AN EFFECTIVE USE OF 3-D CAD/CAM WITHIN AN OVERALL C.I.M. FRAMEWORK

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SUMMARY

The initial objective of this work was an investigation into the possible use of 3-D CAD as a practical and effective design tool for use by a Fuel Control System manufacturer. However, it soon became apparent that CAD should not be considered as a design productivity tool, working in an isolated environment, but as an element in an integrated business system.

The use of 3-D modelling was investigated and it was found that 3-D wireframe models with surfaces could be beneficial to the design function and to other downstream functions. Some of these benefits to the downstream users were found to be available now, whilst others could be made available with greater systems integration. The efficiency of producing these 3-D models was increased by applying a concept called minimum modelling which simplified the model in such a way that it still fulfilled the requirements of the downstream functions. This efficiency was further enhanced by the systematic use of a facility which was available within the CAD system, called layering.

To implement effective 3-D modelling into the design office, required the writing of training exercises and the organising of a training programme. 3-D using minimum modelling and layering techniques was successfully introduced into the design department and is now used on all new designs.

To increase the effectiveness of the system a Finite Element system was specified, selected and implemented, and a suitable training programme was defined. The system selected was interfaced with the CAD system and in operation this proved to be both flexible and powerful, being capable of both 2D and 3D analyses.

The poor performance of the associated CAM system was investigated and found to be caused by a lack of systems development work and by inherent limitations in the software itself. To overcome some of these deficiencies, a program was written which fully simulated, in 3-D, the machining actions of a 4 axis machining centre.

KEYWORDS: 3-D WIREFRAME CAD,CAM,CAE,CIM, NC Verification

FOR VERNA, THOMAS AND ALEXANDER

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LIST OF CONTENTS

	SUMMARY	i
	DEDICATION	ii
	ACKNOWLEDGEMENTS	iii
	LIST OF CONTENTS	iv
	NOTATION	viii
	LIST OF FIGURES	ix
1.	INTRODUCTION	1
1.1	Introduction	2
2.	THE NEED TO INTEGRATE SYSTEMS AND THE USE OF COMPUTERS	8
2.1	The Modern Manufacturing Environment	9
2.2	Causes Of these Fundamental Problems	10
2.3	Response Of Industry To These Fundamental Problems	11
2.3.1.	Group Technology	12
2.3.2.	JIT/MRP II - Manufacturing Production And Control System	16
2.3.3.	Total Quality Control	20
2.3.4.	CAD - Computer Aided Draughting/Design	23
2.3.5.	Computer Aided Engineering (CAE)	30
2.3.6.	CAM - Computer Aided Manufacture	36
2.3.7.	CAPP - Computer Aided Process Planning	44
2.3.7.1.	Retrieval Type Planning System	46
2.3.7.2.	Generative Process Planning Systems	47
2.4	The Need To Integrate And Re-organise A Business	49
2.5	Computer Integrated Manufacture (CIM)	54
3.	CAD - A FOCAL POINT FOR CIM ACTIVITY	58
3.1	The Design Process Using Computer Aided Techniques	59
3.2	Initial Concept And Definition Loops	61
3.3	Product Development Loop	64
3.4	Bill Of Material Functional Link	66
3.5	The Output From CAD Within A CIM System	67

4.	**THE EFFECTIVE USE OF CAD IN A FUEL CONTROL SYSTEMS MANUFACTURING COMPANY**	68
4.1	Introduction	69
4.2	The Business	69
4.3	The Teaching Company Programme	72
4.4	The Project	73
4.5	Project Background Information	74
4.6	The CAD Situation Existing at the Beginning of the Project	75
4.7	Evaluation Of The Features And Potential Of The CAD/CAM System	77
4.7.1.	2-D Draughting	78
4.7.2.	3-D Modelling	79
4.7.2.1.	Wireframe Modelling	80
4.7.2.2.	Wireframe With Surface Modelling	81
4.7.2.3.	Solid Modelling	85
4.8	CAD/CAM Requirements	88
4.8.1.	The Geometry Of A Fuel Control System And It´s Production	88
4.8.2.	Downstream Functions	92
4.8.2.1.	NC Programming	93
4.8.2.2.	Co-ordinate Measuring Machine (CMM)	95
4.8.2.3.	Finite Element Analysis (FEA)	96
4.8.2.4.	Detailing	97
4.8.2.5.	Jigs And Fixtures	98
4.8.2.6.	Technical Publications	99
4.8.2.7.	Other Downstream Functions	101
4.8.3.	Assessment Of The Company´s Hardward And Software Needs	101
4.8.4.	3-D Modelling Implications For The Design Function	104

5.	**MINIMUM MODELLING**	107
5.1	The Concept Of The Minimum Model	108
5.2	Techniques And Applications Of Minimum Modelling	110
5.2.1.	Axi-symetric Geometries	110
5.2.2.	Regular 2 1/2 D Geometries	112
5.2.3.	No Cross-Hatching Of Sections	113
5.2.4.	Combined 2-D Templates And 3-D Geometry	114
5.2.5.	Casting - Flowing Geometry	115
5.2.6.	Reduce Detail And Duplication	117
5.2.7.	Possible Future Minimum Modelling Techniques	119
5.3	Layering And Minimum Modelling	121
5.3.1.	Methodology Of Layering And Colouring	122
5.3.2.	Experience Of Layering And Colouring	127
5.4	A Review Of Effective 3-D Modelling	130

6.	**IMPLEMENTATION OF EFFECTIVE MODELLING IN DESIGN PRACTICE**	133
6.1	The Requirements Of 3-D Modelling For The Designers	134
6.2	Training Of CAD Operators	135
6.2.1.	Individual Training - On Site	136
6.2.2.	Group Training	139
6.2.3.	Individual Off-Site Training	140
6.3	Training Policy	141
6.4	On-Site Training Experiences	142
6.5	Experience Of Implementing And Using 3-D Minimum Modelling	144
6.6	Summary Of 3-D CAD As A Design Tool	148
7.	**COMPUTATIONAL STRESS ANALYSIS**	150
7.1	Background To Product Analysis	151
7.2	Computational Stress Analysis Within The Lucas Group	153
7.3	Options For Undertaking Stress Analysis	158
7.4	Evaluation Of Stress Analysis Options	161
7.5	Specification Of On-Site Stress Analysis Software	162
7.6	Investigation Into An On-Site Computational Stress Capability	164
7.7	Implementation And Training	170
7.8	Experiences	171
7.9	Summary Of The Company Practice In Computational Stress Analysis	173
8.	**COMPUTER AIDED MANUFACTURE CAM**	176
8.1	Capabilities Of The CAM System	177
8.2	Limitations Of The CAM System	180
8.3	Experience Of Operating The NC Vision System	186
8.4	Recommendations To Improve The Utilisation Of The CAM System	191
8.5	Introduction To NC Verification	193
8.5.1.	Current And Future Approaches To NC Verification	195
8.6	Deckel DZ4 Simulation Project	200
8.6.1.	DZ4 Simulation System Design	201
8.6.2.	Simulation Methodology	204
8.6.3.	Features Of The DZ4 Simulation Program	205
8.6.4.	Program Operation, Limitations And Future Developments	209
8.7	Summary Of The CAM System And The Simulation Program	216
9.	**REVIEW, DISCUSSION AND CONCLUSIONS**	221
9.1	Review And Discussion	222
9.2	Conclusions	231

REFERENCES 233

FIGURES 239

APPENDICES

1.	Teaching Company Scheme	284
2.	Training Exercises	286
3.	Multiple Sheet Drawing Frame	299
4.	BEASY/FEA Test Results	304
5.	Deckel DZ4 Machining Statements	310
6.	Sample DZ4 NC Program	315
7.	Simulation Program Operating Instructions	317
8.	Simulation Program Listing	324

NOTATION

AI	Artificial Intelligence
ASD	Advanced Suface Design
APT	Automatically Programmed Tools
AMT	Advanced Manufacturing Technologies
BE	Boundary Element
BEA	Boundary Element Analysis
BOM	Bill Of Materials
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacture
CAPP	Computer Aided Process Planning
CIM	Computer Integrated Manufacture
CMM	Co-ordinate Measuring Machine
CNC	Computer Numerical Control
CV	Computervision
CL	Cutter Location
CPL	Construction Plane
DNC	Direct Numerical Control
DOF	Degrees of Freedom
ESD	Engine System Division
FMS	Flexible Manufacturing System
GT	Group Technology
FE	Finite Element
FEA	Finite Element Analysis
FEM	Finite Element Modelling
JIT	Just in Time
MIT	Massachusetts Institute of Technology
MRP	Material Requirement Planning
MRPII	Manufacturing Resources Planning
NC	Numerical Control
OPT	Optimised Production Technology
PFA	Production Flow Analysis
QA	Quality Assurance
TCA	Teaching Company Assosciate
TCS	Teaching Company Scheme
TDO	Tool Drawing Office
TQC	Total Quality Control
WIP	Work in Progress

LIST OF FIGURES

Fig	(1)	Image Design	239
Fig	(2)	3-D FEA Showing Component Deflecting	240
Fig	(3)	3-D FEA Showing Stress Contours	240
Fig	(4)	Typical Geometric Forms of FE Elements	241
Fig	(5)	FE Mesh Concentration	241
Fig	(6)	Linkages	242
Fig	(7)	Auto Miling/Turning Routines	243
Fig	(8)	A CIM System	244
Fig	(9)	Design as a System	245
Fig	(10)	Product Concept Loop	246
Fig	(11)	Product Definition Loop	246
Fig	(12)	Product Development Loop	246
Fig	(13)	Bill of Material Functional Link	246
Fig	(14)	ESD Network	247
Fig	(15)	2-D Draughting	248
Fig	(16)	Models, Views and Drawings	249
Fig	(17)	3-D Model View	250
Fig	(18)	Wireframe Ambiguity	250
Fig	(19)	Meshed Surface	251
Fig	(20)	Turned and Turned/Milled Components	252
Fig	(21)	CAD-Shade Rough Texture	253
Fig	(22)	CAD-Shade Fine Texture	254
Fig	(23)	Exploded Assembly/Solid Model	255
Fig	(24)	Typical Variations of Components	256
Fig	(25)	Milled Components	257
Fig	(26)	Part Assembly	257
Fig	(27)	Auto Measure View Probe (C M M)	258
Fig	(28)	Axi-Symmetric Geometries	259
Fig	(29)	Regular 2-1/2 D Geometries	260
Fig	(30)	2-1/2 D Contour Pockets	261
Fig	(31)	Combined 2-D Templates with 3-D Features	262
Fig	(32)	Tool Radii Produced Features	263
Fig	(33)	3-D Castings and Flowing Geometries	264
Fig	(34)	Typical Casting Showing Added Cosmetic Lines	265
Fig	(35)	Over Detail Standard Items	266
Fig	(36)	Approximate Aesthetic Intersections	267
Fig	(37)	Reduce Detail on Flange Bolt Holes	267
Fig	(38)	3-D Minimum Modelling Without Layering-Confusing	268
Fig	(39)	Layering and Minimum Modelling	269
Fig	(40)	FE Pre-Processor	270
Fig	(41)	FE Post-Processor	270
Fig	(42)	FE Sub-Sectioning	271
Fig	(43)	FE Shrinking Elements	272
Fig	(44)	FE/BEASY Analysys Modelling Requirements	273
Fig	(45)	FE System And Network	274
Fig	(46)	3-D Isometric View of Cutter Path	275
Fig	(47)	Deckel DZ4	276
Fig	(48)	4 View Layout Showing Toolpath	277
Fig	(49)	Single View Layout Showing Toolpath	277

Fig (50)	Single View Layout Showing Toolpath After 2 Rotations	278
Fig (51)	Single View Layout Showing Toolpath After 3 Rotations	278
Fig (52)	4 View Layout Showing Toolpath After 3 Rotations	279
Fig (53)	Layout of DZ4 Machining Area	280
Fig (54)	Single View (Predicted Collision Situation)	281
Fig (55)	4 View Layout (Predicted Collision Situation)	281
Fig (56)	Rotation Angle	282
Fig (57)	Enlarged Faceted Arc of Toolpath	283

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION.

In recent years, the environment in which most manufacturing companies operate, has become increasingly competitive and to survive, companies must constantly strive to meet the demands of their customers. Various government agencies and industry itself have recognised that to achieve this requires the adoption of Advanced Manufacturing Technologies (A.M.T.).

The field of A.M.T. is so large and is changing so rapidly that no one piece of work can do justice to the total subject in any detail. This work is primarily concerned with one area within this field, namely the effective use of a CAD/CAM system, but it will also consider the relationships CAD/CAM has with other fields under the A.M.T. umbrella.
This work was undertaken as part of a Teaching Company Scheme between the Engine Systems Division (E.S.D.) of Lucas Aerospace and Aston University (Appendix 1).

The original objective of the work was to investigate the possible use of 3-D CAD as a practical and effective design tool for use by E.S.D.
However, it soon became apparent that CAD could not be considered in isolation. As Professor Medland [1] states:-

> 'Design and manufacture are best thought of as one continuum and that the benefits of CAD can only be appreciated if it is seen as something which has an impact on that entire continuum, not just one part of it'.

The reason for this, is that the CAD system generates model geometry, and this is subsequently worked on and passed to many other job functions in the design-through-to-manufacture process. This repeated use of the same model removes the need to recreate geometric information, leads to reduced errors and lead times and contributes to the improved overall effectiveness of a manufacturing company.

The recognition of the use of one common CAD generated geometry gives rise to the possibility of integrating the whole business of creating, transmitting, storing and processing geometrical information. Stover [2] sees this development of the use of CAD generated geometry as playing a key role in the formation of a Computer Integrated Manufacturing system and he writes:-

> 'This geometric integrated sub-system can then be linked via the manufacturing and production control sub-systems to the financial sub-system, thereby producing one unified factory control system,in other words a CIM system'.

Recognising that the CAD model was to be used by many other functions in the business was an important step towards Computer Integrated Manufacture (CIM). Once the value of integration was understood, it then became important and very beneficial to ensure that the CAD model was produced in such a form that it would meet the geometric requirements of not only the design function, but also the other functions. This would reduce the amount of time and effort which these other functions would then need to exert when they in turn received the CAD model.

This realisation of the benefits of integration soon resulted in the author's original project objective being widened to include a study of the practical benefits and effects of 3-D modelling on the downstream functions.

The geometric requirements of the design and other downstream functions which used the model geometry, were found to be dependent on the nature and complexity of the geometry of the products and their manufacturing processes. In the case of E.S.D, which manufactures geometrically complicated components for Aerospace Fuel Control systems, it was found that 3-dimensional wireframe models, using surfaces when needed, were the most practical and beneficial representation of a component for the design and other downstream functions. However, as will be discussed later in this thesis, some operational problems regarding design and N.C. programming were found with this type of CAD model, and so a number of techniques and approaches were developed to overcome these.

This need to develop specific techniques was fully appreciated and understood by Len Weaver [3], the Vice President of the Institution of Production Engineers and Chairman of the Advanced Manufacturing Technology Committee, who said:-

> 'The manufacturing technologies required to achieve a competitive position already largely exist and are being constantly improved. The trick is to tailor techniques to suit the requirements of a particular company'.

Once techniques were developed to overcome the problems of using 3-D models the project evolved into implementing a methodology of designing in 3-D into the design function. This necessitated the development of suitable exercises for the design staff, the writing of training manuals and the organising of a training programme.

These manuals introduced, in a systematic way, the various 3-D modelling commands associated with the commercial CAD system installed at the plant. In addition, they demonstrated the concepts and the techniques which had been developed for the benefit of the design and other downstream functions and showed how to perform the typical tasks required of the company's designers. Many of these tasks were then easy to perform, whereas previously they were very difficult and time consuming. In fact, an important general point to remember, is that in many instances, CAD allows a company to perform tasks that couldn't previously be done. After 3-D modelling was successfully introduced, other areas of the system used by some of the downstream functions, were developed by the author to allow them to use and benefit from the introduction of 3-D models.

A careful analysis showed that the CAM system had a number of deficiencies. To overcome a number of these, an 'off-line' 4-axis simulation program was written. This development program allowed a 3-D CAD model to be 'mounted' on a rotating 3-D fixture and the motions of all the cutting tools and the fixture/component assembly in 3-D space were fully simulated graphically on the CAD terminal. The object of this development work was to reduce expensive N.C. Tape prove out time, by using the CAD/CAM terminals to display and warn of N.C. programming errors. This simulation project achieved its objectives, but was found to be impractical at the time, due to hardware limitations on site.

As a final development to the system, an on site computational stress analysis capability was specified and selected. Subsequently a suitable training programme for an operator was defined and an operator trained. The Finite Element system chosen was integrated into the CAD system so as to use the CAD models and existing CAD/CAM equipment. Following the installation of the specified system a number of successful F.E. analyses were performed, many providing solutions to problems which previously could not be accurately calculated using manual methods.

These projects were all concerned with improving the effectiveness of a commercially available CADCAM system for all the functions within a practical commercial environment, for the benefit of everyone and not just for the designers. However, there are many other areas which can benefit from the development and application of existing CADCAM systems and which were not addressed in detail in this particular project.

Many of the problems currently facing manufacturing can be reduced or avoided by exploiting the benefits of using CAD. This can best be done by taking an integrated manufacturing systems approach to the Advanced Manufacturing Technologies now available.

To understand the full potential of a CAD system and appreciate its role in the 'factory of the future' requires an appreciation of some of the other fields within A.M.T. and an explanation of their relationships to each other. It is from such considerations that the benefits of integrating all the processes and systems into one unified factory system will emerge.

C H A P T E R 2

THE NEED TO INTEGRATE SYSTEMS AND THE USE OF COMPUTERS

THE NEED TO INTEGRATE SYSTEMS AND THE USE OF COMPUTERS

2.1 THE MODERN MANUFACTURING ENVIRONMENT

Not so many years ago, British manufacturing industry had a captive home and Commonwealth market for its products. The effect of having no real industrial competition in these markets lead to a complacent attitude particularly in the nineteen sixties by both workers and management. Meanwhile the other industrial nations forged ahead whilst Britain's industry largely stagnated. The consequences of this inaction were that many industries were no longer competitive and their vulnerability was exposed when the barriers protecting the British and Commonwealth markets were progessively removed. To survive and sell its products, British industry had to and must continue rapidly to modernise its equipment and manufacturing systems to compete in the world market.

Customers throughout the world are constantly demanding shorter lead times, better quality products, smaller batch sizes, shorter product life cycles and production at least cost. In addition, customers are demanding specialised or modified variations of standard products to suit their own particular requirements. The market place is becoming increasingly competitive and more volatile to operate in. 'Hi-tech' products from the West and Japan are now becoming so complex and expensive to develop, that to survive, companies are forced to collaborate with previous economic rivals. Meanwhile the traditional industries are under attack from a wave of lower cost imports from developing countries, where wages are lower and there is generally no labour or environmental legislation acting as a restraint. The only way for a company to survive in this climate is to become evermore competitive by tackling the fundamental problems associated with cost, delivery, quality and responsiveness. This chapter will look at some of the main causes of these problems and following that, some of the responses to these problems required of industry.

2.2 CAUSES OF THE FUNDAMENTAL PROBLEMS.

Before these problems can be tackled, the systems and processes which cause these deficiencies must be investigated and understood. Problem areas can then be identified and treated.

To be the most competitive in terms of price in the world market requires production at least unit cost. However, many companies carry up to one third [4] of unnecessary non value added costs. The Ingersoll report [4] says:-

> 'The major portion of unnecessary overhead costs is due to the fact that factories have evolved haphazardly and without plans. The result of this is that machines and equipment have been fitted-in where space could be found and new products have been manufactured using as much existing equipment as possible. This random mixing of products around the factory floor has created many inefficiencies on the shop floor'.

In order to reduce the complexity of scheduling the work and to reduce the costs associated with set up and change over times, components are usually moved from section to section in batches which are large. This approach leads to manufactured components spending some 95% of their time either being transported around a factory, or queuing to be machined at each stage of the manufacturing process [5]. Of the remaining 5%, 3.5% is spent positioning, loading, gauging etc, whilst actual cutting time is only 1.5% [5]. During its stay on the shop floor, this component is said to be Work In Progress (W.I.P) and this period is usually long in traditional industries. The outcomes of this type of system with its many inefficiencies are:- a growth in overhead costs, reduced quality, longer lead times, and wasted factory floor space.

For many years manufacturing engineers and managers have concentrated all their skills on reducing direct labour costs. The new systems and technologies introduced have typically cut the direct labour costs from 30% to 7% [4]. Presently materials and overheads typically contribute between 85% and 95% of the total production costs [4]. To be competitive, companies must now embark on extensive cost reduction programmes which reduce these overhead costs whilst increasing standards of quality and reliability.

2.3 RESPONSE OF INDUSTRY TO THESE FUNDAMENTAL PROBLEMS.

In recent years, both the government and much of industry has come to believe that the key to remaining competitive and the answer to these problems lies with the vigorous application of Advanced Manufacturing Technology.

In a forward to the Ingersoll report [4] Geoffrey Pattie, then Minister of State for Industry and Information Technology, writes:-

> 'There is an increasing awareness in U.K. industry of the benefits to be gained from the application of information technology to integrate manufacturing activities'.

In recent years the government has set up a wide range of services and programmes to demonstrate, advise and give financial assistance to companies which are considering the introduction of Advanced Manufacturing Technology (A.M.T.). The purpose of these activities is to ensure that all U.K. manufacturing companies are aware of the opportunities that are now available to improve their competitiveness by the use of A.M.T.

Advance Manufacturing Technology is a generic term which embraces many aspects of information technology and enabling disciplines and protocols. The field is very large and includes CAD, CAM, CAE, CIM, JIT, GT, FMS, CAPP, AI, MRP II, Robotics etc. Many of these technologies may be thought of as 'conventional' by academics, although considered 'advanced' by many industrialists, who have actually to implement such systems in a commercially viable manner. A brief description of some of these technologies will follow with comments on how they inter-relate.

2.3.1 GROUP TECHNOLOGY.

In recent years, the wisdom of using the conventional factory layout, has been questioned. The conventional practice was to group machines into departments which specialise according to function type e.g. drilling, grinding, milling, turning etc. This system resulted in many inefficiencies due to the part processed components being constantly moved around the whole factory floor.

Under a concept called Group Technology (G.T.) [6] various types of machines are grouped into process cells which are dedicated to manufacturing a particular type of part or product. The shift is from the traditional task orientated manufacturing environment to a product orientated one.

G.T. is a technique and a philosophy of increasing productivity by grouping a variety of parts having similar forms, dimensions, tolerances and process routes. The rationale behind most G.T. applications is a classification and coding system [7]. The parts can be classified by their form, dimensions, tolerances and manufacturing processes and are codified according to the standard being applied. A code, usually in the form of a string of alpha-numeric digits, provides information about the components which are grouped into a ´family of parts´ sharing a similar code number. A group of various types of machines can then be selected which can completely manufacture all the components within the family. This selection is usually optimised using a technique called Production Flow Analysis (P.F.A.) [8]. The result is called a conceptual manufacturing cell.

In reality though, the conceptual cell is often not enough to make the system work properly and so to optimise efficiency, the physical grouping of these machines within one small factory area must also occur. The physical grouping of the machines within one cell is also arranged in the sequence in which operations are performed for the most logical flow of work within the cell. By grouping together similar components in families, it is possible to gain, for small batch sizes some of the benefits that are normally associated with mass production lines [8].

Each cell should operate almost as if it were a small self contained autonomous factory unit producing the complete component. Occasionally special operations will be required for a part, such as heat-treating, painting, plating etc, and then the part is 'sub-contracted' out of the cell for these operations and then brought back to continue its movement within the cell.

The major manufacturing benefits sought are lower through-put times and cost, since any part which falls into a family can be easily and quickly made within a cell in which the machine tools are already stocked with the necessary cutting tools, most of which are already set up in the machine tool magazines. Furthermore, most if not all the standard fixtures and gauges needed to make these similar parts will be easily accessible. In addition, all the fixtures, dies and tools are designed to allow greatly reduced change over times [8]. As a consequence, set up times can be drastically reduced, allowing smaller batch sizes and thus lower inventory, shorter lead times and as a result allows greater economical variation from the company's standard products [8].

When a part is created it is classified and codified and then entered into the G.T. database. Subsequently, when a new part is required, a search of the G.T. database for a similar descriptive string to that of the new part is made. If a similar part or process plan is found already to exist, then this can be retrieved, copied and modified ready for use, thereby saving time and effort. This new part would then be classified and coded accordingly for possible later retrieval. Gradually a library is built up in which it is easy to locate similar parts and eventually a point is reached where nearly all the new work is similar or identical to previous work, which is easily retrievable.

To gain the full benefits of manufacturing a part using a G.T. cell, requires that the product be a member of a family of parts intended for manufacture in that cell and that as many products as possible can be accomodated within a family. This requires a degree of design rationalisation and standardisation within a family of products. Wilson [9] writes:

> ´By providing a reference to previous designs, group technology avoids design duplication and also helps create and then reinforce design standards. The degree of rationalisation is the key to increased automation, particularly in process planning and product costing´.

It has been shown that G.T. can reduce lead times and W.I.P resulting in improved responsiveness and flexibility to customer´s demands as well as reducing the time taken to introduce new products [4,10]. However, to get the full benefits often requires the standardisation of features throughout a product family.

2.3.2 JIT / MRP II - MANUFACTURING PRODUCTION AND CONTROL SYSTEM.

The current manufacturing philosophy of much of industry is based on producing goods 'Just In Case' they are required. This philosophy ensures that factory production continues regardless of breakdowns, absenteeism, set up times, waiting (for parts, inspectors and tools) etc. The only way this system can work is to have a buffer stock or inventory at every point where production can be interrupted. This buffer stock can take the form of bought in components, raw material or part processed work (W.I.P). This high level of inventory is held 'Just In Case' of interruptions and the cost of this extra stock is substantial. In the Western World, interruptions are allowed to occur because the system is designed to cushion the impact of the interruptions. This cushion hides the inefficiencies of the system.

The Japanese 'Just in Time' (J.I.T) philosophy is one of continuous improvement to reduce waste [11]. It eliminates problems in order to lower inventory and then continues to eliminate any further problems as they appear with the lower inventory until the ideal of no inventory is reached. Whilst it is virtually impossible to remove all interruptions, it is certainly possible to minimise them and plan for them by implementing policies such as planned maintenance, condition monitoring of equipment, only buying from high quality reliable suppliers, and also by involving the work force to a greater extent to identify and eliminate waste in the design-through-to-manufacture process.

By constantly pursuing this policy of eliminating waste, the Japanese and some enlightened western companies have reduced batch size, reduced set up times, increased quality and response to the customer, but most of all reduced inventory and W.I.P. This has saved a significant amount of money and factory floor space and consequently improved the competitiveness of the organisation.

The J.I.T. philosophy regards inventory as wasteful and the answer is to make only the minimum number of units in the smallest possible quantities at the latest possible time. Taiichi Ohno, Toyota's executive vice president said [12]:-

> 'There is nothing more wasteful than producing something you do not need immediately and storing it in a warehouse. Both people and machines are wasted and the warehouse puts your money to sleep'.

J.I.T. has now become the philosophy of production, whereas in many cases MRP II (Manufacturing Resources Planning) [13] or OPT (Optimised Production Technology) [14] are the control system by which its objectives are achieved. For every end product ordered, (usually an assembly) MRP II creates a detailed schedule for each item of the assembly, which contains information regarding raw materials, components, fixtures, tools and when each item should be ordered and delivered.

It is of fundamental importance to any manufacturing control system that an accurate record of stock be maintained, whether finished parts, semi-finished parts, raw material, hardware, or redundant items. Without this accuracy and the capability of accessing the latest information, optimum decisions to control or replenish stock cannot be made. Not controlling this part of the business effectively, can result in either wasted space and money in producing and holding stock, or if components or hardware arrive too late in the manufacturing process, in wasted money, effort, machine utilisation and ultimately in late delivery.

Built into the system is a priority planning capacity [10,13] that allows for a limited plant capacity as well as providing a means to prioritise rush jobs and re-schedule others. A further feature available in MRP II is a closed loop system providing a feedback of information to execute this priority planning capability. The information required by the system comes from the component vendors, stores and the shop floor. The data from the shop floor is gathered from maintenance, WIP control, process planning, stock control, stores and anywhere else that production problems might occur. Shop floor data acquisition can also result in the monitoring of individual machine tools for utilisation, capacity and progress of work.

Finally this production planning system could be linked to the financial system of the company to produce a system which is concerned with many facets of the business including sales, production, inventories and cash flows. This allows easier gathering of accurate financial data regarding any units/departments and from this information, better management decisions can be made.

There are a number of commercially available MRP II systems, many of which can also be used to simulate "what if" questions. Using this facility, the management can consider the probable outcomes of alternative production plans and management decisions.

For MRP II to work in the ideal state, it requires a single real-time integrated company-wide system to gather information and control the business and this is usually where reality differs from the ideal. Few, if any, systems controlling a large or medium-size business are fully integrated and run in real time. Most of these businesses would make one run over-night, thereby being unable to react to changing events during the following day. Obviously, due to the amount of information and the number of transactions, this type of system can only work if it is computerised.

A computerised system offers the possibility of automatically extracting the BOM (Bill of Materials) from the CAD General Assembly drawing and loading it directly into the MRP II system. The BOM itemises each component in an assembly, listing its drawing number with a brief description, the quantities used, whether bought in or manufactured in-house, and where relevant, the suppliers name and catalogue number.

2.3.3. TOTAL QUALITY CONTROL.

The J.I.T. concept challenges the conventional approach to quality and quality control. Quality has traditionally been thought of as an after-the-act process, in that the product is first manufactured and then inspected. True J.I.T production does not allow the luxury of remake (scrap) or rework (repair). Instead, everything must be done 'Right First Time'[11]. This requires a full effort to prevent defective parts from ever being made, thus ensuring quality at source.

Responsibility for conventional quality control rests with a separate department and not with the workers who manufacture the defective products. In this environment it is not the worker's job to find out if a product is scrap, or what is causing it to be defective, or remedying the problem and organising any rework that may be necessary. It is someone else's job, and as a consequence he is not unduly concerned.

The advent of J.I.T has caused the introduction of a new approach to quality called Total Quality Control (T.Q.C.). T.Q.C. is a matter of attitude involving certain principles, many of which run counter to most conventional thought on manufacturing priorities and the cost of quality [11].

These principles are:

a) Everyone is responsible for quality. In particular, each person is responsible for the quality of their own work. This increases the workers interest and motivation and results in higher productivity and quality [4].

b) The drive for quality must come and be seen to come from the top management of the company. Sir John Egan, Chairman and Chief Executive of Jaguar Cars said [12]:-

'The success we had at Jaguar in improving our quality level, stemmed from the single minded way in which the management team attacked the problem'.

c) Reduce the number of suppliers [4,12]. Demand from the remaining suppliers consistently high quality and punctual delivery with strict default penalties, but offer them longer term, higher volume orders if they meet these criteria. Rather than the traditional purchaser/supplier roles; work towards a working partnership.

d) Accept that mistakes can and will occur, but work at these errors and keep working at them to prevent them from recurring.

e) Defect free production is more important than just maintaining the volumes of output. Examples of this are seen in assembly workers having the power to stop production lines to assess any quality problems at Mazda, Nissan or Toyota [12]. Initially this is costly, but gradually all the problems are debugged by workers, technicians and managers and error free production is worked towards.

f) Prevention costs less than doing things a second time. The conventional quality approach assumes that there is a point at which quality begins to cost more than it is worth. This is a misconception based on the idea that quality is some kind of unspecified perfection.

Dr. W. Edwards Deming the American who demonstrated and lectured to the Japanese about the importance of concentrating on quality said [12]:-

> 'Good quality does not necessarily mean high quality. It means a predictable degree of uniformity and dependability at low cost with a quality suited to the market'.

An example of quality products in their respective markets is a Rolls Royce and a Volkswagen Beetle. In this example, quality is not to be confused with luxury.

Total quality does initially cost money, but has been shown to result in sustained cost advantages. Only by systematically charting costs can managers fully appreciate that the true total cost of scrap and rework can account for between 15% and 40% of turnover in a typical company [12]. Some Japanese companies who over a number of years have been committed to Total Quality Control have reduced this figure to as little as 2% [12].

Another important point to note, is that quality is a very powerful marketing tool. P.A. Consultants state that customers prefer to buy and are even prepared to pay more and wait longer for products they perceive as being quality ones [12].

2.3.4 CAD - COMPUTER AIDED DRAUGHTING / DESIGN.

The Engineering drawing has been a standard means of communication in industry for many years. It is the link between design and manufacture. By preparing drawings to predifined draughting standards, information can be quickly communicated and assimilated. Voisnet [15] states:-

> 'That the speed of graphic comprehension can approach a rate of 50,000 times that of reading'.

Fellows [16] writes:-

> 'That the paper drawing may one day disappear, but the need to convey a pictorial method to the human engineer will prevail'.

Whilst the day of the 'Paperless Design Office' is not yet here, the day has arrived when paper is not the only nor necessarily the most useful design information medium. With the recent advances of computer and interactive computer graphics technology, a new medium of design information storage and communication has developed. At first, this new medium was called Computer Aided Draughting (C.A.D). It was used only for accurate dimensioning and the representation of the geometry of an object in 2-D in accordance with standard procedures. Its main advantage over the manual drawing board was its accuracy and quality of line thickness and density. Initially it was used to layout integrated circuits.

More recently, Computer Aided Draughting has evolved into Computer Aided

Design (CAD) and this is what most people now mean when they refer to the term CAD. Computer Aided Design systems are more sophisticated and much cheaper in real terms, than the earlier draughting systems. They now offer the operators many more functions and capabilities which allow the design process to occur in a practical manner. Perhaps the most significant function, now available to the designer, is the ability to model in 3-dimensions. It is believed that designing in 3-dimensions is a much more natural way to conceptualize the creation of an object and is therefore a better design tool than using the traditional approach of 2-D representational views [17]. The graphic representation of the object or component in a CAD system is called the ´model´. This model is mathematically defined and stored in the computer´s memory. CAD designers work interactively with a computer and a cathode ray tube which displays the emerging design as the operator creates it. Plots of this design, often called ´Hard Copies´, can be produced at any stage as required.

CAD can have a synergistic effect [10], magnifying the power of the designer, by leaving the human skills of conceptual independent thinking to the designer, whilst having the computer concentrate on calculations, graphics display and the storage and retrieval of vast amounts of data. Estimates of productivity gains resulting from the use of CAD can vary from less than 1:1 [18], to 100:1 [10]. Typically, values for productivity gains vary between 2:1 and 10:1 [10,19]. The large variation in these figures are due to the following main factors.

a) Complexity of the component represented.

b) Level of detail required in the drawing.

c) Degree of repetitiveness in the designed parts.

d) Degree of symmetry in the parts.

e) Extensiveness of library of commonly used entities.

f) 2-D CAD drawing or 3-D CAD model.

g) Amount of original geometry creation required.

From this list of factors, it can be seen that certain types of products and companies, are going to gain more benefits from using CAD than others.

The advantages of CAD to a design office are:-

1) If used correctly, the term 'Draughtsman's Licence' no longer applies to CAD. As the design is generated very accurately with the aid of a computer, the exact information must be input. In reality, the level of accuracy produced is far greater than the designers themselves actually need. However, this exact data permits the rapid production of highly accurate plots to any required scale, and in a form that is far neater, more uniform and in accord with the company standard than drawings produced using manual methods. Highly accurate, large scale profiles can be produced for optical comparators, used by the inspection function or for optical profile grinding and other similar manufacturing processes.

2) As a result of the accuracy and the improved visualisation of components and assemblies, there can be a reduced time in synthesizing and analysing a design especially when combined with time saved from reduced design errors [10]. The Designer can then consider more design options in the same time, or produce the design in less time. This is especially true of complex work which can now be done rapidly in 3-D, but which would previously have needed many large scale auxiliary views in 2-D. Using 3-D representations, the designer can rotate the component to any required angle, to aid visualisation and understanding.

3) Modifications to existing parts can be easier and quicker. This is especially true of alterations to layouts, or when producing a series of parts which are larger/shorter and where the 'stretch' commands can be used so that all the associated dimensions are automatically updated.

4) As parts are created on the CAD system they can be classified and coded using Group Technology and stored in a data base of previously created parts. These parts, combinations of parts or even just commonly used features can be retrieved and displayed on the screen, ready for quick modification. Any original work can then be added rapidly to form the required finished design.

5) Design quotation drawings produced manually on the drawing board for estimates, which are sent to customers, are usually hurried, inaccurate and incomplete when compared to the detailed manufacturing or general assembly drawings. Using a CAD library of parts, quotation drawings can be accurately and quickly assembled in a very presentable format. The use of CAD library parts, allows greater detail of the components and assemblies to be included in the drawing. By comparision, manual quotation drawings created in the same time as the CAD ones, would probably only have a few detailed sections with the remainder of it being in outline. CAD greatly enhances quotation drawings and improves the image of the company to its customers.

6) If there are many geometric variations of a part, and there is a constant requirement to keep creating these variations on a theme, then it is often beneficial to write a computer program which will create all the model and dimensioning graphics of the part or assembly in question, merely by the designer answering a series of questions. This is called Parametric Programming [20]. It is also very good for letting a designer alter various parameters to iterate towards an optimum design. Using this approach, he can view many variations very quickly.

McClelland and Smith at Ricardo use parametrics for pistons, connecting rods, poppet valves, tappets, seat inserts, valve guides, sprockets, gears etc [21]. They write that the design rules written into the programmes reinforce the company's design standards. This could include using only preferred tool sizes for holes and standard items etc. These programs can be made as complex as required, possibly linking the MRP II system and the the CAD system, automatically transferring and building the Bill of Materials. Similarly process planning could use automatically generated GT codes [7] or features labels with values leading to automatic process planning. If manufacturing logic and data are built into the programme, CAD models which are to be used by the CAM system, complete with machining stock, can also be generated along with operational process planning sketches which detail the various stages of manufacture. The present author is currently involved in this type of work in a practical commercial environment and has demonstrated the benefits which accrue from this integrated approach to designing for manufacture.

7) A data base of all the commonly accessed sections of information can be created, to which all the designers will have access. These designers will be able to call this accurate information on to their own CAD terminal screens whenever it is required. Some examples of this facility could be, preferred tool sizes, standard size and stocked items and material data

etc. Some of this data may also be called and used by the Parametric Programmes. Likewise, the designer may run engineering programs from his terminal, which will calculate required values for typical engineering problems using operator input data values. Typically this could be for spring calculations or for calculating strength and wear values for gear design.

8) Certain types of geometric detail (surfaces and points on surfaces, lines of intersection etc) can be formed quickly which would not even be attempted manually. If the CAM system uses this same geometry, then it can allow greater design variation as the part can now be manufactured accurately and relatively cheaper.

9) Representations of components can be 'Surface Shaded' to produce a very realistic colour image of the finished component Fig (1). This can be very useful in aiding the visualistion and understanding of complex parts and is particularly valuable when aesthetics are a major consideration, such as in Industrial Design.

CAD can offer the designer more accurate information related to geometry, better visualisation and greater standardisation of presentation and component geometry. Modifications to existing parts or the creation of 'similar to' parts can be a major time saver. Thus CAD offers the prospect of reduced lead times, greater quality and standardisation of geometry [10].

The use of CAD also gives potential time saving and quality benefits to manufacturing and other downstream functions. Indeed, this is, perhaps the most significant way in which total economies can be achieved [18,22]. If an integrated stategy is pursued, these benefits can be further enhanced by creating the CAD model in a suitable format. This will be described later.

2.3.5 COMPUTER AIDED ENGINEERING (CAE).

Most engineering designs require some kind of engineering analysis to be performed. Its purpose is to simulate the performance of a system or to predict the behaviour or reliability of a component under a variety of operational conditions. This should lead to an optimum design. Typically an analysis may involve one or many of the following:- stress and strain analysis; heat transfer; dynamic analysis; fluid flow analysis; kinematic analysis etc.

Equations can be formulated and used to describe or predict the performance and characteristics of a system or component in operation.
Much of the above analysis work requires a large number of tedious or complex mathematical calculations to be made. This type of work can only

be done quickly and accurately using computers.

Many stress analyses for parts having complex geometries cannot be produced accurately using a traditional manual approach and so large safety factors are introduced into the design to accommodate uncertain ties [23]. In recent years, with ever increasing demands for performance and reduced weight, there has emerged a greater requirement to engineer components and equipment more effectively and accurately. This emphasis on engineering coupled with the advances in computer and computer graphics technology, has resulted in an explosion of computer based analysis and engineering tools. The use of these tools is generally referred to as Computer Aided Engineering (CAE).

Many of these CAE tools run on or are linked to the CAD/CAM equipment and use the actual CAD model to work from, thereby guaranteeing data integrity whilst removing any duplicated effort needed to recreate the part. An advantage of many of the modern CAD based analysis tools, is that the output is not in the form of many rows and columns of numbers, but is now graphically shown on the screen to allow visualisation and greatly improve understanding. This display could take the form of a component deflecting under load, or as a series of thermal or stress contour lines across the component Figs (2) and (3).

Fellows [16] writes,

'The old saying that a picture is worth a thousand words still holds true and the human eye can feed more information to the brain, in the form of pictures, faster than by any other language means. A computer naturally works best with numerical data, but graphics are without any doubt the best man / machine interface available for our current computer technology'.

Probably the most powerful of these analysis tools available on a CAD system is Finite Element Analysis (FEA) [23]. F.E.A. can analyse the component for stress and strain from physical and for thermal loadings. To use FEA, requires the structure firstly to be divided into a large number of smaller but discrete imaginery elements of simple shape, this is called Finite Element Modelling (FEM). These elements can be of various geometric forms Fig (4) and are considered to be joined to their neighbouring elements at convenient points on their boundaries, known as nodes. These nodes are usually located in the corners and mid-way along the edges of the elements. To maintain the continuum of the structure, if a node of one element moves, then all the adjacent elements which previously shared that node, must also move by the same amount in the same direction. Numerous elements can be put together in a variety of ways and they can be arranged to simulate exceedingly complex shapes. The resulting pattern of elements is often called the 'Mesh'. Each element is essentially a simple unit, the behaviour of which can be readily analysed. The properties of a particular type of element depend upon the number and types of Degrees of Freedom (D.O.F.) and the basic assumptions made in deriving the stiffness properties. The Degrees of Freedom of an element refer to the nodal displacements, rotations and/or strains which are necessary to specify completely the deformation of the element.

The representation of a structure into an equivalent system of elements in this way is called 'discretization'. The relationship between the forces and corresponding displacements at the nodes of each element can be determined by virture of its relatively simple shape. Using a mechanical principle such as the minimization of potential energy [23,24], this can be written in mathematical terms as a set of simultaneous equations, but is usually expressed in matrix form.

Using each element's individual stiffness matrix, the overall or global stiffness matrix and load vector for the entire structure can be assembled [23,24] to give the following matrix equation:-

$$\{ F \} = [K] \{ X \}$$

where [K] is the overall stiffness matrix of the structure, { F } is the external force or load vector at all the nodes and { X } is the list of nodal displacements. { F } and [K] are known and the object is to find {X}, from which the strains and stresses can be calculated. Thus by loading and constraining the movements of nodes within certain elements as required by the prescribed boundary conditions, the behaviour of the entire structure can be analysed. Using a similar approach, but using simultaneous equations of motion, a dynamic analysis can be performed to identify mode shapes and natural frequencies.

When using a CAD model, many elements can be generated automatically using the CAE system, and then manually edited to build and concentrate elements around features such as holes, radii, grooves etc to give very detailed local information Fig (5). Boltz and Avery estimate a productivity gain of 3 when using CAD to build and define the finite element model [18]. Finite Element modelling of non-structural problems, such as heat transfer, is also widely employed in practice.

Another method which also uses a mesh is the Finite Difference Technique. This is mostly used to simulate processes involving fluid flow.

Aerodynamic and Hydrodynamic simulation and analyses can be done by considering fluid flow over an aircraft wing/fuselage or ship hull. This engineering tool is also used to simulate heat transfer, combustion and chemical reaction processes. In contrast to these general purpose tools, there are those which are more specialised such as those which consider the flow of injected plastic into a mould. These analysis packages are now available for use on many CAD systems.

Calculations of properties such as areas, volumes, masses, centres of gravity, moments of inertia, radius of gyrations etc have the widest application and are probably the most commonly available standard engineering analysis facility on most CAD systems. Some of these functions require 3-D models with surfaces and depending on the geometry, there can be a variation in both the ease of use and the accuracy of the individual facilities and these are best determined by experiment with each particular type of system.

Another powerful feature available on many CAD systems is animation. Animation allows kinematic motion to be broken into a set of small discrete steps, each of which are chronologically displayed on the screen. Viewed over a short period of time, (usually in the order of ten or twenty seconds) the total motion of a system can be observed by an operator. These kinematic packages allow the simulation of the motion of simple design mechanisms, such as hinged components and linkages Fig (6). This capability enhances the designer's visualisation of the operations of the mechanism and helps to ensure against interference between components. Without graphical Kinematics on a CAD system, designers often resort to the use of pin and cardboard models to represent the mechanism. These Kinematic packages are often used to model car suspensions or steering mechanisms on CAD systems.

The purpose of all these analysis tools is to predict the performance of a component under any desired operating condition. In many cases it allows designers to economise [25] on material whilst maintaining adequate strength for purpose. Previously many of these analyses would not be performed manually and so generous safety margins were being included in the design, resulting in space and weight penalties.

Design weaknesses such as stress raisers, hot spots etc, can now be identified at a much earlier stage of the design-through-to-manufacture process. When a design weakness is identified, the failed feature can usually be corrected. With the mesh adjusted to suit, an analysis can be re-run and the consequences of ammendments readily assessed. This cycle can be repeated until the error is removed or the desired performance achieved. Previously many of these problems would only have been found at the prototype testing stage, thereby requiring a series of expensive prototypes and tests until an optimum design was reached. Consequently, there can be a reduction in the number of prototypes built [24]. Because problems are identified and corrected much earlier, especially before metal is cut, then there can be significant cost and time benefits [25].

2.3.6 CAM - COMPUTER AIDED MANUFACTURE.

The first demonstration of a computer to control a machine tool was given by John T. Parsons to the U.S. Air Force in 1948 at the servomechanisms laboratory of the Massachusetts Institute of Technology (M.I.T.). To control the machine tool, Parsons used punched cards containing positional co-ordinate data points in space. By using a series of these cards, he was able to produce a series of small incremental movements between consecutive data points, thus enabling a desired airfoil surface to be generated. This technology was called Numerical Control (N.C.).

Over the years, N.C. has been developed and is now able to give the following main benefits to its users:-

1) With reduced set up times, work handling and automatic

tool changing, the cycle times of N.C. machines compared with their conventional counterparts ranged according to a survey from 35% for 5 axis machining centres to 65% for presswork [26]. This reduced non-productive time is of course linked to the batch size.

2) Average lead times were reduced by between 26% and 44%, due to quicker set up procedures and faster rates of production [26].

3) Improved quality control due to greatly improved repeatable accuracy, especially of complicated components, reducing both scrap rates and lower inspections costs. Average scrap rates reduced by between 31% and 44% giving cost savings of about 38% [26].

4) Greater design flexibility allowing more complicated types of work to be designed and manufactured at an acceptable cost and delivery rate.

5) Often, NC machines do not need any costly special fixtures to be made and stored, as the positioning is controlled by the NC tape with a new datum offset being entered by the NC programmer or machine operator. Reduced fixture costs and shorter lead times are a beneficial result.

To perform any N.C. operation using a machine tool, requires that the positional co-ordinate data points be correctly generated and placed in sequential order. Additionally, interspersed amongst these data points, will be machine dependent control commands (speed, feeds, tool changes, GOTO statements, coolant on/off etc). Collectively this data is called the part program, and it must be in a format suitable for use on a specific machine tool.

There are two ways to produce N.C. Programs:-

A) Manual part programming.

B) Computer assisted part programming.

Manual part programming requires that the format be prepared in a very precise manner, as the machine control commands vary for different machine tool controllers. These controllers read and interpret the program of instructions and convert it into the mechanical actions of the machine tool.

Unfortunately, there are many controllers available on the market and each reads and interprets data slightly differently, so that slight differences in input data formats are required. When using manual programming techniques, the programmer must be familiar with the different formats of all the machine tools with which he is involved.

The manual part programmer must also calculate the positional co-ordinate data points from either the finished engineering drawing or the process planning drawing. This approach is adequate for relatively simple point to point work on regular geometries. However, if contour work or non regular geometries involving continuous tool path control movements is required, then manual programming becomes much more time consuming and error prone.

In 1956 the U.S. Air Force sponsored additional research at M.I.T. to overcome these problems by designing a part programming language to assist in the programming of NC machines. In 1959 this research resulted in A.P.T. which is short for Automatically Programmed Tools. The purpose of A.P.T. was to make it convenient for the part programmer to communicate the part geometry, tool motion and operation information (speeds, feeds, coolant, tools etc) to the computer. The vocabulary of A.P.T. words are typically mnemonic and English-like to make the programming easier.

A.P.T. defines the outline geometry to consist of a series of intersecting lines, partial circles and points. The part programmer would break down the required component geometry into these basic elements, which he would identify uniquely and then define the individual element´s location and dimensions. The computer could then calculate the intersections, the intermediate segment positional data points needed when contouring, and the cutter radius offsets. A.P.T. was written as a general purpose language suitable for most machine tools.

Finally the NC programmer would send the completed part programme through a post processor to produce the required NC programme. A post processor is another computer program which has previously been written to convert the general purpose language part program into a format suitable for a particular machine tool and its controller. A representation of the NC program would then be produced on a punched or magnetic tape and then sent to the machine tool.

Since A.P.T. was released, many other part programming languages have been made commercially available, for example ADAPT, EXAPT, SPLIT, COMPACT II, CINTURN II etc. In all of these the computer performs most of the calculations, leaving the programmer to concentrate on defining the component geometry and specifying the operation and sequences of each tool path. Removing the need for manual calculations results in time saving, less errors, higher quality/accuracy and generally more efficient part programming [10].

In the nineteen sixties and seventies, with the advances made in computer and interactive computer graphics technology, a further enhancement to part programming developed. This involved using a cathode ray tube to display entities, a general term for all arcs, lines, splines, conics and points. The operator would input data concering these entities and they would be subsequently generated and displayed as computer graphics on the terminal screen. Whole components could now be designed and displayed on the screen. This was called Computer Aided Design (CAD). NC Programmers, could then use this CAD geometry by selecting the entities in sequence with some identifier such as a cursor or the 'cross-hairs' on the terminal screen. The 'cross-hairs' are controlled by the movement of a hand held 'mouse' or 'joy-stick' and selection is made by placing the 'cross hairs' over the desired entity and pressing the select button on the 'mouse' or 'joy-stick'. When the geometry was being created, the computer automatically stored data about each entity. Consequently, when the programmer selected each entity in turn, he did not need to re-define each entity, as the entity type and positional data already existed. Thus all the geometry co-ordinate data values of a toolpath could be generated and stored automatically by the system.

When assembling the toolpaths together to form the part programme or C.L. (cutter location) file, the programmer still needs to enter A.P.T. or A.P.T-like machine operation commands (speeds, feeds, tool no, coolant, offsets etc.). The result of using this approach, is a major saving in time, as the part does not need to be redrawn nor co-ordinate data re-calculated. Often small amounts of extra geometrical detail may need to be added to the existing CAD geometry more accurately to reflect the geometry of the component at that particular stage of manufacture.

Another common reason to add geometry is to produce the original outline of the bar or billet of material. As most of the original geometry is being used and there is only a small amount of human activity involved in the transferring, modifying or calculating of data, there is a reduced chance of errors leading to higher accuracy and, hence, improved quality.

Many of the commercially available CAD/CAM systems also have common machining routines that enable tool paths to be automatically generated.

These routines can effect the removal of large volumes of material simply by defining only the boundaries and the number, type (roughing/finish) and accuracy of the cuts on the machine Fig (7). There are milling routines for pocketing, contouring and surface machining. Turning routines require similar information with the original bar of material to be defined along with the finished profile. The routine will then produce a toolpath with enough roughing passes to remove the unwanted bar material, contained between the component profile and the original outline of the bar. The routine will then produce a higher quality finish cut.

Some of the better CAD/CAM systems also offer parametric part programming. When a parametric design is produced, it is quite possible that the same program could also automatically generate a CL file or part program ready for post processing. Obviously, this is only worthwhile programming, if there is a sufficiently large product family to manufacture.

Another benefit to CAM of interactive computer graphics is that there is a dynamic tool path simulation feature. Having produced the toolpath, the programmer can verify it, by displaying a representative model of the pre-defined tool moving along the toolpath over a superimposed model of the component. The programmer can check for collisions or errors, by observing the motion of the tool relative to the CAD geometry. Any modifications to the program can then be quickly and easily carried out before the Cutter Location File is post-processed into the NC program.

Delays due to errors and consequent extended lead times can be reduced using this 'off-line' simulation facility.

The benefits of using a CAD/CAM system of the type described above are:-

1) Improved data integrity, as there is no need for geometry re-definition, with its associated errors from the interpretation of drawings and the subsequent manual programming process. Since the CAD generated part contains most of the information, the programmer does not need to redefine the geometry, a considerable time saving over conventional A.P.T. programming. Hence the benefits are increased efficiency and consistently greater accuracy, resulting in less errors and higher quality [10].

2) 'Off-line' visual verification allowing most errors to be corrected immediately after a mistake is made. This results in reduced tape verification times on the actual machine tool, leaving more time for revenue earning production.

3) Automatic programming routines can yield a significant reduction in part programming time, especially on contouring, pockets and surfaces [10].

2.3.7 CAPP - COMPUTER AIDED PROCESS PLANNING.

Process planning is concerned with determining the optimal sequencing of manufacturing operations to produce a component or product [10,28]. This sequence of production operations is documented, usually on a process plan or route sheet. Next to each operation, the planner will define the machine tool and the machining operations (speeds, feeds, depths of cut, tool numbers and fixture numbers etc.). The planner will also calculate set-up times and piece times. Additionally, operation drawings of the component may also be produced for the machine tool operators. These operation drawings show the component at discrete stages of its manufacture, complete with dimensions relative to the manufacturing datums at that stage of manufacture.

The process planning procedure is very much dependant on the experience and judgement of the individual planner and each has his own opinions about what constitutes the optimal routing. The result is a profusion of non optimal process plans and hence reduced efficiency.

There can also be problems in keeping existing process plans up to date. If a machine is scrapped, the job must be re-planned. If a new, better machine is introduced onto the shop floor, then repeated jobs which are not re-planned, may be processed through the factory using the old process plan and associated machine tool, which is no longer the optimal route. Similarly, a new job could have been planned when a machine was being repaired and so was given a diverted routing which was subsequently never updated, resulting in a non-optimal routing when manufactured at a later date.

Process planning is typically a routine task involving a high human manual and clerical content in which similar or identical decisions are frequently repeated. Because of the type of work involved in process planning and with the problems encountered with a manual approach, attempts have been made to computerise the whole process. Computer programs which capturing existing planners´ logic, judgement and experience and which also call on materials machinability and machine tool databases can, given the characteristics of a component, automatically generate a process plan. This is call Computer Aided Process Planning (C.A.P.P.).

C.A.P.P. has the potential dramatically to reduce the clerical work of the planners, whilst generating routings which are rational, consistent and perhaps even optimal. Capes writes [27]:-

> ´The benefits of a computer based production planning system, properly set-up, is possibly more tangible than a massive investment in machine tools, at least from the point of view of financial results. Correct routing of jobs through a factory with the capability to re-route when necessary can often be make or break on the balance sheet, as it reduces raw material and finished stocks to a minimum, and can also result in massive cuts in work in progress.´

Two approaches to CAPP have been developed, these are:-

1) Retrieval type systems (sometimes called variant systems).

2) Generative type systems.

2.3.7.1 RETRIEVAL TYPE PLANNING SYSTEMS.

Retrieval type CAPP systems are based on group technology using a part classification and coding system [28]. All the parts produced in the factory are grouped into families according to their manufacturing characteristics. A standard process plan is then established for each family of parts. This standard process plan can then be modified in order to plan all the parts in the family and each modified plan is stored in a computer file under that part's group technology code. To treat a new member of the family by recalling the process plan of a very similar part and modifying this plan, requires much less effort and so it is a very desirable feature to be able to identify and recall the most similar part already existing on the system.

When a new part needs to be manufactured, the planner will enter into the system the G.T. code for that new part and, if similar parts have previously been planned, he can then retrieve from the database all the G.T. code matches. The planner selects the best match and then copies and edits it to suit the new part. Sometimes, the planner will be able to call up standard text and just enter new values. He can then use the plan to generate estimates and standard times. This new process plan will then be in the system ready to be retrieved in the future, so that the database grows with time. Eventually nearly all the new parts to be manufactured are merely variants of previously planned parts and hence similar process plans exist. This improves not only the speed and efficiency of process planning, but also the general uniformity legibility and quality of the process plan [10,28].

2.3.7.2 GENERATIVE PROCESS PLANNING SYSTEMS.

Generative Process Planning automatically creates a unique process plan without human intervention by employing a set of algorithms to make the logical and technical manufacturing decisions required in its formulation [28]. The planner would need to enter a comprehensive description of the part into the system. This can be in the form of pre-defined features to which the planner enters the values specific to the component. With generative type systems, it is this comprehensive description of the features which make up the component which is stored, rather than the process plan. If the part is re-ordered, a new process plan is generated from this description, thereby producing an optimum process plan each and every time.

Joseph Tulk of Lockheed - Georgia [29] writes of their generative process planning system GENPLAN:-

'GENPLAN synthesizes process plans using the manufacturing logic and rules that were programmed into the system. Its technological data base consists of process decision logic, machine data, factory rules, tooling data and labour formulas'.

Like retrieval CAPP system, generative ones improve speed, efficiency, uniformity, legibility and quality of the process plan produced. The actual generated process plan contains the route with speeds, feeds and standard times and is similar to the output from the retrieval (variant) system. However, an advantage of the generated system is that it can produce very accurate manufacturing cost estimates for quotation purposes every time.

A further advantage of the generative type is its ability quickly to generate an alternative route and process plan through the shop floor to avoid either a 'bottleneck' machine tool, or one which has broken down. When a new machine tool is introduced to the shop floor, or one removed, the optimal routings for many parts will change. In such situations the retrieval type systems will then need to flag all the existing process plans which are affected, as next time these parts are required to be manufactured, the process plans will need to be manually edited for speeds, feeds and times. On the other hand, the generative system, once all the new machine tool algorithms have been defined, will generate complete optimal process plans for all of the existing components every time the job is run [29].

During the implementation stage, the main differences between the two systems are that Generative CAPP systems initially require much more effort to build up the action/decision logic blocks and the technical databases than the retrieval ones which only need to create the GT based databases. Consequently G.T. based systems can almost start working (building and retrieving from the database) immediately, whereas the generative systems take much longer to build up before they can be used. However, once the generative CAPP system is in place, it creates the full optimal process plan everytime without the need for any editing.

If CAD parts are generated parametrically, then within the program, a module can be written automatically to generate a G.T. code suitable for the retrieval CAPP system or files containing feature labels with values for a generative one. In the case of generative files these systems can be read by the CAPP systems and trigger the CAPP programme to run, leading to automatic process planning. Likewise the CAPP system could also be linked to the MRP II system for delivery, routing, scheduling and shop floor loading purposes. This automatic transfer of data, demonstrates the inter-relationships between functions and it is identified as an area which can be exploited to increase the overall effectiveness of the business.

2.4 THE NEED TO INTEGRATE AND RE-ORGANISE A BUSINESS

Many Advanced Manufacturing Technologies, including those discussed above have been applied by industry over recent years and have achieved increases in productivity and quality, with reductions in costs and lead times.

However, there is a limit to what can be achieved by each of these technologies working in isolation, often called 'Islands of Technology'.

Many of the advantages of the above technologies can only be fully realised, if the other technologies are also operating and working together in a co-ordinated manner, automatically feeding each other with any required information as soon as it becomes available. The combining or integrating of these separate functions into one unified system has a synergistic effect, multiplying the effectivenss of each function. By making the information produced in one function match as far as possible, the information requirements of the next function, the whole system can be streamlined. In this process much duplicated and unnecessary work can be identified and removed. This leads to greater integrity of information, shorter lead times and reduced costs [4]. Godfrey [30] writes:-

> 'The overall philosophy of the factory of the future is to discipline the flow of information and material, maximizing the flexibility to accomodate part-to-part and product variations and optimize the processes for yield and throughput. The result should be a very flexible plant producing parts at the lowest total cost.

An example of this is when a piece of information can be useful to a number of users for different purposes. Previously such information would need to be generated and/or entered independently into a number of systems with the inherent risk of errors involved in manual data transfer. The ideal would be to enter and generate information only once and then pass it on in the most usable form to the next function/system, which would in turn generate more information for the next function/system etc. Hence the need to integrate these islands of technology into one unified factory system.

This one factory system will tie all the engineering, manufacturing and financial systems into one useful logical system. Paul Ranky´s [31] diagram of CIM Fig (8), shows some of the most important modules of the engineering, manufacturing and financial systems and indicates the most important data paths.

The traditional departmental structure within a company often results in each department operating almost in isolation from the rest of the company, performing their job functions with little feedback coming into or feed-forward going out of the department. Bad or out of date practices are often perpetuated simply because departments have not communicated. Those departments which are ignorant of the systems, produce work which may be duplicated later and which is often non optimal, giving rise to increased costs and lead times. The inefficiencies of this structure must be eliminated.

The original idea of integrating was to cascade information from the initial order/quotation entry point through to delivery of the goods. This can be developed further, by matching as far as possible the information output of one function, to the requirements of other downstream functions.

An analysis of the information flow within a company should be made to ascertain the most logical and effective position within the information flow chart to generate a given piece of information. This will often result in some sections of work being moved from one traditional department to another, or a department producing more information at a point in time than it did previously. The traditional department which is actioned with this extra work will often complain that its efficiency will be reduced, however their extra 1/2 hour per job at that stage may produce a total time saving of 1 or 2 hours per job at the other downstream functions, thus resulting in a net increase in overall system efficiency.

The next logical step after matching output to requirements is feedback and this has lead to the promotion of the terms 'Design For Manufacture' and 'Right First Time'. Although these are not new terms, they are now being applied much more rigorously and widely than before. They are concerned with giving the designer information at an early enough stage of the design process to keep the costs and lead times to a minimum. It is estimated that 85% of the eventual product cost is determined during the design process, whereas at the time production actually begins, manufacturing can at best effect only a 10% reduction on the final product cost [32]. To reduce costs and lead times requires that large amounts of accurate information are at the finger tips of the designer. This would include current design standards, factory specified standard gauges, fixtures and tools, factory stocked materials and bar/billet sizes, selected components and hardware, quality standards, factory process capabilities etc. In addition to this information there is a need to hold regular interactive discussions throughout the design process involving representatives of all the departments affected by the design i.e. design, process planning, jig and tool, NC programming, quality, inspection, production engineering etc.

These meetings bring healthy feedback into the system, and bring it in at a much early stage, so that costly problems can be designed out of rather than into a design. A product will not now need re-engineering whilst in the prototype or production stages, instead the interactive redesign process occurs whilst still at the design stage, due to the tight feedback loop. Consequently an optimum design, may take longer to produce, but it will now be easier, quicker and cheaper to process and produce the job as a whole, as there are now fewer problem areas for the downsteam functions.

The progression into integration, matching inputs and outputs of job functions, and greater interactivity between departments is causing changes not only at the point of information generation, but also to the way departments operate. One of the main results of this is the erosion of traditional departmental barriers. Both the physical and mental walls between departments are being pulled down in the move towards larger open plan offices. Multi disciplined task forces now work together as a team on projects, design and engineering cells are being set up, adjacent terminals or desks are manned by people of different disciplines, thus increasing the interaction between functions. The result is a major re-organisation concerning how, when and where work is done.

2.5 COMPUTER INTEGRATED MANUFACTURE (CIM)

The advantages of moving towards an integrated system are now becoming recognised by industry. It is therefore not surprising that the concept of integration has now joined the list of technologies which are being actively pursued.

Whilst the concept and benefits of integration are easy to grasp, installing an integrated system and making it work are neither easy, cheap nor quick. There are no 'off the shelf' solutions that will provide a fully integrated system appropriate to an organisation. Each user must develop his own integrated system to suit his own requirements. This initial step is often made with the aid of experienced consultants. Istel have produced a book [33] providing conceptual rules for the design of a CIM System and the Ingersoll Report [4] offers some guidelines on how to approach the setting up of a CIM system. These rules are based on the fact that a fully integrated system is complex and is time consuming to install. They recommend a modular approach with a 'Top-Down' strategy and a 'Bottom-Up' implementation.

A Top-Down strategy will examine the business as whole, both now and in the future, the aim being to simplify and then reorganise the current system into an integrated modular one. The next step is computerise this simplified modular system, which is not merely a computerisation of the old system. This modular systems approach will ensure that when the system is being progressively implemented, module by module, integration and communication can be made between related modules or functions. Once the specifications of each module are produced, the module can be implemented and organised by the users in a 'Bottom-Up' approach.

Integration is the philosophy, but computers are the enabling technology giving the most effective means of achieving it. The Ingersoll report [4] says:-

> 'Effective long term integration is certainly not possible without computers'.

The use of computer technology in integrating a business is called CIM (Computer Integrated Manufacture). Many of the previously discussed technologies are already computer based, purely for their speed, accuracy and extremely large on-line calculating and data storage capacities. It is a logical step therefore to install a computer system which allows communication between all the modules, thus allowing the integration of the often fragmented functions or 'islands of technology' into a single operating system. Information/data need now be generated and entered into the system once only. It can then cascade through the computer system to the relevant departments. In the process, it may also be automatically reformatted and combined with other data on the system to arrive at other modules in the most useful form.

The managers of a company can now control and monitor the work on-line as it progresses through the system. They can make decisions based on the latest data from say the factory floor and run 'what if' simulations on the system. This combination of instantaneous correct data and communications within the one system will allow true JUST IN TIME production.

Unfortunately computer systems manufactured and sold by the various vendors do not readily communicate with each other and so great care must be taken in the 'Top-Down' strategy when specifing the computer systems to be used in each module. If this is not done, computer communications between modules may be difficult, impeding the movement towards CIM.Companies which have set up islands of technology without considering integrating are now incurring large time and cost penalties when they attempt to integrate them [4]. These are the companies which did not consider the long term implications and/or did not take a systems approach to the problems.

Although no company has achieved a full CIM system, many have achieved partial integration, and are seeing the benefits. The Ingersoll Report [4] quotes the following benefits that Ingersoll Engineers found in a survey of CIM installations.

Reduction in engineering design cost	15-30%
Reduction in overall lead time	30-60%
Reduced work in progress	30-60%
Increased productivity of capital equipment	2-3 times
Increased product quality	2-5 times

Clearly CIM is going to be central to successful manufacturing in the future, integrating all the separate systems within an organisation into one unified business system. It brings together many of the new technologies and re-organises the people to interact more effectively with each other and with the new technologies. Although full CIM is the ultimate objective, even partly installed CIM offers greatly increased effectiveness throughout the organisation [4].

The remainder of the work described in this thesis was concerned with the most effective use of the CAD, CAE and CAM systems within a company, which was moving towards CIM. Hence the CAD, CAE and CAM modules cannot be considered as isolated modules, but as one part of the overall system.

CHAPTER 3

CAD - A FOCAL POINT FOR CIM ACTIVITY

CAD - A FOCAL POINT OF CIM ACTIVITY.

3.1 THE DESIGN PROCESS USING COMPUTER AIDED TECHNIQUES.

The design process using Computer Aided Techniques is essentially the same as on the drawing board. The process is still an interactive one, wherein the objective is to satisfy a given specification with an optimum design. Pahl and Beitz [34] show the design process as a system Fig (9). The steps and the feedback loops of the design process shown, must be systematically worked through to achieve an optimum design, regardless of whether the design is represented manually on the drawing board or in 2-D or 3-D on the CAD system.

