_n M_n + A_n) - (t_c M_c + A_c)} \tag{5}$$

Examination of this equation reveals that the numerator is the difference of the pre-production costs, and the denominator the difference of the processing cost.

If we now let $P_n = (t_n M_n + A_n)$,

and $P_c = (t_c M_c + A_c)$;

equation (5) becomes

$$q = \frac{T_c - T_n}{P_n - P_c} \tag{6}$$

Since both $(T_c - T_n)$ and $(P_n - P_c)$ can be either positive or negative, the value of q can be interpreted in four different ways, these are:

Case 1. When the pre-production costs are greater for conventional manufacture than by numerically controlled methods, i.e. $(T_c - T_n)$ is positive; but the processing cost per part is smaller by the conventional method, i.e. $(P_n - P_c)$ is positive. Then q has a positive value below which it is more economical to produce by numerically controlled methods, and above which it is economical to use conventional means.

Case 2. When $(T_c - T_n)$ is positive, and $(P_n - P_c)$ is negative (i.e. the process cost per component is greater by conventional methods) then q is negative (i.e. less than zero) and therefore it is always more economical to produce by numerically controlled methods.

Case 3. When $(T_c - T_n)$ is negative, i.e. $T_n > T_c$, and $P_n - P_c$ is positive, i.e. $(P_n > P_c)$ then q is negative (i.e. less than zero) and it is always cheaper to produce by conventional methods.

Case 4. When $(T_c - T_n)$ is negative, i.e. $T_n > T_c$ but $(P_n - P_c)$ is negative, i.e. $P_c > P_n$, then q again has a positive value above which it is cheaper to use numerically controlled methods, and below which it is cheaper to use conventional means.

Referring to sheet 48 where savings are shown relative to capital expenditure, the following observations should be taken into account:

1. The 20% grant system referred to has now been replaced by a system of investment allowances based on capital outlay to offset against the sum on which the company will pay tax.

This, according to a Government statement, will work out the same as the 20% grant system.

2. As the company must make a profit to benefit from the investment allowance, the implications of the new system should be taken into account and recorded.

3. The cost figures shown for "total production time, setting and cutting" may not be realised in practice if labour costs vary in an unpredictable way. Similarly, the assumption that the output from 2000 hours per annum single shift working will be saleable, may be unrealistic.

It has been shown by Merrett & Sykes (7) that logical analysis alone cannot yield the complete answer to a capital investment problem, depending as it does on the successful forecasting of future events. For this analysis to be justified despite uncertainty and imperfect estimates, it is necessary that the extra effort involved should yield a worthwhile improvement in the quality of the decision taking.

In the foregoing example, for an investment of £25,000, the return per annum is £6,130.

Discounting the series of future returns.

Where A = Annual profit (not known) applicable for n years.

r = Rate of interest (at present 11% per annum).

P = Present value.

Existing Method

Immediate outlay £5,000

Life of machine 10 years

Future income Annual profit A for 10 years

Present value of future income with interest r = 11% per annum

$$P = \frac{A}{(1 + r)} + \frac{A}{(1 + r)^2} \cdots \frac{A}{(1 + r)^n}$$

$$\therefore P = \frac{A\left[1 - (1 + r)^{-n}\right]}{r}$$

$$\therefore P = \frac{A\left[1 - (1.11)^{-10}\right]}{.11}$$

$$P = A\ 5.88923$$

Net gain on present value = 5.88923A - 5,000

N.C. Method

Immediate outlay £30,000

From above n = 10 r = 11%

$$\therefore P_1 = A\left[1 - \frac{(1.11)^{-10}}{.11}\right]$$

$$P_1 = A_1\ 5.88923$$

Net gain on present value = A_1 5.88923 - £30,000

To check which method gives the larger gain in the present value.

From sheet 48 $A_1 - A = 6130$

and N.C. Method - Existing Method:-

$\therefore$ $5.88923A_1 - 30,000 - (5.88923A - 5000)$

$\therefore$ $5.88923(A_1 - A) - 25000$

$\therefore$ $5.88923 \times 6.30 - 25000$

= £11,100

If one of these methods is going to be used the N.C. method appears to be financially the more attractive method (ignoring repair costs). The accuracy of a cost comparison calculation of the type shown on pages 47 - 49, therefore, depends on the following points.

1. The length of trouble-free life of the equipment.
2. The rate of discount employed.
3. Accuracy of the cost saving figure.

This latter item in turn depends upon:-

1. Changing external economic environment invalidating much of the usefulness of past experience particularly in calculating the cost per hour of the two methods.
2. The assumed number of hours per annum of production from which the cost saving figure is obtained.
3. Bias in the data and in its assessment.

CHAPTER 6 Batch Size and Component Complexity

The normal day-to-day work schedule will comprise components of varying complexity in batches of varying sizes. The more complex components may economically justify the use of numerical control over a wide range of batch sizes, whereas the more simple types will inevitably fall into one category or the other, depending upon the balance of these two factors. Decisions have to be made, therefore, for individual components, or types of components.

It is also important in the economics of N.C. to find some rational method of assessing component complexity. Long contouring operations represent a special case in practice and justification for numerical control can frequently be found on technological grounds. Some progress can be made by confining considerations to multiple operations of relatively short individual duration, i.e. positional control.

Depending on the particular application, numerical control increases manufacturing flexibility, reduces the lead time for going into production, and makes small batch production a more economical proposition.

Consideration must then be given to decide what batch size is economic for numerical control, and at what degree of complexity.

In the following calculation from data supplied by Philips of Eindhoven (6), seven possible methods of manufacture were examined and the cost of producing a range of components each requiring a different number of operations was calculated.

All the components were of simple shape, mostly in the form of a flat plate, see Fig.22, which tended if anything to favour jigging, since only cheap fixtures would be required. Factors such as storage and maintenance of fixtures, less scrap, and shorter lead time, were deliberately ignored, so that findings in favour of N.C. can be considered reliable.

Costs were calculated for components with from 5 to 30 holes involving drilling and reaming operations. The seven methods considered for determining hole positions were:-

I. Marking out.

II. Jigging.

III. Centering on a jig-borer.

IV. Manual setting of controller dials of N.C. machine.

V. Automatic tape control N.C. machine.

VI. Stop bar controlled co-ordinator table.

VII. Precision radial table.

The production cost per piece was determined for each method. This was based on machine time, wages and overheads, including capital depreciation. Preparation costs were determined and these included the cost of jig design and manufacture, programming and tape preparation.

Selecting from data thus obtained the figures for an average component with 15 drilled and two reamed holes are given in Table 2. The costs are in Guilders which it would be misleading to convert because of wage rates and costs. The values are, however, valid as indices for comparison.

TABLE 2

Procedure	Method	Wages and overheads per piece FL	Preparation cost FL
I	Marking out	5.54	7.09
II	Jigging	2.43	179.9
III	Centering in Jig borer	5.43	6.4
IV	Numerical control Manual switching	5.03	6.9
V	Numerical control with tapes	3.89	9.30
VI	Stop bar Co-ordinator table	4.21	21.4
VII	Precision radial table	4.75	12.60

Jigging is shown to be the cheapest method of production, followed by numerical control with tape. The preparation costs for jigging are nearly 20 times those for preparing tape. The following table shows the overall cost per batch.

Overall cost = cost of wages and overheads multiplied by batch size plus preparation costs.

TABLE 3

Batch Size	METHOD I	II	III	IV	V	VI	VII
20	117.8	228.5	115.0	107.4	87.1	105.6	107.63
40	228.6	277.1	223.6	208.1	164.9	189.8	202.63
60	339.4	325.7	332.2	302.7	242.7	274.0	297.63
80	450.2	374.1	440.8	409.3	320.5	358.2	392.63
100	561.0	422.9	549.4	509.9	398.3	442.4	487.63
120	671.8	471.5	658.0	610.5	476.1	526.6	582.63
140	782.6	520.1	766.6	711.1	553.9	610.8	677.63
1	12.54	182.33	11.83	11.93	13.19	25.61	17.38
2	18.08	184.76	17.26	16.96	17.08	29.82	22.10
3	23.62	187.19	22.69	21.99	20.97	34.03	26.85
4	29.16	189.62	28.12	27.02	24.86	38.24	31.60

From the graph Fig. 20 Tape control procedure (V) is cheaper than any other method until jigging (procedure II) breaks even at 120 pieces.

In the lower range of batch sizes the graph is drawn to a larger scale, Fig. 21, and it can be seen that centering in a jig borer (procedure III) has a marginal advantage on one piece, but for two pieces manual switching of the numerical control machine (procedure IV) has the advantage. For three pieces, however, tape control (procedure V) breaks through as the most economic method.

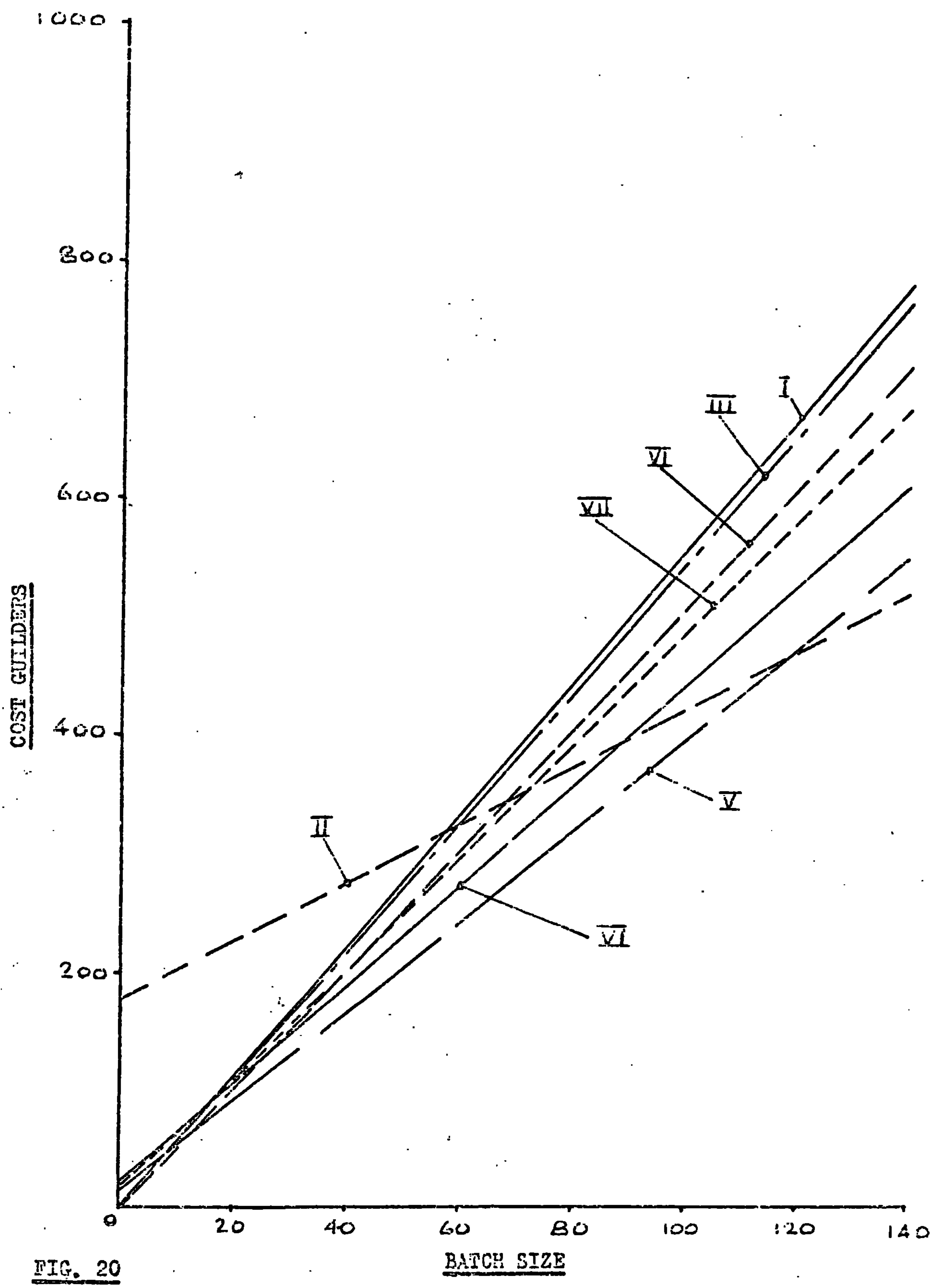
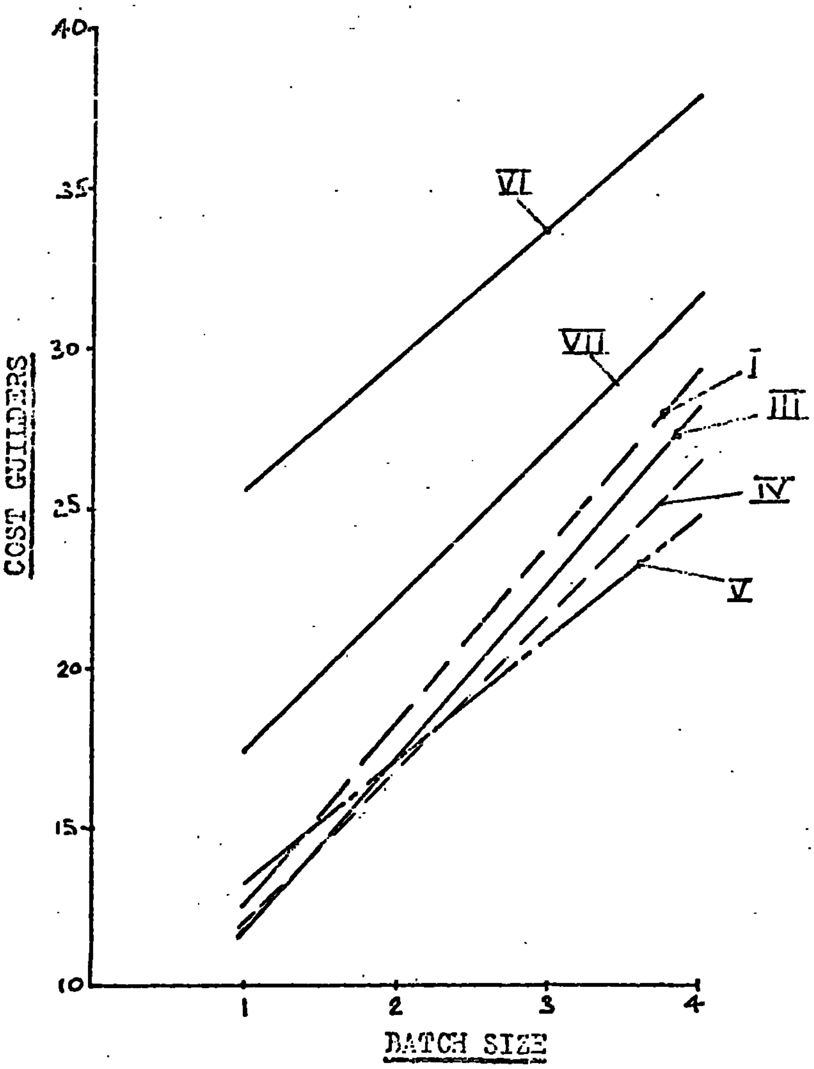

1000
800
600
400
200
0
COST GUILDERS
20
40
60
80
100
120
140
BATCH SIZE
I
II
III
V
VI
VI
VII

FIG. 20



COST GUILDERS
40
35
30
25
20
15
10
1
2
3
4
BATCH SIZE
VI
VII
I
III
IV
V

FIG.21

CHAPTER 7

Economics of Program Preparation

The pre-production work which must be carried out before a component can be released for manufacture on an N.C. machine can be divided into two areas: 1. Planning, 2. Programming.

1. Planning

This section of the work includes fixturing, tooling, selection of machining conditions and order of machining. In order to utilise fully the technological advantages of N.C. machines these must be fully optimised. A further essential requirement for N.C. planning is a thorough knowledge of programming (either manual or computer aided, depending on the facilities within the company).

Planning costs are based on man hours and examples of these can be seen in the previous economic examples.

2. Programming

Enquiries carried out with several major companies in the United Kingdom, i.e. Rolls Royce, Hawker Siddely Aviation, Plessey Numerical Controls and Philips Electrics, have shown that it is inadvisable to quote costs, other than those arrived at in a particular company, due to variations in programmer expertise, complexity, length of programme required and varying computer facilities. The following section will deal with the factors that contribute to the costs under two separate headings - manual and computer assisted. In both instances, tape costs are based on the number of tape blocks required. This is in agreement with Madigan (8).

Manual

The majority of N.C. machines in use in the United Kingdom are point-to-point machines requiring less than sixteen blocks of tape per machine minute and nearly all are programmed by completely manual methods (often with the assistance of a desk calculating machine). Costs can be calculated from the following considerations:

Programming Engineers

An overall cost rate per hour derived from:

Wages per hour (relative to the company concerned).

Plus:

Overheads per cent (in general 1.25% of hourly wage rate).

Tape Punch Operators

An overall cost rate per hour derived from:

Wages per hour (relative to the company concerned).

Plus:

Overheads per cent (in general 1.25% of hourly wage rate).

Plus:

Depreciation recovery on tape typewriter
(usually over ten years).

A competent operator on N.C. work, using the "three-line visual" technique for verification, can punch and check about three thousand tape characters per hour. An N.C. tape block can vary from about six to sixty characters for letter address and tab sequential systems: tape blocks for fixed block-length control systems are usually between twenty and thirty characters long - a typical mean block length, regardless of system type, is about twenty-five characters. Thus, the mean cost of punching an N.C. control tape on a tape typewriter from manually prepared programme sheets remains virtually constant, regardless of program complexity and at these rates would be the overall cost rate per hour of tape punch operators divided by one hundred and twenty, to give cost per block.

Information from the above considerations only shows the order of initial cost of preparing a control tape ready for prove-out, not the cost of a proven tape.

TEST PIECE

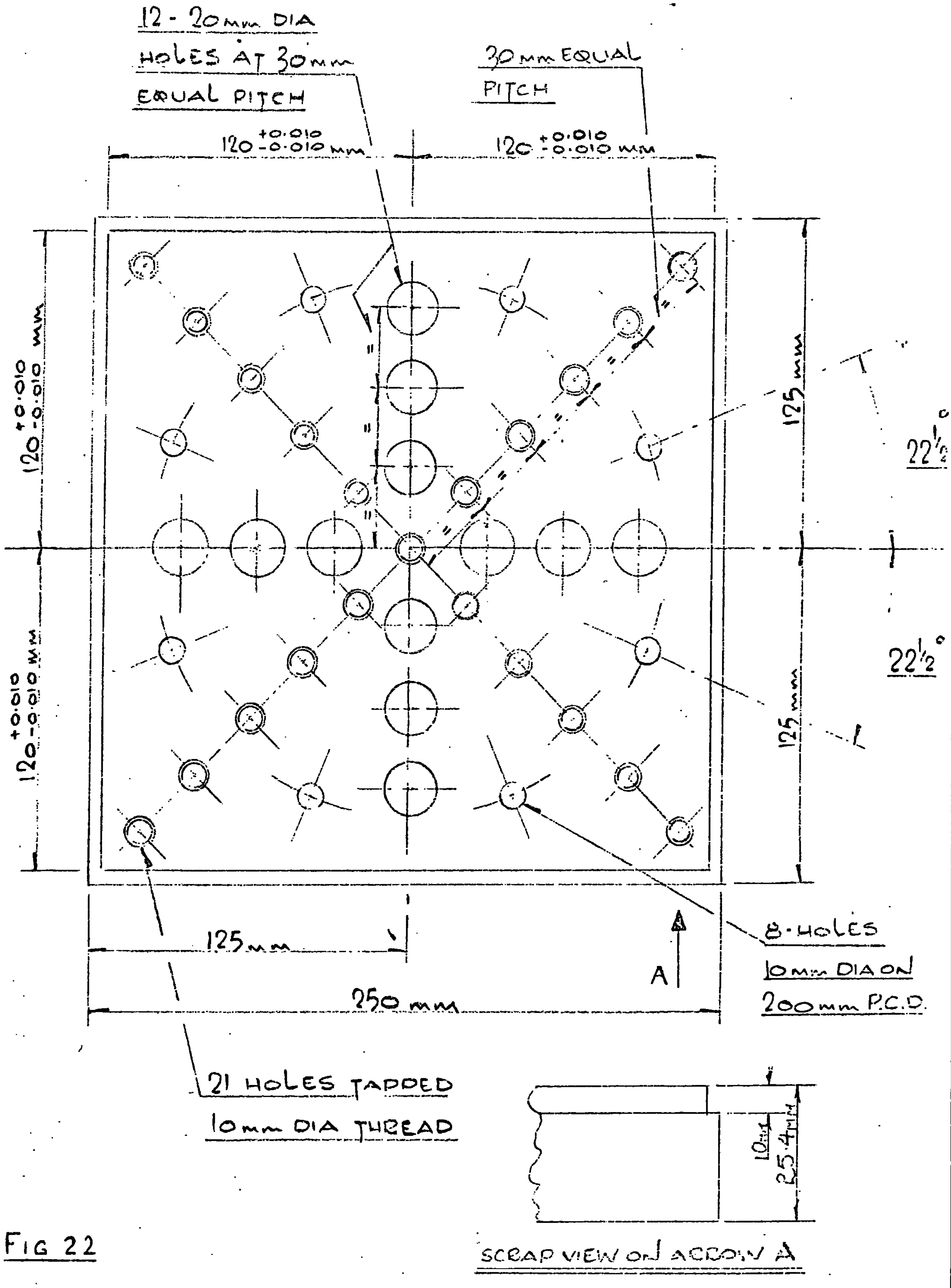


FIG 22

Computer Assisted Programming

Apart from small tapes the computer-produced tape is economically attractive compared with the manually produced one.

