DESIGN METHODS AND DESIGN PRACTICE - A FIELD STUDY OF THE DESIGN PROCESS IN THE ENGINEERING INDUSTRY

Chart it from the start of it,
The when and how and heart of it,
Then study every part of it,
To understand the art of it.

PhD

D. H. W. Hykin

May 1972.

ABSTRACT

This thesis establishes a realistic and usable framework for the study of commercial engineering design and suggests how the reliable empirical data upon which such a study must be based can be accumulated and analysed.

The data presented in this work consist of a series of detailed engineering design case histories which were recorded and collated as the design evolved. The field work was undertaken by the author working in a variety of firms in the engineering industry, usually as a member of the firm's design team.

The analysis of the empirical data is concerned both with the structure and strategy revealed in the individual case histories and their classification based on the factor or factors which appear to dominate each exercise. The results are also related to the important current descriptions of the design process and the proposals for systematic methods of design.

The analysis discovers a significant correlation - in the limited number of case histories investigated - between the nature of the design process and the production quantity being designed for; it is considered equally significant that all the other variables considered have no appreciable direct effect on the nature of the design process. Both these conclusions have important practical implications for design in the engineering industry.

It is hoped that the techniques developed to collate and analyse the case histories, and the methods used to identify and measure the variables involved, will encourage and assist further research programmes in this field. The accumulation of reliable empirical data on commercial design is a prime requirement in the urgent need to understand how the engineering designer works and to improve his performance, education and training.

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PRODUCT

Product is defined as the thing being designed.

In engineering design three types of product are recognised[5].

I) System

This involves the integration of separate units to perform a specified function.

Examples: Assembly line, telepbone system, chemical processing plant.

Synonyms in use: Service, complex, plant.

II) Component

This is any identifiable unit which performs a set of functions.

Examples: Component of a system, radio, hydraulic jack.

Synonyms in use: Device, product, item, good, project.

III) Part

This is a single piece for assembly into a product.

Examples: Nuts, bolts, gears.

Synonyms in use: Component, item.

This thesis is concerned primarily with the design of engineering components and parts, but it is considered that some of the procedures developed, and conclusions reached, will be applicable to, and assist in, any future study of system design.

ENGINEERING DESIGN PROCESS

This term is used to mean the overall pattern of engineering design including its evolution and strategy, where these terms are defined as follows:

Design Strategy

The pattern and nature of the decisions made and actions taken by the designer.

It is difficult in many situations to allocate responsibility for the decisions made during the design process. Many decisions are made informally and are tacitly, almost unconsciously, accepted by those involved, others are made by management rather than the designer, often for reasons apparently unrelated to the content of the design problem.

Design Evolution

The structure of the engineering design process in terms of a sequence of periods (stages) identified by the nature of the tasks being performed.

These stages are not discrete and consecutive, in practice they overlap and considerable recycling takes place between them; nevertheless, they are identifiable in terms of one or several of the following:

(a) the objectives and emphasis of the designer

(b) the division of work

(c) the obvious attainment of an aim

(d) the type of decisions made

Phase

This is defined as a grouping of stages into larger and more easily identifiable periods in the process.

Three phases in the engineering design process are recognised and defined as follows:

I Feasibility Study

During this phase the designer sets out to establish and study the design problem and from this study produce a set of possible solutions. The emphasis during this phase is 'whether' the problem can be solved.

Included and equivalent terms in use: Definition, analysis and synthesis, incubation, convergence and transformation, study, identification and statement of the problem.

II Optimisation

This phase involves a close study of the proposals emanating from the feasibility study, and the selection and development of the best solution. The prime objective during this phase is 'how' the problem will be solved.

Included and equivalent terms in use: Preliminary design, development, evaluation.

III Detailed Design

The aim of this phase is to take the solution produced by the first two phases and to develop from it an engineering description of an economically and physically realistic design.

The emphasis during this phase is on specifying and communicating 'what' is to be done. It is usually characterised by being the least exciting, most exacting and time consuming phase.

Included and equivalent terms in use: consolidation, elaboration, convergence, assessment.

PROJECT LIFE-CYCLE

This term is used to mean the overall sequence of events - including the design stages - which starts with the initial recognition of the need and culminates in the final commissioning, service and obsolescence of the product.

In some situations it is not possible to differentiate between Project Life-cycle and Design Evolution because the designer is involved throughout. In other cases however the designer is given a detailed brief at the outset and is not involved beyond the detail design stage.

Equivalent terms in use: Project Evolution, Design and Manufacture cycle.

PART I

THE CURRENT THEORETICAL FRAMEWORK

INTRODUCTION TO ENGINEERING DESIGN

DESIGN EVOLUTION

DESIGN STRATEGY

DESIGN METHODOLOGIES

FORMULATING THE FIELD STUDY PROGRAMME

INTRODUCTION

Part I is concerned with the current theoretical framework within which this work was planned and executed. It reviews all the important descriptions of design evolution and design strategy, and the methodologies which have been advocated as aids to the designer.

Finally it relates the decisions which were made at the outset of the work when the field study programme was formulated, to this theoretical background.

INTRODUCTION TO ENGINEERING DESIGN

Engineering design covers a wide spectrum of situations and problems varying, for example, from a one-off Nuclear Reactor design to a mass-produced sewing machine component. In some cases it involves purely routine work which can be wholly codified and delegated to a computer [7.8.9.10.], whereas at the other end of the scale a high degree of uncertainty, creativity and judgement may be involved. In reference 11 Koestler draws attention to the characteristic steps in the history of an individual discovery. He describes an initial stage of incubation, followed by illumination (the eureka act) as a result of which a new synthesis emerges - then verification, elaboration and consolidation. All engineering design, whatever its context or complexity, also involves such a logical sequence of events; no matter how much inspiration or drudgery, experience or innovation, reason or intuition may also be required.

In one of the earliest attempts to describe the design process in engineering Wallace[12] advocates as a "recipe for successful design" a sequence of events which he labels: to analyse, theorise, delineate and modify. Marples[13] describes engineering design as 'a sequence of critical decisions leading from the initial statement of the problem to the final specification of the hardware'. Asimov[2] suggests that during an engineering design exercise "a sequence of events unfolds in chronological order forming a pattern which, by and large, is common to all projects". It is perhaps this element of discipline and order during the engineering design process, which differentiates between the engineering designer and the inventor or the artist. Since the mid fifties there have been numerous attempts to identify and codify the stages in design evolution, usually as a first step towards an understanding of how a designer works and how he can be assisted.

It is to be expected that in the study of such a diverse and fundamental activity as designing, there will be a wide variety of approach and opinion and the following example serves to illustrate this. In 1967 meetings[14. 15] were organised by the Institute of Mechanical Engineers to discuss the structure and systematising of engineering design. During the discussion of the papers the following opinions were expressed by two practising engineering designers; they are typical illustrations of the sincerely held, but totally opposed views which reflect their advocates' experiences and prejudices and which serve to confuse any objective analysis of the engineering design process.

"Detail drawing is the key to successful design"

"Preparing the brief is the essence of design, the rest is hackwork"

However, in spite of such apparently conflicting attitudes there is currently a move towards an understanding and statement of the design process; a realisation that, although the emphasis will vary with the designer and the field in which he works, there is a process which is common to all designers. It is interesting to note that each of the quotations above draws attention to what is now becoming accepted as an identifiable phase in engineering design evolution.

In his review of the papers presented at one of the first ever Conferences on Design Methods in 1962 Professor Page[16] pointed out that in a very wide range of design situations, i.e. involving several categories of engineering and other products, one of the few points of almost complete agreement was that designing is "a three stage process demanding analysis, synthesis and evaluation". In engineering design a further phase - presentation - is postulated by Buhl[17] and Zwicky[18] suggests the steps definition, analysis, synthesis and presentation. Jones[5] emphasises the divergent nature of the initial stages, during which there is a "widening of the area of search for interpretations of the problem and for solutions to it" and the convergent nature of the later stages when the emphasis is on evaluation rather than exploration. It is interesting to note that the emphasis on problem formulation, which is a feature of this approach, probably reflects its author's experience as a consultant and his interest in non-engineering areas of design.

Another point on which most of the literature is in agreement is that designing is an iterative process in which the degree of uncertainty is reduced progressively as the design evolves. "This iterative nature is characteristic of design. New information is constantly developed by the design work itself and the affected step must be reworked until the necessary level of confidence is restored"[2].

The accelerated study of design in recent years has led to two distinct approaches: First the attempts to describe the chain of events via which the design evolves and second the development of design methodologies which are intended to assist the designer to handle the information he needs and to guide him through the process to the optimum solution.

Before discussing in detail the more acceptable and valuable of these attempts to describe, codify and assist the engineering design process, it is worth relating them to

a brief account of the current procedure followed by designers in the engineering industry.

DESIGN IN THE ENGINEERING INDUSTRY - CURRENT PRACTICE AND LIMITATIONS

It must be accepted that engineering design is normally concerned with talented practitioners rather than geniuses, and that technical competence, allied to professional skill and conscientiousness is far more prevalent than creative originality[19].

Designers in the engineering industry rarely search for problems, these are usually presented to them - formally, if not comprehensively. The first stage is normally to examine the problem, and although this examination may be informal and not very rigorous, it usually generates a series of related and inter-related sub problems within the competence of the designer and eventually leads to an improved understanding of the basic problem[20]. This is followed by a search for a similar problem or sub problem complete with solution[13]; if this is not available the designer will then consider basic principles.

In those cases where engineering designs tend to evolve over long periods and in small steps the exercise is one of slight extrapolation, or design by adaptation; in these, and many other types of engineering design exercise, there is rarely any formal or written account of the decisions made or their justification. Such a procedure is of course perfectly adequate in many areas of operation; it would be uneconomic for a designer who is very experienced in a particular field to return to basic principles and to follow a systematic procedure on every occasion.