CAD, much like the traditional drawing board, is only a tool for the Designer, so that the quality of the design still depends on how he has utilized the information available to him. CAD will not make a bad design good. What it offers is better visualisation, accuracy and speed (especially when using a library of CAD parts or when modifying parts or when using parametric programmes). Large engineering databases containing the very latest information can be at the finger tips of the designer. Complex surfaces especially for bodywork or moulds can now be produced in a fraction of the time and with far greater accuracy than could be achieved manually. Designers can now attempt more adventurous designs which they would not previously have attempted, as data relating to these accurate design surfaces can now be used directly in the creation of NC programs for complex machining operations on such designs. The kinematics of mechanisms involving linkages can be observed by simulation and potential clashes or interferences designed out. Modelling in 3-D improves visualisation by offering the opportunity to rotate the workpiece to any desired angle, reducing the need for auxiliary or 'true' views, thus allowing a greater appreciation of the design concept. The speed, integrity of the data and accuracy that CAD can offer, results in either a shorter design cycle or allows more variations of each design to be considered.

If CIM, 'Right First Time' and 'Design For Manufacture' are part of a companies' overall strategy, then the relative importance of the design function increases. In such a company there will now be much greater emphasis on the design function, making it a focal point for CIM activity. Prior to any metal being cut, there will now be much greater interaction between design and the downstream functions and this interaction will also now mostly occur during the design process.

At the Design for Manufacture meetings, representatives from each of the downstream functions will be trying to identify and then remove or reduce the impact of any features within the design which they suspect may cause them problems at the various stages of the total product realization process. These representatives will probably suggest more acceptable alternatives, or at least warn of the implications of a design feature.

There will be much more feedback to the design function and it will take place much earlier in the total process than before. The Designer will now be much more aware of the consequences of design decisions providing a powerful aid to attaining an optimum design from all the information that is available. The result of this extra information, is that the design activities themselves may well take longer than before, but as many if not all of the potential problems downstream will have been resolved, the actual total cycle time and the total cost will have been reduced.

The central role an integrated CAD system can have on the design-through-to- manufacturing cycle is briefly discussed in the sections below.

3.2 INITIAL CONCEPT AND DEFINITION LOOPS.

Any new product must meet the requirements of the perceived market. The intelligence provided by market analysis enables the requirements and constraints to be initially specified. This leads naturally into what Pahl and Beitz [34] refer to as the conceptual design process. During this process various analyses will be made to estimate the required performance of the design in operation. Pahl and Beitz [34] write of this phase of the design process:-

> 'The conceptual design phase involves the establishment of function structures, the search for suitable principles and their combination into concept variants'.

An evaluation of each variant is then made and any which do not largely satisfy the specification on technical or rough economic criteria, are eliminated. The evaluation process is made by representatives from the design and marketing functions. The remaining conceptual design(s) then enter the 'embodiment design' phase, which Pahl and Beitz define as [34]:-

> 'The designer starting from the concept, determines the layout and forms and develops a technical product or system in accordance with technical and economic considerations'.

The embodiment design solution(s) may then be passed to the styling function (industrial design) to try and make the appearance of the embodiment design more aesthetically pleasing. The resulting design(s) are then viewed by the people in the marketing function for their consideration. The design(s) may also be shown to selected customers for further market analysis and this may in turn require a modification to the specification. The resulting desired/achievable design will usually be a compromise and specification changes could also have occured and so the marketing function may request the designers to change certain features to achieve a slightly different performance or to make the design more aesthetically pleasing.

A series of interactive loops between job functions can now be seen to start to form and they are shown by Wilson [9] in Fig (10). The aim of the loops is to progress in an interactive manner towards a product definition. As the embodiment design begins to converge towards a general product definition, then representatives from the manufacturing function will become involved Fig (11). These loops can be performed in the traditional sequential departmental fashion, or using a more modern integrated system, which a computer based approach makes possible, allowing some of the work to be done in parallel. Wilson [9] writes:-

> 'Without the benefit of integration, these functions tend to be carried out consecutively rather than simultaneously, which considerably extends the time required for product definition. It also increases the scope for error caused by duplication of information by different functions and slow or inadequate communication. The volume of documentation used when engineering, design and production engineering and styling departments operate independently generates high costs. The handling of design greatly compounds the problems'.

Wilson [9] also argued that if CAD is used, the integration with other functions reduces costs, saves time and improves the quality of information. The aim is a free exchange of CAD geometry and other data between CAD and styling, CAD and CAE, and CAD and CAM so that each contributes to the development of the product database and CAD geometry.

Bjorke, like Wilson, also stresses the importance of a common information flow and structure and says [35]:-

> 'The most important goal on the CAD and CAM areas is to make the production creation in mechanical industry more efficient through an integrated use of the computer. Integration in this context means that all information concerning the product, is

put into and processed in the computer at a certain sub system, at a certain time, is available later to all the other sub systems that may require it´.

3.3 PRODUCT DEVELOPMENT LOOP.

Although using CAE tools for simulation or analysis can give a good indication as to which designs can not perform to specification, they can rarely predict which designs will definitely work. This is mainly due to simplifications made to the model geometry and to the basic assumptions made about the behaviour of the product in operation, these processes are referred to as ´idealisation´. The only definite method of verification of product performance is by prototype testing. However, the more effective use of standard data, parts and features which can be rapidly retrieved and added using CAD system, can reduce the scope of errors, and hence cost and lead time at this phase of development. Although the great majority of manufacturing problems will have been removed or reduced in the ´Design for Manufacture´ loops, in reality the manufacturing processes may also still need to be verified i.e. casting wall thicknesses and draft angles, NC tapes for speeds and feeds, offsets and collisions etc. Even using an integrated system, there is still a need to build and test prototypes, but in reduced numbers and with subsequently fewer resultant design changes.

A product development loop is shown in Fig (12). If this is integrated then the CAD geometry is available for CAM, CAE and after prototype manufacture, for inspection. Inspection processes may use optical comparators which use accurate large scale CAD plots, or co-ordinate measuring machines which can be programmed on the CAD/CAM system using the existing CAD geometry. Due to the increased use of standard parts and features and removal of duplicated geometry creation, there is a reduced number of design changes and errors. Designing for manufacture also reduces the costs, the need for design changes and lead times. Additionally, CAE eliminates many of the proposed designs, thereby reducing the number of prototypes needed to be built and tested, resulting in a further reduction of lead time and cost [25].

Similarly where aesthetics is important, the superior colour shaded graphics images now available on CAD, will allow greater visualistion of the external form of the design and hence reduce the total number of prototype models needed to be made for visualisation purposes. Moreover, these improved graphics will also allow a much greater number of original ideas to be explored and created, but before final selection, only the very best need now be made as prototype models. An integrated product development loop will thus reduce lead times and greatly improve both quality and performance when compared with the traditional approach.

3.4 BILL OF MATERIAL FUNCTIONAL LINK.

The above sections clearly show that CAD generated geometry is the main focal point for the creation and manipulation of product geometry. However, it is not the only focal point of CIM.

The hub for the flow of data between all the systems is the Engineering Database which contains the Bill of Materials Fig (13). Wilson [9] believes this should be a Relational Database which allows access from several distributed computers on the system. The data is to be easy to retrieve and in a format suitable for the user.

Once a product is required to be designed, a record or file is to be generated for the Engineering Database. At the design stage, information is added to the file including the Bill of Material, the product name, G.T. code, list of all the parts and sub-assemblies etc. As more information becomes available at the various stages of the design-through-to-manufacture process, it is added to this block of information. Eventually all the information required to describe and manufacture the part will be held on the system either centrally or in a distributed but linked manner.

It is envisaged that when a Bill of Material for a CAD part is created, then this information opens data files at all the required places in the system and instantaneously passes information as it is created or modified to all relevant data files on the system, updating them instantly in the process. If work is required to be performed by a job function, then the operators or supervisors of these functions will be automatically flagged on the system indicating that they must perform some work function by a set date. The outcome is that people work with the latest information and there is no duplication of data or effort. There are also no work delays, hence increased efficiency and accuracy of the system.

3.5 THE OUTPUT FROM CAD WITHIN A CIM SYSTEM.

As already stated, to increase the effectiveness of an organisation, a CIM system should be organised so that information is generated at the point where it can be of the most benefit to everyone in the system. It must also be in a format that is most suitable for everyone in the system. CAD we have seen is the natural focal point of CIM for geometry creation and so the output from the CAD system must therefore, not only be matched to the needs of design, but also manufacturing, inspection, styling, engineering etc.

The following chapters discuss how this author set about increasing the effectiveness of an existing CAD/CAM systm in a working environment by applying a CIM approach.

CHAPTER 4

THE EFFECTIVE USE OF CAD IN A FUEL CONTROL SYSTEMS MANUFACTURING COMPANY.

THE EFFECTIVE USE OF CAD IN A FUEL CONTROL SYSTEM MANUFACTURING COMPANY.

4.1 INTRODUCTION.

The rest of this thesis is concerned with the effective application, use and development of a CAD/CAM system within a CIM framework, at the Engine Systems Division (ESD) of Lucas Aerospace. Whilst some areas treated are specific to ESD, others are relevant to many other products and industries.

4.2 THE BUSINESS

The Engine Systems Division of the Lucas Group of companies, is primarily concerned with making Fuel Control Systems for high powered aero engines. These aero engines are fitted to both Military and Civil aircraft as well as being used as marine gas turbine engines. In everyday terms, a fuel control system can be thought of as a very sophisticated fuel pump and carburettor.

A fuel delivery and control system is purpose-designed for use on only one particular type of engine. This normally means small production runs for the unit, spread over a number of years. The fuel control system must satisfy a very demanding performance specification, delivering fuel at a desired rate under varying physical conditions. The unit is mounted on the engine, usually in a very small complex space envelope and it is designed to have the minimum possible weight. These fuel control systems are very high value and high quality engineered units containing many precision machined components and mechanisms, many of which are unique to that unit.

The economic environment within which ESD and many other manufacturing companies operate has become increasingly competitive. The customers demand shorter lead times, responsiveness to specification changes, improved spares and repairs service, reduced product weight, higher quality products and of course minimum cost. ESD has worked to meet these demands by the application of Manufacturing Systems Engineering techniques and with the integration of the Engineering and Manufacturing activities.

To implement such a strategy, three main target areas of activity were identified:

1) Make better use of the present resources by:-

   a) Product Grouping - creation of families of parts (group technology) allowing standard geometries, similar fixtures, tools, process planning sheets etc. to be used, leading to economies in manufacturing through reducing the requirements for novel and costly work and through the increased use of standardised features and processes.

   b) Establishing Manufacturing Cells - decentralising the manufacturing area into small business modules with their own objectives and autonomy to improve flexibility and response.

   c) Review Project Structures - use multi-discipline teams on projects, ranging from addressing specific problems to tackling the product realisation process from the initial design concept through to final manufacture.

d) Creating a Product Engineering Department - Concentrate a range of specialist skills in one factory area to facilitate the easy exchange of design and manufacturing ideas. This team to comprise:- designers; detailers; planners; NC programmers; jig and tool designers and estimators. Within this team apply the philosophies of 'Design for Manufacture' and 'Right First Time' as early as possible in the design process.

2) Develop the full potential of the existing computer systems which are currently 'independent islands of technology'. These computer systems are:-

COPICS	A production control system containing MRP (Material Requirement Planning) and MRPII (Manufacturing Resource Planning)
CAPP	Computer Aided Process Planning
CLASS	Component Coding and Classification
DNC	Direct Numerical Control
PARTS LIST	Complete list of parts in any unit or sub-unit
CAD/CAM	Computer Aided Design/Computer Aided Manufacture

3) Integrate/Interface these computer systems to improve the information flow throughout the factory, thereby reducing the duplication of data and the use of out of date information.

4.3 THE TEACHING COMPANY PROGRAMME.

When the Teaching Company Programme was due to commence (Mid 1985) most of the problems associated with the better use of the then current resources had already been analysed and the departments were in the process of being reorganised.

Within the framework of the overall company objectives, the following specific objectives were defined for the Teaching Company Programme:

PHASE 1 Examine the potential of 3-D modelling as a design tool and establish the requirements for achieving a full 3-D modelling based design capability using the CAD/CAM equipment.

Define any hardware, software, methodology and training requirements for implementation.

PHASE II Establish Engineering databases integrated into the CAD/CAM system to serve the needs of ´design for manufacture´ and so reduce the lead times associated with the total design-through-to-manufacture process.

PHASE III Define the interface requirements between the engineering databases and the manufacturing cells to ensure effective control.

The terms of reference for the projects embodied the following constraints:-

i) To work within the Engine Systems Division (ESD) policy/framework on CIM.

ii) To work within the engineering Project Team structure.

iii) Continue to use Computervision (CV) or Computervision compatible hardware and software.

4.4 THE PROJECT.

The particular project that concerns the work of this author and this thesis, was Phase I of the Teaching Company Programme. At this stage, the project was broken down into a number of logical steps:

a) Gather background information.
b) CAD/CAM capability evaluation - learn to use the equipment and discover its limitations and potential.
c) Evaluate requirements from the CAD/CAM output.

d) 3-D modelling implications for design.

e) Investigate 3-D requirements for any methodology, hardware and software.

f) Establish training needs and implement training programme.

4.5 PROJECT BACKGROUND INFORMATION.

In the late nineteen seventies and very early eighties, the Lucas company assembled a multi disciplined task force to investigate the purchase of some of the relatively new computer graphics systems, which could be used to aid the design, analysis and manufacturing processes. If selected these systems were to be suitable for use throughout the various divisions of the company. The task force was required to produce a critical evaluation of the various systems then available and produce a cost justification document for the system most suited to the overall needs of the company.

It became obvious to the task force, right from the beginning, that the full benefits of this computerised technology could only be realised if the CAM and CAE systems could access the CAD data. Therefore a fully integrated system was required, as separate systems would have communication problems when transferring CAD data.

In the early eighties, this narrowed the field of possible vendors to only those who could offer a 'Turnkey' system. A Turnkey system, is one in which all the hardware and software is integrated, supplied and supported by one vendor.

For development and support reasons, any system vendor company would need to be a large, stable one, with the likelihood of long term survival and with a policy of continued development of their system.

The purchasing company was a large concern, with an extensive and diverse range of products. Any Turnkey system to be selected, would need to be a very comprehensive and flexible in order to cope with this large variation of product geometries and applications. Any system selected would have to meet the CAD, CAE and CAM requirements of this diverse mix of products and so a technical specification was drawn up by the investigating task force. This was a set of minimum and desired technical capabilities of any system to be purchased.

A short list of established vendor companies who offered a 'Turnkey' system meeting the technical requirements was drawn up. These systems were then tested or 'bench-marked' [36] and eventually Computervision was selected to be the supplier of CAD/CAM equipment throughout all the companies of the group. A Top-Down stategy had been employed by the company in the selection and purchase of the system. The next logical step was to be a Bottom-Up implementation at each user site, adapting and tailoring the use of the system to local specific requirements. Phase I of the Teaching Company Programme was part of this Bottom-Up implementation process.

4.6 THE CAD SITUATION EXISTING AT THE BEGINNING OF THE PROJECT.

The Computervision (CV) CAD/CAM system had been purchased in 1981 and consisted of 2, CGP 200 Designer 5X systems with a set of 19G storage screen terminals attached to each. Gradually these storage screens were phased out and replaced by 7 Monochrome Instaview terminals and finally by 1986 with 7 more colour Instaviews. The Instaview terminals were 'host' based ones, meaning that the vast majority of the data processing was performed on the shared host computer (CGP200 processor). The 7 colour terminals and Versatec monochrome electrostatic plotter shared one of the CGP200 processors, whilst the 7 monochrome Instaview terminals shared the other processor. The two processors were connected to allow the easy transfer of data.

The system ran CADDS 4X software to perform all the CAD work. The existing features of the CAD system, embodied a 3-D wireframe and meshed surfaces modelling capability and a capacity for generating Finite Element meshes in addition to the usual 2-D draughting facilities. The CAM system ran NC Vision software and could generate a toolpath around the CAD generated component and if required, could display the motion of a tool along this path. The system could be enhanced by allowing full surface shading representation (CAD-Shade) and by using a superior surfacing capability called Advanced Surface Design (ASD).

The CAD/CAM system was to be linked to the proposed engineering database (CDS 5000 system) and this was to become part of the central computer network Fig (14). The CDS 5000 system was a commercially available product from the Computervision company and was to be the central source for the storage and manipulation of engineering data. Eventually it would also provide the link/interface between the existing, but different computer systems at the company.

At the Engine Systems Division, drawings were produced using both the traditional method of pencil and paper on a drawing board and on the Computervision (CV) CAD equipment. The CAD equipment, representing a natural progression from the traditional method, was only used to produce 2-D drawings, even though the system itself was known to be capable of 3-D modelling. It was a considered that the system was being under-utilised and this led to the establishment of phase I of the Teaching Company programme.

There was an awareness that 3-D modelling could bring many advantages, but there were many unresolved problems associated with its successful explotiation. A crucial part of the project was to identify all the problems and either solve them or find ways to reduce their effect. A decision would then be made as to whether 3-D could be an effective use of the CAD/CAM equipment for the company.

4.7 EVALUATION OF THE FEATURES AND POTENTIAL OF THE CAD/CAM SYSTEM

A system familiarisation stage was firstly undertaken. This was a period of on-site training using the standard 'teach yourself' exercises available at the company. It was clearly necessary to become proficient at using the system, in order that a valid evaluation of the various levels of sophistication of the CAD output could be made. The following sections briefly describe these various levels of sophistication of the CAD output. Also included in the sections are brief comments on the effect of the level of CAD output on other activities.

4.7.1 2-D DRAUGHTING FIG (15)

The draughting facility yields conventional 2-D drawings directly comparable to those produced by traditional drawing board methods. The drawings produced using computer aided draughting are of course more accurate and are neater than those produced on the traditional drawing board and mistakes in dimensioning are less likely to occur. However, as with conventional drawings, all lines in all views must be formed separately and construction lines, which can be deleted later, may also be required to be drawn. An example of this would be the creation of an intersection.

There is no 'Associativity' between views, in that a change to a feature line in say the plan view does not result in a change to the same feature in the other views, as each line is an individual entity upon the drawing sheet. It is necessary for the designer himself to ensure that all the views are fully compatible. However, modifications can often be made quite rapidly compared to manually produced drawings on paper.

Using 2-D CAD models on the CAM system allows the direct NC programming of 2 1/2-D milling and regular 2-D turning operations. Regular 2 and 2 1/2 D milling has the Z value or depth of cut incrementally set by the programmer before the toolpath is created, allowing continual movements of the cutting tools to vary only in terms of X and Y. Similarly for regular turning, where Y is always fixed as ZERO (the height of the axis of the rotating work piece) and the tool can again only vary in the X and Z values. Both types of operations only vary in the two dimensions and so can be represented by a 2-D model, which is adequate to create a toolpath using the CAM system. Complex machining of 3-D surfaces cannot be performed using the system and there is no 3-D visualisation of toolpath depths in the 'Z' axis.

From a 2-D drawing it is only possible to generate a 2-D Finite Element Model and so only a 2-D analysis can be performed on the component.

4.7.2 3-D MODELLING.

A 3-D model is created by defining the geometry in 3 dimensional space in terms of a co-ordinate set. To improve model visualisation and understanding, 3-D models can be 'rotated in space', as desired by the operator, and this can lead to a reduced need for models or prototypes, as well as a reduction in the number of engineering change requests during the development of the product. Lamit and Paige write [17]:-

> 'Designers and engineers think in three dimensions and then they try to show the concept in two dimensional views. So designing with a three dimensional system is a much more natural way to conceptualize the creation of an object'

Improved visualisation can also be particularly useful for checking the assembly of components. Any desired view or set of views can be readily generated and they will be truly associative: a feature change in one view results in a feature change to the model and hence is represented in all views. Fig (16) illustrates the relationship between the model and its defined views. The model is 3-dimensional and is shown isometrically. Each view of the model can be seen as a window that frames an area of the model from an operator defined view orientation. These views can then be added and placed as desired on a drawing.

Modifications thus need only be executed in one view and all the other views will then be automatically modified. This is an extremely important benefit resulting in reduced errors especially on large complicated drawings with many views. In a conventional 2-D approach, it is easy for the draughtsman to miss the effects of a modification on some of the views, especially on drawings with which they are not very familiar. Thus an important benefit of 3-D modelling is the ability to rapidly and accurately modify designs.

The information embodied in a 3-D model can be used to construct either a 2-D or 3-D finite element mesh, facilitating a 2-D or 3-D analysis to be performed.

There are basically 3 types of 3-D modelling.

a) Wireframe

b) Wireframe with surfaces

c) Solid

4.7.2.1 WIREFRAME MODELLING.

This consists of points in 3-D space being joined by lines or arcs so that it can be thought of as edge definition. Complex intersections must be constructed in space, as with 2-D drawings, but here they only need to be formed once for the model, as it will be seen in all views. As with 2-D draughting, only 2 1/2-D milling (axes can vary continuously in X and Y and incrementally in Z) and regular turning (axes can vary continuously in X and Z) can be programmed directly using the CAM system, although the cutter depth (Z-axis) is displayed on the screen.

Fig (17) shows the viewing frame for each view of a simple model. In the top left hand corner, an isometric model view is shown in which a slot running along the top and back of the L-block can be visualised. However, many of these lines are not required in the final orthographic manufacturing views and so they must be either ´erased´ or converted into hidden detail in these views. The term ´erased´ means that an entity is made invisible in (a) selected view(s), but is still present as part of the model in the database and in other views.

When working on complex components, this need to erase or convert lines when transforming model views into manufacturing views can result in a large time penalty for the operator [18].

It can also be seen from the isometric view, that because there is no automatic hidden line removal, there is a problem with ambiguity of the model. The problem of ambiguity is clearly demonstrated in Fig (18).

4.7.2.2. WIREFRAME WITH SURFACE MODELLING.

There are two modes of representing the surface of a model and both fully define every point on the chosen surface in mathematical terms. The only difference is that one gives a meshed representation whilst the other displays a full surface.

i) MESHED SURFACE REPRESENTATION FIG (19).

The meshed surface gives superior visualisation over that provided by basic wireframe models, although as there is no hidden line removal, ambiguities can still arise. Fully defined surfaces allow complex 3-D NC toolpaths to be programmed and subsequently verified using the CAM package and this is a significant benefit when compared to 2-D CAD. Before CAD/CAM, surfaces could not be defined or machined quickly, easily or accurately. Surfaces also allow complex intersections between two generated surfaces to be easily and rapidly produced. The intersection between surfaces allow radial slots and holes in turned components to be easily and accurately generated Fig (20). C-axis lathes or Mill/Turn machine tools can now be programmed on CAD to machine the conventional turned form, then mill/slot/drill the component whilst still on the same machine tool. Non-regular flange profiles can also be produced on these machines. Manually to program a C-axis lathe or Mill/Turn machine to perform this type of difficult work, is more time consuming, error prone and costly. Thus the surfacing facility offers increased CAM benefits.

The surfacing facility also allows designers to check for fouls in complex space envelopes and clashes between complex moving geometries. It permits rapid checks for minimum wall thickness between compound drill holes, which are commonly required in the complicated components which are assembled to form a fuel control system.

By fully surface modelling a component, its volume, Centre of Gravity, Mass and Moments of Inertia can be calcuated, although in practice this does not work well on complicated parts, due to the limited capability of the algorithms used in the analysis software. In such a case, an experienced user would break the part into a series of smaller, simpler features and then sum the analysis results in an appropriate way, at the end.

ii) FULL SURFACE REPRESENTATION FIG (21) (22).

Full surface representation allows a conventionally meshed surface to be seen as a complete surface image. This has the advantage of hidden line removal leading to superior visualisation and no ambiguity. This feature is particularly useful for industries in which aesthetics are of major importance;it can increase the number of design options considered, whilst reducing the number of prototypes, thus contributing to reduced lead times and costs.

The CAD system available to this project did not have the capability to perform this full surface representation, although a Computervision software package called CAD-Shade could be purchased to perform this task.

CAD-Shade produces only monochrome images and the quality of the image around the component´s edge lacks clarity. The use of CAD-Shade is time consuming as all the viewed faces of the component require a meshed surface to be generated and then converted to a full surface representation.

This surface shading package allows the operator to vary the origin and the intensity of the light source, with a choice of surface texture, and material types, such as opaque materials or glass. The finer the quality of surface texture, the longer it takes to generate the image. CAD-Shade is probably best used for tendering documents, replacing the Artists Impression (high texture quality) Fig (22) or for better understanding of complex bodies by the designers (low texture quality, but the image is produced rapidly) Fig (21). In order to produce prints of these images an expensive ink-jet plotter is required. Another way to produce these images would be to photograph the screen, but the quality is not as good and it can cause a delay compared to instant plotting.

Furthermore, the system available to this project could only model regular surfaces with ease, more complex surfaces could be created, but were time consuming to generate and were not always suitable for use with the CAM system. Many components have small surface areas containing non-regular forms (blended surfaces and complex fillets) and so it would be either prohibitively long to surface all these areas, or the image generated would have a number of gaps (non-surfaced areas) appearing on the representative image. To overcome this problem, a more versatile surfacing package called Advanced Surface Design (A.S.D) could be purchased from Computervision. This software package was specifically written to create and manipulate complex surfaces and it is extensively used by the auto industry for car body design.

A superior surface shading package to CAD-Shade is available from

Computervision and is called Image Design Fig (1). This gives colour shading and superior definition of both the surface texture and around the component edges. It requires an expensive 32 bit processor rather than the existing 16 bit processor. To produce hard copies of the image, demands that an expensive colour ink-jet plotter be purchased, although inferior quality photographs of the image could also be obtained.

4.7.2.3 SOLID MODELLING.

Solid modelling systems are sometimes known as geometric or volumetric modellers. There are two main types of solid modelling system under development:

1) Construction Solid Geometry (CSG)
2) Boundary Representation (B-rep).

The first of these allows the user to build the model out of solid graphic primitives, such as rectangular blocks, spheres, cylinders, cones, toruses and pyramids. The method uses the Boolean operations of ´Union´ (addition) and ´Differance´ (subtraction) to structure the solid model in the graphics database in such a way as to assemble the appropriate primitives to provide a representation of the whole object [10,17].

With the B-rep method, each face, edge and vertex boundary of an object is explicity defined. The connectivity (or topology) of faces, edges and vertices, plus data defining the surface in which each face lies, make up the model. Simply stated, each face is related to the set of edges which bound it, each edge is related to the two faces which it separates and each edge is related to the two vertices which are at either end of the edge. Care is taken to hold and define the faces in a systematic may so that the system can tell which side is within the component and which is without [17].

The B-rep method requires the user to draw orthographic views of the outline of boundary of the object. By adding interconnecting link lines between the views, the operator can establish a relationship between the views and build up a solid model in the computer database [10].

The two approaches to solid modelling have advantages and disadvantages over one another, but both types can result in a completely defined model. However, both methods have limitations when attempting to use solids to model non-regular geometries. To overcome this problem, the latest research is trying to develop a 'hybrid' of the two methods [17].

Due to the methods of construction, but within the limits mentioned above, solid modelling can fully define, in mathematical terms every spatial point within the model. As a result, volume, centre of gravity, mass and moments of inertia of the solid model can be calculated very easily. Similarly, as every internal point if defined, a complete section of the solid model can be generated, merely by specifying an intersecting plane.

As with the surface package, solid modelling allows intersections/interference and minimum wall thickness calculations to be rapidly and accurately performed when compared to a manual approach. The system provides automatic hidden line removal and a very good visualisation. The display is similar in appearance to a 3-D wireframe model Fig (23), but without the prescence of any surfaces, hidden lines or arcs. The production of an aesthetically correct view, can save a considerable amount of 'erasing' time, when converting model views into detailed views. Another feature available from using solid models is the ability fully to surface shade the object with the option to alter the position and intensity of the light source, colour and surface texture. The image produced would be very similar to that produced using the Image Design surface shading software Fig (1). As with Image Design, this would require a 32 bit processor to handle the computations of the additional solid modelling software package. In addition, a high quality ink-jet plotter would be required to produce fully shaded images.

A 'Lucas Solid Modelling Task Force' issued a report in August 1985 [37]. This task force came to the conclusion that at that stage, solid modelling was not sufficiently developed for general practical use within Lucas. Firstly it would require very considerable computing power to supply a reasonable speed of response and necessary memory. As a consequence, it would be too expensive and slow to use commercially in a design office. Secondly, the software was not able to model non-regular shapes sufficiently accurately for the company's purposes. Thirdly, when using a CAM system there were limitations to the types of machining operations which could be performed.

McClelland and Smith [21] also support these findings and write of solid modelling:-

> 'The present systems are often limited in the range of geometry they can handle, require much larger disc storage space, have poor response, and need much more powerful and expensive hardware. Without a heavy commitment to CAM, particularly 5 axis machining or robotics, a solid modelling system is considered hard to justify in the mechanical engineering sector at the present time'.

However, both the Lucas task force [37] and Pratt [38] did conclude that they saw considerable potential for solid modelling in the future and its progress is currently being monitored by the company.

4.8 CAD/CAM REQUIREMENTS.

After familiarisation with the equipment and its various CAD output capabilities, the next steps were to determine what types of geometry needed to be modelled and as a consequence of this, what type of CAD output would be most beneficial to the downstream users.

4.8.1 THE GEOMETRY OF A FUEL CONTROL SYSTEM AND ITS PRODUCTION.

The company's products were analysed with respect to form, tolerances and manufacturing methods. As mentioned in the introduction, the products were typical of the aerospace components industry:- they were lightweight, small, complex, highly machined units with complicated mechanisms. A fuel control system is dedicated to a particular engine and hence the engineering content and unit cost are high, since production runs are small.

The main elements of a Fuel Control System are shown in Fig (24). A typical Fuel Control System consists of many individual components, many with very complex geometries, examples being a fuel control housing, gear pumps, linkages, cams, control valves and their housings etc. The remainder of the components to be manufactured can be thought of as regular geometries. These regular geometries can all be manufactured on conventional machines such as lathes, drillers and millers. Conventional turning, drilling and boring can be considered to be 2-dimensional in form, whereas conventional milling can be thought of as essentially 2 1/2 dimensional. Much of the work which is turned is getting increasingly complicated. Shafts with integral gears, valves, regulators and sleeves are becoming more common Fig (20). These are now most efficiently made on C-axis lathes or Mill/Turn machines.

The complex shaped fuel control housings (centre back Fig (25)) which are 3-dimensional in form are either machined from solid or cast. These housings are by far the most intensively machined, costly to produce and have the longest lead time of any item within a fuel control system. The housing contains many interconnecting bored, drilled and reamed holes of many different diameters. Many of the holes are compound drill holes and designing a housing with at least the minimum allowable wall thickness between all the holes, is a major problem. Traditionally this would require either complex calculations and/or a series of auxiliary views to be created.

Historically, castings have presented problems associated with their long lead times, fixtures, supplies for spares and quality of form and internal structure. These problems are partly due to small production runs. As a result, there is a trend in parts of the aerospace industry, away from using castings, to that of machining objects from solid, commonly using a copy or profile miller for complex external forms. This requires an accurate reproduction of the finished outer form of the housing to be manufactured for use as a pattern, but this is also a common source of delay, caused by the time to manufacture the pattern. The machine-from-solid outer or cast object is then subject to further machining operations on other machining centres to produce all the bores and mating surfaces.

If a machine-from-solid housing is a very complicated 3-dimensional shape, then profile milling is the best method of manufacture. However, with the trend towards machining from solid influencing design, some of the new housings are now being designed for manufacture, resulting in a predominantly regular 2 1/2-D form (centre Fig (26)), although there are still some requirements for relatively small areas of complex 3-D geometry. Under such circumstances, there are two traditional approaches available to manufacturing.

In the first approach, the complex form of the surface is ignored and a convenient 2 1/2-D form, totally enclosing the complex 3-D geometry is established. The complete machining of the billet could then be performed on one NC machining centre. A disadvantage of this method is that designers cannot use occasional patches of 3-D geometry, resulting in reduced design options and extra weight. An enlarged 2 1/2-D feature might result in a foul or clash, whereas the actual required 3-D feature would give clearance. This constraint of designing only with regular geometry, is recognised by Haigh who writes [24]:-

> 'Traditionally , there is a tendency to produce items of simple shape, but increased marketing pressure is forcing companies to produce components which have more complex geometry'.

The second approach would be to profile mill the external geometrical form including the required complex 3-dimensional features. After this the part-machined billet would be moved to the machining centre, where the internal geometry and any remaining 2 1/2-D outer geometry would be machined. This method of manufacture requires an extra fixture, pattern and machine routing. Thus small areas of 3-D geometry produce a significant cost penalty for relatively small amounts of actual work.

A solution to the problems would be to use the NC machining centre to mill these 3-D geometries, in addition to the internal holes and regular external geometry. Traditionally surfaces were for most applications too difficult and time consuming to define and produce accurately and so they were not available in a commercial environment to many designers. With the advent of CADCAM, these surfaces can now be defined and produced readily, enabling the entire machining process to be performed on the one machining centre. To do this, requires some 3-D surfaces to be added to the 3-D model for the NC programmer to select when using the CAM system.

Apart from 3-D surfaces, another advantage to CAM of using 3-D models, is on the machining of non-orthographic auxiliary faces. This can be performed most readily on 4 or 5 axis machining centres, although it can be done on 3 axis machines, if special fixtures are attached to the machine tool bed. Programming such faces manually requires careful calculations to determine the compound angles of rotation for the workpiece and the exact position of the face relative to the machine tool datum. With 3-D CAD these calculations can be made quickly and accurately. When using a 4 or 5 axis machining centre, a new local co-ordinate system can be defined on the auxiliary face using two existing CAD model entities. The translation and rotation values (offsets) of this local co-ordinate system from the machining datum, can be accurately verified and either manually or automatically input into the part programme. The feature is then machined using the local co-ordinates, with the offsets being compensated for accordingly.

4.8.2 DOWNSTREAM FUNCTIONS

As the design office activity typically represents about 10% of the total product cost, then proportionately large local savings may have little overall benefit [19]. The major benefits can come from the downstream activities which use the CAD generated drawings, models or other associated data to perform their functions [18,22]. It is the benefits which CAD can give to the NC programming, stress analysis, process planning, assembly, inspection and test functions that can lead to shorter lead times, better quality products and reduced costs.

Therefore the effect of 3-D as a tool for design, must not be looked at in isolation, but as part of the overall manufacturing strategy. For this reason, the original scope of the project was enlarged to encompass the overall manufacturing strategy, in other words take a CIM approach.

All the downstream activities that handle or were expected in the near future to handle the CAD output were identified. It is estimated that designers only account for 20% of all the drawings/graphics needed to produce a product, the remainder being for jigs, fixtures, process planning, tool and NC programming etc [35].

Taking a CIM approach to this project meant considering the effect of 3-D modelling to the downstream users and investigating the benefits of 3-D modelling to the company as a whole. Consequently, each of the downstream functions was then analysed and their CAD requirements were investigated. These functions and their CAD associated requirements were:-

4.8.2.1 NC PROGRAMMING.

Components with regular geometries can be NC programmed directly using manual methods from 2-D paper drawings, or using the CAM system from 2-D CAD views or 3-D models. However, as previously explained components are becoming more complex and there is an increasing use of C-axis lathes and Mill/Turn machine tools which combine general turning with drilling, milling and profiling capabilities. The most efficient method of programming these types of machine tools to perform some of the more complex cutting operations, requires that the CAM system be used to generate the part programs. The geometric features which require these complex cutting facilities can also be programmed from either a series of 2-D CAD views, or the 3-D model.

To define and produce 3-D surfaces accurately and efficiently requires that 3-D surfaces be generated on the CAD system for subsequent NC programming using the CAM system. The manual programming of surfaces is in most cases not a practical proposition. In the case of this company, where there is a move towards machining-from-solid, rather than using castings, there are occasions when it would be beneficial to machine some 3-D features on an otherwise mainly regular geometry. To machine these surfaces most efficiently would require the NC programming data to be generated and input using a CAM system. Therefore to create these features most effectively requires a 3-D CAD model with the complex 3-D geometries surfaced.

When programming a 4 or 5 axis machine tool, non-orthographic auxiliary faces can most accurately and quickly be programmed using a 3-D CAD model. Manual programming from a paper drawing or from 2-D representative CAD views is much slower and more error prone.

An advantage of using a 3-D model, rather than a 2-D representation, is that there is a 3-D visual check available on the toolpaths generated, thereby aiding understanding and resulting in a superior verification facility. Previously there was no such check in relation to the depth of cut (Z direction). Thus using 3-D models of assemblies of components and their jigs and fixtures could reduce the risks of tool collisions, especially on 4 or 5 axis NC machining centres, where the machining actions are more complicated and error prone.

However, although the CAM system is capable of 3-D work, programmers would need to develop some new techniques to manipulate the model and the CAM system in order to maximise any benefits of working in 3 dimensions. This topic is discussed in later chapters.

4.8.2.2. CO-ORDINATE MEASURING MACHINE (CMM)

At present the CMM is manually programmed. Unfortunately, with this method there are usually input errors due to the human processing of large amounts of data. However, Computervision have recently demonstrated a prototype software package called 'Auto Measure'. Auto Measure will programme the path of the probe on the CMM in a manner similar to that of a toolpath on the CAM system. It will run a proprietary probe around the component with visual feedback available on the CAD/CAM terminal to check for collisions or mistakes Fig (27). The package does require the use of 3-D models. The Auto Measure package and its dedicated post processor were planned to be installed on the CAD/CAM system by the end of

1986/early 1987. The CAD requirements were stated in an internal Lucas Aerospace report [39]. These requirements were for 3-D models to provide details of any machined part on that component complete with its allowable tolerances; this is the same format of information as required by the NC machines.

4.8.2.3 FINITE ELEMENT ANALYSIS (FEA)

In the past very little FEA was performed by Engine Systems Division. This was mainly due to there being no general requirement for the accurate analysis of irregular shaped components in which stress levels were known to be low. Most stress analysis was performed manually, and any irregular geometries had generous safety margins built into the calculations.

There were other reasons for not using FEA such as the high cost of running the analysis on a mainframe computer at another site and the amount of effort required to manually input every element and node for a model's geometry, as no CAD/FEM interface existed at the site at that time.

The Computervision CAD/CAM system available on site has a Finite Element Modelling capability, enabling finite element meshes to be generated far more accurately and quickly than by hand. Although this facility was not being used, as there were no interfaces between the systems, there was a growing requirement to use some form of computational stress analysis. This growing requirement was due to the customers who were demanding design verifications, primarily for quality assurance reasons. Historically, there was a tendency to design units with generous safety margins where there was any element of doubt. It was realised that computational stress analysis could help to optimise the design and thus contribute towards reducing weight.

Both 2-D and 3-D FEA can be performed from a full 3-D model, but obviously only 2-D analysis can be exercised on a 2-D component drawing. In many cases the types of components or features requiring analysis will require a 3-D formulation so that the CAD/CAM system will in the future require a full 3-D model. It should be stated though, that even with a FE capability fully integrated into the CAD/CAM system, the total number of components analysed is likely to be very small.

4.8.2.4 DETAILING.

Draughting is the process of representing the geometry of an object in two dimensions in accordance with standard procedures. Thus the dimensioning function is always a two dimensional process [17]. On the Computervision system, the act of dimensioning is performed only in a two dimensional mode, ignoring any depth (Z- direction) in each view and using only the X and Y values between the selected entities. Thus there is no difference in principle between dimensioning a series of 2-D CAD views, or a series of defined views of a 3-D model. The only difference when using a 3-D model, is that the operator as he dimensions each view, must set the XY plane to be in the plane of each view. This is a very quick and simple task and so is not a problem. The actual creation and manipulation of an individual component by the design draugtsman, to form a detailed drawing will, like the design stage, have advantages and disadvantages associated with the type of CAD output. These factors will be discussed in more detail at the end of this chapter.

4.8.2.5 JIGS AND FIXTURES.

Jigs and Fixtures are drawn by the Tool Drawing Office (T.D.O) where the CAD models often only provide a starting point for the work of the function. If a Jig or Fixture is to be used to locate a component in the earlier manufacturing stages, then some additional detail may need to be added to the CAD geometry to represent the true geometrical form at that stage of manufacture. Typically this may represent the original billet or bar of material, heat treatment stock, grinding allowances or even machined features which are to be used to locate the workpiece in a later process and which are themselves subsequently removed.

The T.D.O. can use group technology to retrieve similar Jigs or Fixtures and parametric programmes can be used to generate standard types of fixtures [40], or more commonly standard items such as clamps, tools, nuts and bolts etc. The T.D.O. staff can manipulate either 2-D representations or 3-D models, but the latter provides the operator with greatly improved visualisation and understanding.

The ability to create several operator defined views using the 3-D model of the fixture and component is also advantageous as it facilitates the accurate and rapid dimensioning between features which have a complex relationship to each other. To determine these dimensions using 2-D would require the creation of much additional geometry. This feature can be particularly useful when Jigs and Fixtures are needed to clamp and locate components which are to have complex arrangements of auxiliary faces and or compound drill holes machined in them.

Furthermore, if the NC programmers using the CAM system are working with 3-D models, then it is beneficial for the programmers to be able to see the 3-D fixtures which clamp the components, as the improved visibility resulting from this, can reduce the number of tool collisions with these fixtures and clamps. In addition, by carefully positioning the model of the fixture and component in 3-D space, machining datum offsets can be calculated by the system rather than by hand. These advantages become more pronounced with an increase in the complexity of the part and associated fixture/clamping arrangement.

4.8.2.6 TECHNICAL PUBLICATIONS.

The function of the technical publications department is to produce promotional literature, overhaul manuals and other similar documentation for customer use; they usually comprise a combination of illustrations and text. The illustrations may consist of cut away sectional views or exploded isometric views Fig (23). The text refers to the illustrations and often consists of a parts list and/or servicing instructions. To aid clarity and reduce creation time, these illustrations are often simplified to represent the points being highlighted in the text.

In late 1985, the CAD/CAM system at ESD was connected or 'Networked' to the then recently purchased Computervision CDS 3000 CAD/CAM system, which was located at a remote site. The latter could receive CAD models from ESD, manipulate and merge them onto a page containing text which had been previously input by means of a networked personal computer. The CDS 3000 system is a powerful stand alone graphics system capable of creating and manipulating 2-D and 3-D models. The CDS 3000 graphics software also includes a 3-D solid modelling capability (B-Rep) with automatic hidden line removal and the facility to apply perspective.

However, due to the problems associated with solid modellers discussed earlier, it was believed that this facility would be used infrequently. On these rare occasions, when it was to be used, the solid modeller would required a series of orthographic views, which could be generated from either a 3-D model or from a set of 2-D representative views. Also any required sectional views could be created from either 2-D CAD drawings or 3-D model drawings. However, the isometric view would need to be manually created if 2-D representational CAD views were supplied, but if 3-D models were supplied, then the isometric view could be readily defined and generated. Hence, 3-D models are benefical to the technical publications function as they require considerably less effort to produce isometric views.

4.8.2.7 OTHER DOWNSTREAM FUNCTIONS.

A number of functions which currently interpret drawings manually, require drawings with standard orthographic detailed views. This demand can be fulfilled by CAD drawings produced using either a set of 2-D representational views or from a set of operator defined views of a 3-D wireframe model. Examples of these functions are:-

i) Process Planning

ii) Estimating

iii) Conventional Machining

iv) General Assembly

v) Manual Inspection

4.8.3 ASSESMENT OF THE COMPANY'S HARDWARE AND SOFTWARE NEEDS.

From an examination of the various function requirements, for both the present and the near future, it can be seen from the above discussions that by applying a CIM approach to the project, the company as a whole could benefit from using 3-D models with at least surface definition capabilities. In this global context, some departments would benefit while others would remain essentially unaffected.

In late 1985, for the reasons highlighted earlier, solid modelling was discounted as being too impractical and under-developed for use at the company. The products produced at ESD are mostly concerned with funcionality, with aesthetics playing only a minor role in the influence of the design. To produce a surface shaded image requires a fully surfaced model and with the complexity of most ESD products, this would be a very time consuming process, often requiring the use of the Advanced Surface Design (ASD) software. As the designers usually only require a small number of surfaces for the design process, the vast majority of the work performed for a surface shaded image would be wasted. Marketing and sales could use these images, but they would be needed so infrequently, perhaps only 2 or 3 shaded images per year, that this task could be sub-contracted out to Computervision and so would not be a factor in the selection process. Consequently, although CAD-Shade and Image-Design were technically appealing, they and their associated hardware requirements could not be justified for use at E.S.D.

Advanced Surface Design, although useful in a very limited number of instances, was not needed, as the types of surfaces and auxiliary planes typically found on the company's products, could all be adequately defined using the existing surfacing facilities. Thus 3-D wireframe models with a meshed surfacing facility was found to be adequate for the company's needs. No further software was required.

One problem which was discovered during the early trials involving 3-D modelling, was that there was a slight but noticeable reduction in system response time when the majority of the users on a processor were manipulating complex 3-D parts. The only solution would be to buy a more powerful processor or purchase several work stations, on which to perform the most complex work. At that stage it was decided that the system's engineers would monitor the response of the system with the implementation of 3-D modelling and any decision to purchase additional hardware, would accordingly be made later. Although the current system was judged to be adequate, in terms of system response time, it could at times be frustrating and inefficient to use and so the author made a recommendation to the managers, that if any new processors or workstations were to be purchased, then they should be more powerful and be colour ones to aid visual understanding.

4.8.4 3-D MODELLING IMPLICATIONS FOR THE DESIGN FUNCTION.

The discussions in the previous sections have established that advantages would accrue at ESD from the use of 3-D models with surfaces for the functions which are downstream from the design activity. The next step was to investigate more closely the impact of 3-D modelling on the design and detailing functions. An assessment could then be made as to whether it was practical to use 3-D modelling with surfaces as a design tool. This investigation consisted of the author modelling a representative sample of typical ESD components and assemblies which varied in form and complexity. The investigation found both advantages and disadvantages, some of which were supported by available literature. The main findings of this investigation are listed below:-

i) ADVANTAGES

a) Designers think in 3-dimensions and the resulting improved visualisation of complex geometrical forms, especially with the rotation facility,leads to a reduction in design errors [17].

b) Create one model, then define any desired set of views of that model. This is particularly useful for the creation of complex auxiliary views, leading to increased accuracy and reduced draughting time and effort.

c) Associativity of entities, allows changes to the model in one view to occur in all views. This permits rapid and accurate modifications.

d) From the proposed Engineering Database, existing model components or similar model components can be identified (using a group technology code). These can then be merged into the current working model in any desired position and orientation, whereas if the part was to be modelled in 2-D, then the component could only be inserted in the plane of the drawing sheet. The products manufactured by E.S.D. are very complicated and limited for space and components are generally inserted into any available space. This is usually not in a plane parallel with one of the orthographic views and so 3-D modelling can offer a design advantage in these instances.

e) Complex intersections can be quickly and easily formed. Interference between complex shapes as well as minimum wall thicknesses can be checked.

f) The ability quickly and accurately to define and machine complex geometries provides greater design flexibility [24].

g) Possible update of the 3-D wireframe database models into B-rep solid models on a future Computervision solid modeller [10,17].

h) 3-D as a Marketing tool. To survive in the Aerospace industry a company must be seen to be applying the latest technology by its customers. For this reason it is important for the company's image to be seen to be using 3-D design [19,24].

ii) **DISADVANTAGES**

a) The initial formation of a full 3-D model is time consuming.

b) A full 3-D model may contain too many entities and its appearance can be too complicated and confusing, often giving the appearance of a ball of wool rather than a representation of a structural componet or assembly.

c) When a model view is transformed into a manufacturing view, much of the information in that model view is redundant and needs erasing.This is also a time consuming process [18].

The above lists and previous section clearly show that there are major benefits to the company when designing in 3-D. However, at first sight, the disadvantages make 3-D unattractive to designers themselves. Therefore to maximise the effective use of the CAD/CAM system throughout the company, a method of minimising these disadvantages, without neutralising the benefits, needed to be developed. A search of the literature in this field showed that this issue did not appear to have been addressed. Any solution to these problems would therefore have to be developed 'in house' and be of demonstratable value to a commercial design office.

The actual solution employed was to develop techniques for creating simplified 3-D models, this approach lead to the concept which this author called 'Minimum Modelling.' This was found to be effective in terms of effort and time, and was both simple to understand and apply.

C H A P T E R 5

MINIMUM MODELLING

MINIMUM MODELLING.

5 INTRODUCTION.

The concept of a minimum 3-D wireframe model is one which contains enough information to convey to the users all the important features of a component. Compared with a full 3-D wireframe model, the minimum model simplifies, but unambiguously represents standard geometrical forms in 3-dimensional space. These implied forms are to be easy to apply and understand by all users, as well as being usable by all the other functions downstream of the design process itself.

5.1 THE CONCEPT OF THE MINIMUM MODEL.

The philosophy of minimum modelling is to reduce the number of lines, arcs, splines etc. (entities) used in a model to define a component. This approach reduces the modelling time, the erasing time (the time to convert model views into detailed manufacturing items) and, because there are fewer entities, the confusion associated with the model. Although the number of entities is reduced, the minimum model is presented in such a way that it is still adequate for use by the downstream functions, unambiguously representing the true form of the component, enabling it or any feature readily to be visualised and manipulated by all the functions. Any extra entities are wasteful of time and effort, especially as many of these entities will need erasing when creating the manufacturing views. In order to create a minimum model, designers need to be aware of how a feature or component is to be made in order to know how best to represent that feature; that is, they must have a good understanding of modern manufacturing processes.

Minimum models are always created as simply as possible; surfaces will only be added if they assist the designer / detailer or are required by the NC programmer in preparation for 3-D machining. Unnecessary detailing or over modelling of features is to be avoided. As full models are not produced, there will be times when lines are required for aesthetic reasons to complete the appearance of a view. In these cases, ´cosmetic lines´ which are particular to one view only are added. These cosmetic lines are not associated with the model in any way and are not used for manufacturing purposes. When editing one view, say translating a feature, the designer must remember to move any cosmetic lines applied to that feature in all the views, as the cosmetic line will not translate automatically with the feature. Another advantage of reducing the number of entities is that the time taken by the system to refresh the screen or manipulate a model or view is reduced.

NOTE:- 3-D FEA requires a full 3-D geometry. However this technique is used very infrequently compared to the total number of components drawn, so that it would be very inefficient to create the full geometric details for every component. Instead, the task of creating extra geometry, need only be undertaken as and when required from the 3-D minimum model framework.

5.2 TECHNIQUES AND APPLICATIONS OF MINIMUM MODELLING.

During this project, some Minimum Modelling techniques were developed to reduce the construction and manipulation times for 3-D models and to assist in the understanding of these models. Examples of how the technique can be applied to regular engineering forms are demonstrated below. Whilst the individual examples of minimum modelling, may appear fairly trivial on the very limited example geometries, the total effect, when applied to larger and more complex parts was found, during the work of this project, to be significant.

5.2.1 AXI-SYMMETRIC GEOMETRIES

Any Axi-symmetric geometry is quasi 2-D, in that the outline or silhouette remains unchanged when rotating the feature about its own axial centre line. Typical examples of Axi-symmetrical engineering components and features are Shafts, Plungers/Pistons, Drilled/Reamed/Tapped holes, Spigots and Bores. These are all cylindrical features or components and are typically created on lathes, circular grinders (internal and external), borers and drilling machines. For these types of machining operations, 2-D outlines or 'templates' are adequate to produce N.C. toolpaths when using a CAM system. Thus templates in the correct position and orientation in 3-D space can adequately represent any axi-symmetric feature Fig (28).

These templates are produced in the plane of one of the standard orthographic views, so that it will be seen as a true profile, in that view. In other views, the template is usually not required and so it is erased, but if it is required, it may be copied and rotated through the desired angle, and represented as a true profile in this other view. This copied and rotated profile must also be erased in the other views, where it is not required.

For drilling, reaming and tapping operations, where the hole or feature is produced to the maximum diamter of the tool, the NC programmers require a centre line to follow and an indication of depth of cut (often the length of the centre line). For boring, circular grinding and turning, the NC programmers require a 2-D template to supply a profile to follow for the depth of cut and an axial centre line to locate the centre of the feature and to calculate the radius of the cut from the rotating axis.

Circular entities which are perpendicular to the axial centre line of the feature, are there to imply a circular form and to produce the visual image of a circular feature in other views which are perpendicular to the axis of rotation. During the NC programming process, these circular entities are not needed by the CAM system, as they are not a profile to follow and are only for visualisation purposes. The designer can therefore select any circles along the template to add to the model if he judges them to assist visualization.

It is however, advisable to try and select circles which will be useful in at least one other view Fig (28). Circles which will not be seen as circles in views, do not need to be added e.g. those around the 'O' Ring or Circlip groove. There is no requirement for 2 circles of the same diameter to be on a template. Cosmetic lines can be added where appropriate to complete the manufacturing views. It is usually quicker to add a few cosmetic entities to complete a view as it is detailed, rather than to erase a few entities in four or five views.

5.2.2 REGULAR 2 1/2 D GEOMETRIES

Features which are to be milled belong to this class. Fig (29) shows a component which is to be contour milled. For this purpose the CAM system requires a profile to follow and a depth to cut at. The depth can be set manually or found by the system from the lower of the two profiles, as a result the lines connecting the front and rear faces are not used by the CAM system and are there really to aid the visualisation of the component. It is therefore left to the discretion of the designer how many entities, if any, are added.

In Fig (29), diagram 'A' has many lines which confuse both the model and the orthagonal views. Nearly all of these entities need to be erased in the transformation of the model views into the manufacturing views of Fig (29) 'D'.

Fig (29) 'B' shows a greatly reduced number of entities which still imply a connection between the front and rear faces of the feature. These lines have been selected so that they will be seen as edge lines in the orthograpic views, thereby requiring much less erasing work when transforming the model views into manufacturing views.

Fig (29) 'C' shows just the front and rear face of the component or feature. This would be adequate for CAM, but within a complex part, this feature may not be particularly easy to visualise without at least some connecting lines. To transform Fig (29) 'C' into 'D' requires no erasing, but 'C' needs cosmetic lines adding to complete the views.

Fig (30) shows how contour pockets could be modelled. Method 'A' has the pockets fully modelled with 8 vertical lines and the top and bottom completely defined. Method 'B' has 4 lines representing the connection between the pocket floor and the top face of the component and method 'C' has no vertical connecting lines. All are adequate for the CAM system, although method 'C' is more difficult to visualise at first, for anyone who is unfamiliar with this approach. When transforming the model views to manufacturing ones, method 'A' will need more erasing than 'B', although 'C' will not need any erasing, but will require the addition of cosmetic lines.

5.2.3 NO CROSS-HATCHING OF SECTIONS.

The cross section 'A-A' of Fig (30) 'D' is not cross hatched. This is due to the fact that most of the entities visible on the section are at different Z-depths on the model and the cross hatching facility will only work if all boundaries are contained on one plane parallel to the XY plane (2-dimensional function). This is obviously not necessarily the case for 3-D minimum models. Therefore, to represent the cross section of a component with cross hatching, requires a considerable amount of construction work to produce a series of closed boundries on these parallel planes. Experimentation showed it to be far quicker and more reliable merely to edit the section view as required and add a note to that view stating that it is was a section. No cross hatching and no additional construction work is then needed.

Even with 2 dimensional work, the cross hatching function was found to be unreliable in operation, often rejecting a boundary if entities did not quite intersect, even by minute amounts (to 6, 7 or more decimal places). This was clearly an error in the software which the operator had no control over. Computervision were made aware of the problem, but they could not easily correct it.

5.2.4 COMBINED 2-D TEMPLATES AND 3-D GEOMETRY.

The combination of 2-D templates with 3-D geometries can be seen in Fig (31). This component could be manufactured, either on a single Mill/Turn machine, or in separate classes of operation on a lathe and a milling machine.

The 2-D templates are adequate to represent features for which regular turning / boring / drilling type manufacturing processes are appropriate. The 3-D contours supply the milling information and the positions and orientation of the centre lines produce the compound drilling information. Cosmetic lines can then be added when required to the appropriate views.

When representing compound drill holes and similar features by templates, it is often advantageous to produce the holes in the plane of the template, thereby allowing the use of this existing geometry during the construction stage and when complete, rotate the drill hole to its correct orientation about the axial centre line.

5.2.5 CASTING - FLOWING GEOMETRY

If a component, or the pattern for a casting, or a mould for a plastic component are to be N.C. machined using the CAM system, then the component's geometry will need to be defined. For regular geometry (cylindrical, spherical, rectangular and prismatic features) this is relatively quick and easy. For non-regular or complex geometries, this is not the case, as the modelling can become difficult and time consuming to produce. Consequently, techniques were developed to reduce the amount of detail required to define a model of a casting.

A clear understanding of various machining operations can often lead to a simplification of geometric features. For example, specifying the minimum value of standard size fillet radii between features on any component, to correspond to the radius of a 'ball nosed milling cutter' can provide a useful economy of effort and entities. Complex fillet surfacing or detailing can be dispensed with and only one or two radii templates are needed to represent a fillet radius Fig (32). These radii templates can be either cosmetic in the required view(s) or embodied in the model; since the ball nosed cutter will follow the model feature geometry and automatically produce the required fillet form, actually modelling this detail is not required.

To manufacture an accurate mould, say for the production of plastic injected products, the product must be defined adequately to allow NC machining. For products with a complex shape, a considerable amount of time and effort must be invested in producing the complex surfaces of the moulding, although the natural radius of the tool can reduce much of this modelling time. However, most sand castings do not need to be very accurate and consequently do not have their patterns fully modelled for subsequent N.C. machining using a CAD/CAM system. Instead, a drawing is sent via the foundry to the pattern maker, who makes allowances for shrinkage etc. during the casting process. Commonly, the pattern maker makes a wooden pattern, usually by hand from the drawing (manually or CAD produced), making the necessary allowances for shrinkage in the casting process. If the accuracy of the actual casting is entirely dependent on the pattern maker's interpretation of the drawing, then there is no point in spending a great deal of time and effort producing a completely accurate and full 3-D model of the casting.

Rather than fully model the free flowing areas with all their fillets and blends, it is only necessary to define the outline templates and add cosmetic lines. Sometimes for complex parts, a series of cross sectional templates, perpendicular to the outline templates are required, to aid the pattern maker's understanding. In these cases, the cross sectional templates would be created anyway, to aid the designers understanding and be used in the construction of the outline templates. This approach can also apply to components machined from solid by profile milling.

Fig (33) shows a 3-D model of a casting using this technique. The machined features such as mating faces and holes are fully defined in form, position and orientation for machining on the CAM system. The unmachined cast profile which connects the 2 machined flanges is defined by two templates which represent the outlines in the standard orthographic views. Cosmetic lines and notes can then be added to the manufacturing views for fillets, blends etc. Fig (34) 'A' shows a typical complex Lucas casting with many added cosmetic lines, arcs and splines. A spline is the smoothest possible free form curve through a set of user-specified points. In comparison, Fig (34) 'B' shows just the model entities. Guidelines to using cosmetic lines on 3-D models are offered later.

5.2.6 REDUCE DETAIL AND DUPLICATION

It is important not to 'over model' features or components, especially ones which are not required for manufacturing and are only added for aesthetic purposes. 'Over modelling' is inefficient because it takes longer to produce, consequently it takes longer to erase the extra unwanted entities in the manufacturing views and eventually results in a more confusing model. Fig (35) shows over modelling which can be used to represent nuts, bolts or other such standard components.

Commonly used items should be held in a library of standard parts or be generated each time using parametric programs. Either way, usually only the head of a bolt needs to be added to an assembly model and so the designer should exercise the option of merging or generating:- only the head; head and washer; or head, washer and thread section with various standard lengths of bolts. With such a large number of variations on a simple theme, parametric techniques provide the best method of creating large ranges of standard items.

An intersection line between features only needs to be generated accurately, usually using intersecting surfaces, if the intersection entity will be selected by the NC programmer for use in the generation of a toolpath, or if the exact shape needs to be known. If this is not the case, cosmetic intersection lines will often suffice.

As an example of such a case, a drill hole break through can be approximated to an ellipse. Fig (36) shows two cosmetically added ellipses, the drill break-through hole on the flat end piece of the component is in reality an ellipse and so this is an exact representation, whereas the other is only an approximate representation. However, in this example the drill only needs to follow the hole´s centre line when using the CAM system and so the intersection/drill break-through representation need only be approximate, as it is only added to the view(s) for aesthetic reasons. Likewise, intersection lines for non-machined areas of a casting need be added only as cosmetic lines or arcs. To approximate more complex intersections, spline curves can be used, as in Fig (36) on the section view.

Certain types of features are often required in groups; the set of flange bolt holes Fig (37) is an example of this type feature. The NC information for the form of each feature is identical for each hole in the group so that it need be defined only once, however the location of each hole centre must be uniquely defined. Fig (37) 'A' shows the flange with every hole detailed, providing redundant information. Fig (37) 'C' is adequate, being immediately understandable, but not aesthetically as acceptable as say Fig (37) 'B'.

5.2.7 POSSIBLE FUTURE MINIMUM MODELLING TECHNIQUES.

Probably the most time consuming aspect of 3-D modelling of any part, is the generation of the drawing. This is due to the need to define any required views from the model, then dimension, add notes and erase unwanted entites or parts of entities in the manufacturing views. If the model alone can be made acceptable, then the design and detailing time of a component can be drastically reduced, as only the model geometry would need to be defined. In the case of the author's current employer 'Kennametal', the average design time has dropped from 12 hours to 5 hours when using this approach for the design of single point cutting tools.

The CAM system and an integrated co-ordinate measuring machine can both function from using the CAD model without the need for a drawing. If a product is similar to many others produced by a company and it is an assembly of many standard features and items, then process planning, jigs and fixtures, manual inspection and estimating can use the model readily, knowing only a few key dimensions. Hence a fully detailed drawing is not always required. However, this approach can only be applied if the components are to be fully programmed using the CAM system and subsequently manufactured on C.N.C. machines. The process must be fully automated, with the manufacturing information in the form of computer data, as no detailed paper drawings are generated and no manual checks and adjustments are to take place during manufacture. This method requires inspection data generated from the CAD model to be used for standard and automatic inspection. As there is very little manual intervention in the manufacturing process, the machine tool needs to be largely automated, with compensation being made for tool wear with the aid of tool probes and with the computer logging of useage of each individual tool. A useable estimated life of each tool is made and when this figure is, reached, the tool is automatically replaced by a 'back up' tool or 'sister' tool, thereby allowing manufacture to continue. At this stage, the operator is notified that a replacement tool is required.

In addition a pre-defined processing plan is required to route the work through a particular 'cell' on the shop floor, using only CNC machine tools. The tolerances of the part at the various stages of manufacture must be within the standard operating tolerances of the given CNC machine tools.

This approach of creating only a model, can realistically only be performed for families of parts which are very similar and probably not too complex and which have a fully automated manufacturing process. For these reasons, this idea was thought unsuitable for the product ranges produced by ESD, although it could be applied to other industries producing suitable product ranges.

5.3 LAYERING AND MINIMUM MODELLING

Even with a minimum model, the resulting graphical representation of many components, may still contain such a profusion of entities, that visual interpretation may be extremely difficult Fig (38). To overcome this confusion, a facility called layering, must be used in conjunction with minimum modelling.

Layering can best be thought of as superimposing many 3-D bricks of transparent material, with each brick containing a part of the 3-D model such that a combination of these superimposed bricks forms a complete model within 3-D space. All 2-D drawings using layering are a special case of this, as 2-D is performed on only one plane which cuts through these bricks.

Any combination of the 256 layers which are available on the Computervision system can be viewed simultaneously from any defined view. Hence the model can be broken down into managable portions of geometry by placing features on different layers and displaying only the required layers Fig (39). Colour terminals on which the operators may assign various colours to different layers are also beneficial in viewing and understanding overlaid features, as they can assist in separating the individual features within the operators mind.

Layering has another major benefit, in that it allows the user quick and easy erasure of the contents of a layer or set of layers simultaneously, rather than the slow and laborious line by line approach. Thus an unwanted feature or set of features in a view, can be erased quickly, thereby significantly reducing the erasing time and improving productivity.

To make the most effective use of the layering facility requires the developement of strong layering disciplines needing forethought by the operators before committing a representation of some feature to a particular layer. Experimentation showed the benefits of placing all the individual faces, merged parts, 2-D hole templates and any other recognisable feature or set of features on separate layers. Ideally each feature should be assigned a colour to make it more distinguishable from the others.

5.3.1 METHODOLOGY OF LAYERING AND COLOURING.

When deciding how to divide a component into features and on what layer to place these features, a designer must have a picture of the finished drawing in his mind. Knowing the views which must be created, the designer must consider how the features may best be viewed and consequently decide on the most convenient arrangement of layering to adopt as the 3-D model is created. Experience lead to the following useful guidelines:-

Machined Faces: Machined faces are placed on individual layers and are usually observed orthographically. In the case of a flange, put the front face on one layer and the rear face on another.

2-D Templates: Place the external and internal profiles on separate layers. A template is created in the plane of the required view and only remains a valid template if it is displayed normal to that view orientation. If two different views of the same template are required, then copy the template onto another layer and then rotate this copy to the desired angle. This could for instance be used to produce an orthographic sectional view through a main bore as well as a sectional view through an inter-secting compound drill hole.

Generally speaking, templates which are seen in one orthograpic view are rarely seen in other orthograpic views, so place each template on a seperate layer to allow subsequent quick erasing by layers rather than by individual entities. For example, on the casting outline templates on Fig (33), the 'BOTTOM' view template could be on layer 4, and the 'FRONT' view template could be on layer 5, with the circles which imply a circular form to the templates and which are observed in the 'LEFT' view, placed on layer 6. Thus to create say the 'FRONT' view, layers 4 and 6 would be simultaneously erased along with some others, with very little overall effort or thought about individual entities.

Centre lines: The centre line of the template should be on the same layer as the template or on an adjacent layer by itself. The template circle centrelines should also be on the same layer as the circle or an adjacent layer.

Grouped Features: A set of identical features which are identified as a group, and which are displayed together in a view, such as a series of flange bolt holes, should be placed on one layer. Their accompanying centre lines should also all be on the same layer or an adjacent one.

Features on a Block of Layers: When creating a view, the draughtsman knows, which features he wishes to display and which he does not, and so it is logical to place all the layers of a certain feature on a block of consecutive layers. Then features which are not required can be erased in blocks, rather than in a long list of non-consecutive layers e.g. 10-15 (say the rear face feature) 20-27 (say the main bore) 43-97 (say the top face) etc. After passing through a coarse sieve of unwanted features, the view can then pass through finer ones, erasing any unwanted layers of an otherwise require feature and then perhaps even some unwanted entities on a required layer of the same feature. Cosmetic lines can then be added to the view if required.

At the start of this project, only 2-D monochrome CAD was being used at ESD. 2-D draughting, unlike 3-D modelling does not suffer from the problem of complex and confusing models and so only a few layers had been specifically and uniquely designated for certain draughting functions. These layers were for the drawing frame and title blocks, cross-hatching, section lines and dimensions. To reduce the confusion and improve the understanding of 3-D modelling, requires a more comprehensive convention for layering and colouring to be defined. This author defined a basic convention most effectively to use 3-D modelling. This was largely adopted and at the end of the project the general conventions for layering and colouring throughout the Design Office at E.S.D. were:-

Dimensions: always the same colour and always on their one specified unique layer.

Drawing Frame and Title Blocks: Always one colour and always on a group of three specified layers.

Notes: One colour and on one specified layer. This also included manually generated reference dimensions, which are not necessarity accurate and so are regarded as a note. The colour selected for notes was quite different from the normal dimension colour and so allowed operators readily to distinguish between them.