Since the manual production of tapes involves tedious calculations, the method is particularly prone to human errors. The employment of computer assistance removes the arithmetic type errors, and helps to reduce the logical errors. Also the time taken to compile the input information to the computer is considerably less than that taken to manually program part of the data.

All users of numerically controlled machine tools are faced with the problem of preparing tapes quickly and efficiently so as to ensure the successful operation of expensive machinery. Assuming that computer assistance is chosen for the production of tapes, the most suitable program system must be selected to meet the requirements of the company both technologically and economically.

During the selection of the best suited system or systems, it is important to consider all present and future technical requirements. Areas for consideration are:-

(i) The geometrical characteristics of the components to be machined and the capabilities of the machine tools available, e.g. point to point, turning, two axis milling, multi-axis contouring.

(ii) If the above yields more than one component per machine tool grouping it is necessary to consider either (a) an all-embracing program system, and (b) a group of systems. If a group system (b) is desirable then a further consideration would be:- must it contain compatible systems?

(iii) Geometrical calculations (co-ordinate positions, etc.) also technological calculations, i.e. optimum feeds, speeds, depth of cut, and automatic tool selection.

(iv) Extensions to basic central tape preparation, e.g. design functions, tool or material control and machine shop loading.

(v) The necessity of applying the system wholly or in part to conventional operations.

General Purpose Program Systems

Perhaps the most powerful and most widely known of the computer-assisted NC programming systems is APT. Using APT the programmer describes the geometry of the part and the machining operations he wants carried out in a series of statements made up of English-like words - some of them shortened because of computer limitations - and the computer translates these statements, carries out all the calculations and then prepares the actual machine tool control tape. The APT language is virtually an international standard today and is soon to be formally recognised as such. However, the versatility and power of APT, which make it ideally suited to the aerospace type component, virtually preclude its use for the more simple components which are manufactured daily by the majority of industry. The reasons for this are:

a) APT is physically a very large computer program; therefore one central computer costing hundreds of thousands of pounds is required to run it.

b) Because APT has a continuous motion in 5-axes capability, only a small fraction of its facilities are required or can be used for programming point-to-point machines or even 2-axis continuous path machines. Thus, to use it, facilities have to be paid for which may never be employed.

c) APT output is arranged in a generalised form which must be adapted to suit a particular machine tool by means of a 'Post Processor'. And post processors are not available for a large number of the NC machines currently in service.

However, despite these serious drawbacks, the APT concept appears to be a logical and efficient way of solving the NC programming problem. Almost since its inception, simplified versions of APT aimed at specific areas of NC programming have been and are being developed; amongst these are:

1. ADAPT, developed in the U.S.A., which caters for continuous motion in 2 axes and linear path control in a 3rd axis.

2. 2C.L developed at the National Engineering Laboratory which has similar capabilities to ADAPT but with the addition of automatic "Area Clearance" milling and other features which can assist programming.

3. 2P.L which is in the final stages of development at NEL and is aimed at the point-to-point machining centre market and includes automatic tool selection.

4. EXAPT 1 which has similar capabilities to 2P.L but with the addition of "Technology" for the automatic calculation of speeds and feeds, as well as automatic tool selection.

5. AUTOSPOT developed by IBM, mainly for point-to-point work but with limited continuous path milling capability; it comes between 2P.L and 2C.L in both facilities and complexity.

6. PICNIC developed by PERA for point-to-point machines for use on small computers. A sub-set from the APT vocabulary.

Some of these programming systems are true APT "subsets" in that the input language and the generalised output are as near as possible identical to APT. Others are simply "APT-like" and vary in different degrees, as far as both input language and generalised output are concerned.

All of these systems are physically much smaller than APT and can therefore be run at a lower cost on a smaller computer; but a post processor is still needed to convert the generalised output to the tape format for a specific machine tool.

Special Purpose Program Systems

Special purpose program systems designed for a specific machine tool application. For example, if a machine tool is to be used primarily for the manufacture of cams, it may be found desirable to include design calculations for the cams, or scheduling features for transfer line applications. In manufacture the following general points should then be noted:-

a) The system should operate very efficiently in the computer as it has been designed specifically for the job.

b) Core store usage should be more efficient, because of the lack of extraneous calculations produced by generalisation.

c) Restrictive in scope and adaptability.

Relating the above programming systems to the groups of machines to which they are most suitable will help to evaluate the economic benefits or otherwise.

1. NUMERICAL CONTROL BORING MACHINES which spend most of their productive time cutting metal. Control of speeds and feeds and the actual boring operation remains in the hands of the operator, although he is often provided with trip dogs to establish the machining depth and these may be selected from tape. The tape only contains information to position the workpiece relative to the machine spindle.

Computer programming is unlikely to make any significant improvement to programmer productivity unless the particular component requires large amounts of geometric calculation. The programmer is likely to be involved in nearly as much work in describing the machine in APT language as he would be in preparing the program manually.

The recently developed PICNIC program can be used effectively for this class of machining; using some 40 words from the APT vocabulary considerably simplifies programming.

2. SIMPLE NC DRILLING MACHINES mainly for flat plate work where change over from rapid approach to drilling feed and also the final drilling depth are fixed by manually set trip dogs; although one or more alternative sets may be selected from tape.

The situation regarding the application of computer-sided programming to this group is much the same as far Boring Machines. However, a significantly larger part of the work available has a fairly high geometric content - boiler and heat exchanger tube plates and other flat plate components which consist essentially of through-holes in regular patterns. Many of the machines which are mainly engaged on this class of work are already programmed by special-purpose computer programs. For this class of work, where special purpose programs are not available, advantage can be taken of any of the APT sub-set languages.

3. SIMPLE MULTIPURPOSE MACHINES with linear path control on the table motions and trip dog control of the spindle axis. Table feed rates are generally controlled from tape as are miscellaneous functions such as a simple turret tool changer, coolant, and selection of the required canned cycles for drilling, milling, tapping and boring.

An appreciable part of the work for these machines involves multiple operations at the same point, e.g. drill and tap or drill, bore and ream. Therefore, the storage and recall facilities for points and patterns which are available with computer-aided programming can assist the programmer by reducing the change of writing errors when instructing the machine to return to the same point for a later machining operation.

4. MORE VERSATILE MULTIPURPOSE MACHINES with linear path control on the table motions and tape control of the feed change point and machining depth. Spindle speed and quill feed may also be controlled from tape.

These machines have none of the machining depth limitations which apply to the previous groups. Castings and forgings - with a considerable number of different workplanes and with a higher proportion of the work consisting of operations other than drilling - constitute the majority of the work load. These more complex workpieces involve the manual programmer in considerably more calculation; computer-aided programming can therefore improve productivity considerably.

The machines all employ computer canned cycles also, which are essentially an aid to the manual programmer. In order to use canned cycles efficiently, a considerable amount of anticipation of the next machine move is necessary when preparing the control tape.

5. THE MOST VERSATILE AND COMPLEX MULTI-PURPOSE MACHINES have three axes of motion with full linear path control, possibly either a full fourth axis in the form of a tape controlled rotary table

or alternatively a rotary table with indexing called from tape. Spindle speeds and also feed rates on all three main axes are controlled from tape; a full range of miscellaneous functions, and generally an automatic tool changer, are also controlled from tape. Canned cycles are not used.

These versatile machines which normally require between three and five blocks of tape to position and drill a single hole can benefit significantly from computer programming. Since full tape control is available on the spindle axis, the degree of anticipation available from the post processor is sufficient to ensure that computer-prepared tapes are as efficient from a machine productivity point of view as manually programmed ones.

CHAPTER 8 Comparison of methods computer assisted programming

When considering the factors which contribute to the cost of producing control tapes, the relative merits of either an in-house computer or a computer bureau service need to be analysed, under two broad headings: set-up and running costs.

Set-up Costs

Costs involved in the implementation of the computer programs, training of staff, the preparation or purchase of documentation, the creation of files and the initial re-organisation required. These costs must be borne in mind when considering the resultant cost for each tape produced by the system. The in-house user has to bear all these; the bureau user, on the other hand, is only involved in the training of part-programming staff, the creation of files, and the initial re-organisation costs (which should be considerably less than that to the in-house user). A decision as to what period of time over which to recover these costs is left to the user.

Running Costs

All the factors of costs incurred in running an NC program system, except one, are common whichever type of service is used. The exception is a cost for the in-house user of program system maintenance and updating, including annual subscriptions, if any, to the appropriate distributing organisation. The common factors are: part programming, supply of data sheets, data preparation, computer processing time and fault finding. The part programming and fault finding costs are comparable whether using in-house or service bureau. In general the in-house computer time cost is less than the equivalent bureau rate, in that usually the in-house computing service for an organisation is not a profit making centre; consideration must be given to the fact that the bureau user pays only for the computer time used.

When studying the costs of computer bureaux, care should be taken to note which of the above factors are included within the charges for the service. The following table shows a summary of the contributory factors to cost, indicating which costs are incurred by the user of the two types of service.

SUMMARY OF ECONOMIC ASPECTS

	In-House	Bureau
Set-up Costs (recovered over 3 years)		
1. Implementing of program system.	x	
2. Training of operating staff	x	
data prep. staff	x	
part programming staff	x	x
3. Preparing manuals etc.	x	
4. Setting up tool files etc.	x	x
5. Initial re-organisation	x	x/3
Processing Costs		
1. Maintaining & updating of program system.	x	
2. Part programmer time.	x	x
3. Data Sheets	x	x
4. Data Prep.	x	x
5. Computer time.	x	x
6. Fault finding.	x	x
7. Transmission.	?	Minimal.

The foregoing facts can be summarised using the following process to assist potential users of computer assistance for the preparation of numerical control tapes.

DECISION PROCESS

In fig.23 a flowchart is shown representing a typical initial process through which a potential user may go in deciding which type of service to use.

In constructing this flowchart two broad assumptions have been made;

a) that employment of computer assistance in preparing the tapes is essential;

b) that there exists a program system which will be satisfactory for the individual users requirements.

The flowchart is not intended to indicate the final decisions which are to be made, but rather the possibilities which must be considered in the final analysis.

Considering the points raised in the flowchart in greater detail:

Box 1: Study of the present tape requirements, and also the technical aspects of the various program systems which are currently available, as discussed earlier.

Boxes 2-6: All acceptable systems are considered for both in-house and bureau; possible systems are entered on a comparison chart, an example of which is shown on Page 74.

Box 7: Consider all acceptable present systems over a three year period. Repeat the process for future requirements, i.e. the next three year period - the appropriate values are again entered in the comparison sheet.

Boxes 8,9 In order to eliminate the systems which are technically or economically unsuitable, a change of system is considered. The decision to change is based on the technological desirability and cost. The cost should then be added to the comparison chart. If a change is not acceptable all noncontinuing systems should be discarded.

Boxes 10,11: The process of boxes 8, 9 is repeated, this time considering a change in operating mode from in-house to bureau or vice versa. Again, the cost is entered in the comparison chart.

From the above data equivalent cost values are entered on the comparison chart. This is essential if such a comparison is to be of use, as the whole purpose of an exercise of this sort is to help to determine how to manufacture goods within a specified timescale and quality at minimum cost.

The comparison chart represents a system which will enable the different options to be radically reduced in number.

COMPARISON CHART DETAILS

Item 1: Identification of the system.

Item 2-7: The financial case for the system to cater for present needs is considered, successively, by: operating mode (bureau or in-house); sum of set-up costs; costs per average control tape; and total number of tapes; giving a sum of running costs and hence a total cost of the system.

Item 8: The cost of change, if any, from system to system or in-house to bureau.

Item 9: A repeat of the present requirements items 2-7 for future requirements, resulting in a total cost of a system to cover these requirements.

Item 10: The present system cost, cost of change, and future system cost are summed to give a total overall cost.

Item 11: In order to allow for desirability of system and any side benefits, it is suggested that a cost value be added. Examples of possible areas for consideration are turnround, technical suitability, optimisation of tool usage, and auxiliary facilities available.

Item 12: Overall cost.

Initial Decision Process

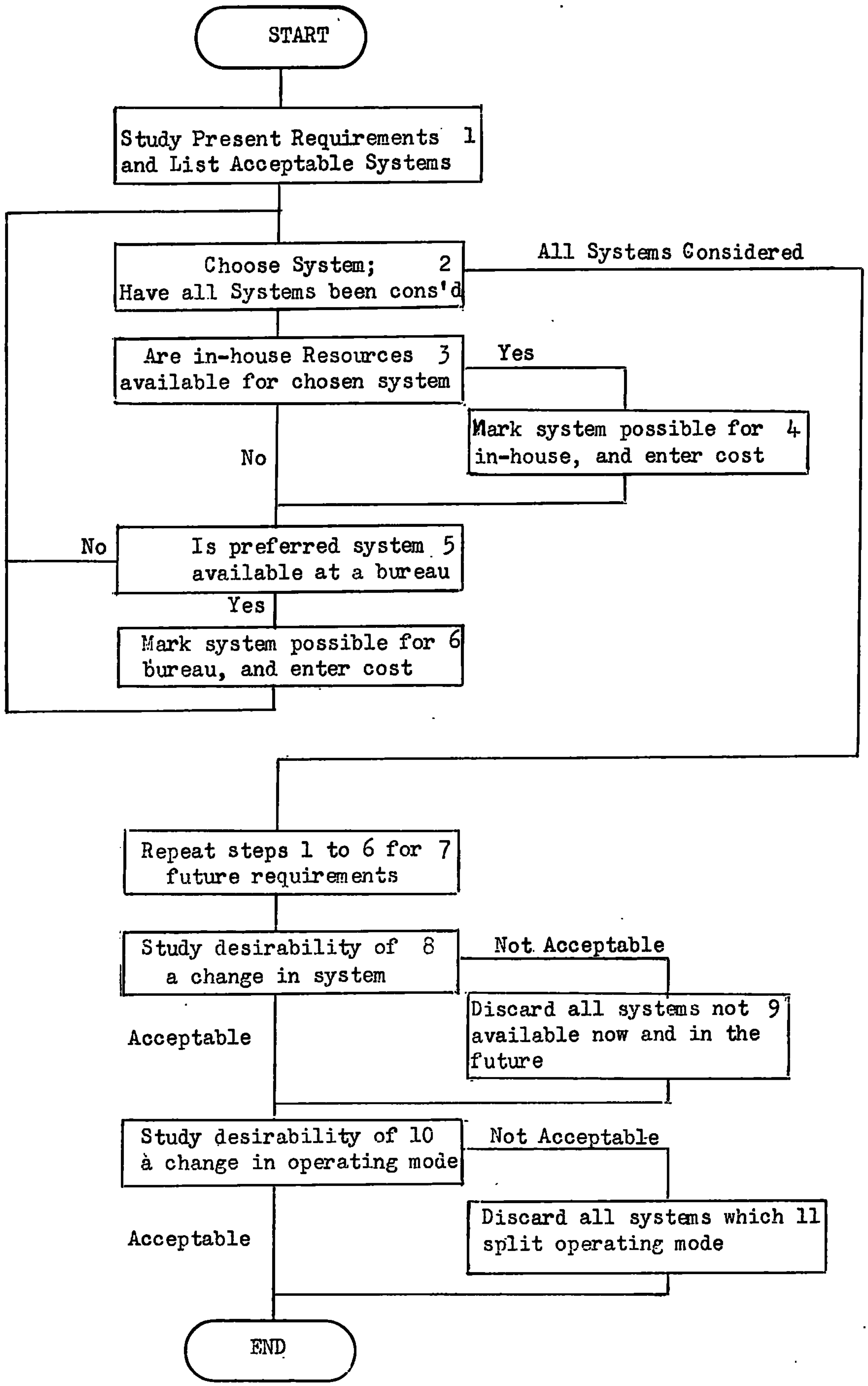


Fig. 23

COMPARISON CHART

Present - 3 years

1. System identification.
2. Bureau or in-house.
3. Set-up cost.
4. Cost per ave. tape.
5. Total number of tapes expected.
6. Running costs.
7. Total present cost of system.
8. Cost of change.
9. These items should be considered on the basis of the present three years, and then repeated for the following three years. In both cases the costs of in-house and bureau should be compared.
10. Total cost.
11. Cost value.
12. Overall cost.

Program Development

The costs calculated from the statements shown at the beginning of this section, assume that the planning work which was carried out before programming commenced was correct in every detail. As this is virtually impossible, nearly the whole of some programming tasks may have to be repeated so that time and costs given would need to be doubled. The expertise of N.C., like any other technique, increases with experience in that particular field.

Initial proving of a completely new tape, by most users of point-to-point machines, consists of a block at a time run through the tape to check that the encoded machine functions are correct. Users of complex and expensive N.C. machines often follow this by a further stage of prove-out with the machine operating continuously but either cutting fresh air or a dummy component made of polystyrene, balsawood, etc. Step-by-step prove-out will generally take two to five times as long as a normal metal cutting run through the same tape.

When a company uses bureau computer assistance for producing control tapes, the following prices published by ICSL (10) illustrate how prohibitive prove-out costs can be; allowing for the fact that the figures shown are for one run only, whereas several runs may be needed before a proven tape is accomplished.

Error charges, previously based on a machine time wasted basis have also been standardised in formulae related to the size of the tape ultimately produced and the section of the system, i.e. the geometry, technology or post-processor phase, within which the error occurs. The charge per error is thus:

Geometry:	£2 + 5p. per 10 output blocks
Technology:	£2 + 10p. per 10 output blocks
Post-processor:	£2 + 15p. per 10 output blocks.

From the economic facts covered earlier, it is evident that if programming could be developed to ensure the production of control tapes on which all information is correct, thus enabling component production to commence without loss of time, the economic advantages would be considerable.

It is not always practical or economical to rely entirely on the N.C. machine tool to check out encoded information. The machine may be so heavily scheduled that it cannot be spared for a long slow prove-out cycle, or the hourly cost of machine and operator time may be so high that this method of prove-out is uneconomic, particularly as the programmer is usually monitoring the operation.

The method and level of verification needed to check the encoded machine functions are correct will depend upon the complexity of the machining program, and in certain cases the value of the component.

Existing methods of prove-out for encoded information can be grouped to show the various levels at present available in the following manner. In many cases, particularly with contouring information, several methods would be used starting with one or more of the lower levels of verification.

Levels of Verification

I. Manually programmed tapes can be checked by a duplicate typing operation on a Flexowriter. The punched tape is inserted into a verifying unit connected to the Flexowriter. The program is then retyped. The verifier automatically compares each character with that on the original tape. If they do not match, the keyboard locks. The operator determines which tape is wrong and makes the correction.

It has been shown by B.L. Soloway (11) that the recently developed Soval system, using fibre optics, enables an operator to produce control tapes identical to the manuscript, thus saving a verification process using a second operator. These methods assume the manually written program to be correct.