However, the procedure described above does have serious limitations, particularly where the level of uncertainty is high, and some of these limitations are listed below:

(a) In many cases unless the designer undertakes a thorough and logical analysis of the problem with which he is presented, he is likely to waste his time producing solutions to the wrong problem and even to a problem which does not exist[21]. This hazard is exacerbated in engineering design by the necessarily loose problem statements with which the designer is often presented.

Even in a situation of design by adaptation it may be that a boundary is reached which invalidates further extrapolation[22]. In this case unless the designer is aware of the basic principles underlying his decisions his solution will be unsatisfactory.

(b) Because of pressures on time and other resources the designer is often forced to sieze upon the first possible solution and to develop it regardless of any further problems it may produce. Once he has adopted such a solution he is very loath to discard it, being apt to become enamoured of his own solution[13], he rarely gives serious consideration to alternatives which can be used for comparison and reverted to if necessary. He is therefore forced to make his adopted solution work; at the best this is a case of adapting and modifying and at the worst a question of "beating it into submission". The art of building in manoeuvrability - the capacity of a design to incorporate options - becomes vital in such an exercise.

(c) Increased competition and rate of technical progress make it necessary for designers to take larger steps in the extrapolation process. Thus it becomes even more likely that they will cross a boundary which invalidates a previously satisfactory solution[23]. It also makes it more essential that they consider first principles, and are guided logically through the design exercise- even though the exercise remains essentially one of extrapolation.

(d) In design situations which are predominantly new, design by evolution is of very limited value - for example in aerospace and nuclear design. The designer in this situation must revert to basic principles, and often needs some procedural guidance.

(e) Some (advanced) engineering design is becoming increasingly complex and interrelated, with a correspondingly higher level of uncertainty and a greater possibility of error - often with serious consequences. It is necessary in such areas for teams of designers to work together collecting, assessing and using a vast amount of information related to their effort[24]. Situations involving sub contractors, remoteness from the production and consumption aspects of the project, or long term design exercises during which personnel and organisational changes occur, make paramount the need for wide clear and formal lines of communication and record.

It has become apparent that new methods of designing are required to match and cater for the more complex and uncertain type of engineering design situation and problem which the engineering designer is being asked to face. The following chapters discuss the attempts which have been made to describe the sequence of events by which a design evolves, the decision and tactics which comprise the design strategy and the methodologies which have been developed and advocated to assist the designer.

DESIGN EVOLUTION

A dictionary definition of evolution is 'an unfolding of a series of events'; in nature it is recognised as a fumbling wasteful process, characterised by sudden mutations of unknown cause, the slow grind of selection and the dead ends of over-specialisation and loss of adpatability. For these reasons - and the implications of variety, adaptability and fluency which it also includes - evolution appears to be a particularly suitable word to apply to the activity and structure involved in engineering design.

A highly idealised and very comprehensive account of the pattern of engineering design is given by Asimov[2]. He considers the chronological structure (morphology) and covers all types of engineering design situations. As this account is very detailed and explicit it is described here first and in detail. Fig. 1 shows the morphology of design evolution according to Asimov and the place occupied in it by the three design phases: feasibility study, preliminary design (optimisation) and detailed design. The phases of production, distribution, consumption and retirement, which follow the three design phases, may lead to modification and redesign but they do not directly affect the initial design, although they will, of course, affect the design phases of the next related design. The iterative nature of the evolution is illustrated and emphasised by means of the unit stage, Fig. 2, from which the whole picture is constructed and which itself contains the three basic steps of analysis, synthesis and evaluation.

The aim of the feasibility study is to produce a set of possible solutions from which the final design can be selected and the first step is to establish the need. In certain industries such as the aircraft and armament industry, the need is usually precise, but in other industries the exercise is more speculative. The 'need analysis' step may involve speculation, experiment and market research.

Having established the need the next step is to analyse it and to produce an understanding and detailed statement of the design problem. The method advocated is to study the required outputs from the component or system which is to be designed, and the inputs related to them. The outputs are divded into desired and undesired. The inputs are related to the desired outputs and classified into:

(a) physical

(b) human

(c) informational

(d) economic

(e) environmental

The inputs necessary to provide the desired outputs will also produce undesired outputs, these are also considered.

The constraints on the system are then analysed, by considering separately the constraints on inputs, outputs and on the product itself - the latter constraints will include such factors as cost, accessibility, weight and available resources. At this stage the designer has produced a list of factors which will affect design decisions. An attempt is now made to quantify and then to relate and compare these factors. First the method of measuring the factors is decided - for material factors such as weight and cost there is no problem, but for less commensurable factors such as comfort and safety the problem is less tractable.

By relating these factors, and comparing them, criteria can be established which can be used to assess proposed designs and the degree of fulfilment of need which they provide. Moreover, these criteria may be in quantified form. The mileage per gallon is an obvious and quantifiable criterion but the comfort per initial cost is not easy to establish. An attempt to produce data of this type related to aircraft cost-effectiveness is given in ref. 25.

Having produced an understanding and a detailed statement of the design problem it is now possible to synthesise possible solutions. It is here that invention and creativity are employed; without these ingredients the process could be as formalised as a work study or method study exercise. Asimov defines creativity as a talent for discovering combinations of principles, materials or components. He offers no suggestions for assisting directly with the creative step.

The final stage in the feasibility exercise is to evaluate the proposed solutions and to produce from them a set of the most likely solutions. The basis of this evaluation is an assessment of the physical and financial attainability of each solution and also of its economic advantage. At this stage Asimov does not suggest an assessment related to the detailed problem statement and the quantified factors which have been established.

The first step in the next phase, preliminary design, is to select the optimum solution from the set of most likely solutions produced at the end of the feasibility study. This optimum design will then be subjected to a detailed design exercise. The method of selecting the most promising design proposal is based on a fairly detailed study of, and comparison between, the tentative solutions. The solutions are of course related to the detailed problem statement and if possible this is done quantitatively. There are however a number of predictions and intuitive decisions to be made at this point. The more

complex the problem the more difficult it is to deal with such matters quantitatively.

A mathematical model of the chosen solution may be formulated at this stage and used to gain an insight into its characteristics and behaviour. Sensitivity, compatibility and stability are aspects which are included in this exercise[21]; a rigorous optimisation study may also be undertaken using the mathematical model[26 27]. The optimisation process is a gradual one, certain solutions will be rejected early, possibly on the basis of a very approximate assessment of value. All these exercises will however lead to a greater understanding of the problem and of the advantages and limitations of the proposed solution. This in turn will lead to a gradual improvement and a reduced level of uncertainity.

As the optimisation process progresses it becomes more detailed and selective. Although it is easier to optimise to only one criterion, others may be introduced by weighting a series of criteria to give an overall optimum; or by converting less important criteria into restraints.

For example in the design of a new motor vehicle capital cost, maximum speed, miles per gallon and comfort could be design criteria and any assessment of the chosen solution could be set against each of them in turn. It would be possible, however, to weight each of these factors and fix an overall criterion involving them all. Alternatively, limits could be set above or below which capital cost, maximum speed and comfort must not rise or fall, thus turning these criteria into restraints. The measurement and weighting of comfort in this example might be largely subjective, or it could be based on consumer research and testing.

Other standards by which the chosen solution is judged are its future potential and possible development. Many of the factors affecting such decisions involve social and economic aspects in addition to technical predictions. Model and laboratory testing may play an important part in the assessment and development of the proposed design at this stage, particularly if partially understood factors such as new materials, techniques and environments are involved.

The final stage in the preliminary design phase is to subject the chosen solution, which has now been developed and improved, to a rigorous and objective attempt at simplification before it is submitted to the detailed design phase which follows. This procedure has now been formalised and is known as 'value analysis'.

Before discussing the detailed design phase it should be emphasised that up

to this point the design process must remain very fluid. The designer must be free to make major changes, to reconsider and reiterate. The close study of the first chosen solution may expose it as unsuitable, in which case one of the other proposals may be adopted, or the feasibility study may be repeated in the light of the new evidence. A reasonable appraisal of the economics of the proposal is possible at this point. The purpose of the detailed design phase is to take the design produced by the first two phases and to develop from it an engineering description of an economically and physically realistic design.

The first step - having decided to proceed - is to prepare a provisional master layout of the overall design. This presents, in drawing form, the results of the preliminary design phase. The sub-systems are then established and investigated in detail - they will of course have been examined to some degree during the analysis stage in the preliminary design phase. The sub-systems may be sufficiently large to be subjected to the same procedure as was used to analyse the overall design. It must be remembered however that the standards applied to the sub-systems must relate to each other and to the overall design. A master layout of each sub-system is prepared as soon as they are sufficiently understood and finalised, and a detailed study of each sub-system is then undertaken by dividing it into components. The design is now becoming progressively less abstract, a concrete design is beginning to evolve and it is becoming increasingly expensive to make alterations, particularly fundamental ones. The results of the component designs lead to a series of component master layouts.

The next step is the detailed design of the elementary pieces which make up each component - the parts. It is here that the details which have been shelved so far, must be resolved. Detailed methods of manufacture and assembly, tolerances, finishes, and all other aspects must be decided in order to produce a complete engineering description of each part and hence of the overall design. When the parts have been detailed the component assemblies can be drawn and any necessary revisions can be made. Finally, the sub-system and overall assembly drawings can be prepared. An accurate appraisal of the economics of the project should now be possible, this is usually desirable since the next stage in the design process is to produce the first prototype.

The transition from drawings to hardware is the first real test of all that has gone before. The basic concepts to be considered will include methods of manufacture, assembly, maintenance, and if possible customer reaction. Close co-operation between design and product construction staff is essential, major changes should be avoided

although all promising ideas should be recognised and recorded. The extent to which this exercise can be fed back into the design varies considerably with the product. A motor car for mass production will normally involve several prototypes, much testing and significant design changes, whereas in the case of a large new 'one-off' ocean liner the prototype is the end product and the design modifications are much more restricted.