The separate colours used for the draughting functions such as dimensions, notes and drawing frames are not unique and can be used again for the geometric entities, as draughting and geometric features they can be readily distinguished on the CAD part.

Standard Items: Whether merged or parametrically produced, commonly used standard items are to be one colour and be on a unique specified block of consecutive layers (10 layers).

Centre Lines: These are associated with features and so are on the feature layer, or on one of the layers set aside by the designer for that associated feature. Centre lines are always the same colour, and no other geometric entity, except for section lines, is allowed to have be this colour. This enables the user readily to distinguish between certain types of lines and features.

Section Lines: The same colour as centre lines, but having a unique layer.

Cosmetic Lines: These are associated with features and so are to be on one of the layers set aside for that feature. Cosmetic lines are always to be one unique distinguishable colour which no other geometric entity may use. Thus, cosmetic lines can be readily identified on any part.

Design Block Layers: An initial block of layers (1-100) was designated for the design representation and includes those used for notes, dimensions and the drawing frame. Any colour other than those specified for Centre Lines/Section Lines and Cosmetic Lines can be used by the designer on any of the unspecified 100 available layers.

Manufacturing Block: The next 100 layers were set aside for the NC programmers for use on the CAM system. The NC programmer would add entities to represent the actual material present at the various stages of manufacture; this may include adding grinding, roughing and heat treatment stock to some features. Geometry added to represent each discrete stage of manufacture would be on a unique layer. Every toolpath generated would be represented on an unused individual layer, as would the extra material added.

Unassigned Block: 50 layers were set aside for other uses, such as quality assurance purposes or Finite Element Modelling.

Part Information: Layer 256, was specified to contain any text information associated with that part.

5.3.2 EXPERIENCES OF LAYERING AND COLOURING.

If a company's products are relatively simple and/or standardised, then certain types of features could always be placed on certain layers with which a selected colour could be associated. The advantage of this type of approach, is that any operator would know that any representation which is say green, would always be on layer 6 and all yellow entities would be on layer 3, thereby allowing the operator to erase layers and hence features, without having to verify which layers assembled to form certain unwanted features.

Experience gained at E.S.D showed that there were only about 10 colours which were easily visible and readily distinguishable from each other on the system. Therefore any product which required more than ten major features overlaid on one another, required a duplication of colours used for different features. This was the case at ESD and so as complex jobs progressed, it was necessary for a designer to keep notes listing the layering and colouring that had been used, for a certain feature, complete with the name of the CPL (construction plane) which had been used to construct the feature. The CPL is essentially a local co-ordinate system defined by the user. It can be positioned and rotated to suit the designers requirements and makes the construction of 3-D geometry in space more convenient. These CPL's are saved as they are defined with unique names, and recalled when required.

It is common for a designer to be introduced to a task after it has started or for the original designer to be requested to modify some part, perhaps after a long time interval. Working on any part which is unfamiliar takes longer, as features and their associated layers must be identified, recognised and understood before any additional/modification work can take place. To ease the learning or remembering process, an experiment was conducted in which a copy of the note with feature names, layers, colours and CPL name was placed on layer 256.

However, due to very large variation of features and the large number of similar geometries within a fuel control system, the unique naming of recognisable features proved to be impractical for this type of product. As a result, the paper list is still produced, but this really only serves as an 'aide memoire' for the actual designer and it may even get lost over time. No solution to this problem was found and so the problem still remains to be solved.

A problem with colour coding will clearly arrive if some terminals in an office are monochrome; specifying the colour of entities can still be performed, but not seen on these terminals and consequently the colouring convention often isn't followed. Layering is unaffected and is used as normal. A partial solution to the colouring problem, was to concentrate the design work and complex work on the colour terminals, leaving the detail work on the smaller simpler individual components and the NC programming process using the CAM system, to be carried out on the monochrome terminals. This is not an ideal solution as some complex NC programming work is performed using complex models on these monochrome terminals and as a consequence, it becomes difficult to distinguish clearly between features, especially when the zoom facility is used, requiring considerable care to be taken to avoid errors. As a result of recognising the importance of colour in understanding graphics, the author recommended that any future purchases of graphic terminals be colour ones.

Some of the above techniques may appear trivial for the limited number of example geometries presented here. However, when applied correctly and consistently to the complex geometries which can figure in a Fuel Control System Fig (38), the effect in terms of increased operator speed, system response and reduced confusion to the observer, is significant.

The techniques demonstrated above are not meant to constrain the designers, only to guide them. The designer is free to include in the model as much information as he deems necessary. Over modelling takes longer to produce and clean up the views, but as minimum modelling requires less effort, it is in the designer's own interest to follow the guidelines. However, the resultant model must be at least adequate for the downstream functions and so the designer must model the component with regard to its manufacturing processes.

There are only two exceptions to the designer's freedom, the first is layering. Certain layers cannot be used, whilst others are reserved for specific features or functions, with some even having colours exclusively reserved for them. The second constraint concerns cosmetic lines, which can not be used to generate a toolpath using the CAM system and so any entities which are to be selected during the programming process, must be created as model entities. Thus the designers must have a basic knowledge of the manufacturing and programming processes.

5.4 A REVIEW OF EFFECTIVE 3-D MODELLING.

The products produced by ESD are highly engineered, high value, complex parts which are often difficult to visualise and manufacture. It was believed that 3-D CAD models would be very useful in the creation and manufacture of these types of products. Consequently, the use of 3-D modelling as a design tool and as an aid to the pre-production activities was examined. It was found that 3-D modelling has many advantages to offer as a design tool for complex designs and if a CIM stategy is taken, then 3-D can be beneficial to many other downstream functions.

It was found that 3-D wire-frame modelling with a meshed surfacing capability was adequate for use at the company. Some disadvantages of using 3-D as a design tool were found and to overcome these and use 3-D modelling effectively as a design tool requires the extensive application of layering and minimum modelling techniques. If these are used, then the problems associated with modelling complex components and assemblies in 3-D, can be reduced to a point where it can be at least as productive as 2-D computer aided draughting. The advantages of 3-D modelling with any required surfaces are then a bonus to the designers and downstream users.

A problem which minimum modelling could mitigate, but not solve, was the response of the system to complex 3-D parts comprising a large number of entities. The system was slower when the majority of the users were manipulating complex 3-D parts. This was due to the extra graphics processing required.

Minimum modelling, layering and the use of colours can all be performed on the existing software. Some software packages such as CAD-Shade and ASD could enhance the system, but would be very rarely used and so the software currently available on the system was adequate for use on the site.

Three dimensional wireframe modelling with surfaces required no additional hardware, although a more powerful computer would also improve the response times of the system, resulting in greater productivity. Ideally, any new terminals should be colour work stations with their own powerful processing capabilities. The more complex CAD and CAM work, usually involving the parts with a large number of entites would be performed on these, leaving the simpler work for the existing Instaview terminals.

Effective 3-D modelling as a design tool was presented to a team of managers in December 1985 and a decision was made to continue the project and investigate the implementation of 3-D modelling using the techniques described above. The next section discusses this investigation, the implementation of 3-D modelling in the design office and considers the final outcome.

CHAPTER 6

IMPLEMENTATION OF EFFECTIVE MODELLING IN DESIGN PRACTICE

IMPLEMENTATION OF EFFECTIVE MODELLING IN DESIGN PRACTICE

6 INTRODUCTION.

So far only the methodology of using 3-D representation techniques in design have been discussed. An important aspect of the total project and logically the next step, was to consider the implications on the design process when using 3-D models with the techniques described previously. In order to successfully implement effective 3-D modelling into the design office, it was recognised that the support and co-operation of the CAD operators and other members of the design department would be crucial so that the transition from 2-D to 3-D operation would be as smooth as possible. Accordingly, it was first necessary to design and implement a new training programme which would complement and add to the scope of those already existing.

6.1 THE REQUIREMENTS OF 3-D MODELLING FOR THE DESIGNERS.

A consideration of the likely impact of 3-D modelling techniques on the designers and detailers showed the following issues to be important:

a) Training the operators to use the CAD equipment and introduce the notion of 3-D modelling.

b) The concept of a minimum model be introduced, understood and applied in a series of exercises.

c) Development of a strong discipline of representation in layers and appreciation of the importance of pre-planning in the successful adoption of layering techniques.

d) Applying 3-D techniques to model a product adequately for subsequent NC programming and other downstream users.

e) A new interpretation of 'engineering sketching' at the conceptual stage of design consequent upon the extremely accurate representation implicit in CAD techniques.

6.2 TRAINING OF CAD OPERATORS.

To be effective, training schemes need to take into account the varying needs of the individuals. In this connection, two main groups were identified.

1) Graduates, traditional designers and detailers and any other new members joining the design and detailing department with no previous CAD experience.

2) Existing CAD detailers and designers who would have a range of experiences and abilities in working in the 2-D representational mode.

There were three types of courses available for training CAD operators:

a) Individual training on-site.
b) Group training on/off site.
c) Individual training off-site.

An evaluation of these was carried out.

6.2.1 INDIVIDUAL TRAINING - ON SITE.

There was an existing individual on site 3-D training exercise and this was firstly evaluated. Essentially, it was an exercise to construct a complex 3-D Braceplate Appendix (2), by following a series of commands and diagrams. For training purposes, it had a number of weaknesses and these were indentified as:-

i) Too substantial a step in complexity from the existing audio visual course which was used for individual training in 2-D computer aided draughting and design.

ii) No information on methods of converting the model into manufacturing views.

iii) No emphasis on layering.

iv) Large number of useful 3-D commands not included.

v) The Exercise model was not particularly relevant to the company's products in terms of geometrical form.

vi) No introduction to the concept of minimum modelling.

vii) No introduction to the concept of modelling to meet the requirements of the downstream functions.

Consequently new training requirements were defined, the objectives of which were to rectify the short comings of the existing training programme. As a result, the author wrote, four new 3-D training exercises using a 'learn by example' approach; these lead the trainees through a series of relevant worked examples and were designed to avoid the excessive use of text. Each exercise was designed progressively to introduce a combination of the following features:-

a) The new exercises modelled a variety of products and features which allowed the introduction of the vast majority of 3-D modelling commands. These commands were of increasing complexity and variety, to match the increasing knowledge and confidence gained by the operator as he proceeded through the exercises. Where possible, the features and commands were relevant to the company's products.

b) Demonstrate approaches to 3-D model construction as well as procedures effectively to transform 3-D model views into manufacturing views.

c) Introduce the minimum modelling concept and other 3-D modelling techniques whilst emphasising the importance of systematic layering.

d) Take an Integrated approach by introducing the CAM modelling requirements, discussed in section (8.3).

The new on-site 3-D training programme was written so as to be suitable for use by the two main groups of individuals described above. The groups were matched to particular blocks of training undertaken in the following order.

1)	Existing CV 2-D Audio/Visual course	-	Group 1
2)	New 3-D Box exercise	-	Groups 1 and 2
3)	New 3-D Flanged Pipe exercise	-	Groups 1 and 2
4)	New 3-D B-Pipe exercise	-	Groups 1 and 2
5)	New 3-D Dimensioning exercise	-	Group 1
6)	Existing 3-D Braceplate exercise	-	Groups 1 and 2

Examples from the New Exercises and an indication of the level of narrative used are given in Appendix (2). To pursue the full training programme usually requires between 3 and 4 weeks full time. On completion, the operator was be capable of creating a 3-D model and detail drawing of any company product.

Individual on site training obviously required the use of a terminal, with the result that an operator sometimes had to be placed on either a late or early shift to ensure the ready availability of a screen, but usually the variety of a designers duties and inevitable absences for other reasons minimised this organisational problem. Apart from cost, the other major advantage of on-site individual training was flexibility, in that operators could work at their own pace and repeat sections which they were unsure about. This flexibility also allowed trainee operators to start their training when it was most convenient for them, rather than have to wait for the start of a CAD vendor organised one.

A further benefit of this flexibility, was that training could be readily halted, allowing more important company work to be performed and upon completion of this task, the training could be resumed with the minimum of disruption. The managers of the operators would monitor the progress of the trainees on the course and where possible, schedule appropriate urgent work between exercises. Thus managers can still retain control of the operators and respond quickly to changing work loads. If the trainee got into any difficulty, there were always other skilled operators or systems engineers around, from whom they could seek advise. This usually took no more than a few minutes of the skilled user's time, so that the whole process was flexible, cost effective and seen to be relevant to the needs of the individual and the company.

6.2.2 GROUP TRAINING.

When a group of between six and twelve people, all with a similar knowledge and ability in CAD techniques need training, then it is usually convenient to train them as a group.

Training groups on site required the use of an instructor, usually from the software vendors and a valuable suite of terminals. For this reason, the training was sometimes carried out off-site at the vendors own training establishments. However, all off-site training courses were more expensive, because the vendors facilites were being used and there was also the accommodation and travel costs of attendees to consider. Experience showed that the total cost of group training at the vendor's establishment was about twice as expensive per person as group training on-site using a vendor's instructor. A major problem with group training is that it is very difficult to organise a time period (usually 1 week), when the vendor's instructor and all the proposed attendees will be available to attend the course. Inevitably, there will be somebody who cannot attend and they will then have to wait until the next available course for training.

A particularly important advantage of group training was the opportunity it provided for tailoring of the course content for relevance to the company. Exercises could be constructed around known products and emphasis placed on commands or procedures of particular relevance. Commands which were not particularly applicable to the company products would be mentioned, but not practiced in the course. In addition, the 3-D minimum modelling concepts, introduced and designed by the present author, could be incorporated into the programme. A disadvantage of group training in a small design office, is the disruption it can cause. In the case of ESD, with 25-30 designers and detailers, group training involving 7 people would result in a 25% reduction of drawing office capacity.

6.2.3 INDIVIDUAL OFF-SITE TRAINING.

Individual off-site training was carried out at the CAD system vendor's establishment and groups consisted of between seven and twelve trainees from various industries. Consequently, a course would be of a general nature, not biased towards any one type of product design. As a result, a significant amount of time and effort on any one course would not be particularly relevant to an industry or its products. These courses are organised at intervals, to suit the training establishment so that there can be problems of placement when individuals are deeply immersed in important projects at their home base. However, an important benefit of any off-site training is that delegates are not distracted by the immediate pressures of on going project.

Vendor organised CAD training courses are usually of one or two weeks duration. Due to the limited time available, these courses can only introduce the basic commands and principles of a subject, leaving many areas uncovered or only briefly mentioned. After attending these courses, there is still a requirement to learn a great deal more and consolidate this knowledge. Thus, contrary to many managers' beliefs, these courses are not complete training programmes, but only an introduction to subject, and so further on-site training is required.

6.3 TRAINING POLICY.

Prior to formulating the Teaching Company Project, only a very small number of designers had benefitted from attendance at the system vendor's establishment; it had been considered that such a procedure was too expensive to broaden its application to all personnel. The remaining staff were required to be largely self taught, by means of an audio visual programme for two dimensional computer aided draughting, with the added benefit of advice and guidance from those who had been trained off site.

With the decision to implement the use of 3-D modelling, this existing training programme became unsatisfactory and so new training programmes, which were capable of training designers and detailers to model in 3-D and produce drawings, were examined. Three types of training were identified, two involved the vendor´s course and instructor, whilst the third was an on-site, self paced course for the individual.

For the individual on-site course, four new training exercises were written to complement the existing on-site self paced courses. The full on-site training programme was judged by the operators and managers to be a very comprehensive and relevant training programme; it was rare for any operator, who had completed the course, to require any further CAD related assistance. The programme had other advantages over the other two, namely its flexibility, minimal disruption to the design office and extremely low cost of training operators. Consequently, after the training exercises were written, it became company policy not to send anybody off site for CAD training which was covered in the exercises.

6.4 ON-SITE TRAINING EXPERIENCES.

As mentioned above, the exercises proved succesful at training people to use 3-D models and produce drawings. Experience showed that after people had progressed through the training programme, it was rare for them to require any CAD related assistance, although they did not reach full operating speed for probably another month or two. During the following 15 month period, about 25 people were trained to use the system using the training programme. Most of these people were new graduates or new designers, but this number also included some NC programmers and systems engineers. The people who had previously attended the off site vendor CAD courses also took any relevant modules from the new on site course to complete their training.

Only minor changes were made to the exercises during the next 15 months. These were usually small syntax errors, or occasionally adding small sections of text explaining a command or procedure in more detail. Other small changes were due to the perodic releases of the new revisions of the CADDS 4X software, which occasionally changed command structures.

The fact that this was an open learning, self paced type training programme, made it particularly useful for training some of the older draughtsmen. Some of these had previously attended a course at the vendor's training establishment, amongst generally much younger classes, and had returned noticeably less enthusiastic than their younger colleagues, often feeling slightly intimidated by the whole experience. Some expressed comments indicating that whilst on the course, they had felt rushed and in constant competition with the younger members of the training group, who seemed more comfortable with the computer equipment and were able to acquire this new knowledge easier and quicker than they did. A self paced course allowed these older draughtsmen to build their confidence and knowledge by learning at their own pace. It was found that older draughtsman, with a positive attitude towards CAD could, given practice and consolidation time, prove the equal of the younger designers and although it might take a little longer to train an older designer up to full speed, the product knowledge which they can bring to the job is well worth this relatively short extra time period.

6.5 EXPERIENCES OF IMPLEMENTING AND USING 3-D MINIMUM MODELLING.

Effective 3-D modelling as a design tool and as a step towards achieving CIM, was presented to the managers of the company in the early part of 1986. A decision was made to adopt 3-D design using the techniques described in the previous chapter. Training in these techniques would be carried out on site using the appropriate on-site training exercises. The implementation and use of 3-D would be monitored by the managers over the following months and reviewed as necessary.

A new product was selected to be the first modelled in three dimensions. The draughtsmen who were to be allocated to this project were trained using the exercises. No major problems were encountered and within two months of this pilot project starting, a decision was taken to develop all new designs in 3-D using the techniques proposed by the author. By the end of the Teaching Company Project, nearly all the designers and detailers had been trained using the on-site exercises and were familiar with the concepts.

Generally speaking, the move to 3-D modelling was fairly smooth. However, not all the operators were completely happy with using 3-D models. The younger designers and detailers prefered designing in 3-D, especially with complicated work. The older designers who created complicated designs also expressed a preference for designing in 3-D and said it aided understanding. However, the older detailers who did the detailing on the simpler and geometrically more regular components, found it to be slower and more clumsy to use with the requirment to create views and then erase entities in these views.

These detailers are correct in saying that relatively simple products are not, in terms of drawing efficiency, as suited to 3-D modelling as complex parts. However, if these smaller components are to be saved and recalled (using a group technology code) in the future for insertion into larger more complicated assemblies, then they need to be created in 3-D for non-orthographic insertion. However, it is the time and effort saved with the resultant better quality on the complicated assemblies and components modelled in 3-D, which reduces the overall lead times and product costs most significantly.

Minimum modelling with its strong emphasis on the formal use of colouring and layering was developed to make 3-D a viable design tool for use in a commercial design office. Since the project was completed, it was found that other companies have adopted similar techniques to make the same step from 2-D draughting to 3-D CAD modelling.

These techniques developed for 3-D modelling proved to be suitable for the downstream functions and were used on the CAM system by the NC programmers and later to provide starting geometry for the Finite Element Modelling process. However, by the end of the project, not all the downstream functions had yet been integrated. In particular, the Co-ordinate Measuring Machine had still not had a software interface written for it and so it could not access any information from the CAD system.

To increase the effectiveness of any commercially available CADCAM systems, requires that a great deal of development work or 'customizing' be performed to suit the particular applications of an industry or customer, as it is unlikely that any general purpose software will entirely meet the needs of a customer. This was recognised by Len Weaver who said, when talking of successful CAD/CAM installations [3]:

> 'The trick is to tailor techniques to suit the requirements of particular company'.

This philosophy was central to this project and pervades the approach to CAD/CAM adopted by the company. Developing the 3-D modelling techniques discussed previously is effectively a process of 'tailoring' to suit a company's applications to allow the most effective use of their CAD/CAM system.

Experience showed that it is very important to listen to operators, who through constant usage are best suited to identifying areas of the system which are limited or could be improved by 'tailoring'. An example of this was when for the first time, training exercises were being written in-house and the operators thought they could contribute to them in a meaningful way, rather that just blindly follow them, accepting any weak or poorly explained areas in the process. Consequently, informed comments about using the exercises and minimum modelling were made. This dialogue naturally lead to a wider debate and this was encouraged on an informal basis, resulting in greater feedback between the operators and the systems development people such as this author. The training exercises were gradually refined by listening and reacting to the comments of the users.

At the request of users, parametric programs were written to generate some commonly used standard items and cutting tools and alternative approaches and methods were developed to overcome the limitations of the software in certain areas.

As 3-D minimum modelling became the standard design medium, a major unforseen problem appeared on a very large and complicated part. This was due to a limitation in the actual CAD software, called a 'bug'. This was a problem which the vendor could not easily remedy and so a method was devised to circumvent it (Appendix (3)). The approach to this type of problem is common and is often referred to as a 'work around'. Most CAD systems have 'bugs' in them and require 'work arounds' to be developed.

The aim of improving the CADCAM system by developing and applying any technique, was always to maximise the effectiveness of the system in general. Developing the effectiveness of the system, by customizing it, is a continual process. This company intends to increase the effectiveness of their system by constantly developing techniques, application programs and integrating into other parts of the organisation.

6.6 SUMMARY OF 3-D CAD AS A DESIGN TOOL.

The use of 3-D modelling as a design tool has been examined in (chapter 4). In the process it was realised that is could not be considered in isolation and so the effects on the downstream functions were investigated. Applying a CIM approach to the project found that 3-D wireframe models with surfaces could be beneficial to both the design function and to the downstream functions. Some downstream benefits are available now, whilst others will become available as increased integration of the computer systems is achieved.

The advantages and disadvantages of 3-D modelling have been identified. By applying a concept discussed in chapter 5, called minimum modelling, these disadvantages were minimised without losing the advantages. The resulting models were still adequate, requiring no additional effort from the downstream functions. Some of the minimum modelling disadvantages were reduced still further by the systematic use of the layering facility. Thus, to use 3-D modelling effectively as a design tool, requires the extensive application of layering and minimum modelling. If these are applied, then 3-D modelling can be realistically used in a working environment.

New training requirements (Chapter 6) to use these new 3-D techniques, were identified and training exercises and documentation were produced as part of the implementation process for the use of 3-D CAD generated models.

The existing CADCAM system was found to be adequate to perform 3-D wireframe modelling with surfaces, although some hardware and software were identified which could enhance the system.

3-D minimum modelling is now being used successfully on all new designs. Further modelling techniques, application programs and training are being developed, monitored and updated as part of a continuing system development process.

CHAPTER 7

COMPUTATIONAL STRESS ANALYSIS

COMPUTATIONAL STRESS ANALYSIS

7 INTRODUCTION.

In recent years, many manufacturing companies around the world have recognised that there is a growing requirment to use some form of computational stress analysis on some of their products. The greater precision made possible by the use of computational stress analysis can lead to improved quality assurance and company image and result in a reduction in weight and lead time [24,25].

During the life of the teaching company programme, the senior management within the company recognised that there were significant potential benefits to be gained from the adoption of computational stress analysis. Accordingly, an investigation of this powerful engineering tool was incorporated within the project and a computational stress analysis project team was established. This team consisted of one Associate (the present author), one adviser from within the company and one from Aston University.

7.1 BACKGROUND TO PRODUCT ANALYSIS.

In general, the company's products are not highly stressed, with rigidity usually being considered to be a more important consideration. The components are mostly small, squat and functional with a high volume to surface area ratio, unlike thin walled plates or shells (membranes). Many of the company's components have regular geometries and their stresses and strains can be accurately calculated manually using elementary strengths of materials, whilst many others with more complicated geometries can be assumed to behave like regular geometries, with suitable stress concentration factors and reasonable or known safety margins added. However, some components such as housings and gear pump casings, possess very complex geometries which can only be analysed manually by greatly simplifying the geometries and loading conditions and by compensating for these simplifications with large safety factors. Such products may fail in either the prototype testing stage or in service, although in the majority of cases, they are overdesigned.

In the past, the complex geometries of many typical features had been found empirically and these typical features were embodied into the general design practice of the office and were subsequently used on many designs. Over the years, no attempt had been made to analyse and refine these geometric features and no allowance had been made for the introduction of new and improved materials and alloys. Consequently the products are commonly overdesigned, resulting in them being larger and heavier than necessary. These are both key factors in the marketing and design of fuel control systems. Although the components with very complex geometries requiring analysis are relatively few in number, they are usually the largest most expensive components, with the longest lead times and are the ones most in need of detailed and accurate computational stress analysis. Thus any major benefits to the design, testing and manufacture of these products can result in significant benefits to the company.

7.2 COMPUTATIONAL STRESS ANALYSIS WITHIN THE LUCAS GROUP.

Within the Lucas Group, there existed a small number of computational stress analysis users. In order to gather background information regarding hardware, software, training requirements, implementation and operation, visits were made to two of these user sites.

The first site visited was the Lucas Group Computing Centre, who had a small Finite Element section which performed analysis work on a sub-contract basis for all the companies in the group. This small section would take a conventional drawing and re-create the model geometry on a graphics terminal using a commercially available software package called FEMGEN. The next step was the FEM (Finite Element Modelling) process where the structured was 'discretized' (section 2.3.5) using the operator's structural engineering experience and knowledge. This process was performed interactively, again using FEMGEN to build the F.E. mesh to represent the structure. Details of the material physical properties, thermal and mechanical loads and imposed restraints (boundary conditions) would then be entered in the FEMGEN software, which would add this information to that already stored about each node and element in the mesh. This information would be stored as a datafile and when complete, would be pre-processed as shown in Fig (40). A pre-processor is a computer program which takes the operator defined (input) datafile, verifies it, reformats it, and defines a new datafile acceptable for use with the subsequent commercially available analysis package, in this case BERSAFE. If any errors are detected by the pre-processor, the process will be halted and any errors will be highlighted to the operator so that corrections can be made.

As stated in section (2.3.5), a structure can be represented by a large number of small but discrete elements, with each element having a number of nodes. The behaviour of each element can be modelled by a set of differential equations and these can be assembled so as to model the behaviour of the entire structure. However, the consequential stiffness matrix (section 2.3.5) can be large, 1000 x 1000 is not uncommon [24], and thus the resulting total number of calculations can be immense. Therefore Finite Element Analysis requires a considerable amount of computer processing time and disc space and consequently requires a powerful computer to run on, usually a mini or a mainframe, see Appendix (4) for some run time figures. The amount of computer processing to be performed can be decreased by running the data through a 'band width optimiser' which re-sequences the order of the set of governing equations so that the actual number of meaningful calculations are concentrated in a narrow band in the stiffness matrix, consequently only these ones are processed [23]. The purchased 'band width optimiser' used at that site was FELBRED.

After passing through the optimiser, the analysis process could be performed. Meguid [23] estimates that over 500 computer program packages have been developed for the solution of a wide variety of structural and solid mechanics problems. BERSAFE was selected for use by the F.E. section because it was regarded as being one of the best and most comprehensive packages and was judged to be capable of analysing the vast majority of Lucas products.

The product of the analysis process is a massive datafile, the interpretation of which requires considerable skill and experience. To assist in making the analysis meaningful to the user, the use of a post-processor is required to convert this numeric data into a graphics format for display on a screen, see Fig (41). The post processor allows the user to interrogate the display output and thus determine the significance of the anlysis. The operator can request that the analysis be displayed as a series of stress contours as in Fig (3), or as a series of displaced nodes or elements Fig (2). Note that Figs (2) and (3) display the component after a 3-D analysis with the post-processor having removed all the hidden lines and mesh details. The post-processor used at this site was called FEMVIEW. After post-processing, the user would apply their structural engineering knowledge and judgement to assess the significance of the results of the analysis.

The second Lucas site visited produced actuators for the aerospace industry. These products are load bearing components, but like the products of E.S.D. were subject to high quality assurance and low weight restrictions. Due to the nature of the products, this site had developed a large stress department and had been using Finite Element Analysis over a period of some years. Although the vast majority of the components were manually analysed using conventional strengths of materials techniques, the most complex ones, could only be accurately treated using Finite Element Analysis.

This site had a Computervision CADCAM system which was identical to that installed at E.S.D. However, with their strong requirements for accurate stress analysis, they had developed their CAE facility, to allow the pre and post analysis functions to be performed directly using the Computervision CAD terminal.

At this second site, the Finite Element specialist would call up the model of the CAD part and based on his experience and judgement, simplify it. The Computervision mesh generation facility would be used to generate a basic mesh and this would then be interactively modified to model any detailed features or to concentrate the mesh around important features. Generally speaking, the use of a finer mesh results in a more accurate analysis and so it is common to concentrate a mesh around likely areas of a high stress Fig (5). Once the mesh has been created and the material properties, loads and constraints had been defined, the FE specialist would run the input datafile through the pre-processor. This pre-processor which had been written on-site, verified and converted the input datafile into a format suitable to perform a finite element analysis using the BERSAFE analysis software package. After pre-processing, the new datafile would be transferred across the network to the mainframe at the group computing centre. Here the datafile would be optimised using the 'band width optimiser' (FELBRED) before being processed using the BERSAFE analysis programme. The resulting output file would be retrieved by the user across the network, post-processed using in-house developed software and then displayed in a selected format on the CAD terminal, to allow an assessment of the analysis to be made by the Finite Element specialist.

There are advantages of having the CAD and Finite Element Modelling facilities closely interfaced, such as at the second site. With an interfaced F.E. system of this type, the users still need to create the Finite Element mesh, but there is no need to recreate geometry, only consider simplifying the features embodied in the CAD file, thereby reducing time and effort. Butler writes [41]:-

> 'The significant advantage in moving most of the control of the CAD/FEM link towards the CAD end is in the reduction of the PIPELINE effect. When as a result of a finite element analysis a design change is made in the CAD system requiring in turn a repeat of the stress anlysis then much less data will need re-inputting if all of the simplified geometry, mesh control, material and physical properties, contraints and loads are there at the point of the design change'.

Having an on-site F.E. capability allows a company to react much more quickly to design changes on components needing analysis, than if the analysis work is performed off site by a sub-contractor.

Another advantage of being interfaced in this way, is that existing hardware can be used for the F.E. modelling and subsequent analysis functions by the F.E. specialist. When the equipment is not being used for F.E. work, it can be used by the CAD or CAM functions and viceversa, leading to increased system flexibility and utilisation.

7.3 OPTIONS FOR UNDERTAKING STRESS ANALYSES.

The first task was to examine the alternative ways in which the company could have a computational stress analysis performed on any of its products. At that time, there were a number of possible options from which to select a stress analysis capability for the company; these were examined and the major points associated with each option have been highlighted below.

a) Sub-contract the work to the Actuator Division, transferring the CAD model over the network. They would perform the Finite Element Modelling and Analysis processes on their CAD system, using a simplified CAD model and feed back the results. The advantage of this option would be that no in house capability/knowledge would have to be bought in or personnel trained since the expertise already existed at the identified site. However this was judged to be a poor option for the company since no local capability for improved design would be developed. This would also not enhance the company's image in the Aerospace industry. A further disadvantange would be the loss of control over prioritising the job with the sub-contractor.

b) Send out the work on a magnetic tape or via a MODEM over the telephone lines to a specialist sub-contractor/bureau service who could handle Computervision generated models and who could perform FE analysis themselves. Outside Bureau Services are expensive, but as they are specialists, usually with many years experience, the quality of the work tends to be good. The economical justification for using a Bureau Service against developing an in house capability can only be determined if a good estimate of the future work load can be made. It is obviously not worthwhile investing in hardware, software and training to create an on-site capability, if only a small number of products are going to be analysed each year, and it would therefore be more economical to use a bureau service. As with all sub-contracted work, the company would lose control over the priority rating of the job. When dealing with a sub-contractor there can be a series of delays, especially if a number of modifications are required. Each time an analysis identifies a defect the problems must be referred back to the remote designers, who then make modifications to the design and these changes must then be issued to the off-site analyst, who in turn alters the model and associated mesh and performs a further analysis. The cycle could then be repeated, but it can be seen that it is a series of actions, each with a delay and the resulting cycle time can be lengthy. Having an on-site capability, would allow immediate interaction between the designer and specialist, thereby reducing the cycle time and facilitating greater discussion about the problem. Using a bureau service also results in no on site capability for design improvement being developed.

c) As this company had the same CADCAM equipment as the Actuator Division (Second user site), then the company could obtain the use of their pre and post processors and perform the pre and post analysis functions on site, with the band width optimisation and analysis processes taking place on the remote mainframe at the group computing centre. The main benefits of this option would be control over the job and the development of an on-site capability. The disadvantages are the cost and time involved in the training of the personnel to model and analyse the computer output.

d) Install one of the commercially available computational stress analysis software packages on the IBM 4361 computer on site. This computer would be the heart of the CDS 5000 system Fig (14). At that time, this system had already been ordered and was soon to be installed at the company. The CDS5000 system had been bought to support the company's engineering database and was intended to be the 'hub' of the proposed CIM system. The system was to be a fixed overhead on the engineering department and was not to be costed to any individual project based on usage. Consequently, the extra cost of using computer time on a project requiring computational stress analysis, would be absorbed as a fixed overhead, which would be levied regardless of usage.

Initially, this would be the most expensive option as the analysis software would need to be purchased. Pre and post processors would also need to be bought or written to allow an interface between the CAD system and this analysis package. In addition, there would be the cost of training a specialist to use this analysis package. Using BERSAFE might alleviate this problem, as the actuator division's existing pre and post processors would, with small modifications be usable. Any analysis work would now be within the control of the company. Also the development of an on site computational stress analysis capability would enhance the company's image to its customers.

7.4 EVALUATION OF STRESS ANALYSIS OPTIONS.

To aid the selection of any system, it was necessary to establish the likely amount of future usage. This would then lead to a cost figure per analysis per system. The most effective systems could then be found and a decision could be made to choose a system.

Establishing numerical values for future usage proved to be difficult, as no project leaders or other managers were prepared to make any predictions as to how many analysis runs their project would need over the coming years. These people were only prepared to say, that if the facility was there, they would probably use it and if it proved to be successful, they would use it with increasing frequency. This attitude was quite understandable in that people were not prepared to commit either themselves or their project to using a technology which was new to so many of them.

At this stage, the management of the company were presented with the computational stress analysis options and they were made aware of the difficulties of forecasting the future usage of such a system at the company. These managers could see the engineering benefits of using a computational stress analysis tool and recongised the growing usage and associated prestige and marketing value within the Aerospace industry. Within the Defence and Aerospace industries it is believed that companies employing 'state of the art' technology will be able to develop a superior optimised product and so companies not employing this technology will produce an inferior, less well developed product. This is of course not necessarily the case, however most companies operating in the Defence and Aerospace industries still believe that they must present a high technology image to their customers.

Inspite of the lack of accurate estimates as to the likely future usage on this site of computational stress analysis, a decision was made to concentrate the investigation on selecting an on site capability.This decision was made in the belief that the use of this tool would grow leading to improved product quality and an enhancement of the company's image in the market place.

7.5 SPECIFICATION OF ON-SITE STRESS ANALYSIS SOFTWARE.

There are many differant analysis packages on the market, the majority of which have been written for particular applications, therefore before selecting any computational stress analysis system, the requirements of the desired system must be defined. The typical geometry of the components, the operating conditions and the type of analysis to be performed, dictated the minimum basic requirements and these were:-

1) Linear-Elastic stress analysis. Products would only need to be analysed within the elastic range of the material, as the product is considered to have failed if the material has entered its plastic range.

2) Some of the company's products operate under high pressure and so there is a requirement to model and analyse pressures as well as point loads. Many packages do not have this facility.

3) The analysis software must be suited to analysing large volume to area ratios, that is to say 'bulky' products, as some packages are more suited to analysing membranes (thin walled cylinders, plates or shells).

4) Due to the complexity of the product and loading patterns, both a 2-D and 3-D analysis capability is required.

5) The computational stress analysis modelling facility to be interfaced with the existing Computervision CAD system to increase productivity [18]. This would allow the creation of any finite element meshes, prior to the analysis process, to be performed on the CAD terminal. After the analysis process, the stress contours and displacements could also be displayed on the CAD terminal.

6) Accurate and computationally efficient analysis, with the ability

to run in batch mode over night. This would remove any mainframe system response problems which might be encountered when running a complex analysis during the day.

Desirable but not essential features were identified as:

1) Sub-sectioning. Fig (42).

After running an analysis using a coarse mesh, sub-sectioning allows a user to concentrate the mesh on a small part of the component and re-analyse just that limited geometry, thereby reducing computer re-run times. The new concentrated mesh boundary conditions are taken from the deflections at the same nodes calculated in the initial coarse analysis, thus allowing an accurate analysis of the limited region to be performed.

2) Shrinking elements for improved visualisation Fig (43).

It is easy for an operator to make a mistake and incompletely define an element when building a mesh manually. Shrinking the elements for visualisation purposes, allows these errors to be identified with much greater ease and speed.

7.6 INVESTIGATION INTO AN ON-SITE COMPUTATIONAL STRESS CAPABILITY.

In early 1986 there appeared to be only two forms of computational analysis that were suited to the company's requirements. These were Finite Element Analysis (FEA) of which there were many commercially available packages, or the relatively new Boundary Element Analysis technique of which, perhaps the best known commercially available package was BEASY. A feasibility study was undertaken, to see whether the BEASY system (Boundary Element Analysis System) would be suitable. This technique had some advantages over FEA.

Unlike FEA, only the surface or 'boundary' of the problem requires subdivision into elements. Fig (44) shows the differences in detail between boundary element and Finite Element modelling. It can be seen that there is much less preparation work on the model using boundary elements. In the finite element method, the displacement pattern is assumed to fit some localized simple form which can introduce a slight artifical stiffness to the model. By contrast boundary elements assume an exact solution and thus provide a more accurate answer [42]. Peak stresses usually occur on the surface or boundary of a component and this is where FEA is least accurate and boundary element analysis most accurate [43]. Brebbia [42], the pioneer of boundary element analysis and Thompson [43] of GKN Technology, state that boundary element analysis is more accurate and user friendly than FEA. Bauer and Svoboda [44] of Daimler Benz, using a similar boundary element package, also found this to be true. Computational Mechanics, the vendor of the BEASY software claim that it is quicker and easier to generate the mesh and also to understand the output than it is using the FE technique, thus leading to reduced training and modelling costs. It has been estimated that creating a suitable mesh for boundary element analysis is 5 times faster than producing an adequate mesh for a finite element analysis [43]. Thompson [43] performed a series of comparative tests between FEA and boundary element analysis and agreed with these findings Appendix (4). Consequently, BEASY was found to be suited to being used by general engineers rather than purely stress specialists, as is the case with FEA. However, structural engineering knowledge and judgement would still need to be exercised.

If BEASY were selected, purpose written pre and post processors would be required to interface with the existing CAD equipment; teething problems could naturally be expected to occur with this software. If the company bought BEASY, a relatively new system, it would have been one of the first major users of 3-D BEASY in this field within the UK. As such, a great deal of pioneering and developing work would be required to be performed by any future operators. This was not a desirable quality, as the company needed a working system for its small stress section, preferably one which would not require very much development. Another problem was the rapid increase in computer disc space and CPU time required for a BEASY analysis of a complex 3-D part [42,43,44]. Thompson [43] found that the disc space required when analysing a 3-D component using FEA, is proportional to the square of D (the number of degrees of freedom) whereas BEASY is related to the cube of D Appendix (4). Thus 3-D boundary element analysis of complex geometries may exceed the available disc space on all but the largest computers. The company's requirements for a well developed, proven system of stress analysis would not be satisfied by the adoption of a BEM package so that it was discarded.

In mid 86, the Actuator division (second site visited) made a decision to install a full finite element capability on their site Fig (45). They intended to sub-license the BERSAFE package through the Group Computing centre and run it on their own recently purchased CDS 5000 system. They would also install FELBRED and their own pre and post processors on this system. Additionally, they would have access to run BERSAFE on the remote mainframe at the Group Computing Centre, as with their existing system. This would allow urgent FE jobs to be run without affecting the other engineering database users. It was also planned to install a dedicated line between a bureau service and the Group Computing Centre. This connection to the bureau service would allow finite element analyses using the 'NASTRAN' FE package to be made. This would be useful, as sometimes American companies demanded in their contracts, for quality assurance reasons, that analyses be performed using 'NASTRAN'.

The proposed system described above also satisfied the F.E. requirements of this company, especially as it used only existing computer hardware. Installing such a system at this company, could have many advantages:-

a) BERSAFE, FELBRED and the Actuator Division's pre and post processors would fulfill the company's initial system specification. If at a later date, these were no longer suitable for the company, then they could be replaced locally by a more suitable package with a minimal cost penalty.

b) By selecting a system which had been implemented on identical equipment, there would be a minimum of disruption as most of the installation and operational problems would have already been resolved.

c) Sub licensing 'BERSAFE' through the Group Computing Centre would give a dramatic price reduction for the package (60% reduction). This would also result in a clear system support commitment from the Group Computing Centre who have past experience of running and supporting BERSAFE on their own mainframe.

d) The existence of application/user knowledge at the Actuator Division with a Computervision/BERSAFE interface. Ideally this knowledge could be best transferred by requesting the Actuator Division to train an operator for this company. This would familiarise the trainee with FE techniques and with the pecularities/intricacies of the system. This could significantly reduce the learning time.

e) Using the Actuator Division's pre and post processors and any other additional associated FE software available on their system, would not only reduce the cost of the system to us, but would also result in rapid updates of this software, such as when new revisions of Computervision CADDS 4X software were installed on the CAD/CAM system. On such occasions they themselves would be engaging in this updating work, we would merely be receiving a copy and so very little extra work would need to be done by them for us.

f) Similarly, when changes to any F.E. software occured, they would also update their associated quality assurance documentation and a copy could be sent to this company. This documentation could then be edited to the particular needs of this company, but all these documents would be at least to NAFEMS (NATIONAL AGENCY FOR FINITE ELEMENT METHODS AND STANDARDS) standards.

g) An on site capability would provide control over job priority. Being 'networked' would allow urgent jobs to be run at the Group Computing Centre, or allow analysis using the 'NASTRAN' software at the remote, but connected bureau service. Hence the system was very flexible.

h) Using the network,there would exist the potential for the transfer of any overload between F.E. sections at the Actuator Division and this company.

i) An on-site capability was good for the company's image.

Due to the above points and the fact that the Actuator Division is part of the Lucas group with existing ties and a history of co-operation, it was decided that this was the best avenue to pursue rather than delay and examine other FE systems. This course of action was recommended by the author at a meeting of the company's managers and a decision was taken to make an approach to the Actuator Division for their assistance in the setting up a similar system at this site. After some negotiation, a basis for collaboration was established concerning training, user support and quality assurance documentation. In addition, the company was also to be allowed to use their pre and post processors, with assurances that future software updates would be supplied.

7.7 IMPLEMENTATION AND TRAINING.

The author created an implementation plan which itemised and scheduled all the required software and training. F.E.A. still requires the application of structural engineering knowledge and experience, both for the modelling and subsequent analysis process and so an engineer with experience of using manual stress analysis techniques was selected to become the FE specialist on site

The training of this selected engineer was then specified. The time period to train a F.E. operator to a standard where they could competantly work unassisted, was recognised to be the longest lead time item in the F.E. implementation plan. Consequently, the necessary software was all ordered for installation and test just before the F.E. operator was due to return from his training. The training programme consisted of on-site CAD training of 4 weeks duration, interspersed by two 1 week periods of theoretical background training at the finite element consultancy firm of 'Robinson and Associate'. This was a very important part of the training [25], as it would demonstrate the scope and limitations of FEA to the operator. The next phase was a two month FEM and analysis period of 'on the job' training at the Actuator Division under the tutorage of experienced users. This on the job training would demonstrate the application of the theory in practice and familiarise the operator with the operation and limitations of the system. An on site F.E. capability and the trained operator to exploit it became available at the end of 1986.

7.8 EXPERIENCES.

Since the F.E. system was installed, many problems have been analysed successfully, allowing problem areas to be identified and corrected accordingly. The system has proved to be quite adequate for the majority of the analysis work which is 2-dimensional. Successful 3-D analyses have also been performed on the system, although, the F.E. modelling time is significantly higher and 2-D analyses are performed in preference. With time, the F.E. operator has progressed to analysing complex geometries in 3-D and these jobs have shown the limitations of both the Actuator Division's pre and post processors and the Computervision mesh generation facility. In such cases, proprietary pre and post processors must be used. Fortunately, interfaces now exist between the Computervision CAD system and the pre (FEMGEN) and post (FEMVIEW) processors, but these processors were licensed for use only at the Group Computing Centre.

On the relatively few occasions when the commercially available processors are required, the CAD model is generated at the company as usual, then transferred to the Group Computing Centre over the network, where the mesh is generated interactively using FEMGEN. This pre-processed data is then transferred back to the company, allowing BERSAFE, the analysis programme to be run on the CDS 5000 system. The analysis data output, is then transferred over the network to the Group Computing Centre for post processing using FEMVIEW and then finally retrieved and displayed on the CAD terminal on site. This transferring of data is performed to keep the amount of computer processing time at the Group Computing Centre to a minimum; this takes maximum advantage of the costing policies associated with such services within the Group of Companies.

During the analysis of assemblies, inaccuracies were found to be occuring at the flanges. When flanges move against each other, they transfer any compression forces across the flange. However, when an assembly is in tension and the flanges are moving away from each other, a gap between the flanges can be produced. To model these mechanical interfaces between flange faces requires the use of a special type of element called a 'GAP' element. 'GAP' elements can behave non-linearly, allowing compression forces in a defined direction to be transmitted, whilst not allowing tension forces, thus modelling the behaviour of the component at the flange. These type of elements had not been considered in the initail specification and were not initially available in BERSAFE, although they have recently been released and are currently under test at the Group Computing Centre. ANSYS, another FEA programme, which has proven 'GAP' elements is also now available with the appropriate CAD/FEM interfaces on the mainframe at the Group Computing Centre and this can now be used on geometries involving flanges.

Due to its flexibility, the FE system is capable of performing to all the current requirements of the company. However, at present, the FE system is not used early in the design stage process but is used only for 'trouble shooting', such as when problems develop later in the design-through-to-manufacture process. By applying this analysis earlier, identifying and correcting errors before prototypes are built, time and money could be saved. The analyses which are being run are specific to a particular job so that a major potential benefit which the system offers is not yet being enjoyed. No analysis is being performed on typical company standard geometric features which are repeatably used on many projects; these standard features could be analysed and optimised using FEA. As further experience is gained by the operator and awareness of the system's capabilities amongst the managers grows, so utilization of the technique will develop as a matter of routine in the design process.

7.9 SUMMARY OF THE COMPANY PRACTICE IN COMPUTATIONAL STRESS ANALYSIS.

At the end of November 1986, the company had an on site Finite Element capability. All the finite element software was installed onto the CDS 5000 system and it is intended to make most of the analysis runs on the system over night, so as not to inconvienence other users. This FE system selected, was identical to the one installed earlier at another site in the group, which had similar hardware and software. The system was installed and working very quickly at this site, as all the usual installation and teething problems had been previously identified and rectified by the other site in the group.

The FE system selected was a very powerful and flexible one and is capable of fulfilling the current analysis requirments of the company. Since the FE system was installed at the company, sucessful 2-D and 3-D analysis has been performed on models generated on the CAD system. However, very complex 3-D analysis or flanges which require the use of special 'GAP' elements, have highlighted some of the inadequacies of the original software, but other software available at the Group Computing Centre has been used successfully to overcome these occasional limitations.

By sub-licencing the analysis programme 'BERSAFE' through the Group Computing Centre and by acquiring the other necessary software from another site in the group, the system was installed at less than half of the normal installation cost.

System and applications support from experienced users and quality assurance documents are available from within the Group. This support from other sites and the relatively cheap purchase price of the software, allowed a small FE section at the company to be established as an operationally feasible unit. This support will continue to be beneficial for effective exploitation of the technique.

Training needs were identified, and a suitable training programme was defined. A stress engineer was selected to become the resident FE specialist and he followed the specified training programme, completing it at the end of November 1986. This engineer is now able to perform Finite Element Modelling using the mesh generation facility on the CAD equipment.

After the analysis is made on the CDS 5000 system, the results are post-processed and graphically displayed on the CAD system for interpretation by the FE specialist.

Although the system is capable of performing FE analysis to the requirements of the company, it is not yet being used as effectively as it could be. It is not being used earlier enough in the design-through-to-manufacture process and in particular, it is not being used to analyse and optimise standard company geometric features and general design practice.

CHAPTER 8

COMPUTER AIDED MANUFACTURE-CAM

8 INTRODUCTION.

A major part of the original justification for the purchase of the whole CADCAM system, was based on the benefits perceived to accrue from producing NC data files with greater efficiency and integrity compared to those produced manually, see section (2.3.6). By mid 1986, the management began to realise that the CAM system was not being utilised to its full potential. This underutilisation of a valuable production tool was seen as a missed opportunity for the company and yet the reasons why the CAM system had so far failed to achieve the initial performance expectations were not understood.

As a result of recognising that a problem existed, it was decided to widen the original scope of the Teaching Company Programme, to accommodate a general development and improvement of the effectiveness of the CADCAM facility at the site. In particular this author was requested to investigate and recommend solutions to the problem(s).

8.1 CAPABILITIES OF THE CAM SYSTEM.

The first step to investigating the problem was to gain an understanding of the operation and application of the current CAM system. This knowledge and appreciation was obtained by attending a CAM system training course, followed by a period gaining on-site experience, working alongside and analysing the techniques used by the company's experienced NC programmers.

The CAM software package of the Computervision system was called ´NC Vision´; it allows an operator to create, edit and process toolpaths for a wide range of manufacturing applications. In addition to general lathe type machining operations (2-D), it is capable of producing machining motions suitable for 2 1/2-D milling machines and 3,4 and 5 axis machining centres. NC Vision allows the operator to use both automatic routines (Section 2.3.6) Fig (7) and manual interactive tool control techniques, depending on what is appropriate to the specific cutting operations being programmed. NC Vision´s automatic tool motion control operations include point to point operations, profiling, pocketing, turning, complex surface machining and surface intersection machining. The manual interactive facility can also perform all of these operations using the Machine Absolute Motion (MABS) set of commands. When programming the CAM system using manual techniques, the operator must interactively and sequentially select individual entities for the representation of the tool to follow.

Whilst the toolpath is generated by the programmer, the tool centreline locations and a representation of the tool used for the job are displayed on the screen at each stage, as in Fig (46). The use of 3-D CAD models Fig (46) allows improved visualisation of the machining process, as the operator can define any desired viewpoint prior to creating the toolpath. In addition, when the prescribed toolpath is complete, the motion of the tool can be dynamically displayed on the screen, also from any user-defined viewpoint. 3-D representation offers a major advantage over conventional 2-D views, in that in addition to the X and Y axes, it provides immediate visual verification to the operator as to whether the tool has been set to the correct cutting height (Z-axis).

When existing CAD geometry only needs its size to be modified, the previously created and associative toolpath, can be ´regenerated´. This regeneration process automatically corrects and updates the toolpath according to the new geometric dimensions. Furthermore, if the tooling for a particular toolpath isn´t available, then a similar tool can be used. This is achieved by firstly modifying the tool description, feeds and other machining parameters. After this, the toolpath which followed the old geometry can be regenerated to produce an N.C. data file using the new replacement tool.

Existing shorter toolpaths can be linked together to form one longer toolpath. Each toolpath´s cutter location file, which contains the positional data (X,Y,Z values) of the centre of the tool tip, can also be manually edited and regenerated, thus allowing visual verification of a manually edited toolpath. This facility was useful for testing small modifications which had been made during the prove out of the NC program on the shop floor, or for small design changes to the component.

The NC Vision software allows free form APT, COMPACT II or SPLIT machining statements to be inserted at any location within the toolpath or at later stages where the toolpaths are assembled into sets or supersets. This facility allows specific machine tool controller dependant statements to be added. These are discussed later. In addition to these specific statements, there would also be more general ones such as coolant on/off, spindle direction, table clamps on etc. All of these statements are considered to be processed commands and are read in that form directly into the part program, before being post processed.

When using 3-D models, the machining operations available in NC Vision are independent of the precise manner in which the component is defined on the CAD system. For example by defining a local co-ordinate system (CPL) on a 3-D geometric CAD feature, the operator would automatically set the machine tool spindle/cutter axis to be parallel with the Z-axis of this local co-ordinate system Fig (46). The tool orientation for a machining operation could therefore be set quickly and accurately using a 3-D CAD model. This was especially true for the machining of auxiliary planes and compound drill holes.

Existing entities on the 3-D CAD model could be selected and their Z-values automatically used to control the depth of the cutting action. Entities which represent the bottom of a slot or pocket could be selected to control the depth of the cutting tool.

8.2 LIMITATIONS OF THE CAM SYSTEM.

At first it appeared that NC Vision could effectively perform, within the terms of the original specification, any NC programming work which the company required from it. However, experience revealed many limitations to its effectiveness.

The NC Vision package covered many aspects of machining ranging, from relatively simple 2 axis up to complex 5 axis machining. The generality of the software package made it large, complex and difficult to use effectively. As it was completely menu driven, it became cumbersome and very inefficient for experienced users. Because of the large field of machining operations covered, the system would ask many redundant questions, especially on the simpler work. This menu driven program was also felt by the operators, to be too rigid. In the middle of generating a toolpath, the operator could not stop the process, then change the orientation of the view, or 'Zoom' into or out of the screen, or modify, or verify entities, and then return to the break off position to continue the creation of the toolpath. Once started, the operator had to continue to the end of the toolpath, or reject and lose the work. When combining the toolpaths and APT statements together to create sets or supersets to form an NC data file, prior to post processing, the system was very unforgiving of any mistakes. Consequently, this process would need to be re-created until it was correctly entered in its entirety.

Within NC Vision, free form machining statements are considered to be already processed; they are thus not checked by the system software nor are they displayed so that no visual checks are provided for any such inserted APT statements. For statements which only control clamps, coolant on/off etc, this may not be very important, but it creates problems for so called 'Canned' machining cycles. A 'Canned' cycle statement is usually one line of data which calls a specific sub-routine to which it passes a set of machining parameters. The sub-routine contains many lines of commands within the machine tool controller and as such, the 'Canned' cycles are machine tool controller dependant. Appendix (5) describes the machining actions of two typical 'Canned' cycles for the DZ4 machining centre, whilst Appendix (6) provides a sample DZ4 NC program with some of these cycles identified. Other typical examples of 'Canned' cycles include Roughing, Peck Drilling, Tapping, Planetary Milling, Helical thread milling, Peck tapping and Boring.

Most modern machine tool controllers have a number of 'Canned'cycles built into them to increase productivity and decrease the apparent size of the NC program. Generally speaking the more complex and expensive the machine tool, the more sophisticated the controller and the greater the number of canned cycles which are available. When expanded, canned cycles can contain a considerable amount of information regarding the motion and action of a cutting tool and yet they cannot to be displayed on the CAD screen, thereby producing 'blind' spots in the NC program which cannot be verified using the CAM system. The only way to display the complete motion, is manually to enter every movement of the tool contained in the 'Canned' cycle. This is of course very time consuming and inefficient.

A possible solution to this problem is to write a set of 'Canned' cycle Macros, which would automatically expand the cycle to create all of these individual tool movements within the displayable toolpath. Whilst programming the part on the screen, the operator would call the macro to expand the cycle at the actual position in the toolpath where it would be used. This idea is discussed later in the chapter.

Essentially these Macros would expand the cycle into a series of simple movements whilst the toolpath was being generated. Each movement could then be displayed on the terminal as it is part of the toolpath.

Unfortunately, with a complex part, which uses many cycles, the memory of the controller can soon be filled with all these expanded cycle statements. This limitation can be overcome, if a Direct Numerical Control (D.N.C.) link to a computer with a larger memory is available. All the NC programs would then be stored on this larger machine. A D.N.C link allows the NC program to be fed into the memory of the controller in small manageable sections of data. The provision of such a D.N.C. link has been planned for the company, but has yet no firm installation date.

Some basic machining operations had no automatic machining routines within the NC Vision software package. Examples were threading, grooving, peck drilling. Likewise some basic data file manipulation operations, such as block resequencing, were missing. Macros similar to those mentioned with canned cycles, could be written to solve some of these problems. A recommendation for further systems development in this area was made to the managers.

A further facility available on many machine tool controllers, but not verifiable through NC Vision, was the use of conditional and unconditional jump statements within the NC data file. Appendix (5) shows a section of an example program with some explanation of how these jump statements work. These statements are frequently used to repeat a set of commands, allowing an incremental change to one or more of the variable parameters. They are particularly useful for incremental machining or for machining a set of repeated features. These jump statements can save much controller memory and make modifying a set of repeated features much quicker. This also leaves the programmer with greater modification confidence, as the values only have to be changed in one place in the NC program, rather than at every place where the feature is repeatedly created. These 'Jump' statements are added manually to the actual NC program and so cannot be seen on the NC Vision display for manual verification.

NC Vision is capable of controlling 2-1/2-D milling machines and 3,4 and 5 axis machining centres. In NC Vision all machining axes are assumed to occur about the cutting tool tip, however many 4 and 5 axis machines do not function in this manner. These machines such as the Deckel DZ4 Fig (47) have only 3 axes (X,Y,Z) available for the movement of the tool, and a 4th rotational axis (B about the Y axis) and sometimes even a 5th rotational axis (C about the Z axis) from rotating tables. These 4th and 5th axes gained from the rotating tables cannot be used within NC Vision, hence only 3 axis machining on these types of machines can be truely verified. In these cases free form machining statements which rotate the table(s) in the 4th and 5th axes must be added, but the resulting rotations of these table(s) are not observable on the screen. Hence, a possible collision between the tool and the rotating fixture/clamps/component arrangement would not be displayed in the simulation.

The start of a toolpath produced by NC Vision only displays the representation of the tool moving from a user specified clearance height to a user specified retract height and then finally to the user specified cutting height, where it starts its cutting motion. When the cutting action is finished, the tool representation rises to the retract height, then to the clearance height. If this had been programmed on a complex part, it would probably have been performed using a local co-ordinate system in the plane of a feature. The next feature to be machined on this complex part could be in an entirely different position with a different Z-depth and this feature could require a new local co-ordinate system. A toolpath similar to the one above could then be produced on this new local set of co-ordinates. However, the NC Vision system does not show the movement between the end of one toolpath and the start of the next. It is very possible that the different Z values of the local co-ordinate systems are sufficiently large to allow a collision between the tool and the fixture/clamps/ component arrangement as the tool moves from the end of one toolpath to the start of the next. This is even more likely, if there is a simultaneous rotation of the table(s) of the 4/5 axis machine tool. Collingwood and Blount [45] note similar difficulties with a twin turret CNC lathe.

The local co-ordinate systems referred to above, are taken into account mathematically by the machine tool controller, but the values of the datum offsets must be entered into the program as free form machining statements Appendix (6). These datum offsets are typed in manually and hence are liable to error. Again it is not possible to verify these manually entered offset values using the NC Vision system.

Thus a number of 'blind spots,' which could not be verified on the screen, particularly on the more complex machining operations were identified.

Therefore, the only way to check the validity of these CAM produced NC programs, was to run them on the actual machine tool.

8.3 EXPERIENCE OF OPERATING THE NC VISION SYSTEM.

It quickly became apparent that to use NC Vision effectively, required that the CAD generated models be presented in the most suitable format. To achieve this, a few very simple guidelines were formulated and they were:

1) All graphics to be created at the dimensional mid-limit of the tolerance. As the CNC machine tool cuts metal, it is driven to this theoretical mid-tolerance value, by the controller. The cumulative working tolerances (+ve and -ve) actually present in every machining operation can then be catered for by the allowed tolerance on the actual machined part. Usually the accuracy of the machine tool is comfortably within the required component tolerances. A part with a dimension and tolerance expressed as say 10.00 - 9.8 would be created with a dimensional value of 9.9. The machine tool controller would be constantly driving the cutting tool towards this mean value, thereby allowing a plus or minus tolerance of 0.1 for the accurancy of the actual cutting process.

2) No gaps are to be present between graphical entities, especially those which represent a machining boundary. It was found that very small gaps, some to only 6 or 7 decimal places

of magnitude, were being created by 'bugs' in the CAD software and by careless design. These gaps caused incorrect toolpaths to be created (usually between 2 non-intersecting arcs), or for the toolpaths to be rejected (line to line or line to arc). This was not only wasteful of effort, but was also particularly frustrating to the operator, as it occurred without warning whilst generating the toolpath. The programmer would need to edit out the offending entities, and start generating the entire toolpath again.

3) All graphical entities to be used for driving a toolpath, must be in model mode, as within NC Vision, entities created in 'Draw' mode (cosmetic lines) cannot be used for toolpath generation. Hence, if cosmetic lines are used to complete detail views, they must not be intended for use in the NC programming process. To avoid this situation, requires that the designer must be educated to understand the basic NC machining and programming processes required to manufacture a component.

These simple guidelines were presented to the designers and once the problems and their consequences were explained, were soon incorporated into all the designs. The importance and relevance of this information was also explained and demonstrated within the CAD training exercises (Chapter 6).

Due to the cumbersome method of generating NC programs using NC Vision, the experienced programmers would program the vast majority of regular 2-D type turning operations manually, usually by working directly from the manufacturing drawings or operational process planning sketches. The regular turning operations could be manually part programmed more quickly, using APT and 'Canned' cycles than by using the CAM system. Sometimes the programs were just written directly for a machine tool as a complete NC program, thereby removing the need for any post processing. This was also found to be the case for much of the regular shaped 2-1/2-D milling. Generally, the NC Vision package was only used when the geometry became too complex or too involved to program manually. In turning, it was only used when the 'C' axis machining facility was required, such as on a 'C' axis lathe or a mill/turn machine. For the 2-1/2 D milling, NC Vision was used either for non-regular profiling, or for its simulation and verification facility for more involved work requiring many machine tool movements. An example of this is profiling, which involves the intersections of many arcs, this being far easier and more accurate to program on NC Vision than by any manual method. For milling work which involved 3 or more axes, the work is always done using NC Vision, as it becomes too complex to program manually.

Initially the use of 3-D CAD models in conjunction with NC Vision caused some problems, as entities at different Z depths could be overlayed in orthographic views. This made the selection of a particular entity difficult, as it was possible to select one of the other superimposed entities at a different Z-depth, usually without any obvious visual warning. However, this problem was overcome by having the programmer define and save, with the appropriate co-ordinate system, isometric type views such as Fig (46). After this, 3-D models did not cause any major problems for the NC programmers, although small amounts of extra geometry were occasionally added. An example of this would be on a milled profile, which when viewed down the Z axis appeared to be one continuous line, but which was in reality serveral entities. In this case, for ease of programming, a single profile line might be added to the model and used in preference to the several entities.

Compared to the programming of representational 2-D geometry, 3-D provided superior visualisation by displaying the Z axis movements and values of the cutting tool. The 3-D minimum modelling technique was completely acceptable to the programmers, as it was adequate to generate toolpaths and helped to simplify the model. Layering also proved to be beneficial to programming as it allowed easier visualisation and selection of features/entities.

There were many commands available in the system with which the operators were not familiar; this was a direct result of the inadequate experience provided by the vendor's training programme, which lasted for only one week. As a large and complex software package, this one week course was completely inadequate, leaving a lot of areas of the software, in particular the application of it, uncovered. An improvement would have been to have the course broken down into more specialised fields and have the specific needs of the users covered in more depth and width in these particular machining areas. Obvious examples would be to have a three day Turning (2-D) course, a 3 or 4 day (2-1/2 D) Milling course and an Advanced 5 day Milling course for 3,4, and 5 axis machining. Also the design of the NC Vision, software could have been improved by writing it as a set of individual modules, each tailored to the specific needs of a particular field of machining. This approach would have reduced the cost to the user, allowing the customer to buy only the modules they required. The resulting modules would also be more suitable for use as there would be a reduction in redundant questions and more specialised functions, particular to that specific area of machining, could also be included in the modules.

When the motion of a toolpath was being displayed on the screen, the representation of the tool would speed up and slow down according to the feedrates previously entered. This was only a relative speed and not a true speed that had any real meaning to the programmers. A small text string could have been output onto the screen, giving speeds and feeds and the direction of the cutting spindle. This would be a very simple, but useful enhancement in NC Vision.

The general support of the CAM system was quite different from that of the CAD system. It was noticeable that the software support from CV was not nearly as good or responsive for NC Vision as it was for the design software (CADDS4X). There was also a lack of awareness, from all levels of the E.S.D. management, of the importance of developing the CAM system to increase the effectiveness and utilisation of the system. System support people were employed, but were directed towards supporting and developing the CAD system only, whereas the NC programmers were largely left to develop the system themselves, but were not given any resources or support from the managers to perform this task. This bias away from programming towards design, was due to a lack of appreciation of this esoteric field and this was probably due to the majority of the managers having a design or performance engineering background, consequently they could relate to the design function better than the programming one. However, even the managers having a manufacturing or production engineering background displayed a lack of real understanding for the importance of developing the CAM system in parallel with the CAD system.

8.4 RECOMMENDATIONS TO IMPROVE THE UTILISATION OF THE CAM SYSTEM.

In late 1986 the utilisation and application of the CAM system at the company was disappointing. The system was not achieving the performance expected in the initial justification for its purchase. As a consequence of this, an investigation into the reasons for this apparent underutilization of a valuable production tool, was initiated. This investigation found that there were two main reasons for this under achievement, and these were:-

a) The NC Vision software was found to have a number of deficiencies and limitations, as discussed in sections (8.2) and (8.3). It was a large and general software package which in practice proved to be cumbersome and inefficient to use. In fact the NC programmers, had found that regular geometries could often be programmed quicker using a manual approach and consequently it was used infrequently for programming components with these types of geometry. The NC Vision software was however used to generate NC programs for components with complex geometries, such as housings. It was these types of components, more than any other, which needed a complete visual display of all the machining actions to identify any errors and to truely verify the NC program.

However, it was the complicated NC programs which machined these complex components which suffered the most from the limitations of the NC Vision simulation facility, namely the lack of visual verification of the datum offsets and of the machining operations in the 'blind' spot areas, as discussed in section (8.3). Thus the NC Vision package, was failing the machining area where it could offer the most benefits.

b) A general lack of awareness amongst the managers of the need to support and develop the CAM system. The NC Vision package needed customising by writing Macros, Tooling Databases and keyfiles etc. It needed a 'champion' to explore the system and develop techniques and applications to allow greater exploitation of the system. Although some keyfiles and macros had already been written, there were many more areas which could be developed. Thus due to the lack of systems development, the CAM system could not reach its full potential and would remain underutilised. As a consequence of this, this author recommended that a meaningful programme of CAM development be initiated, consisting of an investment of human resources in addition to the large financial investment already made in the CAM equipment and software.

The above reasons for the underutilisation of the CAM system were presented to the managers and the main recommendation was accepted. Consequently, it was decided that this author should assume the role of the CAM support and development engineer. A decision was also made to concentrate any initial CAM system development work in improving the simulation of machining complex components. At the time, it seemed unlikely that any pending revision changes to the NC Vision software by Computervision would overcome the NC Vision verification deficiences. Any development of the system, in this area, would therefore need to be performed on site by ourselves. A period was then spent on researching current and developing approaches to NC program verification, to see if any were applicable to the needs of the business.