For N.C. systems that use computer and punched cards from data implementation, accuracy of card coding can be determined by a keypunch verifying machine. This process requires that the operator place the previously coded cards in the verifier. The entire program as outlined in the manuscript would then be retyped. The verifying unit automatically scans the card coding for accuracy of the original punching operation. If there is a mismatch, the incorrect card is rejected. A replacement would then be punched.

The process checks whether the punched cards correspond with the written manuscript. Also that the program language and motion instructions are in the prescribed format.

In general purpose program systems such as APT, both format and language are rigidly prescribed. A grammatical error in punctuation or language could make the statement unintelligible to the computer and thus unprogrammable. Other types of discrepancies include instructions that violate previous instructions.

With APT computer processing the validity of the input program and motion instructions are checked by special screening programs that are part of the soft-ware system. At its present stage of development, the error analysis program for APT can detect about 160 different errors in programming procedure. The location of the error in the program is printed out along with a diagnostic statement of the defect. Not every error can be diagnosed specifically. In some cases the programmer must analyse the problem himself.

II. Consists of examining the pattern of the punched holes to see that they are properly spaced and aligned according to established standards.

Irregularities can occur in the hole pattern because the tape fails to track squarely through the tape punch, particularly in high-speed punches. Some spacing errors occur because of slight deviations in spacing of the sprocket holes.

Improper alignment, skewed or elongated holes and similar irregularities can cause the tape reader in the NC machine to misread data, causing an erratic tool motion or complete machine stoppage.

The punched holes should at least be spot-checked before the tape is put on the NC machine. Both punched cards and tapes can be checked using a simple template and though it is difficult to check an entire tape, the first 2 to 4 metres should be checked.

A more sophisticated gauge can be built to check an entire tape automatically. It is similar to the punched-tape readers used on standard NC machine control units. It employs a photo-electric scanning mechanism coupled with error-detection circuitry. The verifier can rapidly examine the entire tape for conformance to channel and sprocket-hole standards. If deviations are sensed by means of a partial or full cutoff of transmitted light, the machine will automatically stop.

III. This form of verification consists basically of plotting the cutter-centre path of the series of tool positions on a sheet of standard drafting material. For a continuous-path program, the plot will show if the tool path is in correct relation to the part outline.

Graphic techniques can only depict coordinate information. They cannot predict how accurately the actual machined part will correspond to the desired shape. Final results depend on the variable effects of cutter deflection, speeds and feeds, and the dynamic response of the machine tool during the cutting cycle. Plotting techniques, however, are useful for visualising the basic accuracy of the programmed tool movements.

The most accurate way to depict coordinate information graphically is with a numerically controlled drafting machine. It will plot the tool path with an accuracy of 0.050 mm./0.3 metres. The accurate detail from a drafting machine is limited to the motions of X, Y, and Z axis operations. Tool path data involving additional axes, such as swivel and tilt motions, can be plotted to show only excessive errors.

The control tape for the drafting machine is obtained from the computer using a post processor appropriate to the drafting machine. There would be considerable advantages in using the same tape as the one operating the machine tool. Chapter 9 shows an example of this level of verification and indicates the accuracy expected.

IV. The approaches that can be used for checking aspects of the programmed machining cycle cannot be readily visualised by plotting tool path or position, include a machine tool simulation, a universal measuring machine and a simulation run in the machine tool itself (providing the latter is economically justifiable, see first paragraph). They also take into account machine and work set up.

A machine tool simulator is a working mock-up that can duplicate the full range of motions of the actual NC machine on which it is patterned. Vernier scales are used for checking the positions of simulated motions of the movable elements of the machine. To check out an entire program using this technique would be tedious, the main purpose is for spot-checking critical or doubtful parts of the program.

A measuring or inspection machine can also be used in much the same way as a machine tool simulator.

These inspection machines consist essentially of a work-mounting surface and stylus movable in three axes. The coordinate location of the stylus with respect to any selected reference point is shown in numerical form on a readout panel.

To check a program, an accurate part or master is set up on the machine. After being zeroed against a reference point, the stylus is moved to a succession of coordinate locations as called for in the program to check tool position and possible interference problems.

Most users of NC machines still carry out a dry run on the machine tool itself using the actual control tape and a wooden or plastic stylus of the same length and diameter as the cutter. This will prevent damage to the work or machine in case of an impact.

V. The ultimate verification is to machine an actual workpiece. The cycle will positively check the dimensional accuracy of the tape. It will also reflect the numerous unpredictable factors that arise only during an actual machining cycle and whether they will affect the acceptability of the part.

The high investment in NC machines and the value of these machines as short run production tools place a premium on accurate control tapes. A considerable effort to correct a new tape before it reaches the machine is essential. The degree of effort and the type of equipment used depends on balancing the cost of a potential scrapped component or machine down time against the cost of verification.

When numerical control is applied in an organisation the process of controlling the machine tool is largely removed from the shop floor and placed in the planning office, where the part programming operation is carried out.

Most of the factors governing the choice of tools are the same as for manually controlled machines. However, the advantages of using tools with a long cutting life and optimum cutting speeds are more significant, since otherwise a disproportionate amount of machine time may be spent on replacing tools. When large batches of components are being made, a tool inspection and replacement schedule should be associated with the part programme. This eliminates having to scrap components because of undetected deterioration due to tool wear or breakage.

Drill speeds and feeds etc. are also determined as in manually controlled drilling, even when they are programmed on the tape and selected automatically, but with more emphasis placed on optimum settings to give maximum machine output efficiency. The sequence of operations should be that requiring minimum travel from hole to hole. Wherever possible, movements between successive holes should be in the direction of increasing co-ordinate. To eliminate any lost motion, the mechanism travels beyond the point required in the negative direction and reaches final position in a positive direction. Therefore the time required to position in a positive direction is less than in a negative direction.

Where a machine is fitted with a turret and some holes require several operations with different tools, it is usual to carry out all the work making use of one tool before going on to the next stage. However, if the distances between holes are large or if the turret indexing mechanism is very fast, it may be quicker to carry out all the operations on one hole before going on to the next one. It may sometimes be found expedient to follow the same course when the position of two successive tools over a hole are required to be concentric within a very close tolerance.

The specification of such factors as tolerance takes on a different aspect, as in the final analysis they are now a function of the machine control system chosen to carry out the machining operation. Additional errors, arising from the machining process itself, must be added to the combined machine-control system errors.

Tooling for NC is closely related to programming since it involves the choice of size, shape of cutters, and their proper setting in standard holders to match the plan envisaged by the programmer. It is customary for the program to include tool specifications so that the machine operator can get the complete set of tools for a given part without initially having to work out the required list. The programmer must provide the tool room with all the data required for setting up all the tools needed for a given job on a given machine. The tool room must see to it that the tools are correctly ground and held in place so that no unnecessary time is lost correcting tool settings on the NC machine.

As shown by S.J. Martin (3) setting time can be reduced and maximum accuracy maintained by using preset tooling. The effect is to set the tooling from a drawing or chart away from the machine to a specified accuracy, whilst a different batch is being produced. The reduction in machine idle time has to be balanced therefore against the capital cost of the equipment and the increase in the total time spent setting the tools.

A further means of maintaining maximum accuracy and reducing setting time is the use of a module table shown in fig. 24, the purpose being to provide a reference area onto which components may be clamped at known positions for machining. Zero setting positions can be programmed directly. All that is then required is that the operator places the component against the stops in a position pre-determined by the programmer. This dispenses with the need for accurate manual setting. Repositioning errors are eliminated and setting time is reduced very considerably.

Time and trouble in programming is saved if drawings and tables are supplied with ordinates that coincide with the grid positions of the module table. Also the design should allow access to as many faces of the component as possible at a single location on the machine table. The versatility of the numerically controlled machine tool can then be fully exploited.

Design considerations (module table).

The table must be large enough to cover the total travel of the machines axes and must comply to the same design characteristics as the conventional machine bed.

Particular attention should be paid to the accuracy of the grid position bores, location stops, and to the geometric tolerances allocated to them. In all combinations the latter should be within the accuracy capability of the machine.

Calibration

Bores and location stops were accurately calibrated and all data processed using a Fortran program to give:

1. taper per unit length
2. location bore centre distances
3. bore centre to location face distances.

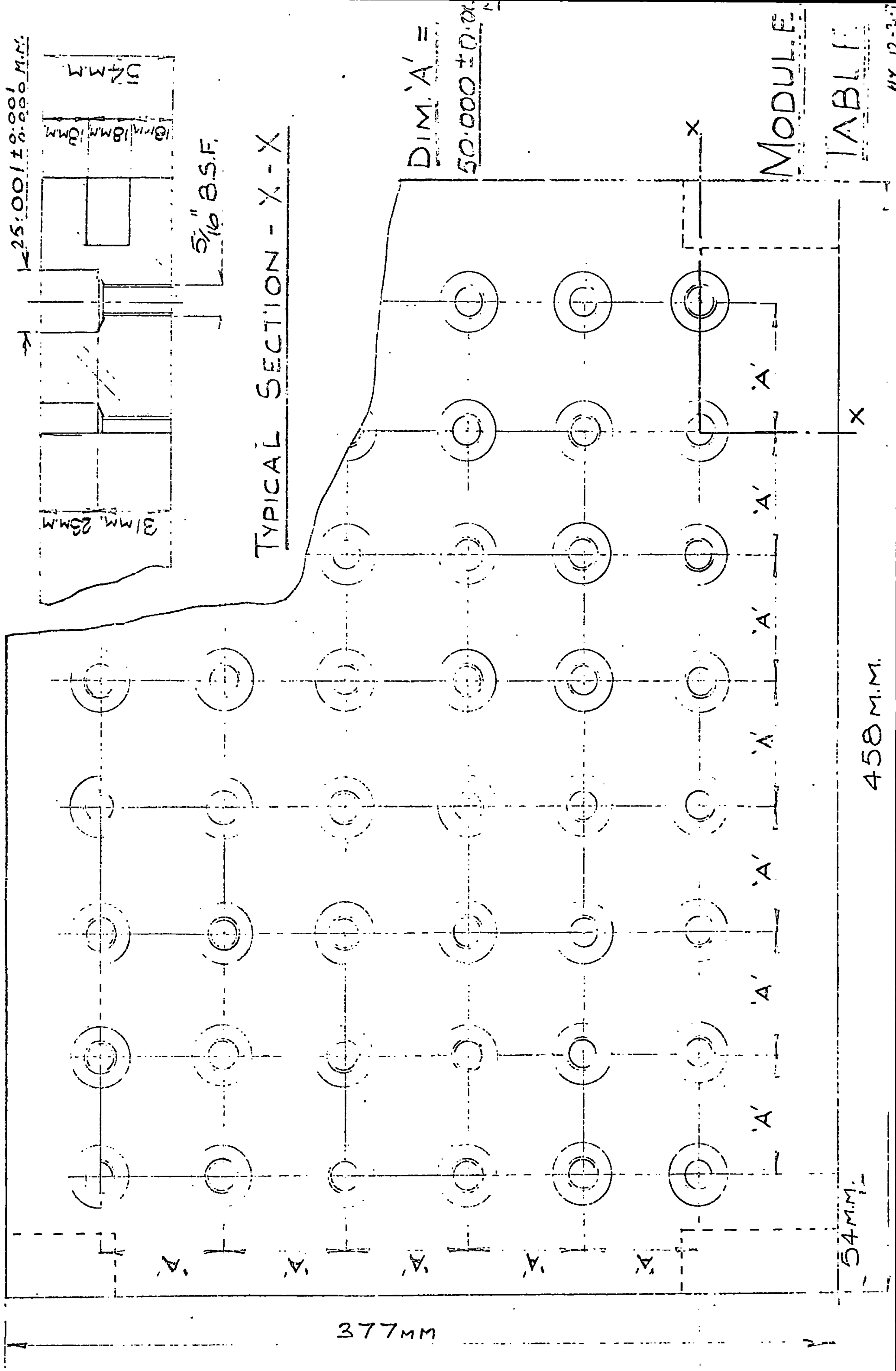

25.001 ±0.001/0.000 M.M.
54M.M
18M.M
18M.M
18M.M
5/16" B.S.F.
TYPICAL SECTION - X - X
31M.M, 25M.M
DIM. 'A' =
50.000 ±0.001
MODULE
TABLE
X
X
'A'
458 M.M.
54M.M.
377MM
63.5MM

Fig. 24

A coding system was used to ensure accuracy of location stops in all combinations of their positions in the module table.

The dimensional accuracy obtained can be seen in appendix B where an extract from the line printer output is shown.

Error Elimination (Manual Programming)

As previously stated in programming economic considerations, the majority of N.C. machines in use in the United Kingdom, estimated at 75% by W.H.P. Leslie (9), are point-to-point, programmed by completely manual methods.

It must be acknowledged that numerical control alters the practice and system of manufacture and unless an accurate control medium, at present in the form of punched or magnetic tape, can be produced its full potential will not be realised.

With the latter thought in mind, the following program has been developed to check format errors during the production of a control tape. Also to ensure the programmed instructions are accurate and in a form that will enable a machine tool to produce an acceptable part.

Equipment

Newall 1520 Auto Positioning Boring and Milling Machine.

The 1520 is of column type design, with open table access.

Table movement can be controlled automatically or manually.

Quill head control is manual only.

Table and cross-slide are mounted on widely spaced vee and flat sideways. Clamps are also incorporated to prevent table movement.

Measurement systems, automatic by Airmec AEI N410, manually by the Newall linear system.

N.C. System Airmec - AEI N410

The control system operates by comparing the programmed position and the position of the machine axis, the table being driven towards the programmed position by a positioner unit measuring absolute angle, until the two positions coincide.

Accuracy is maintained by the use of a very accurate leadscrew, any errors in position being corrected by a cam in the drive gear box.

Backlash is eliminated by ensuring the approach to the final position is always in the same direction.

The required table co-ordinates may be selected in two ways:

a) Manual control panels in which the co-ordinate values and machine functions can be dialled in.

b) A punch tape reader.

The tape reader mechanism embodies a toothed sprocket drum which engages with and supports the tape. Each indexing pulse transmitted to the reader causes the sprocket to move one pitch. Tape reading speed 12 characters per second.

<u>COMPUTER FACILITIES</u>

TYPE	ICL 1902/A
STORE	16,000 words.
	24 bits per word.
	Cycle 1.8 sec.
HARDWARE	Floating point arithmetic unit.
MULTIPLEXER	8 channels.
LANGUAGE	ALGOL
	FORTRAN IV
	COBOL
	NICOL
	PLAN
	SLANG
ELLIOTT 803	Simulator and Mercury Simulator.
	Limited multiple on line processing
	2 Disc Transports
	6 discs each and 10 surfaces per transport
	8,250,000 per transport.

1 Line Printer (300 L/m)

1 Paper Tape Reader (1000 Ch/s.)

1 " " Punch (110 Ch/S.)

1 Card Reader (300 cards/m).

METHOD OF PROGRAMMING

All the tape control data was coded into paper tape, one line of control data being represented by one block of coded characters. The blocks were separated by a block marker which enabled the Autoset to identify the beginning and end of each block.

The following table shows the headings of the columns that a layout sheet must have. The words that may be programmed are also given, showing their letter address if any, and the number of digits that each word must have.

PROGRAMME FORMAT

Operation Code No.	Coordinates	Machine Functions	Sequence No.
(1)	x(6) y(6)	t(3)	n(3)

A block of control data may contain one or all of the above control words. Any words that are programmed must be punched on to the tape in the order as shown.

OPERATION CODE NUMBER

A single digit; no letter address. Operation code numbers are effective only for the block in which they are programmed.

Their purpose is to modify the normal function of the equipment when a slightly different mode of operation is more suitable for a particular operation.

Each operation is effected by operating the auto start button.

At the start of a programme the tape reader of the Autoset reads the first block of information and any commands in that block are initiated; the tape reader continues to read forward the next block up to the 't' code, therefore any 'x' and 'y' numerical data is read in advance, and stored. Except when milling mode is called (by the appropriate t code), positioning will not take place until the quill is fully retracted to top limit.

On operating the auto start button again, any stored 'x' and/or 'y' commands are effected immediately and the machine moves to bring the positioners to balance with no delay for tape reading; while positioning is taking place any programmed 't' words and 'n' words are read and the reader continues again to read any 'x' or 'y' information in the next block as before.

The operation code numbers and their effect on the normal function of the Autoset applied to this machine are as follows. Note that they apply only to the block in which they are programmed.

1. STOP PROGRAMME. After all the commands in the block have been carried out the tape reader is halted, i.e. inhibits the tape reader reading forward. Reset when the auto start button is operated.

2. OMIT MACHINING. Signifies that no head cycle is required for that block, therefore, after all the commands in the block have been completed the next block is initiated without the need to operate the autostart button, i.e. the next block is linked to make a continuous cycle. Normal function is resumed when all linked blocks have been completed.

3. OMIT MACHINING AND STOP PROGRAMME. Signifies that no head cycle is required but that after all the commands in the block have been carried out the tape reader is halted. Reset when the autostart button is operated.

TEST PIECE PROGRAM (For component used see fig. 22).

OP. CODE	Coordinates X	Coordinates Y	Seqn. No. N	Instruction
	X035000	Y125000	N001	Centre Drill
	X065000		N002	
	X095000		N003	
	X125000		N004	
	X155000		N005	
	X185000		N006	
	X215000		N007	
	X125000	Y215000	N008	
		Y185000	N009	
		Y155000	No10	
		Y095000	N011	
		Y065000	N012	
1		Y025000	N013	
	X018935	Y018935	N014	Load Tap Drill
	X040148	Y040148	N015	
	X061361	Y061361	N016	
	X082574	Y082574	N017	
	X103787	Y103787	N018	
	X146213	Y146213	N019	
	X167426	Y167426	N020	
	X188639	Y188639	N021	
	X209852	Y209852	N022	
	X231065	Y231065	N023	
	X018935		N024	
	X040145	Y209852	N025	
	X061361	Y188639	N026	
	X082574	Y167426	N027	
	X103787	Y146213	N028	
	X146213	Y103787	N029	

OP. CODE	Coordinates X	Y	Seqn. No. N	Instruction
	X167426	Y082574	N030	
	X188639	Y061361	N031	
	X209852	Y040148	N032	
1	X231065	Y018935	N033	
	X086732	Y032612	N034	Load 10 MM
	X163268		N035	
	X217388	Y086732	N036	
		Y163268	N037	
	X163268	Y217388	N038	
	X086732		N039	
	X032612	Y163268	N040	
1		Y086732	N041	

PROGRAMMING ERRORS

Considered under two headings; (a) Format errors, (b) geometric or dimensional errors.

(a) Format Errors

Generally known as alpha-numeric errors, can occur both in the language, and the sequence in which they are written. Any deviation from the prescribed coding constitutes an error.

(b) Dimensional Errors

Usually arise from mistakes in the coordinate data, and can still exist when program format is correct.

FORTRAN ERROR SEARCH PROGRAM

General Description

The following program has been developed primarily to check format errors, and in the latter stage, dimensional errors using a graph plotter.

The technique employed in the program is to feed in a single block of data to the computer. Having then established the validity of the block the answer will appear in line printer output, for visual checking by the programmer. Tape output can also be used for dimensional error checking using a graph plotter.

Appendices A and C show the pattern of N.C. machine tool data being checked for format and dimensional errors respectively using the Fortran error search program.

PROGRAM OPERATION (see fig. 25)

1. The Fortran program T.E.S.P. in disc form is presented to the compilers and fed in. The compiler is now ready to accept the N.C. control tape data.

2. Machine tool data on the control tape is received by the compiler a block at a time into a storage area.

3. The main program now begins. The data in the block being sorted and identified into numbers and letters.

4. Starting at the beginning of each block and working through, each section is identified and sent to sub sections for checking.

5. Each section of a block is tested for relevance in these sub sections.

6. When the series of checks are completed the answers are sorted and directed.

7. If an error has been found the error message is called and a visual message on line printer out-put is provided for the programmer. The block containing an error is then abandoned and new one read in.

8. If the information is correct, the data it represents may be presented for visual display in line printer out-put and also tape out-put for use with a graph plotter for dimensional error checking.

9. The program will then either return to the block of information in store (2) to process the next section of data, or may proceed to (1) to read in the next block of data from the control tape.