The final steps in the detailed design phase are the test programme of the prototype, the analysis and prediction of performance which result from it, and the final feed-back into design. Although the iterative nature of design is still in evidence the consequences of each revision must be anticipated with great care. A successful design will 'converge' rapidly during this stage and there will be little need for major modifications or any alterations which would have widespread repercussions.

A less detailed account of design evolution is given by K. W. Norris[28] who has adapted an earlier proposal of Zwicky[18] and presents the pattern shown in fig. 3. He suggests that stages of study and definition take place until a preliminary specification is prepared. This is then followed by analysis and synthesis to produce an acceptable solution prior to presentation. Two interesting features of this description are first that the reduced ratio of questions to answers (uncertainty) is emphasised as the design progresses and second that there is no indication of the cyclic nature of design.

One of the earliest workers in this field was R. J. McCrory[29-30]; a diagram of his version of project life-cycle, with emphasis on the design method, is shown in fig. 4. McCrory has based this construction on his earlier work on scientific method, in the sense of a critical and skeptical approach to enquiry and a readiness to test hypotheses, and its progression through the stages of applying existing knowledge; hypothesis - confirmation - test and proof. The impression of an automatic and coincidental match between the 'state of the art' and the 'recognition of the need' reflects the origins of this proposal, rather than the engineering design structure which it attempts to describe. McCrory does however recognise and illustrate the recurrent and regenerative nature of design evolution.

Several more recent attempts to visualise the overall of project life-cycle, including the engineering design phases, are given by Krick[31], fig. 5, Dixon[32] fig. 6, and Hill[33] fig.7. All these last descriptions illustrate the cyclic nature of the macrocosm

of project evolution but none of them demonstrate how this is reflected also in the microcosm. Dixon in fig. 6 does, however, emphasise clearly that the structure of the engineering analysis reflects closely the overall structure of project evolution; this 'Russion Doll' characteristic of design evolution is recognised by several other authors including Asimov. This characteristic is probably related to the fact that at all levels of an evolutionary hierarchy there must be an equilibrium between the need for autonomy at any stage and the restraints imposed upon the stage by its relationship to the whole.

Stamper[34] fig. 8 and Wearne[6] fig. 9a both recognise the design phases in the project life-cycle and the reiterative nature of the process. The former reference incorporates features from several other proposals, for example the compatibility of need and technical capability and the latter emphasises the overlap between stages - fig. 9a represents 'their order of starting'. Wearne also illustrates the secondary currents of information, fig 9b which have a bearing on earlier decisions and entail recycling.

A further interesting comparison between these two relatively recent attempts to describe engineering design evolution is the absence in the first - which originated in a major aircraft company concerned primarily with the design and manufacture of large complex products - of the closing of the cycle of events so that experience from the operation phase of a project is automatically and comprehensively applied to the next adapted product. This is obviously what happens in most cases, but it is less obvious and important where the product is large, complex and involves a high degree of innovation.

Other descriptions of project life-cycle are given by Rodwell[35] fig. 10 and Woodson[36]. Both recognise the cyclic nature of design evolution and illustrate it imposed upon a linear progression towards a solution. Woodson's description is very close to Asimov's with a fourth or revision phase covering the manufacture of the product and following the detailed design phase.

One other description of the engineering design process is of interest because it was presented by a senior executive of a large engineering company (de Ferranti[37]) and illustrates how the responsibilities and experience of the commentator colour his view of the situation. Plate 1 shows a series of photographs of a model produced by the author based on ref. 37. It shows how the limited resources available are used in undertaking a feasibility study, followed by a preliminary design phase at the end of which a 'much battered prototype appears'. This is then 'modified and coaxed' during

a final phase into an acceptable design for production, with the cost per project slowly being reduced. The iterative nature of the process is illustrated by the introduction of Asimov's unit stage.

This description illustrates the senior executive s concern with the resource-swallowing capacity of engineering design, and related to this, the need strictly to control the use of committed resources and to provide an acceptable solution before they are exhausted. The large volume of the central tank probably reflects Lord Hives comment as Chairman of Rolls Royce Ltd. when, after being congratulated on the quality of his companies engines - very similar products to those described in ref. 37 - he replied that they were a "triumph of development over design".

Several general conclusions may be drawn from this review of current descriptions of engineering design evolution. All but one of the descriptions recognise the iterative progression towards a solution with the cyclic process of analysis, synthesis and evaluation reflected in the overall activity and in the detailed problem solving. Not all the descriptions illustrate that the recycling may involve both minor reconsideration within a stage and major redesign with return to the initial brief. The extent of the iteration depends upon the type of design problem and situation. At one extreme a purely routine engineering design may be entirely linear whereas situations involving a high degree of uncertainty and novelty tend to be predominantly cyclic. The rate at which the process converges and the uncertainty diminshes i so elated to its linear and cyclic characteristics.

It is also interesting to note that these features appear in comparable fields of study. In discussing the basic character of biological, social and mental evolution Koestler[11] concludes that increased complexity means increased risk of breakdown which can only be repaired by processes of the regenerative 'reculer-pour-mieux-sauter' type.

DESIGN STRATEGY

Integrated with design evolution is design strategy which can be considered in terms of a set of actions performed consecutively or concurrently (the tactics), and the pattern of the decisions which are made. An understanding of the strategy involved should enable the designer to assess his progress, and to appreciate more fully the probable ramifications of his actions and decisions at any stage. He should then be able to direct his efforts towards the optimum solution, even in complex and uncertain situations.

Archer[38] presents what is probably the most detailed and explicit attempt yet made to describe the design process. He aims to provide the designer with a map and pedometer to guide him through the exercise, enabling him automatically to measure his p ogress and to select a route to the optimum design solution. The map is an overall picture of the design process showing the significant steps and the consequences of decisions. The pedometer is a method of recording and assessing progress by measuring the merit of any proposed solution compared with the optimum solution.

The methodology associated with this description is discussed 'n the following chapter. The map which it provides, and which the designer is intended to use when the way ahead is not clear, should of necessity be both detailed and accurate. Archer presents the design process as a cyclic progression through a series of inter-related problems and decisions moving steadily towards an optimum solution The s ps of analysis, synthesis and evaluation, common to all the other descriptions, are implicit in both the microcosm of the evolution - the solving of the minor sub-problems - and the macrocosm, where the effects of any decision on the final solution are assessed.

In Ref. 39 Jones is concerned primarily with design methods, most of the current aids to design are described and discussed and a table is presented which relates them to stages in design evolution. The aim is to describe and classify design methods and to encourage and facilitate their use by enabling the designer to select a technique to match his strategy. The work is based mainly on general design but does not exclude engineering design. If the designer operates by consciously choosing a design mtehod to suit his current problem, or the stage he has reached in the design evolution, then the strategy can be considered "simply as a list of the methods that one intends to use". This approach, and the concentration on the sequence of actions taken, leads to a classification of strategies based upon the "degree of pre-planning" and the pattern of search.

Several of the classifications proposed by Jon s, F g 11, are closely allied to engineering design evolution. For example linear strategy relates to the purely routine situations such as design by handbook or computer; cyclic strategy is a fundamental characteristic of engineering design and branching strategy is a more common feature of large design exercises where the work has to be shared.

This last category illustrates clearly the difference between a strategy, which is a set of actions and decisions, and an evolution which is a sequence of stages of work; although it is possible that a design team could simultaneously employ several different methods of gathering information, or developing solutions, it is unlikely that they would undertake both of these stages at the same time on the same problem. It is for this reason that branching does not occur as a characteristic of the descriptions of design evolution except where there is some overlap of adjacent stages.

Adaptive strategy appears to be a formal description of what most engineering designers attempt to do and incremental strategy, which is a limited version of it, is a process of assessing and improving an existing design - perhaps the most common strategy currently used in engineering design.

In Ref. 13 Marples presents the results of one of the f w empirical studies made into engineering design. Two examples of engineering plant design were recorded and analysed and an abstract model of the problem solving pattern was presented, Fig. 12. Some important features are illustrated by this model of the problem formulat'on and solution activity. Any problem may give rise to several solutions, each of which produces a set of sub-problems and these in turn give rise to a further selection of solutions. This rapid branching of the process has led to the title 'decision rees to describe the model.

As the activity proceeds from the original problem formulation to the final sub-problems the considerations progress from the abstract and general to the material and specific. For example in one of the decision trees produced by Marples the original problem is concerned with the type of duct to be adopted for the reactor-heat exchanger ystem in an Advanced Gas-cooled Reactor; the final sub-problem in this decision tree is concerned with the selection of bearing material for a valve required if one type of duct design is opted for.

The relationship between design evolution and design strategy is indicated clearly by the time scale which runs vertically from top to bottom of Marples decision tree model and he also recognises, when analysing the case histories, the parallel attempt

o solve some problems, and the serial examination of others as categ ris d by Jones.

Marples suggests that the designer has two main functions; to conduct a search for possible solutions and to select the best from them. The selection is based on the feasibility and superiority of the set of proposed solu ions The order in which solutions are considered may depend upon their judged feasibility - an intractable sub-problem may render a problem relatively insoluble within the imposed constraints - or according to the judged superiority and advantages which each offers.

In Ref. 40 Morgan criticises Marples model for not recognising the interdependence of design decisions, where the selection of any one option may af ect the range of c oice open for subsequent decision. This oversimplificat' n in M pl s model has also b n pointed out by Wearne Ref. 6. Marples model ha also be c i 'c'sed by Brichta 'n the written discussion to Ref. 6 on the basis that it presents a retrospective account of a sequence of events and although it illustrates what may have happened it should be made clear that it cannot demonstrate how decisions were made.