8.5 INTRODUCTION TO NC VERIFICATION

Current methods of verifying NC part programs results in one of the highest non-recurring costs [46] in producing NC machined parts within the aerospace industry. Some authors [45] report that 50% of total NC production time was spent on the NC 'Tape Prove Out' stage, where the NC program is verified and errors removed. This wastes production time and is a very costly process for a number of reasons:

1) Lost production time of the machine tool. Usually the most complex and expensive machines peform the most complex work and this normally results in longer prove out times. Hence it is the most expensive machines which are unproductive for the longest period of

time. On the DZ4 machine Fig (47), total prove out times of 2-3 man-shifts, spread out over one week, were not unusual when preparing to machine certain complex housings. As production runs in the aerospace fields are usually small in number, the ratio of non productive prove out time to actual machining time is high, resulting in higher cost overheads. As stated above, in the Aerospace industry, 50% of total production time for Tape Prove Out is not unusual [45].

2) During the prove out activity, there is always a risk of programming errors resulting in damage to a tool, fixture, or even an expensive semi-machined part or casting. Another danger of a major collision, is that the machine tool slides or tables can be disturbed from their datum settings. For example, the DZ4 could take up to two days to reset, resulting in a loss of up to 6 working shifts.

An outcome of trying to avoid collisions, especially in areas where machine tool parts are moving simultaneously, is that programmers often put in a large clearance safety margins. This extra distance travelled, results in cycle times, which are longer than necessary and this can be significant in terms of added cost for large production runs.

As a result of these problems and costs, a considerable investment of time, money and effort has been expended in developing 'away from the shop floor' simulations of NC programs. Mostly these are displayed graphically on a screen for human verification. However, visual verification does not validate a program as some optimistically claim [46], although it does act as a coarse sieve to detect the serious geometric errors such as collisions. After passing through this visual verification process, there is still the requirement to 'fine' tune the program on the machine tool to adjust the offsets, speeds and feeds in order to achieve the desired tolerances and surface finishes on the component.

This fine tuning attempts to remove any tool vibration and tries to make allowances for the rigidity of the fixture and clamps. It compensates for the positional cumulative tolerance build up in the linear and rotating tables, spindles and fixture locations. Also the relative tool length variations from nominal must be allowed for. At present, the use of computers can do little to reduce this fine tuning prove out time, although other approaches, such as keeping tools dedicated to a particular machine tool, and constantly checking and compensating for tool wear, can help to reduce this unproductive time.

Fine tuning is also required to avoid any minor fouling or gouging missed during the visual verification stage. Even the latest experimental research [47] accepts that errors of less than .002" are not observable when simulating 3 axis work.

8.5.1 CURRENT AND FUTURE APPROACHES TO NC VERIFICATION

Using graphics to verify NC programs is not new, the early procedures involved reading NC data into a simulation program which interpreted tool movements analogous to CNC controllers. The results of the simulation of the movements of the tool tip would be plotted on a sheet of paper. This was adequate for representing simple 2-D type turning and milling processes, although not really practical for anything more complex [45,48]. They are also of little help in identifying collisions between anything other than those involving the tool tip, thus a collision between the tool shank and a clamp, or the jaws of the chuck etc. would not be detected.

In recent years, some C.N.C controllers have been supplied with a small graphics screen to verify the actual NC program. The resolution of the graphics on the small screen is usually not very good, and is really only adequate to identify major geometric errors. These simulators cannot yet graphically show table rotations so that their applications are mostly limited to turning or the simpler milling type operations. Consequently, they are unsuitable for many of the most complex products produced by the company. In addition, verification of this type, on a production machine tool, can result in a reduction in its utilisation. It is more efficient to simulate and correct the NC program 'off-line' on a seperate piece of equipment, so as not to affect production.

Unlike these NC simulation programs, most commercially available CAM systems do not verify the whole NC program, but only the toolpaths generated on the CADCAM terminal. These toolpaths represent only a part of the actual machining operation and so there are important sections (blind spots) which cannot be visualised and these sections can thus only be verified during tape prove out on the machine tool.

Most current research into NC verification makes use of C.S.G solid modellers [45,46,48]. This simulation approach consists of a cutting tool, such an endmill, which would be represented by a solid model of cylindrical form, and a solid model of the original block of material from which the component was going to be manufactured. The solid modelling simulation works by subtracting, using a Boolean Difference operation, the volume of the cutting tool from the original workpiece volume at any position where the two volumes coincide [46].

By considering the tool motion and the total volume of material removed in a machining pass, the true remaining geometry of the component, can be visualised on the screen. Unfortunately, the geometry of the swept volume resulting from a toolpath, can be extremely complicated, expecially when the orientation of the tool axis changes as in 5-axis work. In 1986 this complexity of geometry was beyond the modelling capability of conventional CSG solid modellers [47]. Furthermore, due to the dynamic nature of the tool motion, the solid modeller has to handle large numbers of primitives. Consequently, it is claimed by General Electric [47], that the General Dynamics approach [46] as discussed above, requires extensive computing resources. General Electric [47,48] claim to have a more efficient approach to the concept which will make it more economically practical. They consider only the envelope of the volume swept by the cutter and the graphical image produced, rather than of the swept volume of the cutter actually used. However, even this approach is very demanding on CPU time and virtual memory storage and it is still recognised to be too excessive for the vast majority of commercial users.

Infact, all the NC verification systems using solid modelling [45,46,47] have, as yet, proved to be impractical for most users for this reason. Su and Loftus [49] write:-

> 'Although this method has much to commend it, it does represent a futuristic approach to NC programming. It is certainly not widely availabe to the general N.C. user.'

However, this method does seem to be the most logical path for NC verification to take in the future. If used correctly, the operator will be able to see the start of the manufacturing process, beginning with an unmachined billet, then watch the simulated machining action gradually remove the metal. At the end of the simulation, the remaining solid model should fully represent the finished component. The original finished component model, used in the programming processes, could then be subtracted from the remaining NC model and any residual volume displayed, would indicate an error. Any collisions between the tool and clamps and/or fixtures etc could also be simulated, with the resultant gouge being displayed.

The approaches taken by the General Electric [48] and General Dynamics [46] have the same basic limitations as the NC Vision package, in that they generate these toolpaths from the CL file rather than the NC program, although the team working on the General Dynamics system [46] are aware of this and are trying to correct it. Again similar to NC vision, both systems also embody the assumption that the 4th and 5th axis are also located in the machine tool spindle.

Only the solid modelling system proposed by Collingwood and Blount [45] uses the actual complete NC program, thereby generating a full simulation of the machining process. This system was sophisticated enough to detect and warn of collisions due to two rotating turrets on a lathe. They also acknowledge that very little research work has been done in detecting collisions of moving parts and fixtures in the field of NC verification. Their system worked by reading the NC program line by line, with each data line being interpreted and converted to a machining movement data file. This data file was then converted and used to produce movements or rotational indexes of the solid models of the twin lathe turrets and their associated cutting tools. After each movement, checks are made to detect interference. The process requires considerable computing power and is usually run over night in batch mode.

Another approach to NC Verification is one which builds up the geometry of the material actually removed, rather than produce toolpaths around the remaining material [49]. This process considers the generated locus of the periphery of a milling cutter (the side walls produced by the slotting/milling action) as it moves along the centre line of the toolpath. The real component is generated in this way. The geometry formed by machining the upper cutting layers is usually changed by the cutting processes in subsequent lower layers. To produce the actual remaining geometry, often requires these higher intermediate cutting phases to be deleted. This removed or machined geometry can then be superimposed onto the CAD model assembly of the component, clamps and fixtures and a visual check can then be made to see if the original CAD component geometry is identical to the model produced by the removed material method.

This method will also show any collisions with the clamps etc. Su and Loftus [49] state that substantial computations and logical judgements are required to provide the desired results. This method, which is under development has been used only for 2-1/2 D milling, but any application to more complex 3-D work will involve significantly more sophisticated logic and computational resources.

8.6 DECKEL DZ4 SIMULATION PROJECT.

As a result of the recommendations (section 8.4) from the investigation into the underutilisation of the CAM system, a decision was made to support and develop it using a Teaching Company Associate. At the time, it was recognised that the greatest area of impact of CAM development for the company, was on getting greater utilisation of the two Deckel DZ4, 4-axis machining centres Fig (47). These expensive machine tools were of central importance to the well being of the company. The majority of the most complex components having the longest lead times were manufactured on these machines and despite being run 24 hours per day in three shifts, these machines comprised a 'bottleneck' in the production process [14]. It was therefore very important to find ways of improving the utilisation of these machine tools.

The main non productive periods on these machine were usually the result of tape prove out. For this reason, the CAM system was identified as having the potential to decrease, through improved simulation, the prove out times, resulting in greater machine utilisation.

In late 1986 a CAM project specification with objectives was written and this author was assigned to the project. The terms of reference were:

'To provide a means of simulating a total NC program sequence for the Deckel DZ4, to create greater confidence at the preparation stage through to completion of the Prove-out stage.'

The objectives of the project were:

a) Reduction of Prove-out time

b) Fuller utilisation of NC CADD to optimise simulation

c) Communicate confidence and reliability in the NC program

d Collate and fix problems raised during the Prove-out stage related to the integrity of the NC program.

e) Post Processor verification

f) Identity usage of in-control repeat cycles over the same toolpath, edited at machine control and not shown/indicated on NC CADDS.

8.6.1. DZ4 SIMULATION SYSTEM DESIGN.

The first step towards producing a useful simulation program was to investigate the machining facilies available on the DZ4 machine and in the process gain an understanding of the operation of the machine. During the machining of a component on the DZ4, it was usual to have the component located on a fixture, which was itself attached to a pallet which was clamped to the machine tool's rotating table. A typical 8" square fixture, called a 'cube' is shown in red in Figs (48) (49). When machining on the DZ4, it was normal practice to have a component machined on one face of the cube and have another of the components from the same batch, but at the next stage of manufacturing, ready to be machined on the opposite face of the cube. The first NC program would run and machine the first component, rotating the table whenever necessary. When it was finished, the second program would run and the other component would be machined.

On completion of both machining cycles, the pallet was automatically removed from the machining area and replaced by another pallet on the DZ4 with an identical arrangement. The original pallet would have the freshly machined components on the fixture unloaded and replaced by semi-finished components or billets of material, in preparation for a repeat of the machining cycles.

Fig (49) shows a typical fixture/component assembly with the components in blue and green. Note that a closer examination reveals the original material outline which can be seen in differant shades or colours. This original material is used in the NC programming process.

During the investigation it became apparent that the only means to achieving the set objectives of the DZ4 project would be to create a full 3-D simulation of all the movements of the tool and the component/clamp/fixture arrangement on the rotating table. This would be similar to the verification programs available on some of the new machine tool controllers, although it would obviously need to be more complex. In addition to fully simulating the machine tool motions, any solution would need to be practical and use available technology.

As already stated (45), very little work had been done in the field of NC verification involving moving parts of a machine tool and as a result, the available literature was not particularly helpful. Also the use of the available technology, that is the Computervision CADCAM system, and the fact that the simulation system was to be practical, ruled out any use of solid models. Consequently the simulation would have to be limited to a visual inspection of 3-D wire frame models and this would require the operator to view any errors as they occured. A certain amount of logic could be included in the program and if general collision rules were violated, the operator could be warned.

However, this approach would only warn if the tool was in an area where a collision could occur. The only way to automatically verify if an actual collison does occur, using the available technology, is by completely surfacing the 3-D models of the tool and fixture/component arrangement. Suitable small incremental rotations of the table and movements of the tool could occur and checks could be made for intersecting surfaces. Apart from the impracticality of surfacing everything, the impoverished response of the system would be completely unacceptable. Hence this approach was not a valid one to pursue.

8.6.2. SIMULATION METHODOLOGY.

In December 1986, the development of a computer program to simulate the actions and operations of the DZ4 machining centre was begun by this author. It was intended that this computer program would use the CAD produced 3-D wireframe models, complete with any existing surfaces and fully simulate every motion of the tool relative to the workpiece/fixture/clamp arrangement. This simulation was to include: 'Canned cycles'; 'Do-loops'; movements between consecutive toolpaths; movement to and from the home position and of course the toolpaths themselves. Full visual verification on the CADCAM terminals could then take place.

To fully simulate the machining actions of the DZ4, required a full scale 3-D CAD model representing all the salient features of the machining area of the DZ4 to be created Fig (53). This included the the tool change or 'Home' position and the centre line of the rotating table. A selection of standard 3-D fixtures were also created. These could be merged into the DZ4 model in the correct position and orientation in 3-D space, so as to represent the actual fixture on the rotating table. The 3-D CAD model representing the component or the original billet material to be machined, could then be merged onto the cube, again in the correct position and orientation. A typical arrangement is shown in Fig (49). Any clamps, bolts, location mechanisms etc could also be added in a similar way.

The actual NC program or data file was to be read, interpreted and converted into a series of movements by the simulation progam. From this, centre line toolpaths were to be generated and when a rotation of the table was called for in the NC program, the entire fixture/components/clamp arrangment would be rotated throught the required angle about the centre line of rotation. Any remaining toolpaths would then continue to be simulated for further visual verification. During the rotation process, the program would also warn of possible collision situations due to insufficient tool withdrawls or tool movements into an area in which the fixture/component was rotating. As datum offsets and resets are used to calculate these actual toolpaths, then they themselves would also be verified by the program.

The above section describes the basic concepts and methodology incorporated by the author into the simulation program in order to achieve the project objectives. In June 1987, a working prototype was ready for demonstrations on the CV CADCAM equipment. The operating instructions for the simulation program are presented in Appendix (7).

8.6.3 FEATURES OF DZ4 SIMULATION PROGRAMME.

To perform a useful simulation of all the major operations, required that a number of approaches and features be developed and incorporated in the program. These features and the methodology employed in the program are discussed below.

All the CAD representative fixtures have a front face with a 'B' axis value set to '0' degree, see Fig (47). The fixture model Fig (49) has 'FRONT 0' degree, '90' degrees, '180' degrees, '270' degrees marked on its 4 faces. A CAM operator will always view it from the 'Home' position and the text which is correctly orientated for reading, is the actual face viewed. In Figs (48) (52) (55), the bottom left hand views clearly demonstrate this feature, which aids the visualisation and understanding process for the operator.

At the start of the program, a radius about the rotating table centre is defined by the operator. This radius just inscribes every part of every object which rotates. This is called the 'sacred' circle and is drawn in yellow Fig (49). This 'sacred' circle is used to define a safety cylinder, such that any stationary object outside of the cylinder will not be in a collision situation when the rotary table revolves.

The program reads the NC data file, as a series of consecutive data lines, immediately acting on each line of data as it is read. Thus the motion of the toolpath is generated not as a whole, but as a series of connected individual movements, corresponding to the true motion of the cutting tool. The speed at which these movements was created was such that it was easy to understand and follow with the human eye.

When a rotation of the table is called for from the NC data file, the program stops and completes the toolpath up to that point. The program then produces a small DISC and a POINT on the white toolpath Fig (54).

The movement from this DISC to the POINT occurs simoultaneously in real time with the rotation of the fixture/component. The program also produces and displays a temporary arc about the point of rotation, which subtends an angle which is equal to the angle of rotation of the fixture/component Fig (56). The magnitude of the angle is also printed out. On the end of the arc is a pointer indicating the direction of rotation.

If during a rotation command, any point on the toolpath between the DISC and the POINT breaks into the 'sacred' circle/cylinder, then a collision could occur and so the system warns the operator with a message and prints out the block no. of the command. By looking at the toolpath displayed in the working view, or even by referencing some of the other views of the 3-D model Fig (55), the operator can make a decision as to whether an actual collision might have occured. The operator can CONTINUE or EXIT the program. Fig (56) shows an actual collision situation which was correctly predicted. The angular rotation about to occur is 180 degrees and during this rotation, the tool tip moves from the DISC to the POINT, both of which are within the 'sacred' circle (Fig (56) Plan View). A collision between the tool and one end of the clamping fixture can be expected to occur at an approximate rotational value of 80 degrees. This would then be verified visually by referring to the Front and Right Views to check for the cutting height. Thus the operator is expected to exercise a degree of judgement at each collision situation.

If CONTINUE is selected, the whole fixture/clamp/component arrangement rotates to the actual position and the toolpath continues from the POINT position. Three consective rotations can be seen in Figs (49),(50),(51). Fig (52) shows the final total toolpath in 4 views.

Everytime a rotation of the table was required, the operator would be able to select the layers of the machined component which were desired for that view. Layers which described the rear or sides of the component, which were not required by the operator and which only confused the view could be made invisible Fig (54), as only the front feature layers are required for that position of the toolpath verification. Just before another rotation occurs, all these invisible component layers are automatically switched back on, otherwise they would not be included in the next rotation.

Whenever a toolpath is first created, it is always on a new unused layer, so that it can be viewed separately later. The operator has the option to define the first toolpath layer and the following toolpaths have layer numbers which increase sequentially. When the tool is changed, the old toolpath layer is made invisible and the new tool is given the next unused layer.

The toolpaths displayed are created as real NC toolpaths, not just as a series of lines or arcs. These toolpaths can thus be used later to dynamically display the cutting motion of the tool. In Fig (49), near the top left hand corner of the blue component, the dynamic motion of an Endmill has been captured and is seen as two moving green circles. The program would only display a representative 1" diameter cutter, although the creation of a small database with tool numbers against tool diameters could allow the true tool model to be displayed.

The operator may also elect to view only a selection of toolpaths. For example toolpaths numbers 5 to 9 inclusive could be selected and the program would rotate the table and component to the start angle of toolpath 5, and work progressively through to toolpath 9. This is particularly useful, especially during tape prove out, to verify limited 'off-line' modifications to existing NC programs.

The program also offers the option of either working automatically through all stages or for it to be used interactively. In automatic mode, it does not stop to wait for CONTINUE or EXIT entries at rotations or errors. Regardless of mode (interactive or automatic), the program makes a note of all the block numbers in which a mistake or possible collision could have occured and prints this out at the end of the simulation. However, if this error file reaches a value of 10 errors, it stops the program and prints out all the offending block numbers. This value could be easily changed if required.

8.6.4 PROGRAM OPERATION, LIMITATIONS AND FUTURE DEVELOPMENTS.

The simulation program was written on the Computervision CADCAM equipment in a language, which was first released in 1986, called 'CVMac'. Appendix (8) contains a listing of a development version of the simulation program. CVMac is an interactive graphics programming language which was written as a basic interface to the graphics software. It could examine and extract data from entities and transform them in space. It was also an application interface to mechanical design for creating geometric and dimensional entities and to numerical control for generating toolpaths.

At this company, it was primarily used for the parametric design of standard items (nuts, bolts etc.) and tools (drills, reamers etc.).

The NC datafile would be read one line (usually called a block) at a time, into the simulation program and this would be interpreted and acted on before the next line was read. Thus the actual actions of the controller were simulated. The method of interpreting the code is similar to that used by Hutton and Hassan [50] who simulated a basic 2-axis CNC lathe.

A typical Deckel NC program is shown In Appendix (6) with a brief description of some of the statements. Both the machine tool controller and the simulation program would initially store all the datum offsets and tool lengths and recall them when required by the NC program.

The simulation program would firstly check to see if the line read in was a data block statement starting with N****. Any data lines not starting with this, were ignored. The program would then read the next set of characters and interrogate them to see if they started with the letter 'G' or 'M'. If the letter 'G' or 'M' was located, it would signify the type of machining statement and the program would jump to an appropriate section for interpretation and analysis. If no 'G' or 'M' letter was present, then the last 'G' or 'M' statement read, would continue to be active until it was overwritten in a later data line by another statement.

After looking for the letter 'G' or 'M', the program would continue to read the subsequent set of characters in the data line for further interrogation. The program logic recognised the line format for each type of statement and the order in which the subsequent types of functional data would be presented, if present in the line. If a data value did not change, then in order to save memory space, the data value was not output on the NC program, but the data value was stored and remained active until overwritten. The program would interrogate each data section in sequential order to see if the next logical data function was present. Having found a logical data function, the program would interrogate that section for a data value. The number of decimal places, if any, could vary. Once the data section was analysed for function and value, the next data section contained in the line would be sought.

Only when the entire data line had been fully interrogated, interpreted and analysed, did the program progress to the graphics generation sub-routine. The tool centre line movement would then appear on the screen; machining values and any notes of interest to the operator, typically speeds and feeds, would be printed on the screen.

On the DZ4, the co-ordinate values output on the NC program are relative to a set of local co-ordinates which themselves are relative to the machine tool datum. Every part of every toopath is relative to some local set of co-ordinates and so to calculate the true position, the local set of co-ordinates' datum offset, must be added to the local position. This was done in the graphics sub-routine, so any errors in the datum offsets or resets would be displayed.

Using CVMac to generate toolpaths presented a number of problems. For example, circular tool movements of the 'G02', 'G03' type, can only be produced on the X Y plane of the co-ordinate system, such that all Z-values were zero. For the purpose of the true simulation of the program, this co-ordinate system was fixed at the machine datum position, however the actual circular tool movements usually had Z-values which were not zero, and hence they could not be produced. To overcome this problem, circular tool movements were broken up into a series of finite linear movements Fig (57), resulting in a faceted arc. The angle subtended by any one facet was a maximum of 9 degress. When viewing on the screen, this was barely noticeable.

Another problem encountered was that there was a limit of only 43 individual movements allowed by CVMac when generating a toolpath. To avoid this problem, a piece of code was written in the program which would generate 43 tool movements, stop the toolpath generation, then start the new toolpath of 43 movements. The first and second toolpaths would then be LINKED into one longer toolpath. The program would then go on generating 43 tool movements and would then link the new toolpath to the previous longer linked toolpath. This would be repeated until the toolpath was finally completed and the tool returned to the home position. This form of construction was invisible to the operator.

As CVMac was relatively new, the people employed at the Computervision software support centre had little experience in the application of CVMac for NC generation purposes, furthermore the NC application engineers at Computervision were unfamiliar with the facilities available in CVMac. Consequently the software support of CVMac for NC generation was very limited and nearly all the solutions to the problems encountered using CVMac were solved on site by the present author.

The only major problem with the program in operation was the speed at which rotations were performed by the system. To manipulate the layers and then to rotate a complex 3-D model, consisting of the two mounted CAD generated components, plus fixture and clamps was too long (typically 4-5 minutes). This time delay for each rotation was unacceptable to the programmers, who wanted a quick verification tool to identify any serious errors.

Re-writing the computer code of the simulation program to increase its processing speed would not have any significant effect, as the problem was not in the calculation or NC toolpath generating part of the process, but in the manipulation and display of a large number of graphical entities which were external to the program. The existing CADCAM system processor was just not powerful enough to perform these functions.

The only way to solve this problem and reduce this time to an acceptable level, would be to use a work station with its own powerful processing unit. These had just become generally available for design offices at about the time this development project was completed (Mid 1987).

Just before the end of the project, the program was demonstrated to simulate an actual job. During this test, it correctly located the errors in the CAM generated NC program before the component had been loaded onto the machine tool. Figs (54) (55) (56) show an actual rotation/collision situation which was correctly predicted.

The simulation program, did however only offer visual verification to identify gross errors. The more time consuming process of fine tuning the NC program to achieve the desired tolerances and surface finishes, is still to be pursued. However, the existing program does act as a coarse sieve, detecting the major errors such as collisions which can result in expensive impact damage. The simulation program therefore improves the integrity of the NC data files, leading to reduced tape prove out time, thus it offers the potential for improved machine utilisation.

The DZ4 post processor could be visually verified ´off-line´ using the simulation program, by post processing CL files which were known to be correct, and displaying them on the CAD terminal. In a test, the program proved successful in simulating the machining of a complex double-curved 3-D surface which was similar in form to a cycle Mudguard. In doing so, it also identified errors in the post processor when using the ´circular interpolation' option. It also proved that the problem could be solved by using the 'linear interpolation' option in the post processor, that is faceting the surface, whilst remaining within the tolerance band entered by the operator.

The ability to fully display all the machining operations, on the CADCAM system, and identify any potential collision situations or data input errors, allows mistakes to be corrected 'off-line', naturally leading to increased confidence and reliability of the NC data file, this in turn leads to a reduction of tape prove out time and hence greater machine tool utilisation. Therefore the program met all its objectives. However, as stated previously, to run the program in a practical and commercial environment required the use of a powerful workstation, but due to financial restraints imposed on all sections at that time, one could not be purchased and so the program was not used or developed further.

The program did have many areas which could be further developed to benefit the company, most of which were initially not envisaged. These areas of potential development are outlined below.

Instead of the user adding a 'sacred' circle to fully enclose the rotation assembly, the user could add a 'sacred' template about the axis of rotation of the table. This template could consist of a number of entities and could therefore take into account the variation in radial clearance with vertical height. This refinement would more accurately reflect the actual situation and so reduce the number of false 'error-possible' collision statements. The operator would still need to exercise his judgement on collision situations, but would be called to do so on fewer occassions.

At the time at which the project ended (mid 87), a Makino MC65 4-axis machining centre similar to the DZ4 was on order. The simulation program could readily be adapted to suit the slightly different NC data format required by the new machine tool controller. Thus similar 4-axis machining centres could also be simulated 'off-line'.

If an extra rotating table were to be fitted to the DZ4 to make it a 5 axis machining centre, the program could be easily adapated to simulate this extra axis.

A simulation program of this type can also be used as an inexpensive way to train NC programmers to use the Deckel or similar machines. Additionally, as all the movements of the toolpaths, speed, feeds and dwell times are known, the program could be used to calculate accurate machine cycle times for components.

8.7 SUMMARY OF THE CAM SYSTEM AND THE SIMULATION PROGRAM.

In the past, component parts were often programmed on the CAD system, using 2-D CAD representational views, but were now programmed using isometric views of 3-D CAD generated minimum models (Chapter 5). The effective use of 3-D minimum models for CAM, necessitated the embodiment of 3 simple, but important guidlines in the CAD model, at the design stage (section 8.3). These guidlines were subsequently incorporated into the training exercises (section 6.2.1.)

A major advantage of using 3-D models over 2-D representation is the improvement in the visual verification facility, as the cutting depth of the tool (Z axis) is now displayed. This improved visualisation leads to improved integrity and confidence in the NC program. In addition, complex surfaces, compound drill holes and other non-orthographic features can be more readily programmed.

After the introduction if 3-D models, there was an increasing awareness amongst the managers, that the system was not fulfilling its potential. Consequently in late 1986, an investigation into the apparent under achievement and underutilisation of the CAM system was initiated. This investigation found that there were two main reasons for this being the case.

Firstly the CAM software, NC Vision was a general purpose tool, covering many areas of machining, ranging from 2-D turning to 5 axis milling. This large and complex package was menu driven, consequently the programmers found it cumbersome and inefficient to use on the simpler, more regular geometries, preferring instead to program these manually. However, the NC Vision package was found to be the most effective way to program the complex components manufactured by the company. These products were usually machined on the Deckel DZ4 machining centres and they were often the longest lead time and highest added value components within a fuel control system.

However, when machining the most complex parts, a number of important limitations within the NC Vision software were identified.Many areas of the NC program could not be visually verified on the CAM system and could only be checked on the shop floor during tape prove out. These ´blind spots´ included ´Canned´ cycles, ´Jump´ statements, table rotations and movements between the end and start of consecutive toolpaths.

Thus the complex components which were most suited to being programmed using the CAM system and which were usually machined on the DZ4, were found to need the verification facility most and yet it was the simulation of the machining process for these components which highlighted some important weaknesses of the CAM systems verification facility.

The support by Computervision of NC Vision and of the NC generation section of CVMac was also found to be disappointing.

Due to the general nature of the NC Vision package and the fact that it was found to be inflexible in many operational modes, it soon became obvious that to make the CAM system work more effectively, required a considerable amount of customising work to be done. Prior to the DZ4 project, very little CAM development work had been performed, consequently as no specific application programs were written to enhance the NC Vision software, it was underutilised, with valuable business opportunities being missed. This underdevelopment was the second main reason why the CAM system was underachieving. This underdevelopment of the system was due to a general lack of awareness amongst the managers of the need to support and develop the CAM system. Consequently, the main recommendation of the investigation, was that a meaninful programme of CAM development be initiated.

An area of CAM development which would most benefit the company was identified. A project to completely simulate the machining actions of the DZ4 machining centres was defined. This would overcome the shortcomings of the NC Vision visual verification facility, resulting in improved integrity of NC programs and reduced tape prove out times. The methodology employed by this author, to perform this task, required a full 3-D Deckel DZ4 simulation program to be written for use on the existing CADCAM system.

This development program allowed all the machining actions and movements including the 'blind' spots to be fully displayed and visually verified. Areas of the NC program where potential collisions, especially during rotation of the table, might occur, were identified and warnings issued complete with details of the exact position in the NC program with which they were associated.

Whilst the program met its objectives, it was slow at manipulating and rotating the complex parts and fixture assembly (typically between 4 and 5 minutes) and so it was found to be impractical for daily use, although the general technology had been proved. Consequently, the program was not used by the programmers and was not developed further, although many other useful further developments of the program were identified.

However, the problem regarding excessive graphics manipulation time, could have been significantly reduced to acceptable levels with the purchase of a powerful colour workstation similar to the ones which had just been released at that time. If this were done, then the simulation program would be beneficial to the programmers in locating serious errors, leading to reduced prove out time, greater programming confidence and increased DZ4 machine utilisation.

CHAPTER 9

REVIEW, DISCUSSION AND CONCLUSIONS

REVIEW, DISCUSSION AND CONCLUSIONS

9.1 REVIEW AND DISCUSSION

In recent years, the commercial environment in which most companies operate has become increasingly harsh. In order to survive, companies must constantly strive to remain competitive and meet the requirements of their customers, who demand shorter lead times, better quality, improved responsiveness to special products and lower costs. Both the government and industry believe that the key to remaining competitive and to meeting the customer's demands, lies with the rigourous application of Advanced Manufacturing Technology (AMT). The various fields of technology within AMT, can be applied individually to solve many problems, but when they are applied in a logical integrated manner, supplying and sharing data between functions in one unified system, the overall benefits can be multiplied many times over (Chapter 2).

The initial objective of this work was an investigation into the possible use of 3-D CAD as a practical and effective design tool for use by the Engine Systems Division of Lucas Aerospace. However, it soon became apparent that CAD should not be considered as a design productivity tool, working in an isolated environment, but as part of an integrated business productivity tool. Accordingly, the terms of reference of the project were widened to examine the effects and benefits which could accrue to the entire business.

The Design function and its role within a business were investigated (Chapter 3) and it was found to be the natural focal point of all graphics information generation. From this, the full benefits of using CAD were seen to come from its position as the initiator of information and its ability to electronically transfer graphical data to the many subsequent activities in the design-through-to-manufacture process. In order to gain the maximum effectiveness that CAD has to offer, an integrated strategy must be applied and the output must be made available to all the downstream functions who need it and for it to be presented in the most appropriate format.

The use of 3-D modelling was investigated and it was found that 3-D wireframe models with surfaces could be beneficial to the design function itself, as well as to other downstream functions (Chapter 4). This type of modelling could be performed using the existing hardware and software, although the purchase of more powerful colour workstations would be useful to increase the speed of system response and aid visual understanding (section 4.8.3).

Some of the downstream functions are now able to benefit from the use of 3-D CAD models, whilst others remain unaffected. However, some functions and facilities (Chapters 2 & 4) which are not yet connected or fully interfaced, could have their effectiveness increased with greater systems integration, thereby allowing them to access and use the 3-D CAD generated models and their associated data. Much of the potential for the integration of the system, discussed earlier (Chapter 2 and 4) will be completed or be available to exploit when the Engineering Database (CDS 5000 system) is fully implemented, althought the planned connection to the C.M.M. (Co-ordinate Measuring Machine) has been suspended until an interface between the C.M.M. controller and the CAD system is written.

During the investigation, many advantages and disadvantages of using 3-D modelling as a design tool were identified. By introducing a concept, which this author called minimum modelling (Chapter 5), the 3-D model was simplified in a controlled way in order that the design and downstream requirements of the model were still satisfied. In this process, a facility called layering was exploited (section 5.3) The work done demonstrated that, if minimum modelling and layering were extensively applied, then 3-D modelling could be used effectively as a design tool.

Having demonstrated the value of the concept, the next step in the project was the implementation of effective 3-D modelling practice in the design office (Chapter 6). This stage of the project required the author to develop training exercises and documentation, as well as to organise a training programme. The resulting self-paced on-site training programme introduced and demonstrate the concepts, techniques and commands needed to use 3-D modelling as an effective design tool. The training programme also induced the designers to consider the downstream users and their requirements from the CAD model, thereby leading to the creation of models in the most suitable format for all the users.

Experience showed that the training programme was sufficiently comprehensive, easy to use and understand, and on completion the operators found that they required little or no additional CAD training to create 3-D models and drawings of all the company's products. As the course was self paced and based on site, it had many advantages over the CAD vendor's course, in that it was an extremely cost effective way to train operators and with its inherent flexibility, it allowed the managers to schedule and organise work with far greater efficiency and ease. The programme proved to be so successful at training operators, that after its introduction, all operators were trained on site using it.

Subsequent to the completion of the training programme, the 3-D methodology embodying minimum modelling and layering techniques was successfully introduced into the design department. Since that time, all new designs at the company have been created in this way. As part of an ongoing system development process, all the modelling techniques and training exercises are constantly being monitored and updated.

It was believed that by applying a strategy of integration and by regarding CAD as the focal point of graphics generation, rather than just an isolated design tool, that some of the other fields within AMT which are able to use the CAD models, could also be developed to increase the effectiveness of the CADCAM system. As a result of this integrated approach, the scope of the project was widened to include the development of the CADCAM system for the benefit of the business as a whole.

The first major development springing from this widening of the project,was an investigation into the selection of a computational stress analysis system which could be used by the company. Various options were considered, ranging from using a Bureau service to installing a full on-site capability. From these options, one system was selected and this led to the specification, purchase and implementation of a Finite Element (FE) system for use on site (Chapter 7). All the necessary software was installed on-site, on the company's mainframe computer, which was part of the so called CDS5000 system, which had originally been purchased as the central engineering database computer.

The FE system uses the CAD model to provide the initial geometry from which to perform the subsequent finite element modelling (FEM) process using the CAD equipment. On completion of this process, the data would be transferred to the mainframe where the actual finite element analysis would be performed. After the FE analysis, the data was transferred back to the CAD terminal to allow the FE specialist to view the results and assess their significance.

The chosen FE system was a powerful and flexible one, which was capable of fulfilling the analysis requirements of the Company. The modelling and analysis processes could, if required, be performed either on site or at other remote sites which were connected to the Lucas computer network. Depending on the particular application, this networking facility allowed other types of pre and post processors and finite element analysis software packages to be used. System and application support for the specified system was already available from experienced users within the Lucas group. Training needs were identified and a suitable FE training programme was defined. The training programme, consisting of periods of theoretical training interspersed with periods of 'on the job' training with experienced users on an identical system, at an other location, proved to be very successful.

Since the FE system was installed at the Company, sucesssful 2-D and 3-D analyses have been performed on CAD generated models. However, the FE system is not yet being used to its full potential; it is only been used in a 'trouble-shooting' mode. It is not yet being used early enough in the design-through-to-manufacture process to analyse or optimise standard geometrical features and design practice for the company's products.

In Mid 1986, after the successful introduction of 3-D models, there was an increasing awareness that the CAM system was failing to perform to initial expectations and was being underutilised. This author was assigned to investigate the reasons for this underachievement. The CAM system was already integrated with the CAD system and used the CAD models to generate toolpaths. The CAM software 'NC Vision' covered many aspects of machining, ranging from 2-D turning up to complex 5 axis milling. The software package was thus large, complex and being general purpose was found to be cumbersome (Section 8.2). Consequently, it was only used on the more complex types of work which were usually machined on 4 axis Deckel DZ4 machining centres.

It was found that many of the limitations of the visual verification capabilities of NC Vision became most evident when programming the most complex components and it was these types of components which needed this facility most. It was found when simulating the cutting actions implicit in an NC program which utilised many of the facilities available on a complex machine tool such as the Deckel DZ4, that a number of areas of the NC program could not be displayed on the graphics screen. These 'blind' spots, result in only partial visual verification of the NC program and often involve areas where collisions are most likely to occur.

One of the major reasons for the underachievement of the CAM system was due to a general lack of support and development activities and consequently no specific application programs were written to enhance the NC Vision software. A recommendation was made to initialise a CAM development programme and this was started at the end of 1986.

With the move to using 3-D CAD models, new areas of the system, such as that for complete visual verification of NC programs, became available to exploit and develop. NC verification was identified as an important area for CAM development, since improvements here would lead to reduced tape prove out times, greater machine utilisation and enhanced economic performance.

Accordingly, a full 3-D simulation program of the machining actions of the DZ4 was written by this author for use on the existing CADCAM system

(Section 8.6). This represented the machining area of the Deckel using a 3-D model of the components, accurately positioned on a 3-D model of the fixture/clamp(s) assembly, located in turn on a 3-D model of a rotating table. The program fully displayed every feature of the toolpath as well as the rotation of the fixture/components/clamp(s) assembly. The program overcame many of the limitations of the existing NC Vision visual verification facility as it offered full visual verification on the CAD terminal. This allowed major errors, such as collisions, to be identified by the programmer, although the task of fine tuning the NC program to achieve the desired tolerances and surface finishes still remained.

The simulation development program achieved all its objectives, but as each rotation of the components fixture assembly took between 4 and 5 minutes, it was judged to be too slow for practical use. The only way to reduce this time span to an acceptable level, would be to install a colour workstation with its own powerful processor.

The simulation program can be easily modified to allow full verification for other similar machine tools, or be modified to simulate a 5th axis, representing the addition of another rotating table. In addition, the program could be used as an efficient and very economical aid to train NC programmers. Furthermore, as it reads and interprets every line of the NC datafile, it could generate extremely accurate machining cycle times.

The CAD, CAE and CAM projects discussed in this thesis are all interrelated in that they use the same CAD generated models on the same

CADCAM system. Throughout this work, an integrated approach was taken, so that 3-D CAD models were generated such that they required the minimum amount of time and effort to create, but were still in a format which was appropriate for use by the downstream functions. The project work was concerned with maximising the benefits of a commercially available CADCAM system to all the functions within a practical commercial enviroment.

To maximise the benefits of any field of AMT, requires the development of techniques and applications which are specific to the particular needs of the company involved. The applications and developments in the projects in this thesis are of course particular to this company and its products, but the general approaches, especially to 3-D design and integration, are applicable to many types of products and industries.

The applications and techniques which can be developed are dependant on the needs of all the functions involved in the design-through-to-manufacture process. The needs of these functions are themselves dependant on the operational and geometrical requirements of the products. Once the functions and their requirements are identified, the effectiveness of the whole business can be increased by integration. An integrated approach means producing information at the most appropriate function and in the most suitable format to fulfull the requirements of the other associated functions. With this approach, any redundant information is seen as waste, and as such, is eliminated.

9.2 CONCLUSIONS

To make the most effective use of a CADCAM system requires that an integrated approach be taken and within this CIM framework, applications and techniques are developed which are specific to the particular needs of the company. Consequently, CAD must not be looked at in isolation, as a design productivity tool, but as an essential element in an integrated business system, generating graphics and data in the most useful format for the downstream functions.

In taking an integrated approach of this kind, 3-D wireframe modelling with a surfacing facility was found to be the most effective method of representing the Company's products, both for the design and to the downstream functions. To create and manipulate these models most efficiently required the development of minimum modelling and layering techniques. This methodology was successfully introduced into the Company with the aid of a training programme which was developed as an integral part of the Teaching Company Programme. All new designs at the Company are now created in 3-D using these techniques.

A powerful and flexible FE system which is interfaced to the CAD system has been selected and installed on site. Both 2-D and 3-D stress analysis using idealised CAD models have been used with favourable results to demonstrate and correct complex modes of failure. As the system is currently only being used in a 'trouble shooting' role, it is not being used to it's full potential. It should also be used to optimise general design practice and any standard features used in the company's products.

The CAM software NC Vision, was found in operation to have a number of inherent deficiencies. However, some of these weaknesses could be overcome by customising and developing the system; writing application programs and macros etc.

To mitigate the limitations of the NC verification facility in NC Vision a program was written which fully simulates, in 3-D, all the machining actions of a 4 axis machining centre. This program would graphically display all the instructions contained in an NC data file, thereby facilitating full visual verification of the NC program. The program also succeeded in automatically identifying potential collision situations and consequently, could reduce tape prove out times. However due to the limited computer processing power then available, it was judged to be too slow to run for practical purposes.

It is therefore recommended that a powerful colour workstation be purchased to overcome this problem.

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16th CIRP International Seminar on Manufacturing Systems, Tokyo, 1984, pp. 127-136.

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Proc. Conference on Computer Aided Production Engineering, Edinburgh, April 1986, pp. 411-418.

50) HUTTON D.V. 'Computer Graphics Simualation of a C.N.C. Lathe'.

Computers in Education, Vol 9 No 2, 1985, pp. 127-134.

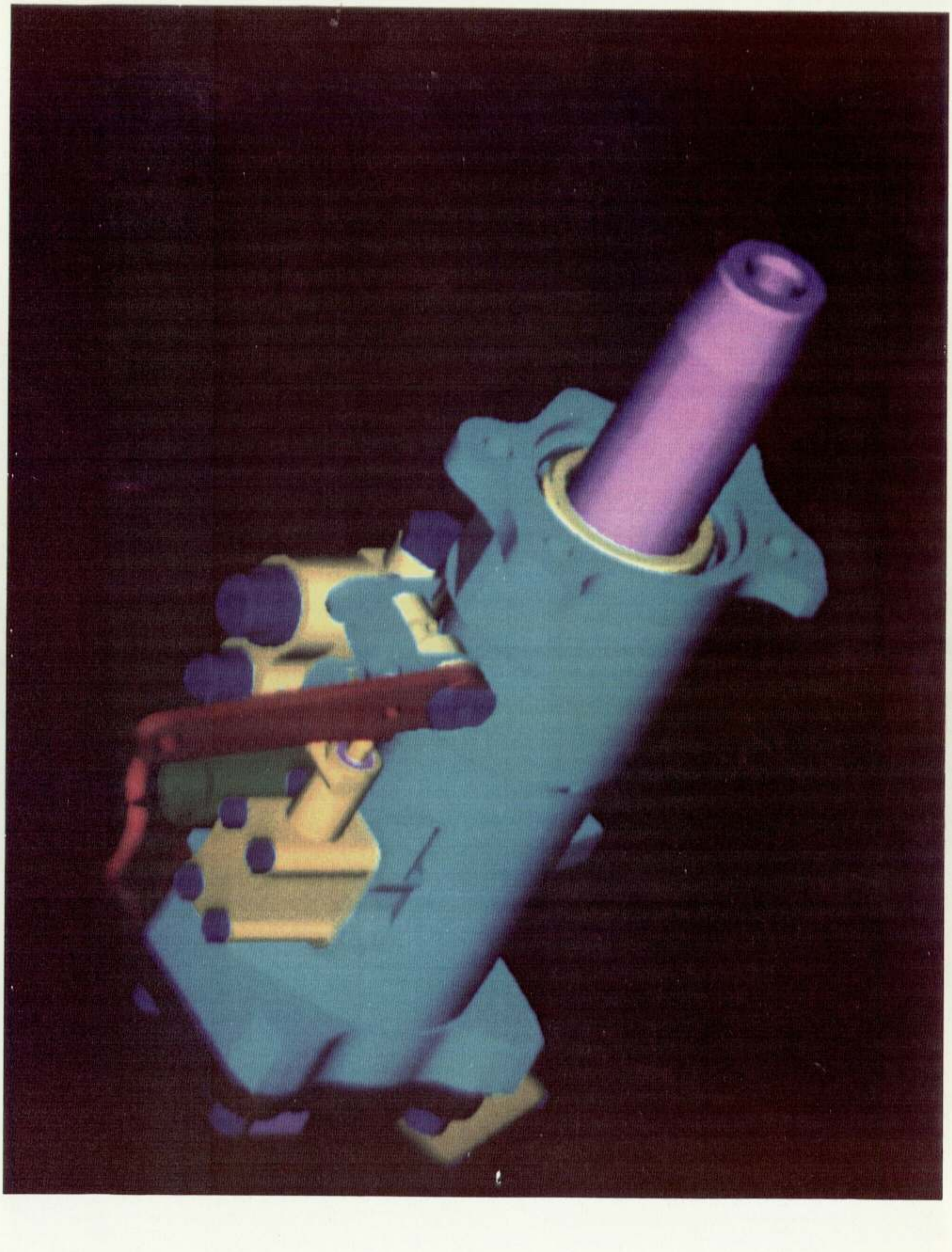


Fig (1) Image Design

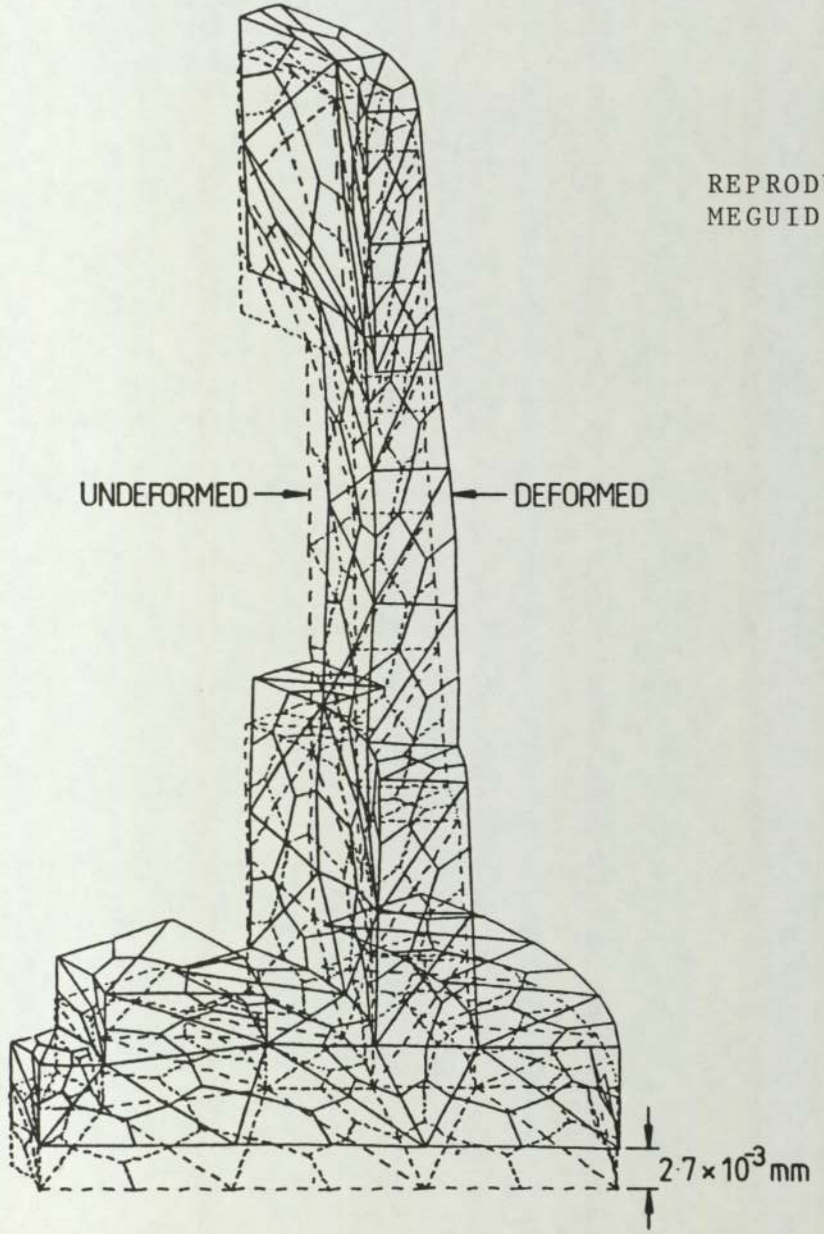


Fig (2) 3-D FEA Showing Component Deflecting

REPRODUCED FROM
MEGUID [23].

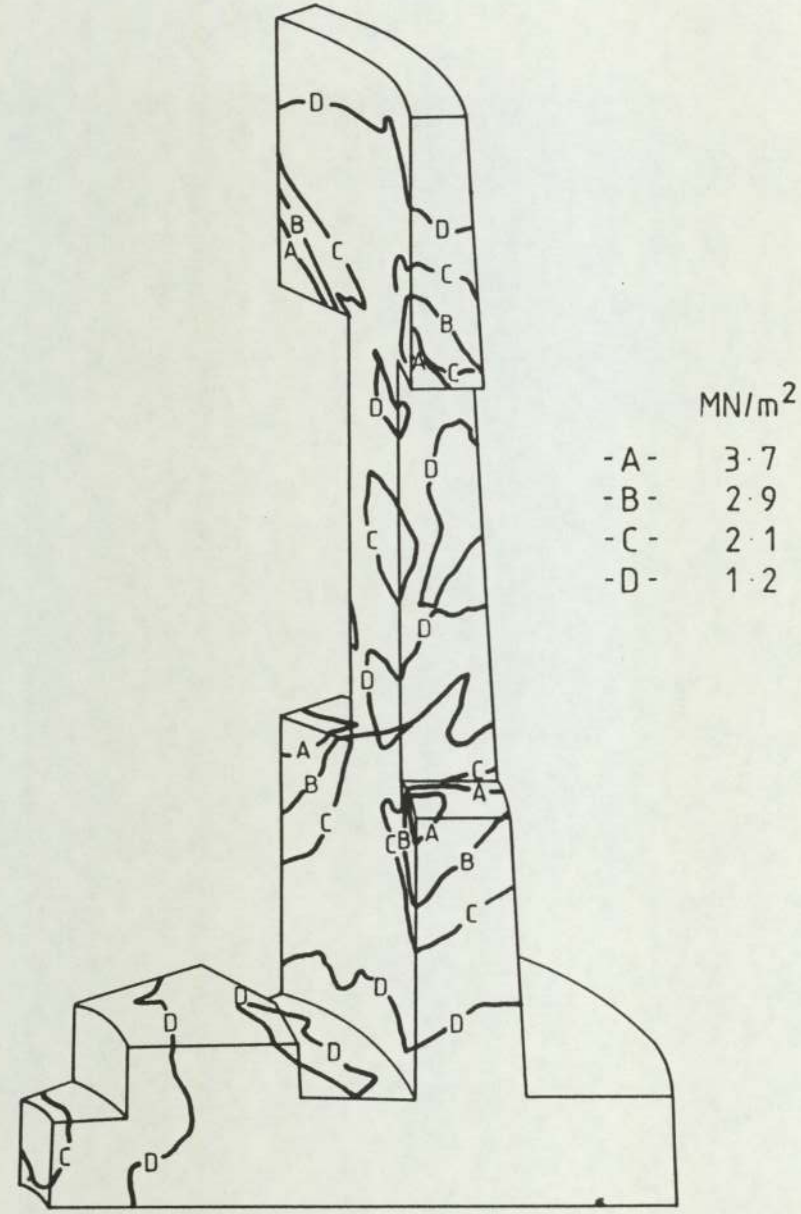
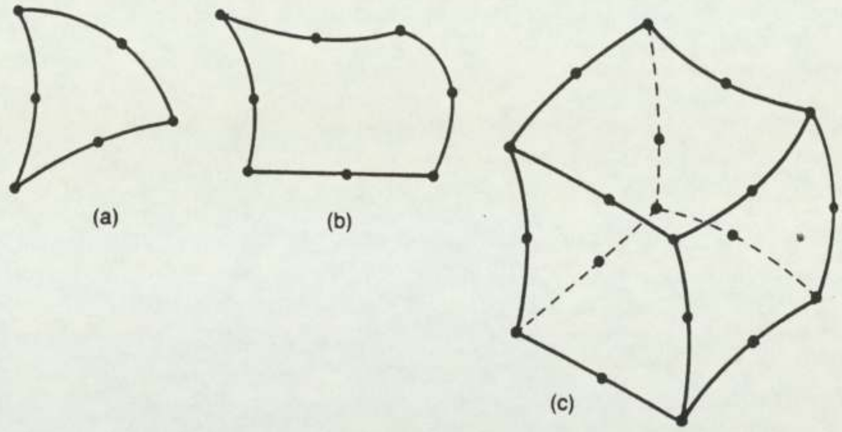
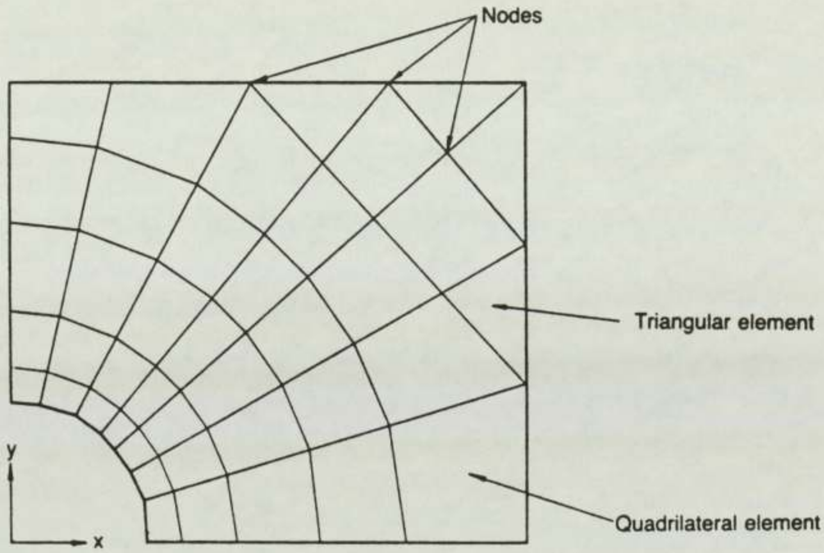


Fig (3) 3-D FEA Showing Stress Contours

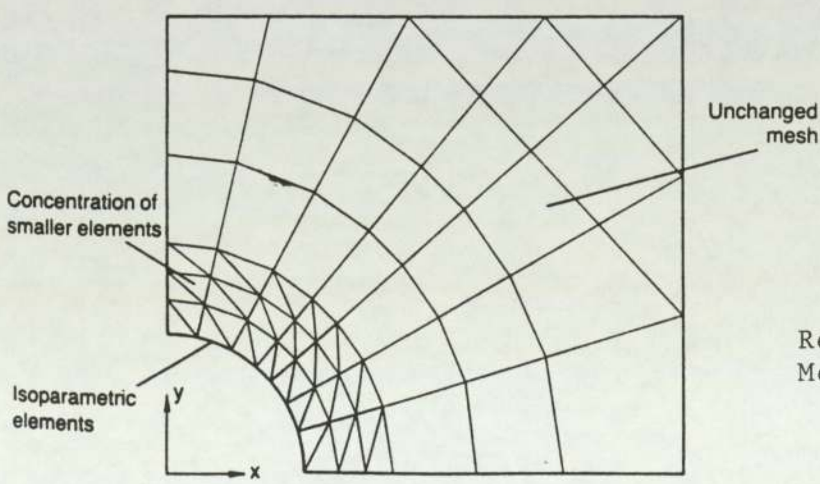


Isoparametric elements.
a = Triangular six-noded element.
b = Eight-noded curvilinear, quadrilateral element.
c = Twenty-noded three-dimensional brick element.

Fig (4) Typical Geometric Forms of FE Elements
Reproduced from Haigh [24].



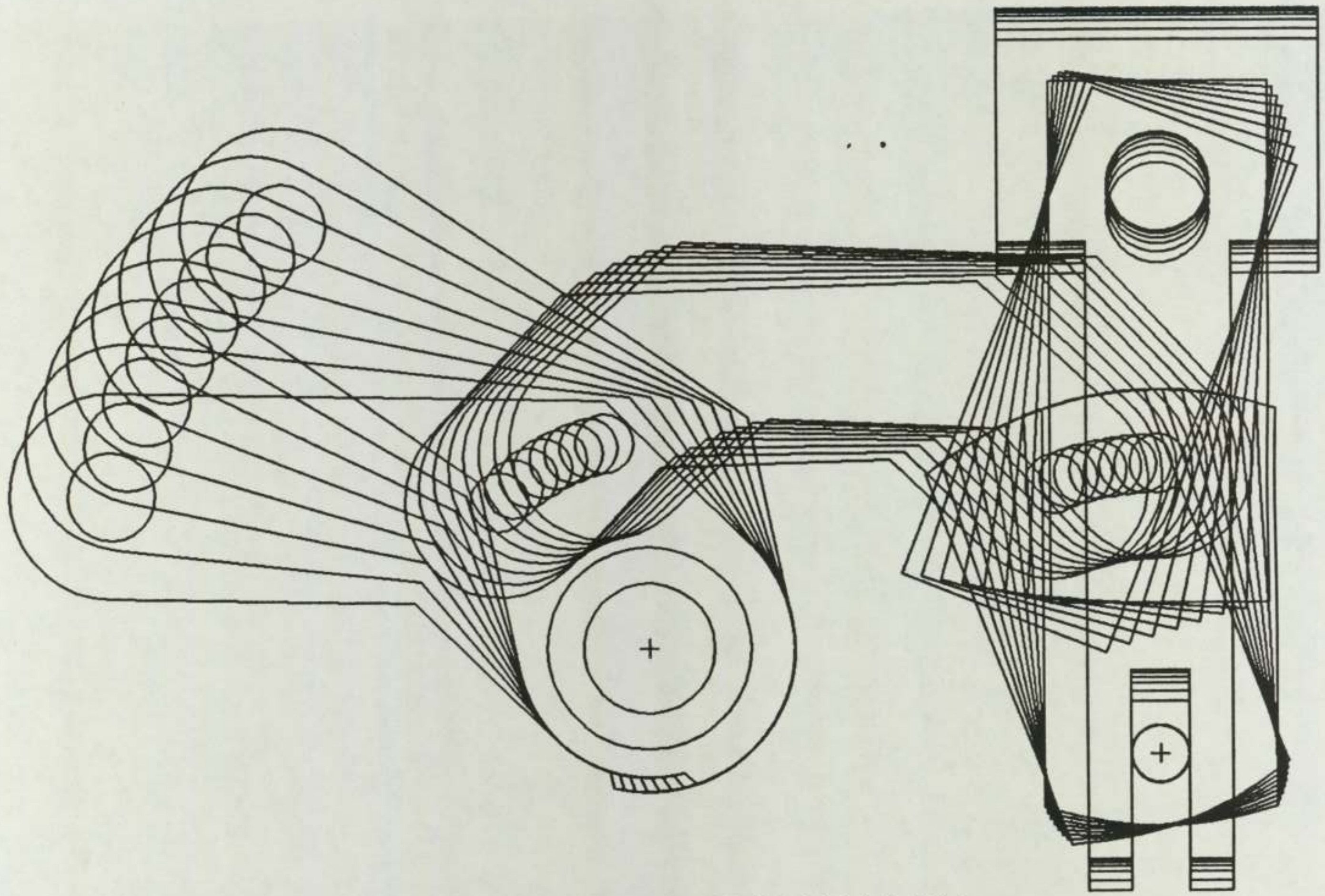
First Attempt at Discretization- Coarse Mesh



Reproduced from Meguid [23].

Refined Meshed Showing Concentration of Elements in the Region of the Hole

Fig (5) FE Mesh Concentration



ANIMATION OF LINKAGE MECHANISM

Fig (6) Linkages

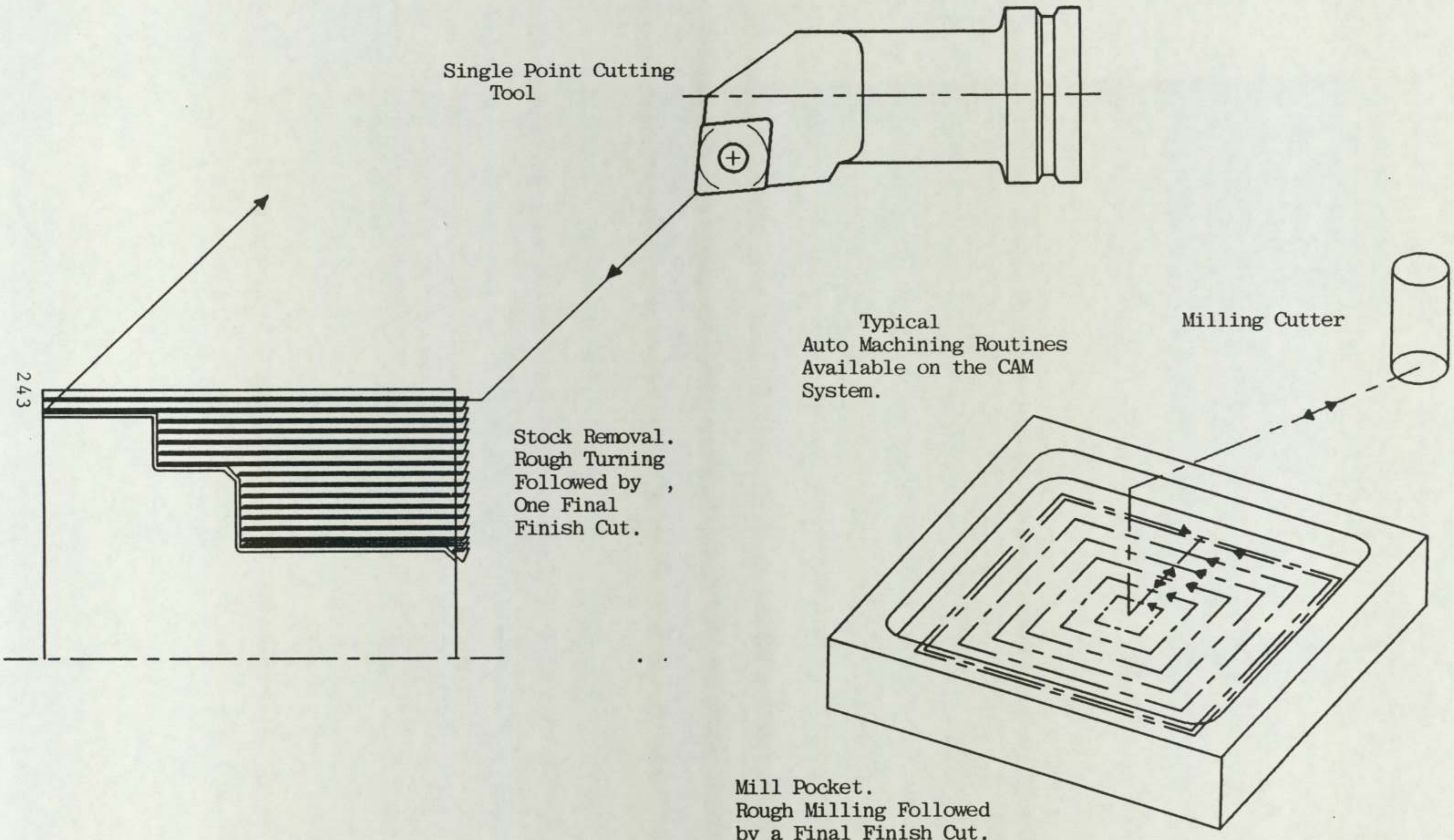


Fig (7) Auto Milling/Turning Routines

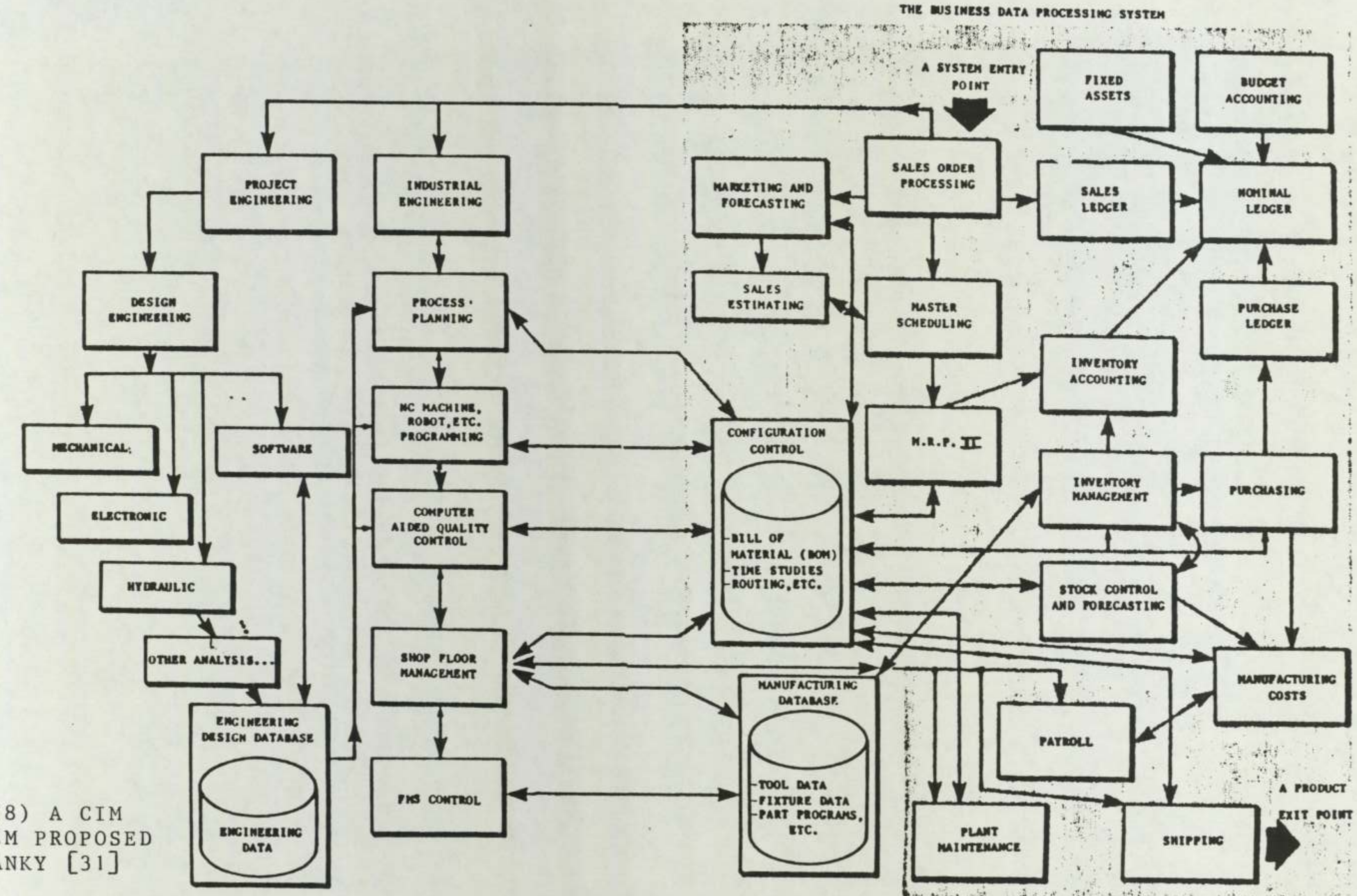
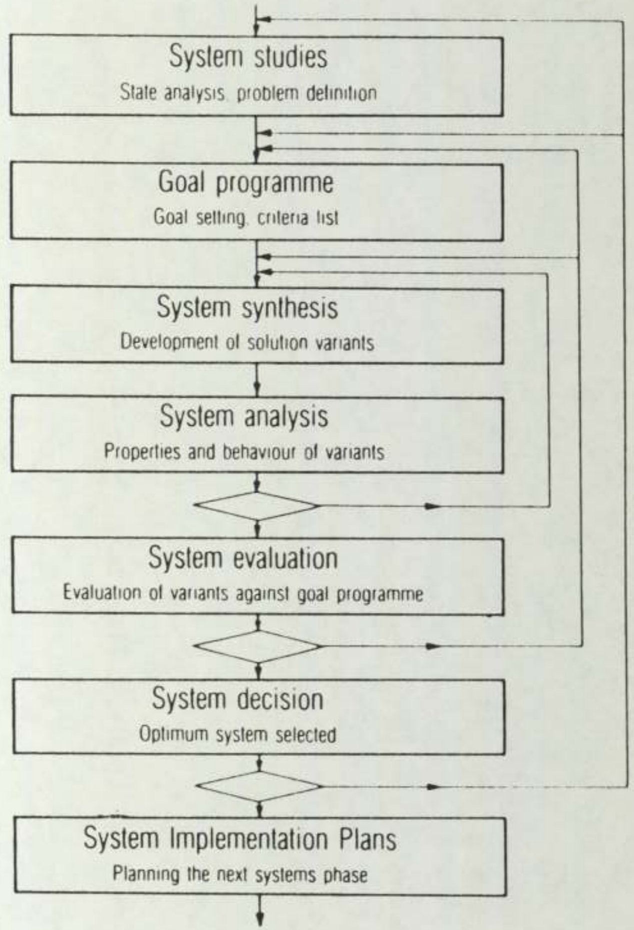
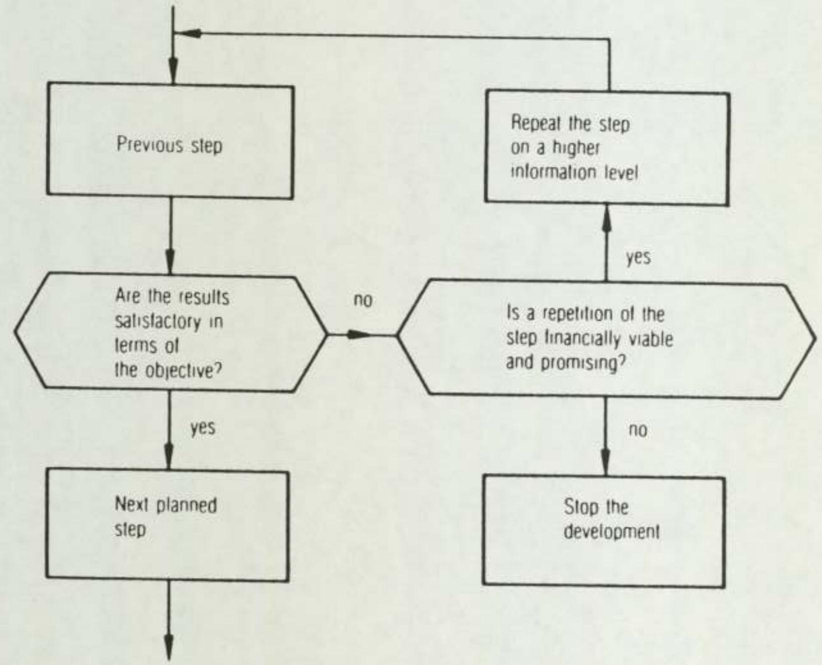


Fig (8) A CIM SYSTEM PROPOSED BY RANKY [31]

An overall CIM model integrating business data processing, Computer Aided Design (CAD), Computer Aided Manufacture (CAM) and Flexible Manufacturing Systems (FMS), incorporating machining, assembly, test and other processes.