GENERAL FLOW DIAGRAM

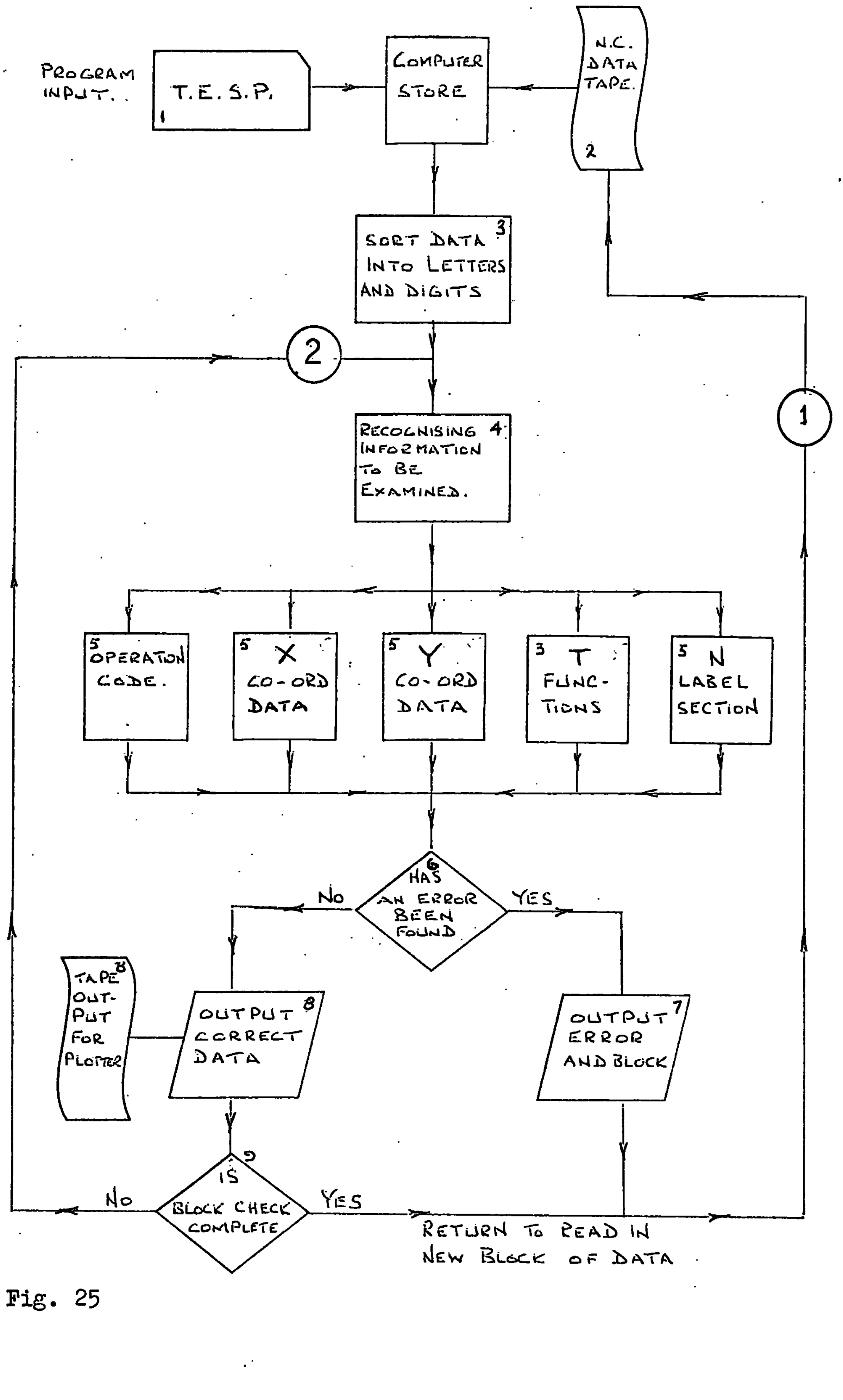


Fig. 25

Using the Fortran error search program 120 blocks of information on line printer output can be produced in two minutes, and any existing format errors shown on the line printer output can be located immediately.

Checking carried out by an experienced programmer for the equivalent number of blocks would take fifteen minutes. Also this line by line method of checking is extremely tedious and there is no guarantee of accuracy.

It must be borne in mind that a core store of 5K is required to use the error search program. There are, however, many companies in the U.K. using manual programming methods for short batch production, who do have this facility. Therefore the error search program could be used to considerable advantage when manually programming N.C. machine tool data.

CHAPTER 10 CONCLUSIONS AND RECOMMENDATIONS

The economic justification of numerically controlled machine tools will depend upon careful consideration of the following facts:-

Direct Savings

The direct savings, which can be expressed in terms of time and money, may occur in the pre-production stage by the simplification or elimination of jigs, fixtures and special tooling. At the production stage, savings are due to the exclusion of marking out, and reduction in setting, machining, handling and inspection times. As a result of improved product quality, fitting and assembly times are reduced at the assembly stage.

Savings achieved in the pre-production, production assembly and fitting stages are determined, to varying degrees, by component complexity and batch size. These facts are illustrated in chapter 6 table 3, and from the graphs (figures 20 and 21) it can be seen that for batch sizes from three to one hundred and twenty, tape control is economically advantageous. Numerical control can be readily justified for complex components over a much wider range of batch sizes. Long contouring operations represent a special case in practice and numerically controlled methods can usually be justified technologically.

Indirect Savings

Indirect savings, which can be attributed to the introduction of numerical control, should involve the following considerations.

Jigs, fixtures and special tooling can be eliminated, therefore, considerable savings can be made, due to the liberation of design, manufacture, maintenance and storage of these items.

Production operations, such as marking out, can be dispensed with and inspection reduced. Savings in these areas are not total as time is taken proving control tapes on the machines.

Machining errors are reduced under numerical control once input data has been verified as correct; a fact that may be of overriding importance where the component value is high, due to expensive machining operations.

An important asset of numerically controlled methods is the ease with which a program can be altered in order to accommodate design change. Where jigs have been used conventionally, modification was a lengthy and expensive process. Savings in transportation of parts between operations, progressing, inspection and storage due to the elimination and shortening of operations thus creating a reduction in lead time, which consequently reduces the volume of work in progress.

Machine operators can be directed to such tasks as controlling a number of machines, inspection duties and tool organisation, as direct involvement with the operation is considerably reduced.

Intangible savings are difficult to assess but can show quite significant benefits in the following areas: operator fatigue causing scrap, particularly where the work is of an accurate and intricate nature; reduction in cutting tool costs, due to their more disciplined use; production can be switched between machines or factories with an assurance of consistency, (the alternative to the transfer of control tapes is the costly and complex removal of machines).

The cost analysis (pages 33-37) based on the factors discussed, show a saving on one machine of £559 per annum for single shift working and £2,830 when working a two shift system. A further example (page 42) based on component quantity, shows a saving of £7,272 per annum.

Justification calculations of the type mentioned in the previous paragraph are essential when considering the introduction of numerical control. This fact is emphasised when data obtained from the use of numerically controlled machines is used in a short cut calculation (page 51). The facts obtained from the latter method would be a deterrent to potential users of numerical control.

The analysis of capital investment, Chapter 5, has shown that accurate forecasting and alternative methods of investment must be considered to yield the quality of decision necessary for investment in numerical control. From the example calculated, numerical control proves to be financially the more attractive method, providing the factors affecting the following points are considered:

(a) the rate of discount employed and (b) the accuracy of the cost saving figure.

Programming Economics

In order to decide which is the better method of programming, it is essential to take into account, primarily, the economic factors. Assuming that computer assistance is chosen for the production of control tapes, the most suitable program system must be selected to meet the requirements of the company, both technologically and economically. Furthermore, the relative merits of either an in-house computer or a computer bureau service need to be analysed.

The latter considerations are summarised in Chapter 7. Provided the decision has been made that computer assistance in preparing control tapes is essential, also that a program system exists which is satisfactory, the decision process outlined can be used. If the data obtained from using the decision process is entered on a comparison chart, as described, the many different options will be reduced in number and a logical conclusion arrived at.

It is an established fact that manual programming is the most widely used method of preparing control tapes and the initial cost calculated only takes into account a control tape ready for prove-out. The prohibitive costs required to ultimately produce a correct tape emphasises the urgent need for program development to include an error checking facility in this area of control tape production.

The program developed using Fortran IV shows considerable benefit in time saved checking manually programmed data away from the machine, therefore, reducing downtime.

Direct savings would be due to profit from continued production, using a machine of high capital value at the rate of £10 per hour. This would be an additional saving to costs incurred by prove out runs on the same machine. A further saving would be the time taken by a planning engineer to check the equivalent amount of data. Against these savings there is, of course, the cost of running the program on the computer.

Intangible savings from such facts as no guarantee of accuracy from manual checking, resulting in scrap work and no accurate knowledge of the number of proving runs required to produce an acceptable part,

Using the subroutine at the end of the error checking program, tool position can be checked to an accuracy dependent upon the type of graph plotter used. This can be as low as 0.02 mm. and it is, therefore, quite feasible to note dimensional errors visually of this magnitude, if the chart is used on an optical projector.

The error checking program now available on disc in the Computer Department of the Polytechnic will be offered as a checking service to industry in the region, using the same program format.

Further advantage can be gained from using preset tooling and module tables, as shown in Chapter 9. The magnitude of the errors which occur in this area are usually in the order of 0.02 mm., and are often not located until the component assembly stage.

Every possible effort should be made to eliminate errors from the control tape without creating machine downtime, therefore, the advantages gained from using the type of tooling mentioned above should be fully exploited.

The decision to invest in numerical control should only be taken after making an economic appraisal, centred on the relative economics of numerically controlled equipment compared with existing manufacturing methods, embracing all the facts discussed in this thesis.

APPENDIX A

PROGRAM DESCRIPTION T.E.S.P.

This is a Numerically Controlled Machine Tool Tape Error Search Program (T.E.S.P.). It is designed to examine 8 channel tape that has been prepared for an N.C. point-to-point jig boring machine.

The program is written in Fortran IV and is available on disc in the Polytechnic's ICL 1902A computer.

PROGRAM DESCRIPTION SEGMENT

Input

The tape reader unit is used to input the N.C. tape to the computer, the program will read this tape a block at a time until the end of the tape is reached.

Output

The program is designed to give two forms of output: (1) Line printer paper, (2) Paper tape.

(1) Line printer output (see Appendix A, page 123 for layout) gives visual representation of the processed N.C. tape information. The status of each block of N.C. data will be shown by the printout position on the page. Errors are made easily visible by the format of the script.

(2) The tape output is used on the Elliott 803 computer to drive the graph plotting machine and give a visual co-ordinate representation.

MASTER SEGMENT DESCRIPTION

Every Fortran IV program needs a defined master segment for the program to be operational. The master segment in this program is given the initial letters of the program title, i.e. T.E.S.P.

At the beginning of the program, instructions are given that define the mode in which the program is going to be operated. Constants are set up and the preparations for the program to run effectively are made.

M1.12 This statement brings into the computer the first and each block of N.C. data to be processed. Because the nature of each character in the block of data is initially unknown, a counter is set up, M1.14 and a loop of program performed with each character in the block, to establish whether it is a number or a letter, and also to store it in its correct representation. This is performed in the section M1.15 to M13.10. It is done by comparing the store value within the computer with known store values for specific numbers, and hence it is possible to attain their real value.

When this first sort of the block data into a more handlable form is complete, the program segment must examine block data in detail to decide which section of the data is to be checked.

In M3.11 a variable (JJ) is set up which throughout the program will check by testing against constants to ensure that the data has been presented in the correct order.

The correct data presentation order can start with an Operation Code. So the loop of program MS3.12 to MS7.14 comprises the sorting of the data starting with operation codes first into the correct SUB-ROUTINE so that each section may be checked for errors.

At the entry of this loop the first value of block data is taken and it proceeds through the contents of the loop until the section is identified. Non-identification constitutes an error. Then after this data and any further characters of the block data which may be called for has been processed, the NEXT character in the stored block data will follow the same path through the loop.

With the first data an operation code is looked for in MS3.15 and, if found, the appropriate subroutine is called MS3.16. Should this section be used at the beginning of a block it cannot be used again. The findings of the subroutine are directed at MS3.18 onward to the ERROR SUBROUTINE.

Section MS4.10 - MS4.15 decides whether the data being examined is coordinate data for the X section by deciding whether the data presented is a letter X or not. This uses a FORTRAN LIBRARY SUBROUTINE CALL COMP which will compare one set of data against a fixed set and alter a variable value accordingly. A test on this variable value provides the answer to the question of whether the examined data is an X or not. If the answer is yes the SUBROUTINE for the X section is called, if not the data passes on for further examination by the same technique for the Y, T, and N sections.

After examination in the X subroutine for errors, the error section may be called if any have been found, or otherwise the data count is updated, and the process continues with a new piece of data from the block stored.

This is repeated in the other sections.

At the end of this loop the size of the count is monitored to see if the end of the block of data is reached. MS3.18. If this is so the program returns to the beginning of the master segment and a new block of data is read in.

SUBROUTINE DESCRIPTIONS

SUB NUMBERS

In this subroutine the value of the operation code will be checked. To get as far as this subroutine a number between 0 and 9 must have been found at MS3.15, therefore it remains for this subroutine only to check the size and also the position in the block of the data.

If the number has appeared in the block after an X section has already been checked then it constitutes an error. This will be found by the test of the size of JJ at Snl.12. The acceptable size of an operation code for the machine tool system we are dealing with requires it to be a whole number greater than 0 and less than or equal to 4. This is checked at SN1.14. Depending on the answers to the checks, the subroutine will write out the checked output (1) or recommend an error signal.

SUB TEST X and SUB TEST Y

The methods employed in these two subroutines are identical, only the variable names are changed with also the different value of one constant.

The subroutines start on a check, of the order of calling up the section SX1.11.

Next the data for the next six characters is read in from the stored block and each one checked for validity as a number. SC1.14. After this the numbers are assembled into the coordinate value by raising the number to the power of ten, descending from 6 by 1 for each value read in. Each complete number is assembled by using a program loop. The size of this data is checked at SX2.10 to ensure the coordinate size is below the max. machine size of travel.

The coordinate numbers are stored in variable stores for use with the graph plotter tape output (2). If the checks have been carried, without any errors found, the section will print out the sections on output (1) or conversely the error subroutine will be called.

SUBROUTINE TEST T

This subroutine is basically the same as the X and Y described above. The main difference being that the check is carried out for the milling sequence numbers which can be between 100 and 400 inclusive.

SUBROUTINE TEST N

Again the subroutine is very similar to the previous ones, especially in the main construction. At the latter stages of the subroutine it has a check for the number size, i.e. is the label less than 999.

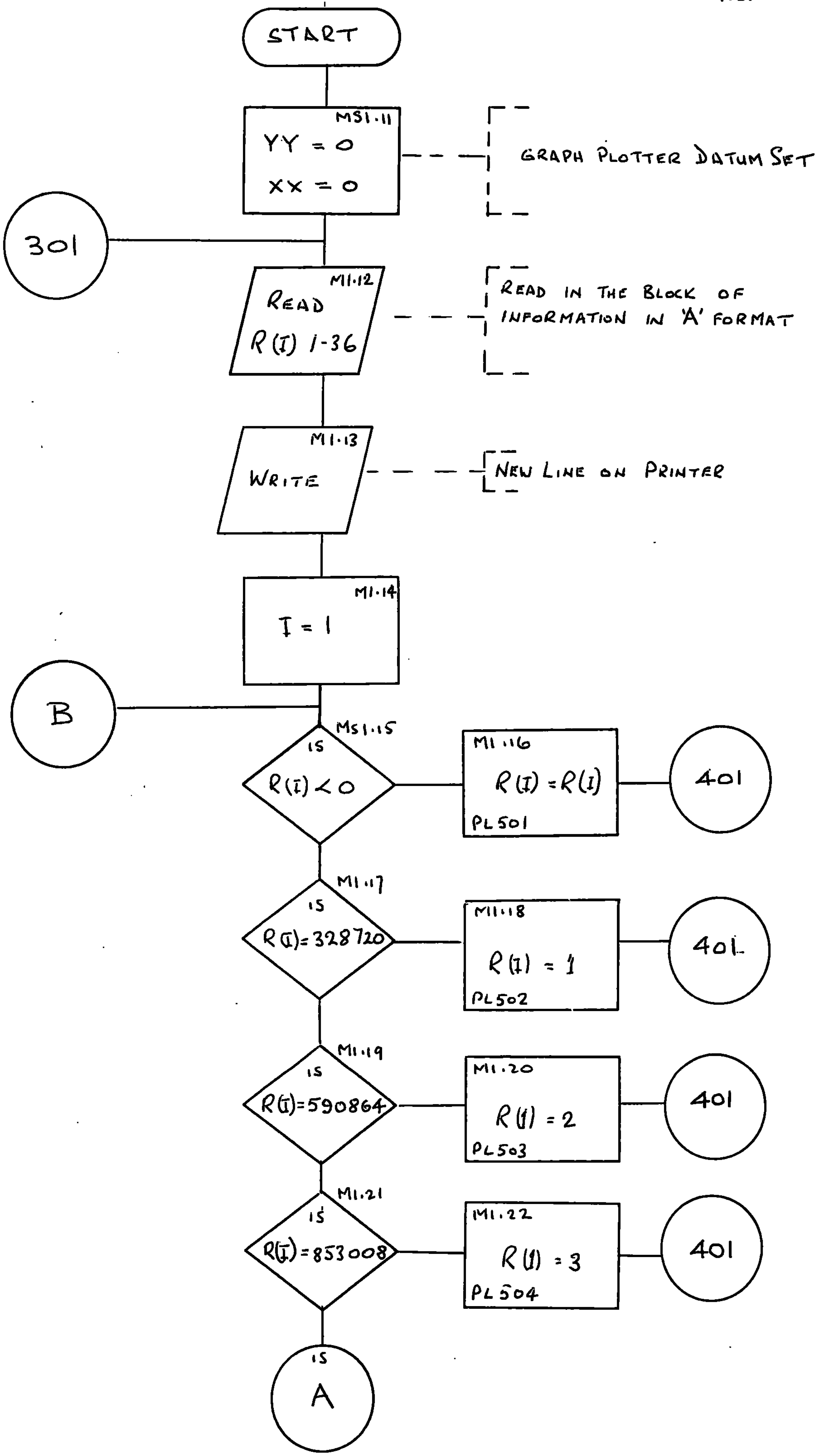
The last section involves the calling of special library subroutines for the correct output of the paper tape for graph plotting. These are in this position because the correct last section of a block of information is an N section, and here where they are correctly punched out. If there is a previous error, this is missed and hence errors of this kind show in plotting.