Morgan[40.72] advocates a network procedure (AIDA) to aid the design team in deciding the best strategy to adopt and to pro ide a framework s tha a those involved making decisions can relate them to the overall situati n. This th d has the advantage that a crude network involving the ma'n decis'on areas c n be drawn at the start of the exercise and can then be expanded and refined as the design evolves. This procedure should not be confused with the Network Analysis techniques where a complete and detailed network is drawn at the outset and is used to monitor and control a programme of work.

DESIGN METHODOLOGIES

Although current practice in engineering design may still prove adequate in many situations its limitations have been exposed by new technological developments and the increased complexity and higher levels of uncertainty of many modern design problems. Increased competition at national and internation level, and an awarene s of the need to cater for the total effect of a design, have accelerated the search for methodologies to assist the designer. This chapter is concerned with an account of the more important of the e techniques.

Most of the methodologies currently in use have been developed for non-engineering design and few of them have been applied intensively to commercial des'gn ercises. They can be divided into two categories; those which are intended primarily o guide the designer to progress logically and economically through the evolution of the esign (monitoring) and those developed to assist him with either the procedural or the ntuitive steps in the design strategy (motoring). Of the few methodolgies develaped for, nd applied to, engineering design, the maiority fall into the first category - monitoring - nd are intended to assist the designer to measure and direct his progress, and to collate d process the necessary information.

Few techniques in the motoring category have been developed specifically for ngineering design although some of the more general techniques are relevant to it. Although it is not possible always to draw a clear distinction the methodologies described have been separated for convenience into monitoring and 'motoring' categories and for ase of reference the authors' own terminology has been adopted in each case. The monitoring methodologies are described in greater detail than the motoring techniques as he former all contain elements of the latter and also they relate more closely to engineering esign evolution.

MONITORING METHODOLOGIES

Among the best documented of those methodologies currently in use in engineering design is Problem Analysis By Logical Approach (PABLA),[43.44] which has been developed and used by the Atomic Weapons Research Establishment as a design tool. PABLA has its roots in Method Study, and acknowledges the pioneer work in this respect of Matchett[1]. It is aimed at exposing key problems, guiding the search for viable solutions and assisting with the selection of those solutions which match the real needs of the problem. It therefore falls into the monitoring category of methodologies, although since it provides a clear appreciation of the real problem and assists with other steps in the design strategy, it also has a motoring function.

PABLA reflects the design environment in which it was developed; namely the design of one-off items of scientific and engineering equipment. The emphasis is on the initial phase of design evolution in order to guarantee an acceptable solution without too much development and redesign. A formalised procedure is used based on a series of charts which the designer completes as the design evolves. Charts were chosen because they are simple and quick to use and provide a convenient method of storing information. Each chart is associated with a stage in the evolution of the design. The first (C1) attempts to establish the need, the second (C2) is a precise statement of the problem, the third (C3) assists the search for solutions and the fourth (C4) is used to develop the chosen solution.

It must be emphasised that the process remains very fluid, feedback is continual and occurs from any one stage of the design to any preceeding stage. As the implementation of PABLA is based on the charts, they are worth considering in detail. In order to complete the first chart (C1) the designer is forced to consider all (or most) of the factors which will affect his design. These factors are categorised into usage, influences and existing resources. When the chart is completed the designer has a clearer understanding of the factors which will affect his decisions, where he is short of information and how he can obtain it.

The designer now turns his attention to a precise statement of his problem and attempts to prepare his design specification by completing chart (C2). This also has three main headings, objectives, performance and assumptions. Two other boxes on this chart ask the designer to consider the effect his design will have on its environment, and the artificial restrictions imposed upon his design by such considerations as the use of existing facilities or components.

The close study of the problem which has been forced upon the designer as he completes charts C1 and C2 should have prepared him to produce solutions, and in chart C3 he lists and studies possible solutions to the problem he has posed. The aim of this chart is to encourage the designer to produce several solutions, to assist him to assess them and finally to decide upon the optimum solution.

The optimum solution is then developed by using the next chart, C4, on which the designer breaks his design into components and parts (features). The function of each feature is lised first and below this are spaces for recording the known performances and characteristics of the features which have been decided, and also the required performance of the features which have yet to be decided. The person responsible for making the decisions on the feature, and its source of supply, are also listed on chart C4 for information and administrative purposes.

On completion of chart C4 the detailed design stage can proceed and further charts are available as aids to this process. C5 is an aid to the selection of materials and C6 is an attempt at simplifications of the detail design by an analysis of its features. An attempt to 'weight' the importance of a feature or detail is made on chart C7 which enables the designer to establish his priorities and let his decisions be made known to others involved in the design process. Chart C8 is a method of checking the conflict between the features settled in the design and the limitations imposed upon it.

PABLA is more formalised, and has been used more often in engineering design, than any other methodology. It shows some bias towards its origins in concentrating on the development of a correct design first time, with very little provision for development, testing and redesign. The main emphasis is on preparing a clear, detailed and accurate appreciation of the problem, and a statement of a satisfactory solution.

An obvious criticism of PABLA is that too much time is wasted completing the charts. The authors answer to this is that the good designer always spends time clearly establishing his brief before proceeding. Moreoever there is an overall saving of time when subsequent steps such as manufacture and development are taken into account; this is discussed fully in ref. 43. It is possible that the use of charts also emanates from the origins of the system, and its use for training designers. However it is not easy to devise a better method of producing a complete, detailed and accurate design specification, whilst providing at the same time a convenient method of recording the decisions made. The authors of PABLA are at pains to emphasise that it is not a method of instant, automatic design. Its aim is to prepare the ground for the designer and to assist him to make creative leaps in the correct direction.

During a discussion with a Senior Designer at A.W.R.E. an interesting use of chart C1 was mentioned. The chart is given to a designer who does not normally use PABLA a few days after he has been presented with a design problem. The extent to which he can complete this chart gives a clear picture of his real appreciation of the problem which he has been attempting to solve. A further interesting aspect of PABLA which also stems from the environment in which it was developed, is its value as a formal record of the decisions which have been made. The need for the engineering designers to elicit a clear statement of the problem and brief presented to them, usually by non-engineers, has led to its use as a semi-political document.

Another methodology in the monitoring category has been mentioned earlier; in a thesis[38] Archer describes his Systematic Design Method (S.D.M.) which has also been the subject of several lectures[45,46]. S.D.M. attempts to transform notional

concepts into material terms, to allocate numbers to such aspects as degree of comfort and appearance. It also suggests that all such factors relating to a design exercise can be weighted to produce an overall index of performance. It is obvious that once cardinal values have been allocated the factors can be dealt with by computer.

So far the method has only been applied to minor items of equipment, but it appears to represent the first detailed and complete attempt to systematise the design process. The first step in the method is to establish the factors affecting the design and to draw up a series of interaction curves. An interaction curve shows how two properties are related to each other for a given design. Some typical interaction curves are shown in Fig. 13.

Fig. 13a shows a possible relationship between weight and cost and 13b between visibility and light intensity; all these factors could be design features on which decisions would have to be made. Fig. 13c shows two interaction curves relating performance and cost for two different design proposals; the diagram is taken from a cost-effectiveness study[25]. On the vertical scale of these graphs some level is established as the 'just acceptable' level of fulfilment of requirement. The vertical scale is graduated from 0-1 the value 1 being allocated to the optimum design. Thus once the interaction curve has been drawn, any proposed design can be plotted on it and its degree of fulfilment established.

Deciding upon the degree of fulfilment may be precise and straightforward (cost, weight or performance), in which case it is given a cardinal allocation. On the other hand it may be selective and less obvious (comfort, appearance), in which case it is given an ordinal rating. A third category relates to the go or no-go properties such as a safety regulation which must be satisified, or a leak rate which cannot exceed a certain value. An attempt is made to transform ordinal factors into cardinal ones by placing a particular proposal in order among enough others to make it possible to fix it on a scale from 1-100.

The next step is to identify and measure any relationship between the various interaction curves. Controlling factors, and decisions made by the designer, determine the state of any property such as the weight or intensity of light. By referring to the relevant interaction curve the degree of fulfilment which the state of this property provides can be established; this is the output. However the output from the process may also apply controls (limitations) to some other property, thus giving a link between the various interaction curves.

For example a given design proposal might be of a weight which would ensure an acceptable cost level from the relevant interaction curve, but it might also affect a second interaction curve which related comfort and appearance. A diagram or programme which represents the links between all the interaction curves is capable of representing a complex situation and giving an overall picture of the design process which could assist the designer to assess the effects of his decisions.

It is possible to weight all the properties which are being considered and, by applying the weighting factors to the corresponding degrees of fulfilment, obtain an overall index of performance for a design. It is obvious that if more than a few simple properties are involved the process of setting up and manipulating the algorithm which this method provides is very complex. Archer has written several numerical programmes to achieve this.

S.D.M. is the most comprehensive monitoring methodology so far proposed; it has been developed and used in the Industrial Design (Engineering) Research Centre at the Royal College of Art and has been applied to engineering design, although only to uncomplicated items of equipment and well defined problems. A major criticism of the proposal is its complexity and the manual and computer time involved in preparing and using it. Moreover the proposal appears to ignore the fact that many problems cannot properly be understood until several possible solutions have been formulated and investigated, and it also implies that no truly creative or intuitive leaps will occur late in the design evolution.

The final monitoring methodology to be discussed in any details is by Bond[48]. Unfortunately very little has been published on this Logical Approach to Design although it has been the subject of several lectures and the author worked closely with Mr. Bond for several years.

Although the methodology provides a guide and assists the designer through the evolution of the design it is confined primarily to the initial phase of feasibility where it provides a semi-formalised, simple and practical technique for establishing, analysing and specifying the real problem and also generating possible solutions.