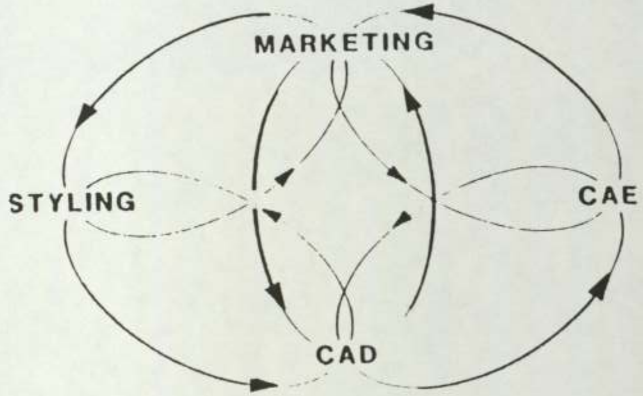
Steps of the systems approach



General decision process

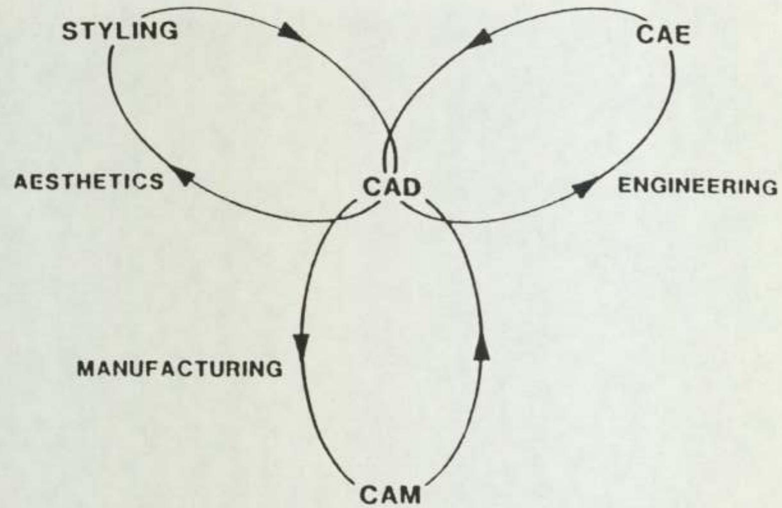
Fig (9) Design as a system

Reproduced from Pahl and Beitz [34].



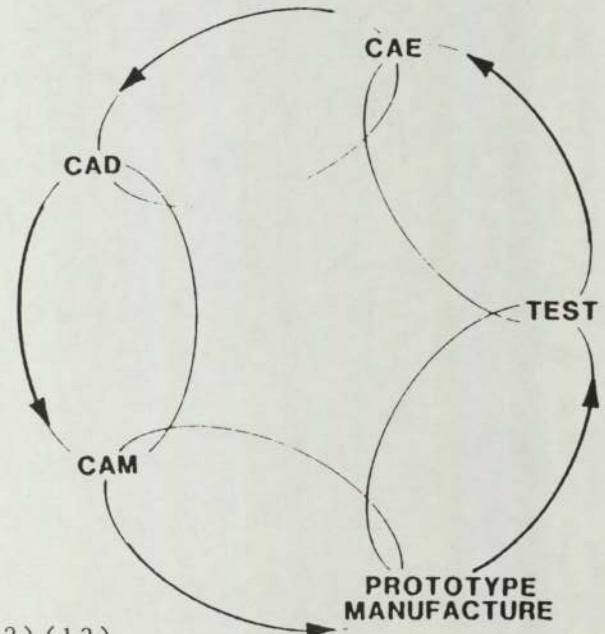
Product concept

Fig (10)



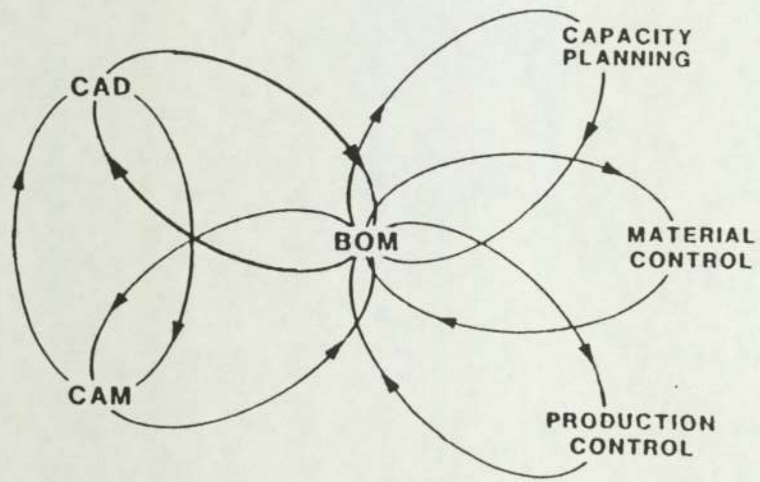
Product definition

Fig (11)



Product development loop

Fig (12)



Bill of material functional link

Fig (13)

Figs (10)(11)(12)(13) reproduced from Wilson [9].

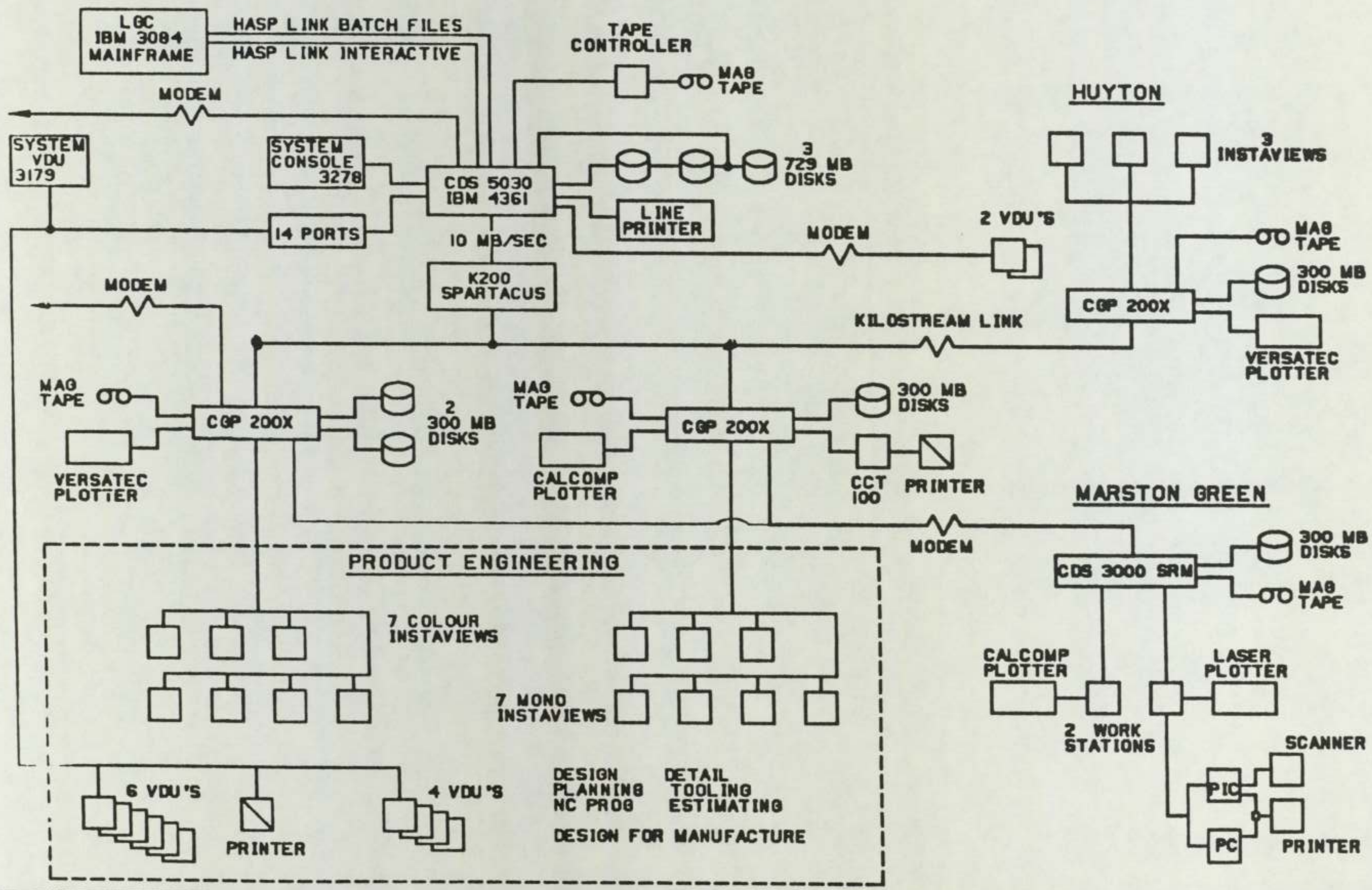


Fig (14) ESD network, CDS 5000 system

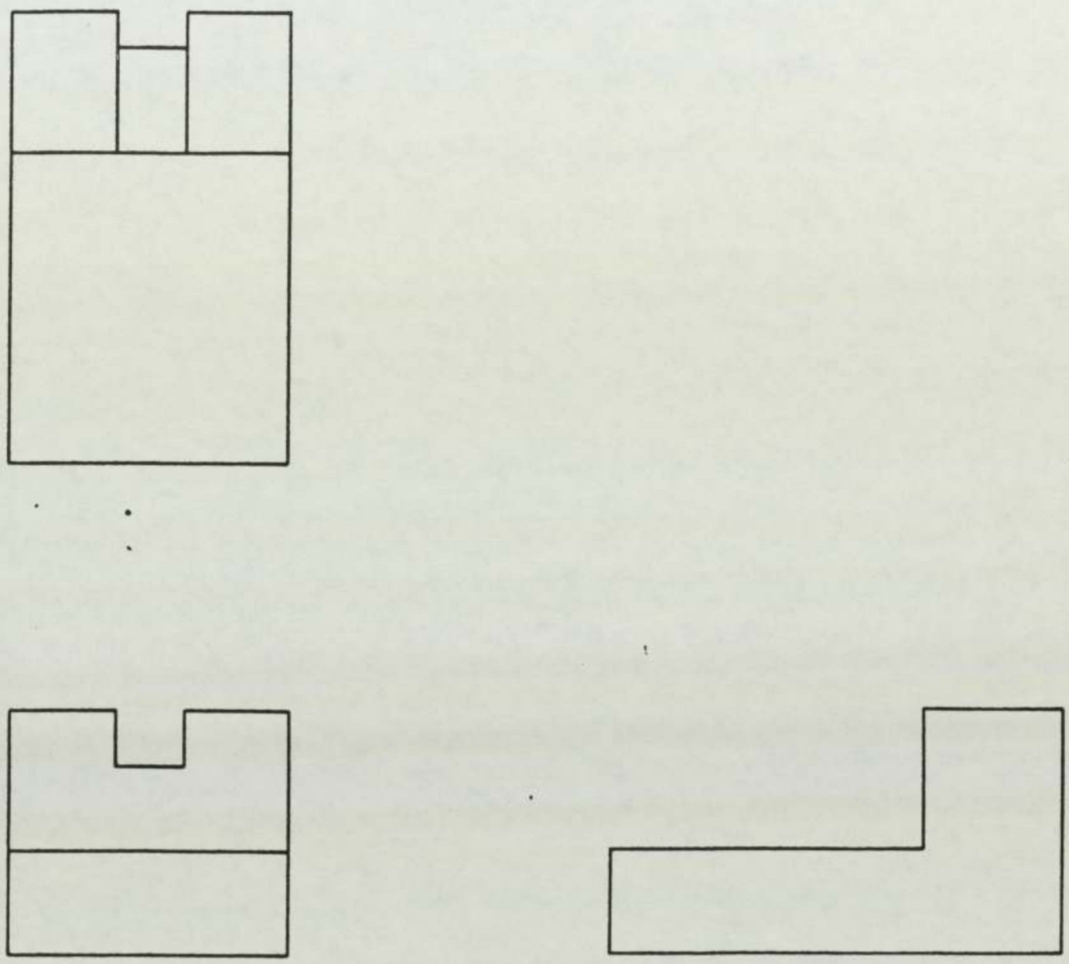
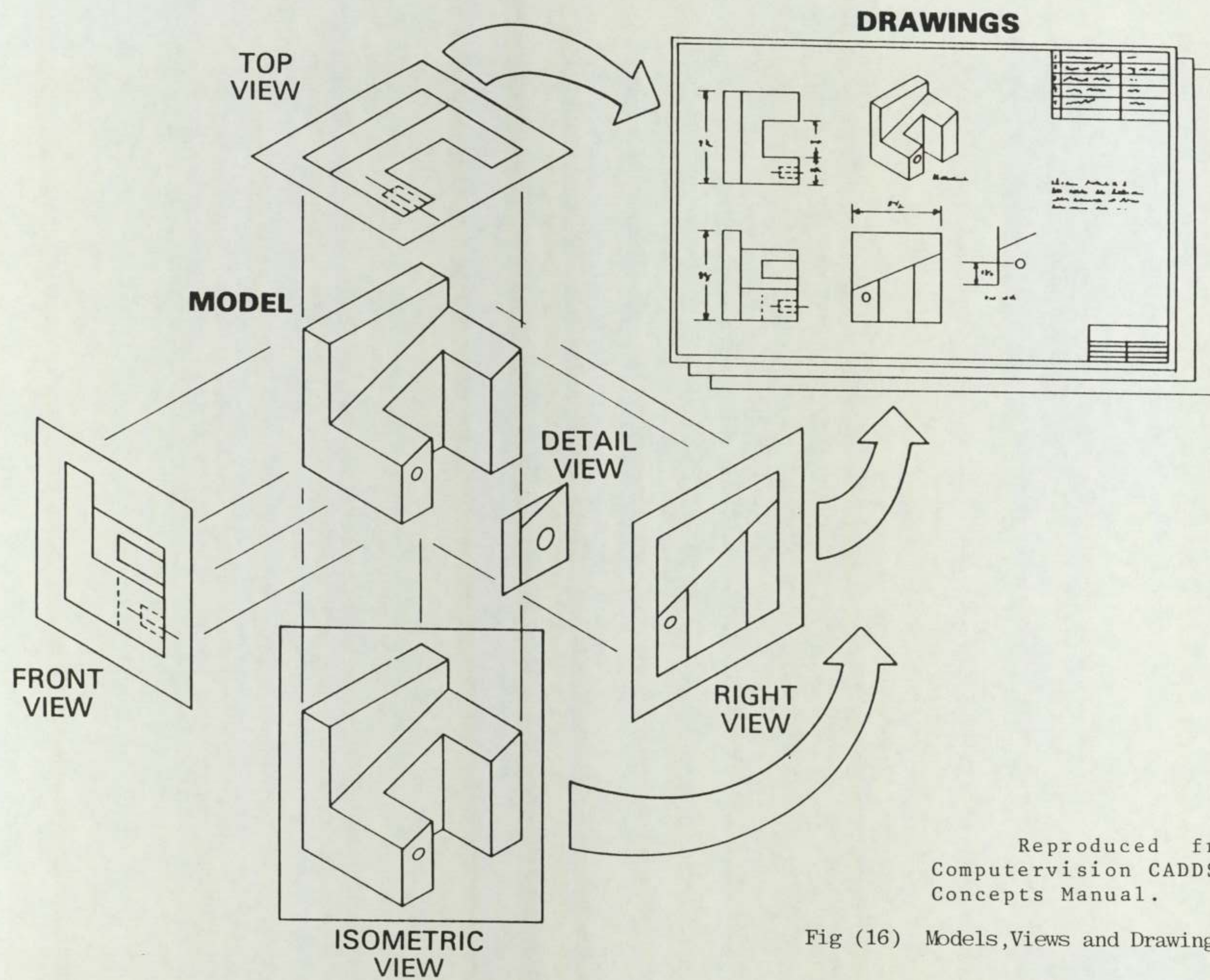


Fig (15) 2-D Draughting



Reproduced from Computervision CADDS 4X Concepts Manual.

Fig (16) Models,Views and Drawings

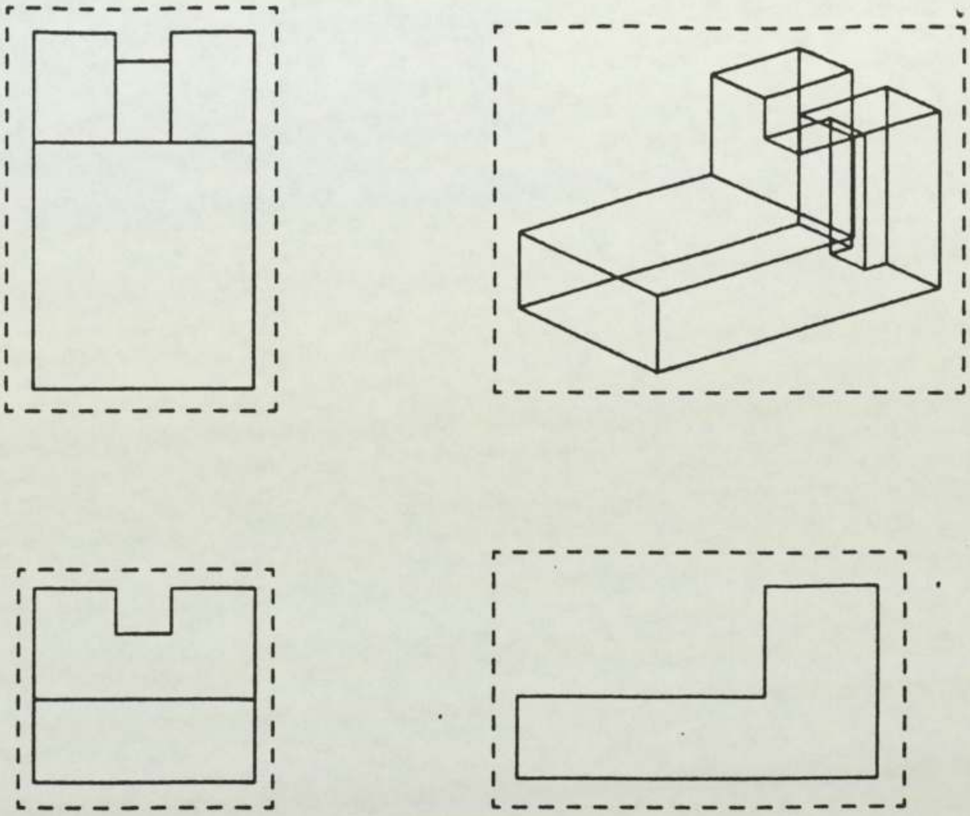


Fig (17) 3-D Model Drawing

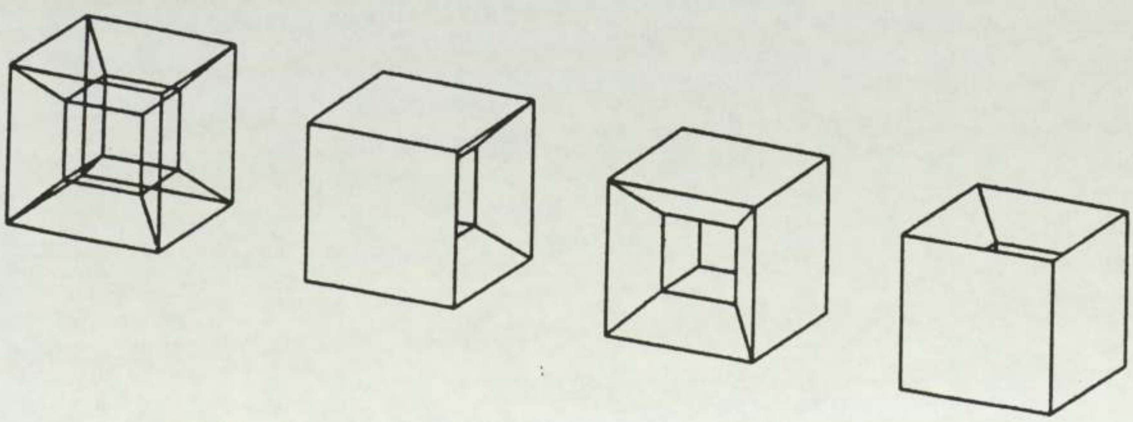


Fig (18) Wireframe Ambiguity

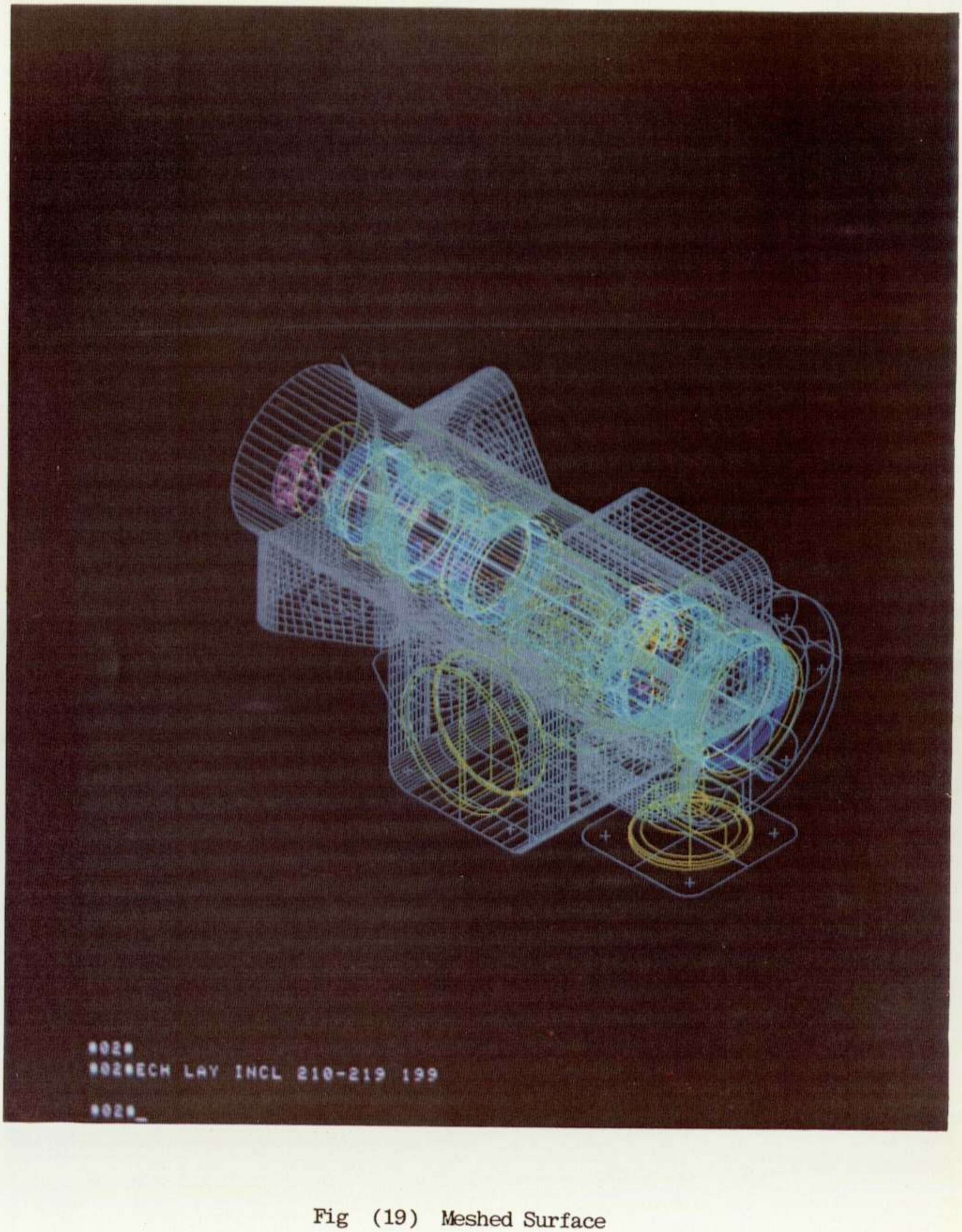


Fig (19) Meshed Surface

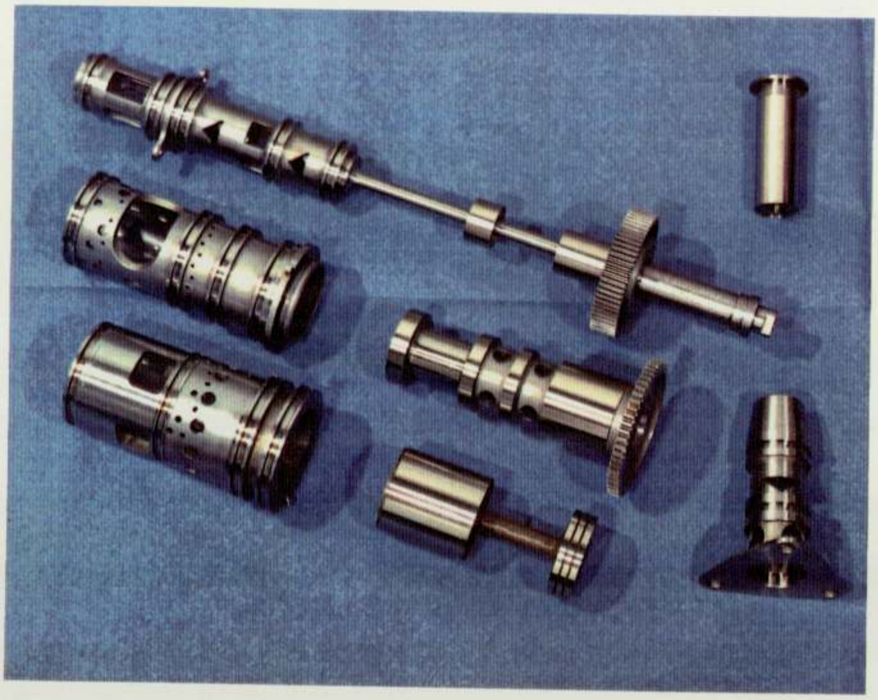


Fig (20) Turned and Turned/Milled Components

Fig (21) CAD-Shade Rough Texture

Fig (22) CAD-Shade Fine Texture

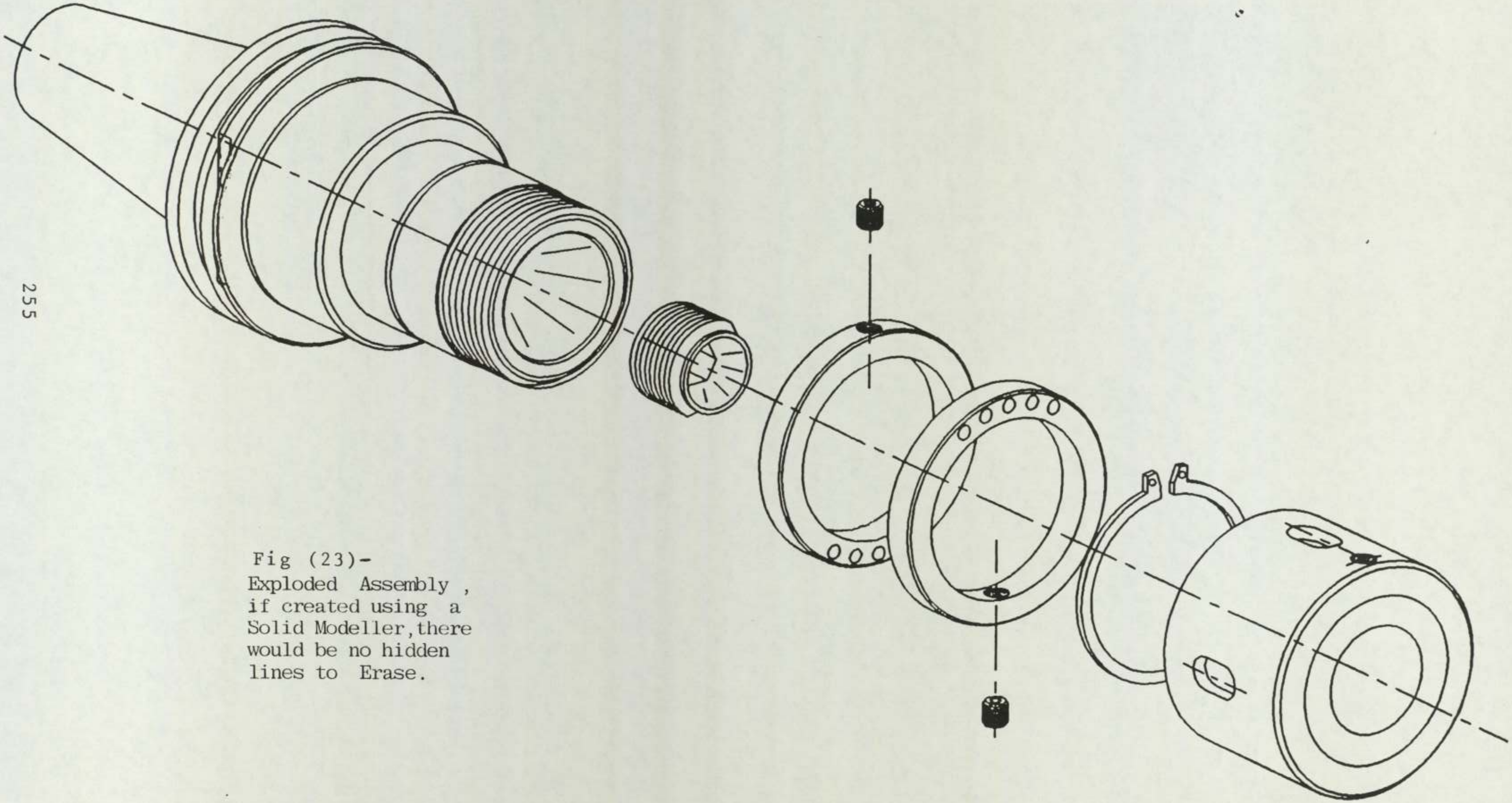


Fig (23)-
Exploded Assembly , if created using a Solid Modeller, there would be no hidden lines to Erase.

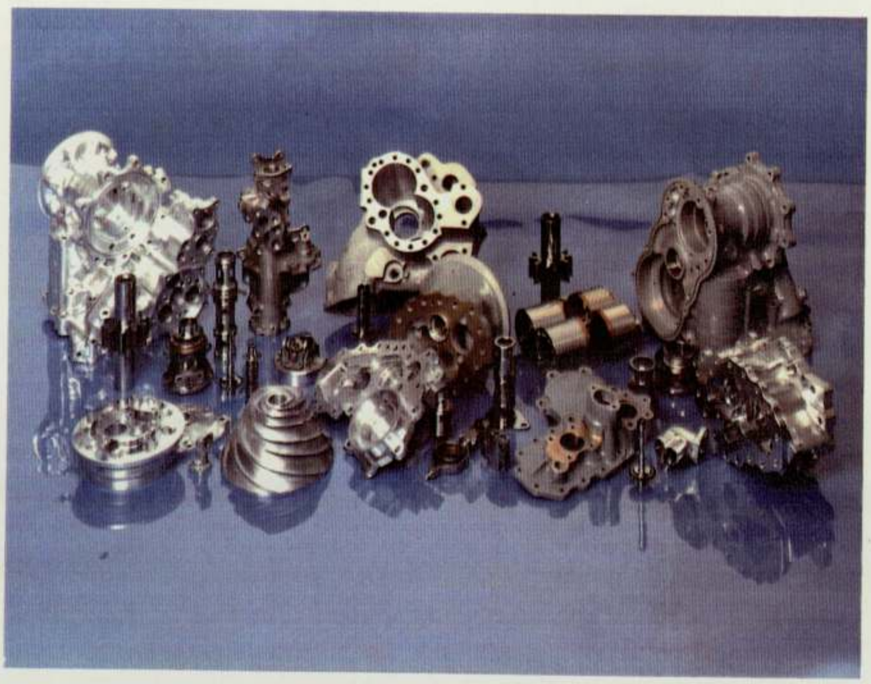


Fig (24) Typical Variations of Components

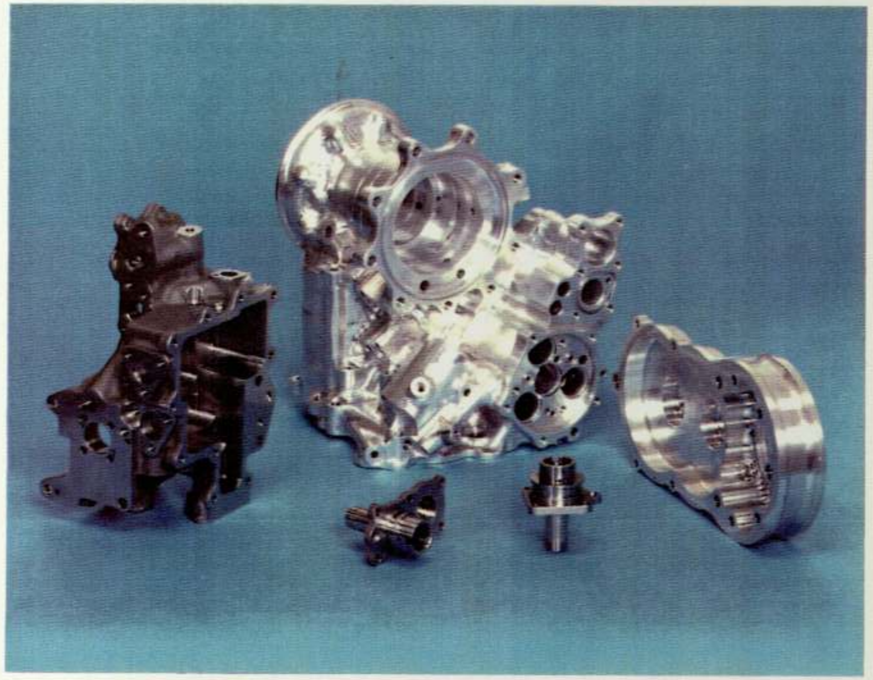


Fig (25) Milled Components

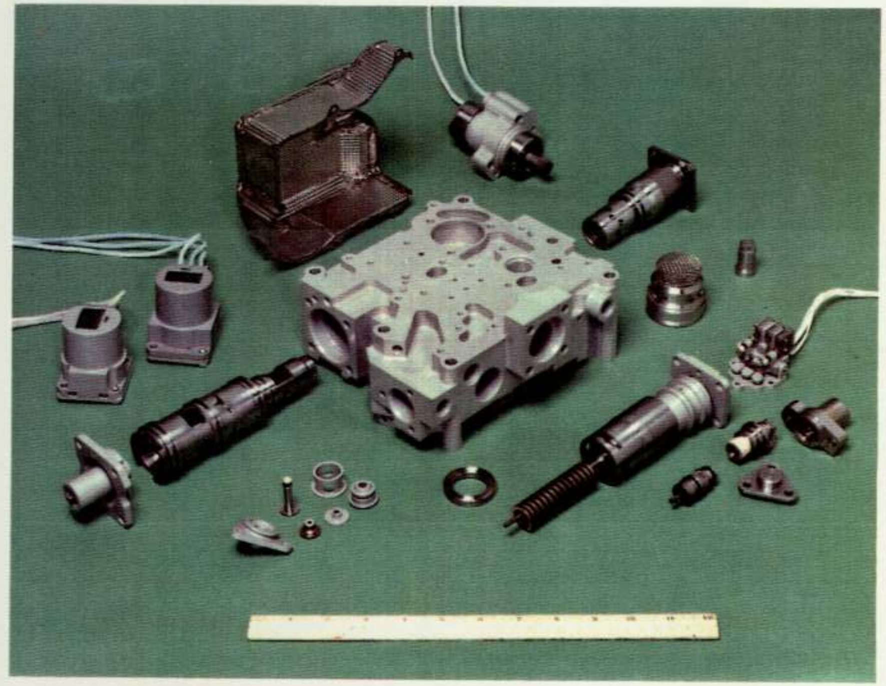


Fig (26) Part Assembly

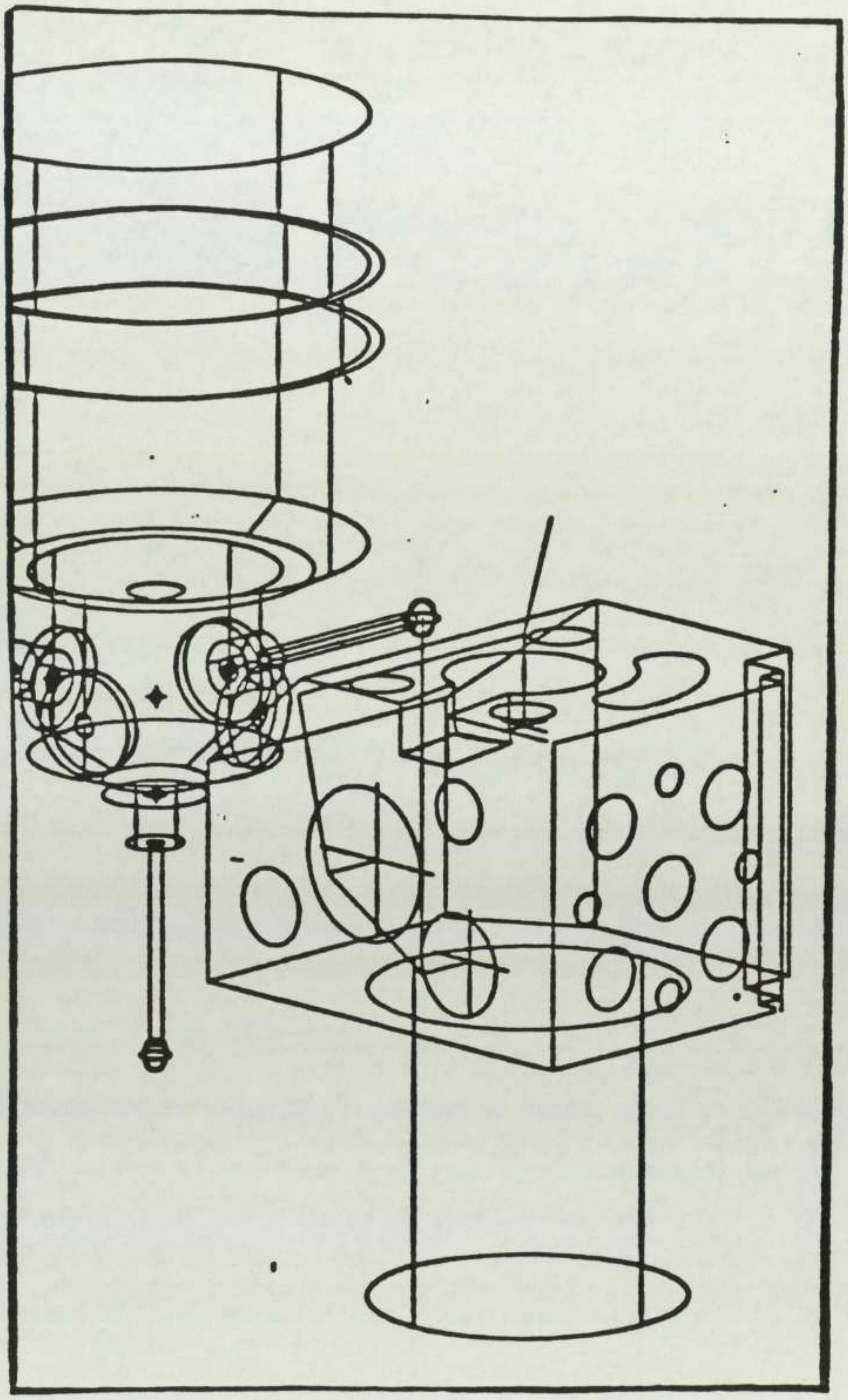
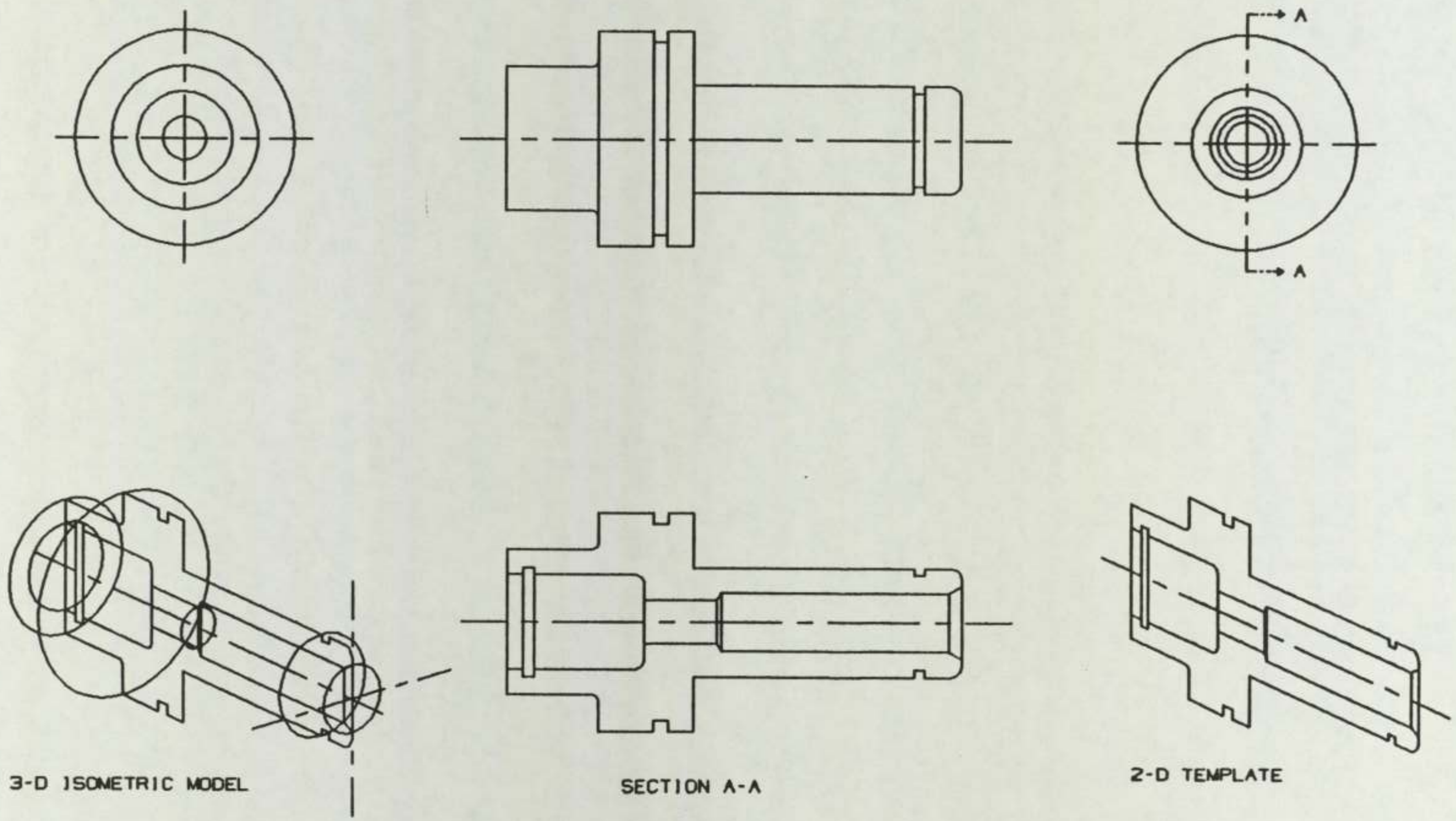
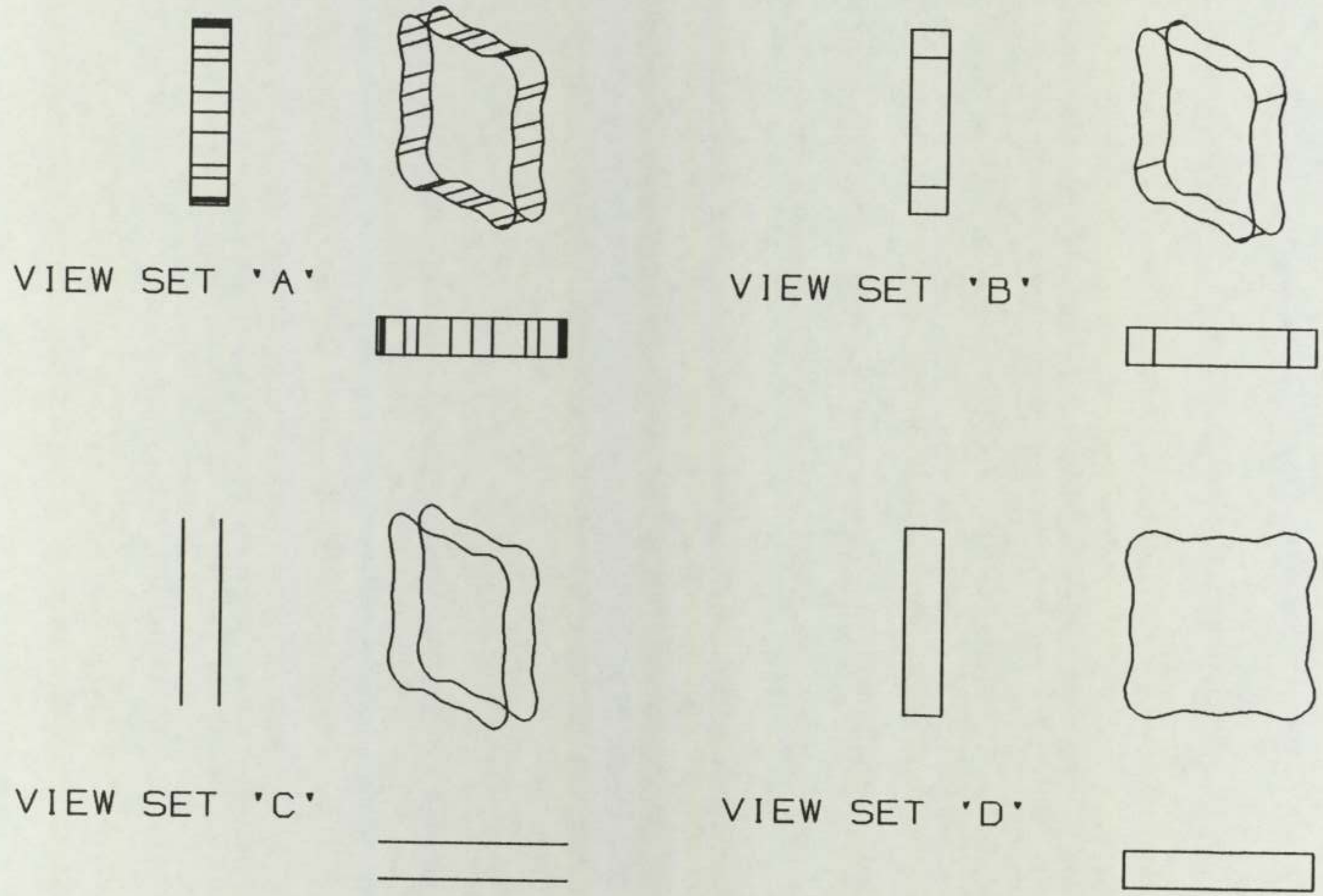


Fig (27) Auto-Measure View Probe



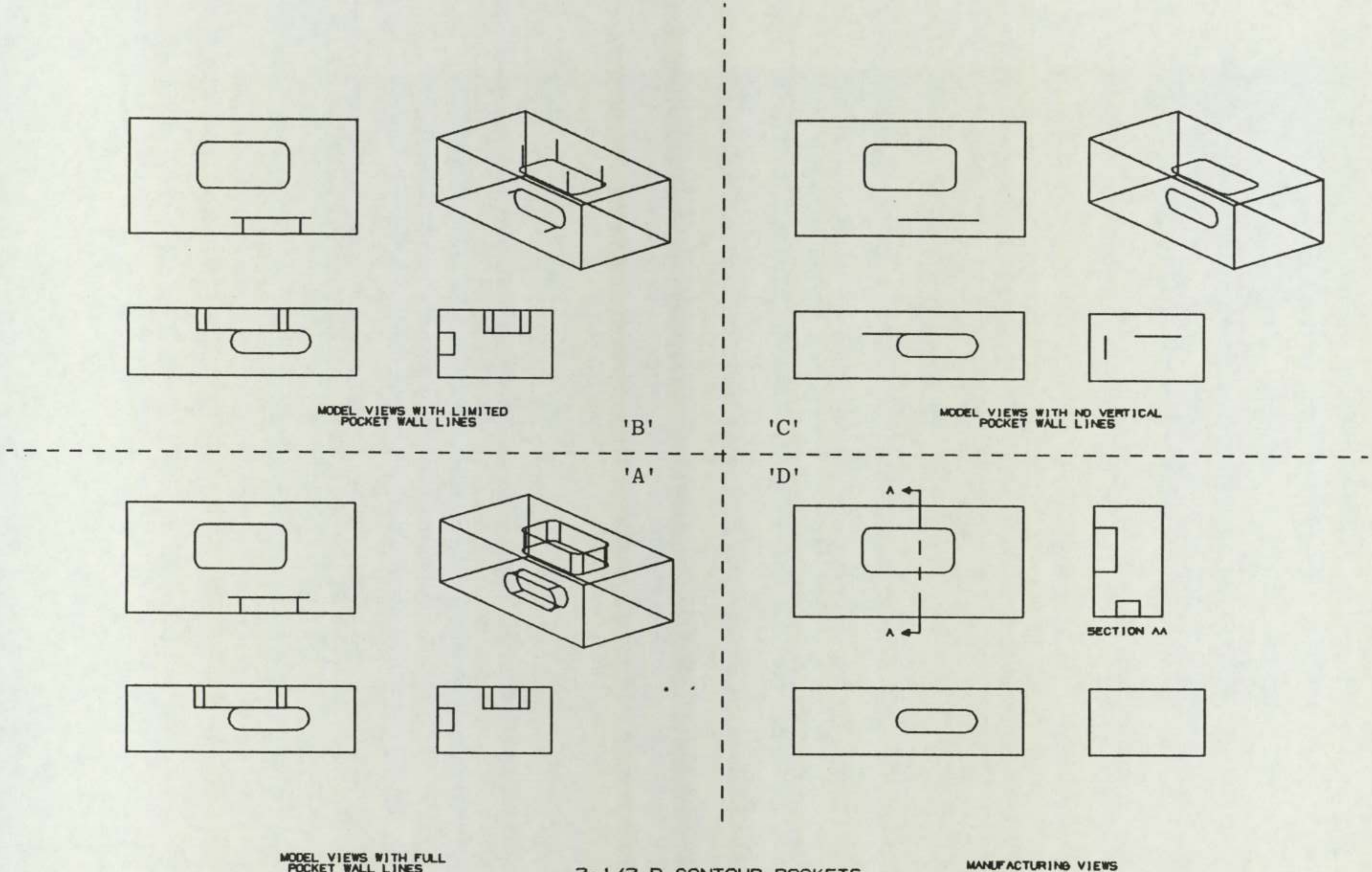
AXI-SYMETRICAL GEOMETRIES 2-D FORM
USE 2-D TEMPLATES WITH CIRCLES AT EITHER END

Fig (28)



REGULAR 2-1/2 D GEOMETRIES

Fig (29) MANY LINES CAN BE USED TO IMPLY THE FORM. USE THE MINIMUM NUMBER OF LINES AND USE THOSE LINES WHICH CAN BE USEFUL IN OTHORGRAPHIC VIEWS.



2-1/2 D CONTOUR POCKETS

Fig (30)

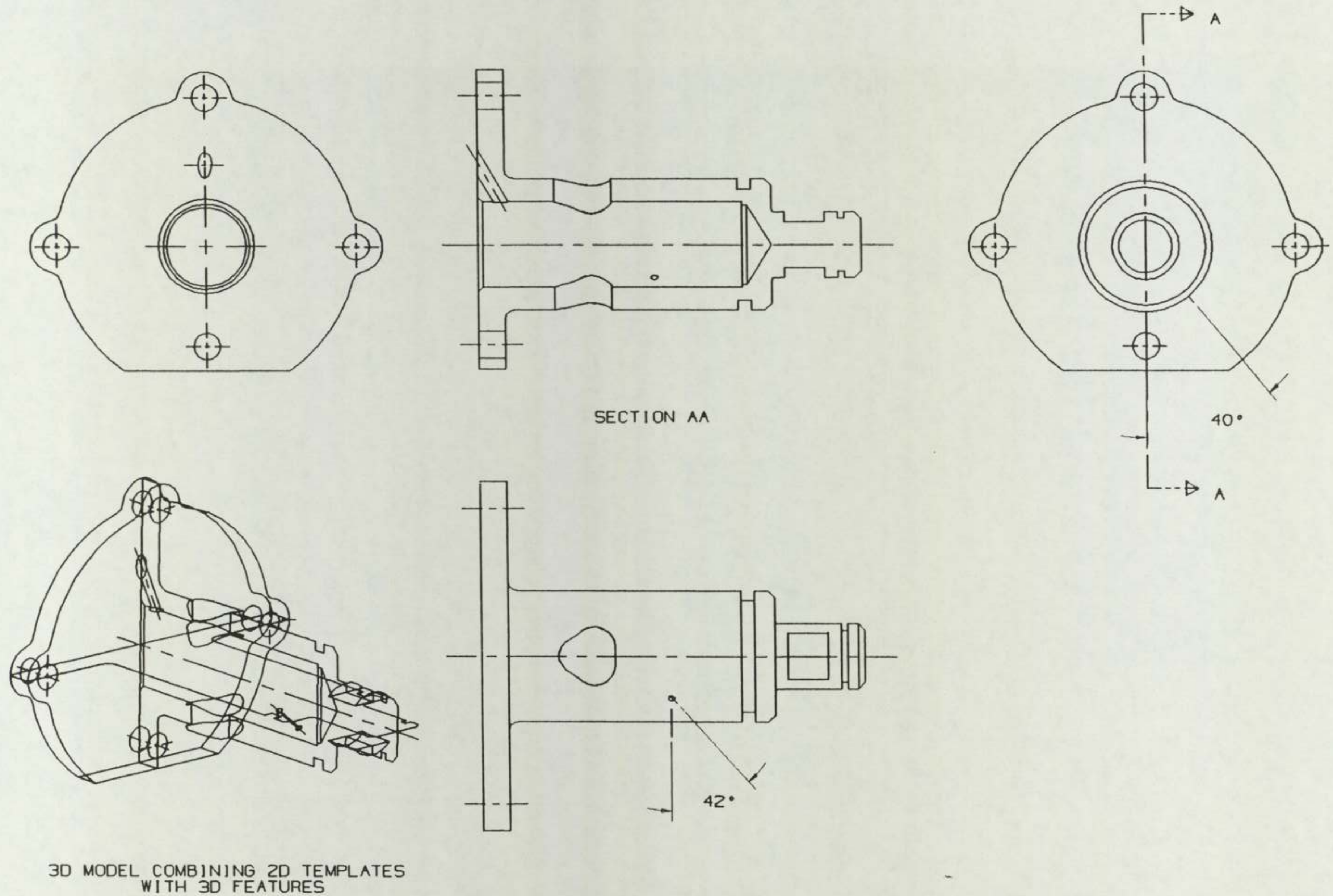

A
A
40°
SECTION AA
42°
3D MODEL COMBINING 2D TEMPLATES
WITH 3D FEATURES

Fig (31)

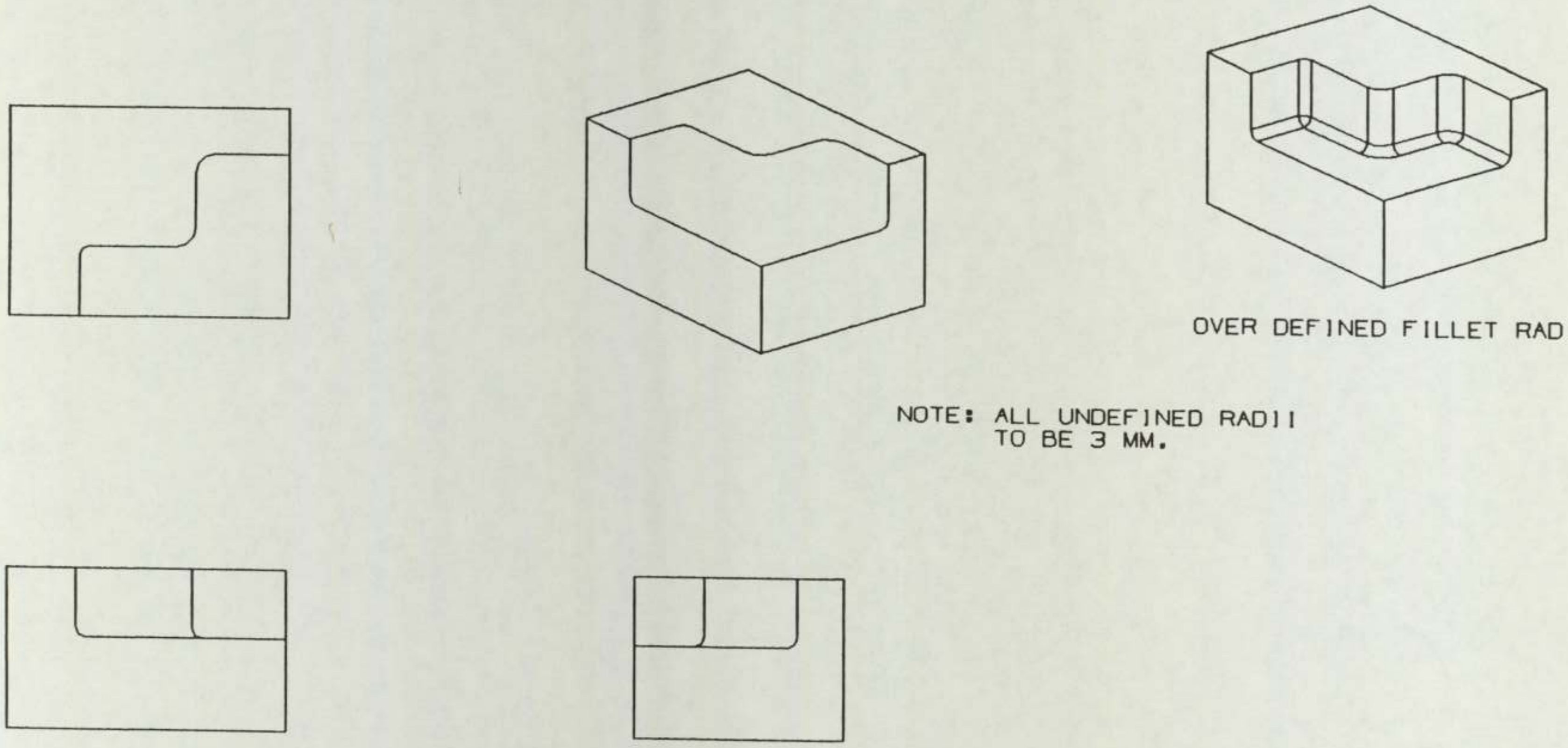
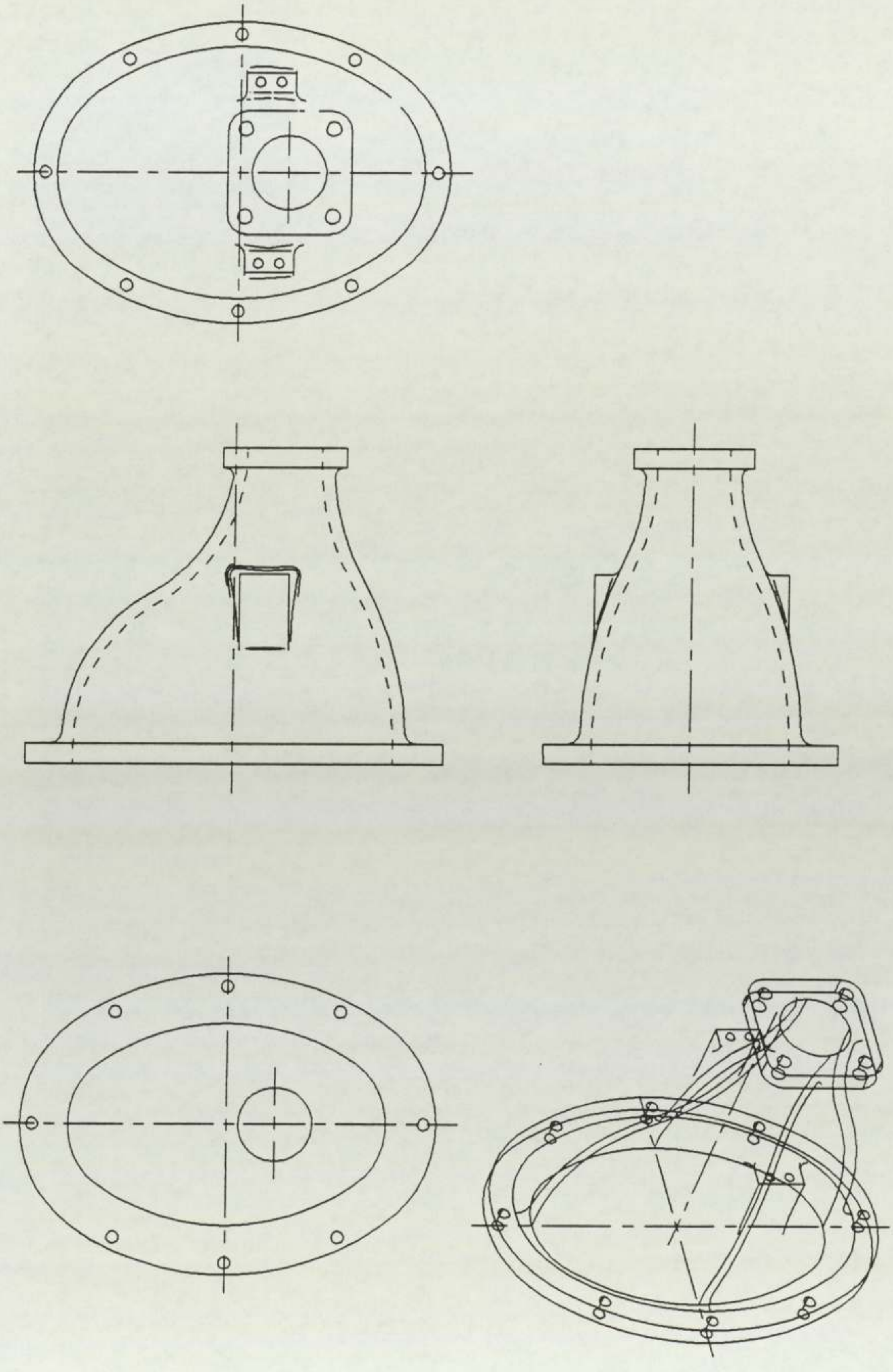
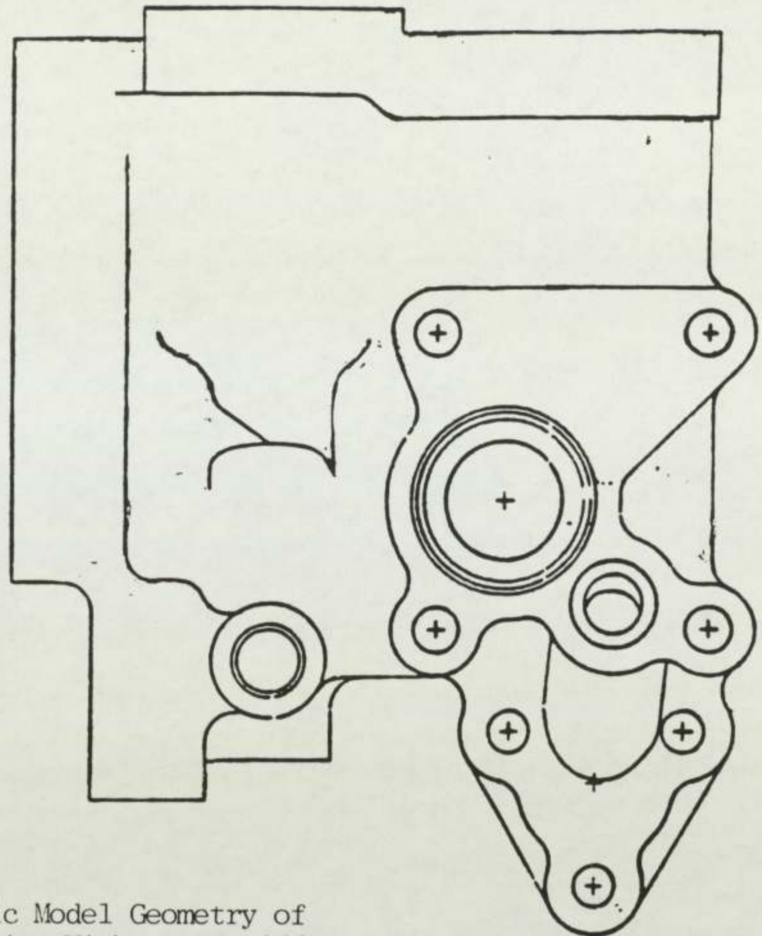

OVER DEFINED FILLET RADII
NOTE: ALL UNDEFINED RADII
TO BE 3 MM.
RADII PRODUCED AUTOMATICALLY
BY THE BALL NOSED CUTTER.
HENCE NO NEED TO MODEL
IN ANY GREAT DETAIL.