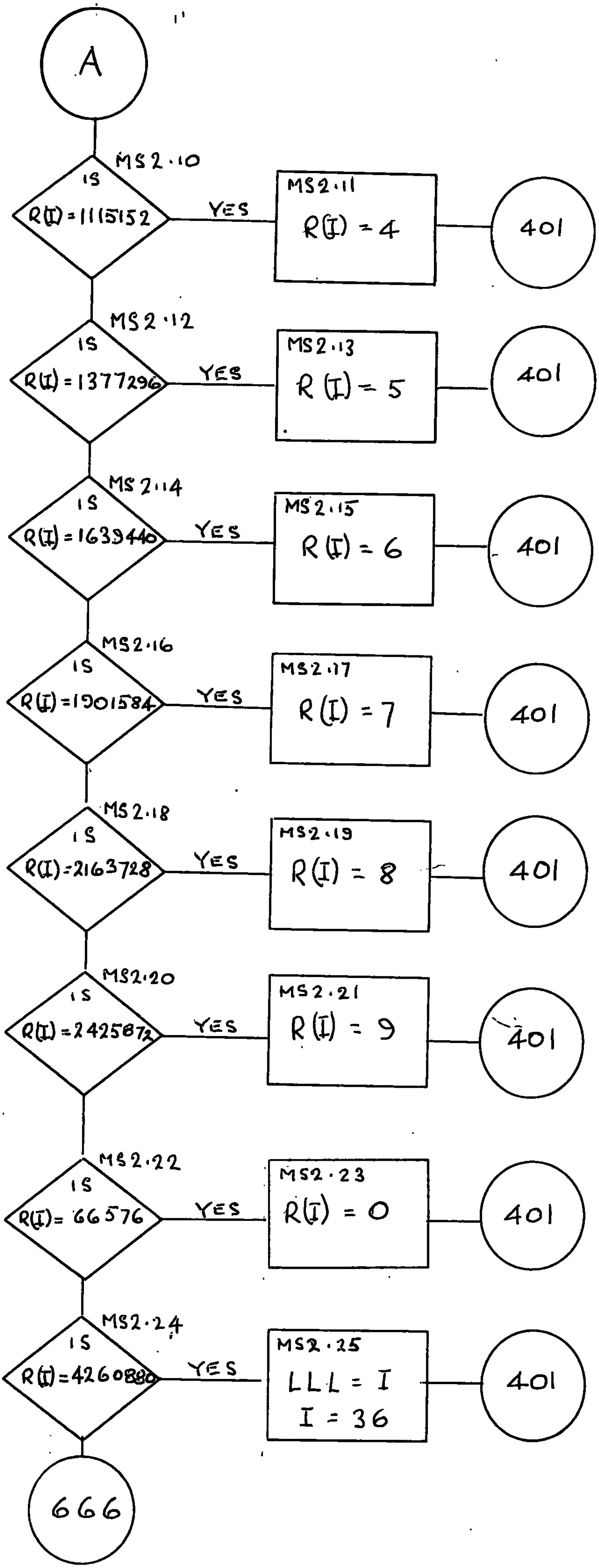
REFERENCE LABELLING SYSTEM

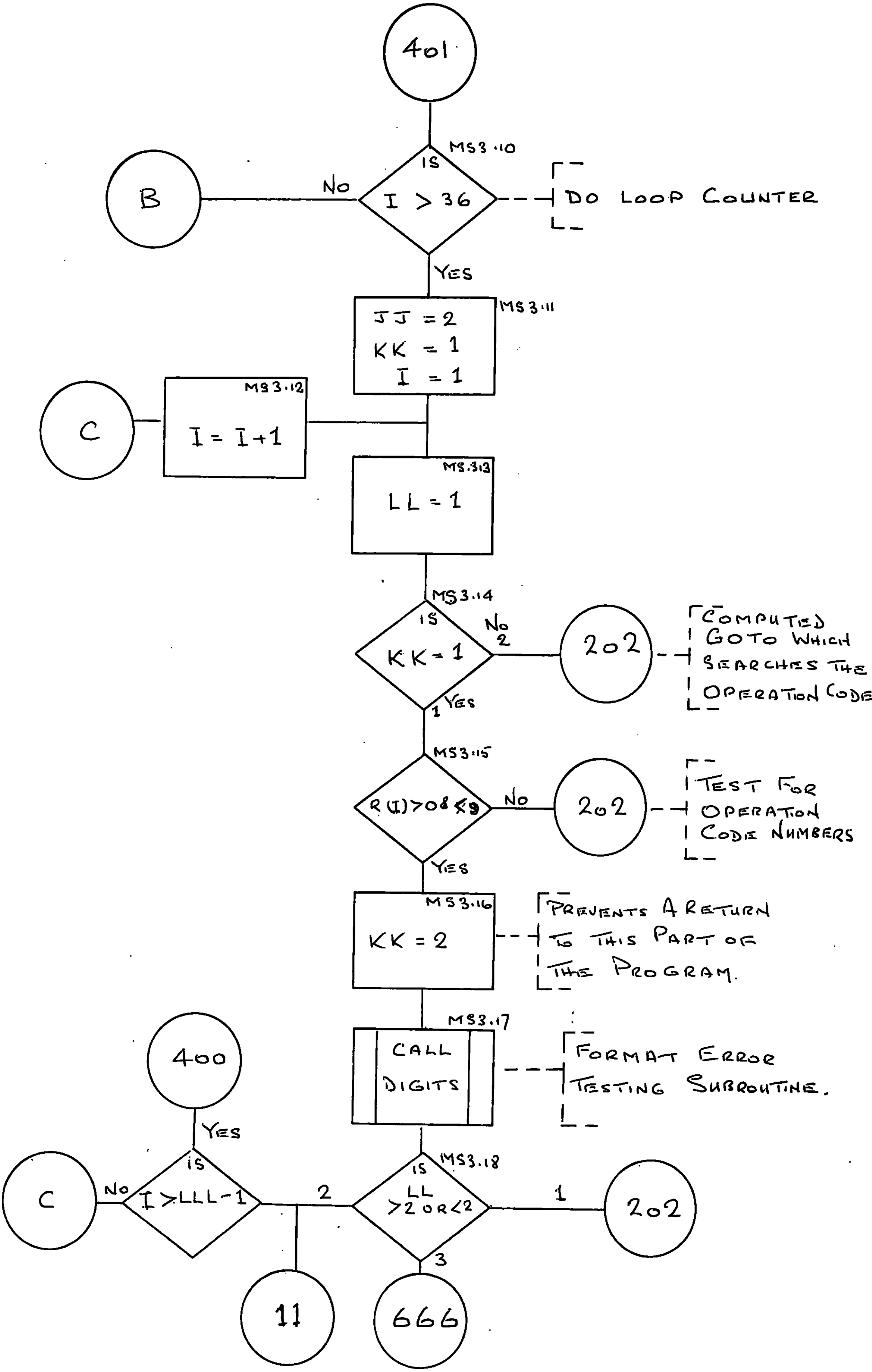
301	Position labels
500's	
400-1	Master segment DO loop labels
11	" " internal. DO loop label
12-15	Subroutine. DO loop labels
2011	Program switching and comparison routines
201	Labels
211	
231-3	Numbers. subroutine labels
241-9	Test X subroutine labels
251-9	Test Y subroutine labels
261-9	Test T subroutine labels
271-9	Test N subroutine labels
666	Call Error subroutine label
901-999	Format labels

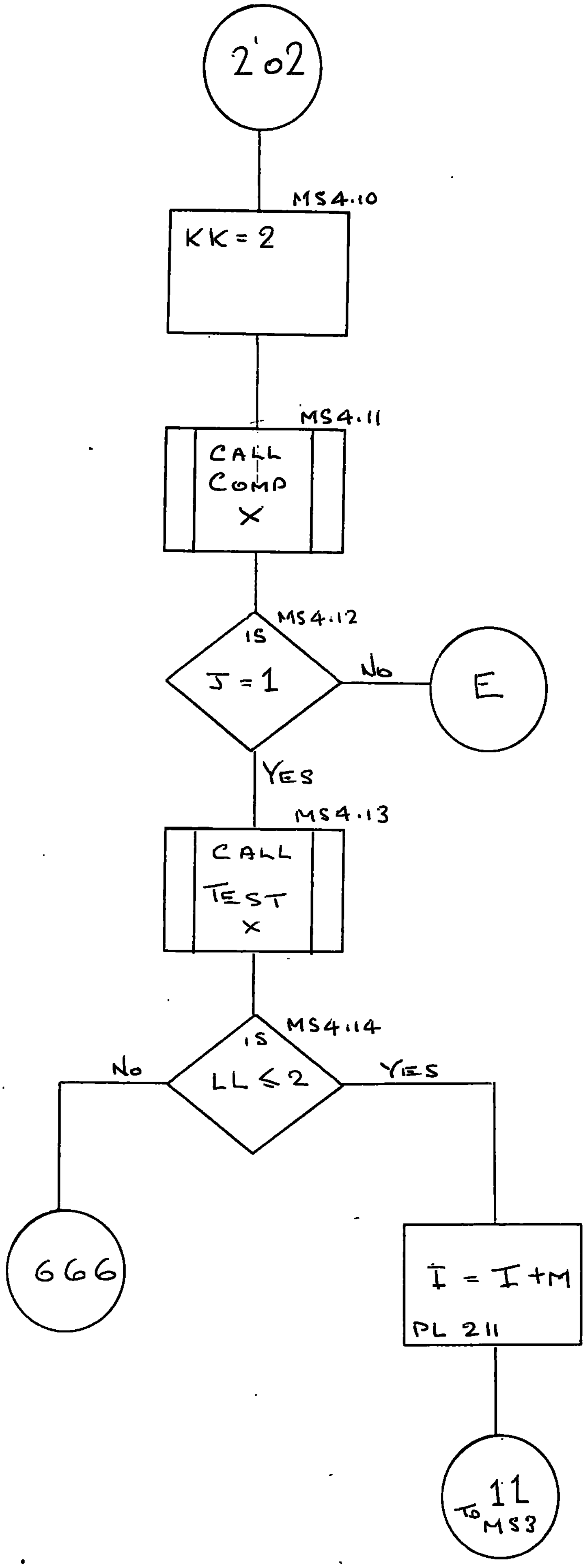
LIST OF CONSTANTS IN T.E.S.P.

CONSTANT	USE
LLL	Gives the Block size to master segment loop which processes the block information.
JJ	A progressing constant which is updated after each function subroutine and prevents order errors.
KK	A constant of 2 values which is switched depending whether an operation code has been found or not.
LL	The value of LL which may be 1, 2, 3, will determine a route the program is to follow usually proceeding or call error
J	This constant is the constant of comparison for the library subroutine named CALL COMP
M	A constant that will update the loop count on the program checks function by function through the block of information
NNOS	A no. which will govern the order sequence for the NOS subroutine
NX	A no. which will decide upon the order sequence being used in the SUBROUTINE TEST X
NY	" " " SUBROUTINE TEST Y
NT	" " " SUBROUTINE TEST T
NN	" " " SUBROUTINE TEST N

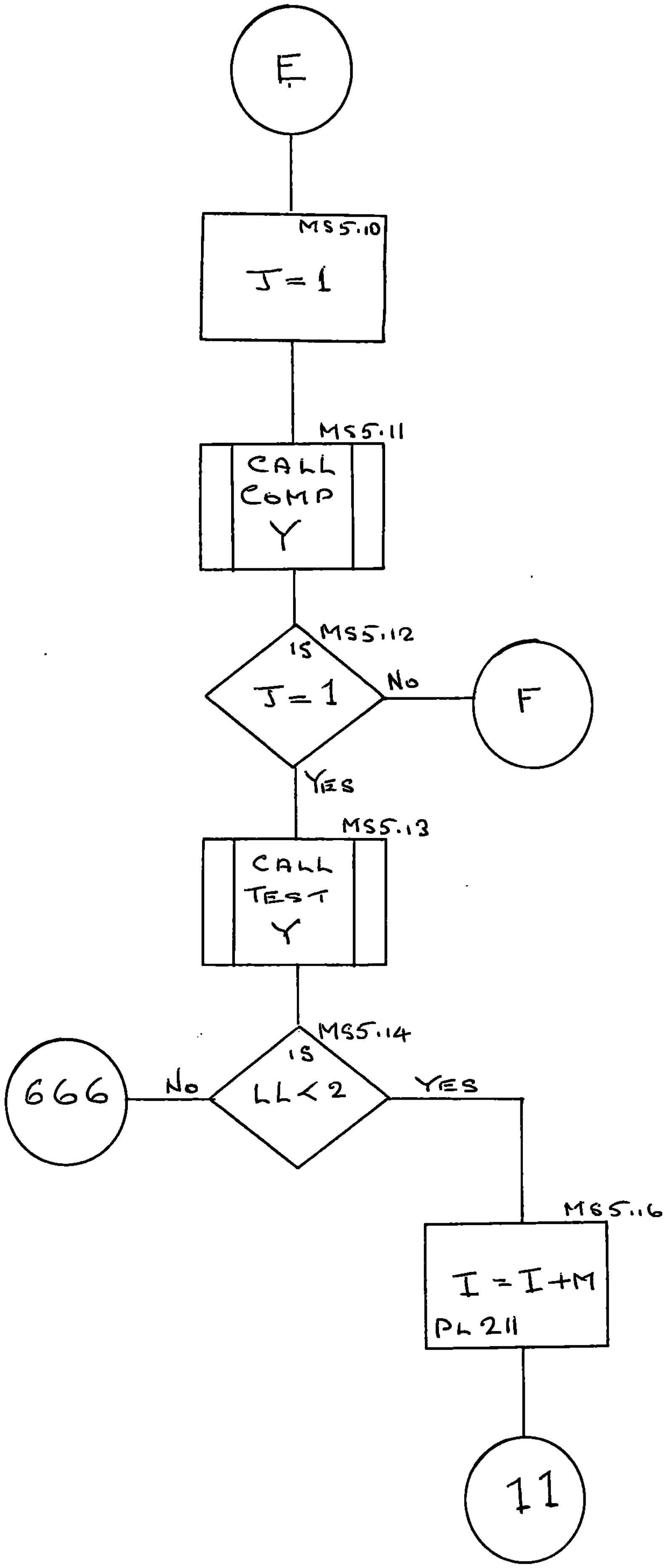

START
MSI·11
YY = 0
XX = 0
GRAPH PLOTTER DATUM SET
301
M1·12
READ
R(I) 1-36
READ IN THE BLOCK OF INFORMATION IN 'A' FORMAT
M1·13
WRITE
NEW LINE ON PRINTER
M1·14
I = 1
B
MS1·15
IS
R(I) < 0
M1·16
R(I) = R(I)
PL501
401
M1·17
IS
R(I) = 328720
M1·18
R(I) = 1
PL502
401
M1·19
IS
R(I) = 590864
M1·20
R(I) = 2
PL503
401
M1·21
IS
R(I) = 853008
M1·22
R(I) = 3
PL504
401
IS
A

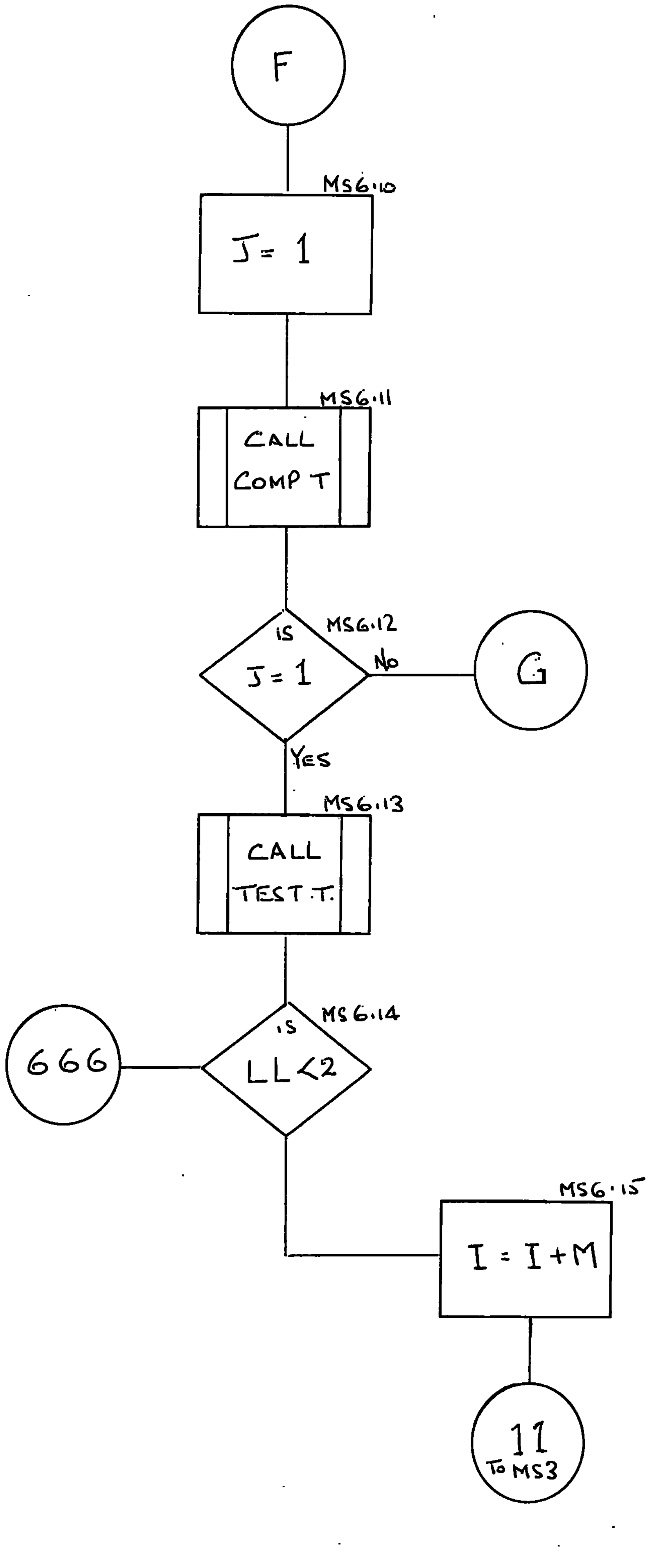

A
MS2·10
IS
R(I) = 1115152
YES
MS2·11
R(I) = 4
401
MS2·12
IS
R(I) = 1377296
YES
MS2·13
R(I) = 5
401
MS2·14
IS
R(I) = 1639440
YES
MS2·15
R(I) = 6
401
MS2·16
IS
R(I) = 1901584
YES
MS2·17
R(I) = 7
401
MS2·18
IS
R(I) = 2163728
YES
MS2·19
R(I) = 8
401
MS2·20
IS
R(I) = 2425872
YES
MS2·21
R(I) = 9
401
MS2·22
IS
R(I) = 66576
YES
MS2·23
R(I) = 0
401
MS2·24
IS
R(I) = 4260880
YES
MS2·25
LLL = I
I = 36
401
666

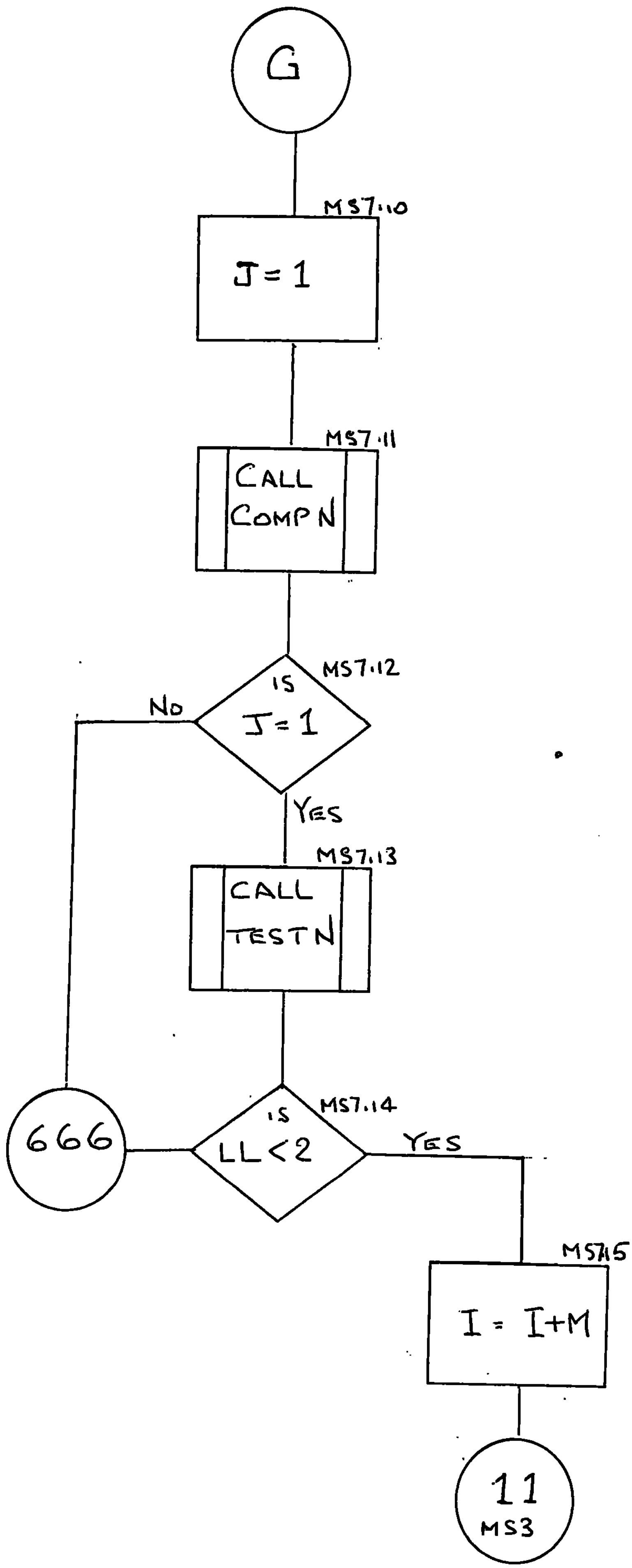

401
MS3.10
IS
I > 36
No
B
DO LOOP COUNTER
YES
MS3.11
JJ = 2
KK = 1
I = 1
MS3.12
I = I+1
C
MS3.13
LL = 1
MS3.14
IS
KK = 1
No
2
202
COMPUTED GOTO WHICH SEARCHES THE OPERATION CODE
1
YES
MS3.15
R(I)>08 <9
No
202
TEST FOR OPERATION CODE NUMBERS
YES
MS3.16
KK = 2
PREVENTS A RETURN TO THIS PART OF THE PROGRAM.
MS3.17
CALL DIGITS
FORMAT ERROR TESTING SUBROUTINE.
400
YES
IS
I >LLL-1
No
C
2
MS3.18
IS
LL >2 OR<2
1
202
3
11
666