The first step is to list as many factors as possible which will influence the design. This list of factors is produced in a completely random way by the designer or design team involved. Many of the factors listed will raise questions which require answers, these answers are sought at this early stage and often lead to further factors. When it is considered to be reasonably complete the list of factors is grouped under two main headings, Organisation Factors and Engineering Factors.

Organisation Factors include all those for which the designer must seek external decisions, for example the economics of the project, the market aimed at, and the time and resources available. All these will depend upon the firm's policy whereas further factors such as safety, overseas markets and legal aspects may involve consultation with other external authorities. Engineering Factors include all items which can be decided by the designer and which, in most cases, can be left until the detail design stage - stress levels, choice of materials, choice of components and parts.

The procedure advocated is to list all the Organisation Factors and attempt to assess them. This is done by first selecting any mandatory factors such as safety and selling price, and eliminating any non-essential factors. The remaining factors are known as the Essential Organisation Factors. In order to weight these factors a 'Triangle of Pairs' technique is used. This involves comparing every factor in turn with every other factor. The number of times each factor is given preference is then totalled to give the order of priority. Since the factors are considered in pairs it is easier to achieve a realistic weighting. Having listed all the factors which affect the design and attempted to establish an order of priority for the Essential Organisation Factors, the designer can now proceed to develop solutions to the problem.

The first step is to divide the design search into main features which are then written down as the bases of branches of a family tree. Each branch is then pursued in detail; possible solutions, shortages of information, sources of information and any useful thoughts on possible solutions are added. Possible solutions emerge as questions are answered and the tree grows. Any important branches which have been missed usually appear as secondary branches as the tree is built up. For a large project a branch may develop into a complete tree, in which case it is presented as a separate sheet. In this case however the 'master tree' provides the essential compatibility between features.

The first tree, or series of trees, establishes the important features of the design by posing, and then seeking answers to numerous questions. To prevent the system being too awkward to handle a second tree is drawn up which aims at summarising the first. This tree contains more decisions than questions but it still presents several likely solutions, rather than one chosen solution. The final step is to draw up from the second tree a final tree in which all the features and related decisions are listed. It is on this tree that the chosen solution tends to emerge.

No procedure is suggested for the succeeding phases in the design evolution,

the view is that having prepared the ground by establishing and analysing the problem, the designer should be free to proceed in any way he chooses; any further problems which arise can, of course, be tackled using the logical approach. The technique advocated is valuable as an aid to understanding the problem and to finding solutions. Also because it is formalised, it provides a convenient and comprehensive means of communication and it automatically eliminates unnecessary information.

Other advantages which it is claimed have been proved in practice include the fact that by listing the factors affecting the design, and the questions which arise, the designer is forced to produce answers and to make everyone concerned aware of these answers, the resultant decisions and their source. This 'political' nature of the method is of particular value in certain design situations. In addition to this the formalised method of deciding priorities enables everyone concerned to be aware of how these priorities are allocated and if necessary they can be actually involved in the 'Triangle of Pairs' exercise.

The family tree can also be used to record any idea which occurs to the designer at any stage and other relevant, but not directly related, information such as time schedules, references and personnel. Finally the logical approach enables reliable and early cost estimates to be made and other forecasting such as time scheduling, and part supply programming to be improved. These are often important advantages in practice.

Other monitoring methodologies which have been developed for engineering design include Methodical Analysis for Use in Design (MAUD)[49] and Provide a Means Diagram (PAM)[49]; the first is used to 'uncover the true needs and the particular set of circumstances that are required of a design' and the second to 'stimulate the synthesis of knowledge, needs and circumstances and the evaluation of the design concepts'. Both these methodologies have been developed from Method Study techniques.

A different type of monitoring methodology which is also based on Method Study and is among the best documented is Fundamental Design Method (FDM) developed and advocated by Matchett.[1.50.51.] This methodology emphasises the concept that design ability is enhanced by an understanding of the mental skills and attitudes employed in designing. Techniques are offered which assist the designer to improve his mental approach to design, rather than to guide him formally through a predetermined technique.

Charts are used at the initial stages in order to establish and investigate the major design requirements (Primary Functional Needs) and Function Process Charts are used at a later stage to investigate sequences of operations. It is claimed that these charts, and other similar techniques, are some of the means whereby the designer is

encouraged to think in abstract terms and to be more aware of his thought processes. A Primary Functional Need is defined as a need which, if it is not satisfied, invalidates all the others. In this analysis the method study technique of asking 'why, what, when, where and how?' is used. Charts are drawn up from this exercise, each of which relates to one of the Primary Functional Needs.

The first step in the search for solutions to the problem posed by the Primary Functional Needs is to attempt a crude solution which is then analysed in detail. This analysis establishes the prime features of the proposed design, and uses functional process charts to study relationships between them. A tabulated method of eliminating, combining, transforming and modifying is also adopted.

So far the analysis has been carried out in an abstract form. Only one rough sketch has been produced but by using the charts a real understanding of how the primary needs can be satisfied should have been acquired. From this real understanding of the need and functional requirements of the components of a solution, a chosen solution is evolved.

The chosen design is analysed using process charts, a compatibility matrix, models, mock-ups and other aids. Preliminary sketches are then prepared and stress analysis undertaken. A prototype is then built and tested. Final drawings, detailed stress analysis, etc. and production then follow.

The Fundamental Design Method is characterised by the emphasis on the mental approach of the designer. It is closely allied to method study, critical examination techniques and in fact it appears to be a technique of value analysis - or redesign - rather than of original design. All the examples quoted to illustrate the method are redesign exercises and most of these are fairly simple mechanisms.

There is no doubt that disciplining the designer to think in abstract terms in the initial stages, to keep an open mind for as long as possible, is a useful step. On the other hand a contradiction is that the evolution of the chosen solution is based on the study of one 'first attempt' at a solution, and the implication is that the elements of the optimum solution are either contained in this or can be evolved from it.

No mention is made of numerous other factors which affect design solutions, particularly in a broader type of exercise, for example: costing, production techniques and marketing. Nor does there appear to be any recognition of the possibility of a bisociative or irrational solution.

Several less ambitious procedures have also been used to monitor the design

process in the engineering industry, for example, progressing controls such as Bar Charts, Critical Path and Programming Charts - an example of the last occurs in Case History E in part II of this thesis. These controls were originally developed as management tools to progress the production part of project evolution but as the need to control and formalise the design process increases, more sophisticated techniques of this type are being adapted and developed by designers and management.

MOTORING METHODOLOGIES

A comprehensive literature[17,32,36,53,54] is now appearing on this type of methodology. In spite of some extravagant claims it is becoming clear that they are in fact fairly limited tools which should be selected and used to match the particular problem or stage in the design evolution, which has been reached.

As mentioned earlier Jones[39] gives a detailed account of several methodologies and also attempts to relate them to phases in the design evolution. The criteria used to select any methodology for this anthology were effectiveness, relevance and convenience; in addition to the availability of reliable information and known limitations. Jones includes a brief description of each methodology and presents a chart which enables the designer to select the technique appropriate to his immediate problem. It is emphasised that the methodologies included are not limited to engineering design and in fact few of them have been applied to it commercially.

Flowerday[52] also presents a review of design methodologies but restricts his choice to those related to engineering design.

A classification of the motoring methodologies based on the phases of engineering design evolution to which they are most apposite, assists to emphasise their value and limitations. For example at the start of the Feasibility Study, techniques for accumulating, assessing and manipulating information are all valuable tools and Market Research, Information Retrieval and Sampling have all been applied to this problem formulation stage.

Several motoring methodologies are also available during the next stage when a detailed appreciation and statement of the real problem is being prepared. Apart from the techniques of Objective Clarification and Objective Statement which have already been described in principle as part of some of the monitoring techniques, others have been used including Check Lists, Needs Appreciation and Boundary Searching. Having prepared the ground, the final stage in the Feasibility Study is the generation of

possible solutions; as this is an important and distinguishing feature of the design process it is worth considering in detail.

In discussing this process of 'bridging the gap between the pre-conceived problem and its solution' Koestler[11] emphasises that one of the basic mechanisms is the discovery of the hidden analogy. He postulates two levels at which synthesis occurs. The associative, which is characterised by a reasoning, adapting routine search for valuable connections in a limited plane of reference - this semi-automated search for analogies is comparable to rigid and flexible mental skills, for example arithmetical operations where a limited number of pre-set routines may be employed to produce solutions - and in contrast to this he has coined the word bisociative to describe the truly creative act where a connection is perceived between two habitually incompatible planes of reference.

As an example; the conscious selection or adaptation of a power source or steering system from the designers experience and knowledge is associative; whereas the unconscious, inspired leap from a kettle to a steam engine, or from the level of water in a bath to the concept of density, are both bisociative. One of the case histories in Part II of this thesis illustrates an associative process of selecting what type of mechanism to use and later a bisociative act where a rubber pad from a car roof rack is suddenly seen as the solution to a problem in the machine being designed. The 'emotional manifestations of the bisociative eureka act' discussed by Koestler were certainly in evidence in this example.

The English philosopher Hobbes may have been the first to recognise the difference between the free and controlled association of ideas. In Ref. 55 Woodworth quotes "The train of thoughts, or mental discourse, is of two sorts. The first is unguided, without design, and inconstant ... The second is more constant as being regulated by some desire and design". Polya[56] contrasts solutions which involve 'substituting special data into a formerly solved general problem or following step by step, without any trace of originality, some well-worn conspicuous example' with those where brains, good luck and a bright idea are required.

Although it would seem that most engineering design problems are solved somewhere between these two extremes, any motoring methodology which professes to assist with the generation of solutions, can be related to them. In this category there are those techniques which attempt to move the irrational, intuitive, unconscious act closer to the routine, conscious end of the spectrum; and those which attempt to establish an atmosphere which encourages the truly creative act. The first category by rote and the second by rune.