Fig (32)

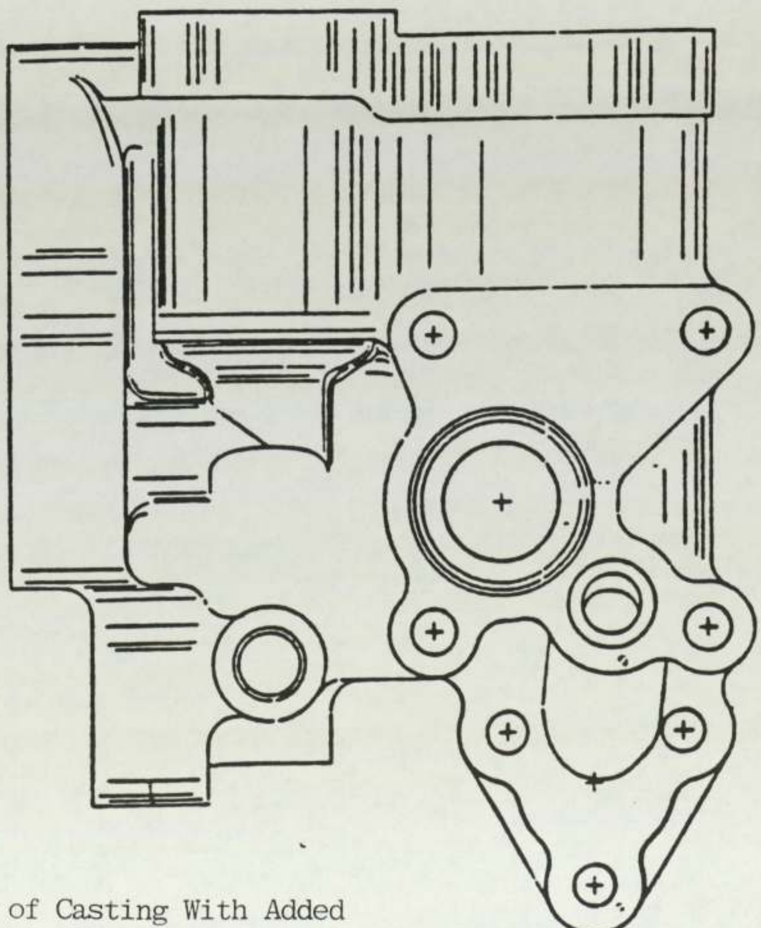


3D CASTING AND FLOWING GEOMETRIES

Fig (33)



Basic Model Geometry of
Casting Without any Added
Cosmetic Lines



View of Casting With Added
Cosmetic Lines

Fig (34)

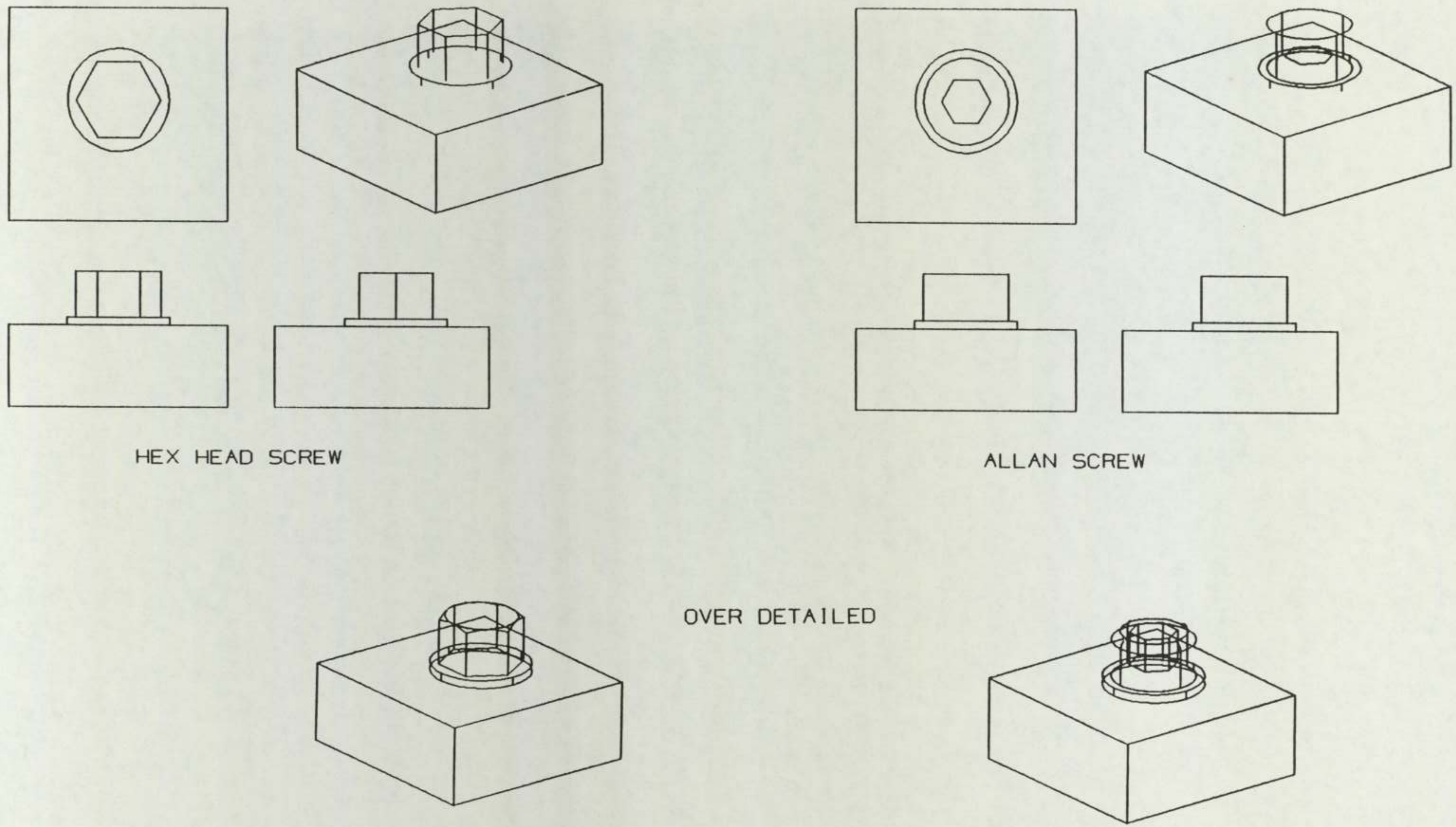


Fig (35) Do Not Over Detail Standard Items

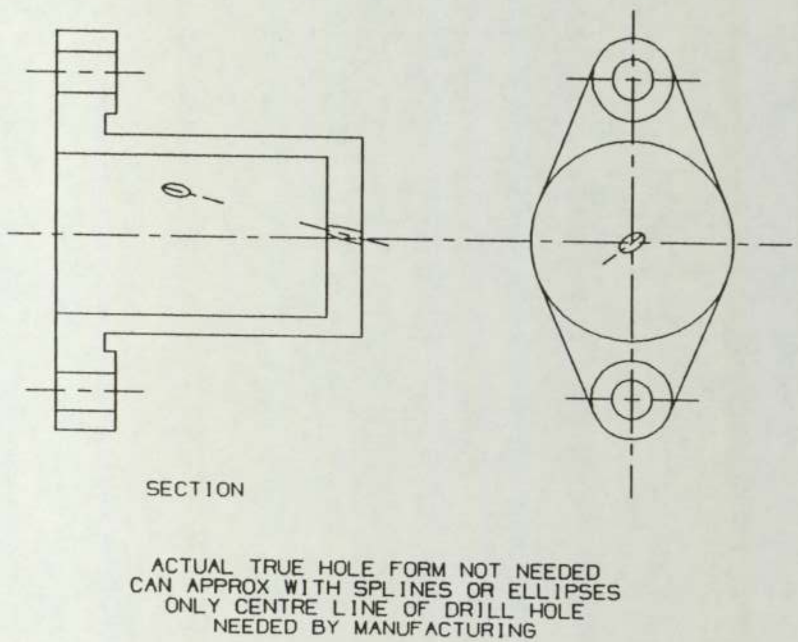
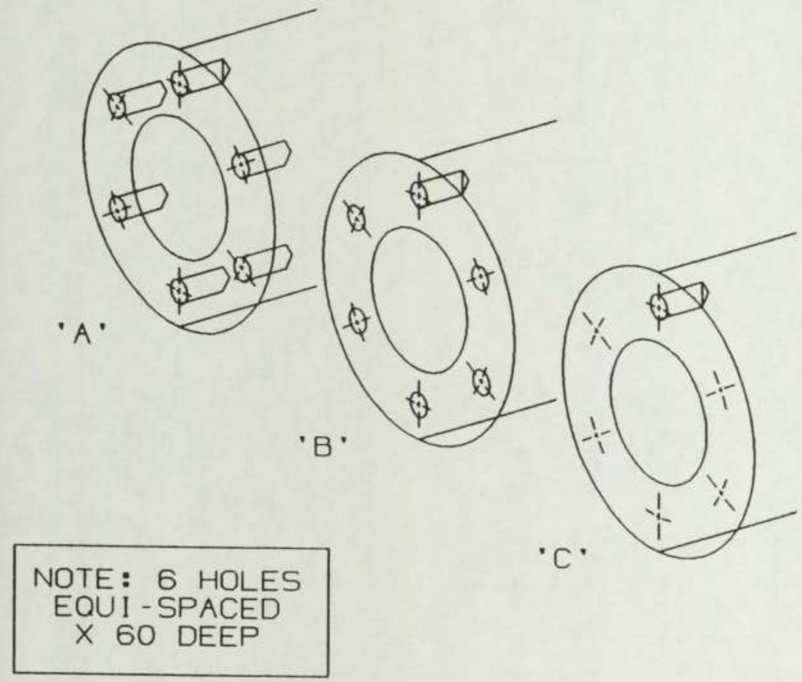


Fig (36)



REDUCE DETAIL ON FLANGE BOLT HOLES

Fig (37)

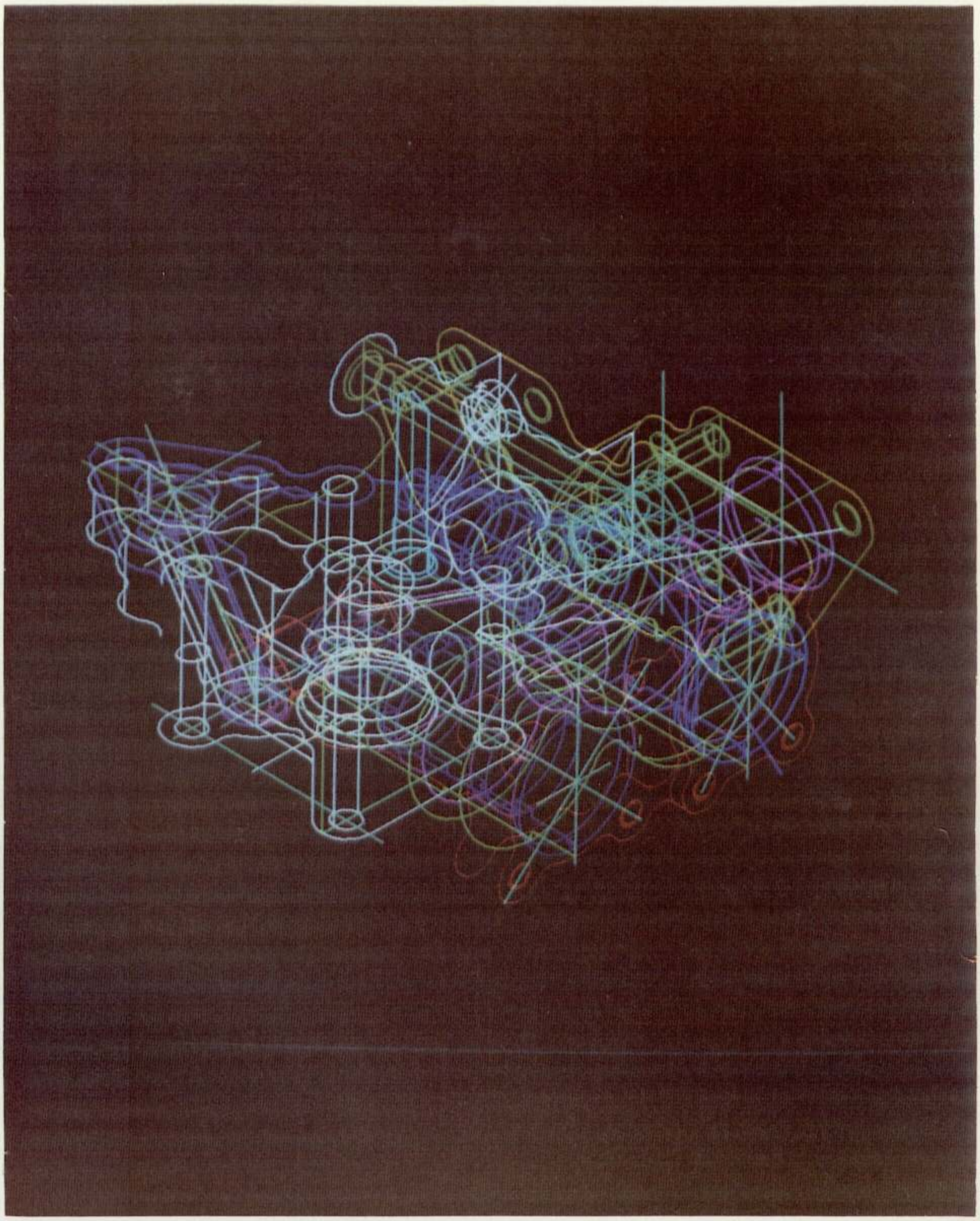
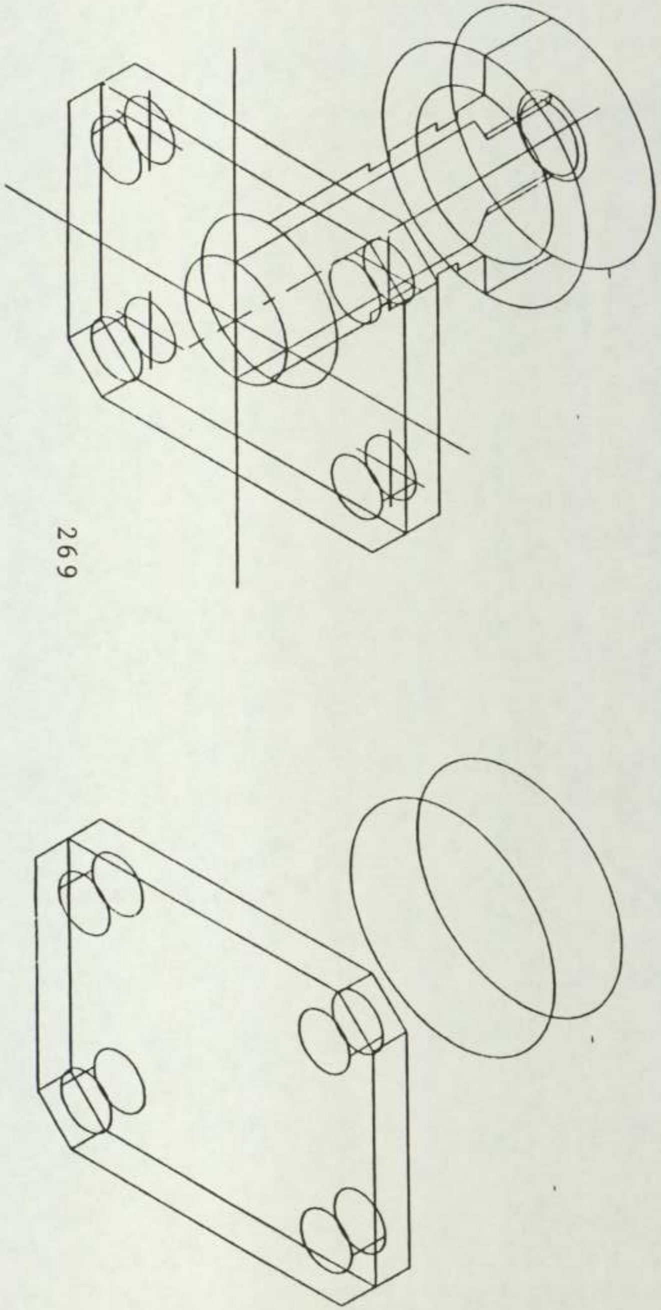
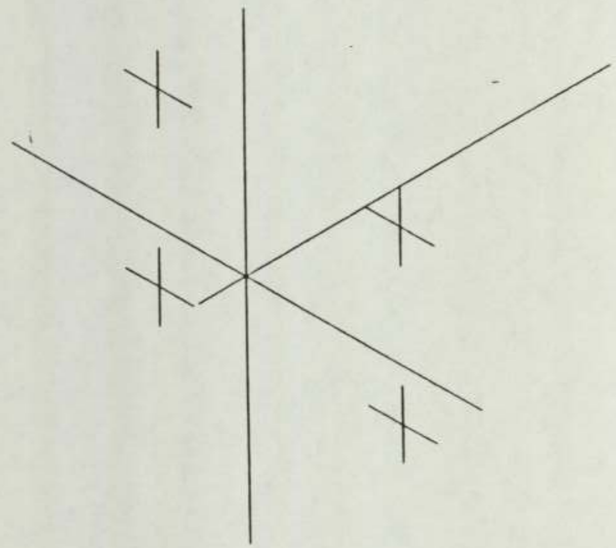


Fig (38) 3-D Minimum Model Without Layering
- Confusing

LAYERING AND MINIMUM MODELLING

LAYERING MUST BE EXTENSIVELY USED TOGETHER WITH MINIMUM MODELLING TO GAIN THE MAXIMUM BENEFITS OF THIS APPROACH





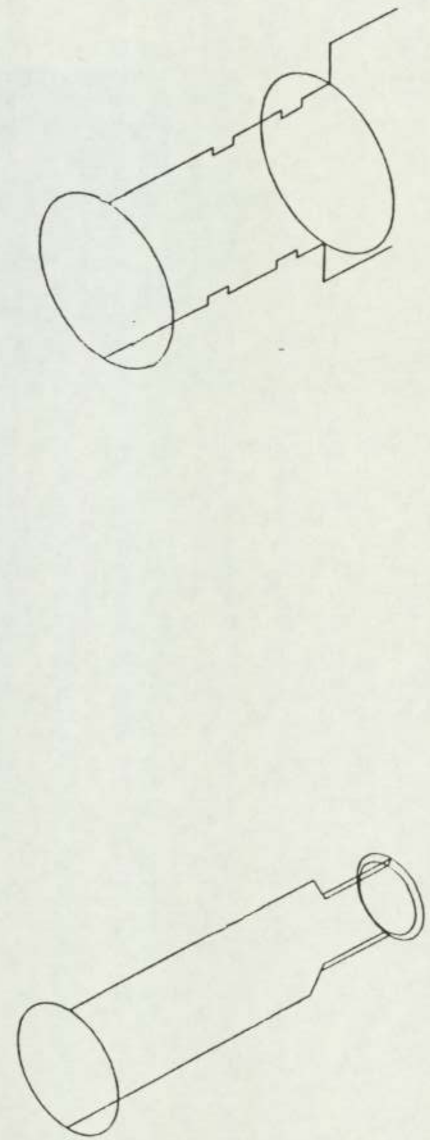


Fig (39)

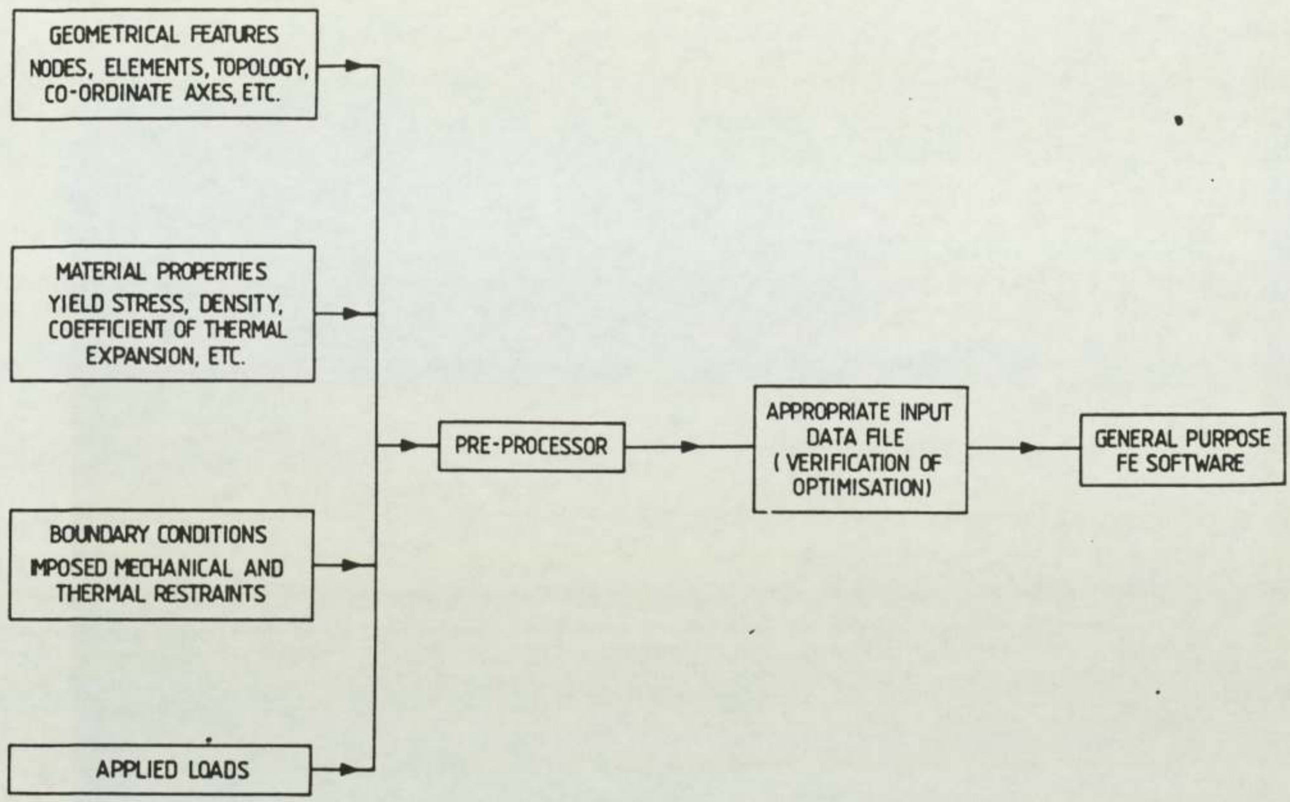


Fig (40) FE Pre-Processor

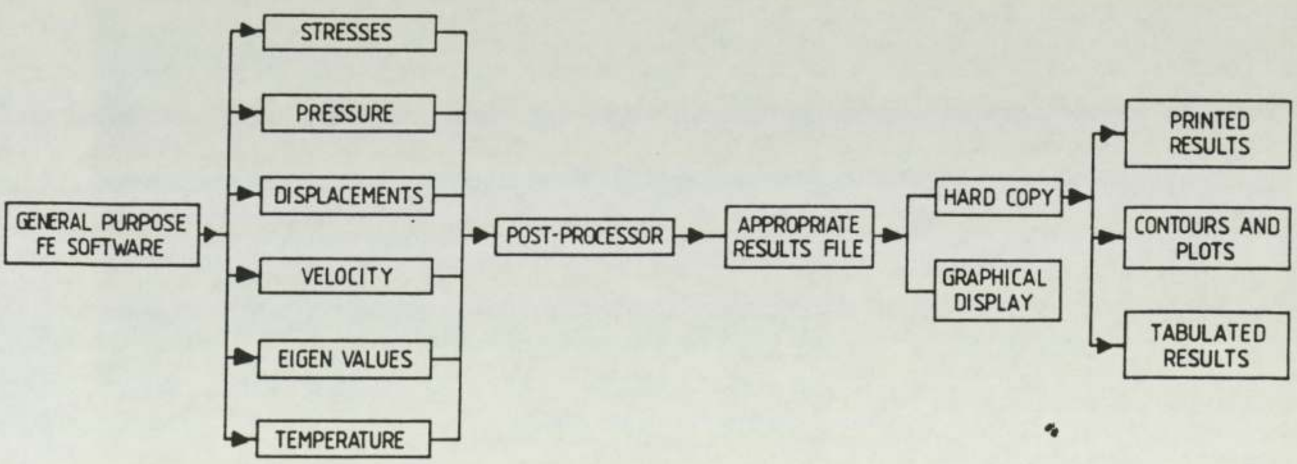
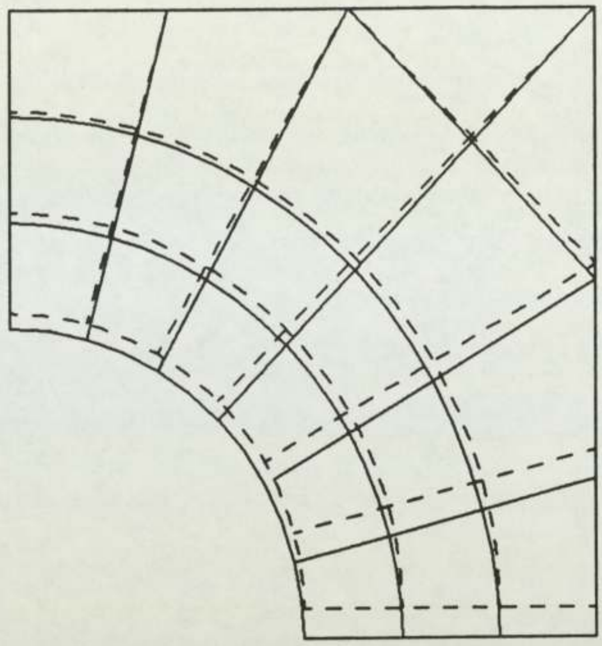
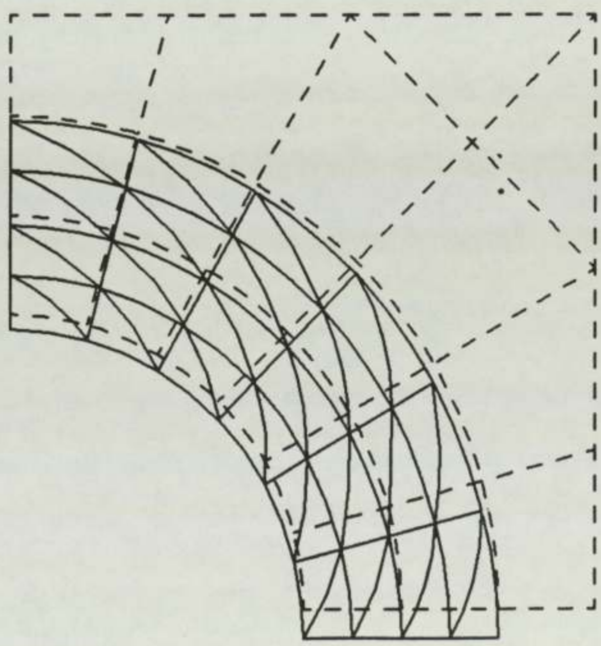


Fig (41) FE Post-Processor

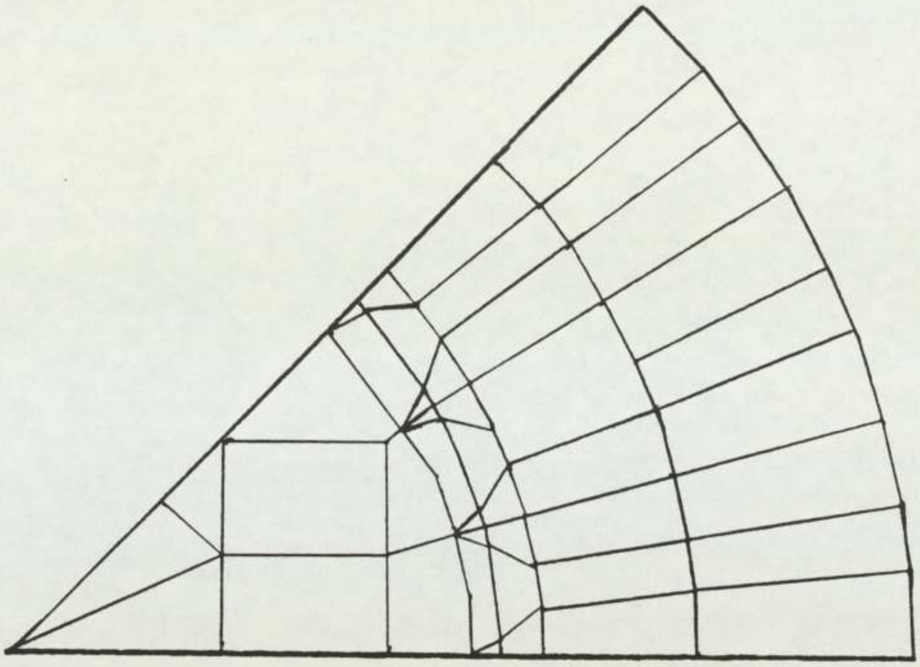


Initial FEA Using Coarse Mesh

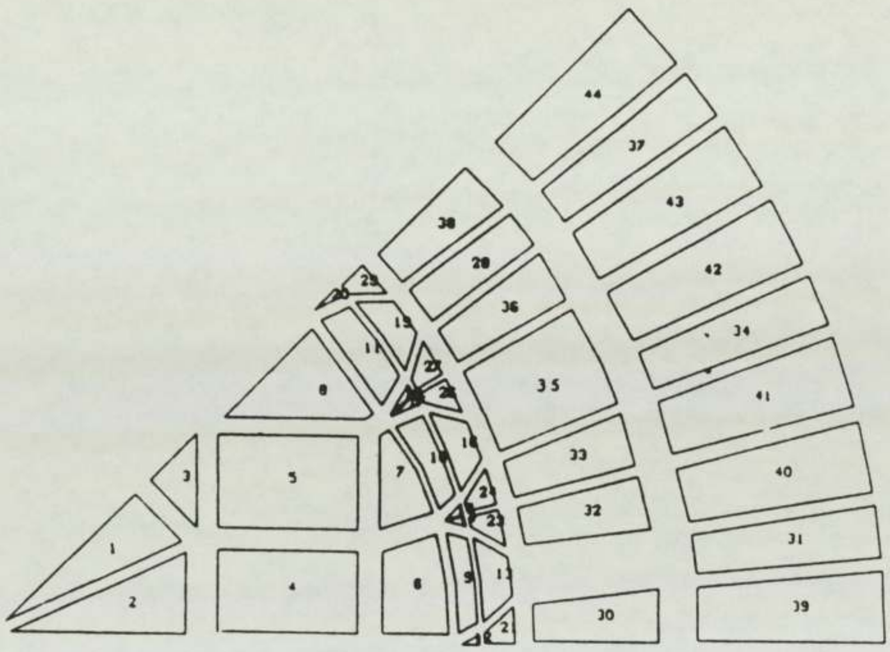


Sub-section Critical Area ,Concentrate Refined Mesh Around Hole ,Use Deformations From Initial Analysis as Boundary Deformations for the Sub-sectioned Critical Area.

Fig (42) FE Sub-sectioning



Complete Mesh



Finite element display. Each element is reduced to 90% of its size around its centre of mass. This allows the detection of holes (the space between elements 13, 30, 31 and 32) and incompatibilities (the interface of elements 34 and 42 with element 35)

Shrink Elements to Check for Holes in the Mesh and Incompatibilities at the Common Boundaries.

Fig (43) FE Shrinking Elements

Reproduced from Meguid [23].

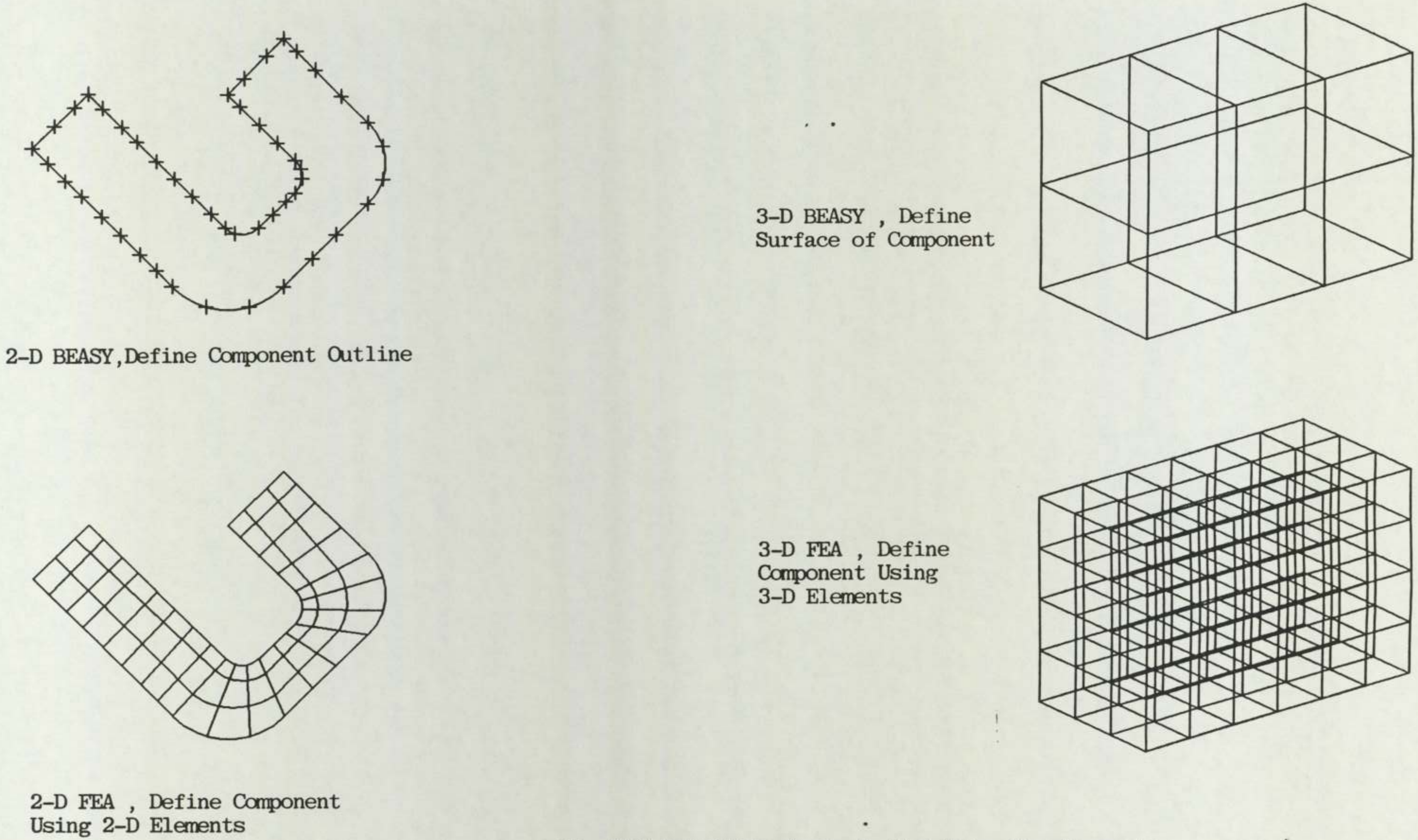


Fig (44) FE/BEASY Analysis Modelling Requirements

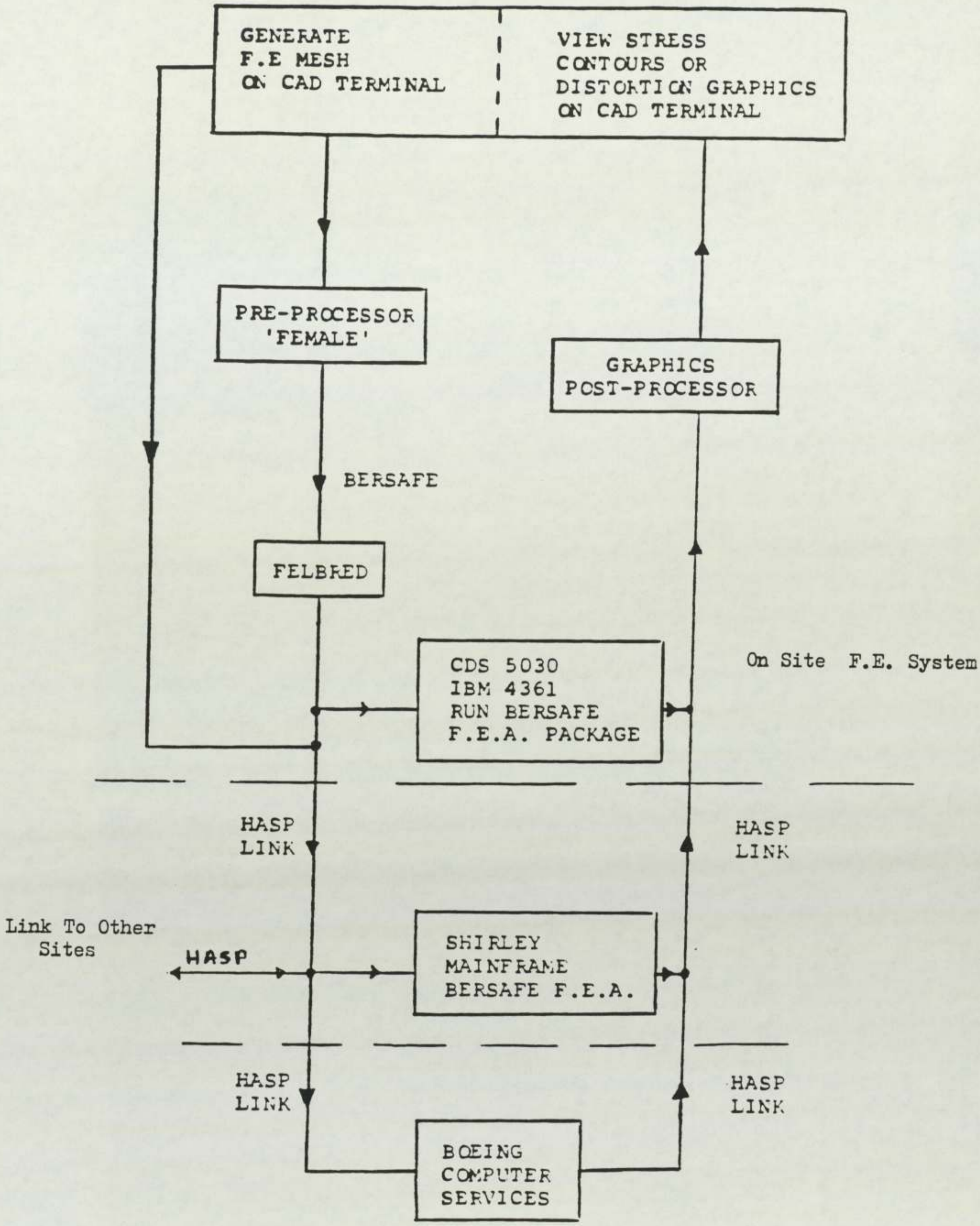
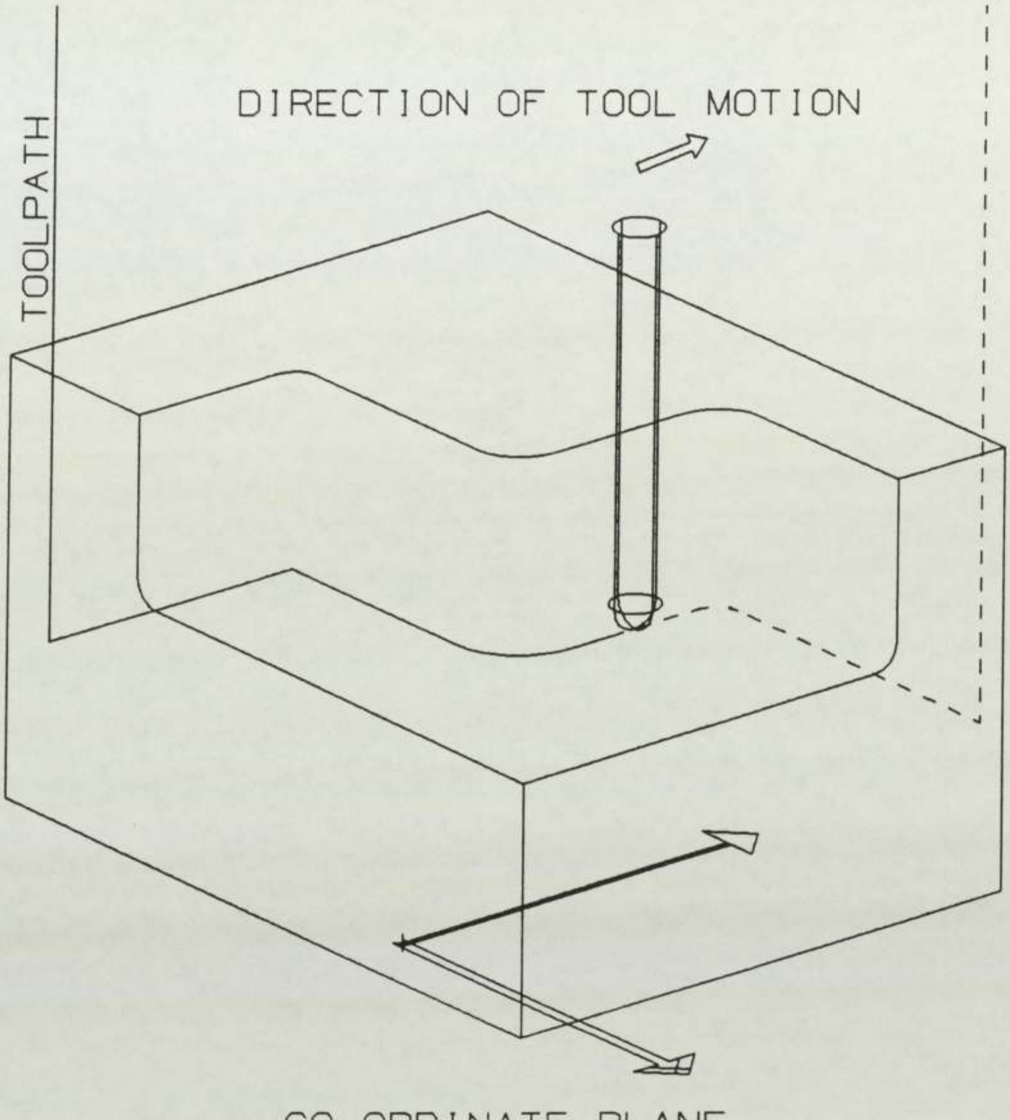


Fig (45) F.E. SYSTEM AND NETWORK



3D ISOMETRIC VIEW OF CUTTER FOLLOWING PROFILE

Fig (46)