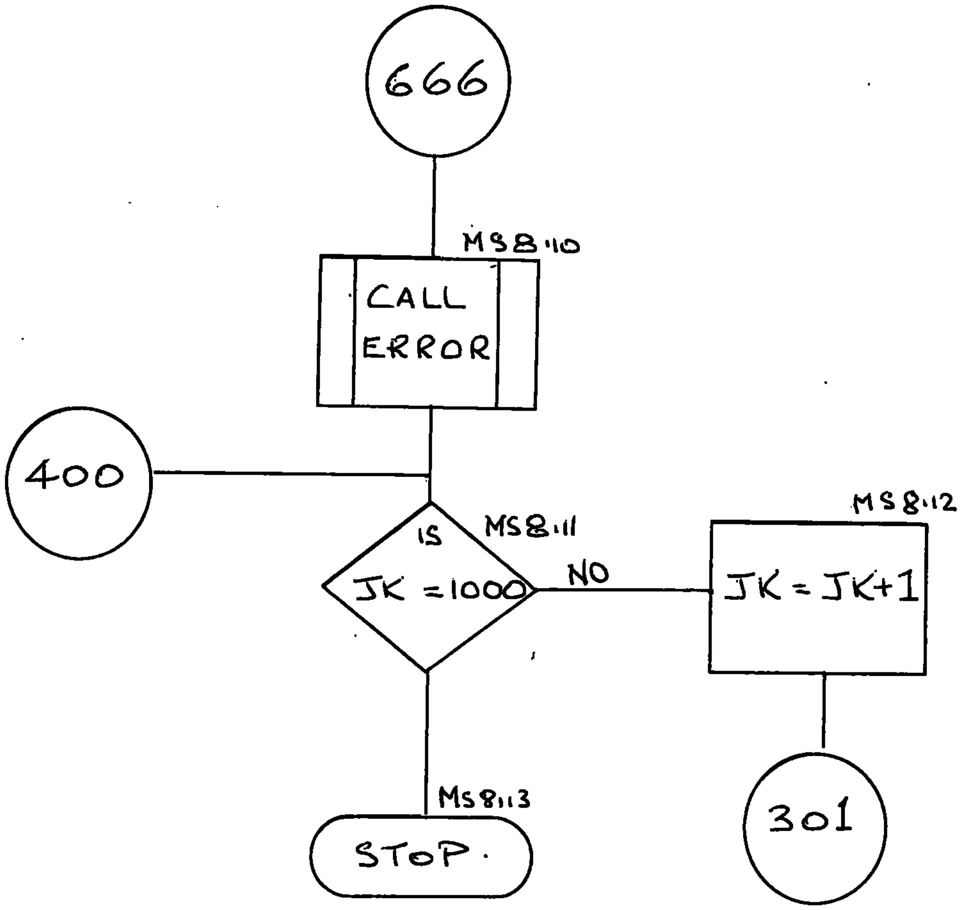


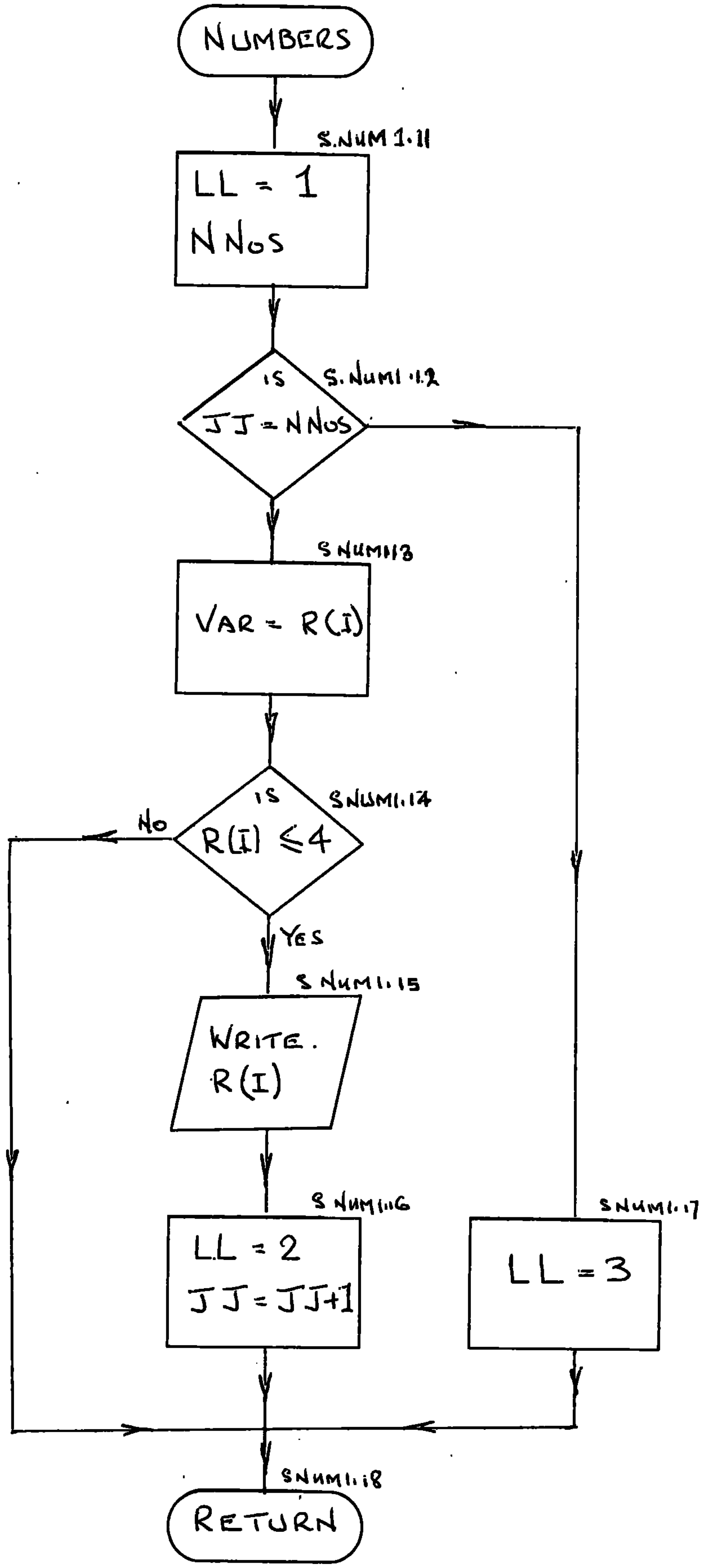
2'02
MS4.10
KK = 2
MS4.11
CALL
COMP
X
MS4.12
IS
J = 1
No
E
YES
MS4.13
CALL
TEST
X
MS4.14
IS
LL ≤ 2
No
YES
666
I = I + M
PL 211
11
TO MS3

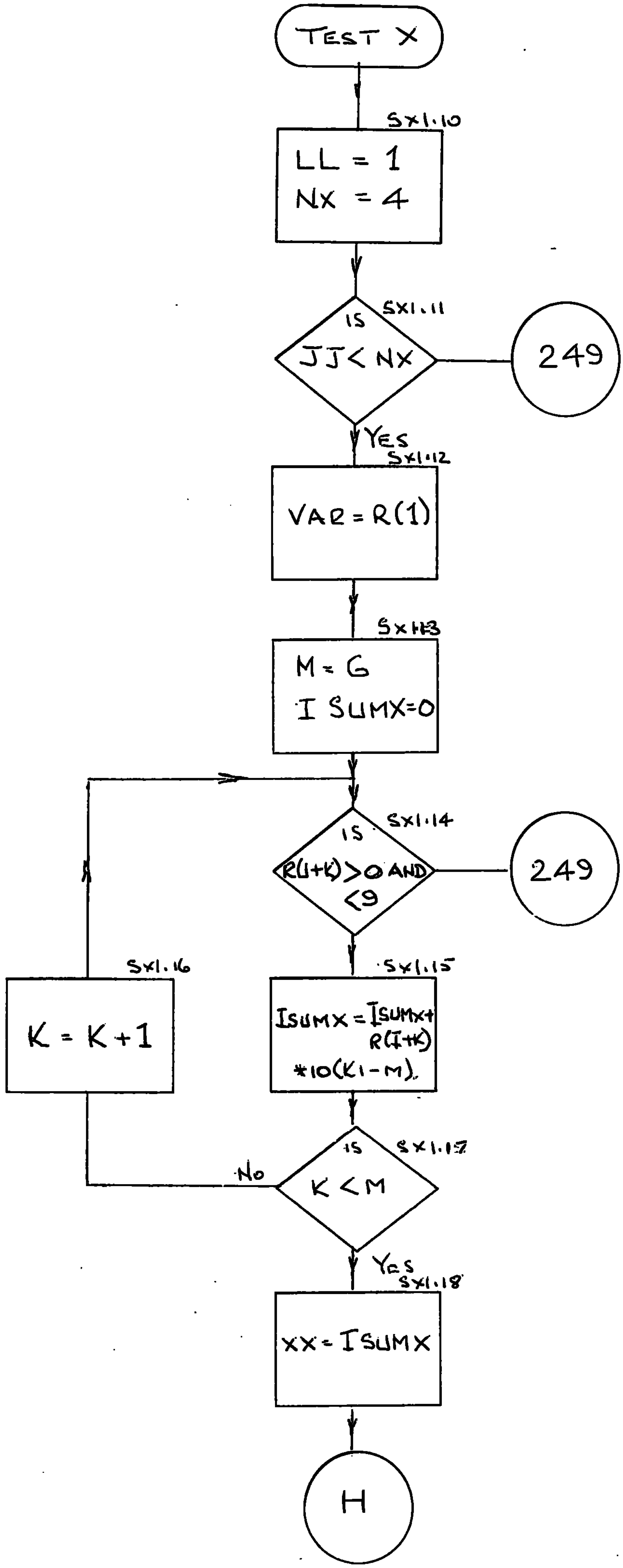

E
MS5.10
J=1
MS5.11
CALL
COMP
Y
MS5.12
IS
J=1
No
F
YES
MS5.13
CALL
TEST
Y
MS5.14
IS
LL<2
No
666
YES
MS5.16
I=I+M
PL 211
11

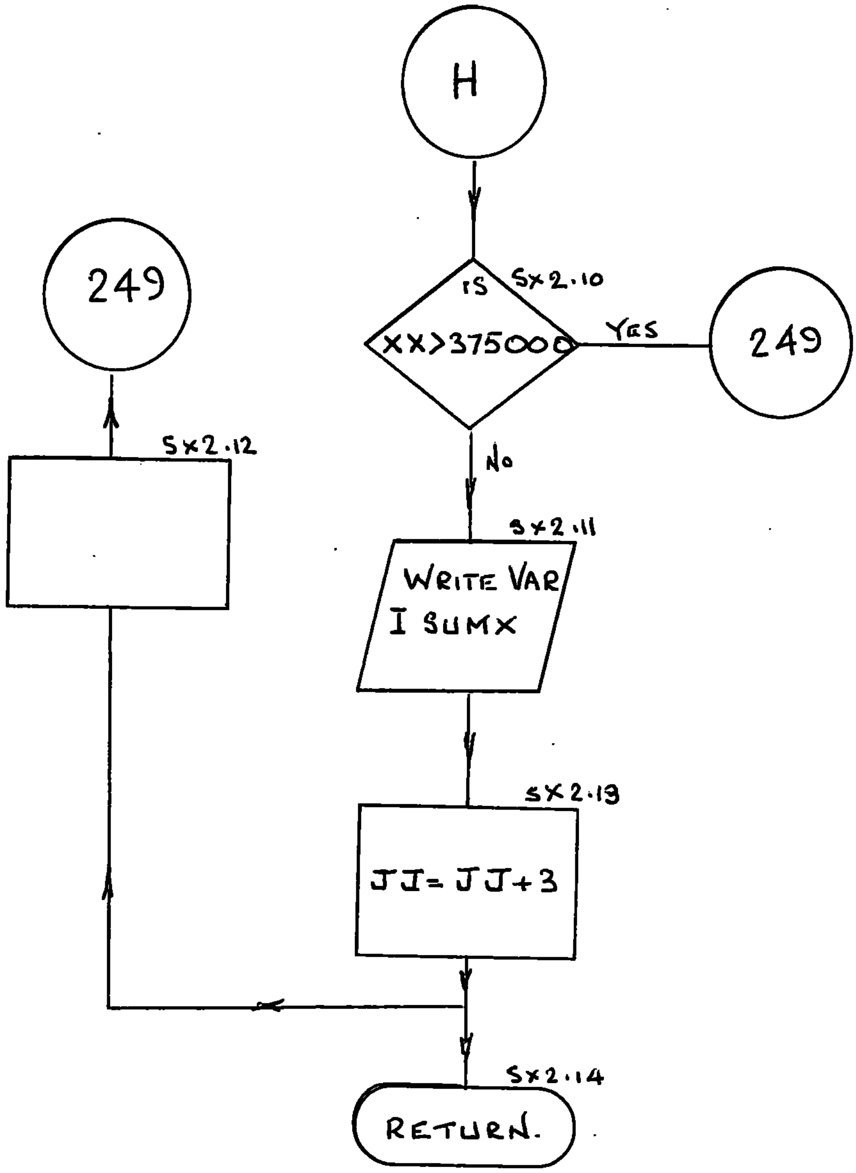

F
MS6.10
J = 1
MS6.11
CALL
COMP T
MS6.12
IS
J = 1
No
G
YES
MS6.13
CALL
TEST T.
MS6.14
IS
LL<2
666
MS6.15
I = I + M
11
To MS3