Techniques which attempt to rationalise and codify the generation of solutions include Morphological Charts, Interaction Matrices and Nets, Idea Association, Attribute Listing and Input-Output. All these techniques have developed in activities with a high creative content and therefore offer some guidance and assistance to the engineering designer. The motoring methodologies which operate by contriving the correct atmosphere and attitudes for the generation of solutions include: Brainstorming where the emphasis is on an informal even wild, and uncritical exchange between a group of people; Synectics where a specially chosen group is deliberately set up to produce solutions - via analogies - to a wide variety of problems, and Block Removal where the mental approach of the designer, and the atmosphere in which he works, are modified in order to remove constraints, inhibitions and rigidity.

The phases of Preliminary Design and Detail Design which follow the Feasibility Study can also be related to motoring methodologies intended to assist the design activity. At these later stages in the design evolution the problems have become less abstract and more detailed, and the level of uncertainty is lower; the type of methodology most appropriate to these stages tends to reflect this and is usually highly formalised and detailed.

During the evaluation stage procedures are available to compare the performance of any design proposal either with an optimum or with any other proposal, or with the problem specification. For example Archer's Interaction Curves, once drawn, give the level of fulfilment of any design, and Bond's Triangle of Pairs may be used to compare and evaluate a variety of possible solutions. Checklists developed from a previous similar design, Ranking, Weighting and charts or tables for comparing the detail of any solution with the specification, have all been used in engineering design situations.

During the development stage the methodologies available to the designer are more traditional and conventional, for example the use of mathematical, iconic and analogue models to investigate and improve the performance of the chosen design. It should be emphasised however that during this and any subsequent stage, new sub-problems may arise which could entail the use of any of the more abstract motoring methodologies described earlier.

One of the most widely used, and proven, of all the motoring methodologies in engineering design is Value Analysis. This very formalised technique is not new and is based on a common sense approach to the simplification of any design proposal. Its prime aim is to reduce the cost of the design without reducing quality or reliability. An

important aspect of using the technique is to set up a team to undertake an unconstrained, but routine, evaluation of the features of any design. Ref. 57 lists sixteen case histories in engineering design where significant reductions in cost and other improvements in existing designs have been effected by means of Value Analysis. Variety Reduction is a methodology similar in execution but with the prime aim of reducing costs and simplifying manufacture and maintenance.

In concluding this chapter on Methodologies it should be reiterated that very little experience is available of applying most of these techniques to commercial engineering design and that they represent only tools which attempt to isolate and assist - by making more conscious - the discrete and intuitive decisions which are part of the overall design evolution. They should be selected and used with care; complexity of thought is no measure of originality and complexity of methodology cannot guarantee creativity and an optimum solution.

FORMULATING THE FIELD STUDY PROGRAMME

It can be appreciated from the preceding chapters that this research programme started at a time when there was considerable interest in engineering design and numerous hypotheses were being framed to describe how design was undertaken and how the performance of designers could be improved. Most of these hypotheses were based on experience, speculation and intuition, and very little empirical work had been done to substantiate or confute them.

In view of this it was emphasised when the field study programme for this research was being formulated, that it should attempt to collect and analyse some of the data necessary to validate - or otherwise - the more popular hypotheses. It was appreciated that this project alone could not hope to collate sufficient empirical data from which fundamental, valid and universally applicable conclusions could be drawn; but it was considered that sufficient information could be obtained to draw some valuable, if limited, conclusions.

It was also recognised that an important aspect of the programme would be to establish what type of empirical data were required and to explore techniques by which they could reasonably and reliably be obtained. This approach was consistent with the methods adopted by some social science research groups who were, at the time, becoming increasingly interested in field studies as a means of validating hypotheses, particularly in management theory.

In view of the novelty of the field study, and its theoretical context, it was decided initially that the programme should be as flexible and adaptable as possible. In order to achieve this it was agreed that a series of design exercises in the engineering industry would be collected, these case histories would be recorded concurrently and chronologically as events occurred, and would initially include all conceivably relevant detail.

Further important decisions made at this stage were that the methods used to collect the case histories and the value of the data obtained, would be continually monitored and assessed; also no attempt would be made to structure the field work to match any particular existing description of the design process or advocated methodology. The field work was to be flexible, adaptable, open ended and open minded. Although it was decided not to use any other techniques, such as interviews, questionnaires, or the sequential recording of layout drawings, as the basis of the field work it was agreed that any of them might be adopted if they became appropriate.

Several engineering firms were then contacted some of which agreed to co-operate with the project. At the outset of the programme no attempt was made to ensure the anonymity of the firms and personnel involved, although a written agreement covering three of the case histories and verbal agreements for the remainder, were made to the effect that nothing would be published without permission of the firm. No conscious efforts were made when initiating the programme to select any particular types of engineering design exercise. The only bias involved in their selection was the willingness of the firm to cooperate and this depended so much upon such factors as the timing and method of approach, and to whom it was made, that it is not considered to be a significant feature of the companies involved, or to reflect in any way a characteristic common to them all.

In the event the field study programme reflected the pattern of the exercise it was intended to study. The initial analysis of the problem and the formulation of an approach to the empirical work enabled a procedure to be evolved. This procedure was continuously reviewed and revised in the light of the results achieved and the experience gained in the field until it proved satisfactory.

PART II

THE FIELD STUDY

THE FIELD STUDY METHOD

LIST OF CASE HISTORIES AND CODING SYSTEM

BACKGROUND TO EACH CASE HISTORY

THE CASE HISTORIES

INTRODUCTION

Part II of this thesis is concerned with the procedures employed during the empirical programme and the presentation of the results obtained. The first section gives an account of the problems faced in deciding how to undertake the field study and describes the procedure initially adopted and the developments and modifications as the work progressed; the case histories and the code used to identify them throughout the work are then listed.

The circumstances and environment in which each case history was recorded is described in the next section, including the relationship between the author and the design organisation involved and a brief description of each product. Finally each chronological case history is presented in a form which is sufficiently detailed to justify the analysis given in Part III. The relevant diagrams are presented at the end of each case history and brief conclusions are drawn and presented with each one so that their significance may readily be related to the record of events.

THE FIELD STUDY METHOD

The agreed and stated aim at the outset of this research programme was to establish and define the basic features and procedures involved in the design activity in the engineering industry. Two problems which were recognised before the field work started were the absence of accepted techniques of recognising, measuring, recording and interpreting the type of information which would be required, and also the impracticality of accumulating sufficient information to draw even tentative conclusions.

In deciding the method to be adopted for collecting the case histories it was agreed that by recording a detailed case history of events as they occurred, in chronological order, all the required data would be included. Subsequent analysis as the work developed would enable the information to be sifted and the significant data selected. At this stage it was considered possible that an indication of how this type of field work should be organised and undertaken, the variables to look for and how to recognise and measure them, might be the only useful outcome of the whole programme.

Brief discussions with the Industrial Sociology group at Imperial College suggested that the case history approach was realistic and compared with their own empirical research programme into management organisation in British industry. It was also recognised during these discussions that a serious problem of semantics and emphasis existed between the author and the sociologists. The need to define terms at the outset became very apparent and also the possibility of considering non-technical factors which might contribute significantly to the contingent character of the design activity.

Early in 1967 the author had already made contact with various firms and design teams with the aim of recording a diverse series of detailed and concurrent engineering design case histories. As no reliable information was then available on significant categories of engineering design no attempt was made to select the design case histories at this stage. Some of the contacts made by the author stemmed from his own background in engineering design and others were sought through the College. In some cases a verbal agreement was made between the author and the firms' management but in other cases it was necessary to draw up a written agreement on the author's terms of reference and the firms' right to withdraw permission to publish.

The usual danger of the observer influencing the events he observes was recognised at the outset and the author usually attempted to act as a detached recorder of events rather than a participator. This was not always possible however and in the protracted case histories during which the author acted as a member of the design team his

detailed knowledge and record of events became fairly valuable. In even the most extreme example of this however the author's role never exceeded that of any other member of the team and was usually confined to providing background information when this was required. Although the author found it valuable, in fact almost essential, to establish his technical competence and credibility in order to obtain the necessary information and cooperation from the design teams, he rarely had any special knowledge or authority which enabled him significantly to affect the design activity which he was recording.

In some cases the author worked closely with the Chief designer or a senior member of the design team and used him as the main source of information. The procedure in this case was to arrange regular meetings to check and record the events and decisions which had been made. Although with this procedure the author had less access to the details of the case history, there was obviously less danger of him influencing events. One other procedure was adopted, in this the author was the sole or senior designer and recorded the development of his own design efforts. The shortest case history took two months and the longest about five years. The shortest period spent in any one firm was half a day and the longest was three weeks; the latter was on site during the assembly, erection and testing of one of the more complex products.

In 1969 an attempt was made at a preliminary analysis in order to prepare papers for the Summer School at Loughborough University and for some postgraduate lectures at Imperial College. These papers were prepared from the very detailed chronological record of events which had been made. The preliminary analysis was very encouraging in that it suggested that the field study procedure adopted was producing results which would enable the design process to be codified and presented systematically. It also indicated that some of the information recorded, particularly the technical detail, was superfluous and could be omitted without reducing the validity and significance of the conclusions which might be drawn. This preliminary analysis also indicated that the presence of a clear sequence of events in each design process, and possible methods of recognising the design phase in hand, should be looked for and recorded in future.

As the work progressed it became clear that some of the firms and individuals involved were apprehensive about possible reactions to what was to be published and it was decided therefore to preserve their anonymity. A paper[6] published in October 1970 based on case studies in industry, was one of the first of this type to appear in the engineering publications. A discussion with the author confirmed the view that it was essential to retain the anonymity of the firms involved in order to safeguard them from any

consequencies resulting from publication and so as not to deter them from cooperating in future research programmes.

A memorandum published by the British Institute of Management (Ref. 70) relating to management research was subsequently used as a guide to completing, presenting and obtaining approval for publication of the case histories.