MACHINE AXES
Machining Centre DZ4

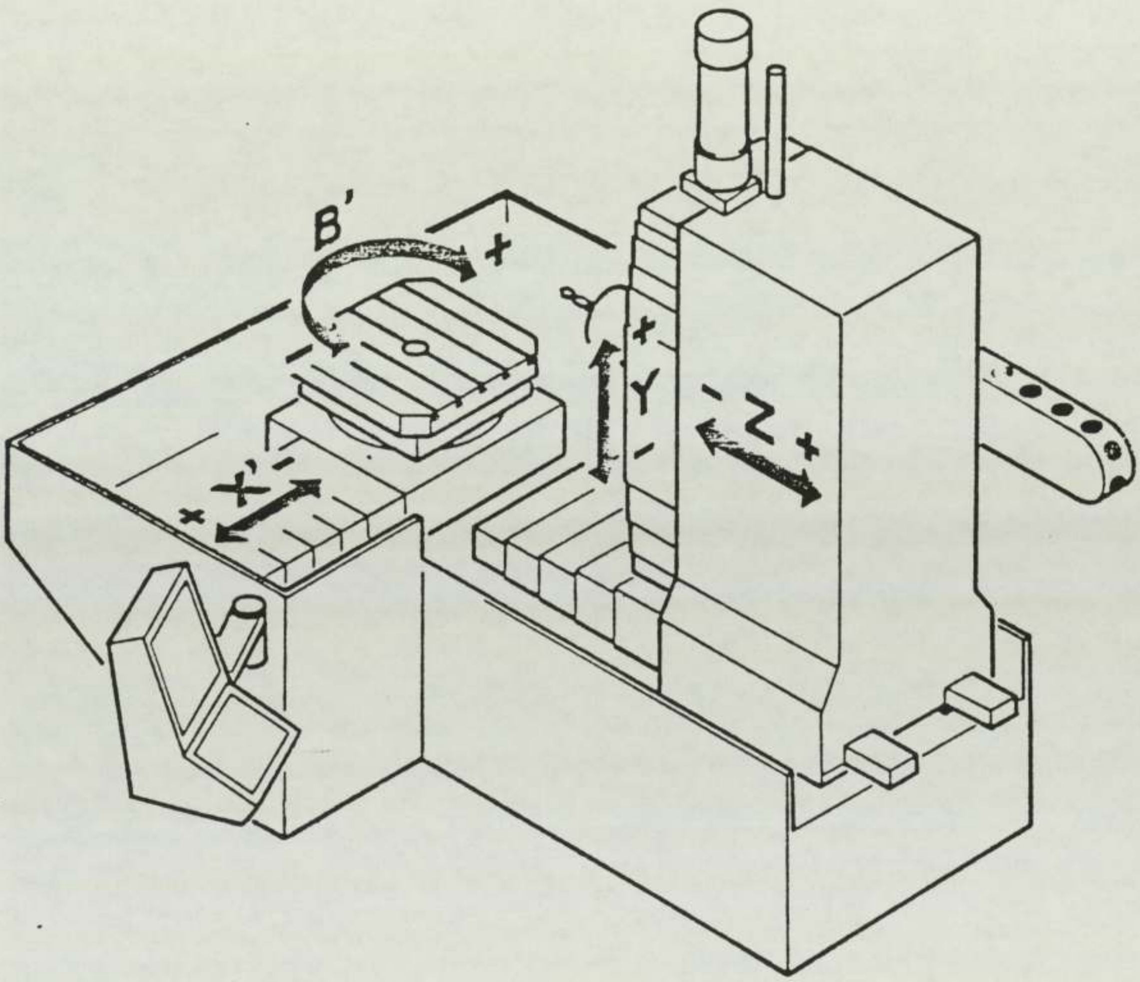


Fig (47) Deckel DZ4

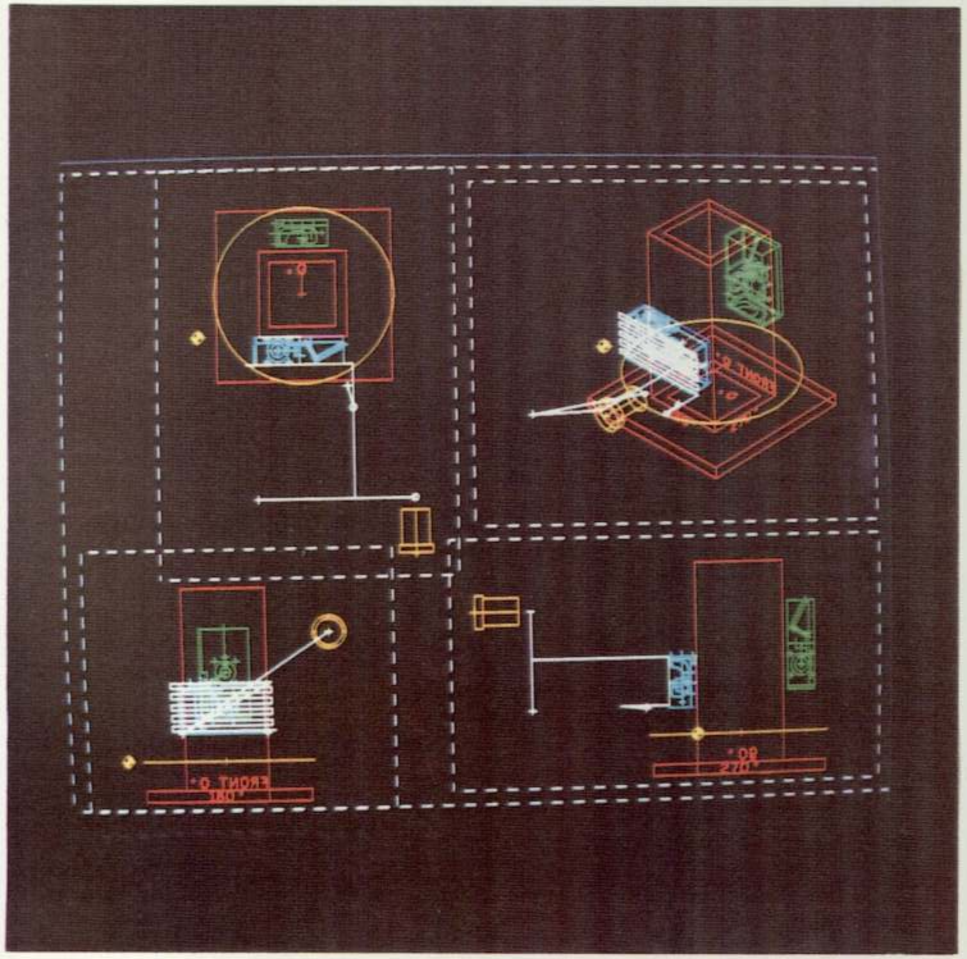


Fig (48) 4 View Layout Showing
Toolpath

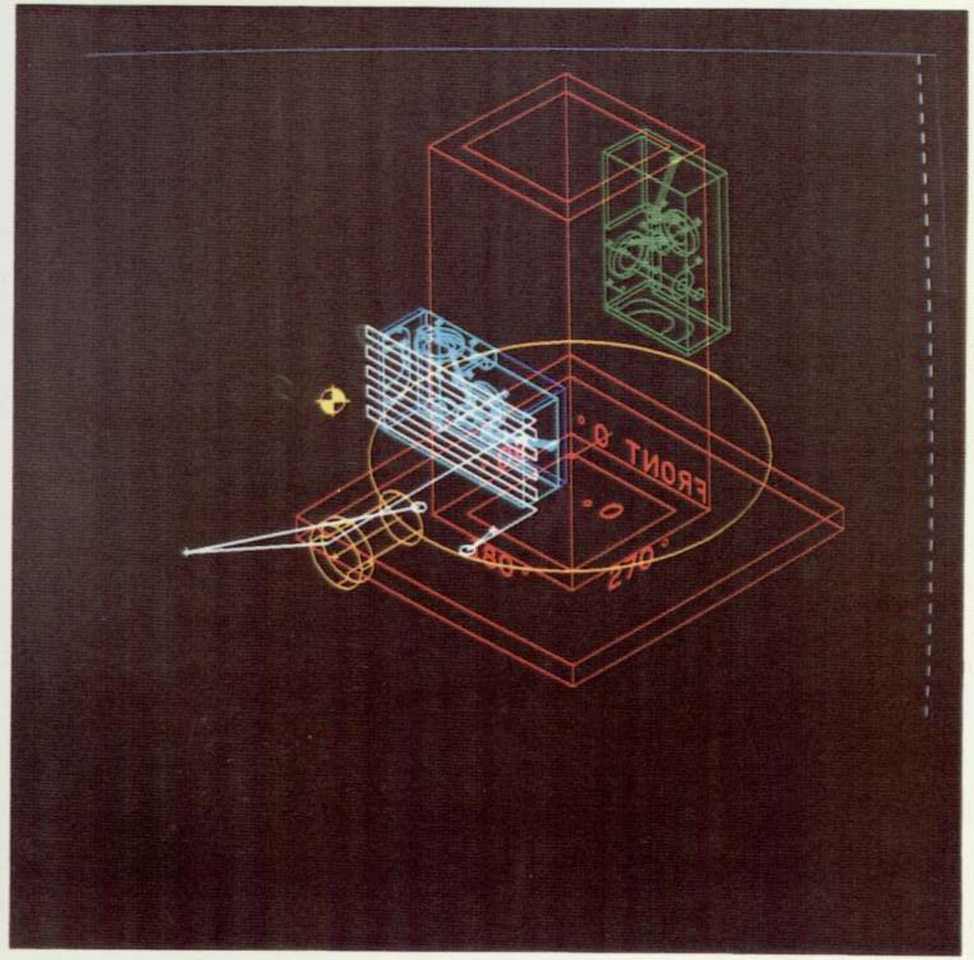


Fig (49) Single View Showing
Toolpath

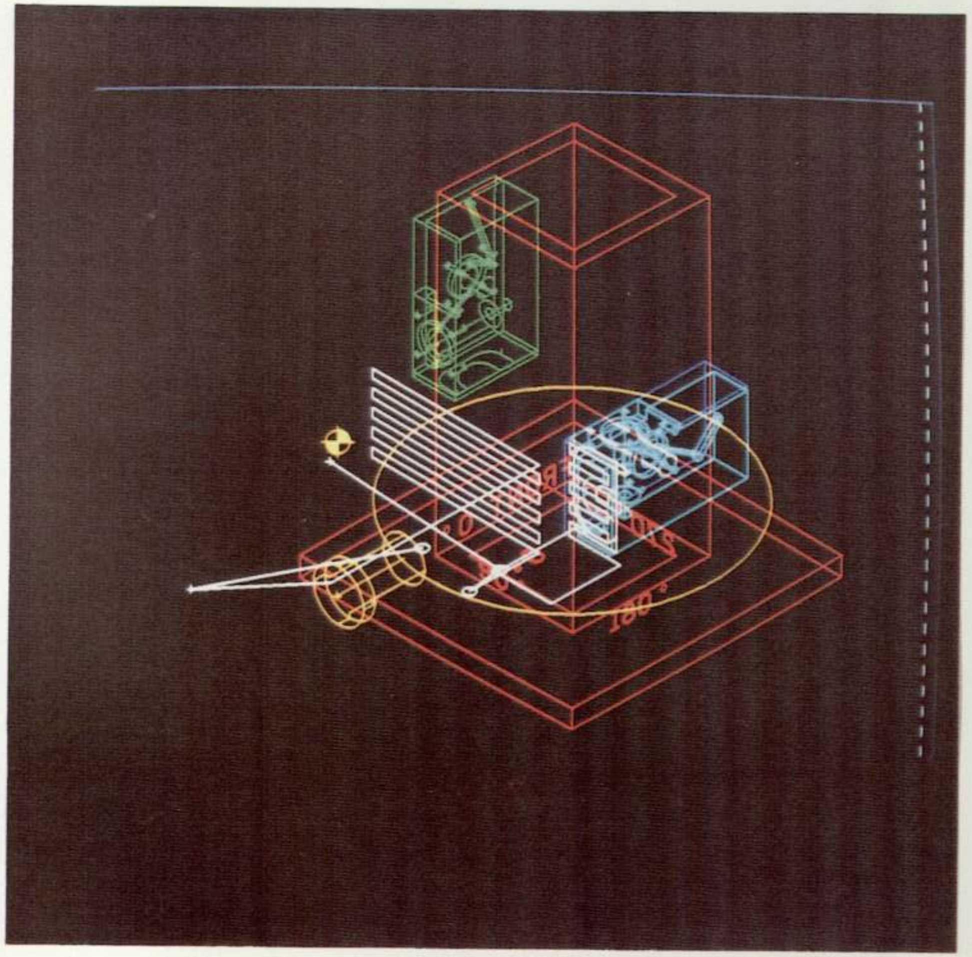


Fig (50) Single View Showing Toolpath After 2 Rotations

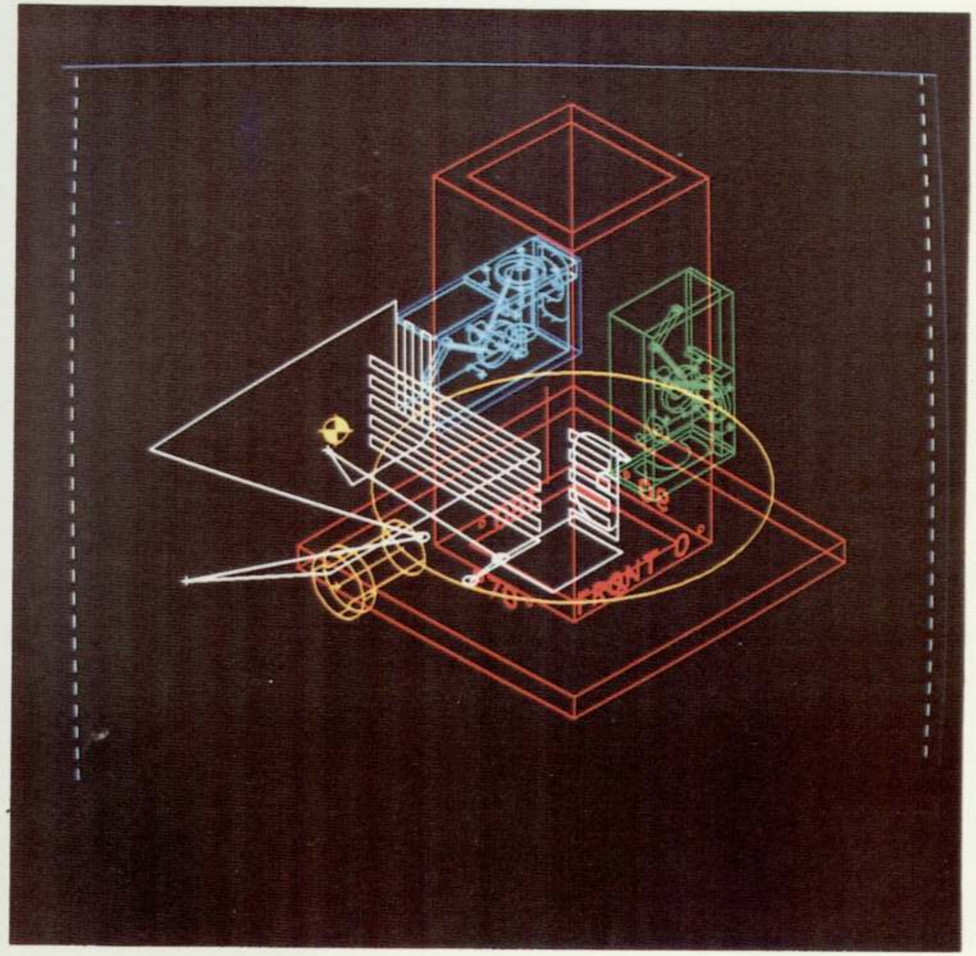


Fig (51) Single View Showing Toolpath After 3 Rotations

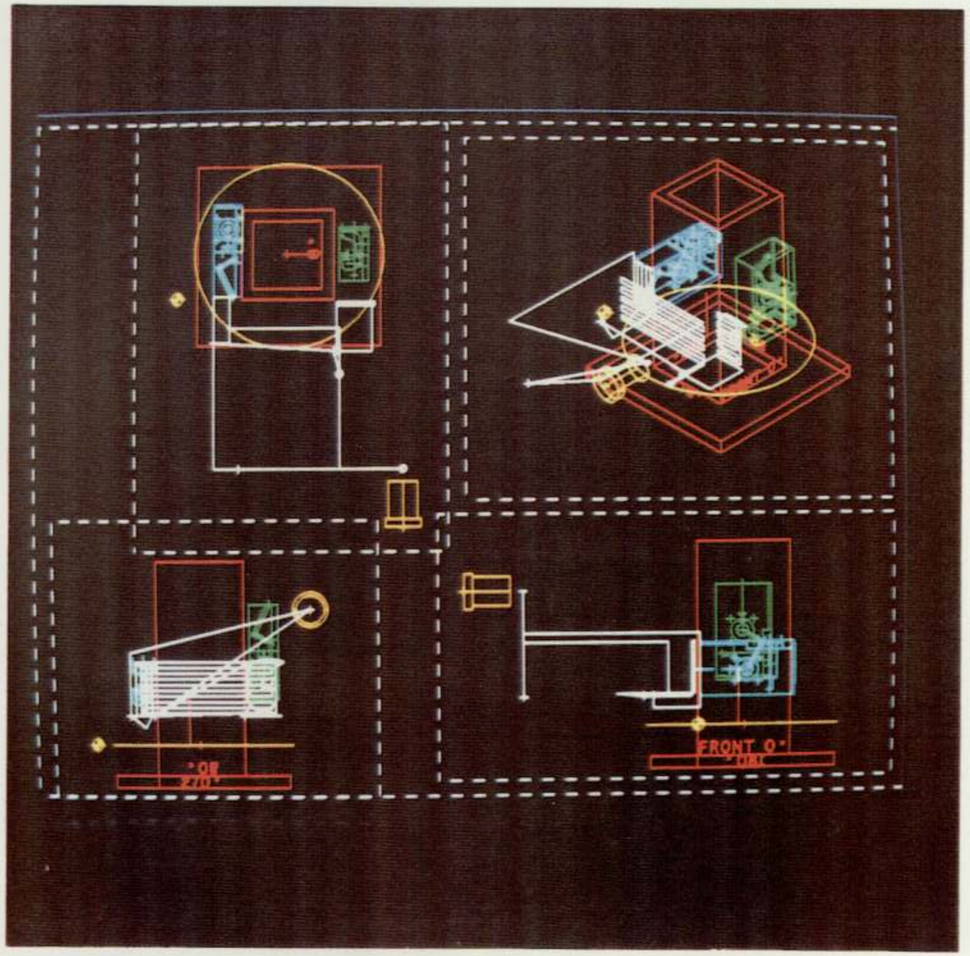


Fig (52) 4 View Layout Showing
Toolpath After 3 Rotations

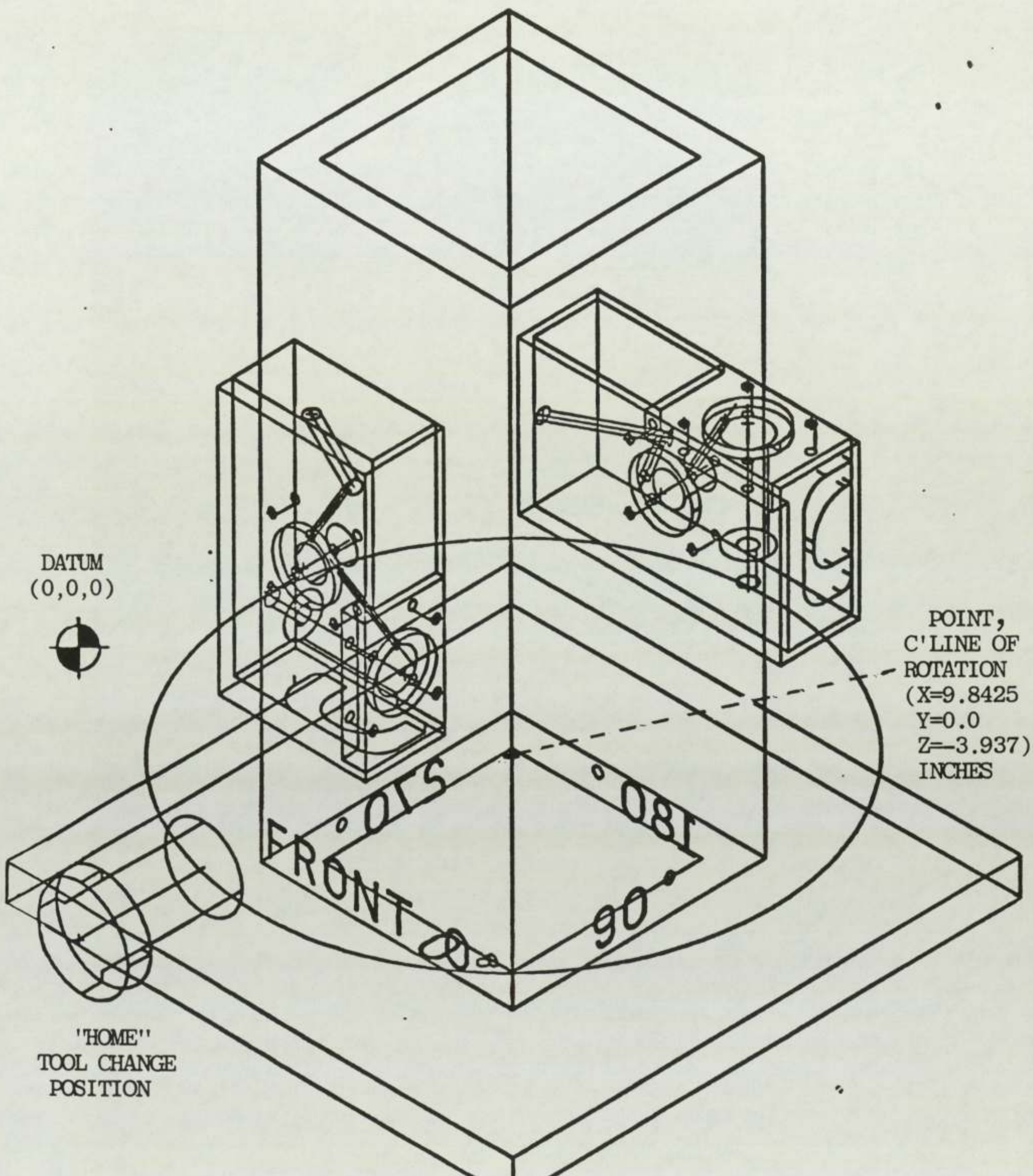


Fig (53) Layout of DZ4 Machining Area

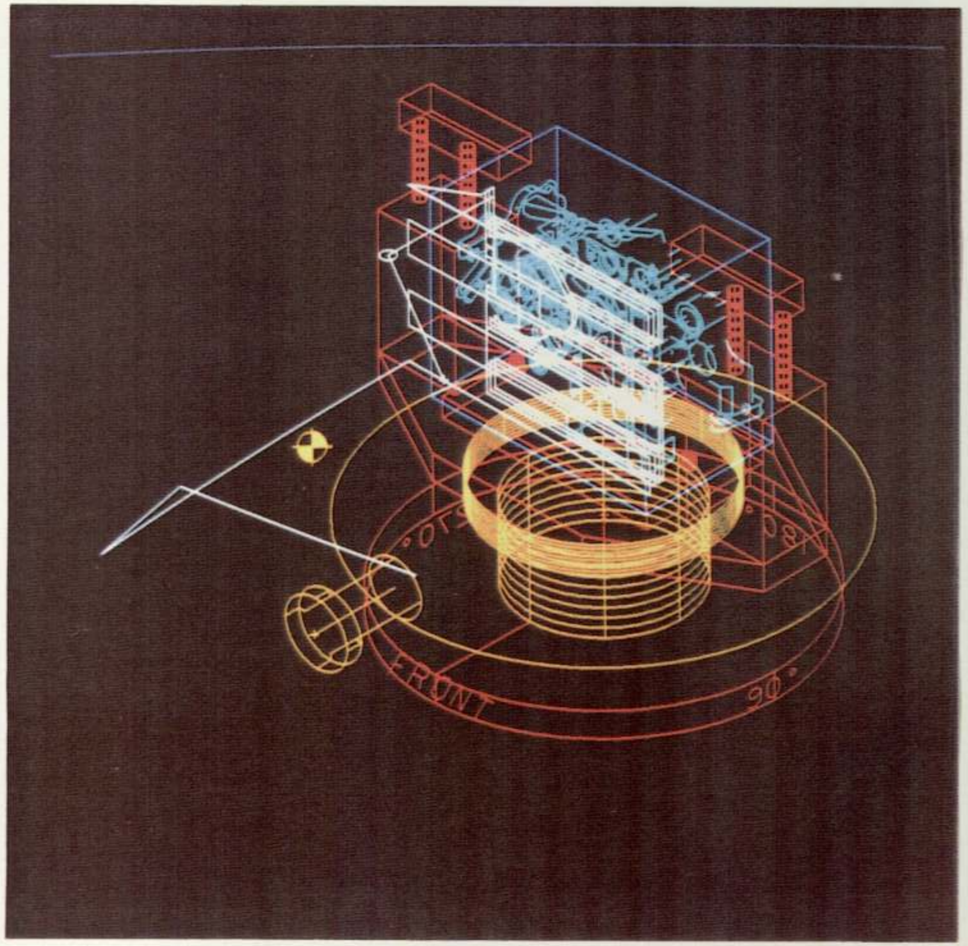


Fig (54) Single View

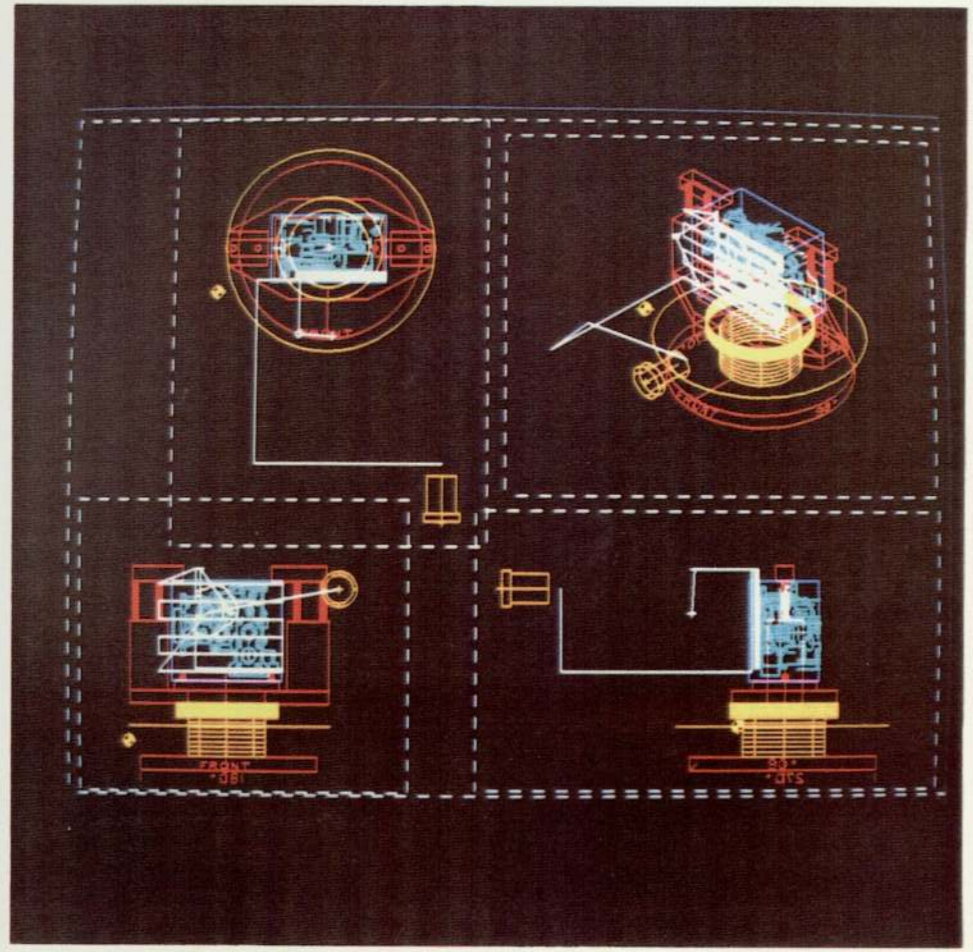


Fig (55) 4 View Layout

PREDICTED COLLISION SITUATION

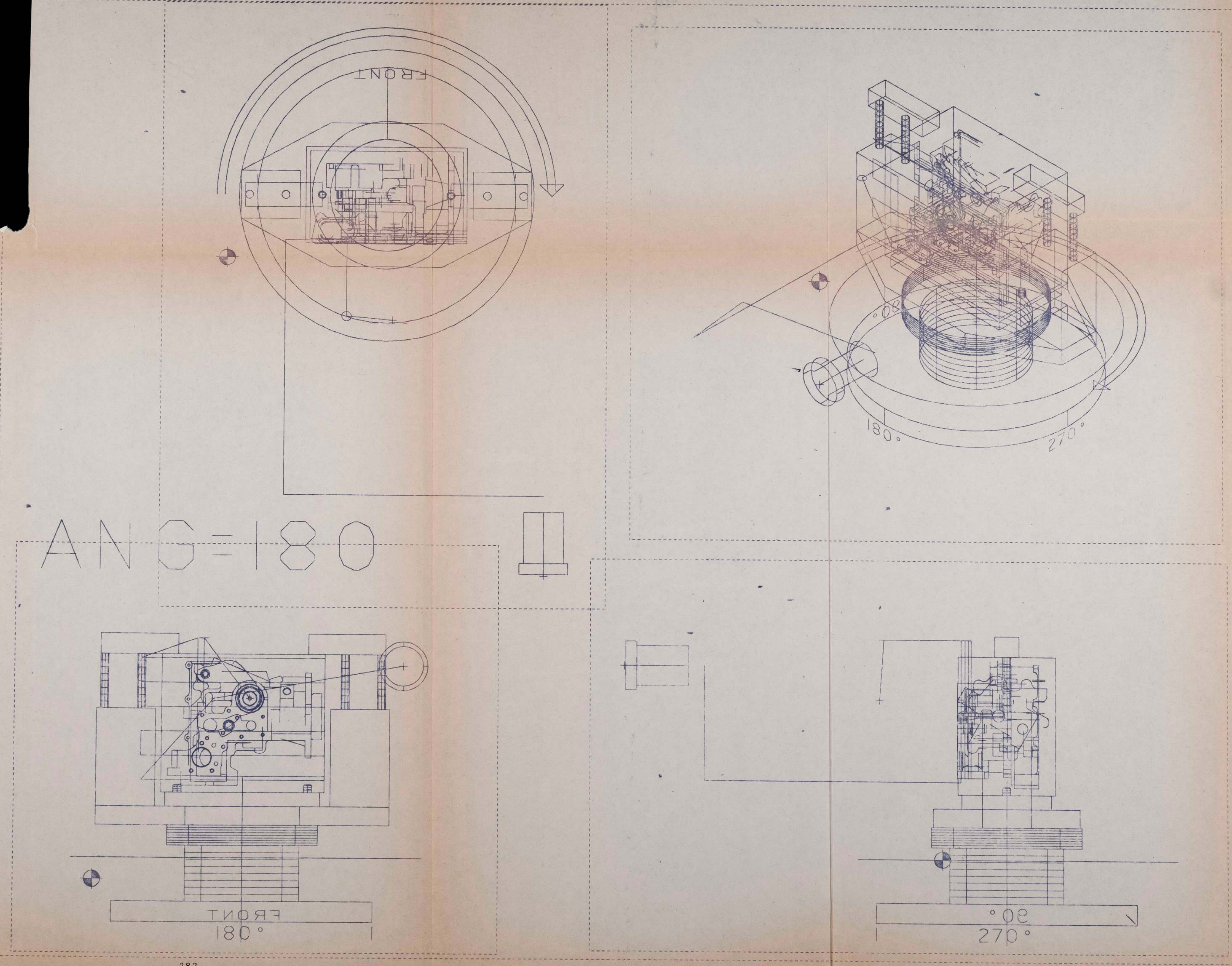
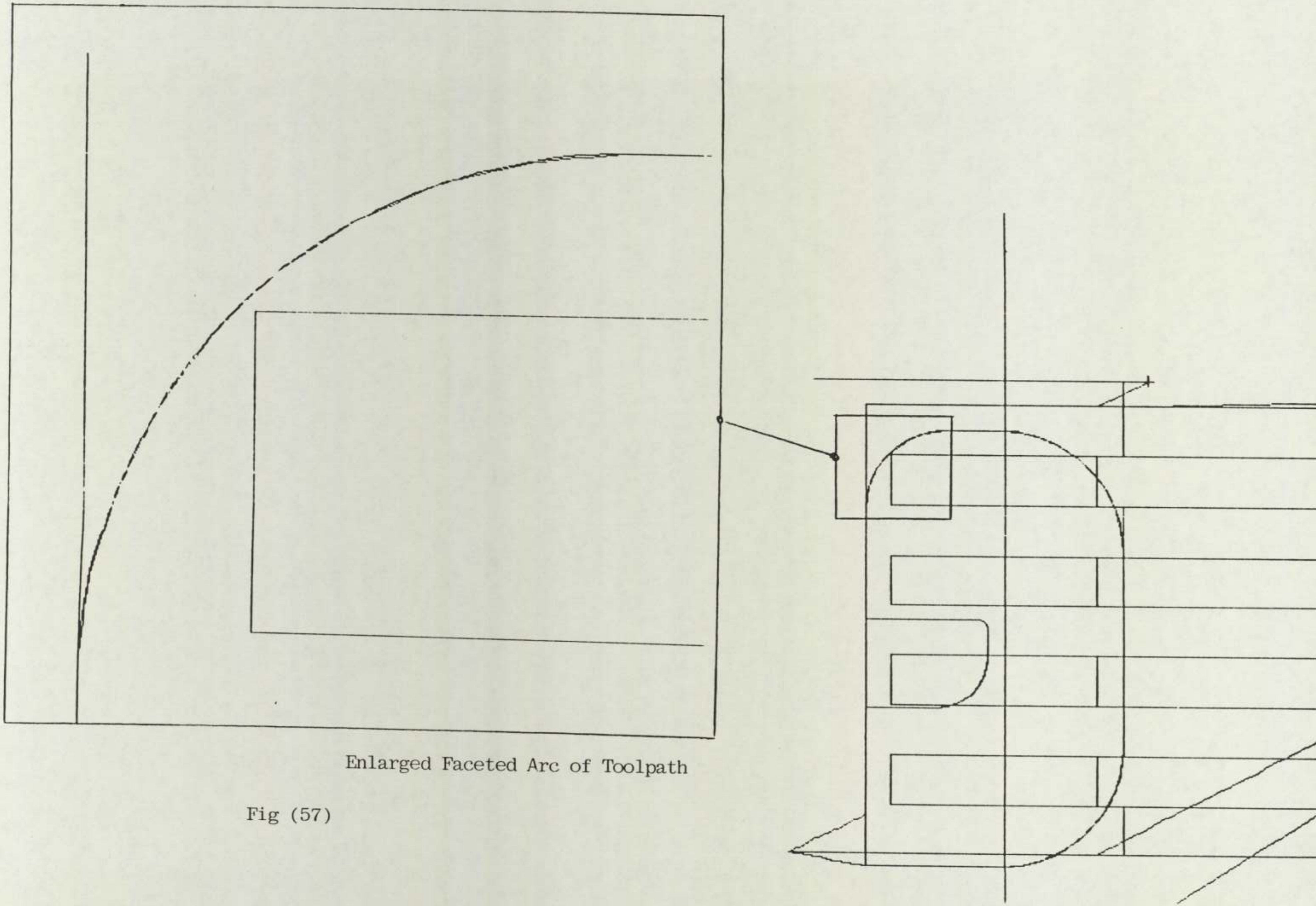


Fig (56) ROTATION ANGLE



Enlarged Faceted Arc of Toolpath

Fig (57)

APPENDIX (1)

THE TEACHING COMPANY SCHEME (TCS)

The Teaching Company Scheme was establised by SERC (the Science and Engineering Research Council) and the DTI (Department of Trade and Industry) in order to:

Raise the level of industrial performance by effective use of academic resources.

Improve manufacturing and industrial methods by the effective implementation of advanced technology.

Train able graduates for careers in industry.

Develop and retrain existing company and academic staff.

Give academic staff broad and direct involvement with industry to benefit research and enhance the relevance of teaching.

Teaching Company programmes are intended to bring together Universities and Polytechnics with industrial companies which are committed to making substantial changes in their operations.

Academic staff make a positive contribution to the programmes, but most of the key work is done by high-calibre graduates, usually engineers, who are recruited as Teaching Company Associates on two year appointments.

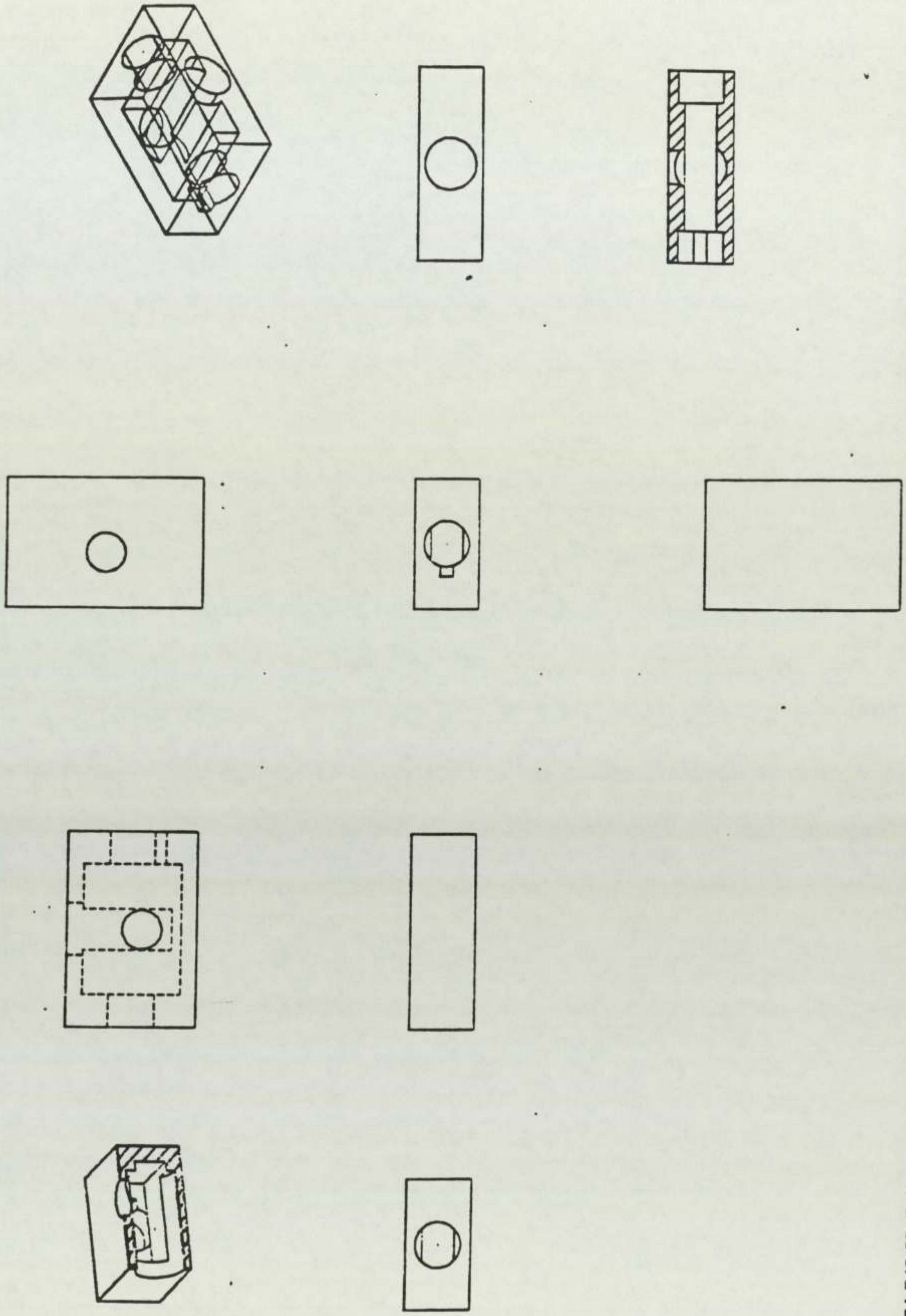
These associates work in collaboration with the company and with the academic staff on tasks within the programme. They are normally based full-time at the company and their appointments should lead to posts in industry with substantial responsibility, prospects and reward.

The Teaching Company Scheme is funded by SERC and the DTI. Grants are made to individual programmes to cover the basic salaries of the Associates and other support costs. Further support may also be made available under the scheme or through other DTI and SERC channels.

The Scheme is run by a national management committee and a Directorate, which is based at SERC.

In July, 1985, a Teaching Company Scheme was started between the Engine System Division of Lucas Aerospace and the University of Aston (Mechanical and Production Engineering department).

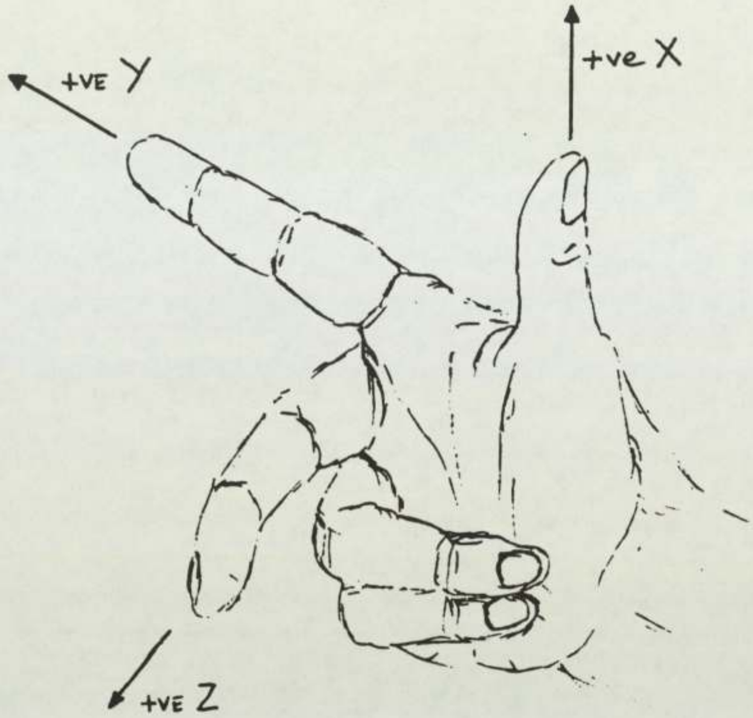
Appendix (2) Training Exercises -(A set of sample sheets from each exercise)

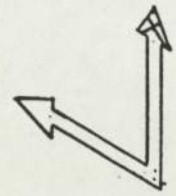


TRA.PJS.3D-BOX

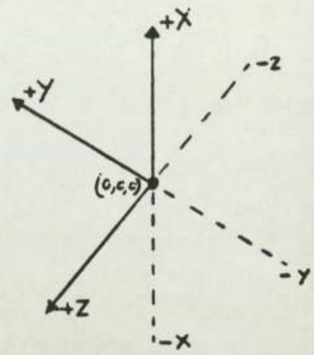
CADDS - RIGHT HAND RULE

TO DEFINE +VE X,Y,Z, CO-ORDINATE AXIS





ECHO CPL

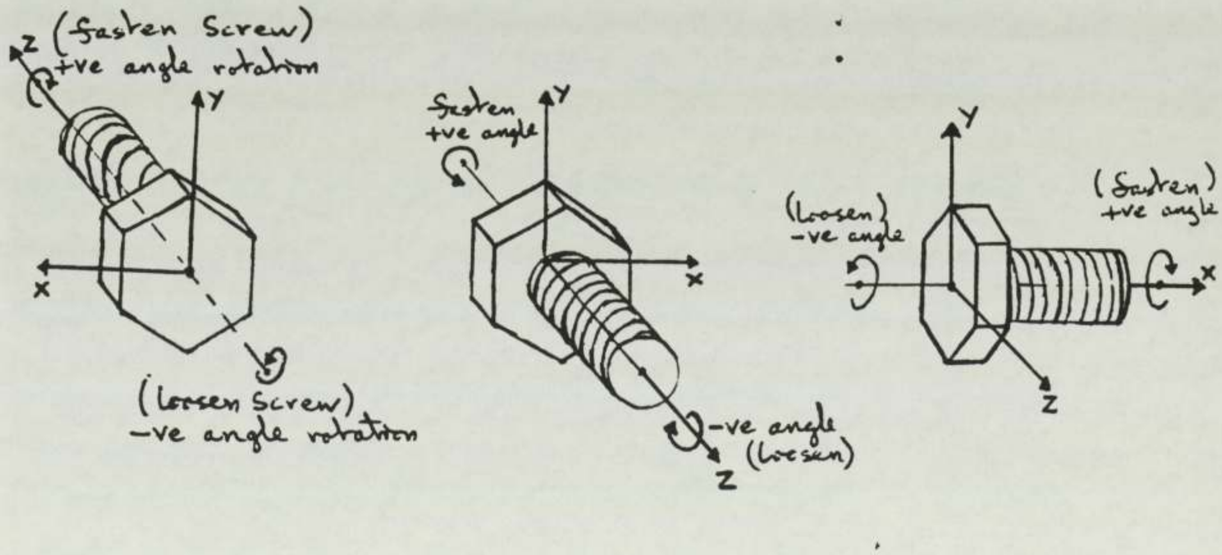


3-D CO-ORDINATES

TO DEFINE DIRECTION OF ROTATION

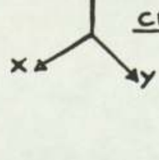
ALL +VE ANGLE ROTATIONS ABOUT ANY AXIS CAN BE THOUGHT OF AS FASTENING A SCREW, SO THAT THE SCREW MOVES IN THE DIRECTION OF INCREASING +VE VALUE OF THAT AXIS.

NEGATIVE ROTATION IS SIMILARLY ANALOGOUS TO LOOSENING SCREW.

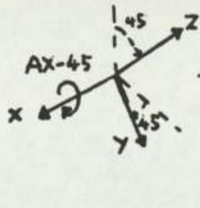


THIS PRINCIPLE APPLIES TO DEFINING ROTATIONS OF ONE CPL RELATIVE TO ANOTHER, ASWELL AS ROTATION OF ENTITIES.

#01 # DEF CPL DRILL FROM TOP AX-45 : DRAW Loc d



CPL TOP



CPL DRILL

P.T.

REF FIG 10

CHANGE INTERNAL BORE SOLID LINES INTO DASHED LINES IN ALL VIEWS.
#07#CHA APP FONT DASHED ALLVIEWS: MODEL ent d1d2d3d4d5d6d7d8d9d10d11d12
12 ENTITIES HAVE BEEN CHANGED
CHANGE BORE CENTRE LINE TO PHANTOM IN ALL VIEWS
#07#CHA APP FONT PHANTOM ALLVIEWS: MODEL ent d13d14d15

3 ENTITIES HAVE BEEN CHANGED

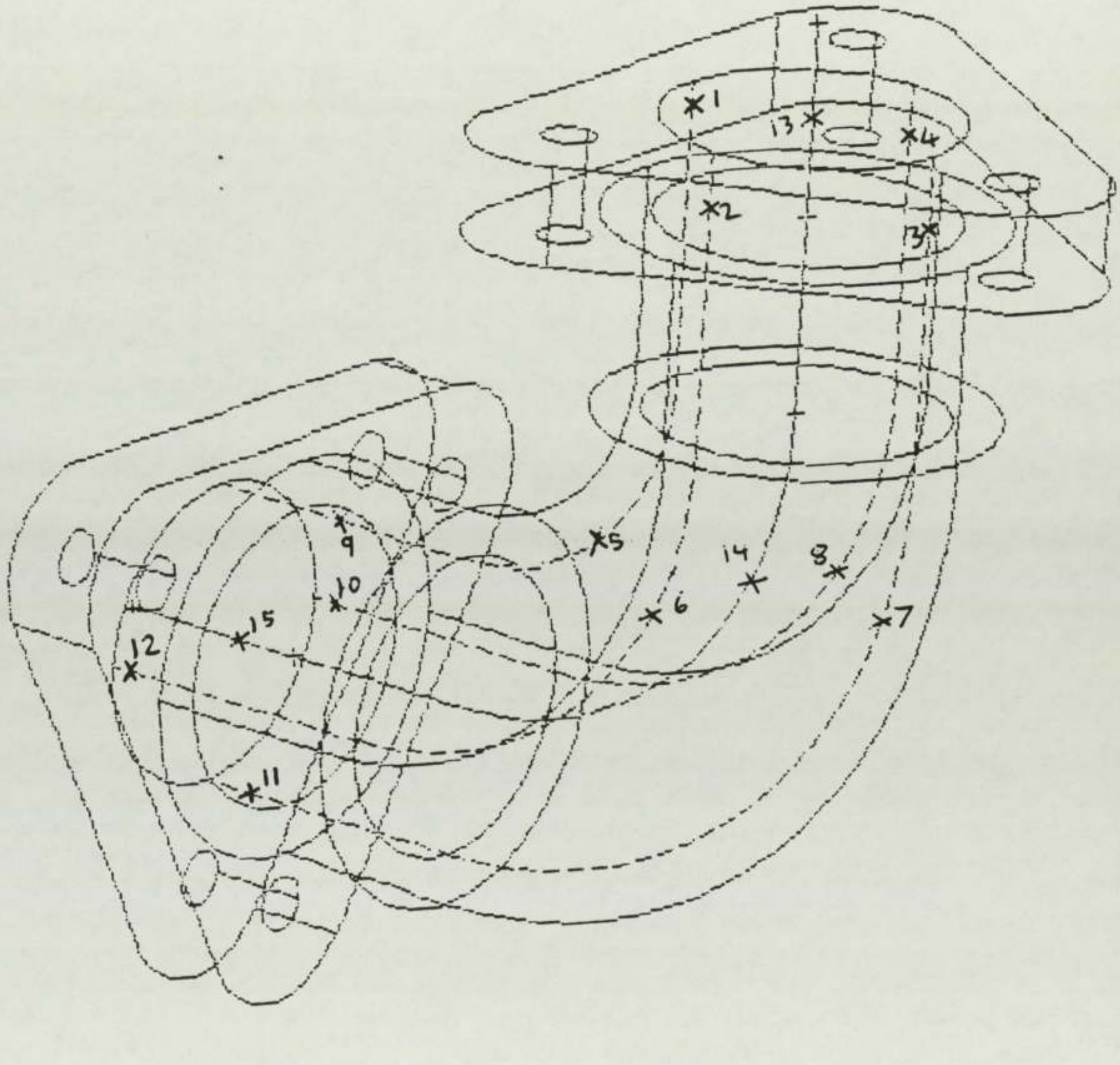


FIG 10

REF FIG 14

Entities which are required to complete a manufacturing view and which don't serve any model defining purpose in other views are often inserted in draw mode. Inserting in draw mode places the entity in one view and one view only.

#07#SEL MODe DRAW

 SELECTED MODE IS DRAW.
#07#INS LIN VERT: DRAW LOC d1 END d2 DRAW loc
#07#INS LIN HOR: DRAW loc d3 END d4 DRAW loc
#07#SEL MODe MODEL
 SELECTED MODE IS MODEL.

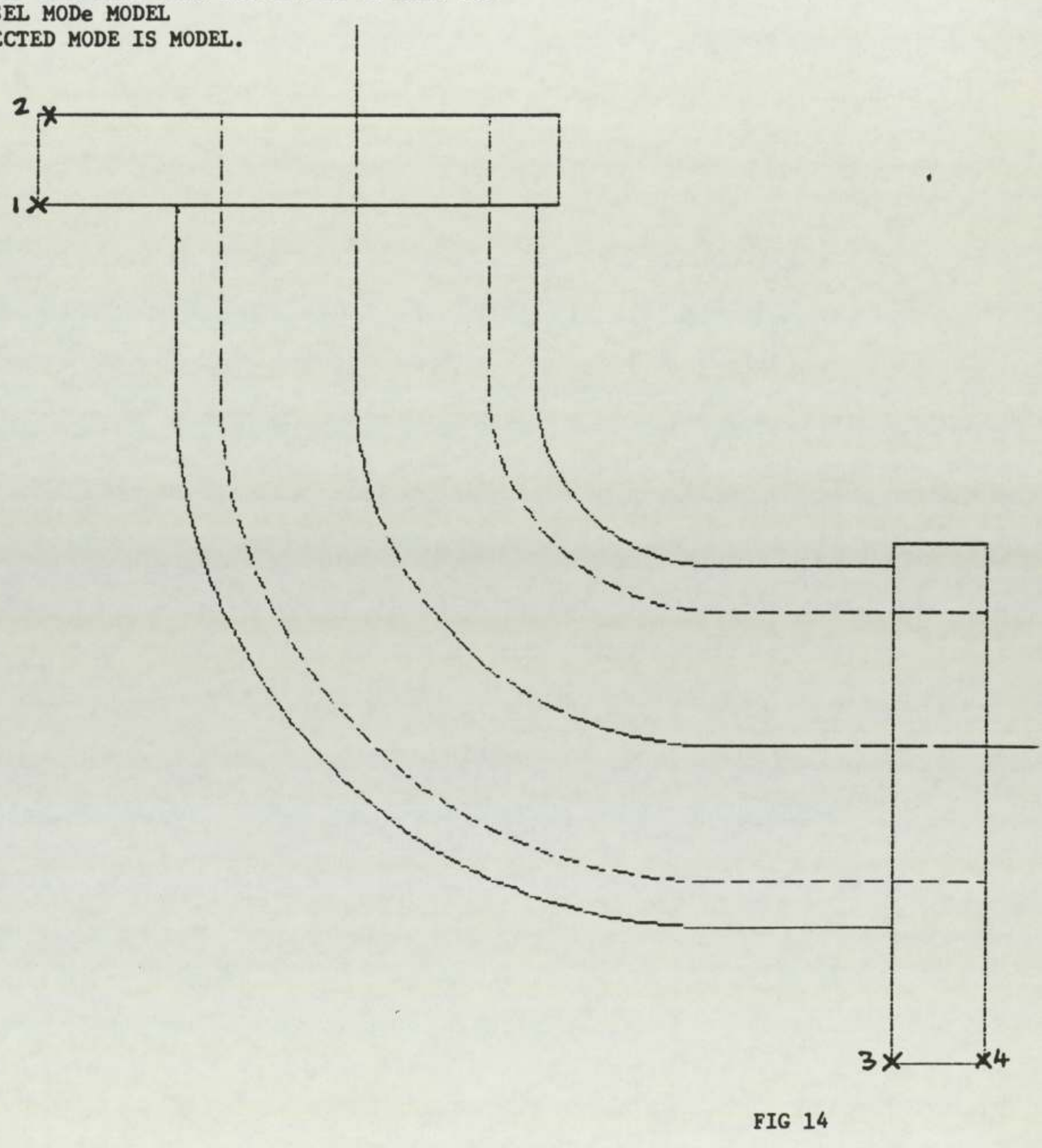


FIG 14

Magnify auxiliary views in order to detail

REF FIG 22

Magnify the view size of the flange by 2:1 in order to detail

#01#ZOO VIE R2: view d1
#01#REVISE VIE CLIP:VIEWd2; Draw loc d3d4
Magnify the view size of the threaded hole by 6:1
#01#ZOO VIE R6: View d5
#01#REVISE VIE CLIP: View d6, Draw loc d7d8

Scroll views where necessary.
All later dimensioning will be according to the true model size, not the view size.

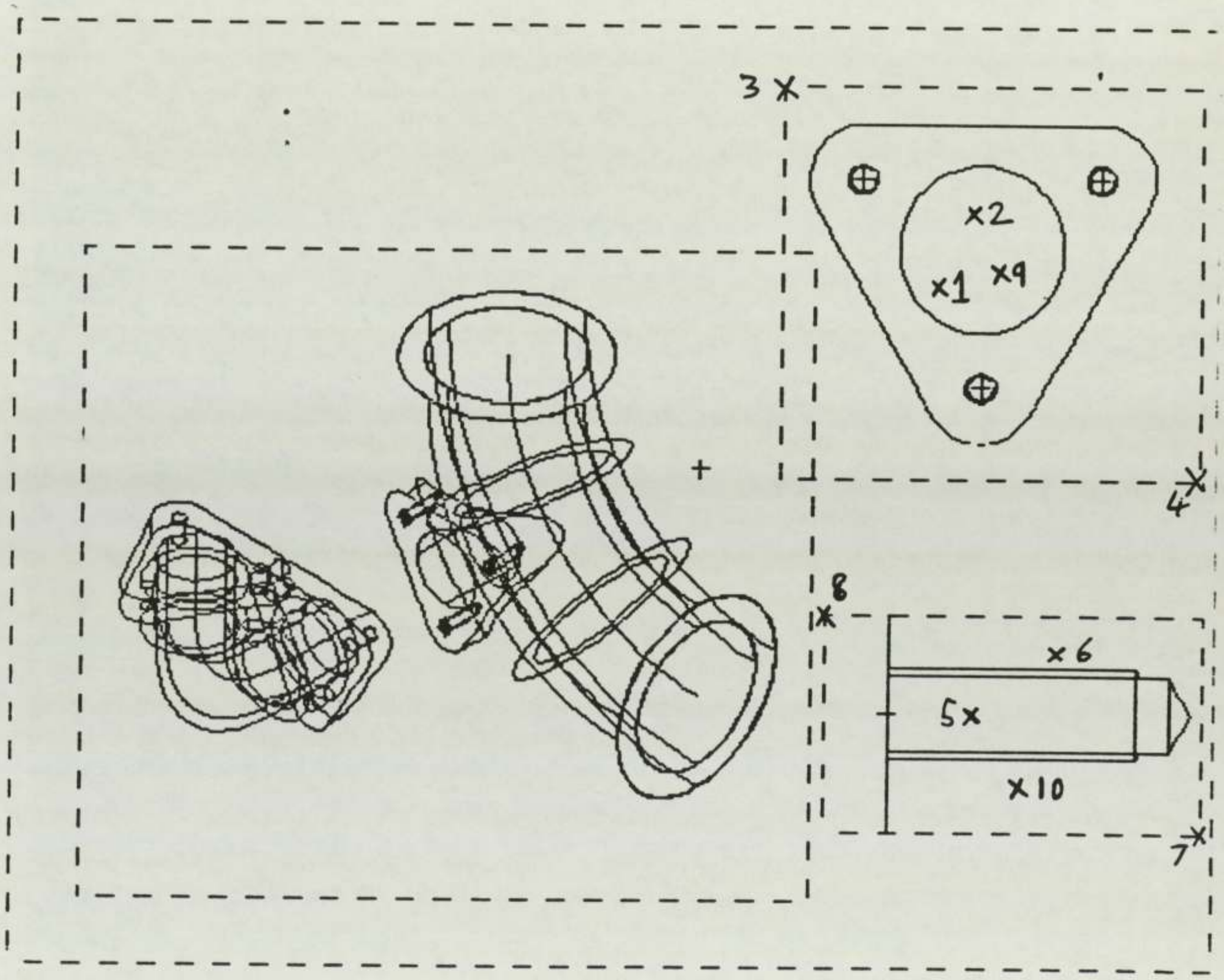


FIG 22

To set these magnified views
#01# SET VIEW: view d9 d10

Construct angled drill hole and section through drill hole

Ref Fig 11

```
#01#SEL LAY 9
#01#ECHO LAY Ø 1 170
#01#ROT ENT COPY ANGLE 15: MODEL ent WIN d1 d2 POI d3
#01#INS CIRCLE DIAM 27.8: MODEL loc POI d3
#01#INS POI: MODEL loc INTOF d4 d5
#01#SEL CPL 3
#01#INS LIN ANGLE 60: MODEL ent d6 MODEL loc POI d7 loc X-60
#01#CHA APP FONT SOLID ALLVIEWS: MODEL ent d8
```

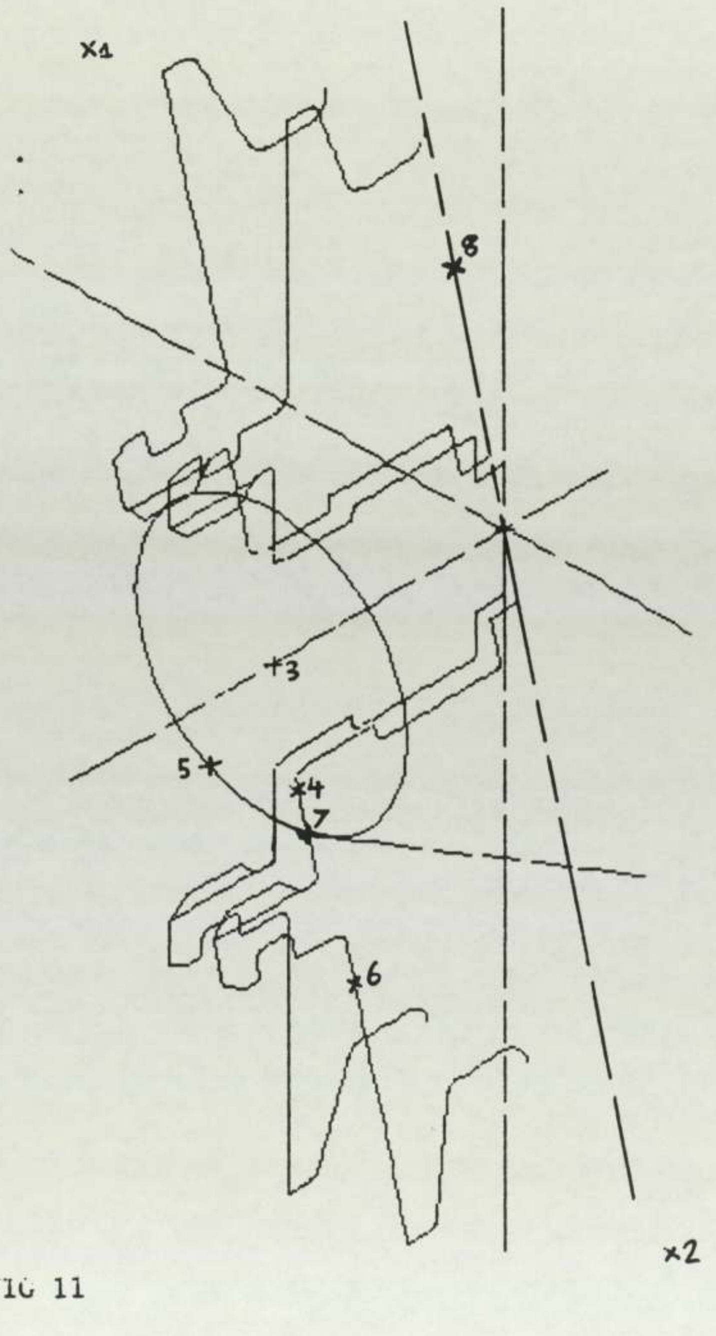


FIG 11

Ref Fig 12

#01#TRIM ent: MODEL ent END d1 model loc IX-10

Define a CPL named DRILL which is normal to the drill hole axis. Digitise d2 represents the origin of the CPL, d3 the +ve Z direction vector and d4 the X direction vector.

```
#01#DEF CPL DRILL NORMAL: MODEL loc END d2 d3 d4
#01#SEL CPL DRILL
#01#INS CIRC DIAM 3.0: MODEL loc END d5 d6
#01#DEL ENT: MODEL ent d7 POI D8
```

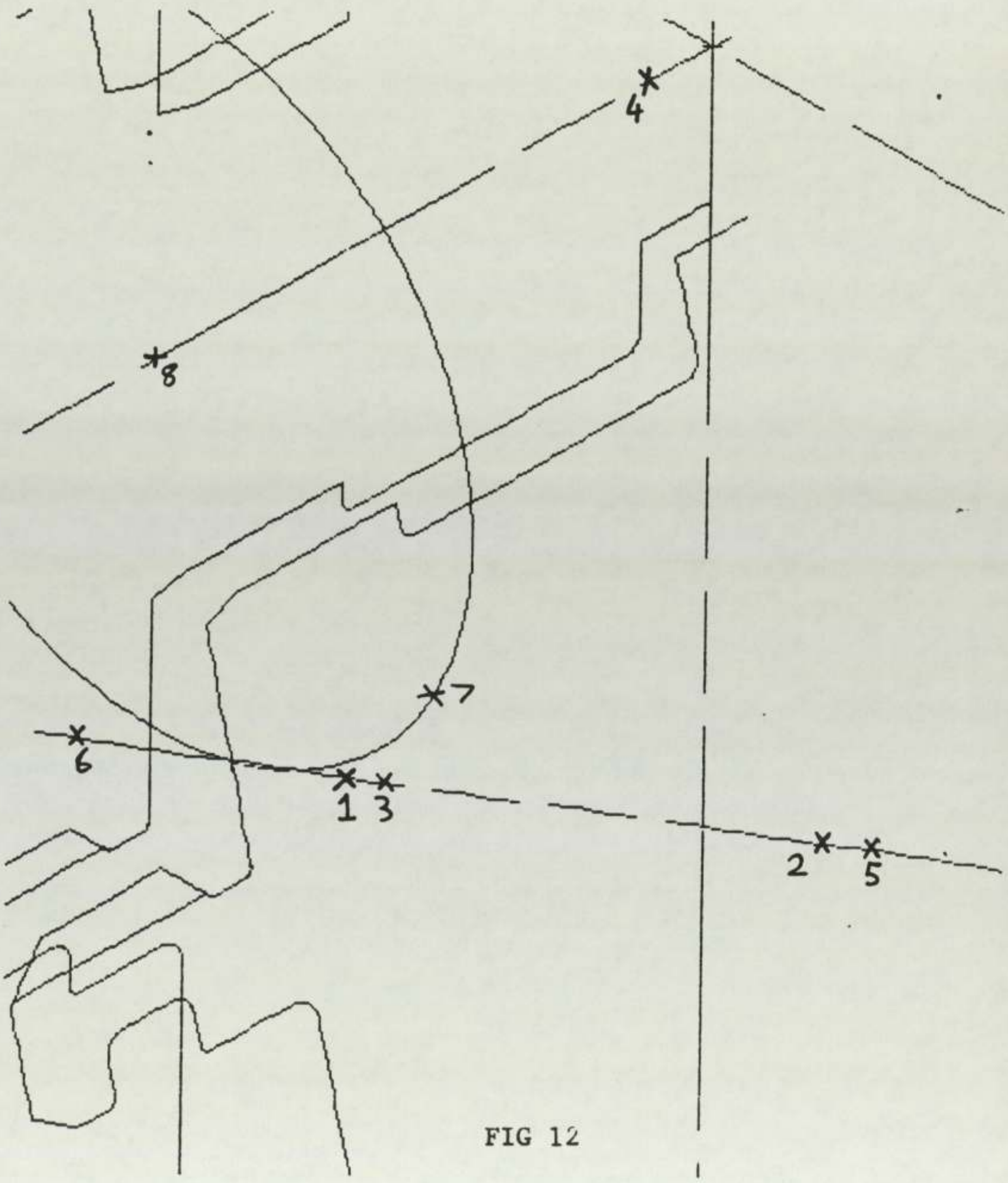


FIG 12

Ref Fig 13

```
#01#INS RSURF MESH 4 x 4: MODEL ent d1 d2
#01#INS SREV MESH 3 x 3: MODEL ent d3 d4; MODEL loc END d5 d6
#01#CUT SURF: MODEL ent d7 d8:
              solution in progress
              MODEL ent d7 d9
              solution in progress
#01#DEL ENT: MODEL ent SREV d8 d9
```

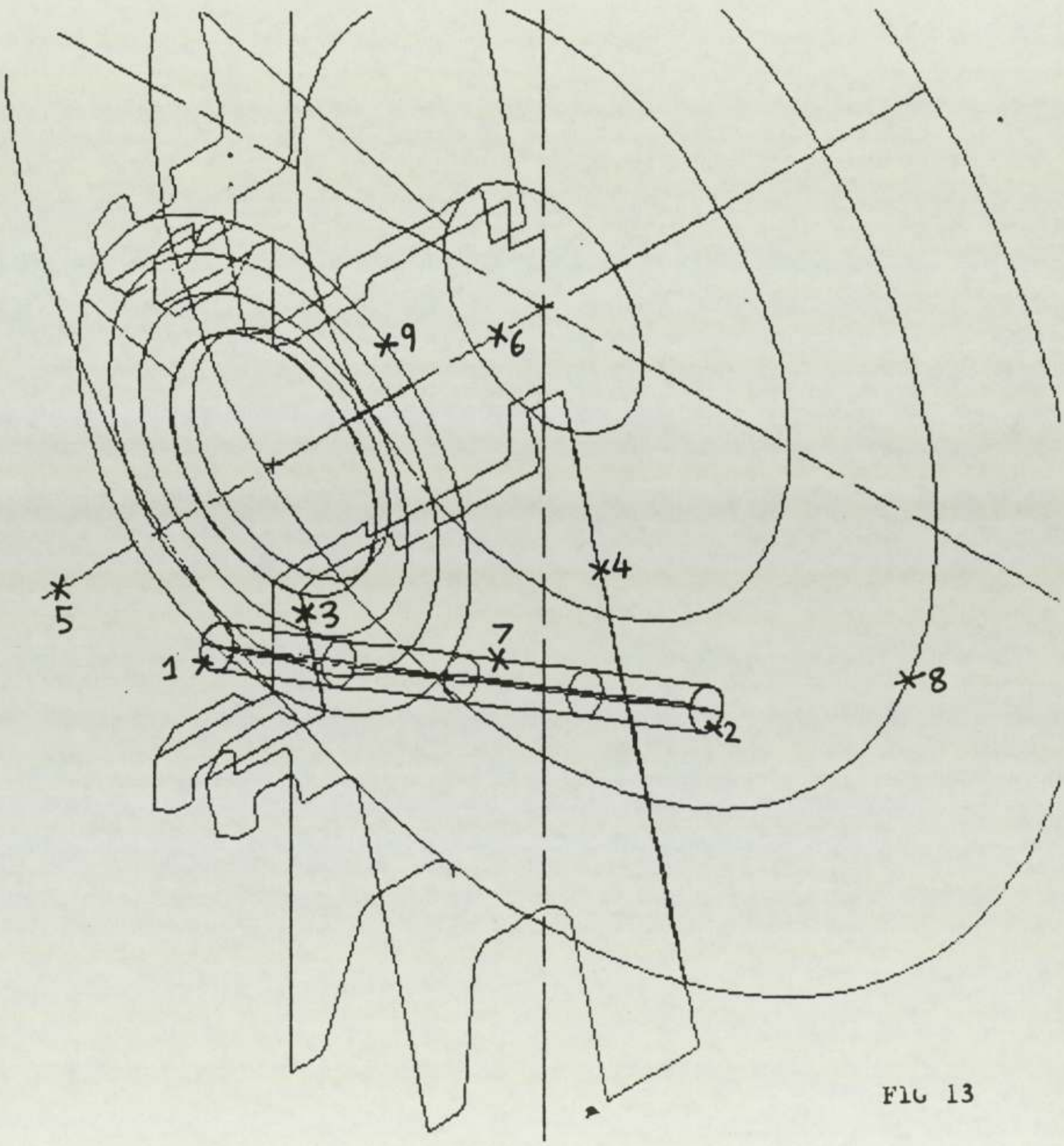


FIG 13

Ref Fig 14

```
#01#INS RSURF  MESH 4x4; MODEL ENT d1 d2
#01#CUT SURF: MODEL ent d3 d4
              solution in progress
#01#DEL ENT: MODEL ent RSURF d3 d4 CIRC d5 d6
```

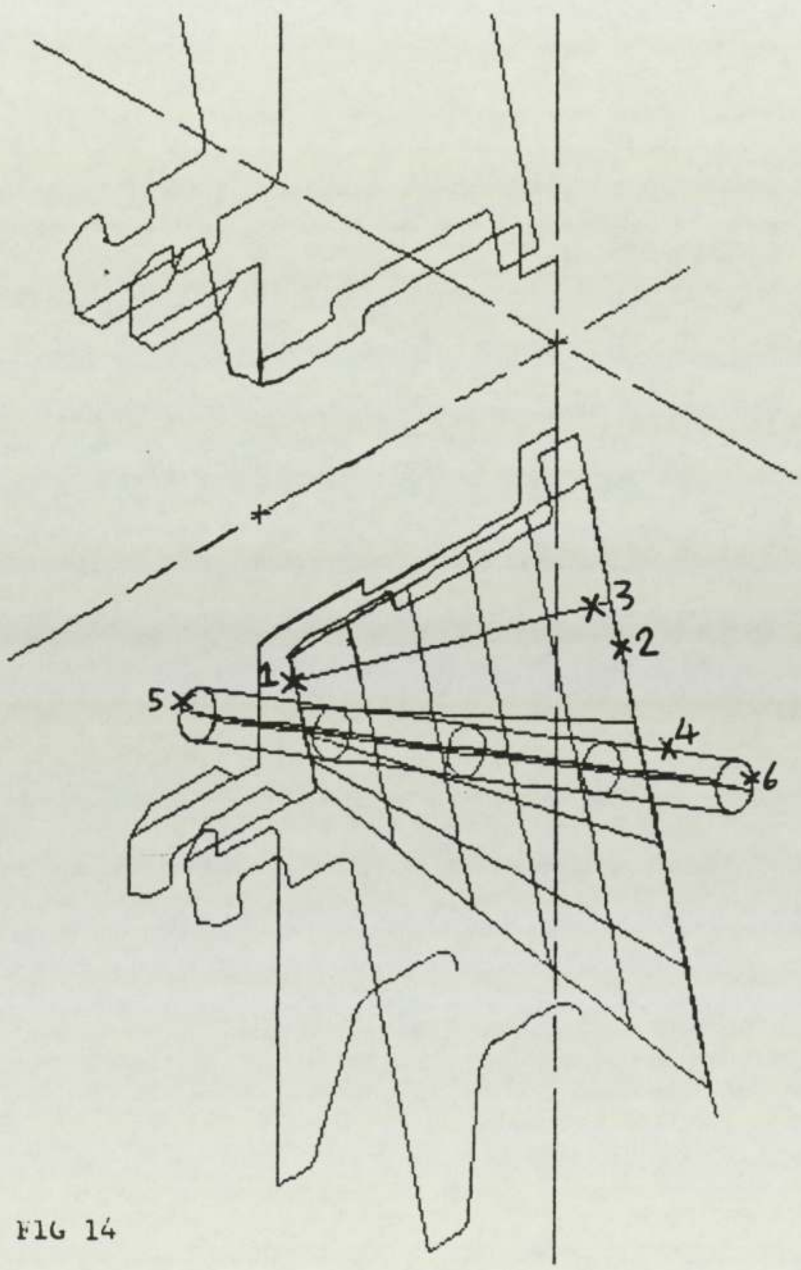


FIG 14

Ref Fig 15

Translate ENT Copy 2 crosswire centre lines to the 2 new centres of the compound drilling.

Move the entries to more suitable layers before detailing

#01#CHA LAY 3: MODEL ent d1 d2 d3
#01#CHA LAY 7: MODEL ent d4 d5 d6
#01#CHA FONT MM PHANTOM ALLVIEWS LAY 170: MODEL ent d
TRIM ENT to complete the full sectional form of the section C-C.

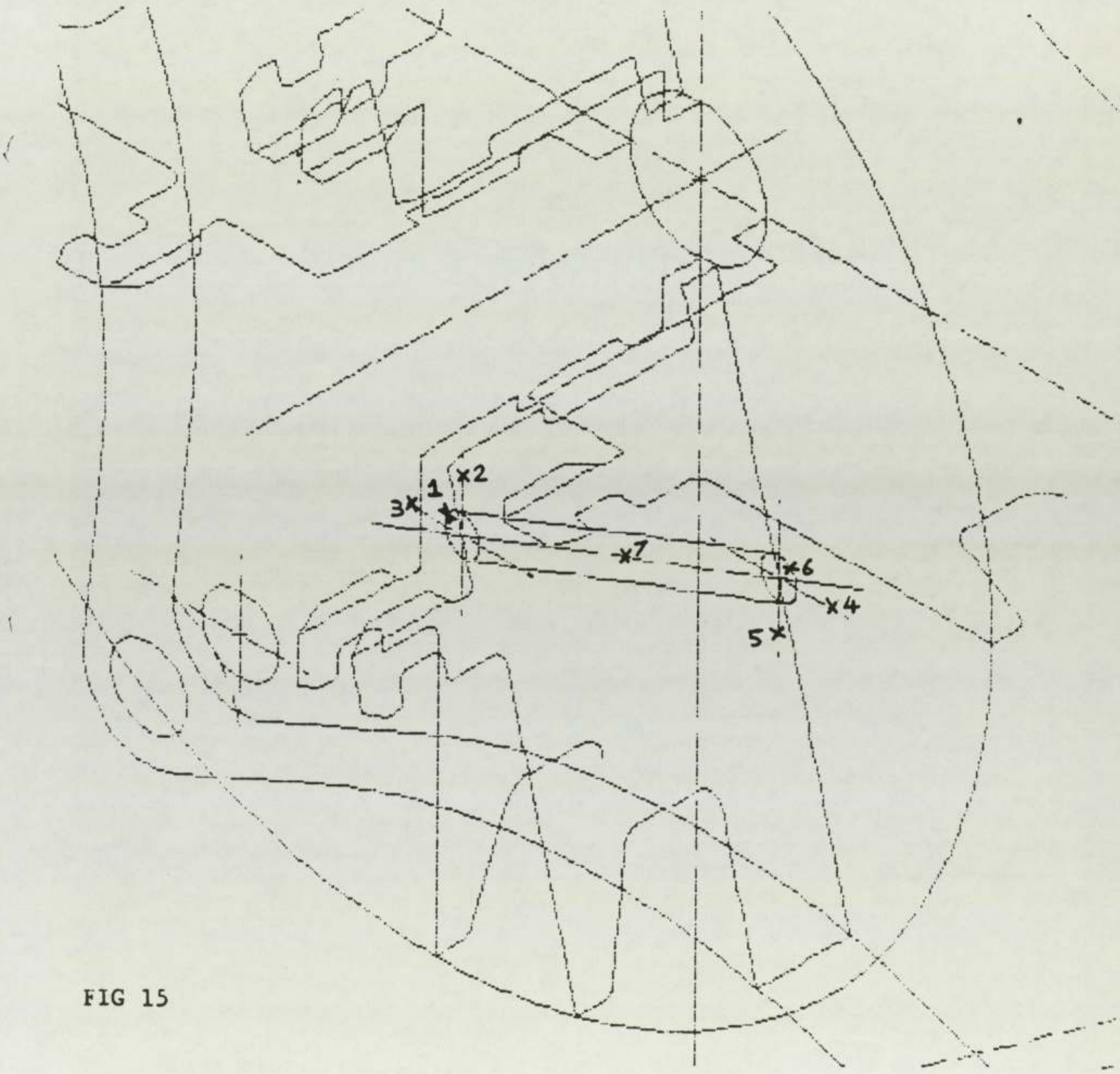


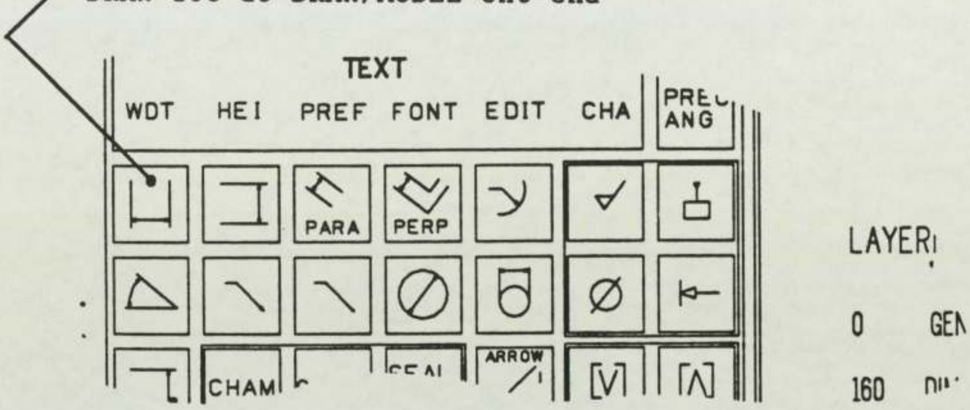
FIG 15

(i) INSERTING HORIZONTAL DIMENSIONS

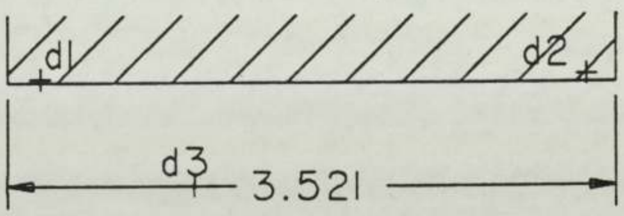
To insert a horizontal dimension, we need to specify the two ends of the entity to be dimensioned, and a third point for the location of the dimension text.

Command Syntax:

#01# INSert LDImension HORizontal: DRAW/MODEL ent-end d1d2 DRAW loc d3 DRAW/MODEL ent-end

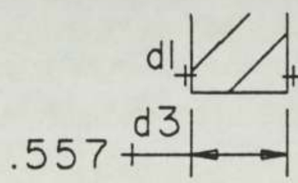


EXAMPLES

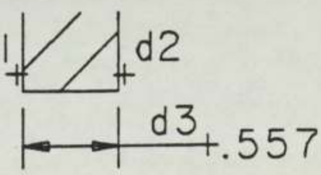


If the third digitize is outside the extension lines, the result will be as follows:

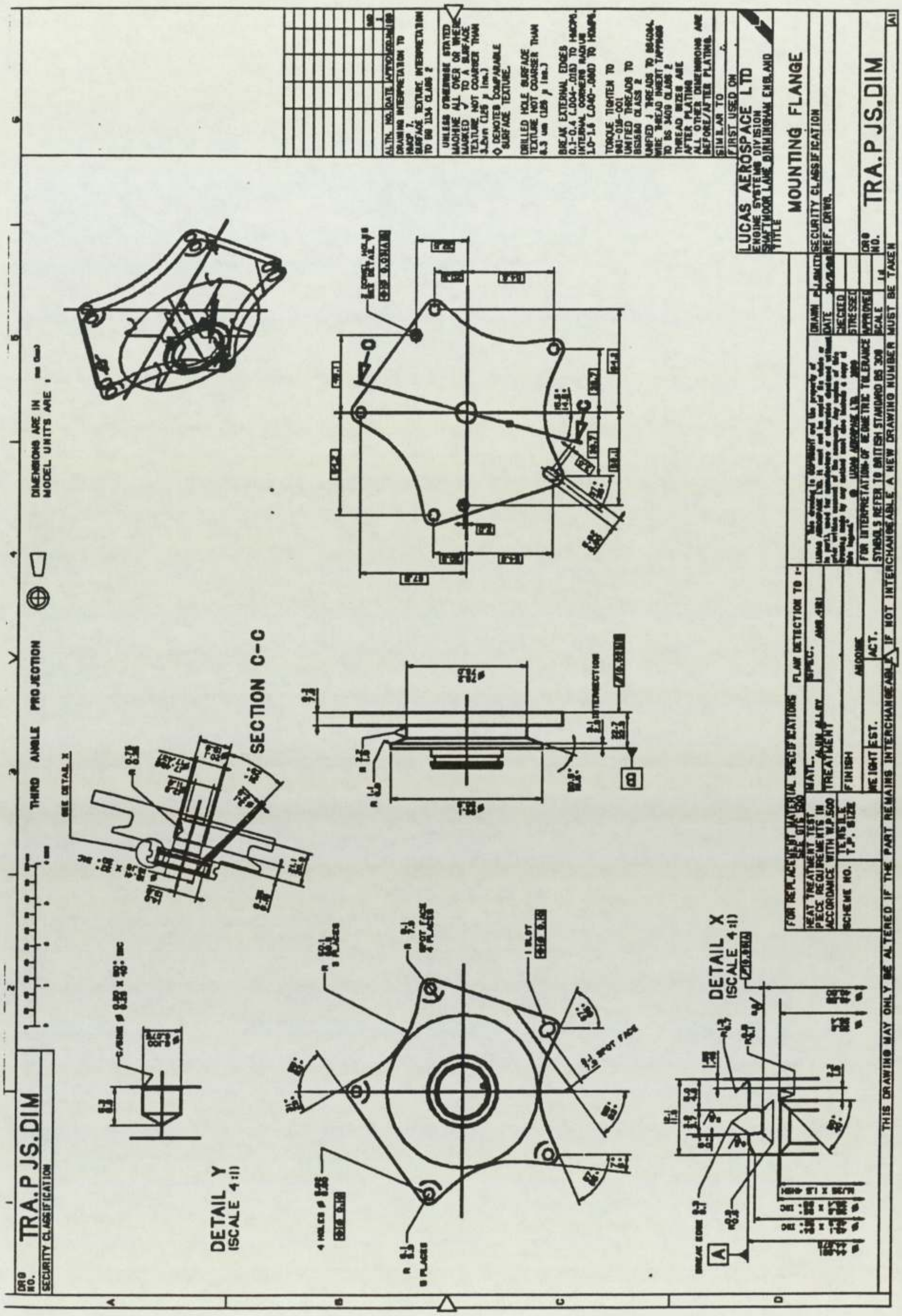
either

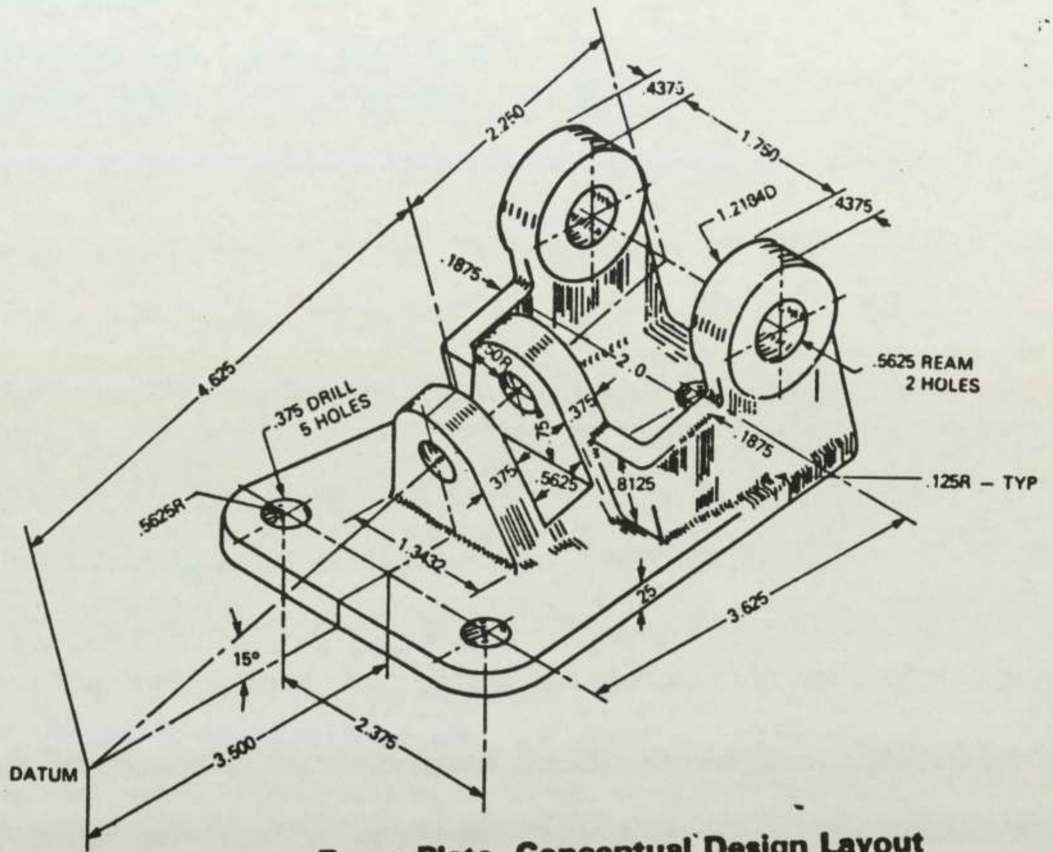


or

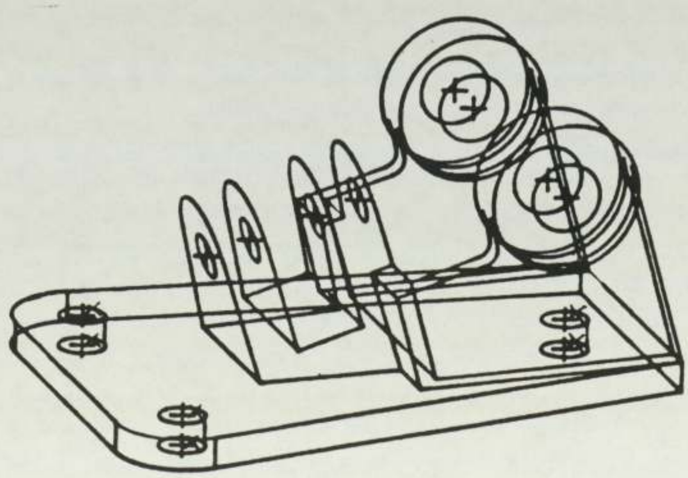


If there is inadequate space between the extension lines, the arrows, will be flipped automatically. In some cases, the dimension text will also be flipped outside the extension lines.


THIRD ANGLE PROJECTION
DIMENSIONS ARE IN
MODEL UNITS ARE 1
SECTION C-C
DETAIL X
(SCALE 4:1)
DETAIL Y
(SCALE 4:1)
LUCAS AEROSPACE LTD
MOUNTING FLANGE
TRA.P JS.DIM
THIS DRAWING MAY ONLY BE ALTERED IF THE PART REMAINS INTERCHANGEABLE IF NOT INTERCHANGEABLE A NEW DRAWING NUMBER MUST BE TAKEN



Brace Plate, Conceptual Design Layout



P J Smith T.C.A.

Appendix (3)

MULTIPLE SHEET/FRAME DRAWING

Forming one large drawing which contains all the individual sheet drawings of one part has advantages over forming a part which is made up of many individual sheets. The greatest advantage is speed of moving from one sheet to another. Alterations to the model on one sheet, means that the other individual sheets require to be regenerated before they can be displayed.

For a complex part containing many entities with many views on separate sheets, the delay can be of the order of a few hours per displayed sheet. However if all these sheet drawings are contained on one large sheet, then this one large sheet then behaves as a normal 1 sheet part allowing changes to be seen in all views immediately.

This large sheet then contains very many views which are broken into manageable sets of images by drawing frames.

Method

activate the part as normal

#ACT PART OPN.PJS.MSHT

activate the drawing with frame to the desired size - A0 using the keyfile (Ref fig 1)

#ACT DRA A FORM ABW5.FRAME.A0 DRAW A

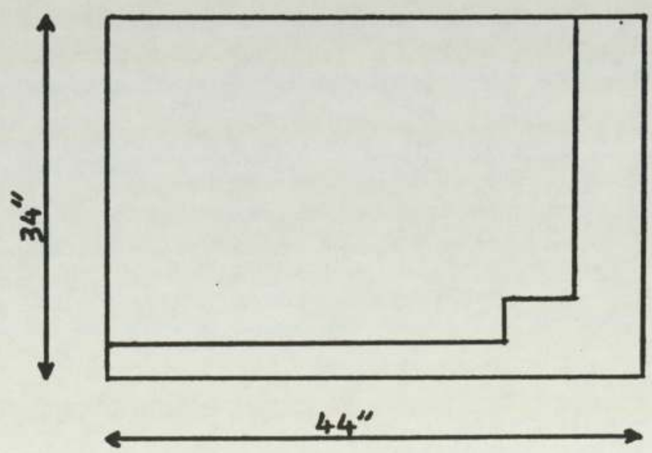


FIG.1

Call up the drawing frame input the model text required.

#DRG FRA

Follow this by activating a dummy drawing, as you cannot enlarge a drawing whilst in that drawing (DRA A).

#ACT DRA DUMMY

If we desire say 6 sheets with a format of 3 x 2 sheet drawings (Ref fig 2) each of size A0 and a size A0 drawing is 34" x 44" then

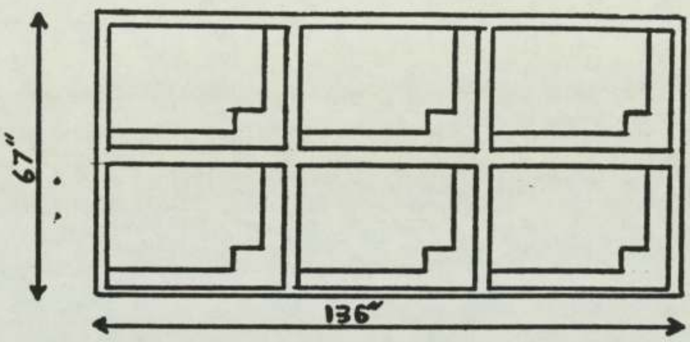


FIG.2

the new drawing ought to be at least

34 x 2 = 64" in height
44 x 3 = 132" in width

add approx. 1" to the boundary and between drawing frames to give a requirement for a sheet approx. 67" in height and 136" in width. If a metric part was specified then metric units must be used i.e. height 1700 width 3450 mm.