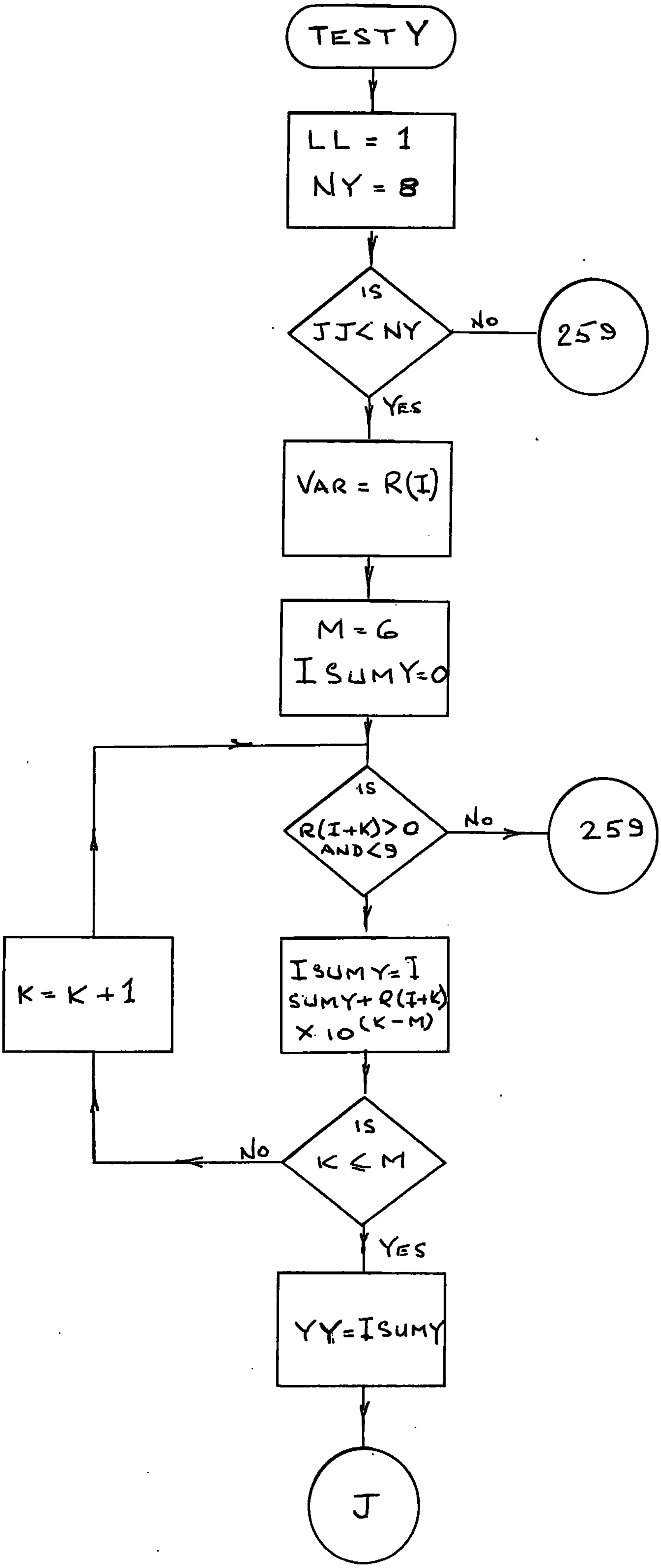

G
MS7.10
J = 1
MS7.11
CALL
COMP N
MS7.12
IS
J = 1
No
YES
MS7.13
CALL
TEST N
MS7.14
IS
LL<2
666
YES
MS7.15
I = I+M
11
MS3

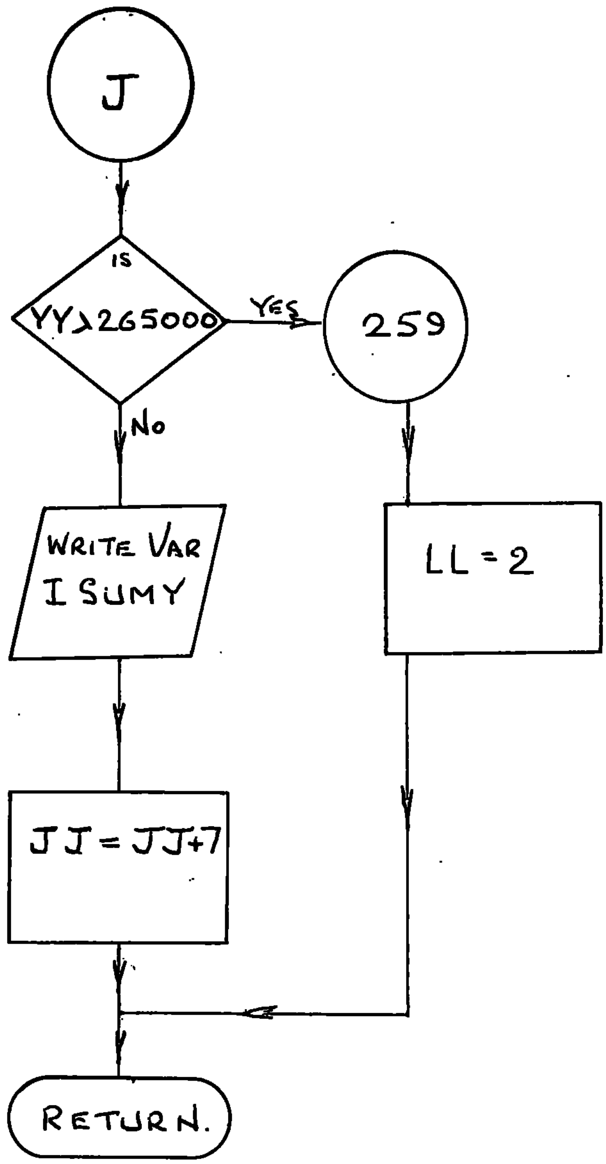

666
MS8.10
CALL ERROR
400
IS JK = 1000
MS8.11
NO
MS8.12
JK = JK+1
MS8.13
STOP.
301

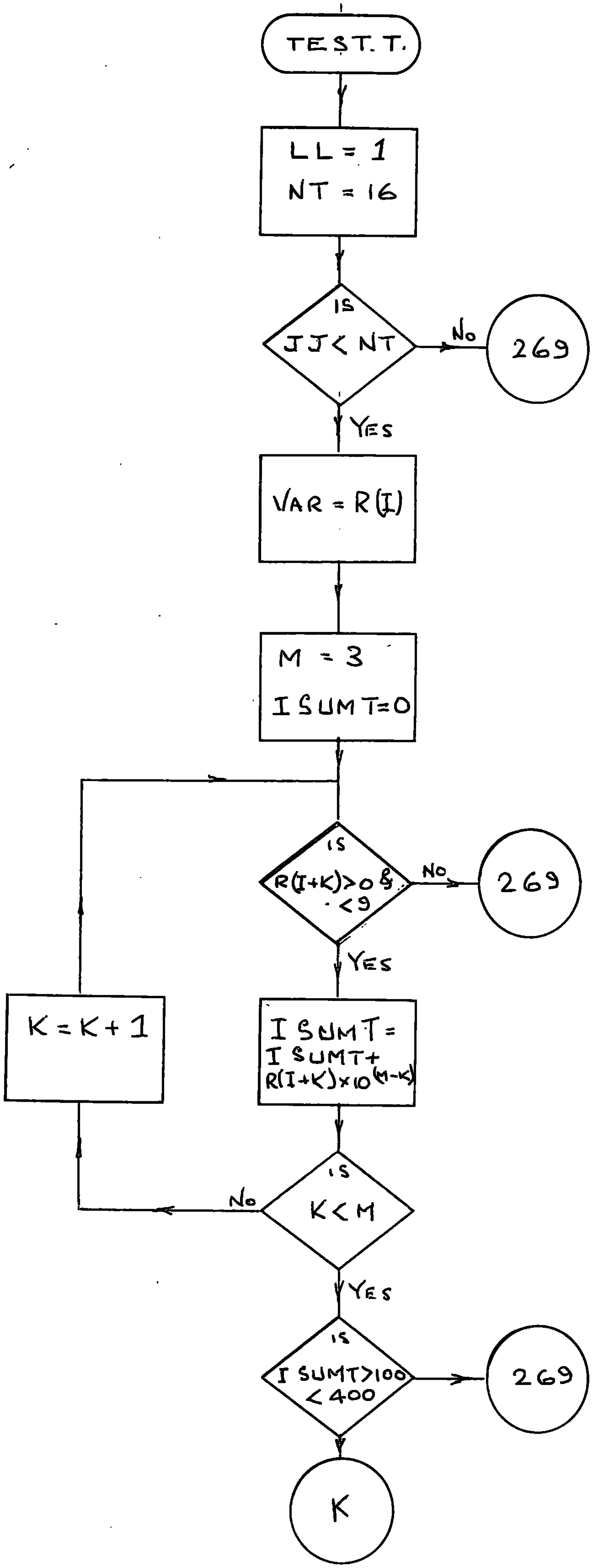

NUMBERS
S.NUM 1.11
LL = 1
N Nos
IS
S.NUM1.12
JJ = NNos
SNUM113
VAR = R(I)
IS
SNUM1.14
R(I) ≤ 4
No
YES
SNUM1.15
WRITE.
R(I)
SNUM116
LL = 2
JJ = JJ+1
SNUM1.17
LL = 3
SNUM1.18
RETURN

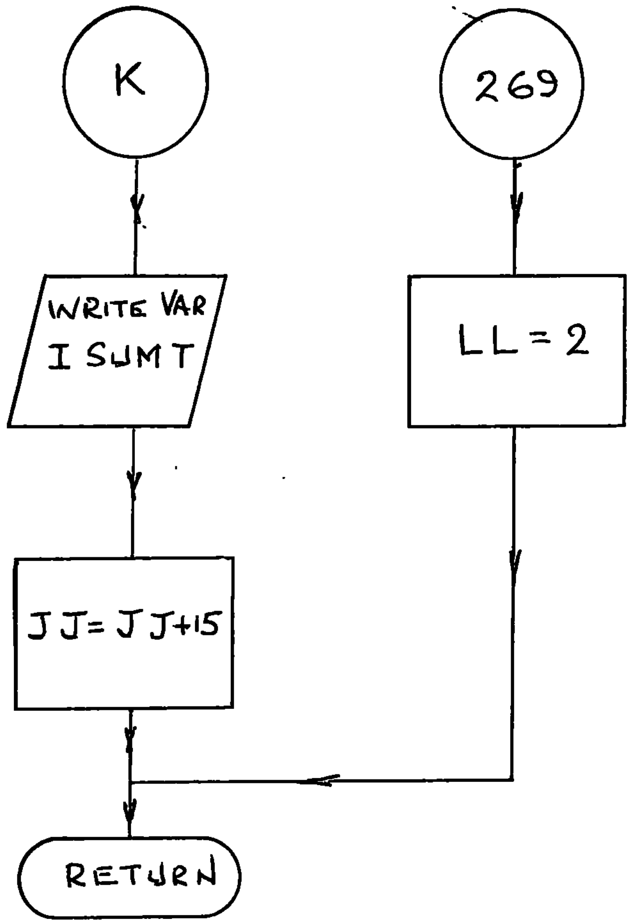

TEST X
SX1.10
LL = 1
NX = 4
SX1.11
IS
JJ < NX
249
YES
SX1.12
VAR = R(1)
SX1.13
M = 6
ISUMX=0
SX1.14
IS
R(I+K) > 0 AND
< 9
249
SX1.15
ISUMX = ISUMX+
R(I+K)
*10(K1-M)
SX1.16
K = K+1
SX1.17
IS
K < M
No
Yes
SX1.18
XX = ISUMX
H

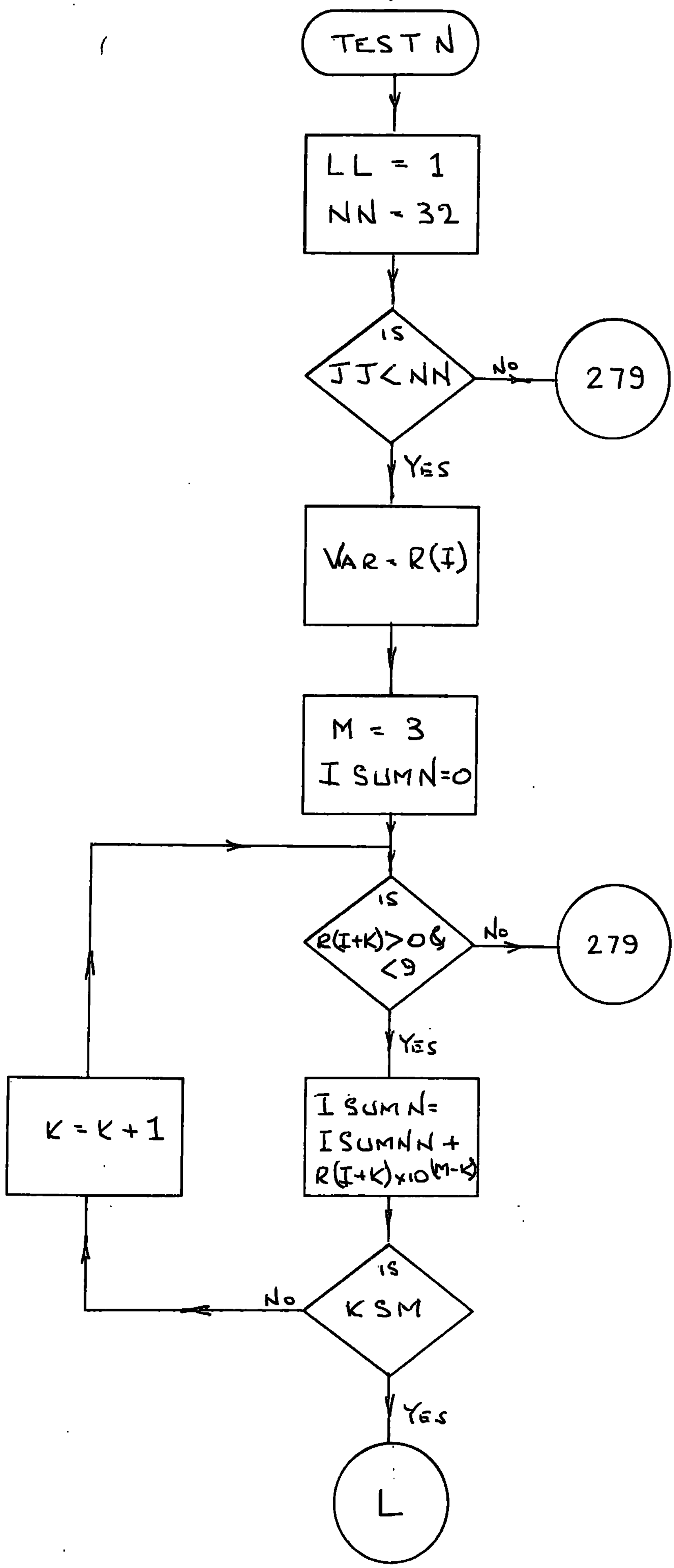

H
IS
XX>375000
Sx2.10
YES
249
No
249
Sx2.12
Sx2.11
WRITE VAR
I SUMX
Sx2.13
JJ= JJ+3
Sx2.14
RETURN.

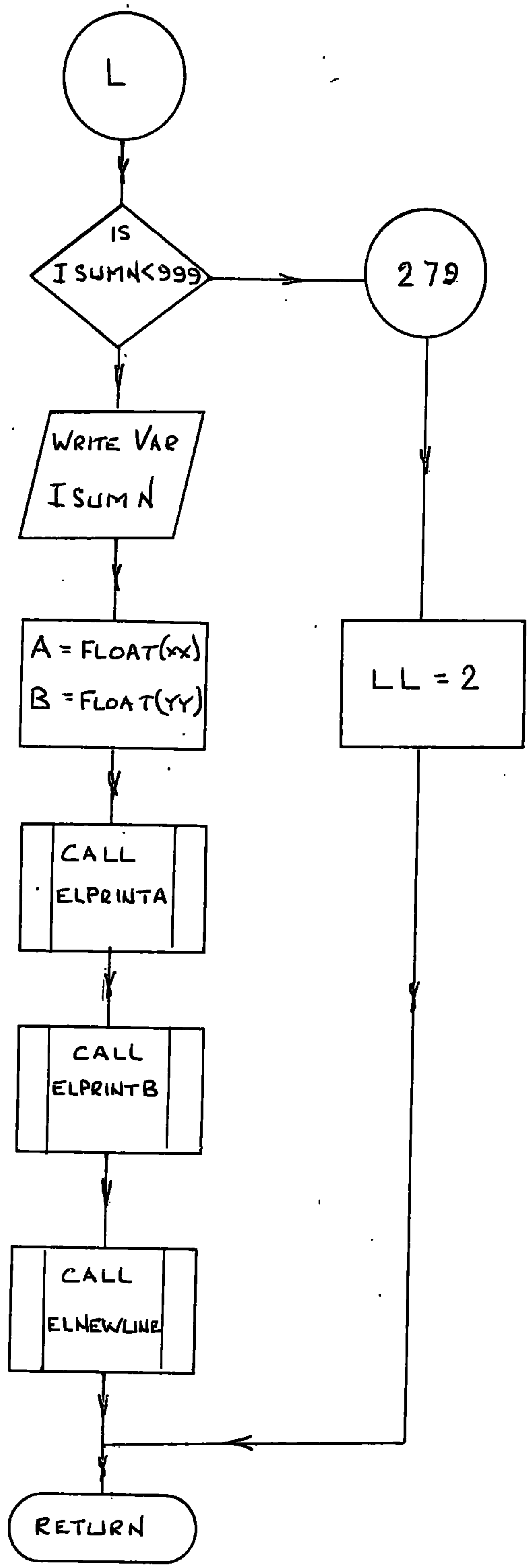

TEST Y
LL = 1
NY = 8
IS
JJ < NY
NO
259
YES
VAR = R(I)
M = 6
ISUMY=0
IS
R(I+K)>0
AND<9
NO
259
ISUMY=I
SUMY+R(I+K)
X 10^(K-M)
K = K + 1
IS
K ≤ M
NO
YES
YY=ISUMY
J


J
IS
YY>265000
YES
259
No
WRITE VAR
I SUMY
LL = 2
JJ = JJ+7
RETURN.


TEST. T.
LL = 1
NT = 16
IS
JJ < NT
No
269
YES
VAR = R(I)
M = 3
I SUMT=0
IS
R(I+K)>0 &
<9
NO
269
YES
K = K + 1
I SUMT =
I SUMT+
R(I+K)×10^(M-K)
IS
K < M
No
YES
IS
I SUMT>100
< 400
269
K


K
269
WRITE VAR
I SUMT
LL = 2
JJ= JJ+15
RETURN


TEST N
LL = 1
NN = 32
IS
JJ<NN
No
279
YES
VAR = R(I)
M = 3
I SUMN=0
IS
R(I+K)>0 &
<9
No
279
YES
I SUM N=
ISUMNN +
R(I+K)x10^(M-K)
K = K + 1
IS
K S M
No
YES
L


L
IS
ISUMN<999
279
WRITE VAR
ISUMN
A = FLOAT(XX)
B = FLOAT(YY)
LL = 2
CALL
ELPRINTA
CALL
ELPRINTB
CALL
ELNEWLINE
RETURN

```
      INPUT10=CR0
      INPUT20=TR0
      OUTPUT30=LP0
      OUTPUT40=TP0
      TRACE2
      END
      MASTER TESP
      INTEGER JJ,R,I,LL,XX,YY,VAR,LLL,A
      COMMON JJ,R(50),I,LL,XX,YY,VAR,M,LLL,A
      DATA X,Y,T,N  /1HX, 1HY, 1HT, 1HN /
      YY=0
      XX=0
  301 DO 400 JK=1,1000
      READ(20,921)(R(I),I=1,36)
  921 FORMAT(36A1)
      WRITE(30,922)
  922 FORMAT(1H )
      DO 401 I=1,36
      IF(R(I).LT.0)GOTO 501
      IF(R(I).EQ.328720)GOTO 502
      IF(R(I).EQ.590864)GOTO 503
      IF(R(I).EQ.853008)GOTO 504
      IF(R(I).EQ.1115152)GOTO 506
      IF(R(I).EQ.1377296)GOTO 507
      IF(R(I).EQ.1639440)GOTO 508
      IF(R(I).EQ.1901584)GOTO 509
      IF(R(I).EQ.2163728)GOTO 510
      IF(R(I).EQ.2425872)GOTO 511
      IF(R(I).EQ.66576)GOTO 512
      IF(R(I).EQ.4260880)GOTO 513
      GOTO 666
  502 R(I)=1
      GOTO 401
  503 R(I)=2
      GOTO 401
  504 R(I)=3
      GOTO 401
  506 R(I)=4
      GOTO 401
  507 R(I)=5
      GOTO 401
  508 R(I)=6
      GOTO 401
  509 R(I)=7
      GOTO 401
  510 R(I)=8
      GOTO 401
  511 R(I)=9
      GOTO 401
  512 R(I)=0
      GOTO 401
  501 R(I)=R(I)
      GOTO 401
  513 LLL=I
      I=36
      GOTO 401
  401 CONTINUE
```

```
      JJ=2
      KK=1
      DO 11 I=1,(LLL-1)
      LL=1
      GOTO (2011,202)KK
2011  IF(R(I).GE.0.AND.R(I).LE.9)GOTO 201
      KK=2
      GOTO 202
 201  KK=2
      CALL NUMBERS
      GOTO(202, 11,666)LL
  202 J=1
      CALL COMP(J,R(I),1,X,1)
      IF(J.EQ.1)GOTO 203
      J=1
      CALL COMP(J,R(I),1,Y,1)
      IF( J.EQ.1)GOTO 204
      J=1
      CALL COMP(J,R(I),1,T,1)
      IF(J.EQ.1)GOTO 205
      J=1
      CALL COMP(J,R(I),1,N,1)
      IF( J.EQ.1)GOTO 206
      GOTO 666
  203 CALL TESTX
      GOTO(211,666)LL
  204 CALL TESTY
      GOTO(211,666)LL
  205 CALL TESTT
      GOTO(211,666)LL
  206 CALL TESTN
      GOTO(211,666)LL
 211  I=I+M
   11 CONTINUE
      GOTO 400
  666 CALL ERROR
  400 CONTINUE
  901 FORMAT(I1,1A1,6I1,1A1,6I1,1A1,3I1,1A1,3I1)
      STOP
      END

END OF SEGMENT, LENGTH   611, NAME  TESP

      SUBROUTINE NUMBERS
      INTEGER JJ,R,I,LL,XX,YY,VAR,LLL,A
      COMMON JJ,R(50),I,LL,XX,YY,VAR,M,LLL,A
      LL=1
      NNOS=2
      IF(NNOS.EQ.JJ)GOTO 231
      LL=3
      GOTO 233
  231 VAR=R(I)
      IF(VAR.LE.4)GOTO 232
      GOTO 233
  232 WRITE(30,902)R(I)
      LL=2
      JJ=JJ+1
  233 RETURN
 902  FORMAT(1H+,2X,I1)
      END

END OF SEGMENT, LENGTH    87, NAME  NUMBERS
```

```
      SUBROUTINE TESTX
      INTEGER JJ,R,I,LL,XX,YY,VAR,LLL,A
      COMMON JJ,R(50),I,LL,XX,YY,VAR,M,LLL,A
      LL=1
      NX=4
      IF(JJ.LT.NX)GOTO 241
      LL=2
      GOTO 249
  241 VAR=R(I)
      M=6
      ISUMX=0
      DO 12 K=1,M
      IF(R(I+K).GE.0.AND.R(I+K).LE.9)GOTO 242
      LL=2
      GOTO 249
  242 ISUMX=ISUMX+R(I+K)*10**(M-K)
   12 CONTINUE
      XX=ISUMX
      IF(XX.LE.375000)GOTO 243
      GOTO 249
  243 WRITE(30,903)VAR,ISUMX
      JJ=JJ+3
  249 RETURN
  903 FORMAT(1H+,5X,1A1,1X,I6)
      END

 END OF SEGMENT, LENGTH   174, NAME  TESTX
      SUBROUTINE TESTY
      INTEGER JJ,R,I,LL,XX,YY,VAR,LLL,A
      COMMON JJ,R(50),I,LL,XX,YY,VAR,M,LLL,A
      LL=1
      NY=8
      IF(JJ.LT.NY)GOTO 251
      LL=2
      GOTO 259
  251 VAR=R(I)
      M=6
      ISUMY=0
      DO 13 K=1,M
      IF(R(I+K).GE.0.AND.R(I+K).LE.9)GOTO 252
      LL=2
      GOTO 259
  252 ISUMY=ISUMY+R(I+K)*10**(M-K)
   13 CONTINUE
      YY=ISUMY
      IF(YY.LE.250000)GOTO 253
      LL=2
      GOTO 259
  253 WRITE(30,904)VAR,ISUMY
      JJ=JJ+7
  259 RETURN
  904 FORMAT(1H+,15X,1A1,1X,I6)
      END

 END OF SEGMENT, LENGTH   179, NAME  TESTY
```

```
      SUBROUTINE TESTT
      INTEGER JJ,R,I,LL,XX,YY,VAR,LLL,A
      COMMON JJ,R(50),I,LL,XX,YY,VAR,M,LLL,A
      LL=1
      NT=16
      IF(JJ.LT.NT)GOTO 261
      LL=2
      GOTO 269
  261 VAR=R(I)
      M=3
      ISUMT=0
      DO 14 K=1,M
      IF(R(I+K).GE.0.AND.R(I+K).LE.9)GOTO 262
      LL=2
      GOTO 269
  262 ISUMT=ISUMT+R(I+K)*10**(M-K)
   14 CONTINUE
      IF(ISUMT.GE.100.OR.ISUMT.LE.400)GOTO 263
      LL=2
      GOTO 269
  263 WRITE(30,905)VAR,ISUMT
      JJ=JJ+15
  269 RETURN
  905 FORMAT(1H+,25X,1A1,1X,I3)
      END
```