A further development at this stage was the decision to organise a series of lectures to be given by some of the designers and design teams involved, and to conclude them with a presentation of the analysis then undertaken by the author. This final lecture, particularly the discussion during which several of the other lecturers were present, also suggested some modifications to the field study procedure including the elimination of further superfluous information, and suggestions on categories of design situations which could be considered and allowed for.

It was soon after this that work in related fields began to be published which tended to reinforce and confirm the tentative conclusions reached by the author. It was decided therefore to continue the field study programme in its slightly modified form. The published work also indicated that some significant conclusions could be drawn from the eleven case histories then in hand and that this information should be published without undue delay; it was decided to finalise the current field study programme as the case histories then in hand were concluded.

LIST OF CASE HISTORIES AND CODING SYSTEM

CODE	DESCRIPTION
A	Butter Packing Machine - Carton Feeder and Erector
B	Gas Circulator Mountings in Nuclear Reactor
C	Plastics Moulding Panels on Stencil Duplicator
D	Temperature Control Valve in Aircraft Equipment Bay
E	Component in Air Conditioning System in Private Motor Vehicle
F	Reaction Control Valve in V/S.T.O.L. Aircraft
G	Wire Stripping and Cutting Attachment
H	Machine for Attaching Plastics Labels to Glass Bottles
J	Graphite Moderator Support Structure
K	Bearings for Moderator Support Structure
L	Two Fence Sewing Machine Foot

BACKGROUND TO EACH CASE HISTORY

This section attempts to set the context of each of the recorded case histories in a form which facilitates comparison and analysis. A brief description of each firm and product is given and also the scope of each design exercise and the relationship which existed between the author and the design team.

CASE HISTORY A - CASE ERECTING MECHANISM IN BUTTER PACKAGING MACHINE

Firm A is a Division of a well known engineering group with an excellent reputation for the design and manufacture of technically advanced and complex engineering products.

Fundamental reorganisation of the Group led to the creation of several Divisions each of which specialises in a limited range of products and is intended to achieve some measure of economic independence.

Case history A was recorded in the Packaging and Bottling Division of the group. The design team possessed considerable expertise in complex and technically advanced engineering design but at the outset its knowledge in the field of butter packaging, as opposed to butter processing, was negligible, although it had knowledge in the general field of packaging.

The team was responsible for the complete design, including all sub-systems; only proprietary articles were bought out. The author worked closely with the Chief Designer to record this case history during its final stages. The sketches illustrating this case history are, in fact, copies of those produced by the Chief Designer concerned.

The case history recorded covers only part of a large automatic butter packaging machine. It involves the feeding and erection of the large cardboard cartons into which 56 lb packs of butter are fed at the rate of 4 per minute.

CASE HISTORY B - GAS CIRCULATOR MOUNTINGS IN A NUCLEAR REACTOR

Firm B was one of the first consortia formed in the United Kingdom to design and construct commercial nuclear power stations.

Considerable reorganisation of the industry and the firm took place during the recording of the case history but the key personnel in the reactor design section of the

parent organisation remained unchanged throughout.

The design team was responsible for the initial design of the system and some detail of the sub-systems, but tended to act as co-ordinator of the interest and efforts of the purchaser, manufacture and erector during the later stages of the design exercise.

Considerable analytical and experimental resources were possessed by, or available to, the design team; these were essential in view of the complex, innovatory and advanced technical nature of the design exercise. The author worked with the design team throughout the exercise which took about five years to complete.

The case history concerns only one component in the nuclear power station design; the mountings for the four circulators which pump the primary heat transfer gas around the reactor core. Each mounting consists of a large ring forging - 10 to 12 ft in diameter - with unique design features to cater for the very severe and stringent design requirements.

CASE HISTORY C - PLASTICS MOULDING PANELS ON STENCIL DUPLICATOR

Firm C is linked to a large diversified engineering group and has very successfully specialised in the design and manufacture of duplicating machines for commercial use. In this very competitive field it is essential continually to review the current model in order to develop new models to match changing customer requirements and competitors' efforts.

The firm's policy has always been to design and manufacture as much of their machines as possible; the design team possesses considerable experience of duplicating machine design and has ready access to the manufacturing works and a well organised prototype shop both of which are situated next to the design offices.

The large plastics panels with which this case history is concerned could not be produced economically by the firm; although prime design responsibility was retained, the detail design involved an industrial design consultant and a specialist plastics company. This case history was recorded with the assistance of the Chief Designer during the project.

CASE HISTORY D - TEMPERATURE CONTROL VALVE FOR THE EQUIPMENT CONDITIONING SYSTEM ON AN AIRCRAFT

Case histories D and F were both undertaken with the same firm, and both involve an aircraft with an advanced Vertical/Short Take off and Landing (V/STOL) capability.

Firm D is a member of a group which has an international reputation for the design and manufacture of a wide range of civil and military aircraft. The aircraft involved in this case history was designed and built by firm D whose design team has very considerable experience in the field of military aircraft but no prior experience in V/STOL aircraft.

A brief account of the evolution of the aircraft is given here in order to provide the background to case histories D and F.

The first V/STOL aircraft to be considered by firm D appeared in the Project Office in October 1957 and the first hovers of the aircraft took place four years later. Two aircraft were built, initially as a private venture and finally with backing from the Ministry of Aviation.

In January 1962 version B, a development from version A, was submitted to a N.A.T.O. Specification and although it emerged as technical first, the political and economic situation prevented any firm orders from being placed.

Further development of version B continued until February 1965 when the final service design - version C - was cancelled by the Government. Initially the exercise had been an attempt to combine the requirements of the Air Force and Navy in one aircraft. In practice it became impossible to reconcile the two Service roles and the final design was 'doomed to be unloved by either Service because of its over-compromised mediocrity'.

However, development of version A continued and a version D was successfully evaluated by several foreign air forces.

In February 1965 it was announced that an advanced version of version D would be designed and built for service with the Air Force as a close support fighter.

This aircraft became version E and entered squadron service in April 1969, as the world's first fully-operational military aircraft of its type.

The specification given to the company in February 1965 was of course both detailed and realistic since it was based on all the work which had taken place on earlier versions. It was, in effect, to 'modify version D, fit a boosted engine, keep a very firm hold on time-scales and costs and deliver a V/STOL combat aircraft to the following detailed specification .....'

Case history D concerns the design of a temperature control valve in the air conditioning system which controls the environment in one of the electronic equipment bays in the aircraft. Although this valve was based on an earlier design for a conventional aircraft there were some design requirements imposed by the unique characteristics of the aircraft. The design team in firm D was responsible for the system design, for the detail design of many of the sub-systems and for the design of some of the parts, although other parts were sub-contracted.

The design team has considerable analytical experience and resources and also includes its own systems testing and development section.

The author had been employed by firm D and was familiar with much of the background to this case history. The details were obtained by working closely with the Senior Development Engineer on the project.

CASE HISTORY E - THE AIR CONDITIONING SYSTEM IN A PRIVATE MOTOR VEHICLE

Firm E is the United Kingdom Division of one of the world's largest motor vehicle manufacturers, with a reputation for reliable, economic, mass produced vehicles for the private motorist. The firm is backed by the very considerable resources of its parent overseas Company but retains a high degree of independence on questions of design and manufacture.

Firm E operates in a very competitive market where the need continually to revise and improve a design is matched by the importance of keeping the final product price as low as possible.

The firm also has to cater for the demands imposed by designing for the mass-production of a technically advanced and complex product.

Case history E is concerned with part of the air conditioning system in one of the firm's models. The product studied includes an impeller, radiator, control flaps and ducting.

The design team was responsible for the design and proving of the system and also the sub-systems, with the exception of a few proprietary and bought out parts. The manufacture of the proved design was sub-contracted. This case history was recorded by working with the Senior Designer on the project during its final stages.

CASE HISTORY F - REACTION CONTROL VALVE USED IN V/STOL AIRCRAFT

This case history was also recorded with a member of the design team from firm D and the description of firm F and the genealogy of the aircraft concerned are given above.

Case history F is concerned with a shut-off valve which isolates the reaction control system when it is not in use. This valve is peculiar to the V/STOL concept and was therefore novel to the design team.

Firm F was responsible for the design and assembly of the reaction control system but sub-contracted much of the sub-system design and manufacture. In the case of the shut -off valve, however, they were ultimately responsible for its design, manufacture and testing. This case history was recorded in the same way as case history D but with a different member of the design organisation.

CASE HISTORY G - WIRE STRIPPING AND CUTTING ATTACHMENT

Firm G is a large electrical and electronic based organisation which specialises in the design and manufacture of computers and their accessories.

Case history G was undertaken in the Engineering Training School of the firm by a graduate trainee under the supervision of the staff of the school. The problem originated in one of the firm's production lines which are located near the school.

As the designer was a graduate who was seeking a permanent position in one of the firm's design offices, he was given complete control over the design, testing and manufacture of the component and was anxious to prove his competence to the firm.

The design exercise described arose from the need to improve the efficiency of female operatives who solder connections to the back plates into which printed circuit boards are plugged. No previous experience of this type of design project was available and the design was very development dependent.

This case history was recorded concurrently while working with the designer concerned.

CASE HISTORY H - MACHINE FOR ATTACHING PLASTICS LABELS TO GLASS BOTTLES ON A PRODUCTION LINE

This case history is different from any other in this series in that the designer directly responsible for it was at the time undertaking the final industrial phase of his engineering Diploma course in the Design Office of firm H. He completed the design exercise as his final year project in College.

Firm H is the distillery of a large Company which specialises in the distilling, bottling and sale of a well known brand of gin. The Engineering and Maintenance Section of the firm is a small group which is responsible for the maintenance of the existing production lines and for introducing new machinery.