Enlarge draw A to fulfill this requirement

#ENLARGE DRA A HEI 67 WIDTH 136

#ACT DRA A

(Ref fig 3) note the origin of the drawing and frame is in the bottom left hand corner.

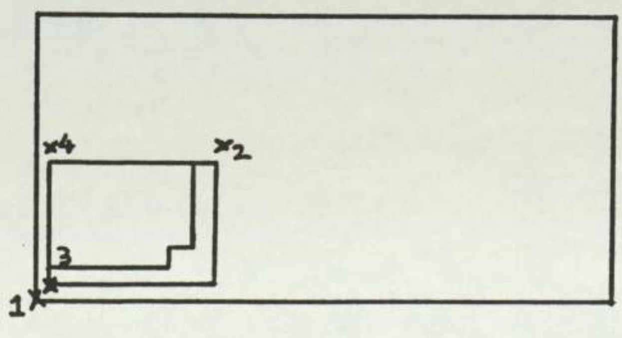


FIG.3

Copy the drawing frame and translate it to the other required positions on the large sheet in DRAW MODE.

#TRANS Ent copy: DRAW ent win dl d2; Org d3 loc d4

Similarly this can then result in providing the 6 required frames (Ref fig 4). Each drawing frame's nodal text is then edited to suit that individual sheet e.g sheet no.

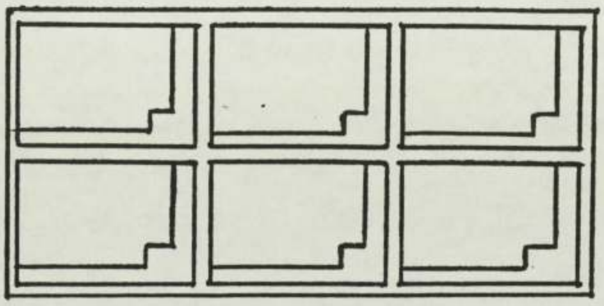


FIG.4

Using a similar technique the drawing can be further enlarged again or even reduced to encompass the latest requirements of the part.

Do's and Don'ts

Give each sheet/frame an Image no. and always call up that sheet/frame using RESTORE IMAGE.

e.g. give sheet/frame no. 1   Image no. 1
        sheet/frame no. 2   Image no. 2   etc

Don't forget and use ZOOM DRA ALL unless you really do want all the sheets/frames to be viewed simultaneously as zoom DRA ALL can take a long time for a complex set of drawing sheets/frames to appear.

Plotting Multi Frame Sheets

Remember, the plotter can not plot drawings of size A0 due to the width, so all A0 size drawing sheets must be rotated and plotted sideways.

(Ref fig 5) To plot one of these A0 sheets, use a window or just restore the required Image before plotting

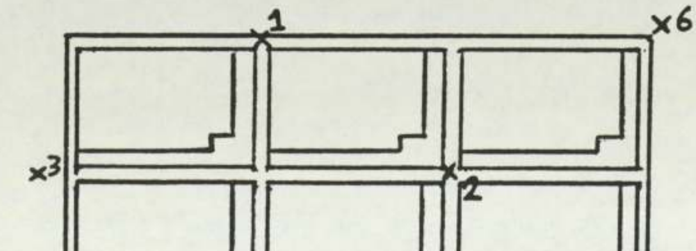


FIG.5

RESTORE IMAGE 3

PLOT DOT ROT

or

ZOOM DRA WIN : DRAW loc d1 d2

PLOT DOT ROT

A string of drawing sheets can be printed sideways rather like a roll.

ZOOM DRA WIN : DRAW loc d3 d4

PLOT DOT ROT

Or if the drawing sheets are only in 2 rows then all the sheets can be printed together as a block at 1/2 scale. If 3 rows 1/3 scale etc.

ZOOM DRA WIN : DRAW loc d5 d6

PLOT DOT ROT SCALE 0.5

Entity Manipulation

Parts that require multiple sheets are usually complex with many entities and views. Keeping track of view status and any erased entities can often be confusing, especially towards the end of job when alterations can unwittingly ruin other views which were previously correct. Some techniques for large parts have been developed which may prove useful, particularly after the model views have been converted into manufacturing views.

If revising the location of a view, then any Draw Mode entities will be left in place. In Draw Mode unrelate the entities (in case they are already related to another view by virtue of being copied entities). Having done this, relate just the desired Draw Mode ents to that view which needs moving. The view can now be moved complete with dimensions/text and any cosmetic lines. The view can be moved from say frame/image 2 to 5 as they are both on the one large sheet.

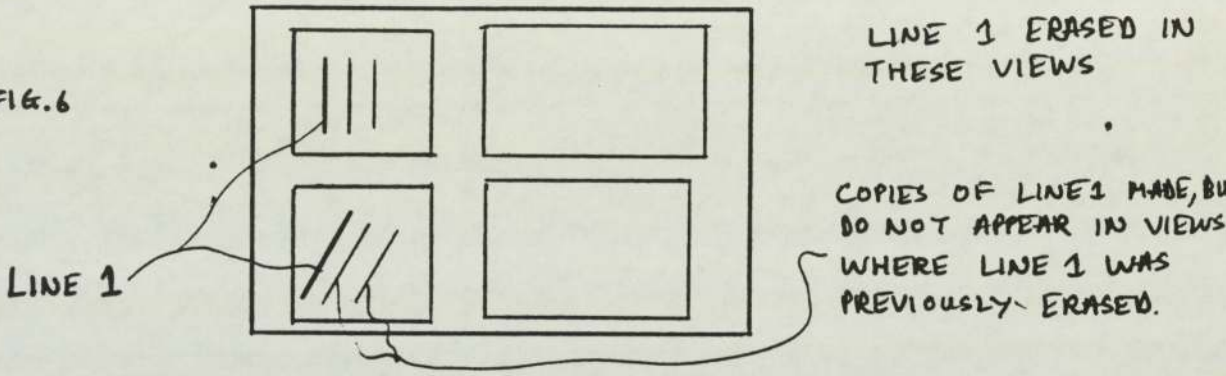
Unrelate View : Draw ent Win d d
Relate View : view d, Draw ent Win d d
Revise View Location : view d loc d d

Another good idea is to create a view on one frame in which every entity is erased. Thus after a phase of construction, every new entity formed in this phase can be clearly seen in this otherwise blank view. These freshly constructed lines can then be erased in the blank view and in any other desired views.

This technique reduces the risk of entities accidently being formed and left in other views which don't require these new entities, particularly already completed manufacturing views.

Another useful technique with a similar objective uses the idea of copying erased lines. If an entity is erased in a view and copies of that entity are made in another non-erased view, then these copied entities will not show in the erased view. These copied entities can then be stretched, changed, rotated, trimmed and divided etc without effecting the erased views. (Ref fig 6)

FIG.6



This idea can be put to good effect by setting up some dummy lines either in or next to the isometric 3-D model. These dummy lines could consist of one line in the X, Y and Z direction with perhaps one or two circles and fillets. These dummy ents would then be erased in all the other views.

Then as entities were required in a particular view the required ones could be Re-Echoed back into that view. These would then be copied onto the desired layers and/or trimmed, rotated etc. This would mean that no further erasing of these new construction entities in other completed views would be necessary. Again useful if completed manufacturing views exist.

Appendix (4)

BEASY/FEA Results - Taken From the GKN Technology Report
By G.Thompson

	PROBLEM DESCRIPTION	THEORETICAL SOLUTION	MEAN VAL. OBTAINED	MEAN % ERROR	CPU TIME	DISC SPACE	NO. OF ELEMENTS	NO. OF NODES
	STRAIGHT CANTILEVER:							
	PAFEC linear elts	2.0	2.124	6.2	0:05:51	1340	32	45
	BEASY linear elts	2.0	2.186	9.3	0:01:07	1206	24	48
	BEASY linear elts (2 zones)	2.0	2.18	9.3	0:01:11	1571	28	56
	PAFEC quadratic elts	2.0	2.05	2.5	0:06:53	1710	32	121
	BEASY quadratic elts	2.0	2.02	1.1	0:02:11	2615	24	72
	CURVED CANTILEVER:							
	PAFEC quadratic elts	1.47262	1.49471	1.5	0:06:52	1700	30	113
	BEASY quadratic elts	1.47262	1.48587	0.9	0:01:30	1792	20	60
	CRACKED BODY:							
	PAFEC quadratic elts	8.0	7.032	12.1	0:06:47	1668	30	115
	BEASY quadratic elts	8.0	7.848	1.9	0:02:04	2533	24	48
Figure A(10)	**RECTANGULAR BAR:**							
	BEASY constant elts	7.68F-3	6.98E-3	9.0	0:03:20	1746	40	40
	BEASY constant elts (2 zones)	7.68E-3	7.14E-3	7.0	0:02:46	1849	41	41
	PAFEC linear elts	7.68E-3	3.32E-3	56.8	0:06:30	1488	16	44
	BEASY linear elts (2 zones)	7.68E-3	7.68E-3	0.0	0:57:02	27045	40	160
	PAFEC quadratic elts	7.68E-3	5.67E-3	26.1	0:12:51	2815	16	141
Figure A(12)	BEASY quadratic elts	7.68E-3	7.68E-3	0.0	9:13:07	134400	40	360
Figure A(13)	PAFEC quadratic elts (realistic mesh)	7.68E-3	7.01E-3	8.7	8:04:18	70746	512	2777
	LITTLE END:							
Figure A(14)	PAFEC quadratic elts	-------	-------	----	0:37:26	9700	203	1274
Figure A(15)	BEASY quadratic elts	- CRASHED -	INSUFFIC.DISC SPACE		2:00:00	335148+	63	567

Table 1 The results of the PAFEC and BEASY analyses

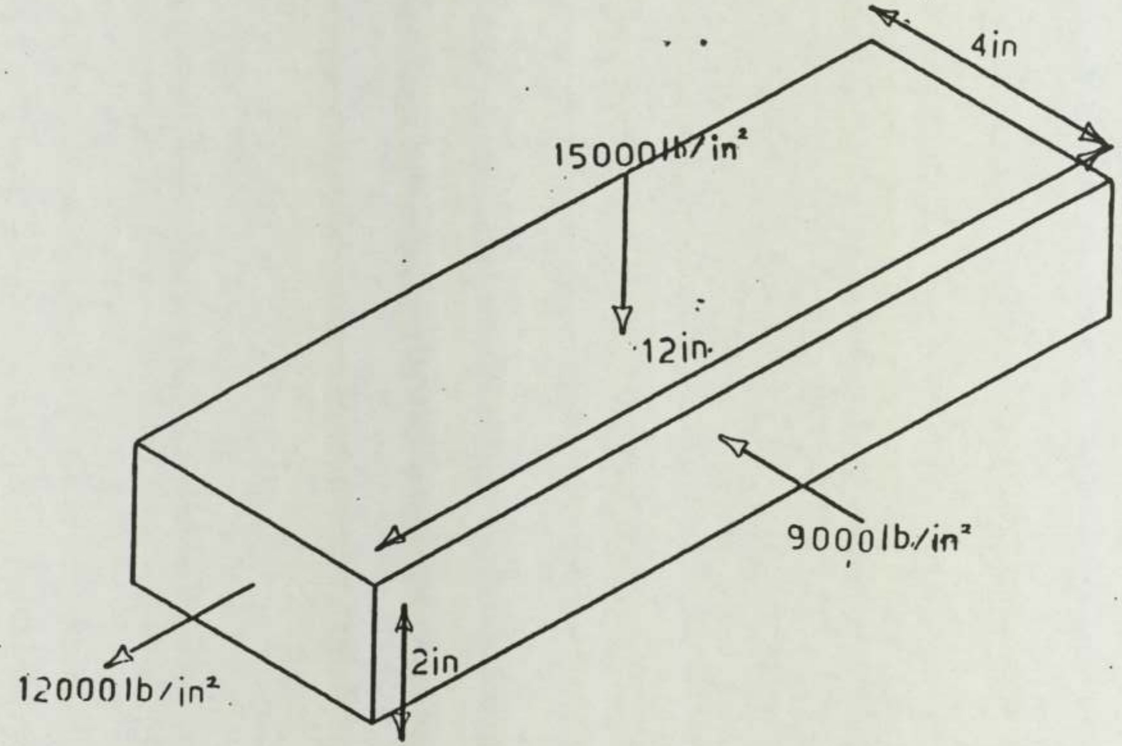
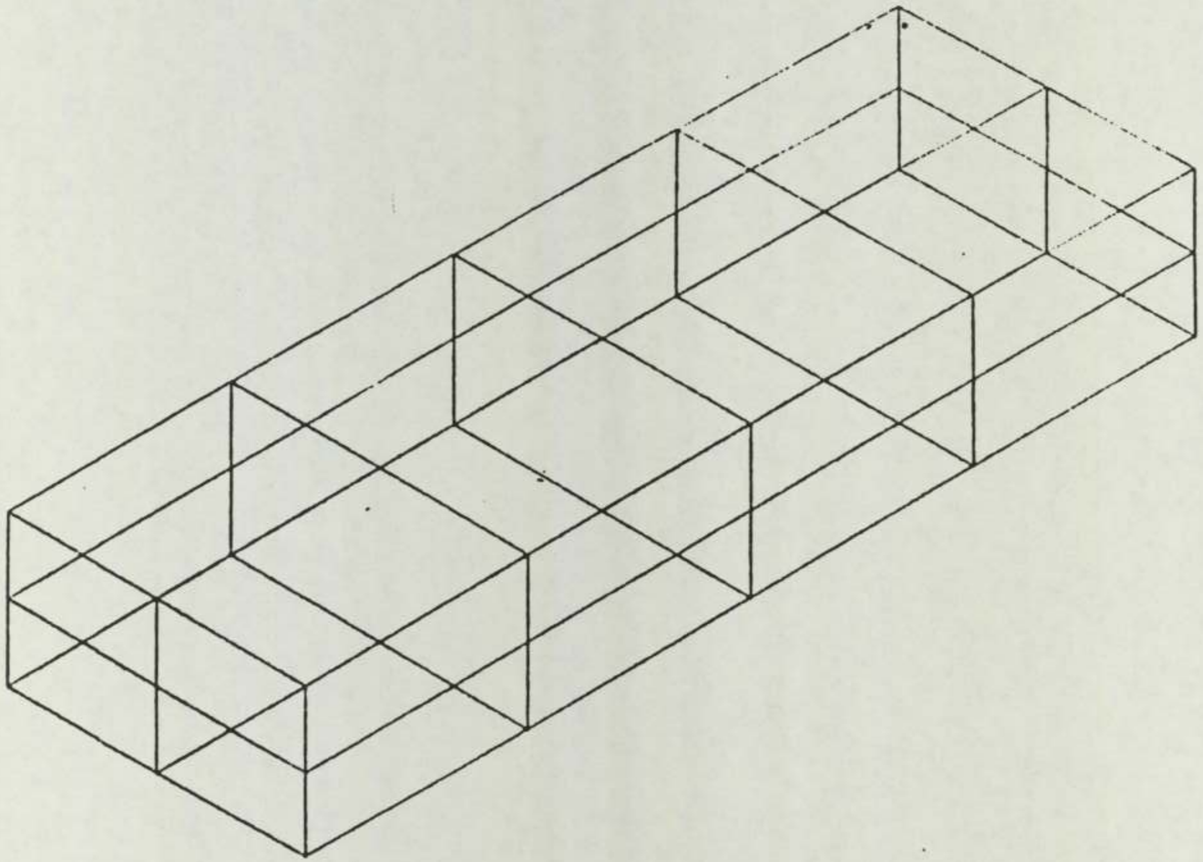


Figure A(10). The rectangular steel block test problem.



FigureA(12). BEASY mesh for the rectangular steel block.

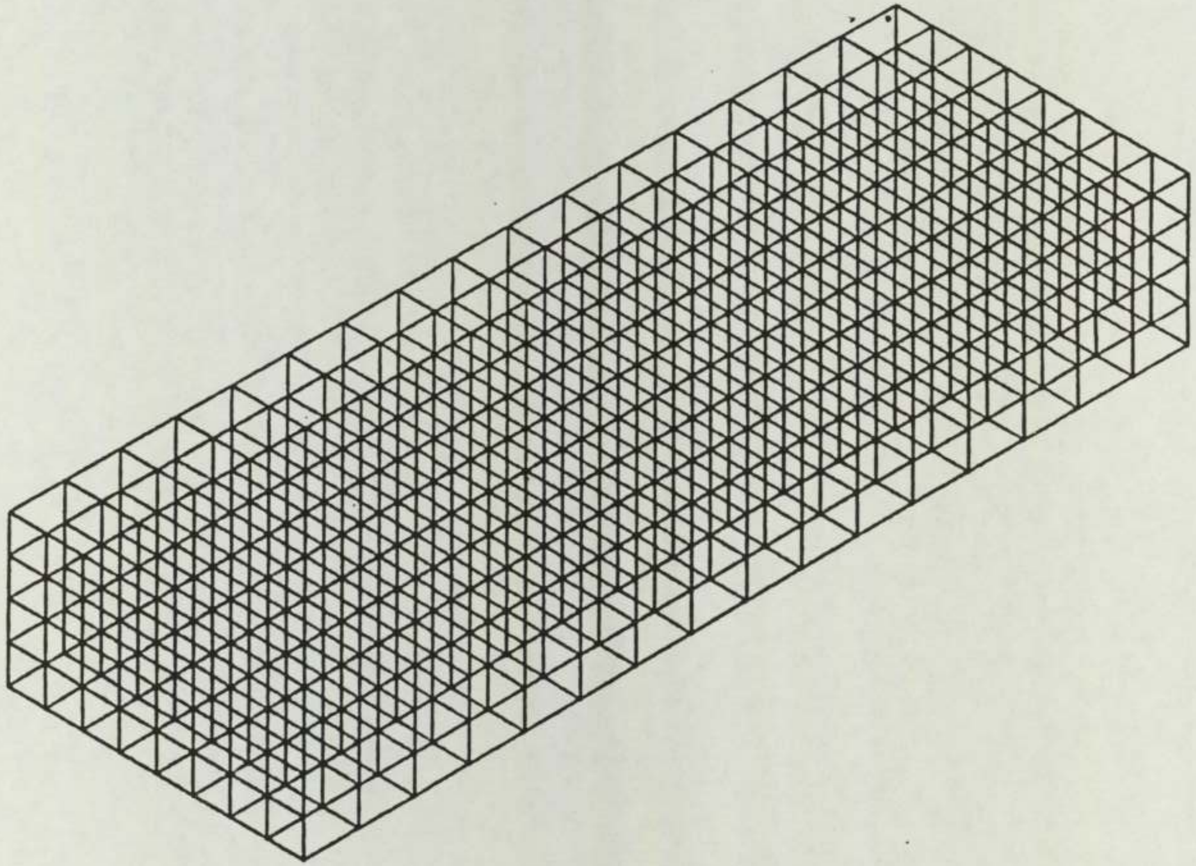
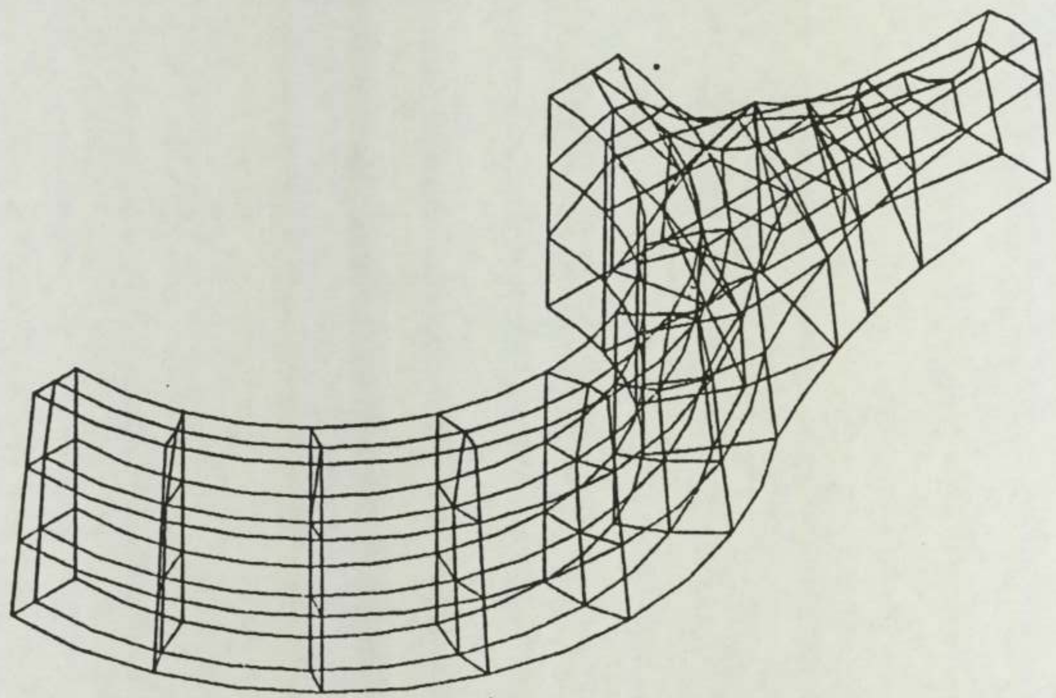
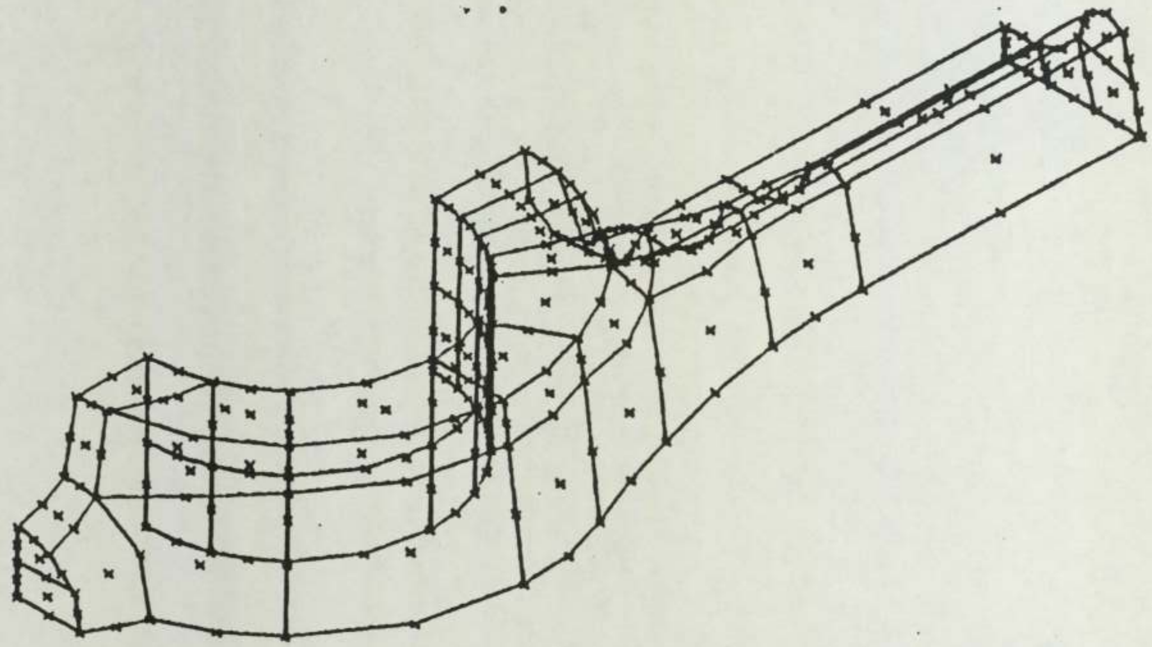


Figure A(13). Refined PAFEC mesh for the rectangular steel block.



FigureA(14). PAFEC mesh for the little end of a conrod (quarter model).



FigureA(15). BEASY mesh for the little end of a conrod (quarter model).

Appendix (5) Deckel DZ4 Machining Statements

Typical Example Of 'Canned Cycle'

L84 (Tapping)

The following R parameters must be defined.

R02 Reference Plane
R03 Final Depth
R04 Dwell (0.3)
R06 Spindle Reversal
R07 Original Spindle Direction
R10 Clearance Plane

Action

Rapid to R02
Feed in to R03
Dwell R04 and reverse spindle R06
Feed out to R02
Rapid retract to R10 and reverse spindle R07

```
L8400(TAPPING)
G0 G90 G60 ZR02
G01 G63 ZR03
G04 FR04 MR06
ZR02
@03 5 R02 R10
R11 0 R10
@00 10
N5 R11 0 R02
N10 G60 G0 ZR11 MR07 M17
```

L86 (Planetary Milling)

The following R parameters must be defined.

R02	Reference Plane
R03	Final Depth
R04	Radius Offset (100-199)
R06	Rapid or feed in to depth (00 or 01)
R10	Clearance Plane
R12	Radius to be cut
R13	Cutter Radius
R17	Lift off in Z on run-off arc (0 or .003")

Action

Rapid to R02
Feed or rapid in at R06 to R03
Position X and Y to start of run on arc and activate R04
Mill run on arc
Mill radius R12
Mill run off arc and lift off in Z R17
Rapid X and Y to hole centre and cancel R04

Note:

Radius offset R04 (100-199) must be loaded at start of program with cutter radius value.

```
L8600(PLANETARY-MILLING)
G00 G60 G90 ZR02
@03 10 R13 R12
GR06 ZR03
R16 0 R12
R21 0 R13
R14 0.5
R21 R16
R14 . R21
R16 - R14
R15 0 R16
G91 G41 DR04 X- R15 YR14
G03 X- R14 Y- R14 PR14
X0 Y0 IR12 J0
XR14 Y- R14 PR14 ZR17
G00 G41 D00 XR15 YR14
N10 @03 20 R02 R10
R11 0 R10
@00 30
N20 R11 0 R02
N30 G90 G00 ZR11 M17
```

Sample Programme Involving
'Jump' Statements.

● 01, ● 02, ● 03 "Conditional jump"

Application: The conditional jumps permit program branching dependent upon the condition:
equal to ● 01
larger than ● 02
larger than or equal to ● 03

Programming: ●.. ± 1234 R.. R..

Command and jump condition

The jump target precedes (-) or follows the jump command. The control searches for the jump target in the defined direction

Block number of the jump target, max 4 decades

R-parameter comparison for the conditional jump:
1st parameter equal to the 2nd parameter ● 01
1st parameter larger than the 2nd parameter ● 02
1st parameter larger than or equal to the 2nd parameter ● 03

1st parameter

The control compares the parameter contents in the mathematical sense
(e.g. – 213 is smaller than – 7)

2nd parameter

● 00 "Unconditional jump"

Application: With a conditional (absolute) jump, it is possible to jump over parts of a program. The jumped blocks are not executed.

Programming: ● 00 ± 1234

Command: Unconditional jump

The jump target precedes (-) or follows (+) the jump command. The control searches for the jump target in the defined direction.

Block number of the jump target max. 4 decades

For a special case, an R parameter and its sign can be added in order to generate different jump targets. This special case is shown on the right hand side of the following figures.

'Jump' cont.

```
N520 G80
N530 R30 R31
N540 @02 560 R30 R40
N550 @00-500
N560 L924 R01 500 R02 0941 (3/8 RIPPER)
N570 R30 0 R31 120 R40 240
N580 G X Y1.28 G43 D04 Z2. B R30
N590 G Y1.28 Z.93 B R30
N600 G1 Z.65 F4. G64
N610 Y1.41 F2.
N620 X-.180
N630 Y.3
N640 X.180
N650 Y1.41
N655 X
N660 Y1.28 Z.93 G60 F100.
N670 R30 R31
N680 @02 700 R30 R40
N690 @00-590
N700 L924 R01 1500 R02 118 (1/4 END MILL)
N710 R30 0 R31 120 R40 240
N720 G X-.9 Y.88 G43 D05 Z2. B R30
N730 G Y.88 Z.795 B R30
N740 G1 X.9 F4.
N750 Z.93 F100.
N760 G G41 D105 X Y1.28
N770 G1 G64 Z.57
N780 X-.249 Y1.492 F2.
N790 Y.228
N800 X.249
N810 Y1.492
N820 X-.249
N830 Y.228 F5.
N840 X.249
N850 Y1.492
N860 X-.249
N870 G60 X Y1.28 Z.93 F100.
N880 G41 D00 X-.9 Y.88
N890 R30 R31
N900 @02 920 R30 R40
N910 @00-730
N920 L924 R01 300 R02 0839 (5/8 END MILL)
N930 R30 60 R31 120 R40 300
N940 G X-1.4 Y.565 G43 D06 Z2. B R30
N950 G Y.565 Z.937 B R30
N960 G1 X F2.
N970 Y.443
N971 Z1.2 F10.
N972 Z.937 F2.
N980 Y.565 F10.
N990 X1. F2.
N1000 X-1.4 F50.
N1010 R30 R31
N1020 @02 1040 R30 R40
N1030 @00-950
N1040 L924 R01 2000 R02 0841 (DRILL .120 IN FACE)
N1050 R30 60 R31 120 R40 300
N1060 G X Y.214 G43 D07 Z2. B R30
```

N710 Parameter Statement R30 = 0
R31 = 120
R40 = 240

N730 'B R30' Rotate About the B Axis to Parameter Value R30

N890 'R30 R31' R30 = R30 + R31

N900 Conditional Jump , if R30 Larger Than R40 ,Jump to Line N920

N910 Unconditional Jump ,Jump to Line N730 —to Repeat the Machining Cycle.

Appendix (6)
SAMPLE DZ4 NC PROGRAMME

3D-SIM-DZ4-F

```
[A
[$
[N120
["PARTNO/OPN.PJS.NCMODEL2
[N120
[S     0
DEL2<>
N0020 G59 N1 X5.593 Y2.594 Z2.563 B0. <>
N0030 G59 N2 X13.843 Y2.594 Z0.563 B0. <>
N0040 G59 N3 X3.343 Y2.594 Z-0.187 B0. <>
N0050 G59 N4 X3.744 Y4.844 Z-2.985 B0. <>      Store Local Datum Offsets
N0060 G59 N5 X14.344 Y4. Z-1.562 B0. <>
N0070 G59 N6 X2.841 Y4.251 Z-1.562 B0. <>
N0080 G59 N7 X7.468 Y4.251 Z2.564 B0. <>
N0090 G92 D01 D5.0 <>
N0100 G92 D02 D5.0 <>
N0110 G92 D03 D9.0 <>                          Store Tool Lengths
N0120 G92 D04 D6.75 <>
N0130 G92 D05 D5.0 <>
N0140 G92 D06 D10.0
N0150 L907 R021712                             Get Tool No. 1712
N0160 L924 R011500 R021815                     Load Tool ,Start Spindle at 1500 rpm
N0170 M57 G54 L999                             Get Tool No. 1815
N0180 G00 X0. Y0. B180.
N0190 X0. Y0. <>
N0200 X8.7484 Y4.75 <>
N0210 G43 D01 Z4. <>
N0220 Z0.25 <>                                 Call First Local Datum Offset
N0230 Z0. <>
N0240 X-1.0016 <>                              'G43' Load 'D01' Tool Offset Length
N0250 Y4.25 <>
N0260 X8.7484 <>
N0270 Y3.75 <>
N0280 X-1.0016 <>
N0290 Y3.25 <>
N0300 X8.7484 <>
N0310 Y2.75 <>
N0320 X-1.0016 <>
N0330 Y2.25 <>
N0340 X8.7484 <>
N0350 Y1.75 <>
N0360 X-1.0016 <>
N0370 Y1.25 <>
N0380 X8.74     <>
N0390 Y0.75 <>
N0400 X-1.0016 <>
N0410 Y0.25 <>
N0420 X8.7484 <>
N0430 Z0.25 <>
N0440 Z4.
N0450 M57 G55 L999                             Call 2nd Local Datum Offset
N0460 X0. Y0. B90.
N0470 X3.2484 <>
N0480 Z3.9973 <>
N0490 Z0.2473 <>
N0500 Z-0.0027 <>
N0510 X2.4984 <>
N0520 X0.2484 <>
N0530 Y0.75 <>
N0540 X2.4984 <>
N0550 Y1.25 <>
N0560 X0.2484 <>
N0570 Y1.75 <>
N0580 X2.4984 <>
N0590 Y2.25 <>
N0600 X0.2484 <>
N0610 Y2.75 <>
N0620 X2.4984 <>
N0630 Y3.25 <>
```

SAMPLE DZ4 NC PROGRAMME CONT.

```
N1080 X-0.0004 Y5.5 <>
N1090 Z0.25 <>
N1100 Z4.
N1110 L924 R012000 R021665             Load Tool , Start Spindle at 2000 rpm
N1120 M57 G57 L999                     Get Tool No. 1665
N1130 G00 X0. Y0. B297.5           Call 4th Local Datum Offset
N1140 X0. Y0. <>
N1150 X0.0003 Y0. <>                    Rotate About B Axis 297.5 Degrees
N1160 G43 D02 Z0.2501 <>
N1170 G81R020.25R03-0.15R100.25F5.5 <>
N1180 G80
N1190 L924 R011750 R021805               'G81' Drilling,Centering 'Canned Cycle
N1200 M57 G57 L999
N1210 G00 X0. Y0. B297.5                 'G80' Cancel Cycle
N1220 X0. Y0. <>
N1230 X0.0003 Y0. <>
N1240 G43 D03 Z0.2001 <>
N1250 G83R002.R010.75R020.4R033.R042.R050.5R100.35F7. <>
N1260 G80
N1270 L924 R010060 R021712              'G83' Peck Drilling 'Canned Cycle'
N1280 M57 G57 L999
N1290 G00 X0. YO. B297.5                'G84' Tapping Cycle 'Canned  Cycle'
N1300 X0. Y0. <>
N1310 X0.0003 Y0. <>
N1320 G43 D04 Z0.3001 <>
N1330 G84R020.3R032.R040.3R0604R0703R100.9F3. <>
N1340 G80 <>
```

```
N2710 X0.2513 Y2.9996 <>
N2720 Z0.25 <>
N2730 G83R004 R010.2R020.1R03-0.75R044.R050.25R100.25F5. <>
N2740 X2.2513 Y2.9991 <>
N2750 X2.2507 Y0.9991 <>
N2760 X0.2507 Y0.9996 <>                'G83' Peck Drilling 'Canned Cycle
N2770 G80 <>                                  at 4 Locations

                                        'G80'  Cancel Cycle
```

Appendix (7)
DZ4 Simulation Programme
Operating Instructions.

Peter Smith T.C.A.
June 1987

DZ4 Simulation Program

This program simulates all the actions of the DZ4 machining centre. This program displays on the CADCAM terminals every motion of the tool relative to the workpiece and fixture. This includes CANNED cycles, Do-loops, Movement between consecutive toolpaths, movements to an from the home position and of course the toolpaths themselves.

The program warns of possible collision situations due to insufficient tool withdrawals or tool movements into an area which the fixture/component is rotating in. Additionally, from the display, the operator can see if the toolpath is incorrect, or if the datum offsets have been entered incorrectly.

The programme requires that the 3-D component model and fixture be located in the exact position in space relative to the machine tool origin (also model origin of part), see Fig 1. The fixture and component should also be in the exact 'B' axis position which has been assumed as the starting point of the N.C. program. If the PREFAB model is used, layers 1-7 will be used. In any case, layers 1-98 are reserved for the model. Layer 100 for non rotating details such as the home and datum position. Layer 99 the original piece of material or billet. Layer 0 contains the fixture, clamps and any rotating information. Layers 101-199 are reserved for the toolpaths.

To run the simulation program enter:-

#01# RUN CVM SOP.PJS. PRACTISE

The program then asks for the NC Tape file name:-

ENTER FILENAME OF THE N.C. PROGRAMME YOU WISH TO SIMULATE?

ENTER FILENAME: NC TAPE. T909090
enter name

The programme then asks the operator to confirm the name of the program, or if he wants to re-enter the NC Tape name.

NAME OF FILE NC TAPE.T909090
ENTER Y or N: Y

Y continues, but N asks for a repeated entry of the file name.

Select radius of swept cylinder. The circle produced should just surround every rotating part of the components/clamps i.e. the parts which when rotated could cause a collision Fig 2.

SELECT RADIUS OF SACRED CIRCLE
ENTER RADIUS VALUE: 6.25   enter value

The program draws the circle in this case of radius 6.25 and the operator has the option then to delete this one and replace it with another.

RADIUS SATISFACTORY, Y or N: Y

enter Y to continue, enter N to delete circle and re-enter another value for the circle radius.

When selecting the toolpath layers, it is a good idea that all the motions of the first tool should go onto layer 101. All the motions of the second tool on layer 102, third tool layer 103 etc. This does simplify any later checking work for the operator. As the layers increment sequentially with the tools then only the first used layer needs to be specified.

SELECT LAYER FOR 1ST TOOLPATH - GREATER THAN 100 SUGGEST 101
ENTER LAYER No: 101   enter value

Note if the operator wanted to see the third tool used first, he would select layer 103, and later ask to see the third tool used first.

Interactive mode, is when the operator wants to see each move and needs the facility to stop and consider the output at various stages. Non-interactive or automatic mode runs the program through with no stops, once the initial set up information is entered. Usually interactive mode will be selected.

INTERACTIVE MODE? ENTER Y or N: Y

Y switches to interactive mode, N switches to automatic.

When in interactive mode, the following facilities are available.

To simplify the views and thus aid understanding, there is the facility to view only selected layers ater each rotation and at the beginning. Layer 0, 99, 100 and the current toolpath layer are always shown. The operator merely selects the desired viewing layers of the 3-D model. Once selected, the operator has the option to re-select the viewable layers.

ENTER COMPONENT VIEW LAYER/S: 7 2-4
entered layers

views then show layers 0, 99, 100 and 7 and 2 - 4 inclusive

LAYERS SATISFACTORY, Y or N: Y

enter Y to continue, N to re-select the layers.

Sometimes, the operator may only wish to see a selection of tools, rather than the full programme. He is given this opportunity and asked to enter the first tool and the last tool he wants to see. If he wishes to see only tool no. 5, he would select layer 105, and enter 5 to both questions. If he wanted to see tools 4 - 9 inclusive, he would select layer 104 and answer 4 to the first question and none to the second one. After tool 9 has been displayed, the program asks the operator if he desires to see another selection of tools, or if he wishes to quit.

DO YOU WANT TO SIMULATE THE FULL N.C. PROGRAM (Y) OR JUST A SLECTION OF THE TOOLPATHS (N)?

If Y is entered, the program continues. If N is entered, the program asks,

START TOOLPATH SEQUENCE NUMBER: 4
INCLUDED FINISH TOOLPATH SEQUENCE NUMBER 9

Once toolpath 9 is displayed, the program asks

VIEW MORE SELECTED TOOLPATHS (Y) OR EXIT (E)?

If E is entered, the program stops. If not, then it asks for the starting and included finish tool number, as above.

When the component is due to be rotated, the program stops and produces the toolpath up to that point. In addition it produces a small DISC and a POINT. The movement from this DISC to the POINT occurs simultaneously in real time with the rotation of the fixture/component. The programme produces an arc about the point of rotation, which subtends an angle which is equal to the angle of rotation of the fixture/component Fig 3. The magnitude of this angle is also printed out. On the end of the arc is pointer indicating the direction of rotation. If during a rotation command, the POINT or the motion between the DISC and POINT breaks into the sacred cirle/cylinder at any positions, then a collision may occur and the system warns the operator with a message and prints out the block no. of the command. The operator can then make a judgement, by looking at the toolpath display on the views, to see if an actual collision occurs. He then has the option to continue or exit the program.

Regardless of mode (interactive/automatic) the program prints out at the end, all the block nos where errors or collisions might have occurred.

The programme is to be used to check the output from the CAM system before it goes to the shop floor for tape prove out. It will detect major errors, but it is unrealistic to expect it to locate tolerance errors. This can only be done on the actual machine tool after cutting the component.

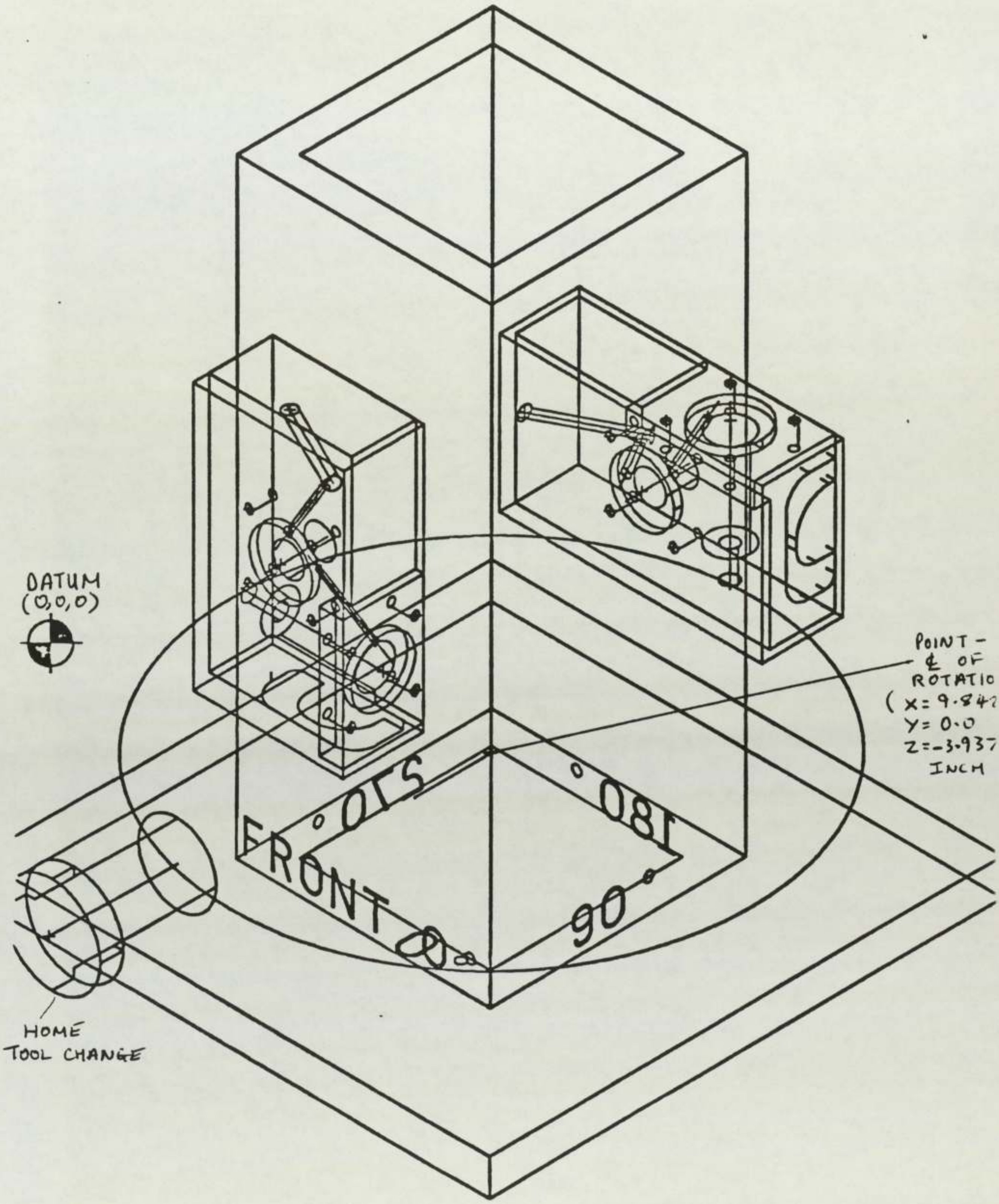

DATUM
(0,0,0)
POINT -
℄ OF
ROTATIO
(x= 9.842
y= 0.0
z=-3.937
INCH
270
180
FRONT
90
0
HOME
TOOL CHANGE

FIG 1

B=0°

i

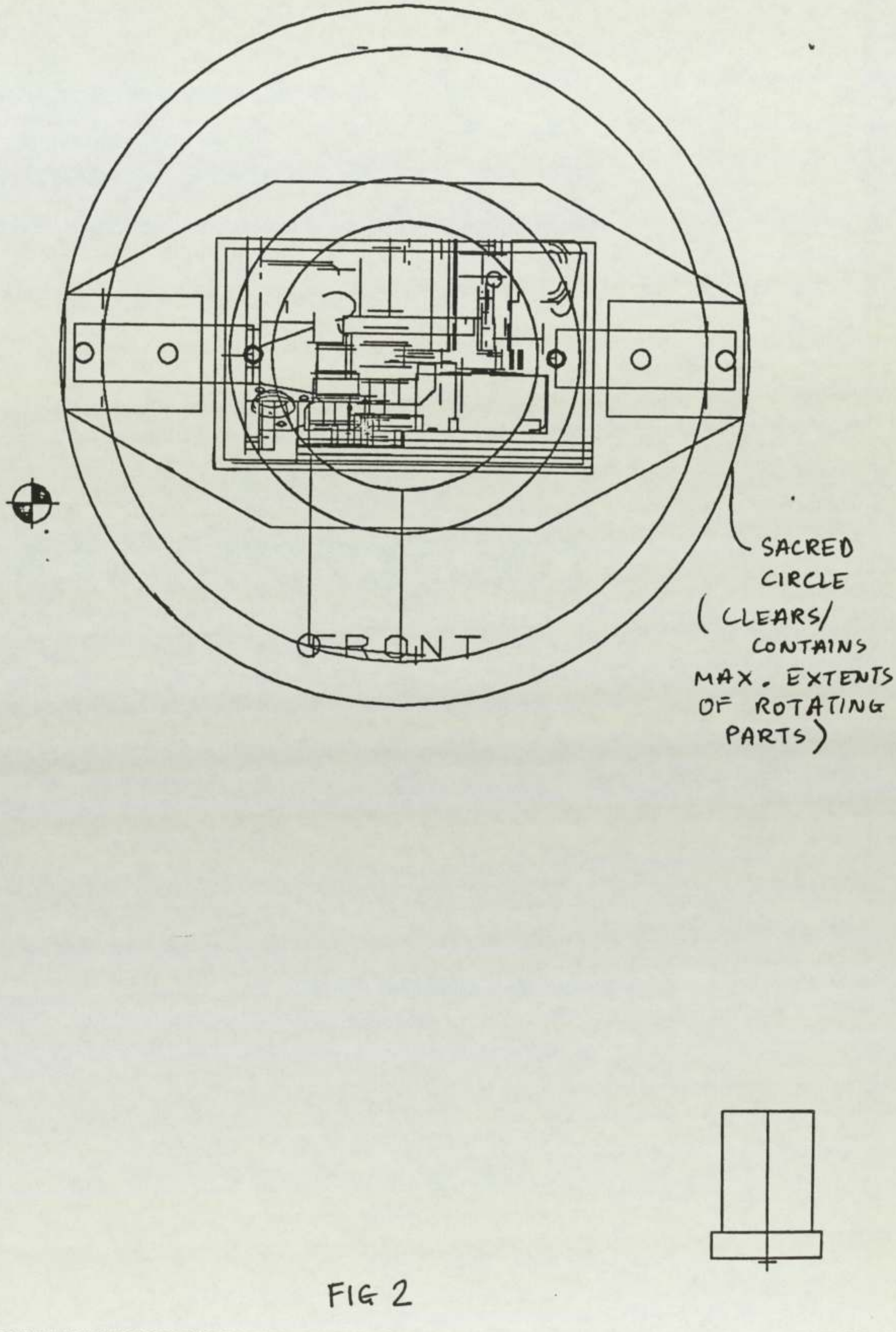

FRONT
SACRED CIRCLE (CLEARS/ CONTAINS MAX. EXTENTS OF ROTATING PARTS)

FIG 2

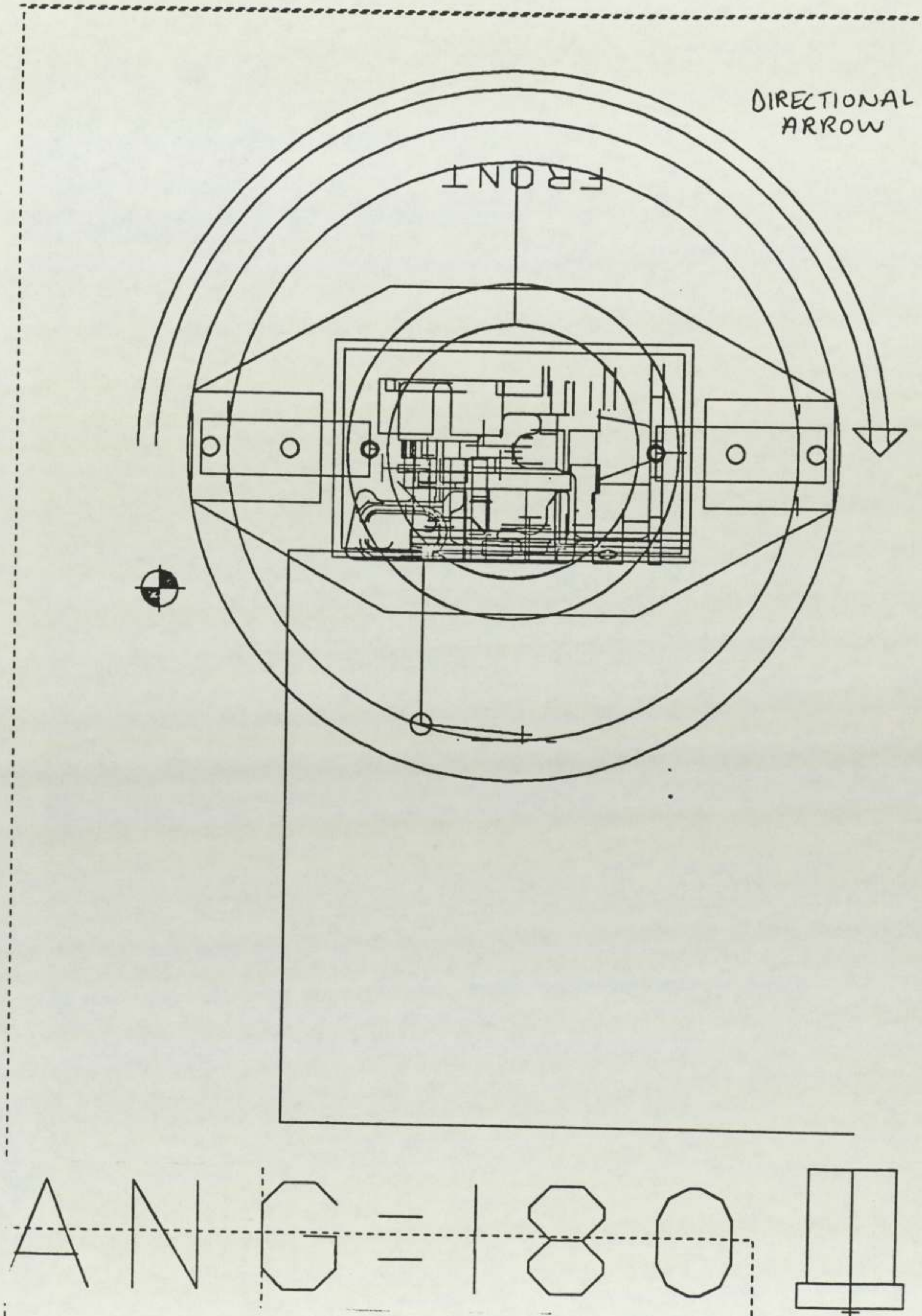


FIG 3

Appendix(8) Simulation Programme Listing

```
        IF (&LINE(8,9).GE."04") GOTO 15  <# IF G CODE > THAN 3 GOTO 15

        DECLARE VECTOR @VO(13)
        DECLARE REAL BO(12)
        DECLARE REAL TOFF(70)
        DECLARE ENTITY $ENT(500)
        X=0,Y=0,Z=0,X1=0,Y1=0,Z1=0,F=0,B=0,B1=0,E=0
        GAP=0.04,ANGL=0,I=0,J=0,K=0,N=1,LAYR=102
        PRINT SOP.PJS.PRACTISE
        PRINT ************************************************
        PRINT *                                              *
        PRINT *             DECKEL DZ4 N.C. SIMULATION       *
        PRINT *                                              *
        PRINT *             PETER SMITH     DEC. 1986        *
        PRINT *                                              *
        PRINT ************************************************
#2      PRINT ENTER FILENAME OF THE N.C. PROGRAMME YOU WISH TO SIMULATE ?
        READ (ENTER FILENAME : ) &FN
        PRINT NAME OF FILE (&FN)
        READ (ENTER Y OR N : ) &ANS
        IF (&ANS ="N") GOTO 2
        SELECT (LAYER) LAYR      <# SELECT LAYER FOR TOOLPATH
        SELECT (ACS) "2"      <# SELECT CPL 2 OR FRONT
        OPENR 1,&FN
#1      READL 1,&LINE     <# READ FROM NCTAPE FILE
        PRINT (&LINE)
        PRINT (&LINE(1))
        IF (&LINE(1) = "N") GOTO DATA       <# REMOVE NONE DATA
        IF (&LINE(1) = " ") GOTO DATA
        PRINT NOT DATA
        GOTO 1
#DATA PRINT(&LINE(2,5)) (&LINE(8,9))  (&LINE(9,11))
        N =N +1
        BN =&LINE(2,5) ,NSFI =7
        PRINT CYCLE NOT CONTINUOUS
        IF (&LINE(7) ="M") GOTO 18       <# IF M CODE GOTO 18
        PRINT NOT M
        IF (&LINE(7) ="L") GOTO 10       <# IF L CODE GOTO 10
        PRINT NOT L
        IF (&LINE(7).NE."G") GOTO 5      <# IF G CODE CONT. GOTO 5
        PRINT GCODE
        IF (&LINE(8,9).GE."04") GOTO 15  <# IF G CODE > THAN 3 GOTO 15
        PRINT LESS THAN 04
        NSFI =11
        WHEN (HFLAG =1)  <# RESET VALUES AFTER PREVIOUS OFFSET INPUTS
         X =0
         Y =0
         Z =0
         B =0
         HFLAG =0
        ENDWHEN
        IF (&LINE(9) ="0") &GCODE ="G00"
        IF (&LINE(9) ="1") &GCODE ="G01"
        IF (&LINE(9) ="2") &GCODE ="G02"
        IF (&LINE(9) ="3") &GCODE ="G03"
        PRINT (&GCODE)  GCODE
```

```
#5    WHEN(&LINE(NSFI) ="X")   <# ASSIGN VALUES FROM DATA
       GOSUB SIGF
       X = VAL
       PRINT SIGF RETURN
      ENDWHEN
      WHEN(&LINE(NSFI) ="Y")
       GOSUB SIGF
       Y = VAL
      ENDWHEN
      WHEN(&LINE(NSFI) ="Z")
       GOSUB SIGF
       Z = VAL
      ENDWHEN
      IF (CYCC =1) GOTO CCON  <# IF CYCLE CONT. ,GOTO CCON
      WHEN(&LINE(NSFI) ="I")
       GOSUB SIGF
       I = VAL
      ENDWHEN
      WHEN(&LINE(NSFI) ="J")
       GOSUB SIGF
       J = VAL
      ENDWHEN
      WHEN(&LINE(NSFI) ="K")
       GOSUB SIGF
       K = VAL
      ENDWHEN
      WHEN(&LINE(NSFI) ="B")
       GOSUB SIGF
       B = VAL
       ANGL =B -B1
      ENDWHEN
      IF (NFLAG =1) GOTO 16    <# IF ASSIGNING OFFSET VALS. GOTO 16
      WHEN(&LINE(NSFI) ="F")
       GOSUB SIGF
       F = VAL
      ENDWHEN
      IF (N =50 ) GOTO 11
      GOSUB DRAW   <# DRAW FROM END OF LAST CYCLE TO START OF NEW CYCLE
      GOTO 1
#15   IF (&LINE(8) ="8") GOTO CYC    <# IF GCODE REPS. A CYCLE GOTO CYC
      WHEN (&LINE(8,9) ="92")         <# TOOL LENGTH OFFSET GCODE
       TON =&LINE(12,13)
       NSFI =15
       GOSUB SIGF
       TOFF(TON) =VAL
      ENDWHEN
      IF (&LINE(8,9).NE."59") GOTO 11  <# IF GCODE IS OFFSET ,CONTINUE
      NSFI =14
      NFLAG =1
      HFLAG =1
      PRINT NFLAG =1
      GOTO 5  <# ASSIGN OFFSET VALS. GOTO 5
#16   NO =&LINE(12,13)    <# OFFSET NUMBER
      XO =X
      YO =Y
      ZO =Z
      BO =B
```

```
        @VO(NO) = VECT(XO,YO,ZO)    <# OFFSET NUMBER AND VALUE
        PRINT (@VO(NO))  (BO(NO))
        NFLAG =0
        PRINT NFLAG=0
        GOTO 1
#18     CONTINUE
        WHEN (&LINE(8,9) ="03")
         &SDIR ="CW"
        OR (&LINE(8,9) ="04")
         &SDIR ="CCW"
        ENDWHEN
        IF (&LINE(11).NE."G") GOTO 11
        NO =&LINE(13)  <# CALL UP OFFSET VECTOR
        WHEN (&LINE(9) ="7")
         NO =NO -3
        ENDWHEN
        WHEN (&LINE(9) ="8")
         NO =NO +1
        ENDWHEN
        WHEN (&LINE(9) ="9")
         NO =NO +5
        ENDWHEN
        PRINT OFFSET =N(NO)
        GOTO 1
#10     CONTINUE
        WHEN (&LINE (8,10) ="907")     <# SUBROUTINES TO SELECT FIRST TOOL
         TOOL =&LINE(15,18)
         PRINT SELECT & LOAD TOOL (TOOL)
         TON =0
         HOME =1    <# TO OR FROM HOME - A SWITCH
        OR (&LINE(8,10) ="924")      <# SPINDLE SPEED & NEXT TOOL
         RPM =&LINE(15,18)
         NTOOL =&LINE(23,26)
         &SDIR ="CW"
         PRINT TOOL (TOOL) SPEED (RPM) (&SDIR) -SELECT NEXT TOOL (NTOOL)
         TOOL =NTOOL
         TON =TON + 1
         XH =19.685       <# HOME X-VAL. FROM DATUM
         YH =11.811       <# HOME Y-VAL. FROM DATUM
         ZH =19.685 -TOFF(TON)    <# HOME Z-VAL. MINUS TOOL LENGTH OFFSET #
         WHEN (HOME =1)           <# TO FROM HOME -SWITCH MECHANISM
          HOME =0
          FHOME =1
          THOME =0
         ELSE
          HOME =1
          FHOME =0
          THOME =1
         ENDWHEN
        ENDWHEN
        GOTO 1
#CCON   GOSUB DRAW   <# DRAW NEW CYCLE START POSITION
        PRINT CCON
        GOTO CMOT    <# TO SHOW CYCLE MOTION GOTO CMOT
#CYC    WHEN (&LINE(8,9) ="80")    <# CYCLE STATEMENTS OFF
         CYCC =0
         &CN ="G80"
         PRINT CYCLE OFF -G80
        ENDWHEN
```

```
       WHEN (&LINE(8,9) ="81")  <# CYCLE STATEMENTS
        &CN ="G81"
        CYCC =1
        PRINT CYCC =1
        NSFI =9
        GOSUB CVAL
        R02 =VAL
        GOSUB CVAL
        R03 =VAL
        GOSUB CVAL
        R10 =VAL
        NSFI =NSFF +1
        WHEN (&LINE(NSFI) ="F")
         GOSUB SIGF
         FI =VAL
         PRINT FI =(FI)
        ENDWHEN
       ENDWHEN
       WHEN (&LINE(8,9) ="83")
        &CN ="G83"
        CYCC =1
        PRINT CYCC =1
        NSFI =9
        GOSUB CVAL
        R00 =VAL
        GOSUB CVAL
        R01 =VAL
        GOSUB CVAL
        R02 =VAL
        GOSUB CVAL
        R03 =VAL
        GOSUB CVAL
        R04 =VAL
        GOSUB CVAL
        R05 =VAL
        GOSUB CVAL
        R10 =VAL
        NSFI =NSFF +1
        WHEN (&LINE(NSFI) ="F")
         GOSUB SIGF
         FI =VAL
         PRINT FI =(FI)
        ENDWHEN
       ENDWHEN
       WHEN (&LINE(8,9) ="84")
        &CN ="G84"
        CYCC =1
        PRINT CYCC =1
        NSFI =9
        GOSUB CVAL
        R02 =VAL
        GOSUB CVAL
        R03 =VAL
        GOSUB CVAL
        R04 =VAL
        GOSUB CVAL
        R06 =VAL
        GOSUB CVAL
        R07 =VAL
        GOSUB CV
```

```
         R10 =VAL
         NSFI =NSFF +1
         WHEN (&LINE(NSFI) ="F")
          GOSUB SIGF
          FI =VAL
          PRINT FI =(FI)
         ENDWHEN
        ENDWHEN
#CMOT   WHEN (&CN ="G81")      <# MOTION OF CYCLE G81
         &GCODE ="G00"
         Z =R02
         PRINT R02 =(R02)   F=RAPID
         GOSUB DRAW
         Z =R03
         &GCODE ="G01"
         F =FI
         PRINT R03 =(R03)   F=(FI)
         GOSUB DRAW
         Z =R10
         &GCODE ="G00"
         PRINT R10 =(R10)  F=RAPID
         GOSUB DRAW
        ENDWHEN
        WHEN (&CN ="G83")      <# MOTION OF CYCLE G83
         &GCODE ="G00"
         Z =R02
         PRINT R02 =(R02)
         GOSUB DRAW
         NPECK =1
         PRINT PECK (NPECK)
         &GCODE ="G01"
         F =FI
         DRILL =R02 -R01
         Z =DRILL
         GOSUB DRAW
         PRINT DWELL (R04) SECS.
         &GCODE ="G00"
         Z =R02
         GOSUB DRAW
#PECK    NPECK =NPECK +1
         PRINT PECK (NPECK)
         PRINT DWELL (R00) SECS.
         Z =DRILL +GAP
         GOSUB DRAW
         &GCODE ="G01"
         REM =DRILL -R03
         IF (REM.LT.R05) R05 =REM
         Z =DRILL -R05
         F =FI
         GOSUB DRAW
         PRINT DWELL (R04)SECS.
         &GCODE ="G00"
         Z =R02
         GOSUB DRAW
         DRILL =DRILL -R05
         IF (R05.NE.REM) GOTO PECK
        ENDWHEN
        WHEN (&CN ="G84")      <# MOTION OF CYCLE G84
         &GCODE ="G00"
         Z =R02
         PRINT R02 =(R02)   F=RAPID
```

```
          GOSUB DRAW
          Z =R03
          &GCODE ="G01"
          F =FI
          PRINT TAP TO LEVEL OF (R03)  F=(FI)  SPINDLE DIRECTION = (&SDIR)
          GOSUB DRAW
          PRINT DWELL (R04) SECS
          WHEN (R06 =03)
           &SDIR ="CW"
          OR (R06 =04)
           &SDIR ="CCW"
          ENDWHEN
          Z =R10
          PRINT RETRACT TO LEVEL (R10)   F=(FI)  &SDIR=(&SDIR)
          GOSUB DRAW
          WHEN (R07 =03)
           &SDIR ="CW"
          OR (R07 =04)
           &SDIR ="CCW"
          ENDWHEN
          &GCODE ="G00"
          PRINT &SDIR =(&SDIR) GCODE=(&GCODE) F=RAPID
        ENDWHEN
        GOTO 1
#11     END
#SIGF NSFI = NSFI + 1   <# ASSIGN VALS TO VARIABLES-WITH A SPACE
      PRINT SIGF
      NSFF =NSFI
#DIG  NSFF = NSFF + 1
      IF (&LINE(NSFF).NE." ") GOTO DIG
      VAL = &LINE(NSFI,NSFF)
      PRINT (NSFI) (NSFF)
      NSFI = NSFF + 1
      RTNSUB
#CVAL NSFI = NSFI + 4   <# ASSIGN VALS TO VARIABLES-WITHOUT A SPACE
      PRINT CVAL
      NSFF =NSFI
#NFIG NSFF = NSFF + 1
      IF (&LINE(NSFF).NE."R".AND.&LINE(NSFF).NE."F") GOTO NFIG
      NSFF =NSFF -1
      VAL = &LINE(NSFI,NSFF)
      PRINT (NSFI) (NSFF)
      NSFI =NSFF
      RTNSUB
#DRAW @VEC =VECT(X,Y,Z)  <# TOOLPATH POSITION + OFFSET
      @VEC1 =VECT(X1,Y1,Z1)
      WHEN (FHOME =1)
       @TOT1 =VECT(X#,Y#,Z#)    <# FROM HOME ,NO OFFSET REQUIRED
       FHOME =0
      ELSE
       @TOT =@VEC.VADD.@VO(NO)
      ENDWHEN
      WHEN (THOME =1)
       @TOT =VECT(X#,Y#,Z#)  <# TO HOME ,NO OFFSET REQUIRED
       THOME =0
      ELSE
       @TOT1 =@VEC1.VADD.@VO(NO)
      ENDWHEN
```

```
 E =E +1    <# ENTITY NO. FOR LINE OR ARC
  WHEN (ANGL.NE.0.0)  <# ROTATE COMP. + FIXTURE THROUGH ANGL DEGS.
   SELECT (LAYER) 0
!! ECHO LAY EXCL 101 (LAYR) <# ECH HOME/DATUM/PRECEEDING T-PATH OFF
!! ROTATE ENT AY (ANGL):VWIN NAME 1;X9.8425Y0Z-3.937 <#ROT PLAN VIEW
!! ECHO LAY INCL 101 (LAYR)  <# ECHO HOME/DATUM/PREC. TOOLPATH ON
   SELECT (LAYER) LAYR
   PRINT ANGL =(ANGL)
  ENDWHEN
 WHEN (&GCODE ="G00")  <# DRAW TOOLPATH MOTION
  PRINT (&GCODE) (B) F=RAPID (BN)  (@VEC1)  (@VEC)
  $ENT(E) = LINE/@TOT1,@TOT
 ENDWHEN
 WHEN (&GCODE ="G01")
  PRINT (&GCODE) (B) (F) (BN)  (@VEC1)  (@VEC)
  $ENT(E) = LINE/@TOT1,@TOT
 ENDWHEN
 WHEN (&GCODE ="G02
  PRINT (&GCODE) (I) (J) (K) (F) (BN) (@VEC1)  (@VEC)
  @CCIRI =VECT(I,J,K)
  @CIRC =@TOT1.VADD.@CCIRI
  RC =SQRT(I*I +J*J + K*K)
  $ENT(E) = CIRCLE/CENTER,@CIRC,RADIUS,RC,PGO,@TOT,PEND,@TOT1
 ENDWHEN
 WHEN (&GCODE ="G03")
  PRINT (&GCODE) (I) (J) (K) (F) (BN)  (@VEC1)  (@VEC)
  @CCIRI =VECT(I,J,K)
  @CIRC =@TOT1.VADD.@CCIRI
  RC = SQRT(I*I +J*J +K*K)
  $ENT(E) = CIRCLE/CENTER,@CIRC,RADIUS,RC,PGO,@TOT1,PEND,@TOT
 ENDWHEN
 X1 =X      <# RESET VALUES FOR NEXT MOTION
 Y1 =Y
 Z1 =Z
 B1 =B
 ANGL =0
 I =0
 J =0
 K =0
 RTNSUB
```