END OF SEGMENT, LENGTH 181, NAME TESTT

```
      SUBROUTINE TESTN
      INTEGER JJ,R,I,LL,XX,YY,VAR,LLL,A
      COMMON JJ,R(50),I,LL,XX,YY,VAR,M,LLL,A
      LL=1
      NN=32
      IF(JJ.LT.NN)GOTO 271
      GOTO 279
  271 VAR=R(I)
      M=3
      ISUMN=0
      DO 15 K=1,M
      IF(R(I+K).GE.0.AND.R(I+K).LE.9)GOTO 272
      LL=2
      GOTO 279
  272 ISUMN=ISUMN+R(I+K)*10**(M-K)
   15 CONTINUE
      IF(ISUMN.LT.999)GOTO 273
      LL=2
      GOTO 279
  273 WRITE(30,906)VAR,ISUMN
      A=FLOAT(XX)
      B=FLOAT(YY)
      CALL ELPRINT(A/1000.,4)
      CALL ELPRINT(B/1000.,4)
      CALL ELNEWLINE(1)
  279 RETURN
  906 FORMAT(1H+,32X, 1A1,1X,I3)
      END
```

END OF SEGMENT, LENGTH 194, NAME TESTN

```
      SUBROUTINE ERROR
      INTEGER JJ,R,I,LL,XX,YY,VAR,LLL,A
      COMMON JJ,R(50),I,LL,XX,YY,VAR,M,LLL,A
      WRITE (30,999)(R(I), I=1,36)
      RETURN
 999   FORMAT (1H+,50X,5HERROR,5X,36A1)
      END


 END OF SEGMENT, LENGTH     33, NAME  ERROR

      FINISH

 END OF COMPILATION -  NO ERRORS


 S/C SUBFILE:      38 BUCKETS USED



 CONSOLIDATED BY XPCK 11C    DATE    30/03/71   TIME 12/46/56

 PROGRAM BJEL
 COMPACT DATA (15AM)
 COMPACT PROGRAM (DBM)
 CORE               6144


                    SEG      TESP
                    SEG      NUMBERS
                    SEG      COMP
                    SEG      TESTX
                    SEG      TESTY
                    SEG      TESTT
                    SEG      TESTN
                    SEG      ERROR
                    SEG      FLOAT
                    SEG      ELPRINT
                    SEG      ELNEWLINE
                    ENT      FTRAP
                    ENT      FRESET
     X   35000   Y 125000           N   1
     X   65000   Y 125000           N   2
     X   95000                      N   3
     X  125000                      N   4
     X  155000                      N   5
     X  185000                      N   6
     X  215000                      N   7
     X  125000   Y 215000           N   8
                 Y 185000           N   9
                 Y 155000           N  10
                 Y  95000           N  11
                 Y  65000           N  12
                 Y  35000           N  13
```

X 18935	Y 18935	N 14
X 40148	Y 40148	N 15
X 61361	Y 61361	N 16
X 82574	Y 82574	N 17
X 103787	Y 103787	N 18
X 146213	Y 146213	N 19
X 167426	Y 167426	N 20
X 188639	Y 188639	N 21
X 209852	Y 209852	N 22
X 231065	Y 231065	N 23
X 18935		N 24
X 40145	Y 209852	N 25
X 61361	Y 188639	N 26
X 82574	Y 167462	N 27
X 103787	Y 146213	N 28
X 146213	Y 103787	N 29
X 167426	Y 82574	N 30
X 188639	Y 61361	N 31
X 209852	Y 40148	N 32
X 231065	Y 18935	N 33
X 86732	Y 32612	N 34
X 163268		N 35
X 217388	Y 86732	N 36
	Y 163268	N 37
X 163268	Y 217388	N 38
X 86732		N 39
X 32612	Y 163268	N 40
	Y 86732	N 41
X 35000	Y 125000	N 42
X 65000	Y 125000	N 43
X 95000		N 44
X 155000		N 45
X 185000		N 46
X 215000		N 47
X 125000	Y 215000	N 48
	Y 185000	N 49
	Y 155000	N 50
	Y 95000	N 51
	Y 65000	N 52
	Y 35000	N 53
X 18935	Y 18935	N 54
X 40148	Y 40148	N 55
X 61361	Y 61361	N 56
X 82574	Y 82574	N 57
X 103787	Y 103787	N 58
X 125000	Y 125000	N 59
X 146213	Y 146213	N 60
X 167426	Y 167426	N 61
X 188639	Y 188639	N 62
X 209852	Y 209852	N 63
X 231065	Y 231065	N 64
X 18935		N 65

X	40145	Y	209852	N	66
X	61361	Y	188639	N	67
X	82574	Y	167462	N	68
X	103787	Y	146213	N	69
X	146213	Y	103787	N	70
X	167426	Y	82574	N	71
X	188639	Y	61361	N	72
X	209852	Y	40148	N	73
X	231065	Y	18935	N	74
X	86732	Y	32612	N	75
X	163268			N	76
X	217388	Y	86732	N	77
		Y	163268	N	78
X	163268	Y	217388	N	79
X	86732			N	80
X	32612	Y	163268	N	81
		Y	86732	N	82
X	18935	Y	18935	N	83
X	40148	Y	40148	N	84
X	61361	Y	61361	N	85
X	82574	Y	82574	N	86
X	103787	Y	103787	N	87
X	146213	Y	146213	N	88
X	167426	Y	167426	N	89
X	188639	Y	188639	N	90
X	209852	Y	209852	N	91
X	231065	Y	231065	N	92
X	18935			N	93
X	40145	Y	209852	N	94
X	61361	Y	188639	N	95
X	82574	Y	167462	N	96
X	103787	Y	146213	N	97
X	125000	Y	125000	N	98
X	146213	Y	103787	N	99
X	167426	Y	82574	N	100
X	188639	Y	61361	N	101
X	209852	Y	40148	N	102
X	231065	Y	18935	N	103
X	35000	Y	125000	N	104
X	215000			N	105
X	125000	Y	215000	N	106
		Y	35000	N	107

```
         INPUT10=CR0
         INPUT20=TR0
         OUTPUT30=LP0
         OUTPUT40=TP0
         TRACE2
         END
         MASTER TESP

END OF SEGMENT, LENGTH   611, NAME  TESP

         SUBROUTINE NUMBERS

END OF SEGMENT, LENGTH    87, NAME  NUMBERS

         SUBROUTINE TESTX

END OF SEGMENT, LENGTH   174, NAME  TESTX

         SUBROUTINE TESTY

END OF SEGMENT, LENGTH   179, NAME  TESTY

         SUBROUTINE TESTT

END OF SEGMENT, LENGTH   181, NAME  TESTT

         SUBROUTINE TESTN

END OF SEGMENT, LENGTH   194, NAME  TESTN

         SUBROUTINE ERROR

END OF SEGMENT, LENGTH    33, NAME  ERROR

         FINISH

END OF COMPILATION -  NO ERRORS

S/C SUBFILE:      38 BUCKETS USED
```

```
CONSOLIDATED BY XPCK 11C     DATE     10/05/71   TIME 12/08/33

PROGRAM BJEL
COMPACT DATA (15AM)
COMPACT PROGRAM (DBM)
CORE                6144

      X   35000  Y 125000         N   1
      X   65000  Y 125000         N   2
      X   95000                   N   3
      X  125000                   N   4
      X  155000                   N   5
      X  185000                   N   6
      X  215000                   N   7
      X  125000  Y 215000         N   8
                 Y 185000         N   9
                                           ERROR      VY000000N000
                 Y   95000        N  11
                 Y   65000        N  12
                                           ERROR      W000000N000
      X   18935  Y   19935        N  14
      X   40148  Y   40148        N  15
                                           ERROR      X000'61Y061361N016
      X   82574  Y   82574        N  17
      X  103787  Y  103787        N  18
      X  146213  Y  146213        N  19
      X   67426  Y  167426        N  20
      X  188639  Y  188639        N  21
      X  209852
                                           ERROR      X000000Y000000N000
      X  231065  Y  231065        N  23
      X   18935                   N  24
      X   40145  Y  209852        N  25
      X   61361  Y  188639        N  26
      X   82574  Y  167462        N  27
      X  103787
      X  146213  Y  103787        N  29
      X  167426  Y   82574        N  30
      X  188639  Y   61361        N  31
      X  209852  Y   40148        N  32
                 Y   18935        N  33
      X   86732  Y   32612        N  34
      X  163268                   N  35
      X  217388  Y   86732        N  36
                                           ERROR      0Y000000N000
      X  163268  Y  217388        N  38
      X   86732                   N  39
      X   32612  Y  163268        N  40
1                Y   86732        N  41
      X   35000  Y  125000        N  42
      X   65000  Y  125000        N  43
      X   95000                   N  44
      X  155000                   N  45
      X  185000                   N  46
      X  215000                   N  47
      X  125000  Y  215000        N  48
                 Y  185000        N  49
                 Y  155000        N  50
                 Y   95000        N  51
```

```
          Y  65000     N  52
          Y  35000     N  53
X  18935  Y  18935     N  54
X  40148  Y  40148     N  55
X  61361  Y  61361     N  56
X  82574  Y  82574     N  57
X 103787  Y 103787     N  58
X 125000  Y 125000     N  59
X 146213  Y 146213     N  60
X 167426  Y 167426     N  61
X 188639  Y 188639     N  62
X 209852                       ERROR     X000000YA00000N000
X 231065  Y 231065     N  64
X  18935               N  65
X  40145  Y 209852     N  66
X  61361  Y 188639     N  67
X  82574  Y 167462     N  68
X 103787  Y 146213     N  69
X 146213  Y 103787     N  70
X 167426  Y  82574     N  71
X 188639  Y  61361     N  72
X 209852  Y  40148     N  73
X 231065  Y  18935     N  74
X  86732  Y  32612     N  75
X 163268               N  76
          Y  86732     N  77
          Y 163268     N  78
X 163268  Y 217388     N  79
X  86732               N  80
X  32612  Y 163268     N  81
1          Y  86732     N  82
X  18935  Y  18935     N  83
X  40148  Y  40148     N  84
X  61361  Y  61361     N  85
X  82574  Y  82574     N  86
X 103787  Y 103787     N  87
X 146213  Y 146213     N  88
X 167426  Y 167426     N  89
X 188639  Y 188639     N  90
X 209852  Y 209852     N  91
X 231065  Y 231065     N  92
X  18935               N  93
X  40145  Y 209852     N  94
X  61361  Y 188639     N  95
X  82574  Y 167462     N  96
X 103787  Y 146213     N  97
X 125000  Y 125000     N  98
          Y 125000             ERROR     Y000000X0000000N000
X 167426  Y  82574     N 100
X 188639  Y  61361     N 101
X 209852  Y  40148     N 102
X 231065  Y  18935     N 103
X  35000  Y 125000     N 104
X 215000               N 105
X 125000  Y 215000     N 106
          Y  35000     N 107
```

APPENDIX B

```
FINISH

END OF COMPILATION -  NO ERRORS

S/C SUBFILE:     12 BUCKETS USED

CONSOLIDATED BY XPCK 11C    DATE    16/06/71   TIME 09/33/08

PROGRAM BJEL
COMPACT DATA (15AM)
COMPACT PROGRAM (DBM)
CORE             2624

                SEG     PLUGS
                SEG     CONVERT
                ENT     FTRAP
                ENT     FRESET
          MODULE TABLE PLUG FIXTURE SIZES


   PLUG NO *1


   50MM DIA

  49.99721    49.99746    49.99746    49.99797    49.99752

  50.00063    50.00140    50.00025    50.00025    50.00063

  50.00330    50.00343    50.00343    50.00305    50.00330

  -0.00029
   25MM DIA TOP

  24.99111    24.99111    24.99111    24.99111    24.99111

  24.98984    24.98984    24.98984    24.98984    24.98984

  24.98984    24.98984    24.98984    24.98984    24.98984

   TAPER PER UNIT LENGTH

  0.00005
   25MM DIA BOTTOM

  24.99746    24.99746    24.99746    24.99809    24.99762

  24.99809    24.99619    24.99619    24.99619    24.99667

  24.99619    24.99619    24.99619    24.99683    24.99635

   TAPER PER UNIT LENGTH

  0.00005
   PLUG NO *2
```

50MM DIA

49.99848	49.99911	49.99898	49.99848	49.99876
50.00140	50.00241	50.00318	50.00254	50.00238
50.00483	50.00419	50.00381	50.00406	50.00422

-0.00028

25MM DIA TOP

24.99365	24.99301	24.99365	24.99365	24.99349
24.99365	24.99429	24.99365	24.99365	24.99381
24.99683	24.99619	24.99619	24.99619	24.99635

TAPER PER UNIT LENGTH

-0.00011

25MM DIA BOTTOM

24.99619	24.99619	24.99619	24.99619	24.99619
24.99619	24.99619	24.99619	24.99619	24.99619
24.99683	24.99683	24.99683	24.99683	24.99683

TAPER PER UNIT LENGTH

-0.00002

PLUG NO *3

50MM DIA

50.00711	50.00737	50.00686	50.00660	50.00699
50.00711	50.00737	50.00737	50.00660	50.00711
50.00483	50.00508	50.00457	50.00432	50.00470

0.00012

25MM DIA TOP

24.98730	24.98730	24.98730	24.98730	24.98730
24.98666	24.98666	24.98666	24.98666	24.98666
24.98540	24.98540	24.98603	24.98540	24.98555

TAPER PER UNIT LENGTH

0.00007

25MM DIA BOTTOM

24.99238	24.99238	24.99365	24.99365	24.99302
24.99365	24.99175	24.99175	24.99048	24.99190
24.98984	24.99048	24.99111	24.99048	24.99048

TAPER PER UNIT LENGTH

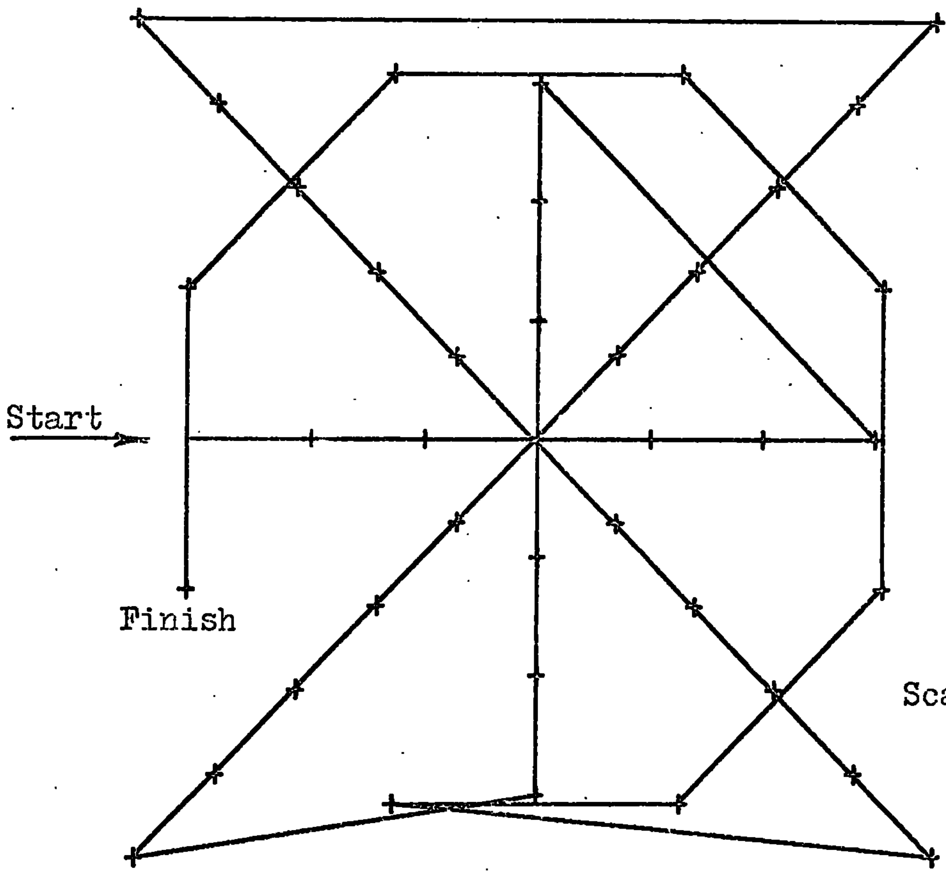
0.00010

PLUG NO *4

APPENDIX C

Drill head position shown x

Deviation from straight-line indicates error



Scale $\frac{1}{2}$: 1

Graph plotter output for test piece shown fig. 22. All drill head positions correct.

Fig. 26

Graph plotter output for test piece shown Fig. 22 indicating dimensional errors evident in appendix A.

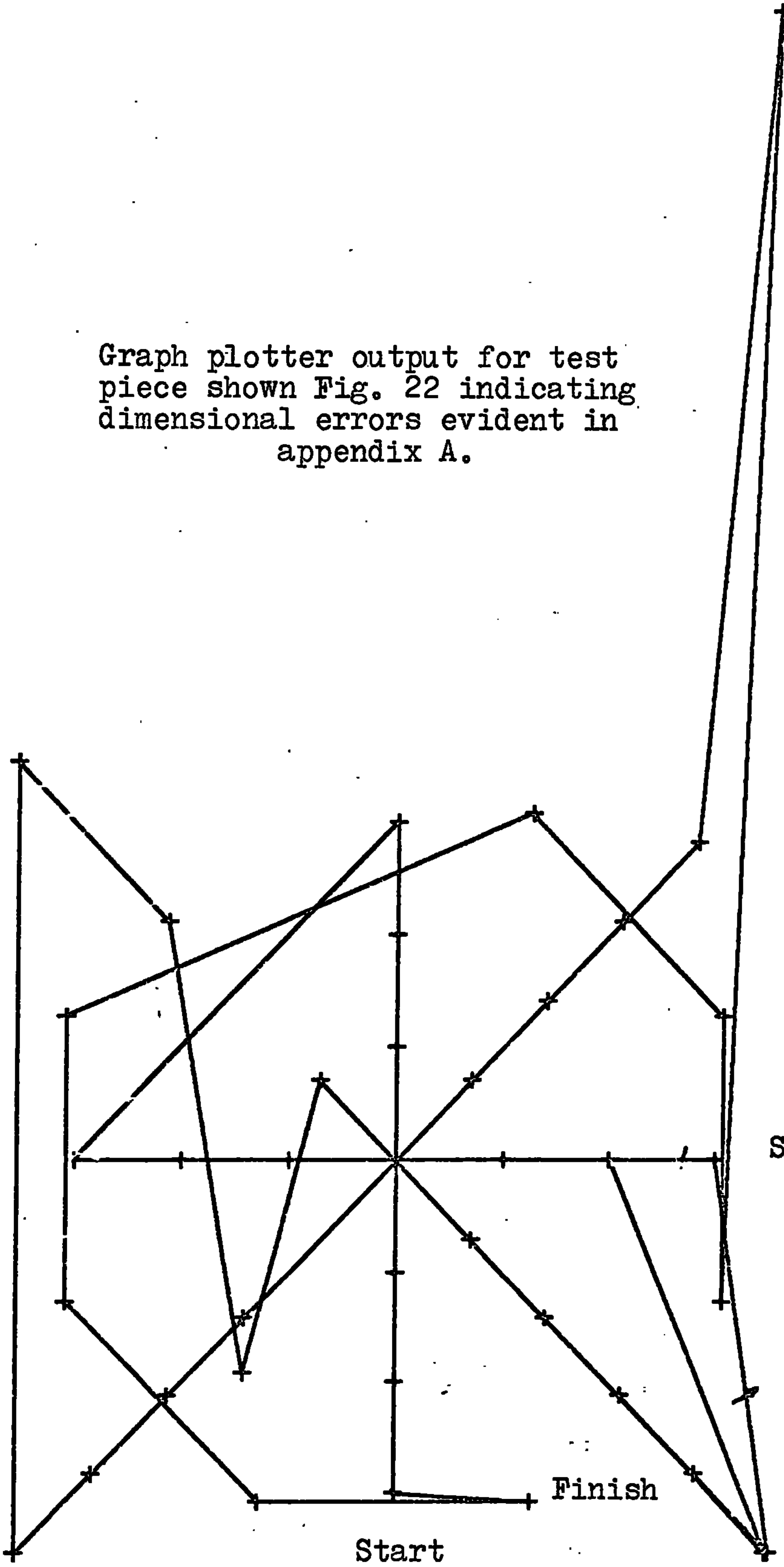


Fig. 27

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