Although most of the large items of equipment are bought-out some aspects of the production line are so specialised that it is necessary for the engineering section to design and manufacture their own equipment. When this happens the design team is responsible for the design, development, manufacture and commissioning of the machine, although specialist sub-contractors may be used for some components.

Case history H is concerned with a special purpose machine for attaching small plastics seals - motifs - to bottles of export gin on a main production line in firm H. It was anticipated that the machine would replace at least four female operators.

The author worked with the design team throughout this project.

CASE HISTORY J - SUPPORT STRUCTURE FOR GRAPHITE MODERATOR IN NUCLEAR REACTOR

Firm J is the same consortia as described under firm B above, but as case history J preceded case history B by several years the design organisation and personnel had changed significantly.

The commercial nuclear power station involved in this case history was one of the first built in the United Kingdom and the consortia was only a few years old at the time. The design team was an amalgam of experienced designers from a range of industries but with very little experience of nuclear power station design.

The author joined this team from the aircraft industry as Section Leader of the Structural Design group. He was responsible for the overall concept of the design and its analysis, although detail design, construction and erection on site were sub-contracted.

Case history J is concerned with the large, highly redundant structure which supports the graphite core of the reactor. The design team had no previous experience of structures of this size and complexity, nor was any information available on the solutions being developed by the competing consortia.

Preliminary design work was undertaken in order to prepare a feasible solution for the tender submission and throughout the exercise the customer acted as design consultant and assessor.

The author was the leader of the design team throughout this project, he had made personal notes on its progress as it developed and produced this case history from these notes and the firm's records to which he was later given access.

CASE HISTORY K - BEARINGS FOR MODERATOR SUPPORT STRUCTURE IN NUCLEAR REACTOR

This case history was recorded with case history B in the same firm - one of the United Kingdom Nuclear Power Station consortia. The nuclear power station involved is one of the 'second generation' stations and firm B had been in existence for about eight years when work on it commenced.

The firm had also successfully designed and supervised the construction of one of the earlier type of stations (case history J) and the design team had therefore accumulated considerable experience in this field.

Case history K concerns the roller bearings which are inserted between the top of the support columns and the diagrid which carries the graphite moderator and side shields. These bearings cater for the thermal and stress induced displacements between the columns and the diagrid.

Firm K was responsible for the overall design concept but the detail design of the bearings was finalised in consultation with the sub-contractors who were specialists in the design, manufacture and erection of large bearings of this type for roads and rail bridges.

The author worked with the design team throughout this project over a period of about five years.

CASE HISTORY L - SEWING MACHINE TWO-FENCE FOOT

Firm L is a medium sized factory producing female clothes. The managing director of the firm has a reputation in the trade for his progressive ideas on production methods and his workshops are considered to be technically advanced for the industry.

The author was commissioned by the managing director to design and manufacture a small component to be fitted to sewing machines in order to improve production rates. The component would eventually be fitted to a special automated sewing machine which he had also commissioned, but it was also to be made to suit the existing machines in the workshop.

The designer had no previous experience of the design of sewing machine components or of the clothing industry. He was, however, given total access to all the facilities in the factory and worked closely with the managing director who was very experienced in the field and was totally involved in, and committed to, the design concept.

THE CASE HISTORIES

CASE HISTORY A

BUTTER PACKING MACHINE - CARTON FEEDER AND ERECTOR

INTRODUCTION

In late 1962 the Packaging and Bottling Division of the group considered the possibility of the design of a large butter-packing machine for a New Zealand dairy, after an initial approach by the Dairy. After considerations of future potential and marketing, visits to New Zealand, agreement was reached and first schematic designs were commenced in late 1963.

The machine was basically a one off, or at the best a small batch, project with a target price in the tens of thousands of pounds this being related to the cost of the labour which would be saved in a given period of amortisation.

At one end of the 40ft. long machine (A Plate 1) 25 cwt. packs of butter from the churns are fed into an extruder which delivers 56lb. blocks of butter at 4 blocks per minute to a conveyor. The blocks of butter are then weight corrected, wrapped in parchment and delivered to the central section of the machine where a cardboard carton is erected and the wrapped block inserted into the erected carton.

The final section of the machine seals the centre, edge tapes the cartons and delivers them to a store. The machine is intended to run continuously although there are in practice some fluctuations in supply and demand.

This case history is concerned with the section of the machine where the flat cardboard cartons are fed from a hopper and erected for insertion of the wrapped pack of butter and delivered to the end sealing and taping mechanism, (A Plate 1)

THE PROBLEM

The problem facing the designer in this case history was therefore to feed a cardboard carton from a stack of flat cartons in a hopper, to erect it so that the wrapped 56lb. block of butter could be inserted and then to turn the pack for entry into the end sealing mechanism.

The difficulties of designing a one-off machine for use by personnel of limited expertise on the other side of the world, was recognised at the outset. For this reason it was decided to adopt a mechanical solution. Samples of the cartons to be used were requested following standard design practice on packaging equipment.

The important factors which were established at this stage in systematically studying the problem included:

Dimensions and tolerances of carton in the flat and when erected.

Dimensions and presentation of the wrapped product.

The entry conditions of the sealing mechanism.

Power supplies - Electricity at 440 volt

A mechanical layshaft

Air at 80 p.s.i.

A limited supply of cartons from which to assess tolerances, finish, etc.

Rate of supply of product - 4 blocks per minute.

Limited expertise of maintenance staff.

Price of overall line of which the required design formed a part.

Major maintenance period - Once per annum.

Situation of line - several thousand miles from place of manufacture.

The whole operation, except possibly for stacking the hopper, to be automatic.

INITIAL DESIGN PROPOSALS

In studying the problem in detail and attempting to evolve solutions it was separated into its physical elements, feed, erection and deliver.

a) The Feed

The problem here was to select a unit carton from a stack and present it at the right point in time for crossfeed to the erecting mechanism. An examination of the cartons showed that the folded edges were rounded enabling a knife to be inserted to split off a carton. This suggested the first possible solution which followed the method which would be used by an operator if he were packing a carton from a stack. If the human process were inverted, then gravity could be used as a self feeding feature of the stack, the fingers being timed from the main layshaft, A Fig. 1.

As the fingers dropped the selected carton, then this would land on a cross conveyor which would transfer the carton. The conveyor could be powered by the layshaft and timing of the rammer would be maintained.

In the event of no block of butter being delivered, this could be detected and additional fingers would restrain the drop of the carton which had been selected.

An alternative solution which was considered at this stage, was to use an indexing rising table to lift the stack, A Fig. 2, and to push off the top carton using a rammer. Alternatively a suction device could be used to grip the top surface of the carton and effect the cross transfer.

These alternative proposals had the following disadvantages however:

1) The use of a rising table was costly and complex.
2) Replenishing a rising stack is more difficult than for a stack which is gravity fed.
3) The rounded edges of the carton were geometrically wrong for pushing due to the limited height available for the rammer face and gave little assurance that there would be no adverse reaction against the one beneath the case to be transferred.

On a balance of simplicity and estimated cost it was therefore agreed to proceed with a detail layout of the first scheme.

b) The Erection

The second problem solved by the same personnel was the erection of the delivered carton.

The action of erecting a carton from the flat after it had been delivered from the store, A Fig. 3, constitutes breaking the scored corner hinge lines and then positioning it in the open condition, A. Fig. 4.

There are three possible attacks to this problem:

1) To apply pressure at the two edges of the flat carton so that the two board membranes flex and a critical point is reached where the two scored hinge lines break. In order to avoid both boards deflecting in the same direction under pressure it is necessary to arrange a restraint to one board at least.

2) To insert finger knives between the boards which will then be given a geometrical path to open the carton.

3) To apply suction to one or both boards on the outside surfaces and give the suction cups the right geometric path.

The manual method of breaking and opening a carton is a mixture of (1) and (2) above, because of the difficulty of applying suction. However, if two suction cups are held in the hands it will be seen that this is the easiest motion to perform to break a case.

The simplicity of the motion had to be weighed against the addition of a vacuum pump to the system. Simple layouts showed that the cost of the vacuum pump could be embodied in the design and still break to a cheaper solution than the schemes in alternatives (1) and (2). The choice of philosophy therefore lay in assessing the probability of reliability.

The use of knives to enter between the boards was quite positive provided that the tolerances of the cartons could be ensured and no damage in transit occurred to the raw edges of the board.

Suction cups were considered to be relatively flexible and would permit variation of surfaces. Reliability of vacuum pumps was well known and proven and could certainly achieve the number of strokes required between the major overhaul periods. Some preplanned maintenance would be required to ensure the satisfactory condition of suction cups and vacuum pump seals.

On balance the risk element for a continuous process line would seem to be minimised by adopting the vacuum system and this indeed was proceeded with. The cost also favoured this solution.

It was recognised at this stage, that there would be secondary problems of shape and location of the erected carton relative to the butter package. It was considered however that these problems would best be dealt with at the detail stage since this solution would depend to a large extent, upon the primary design decision.

c) The Delivery

The feed to the end sealing mechanism was not seen as a major problem at this stage and since the solution would also depend upon the other decisions it was not considered in great detail. It was, however, agreed that the cartons should be erected on a rotating table to facilitate orientation to the position required for transfer to the sealing mechanism.

DESIGN DEVELOPMENT

In 1963, the proposals produced by the initial studies were being fully developed.

For the feed mechanism a system of interrupted knife discs was developed, the discs being driven by the layshaft through suitable gearing. The discs, which were revolving, supported the stack of cartons and as the interruptions or gaps came in line with the stack, the latter dropped onto a second set of discs, which were also interrupted but in a different position from the top discs. Thus a carton was split off from the stack and when the gaps in the lower discs come into correct orientation the selected carton was dropped onto a continuously running band conveyor which transferred it to the carton erecting device.

Additional semi-rotary fingers were built into the design which prevented the selected carton from dropping in the event of no product being delivered; these were actuated by tiny pneumatic cylinders operated by a simple trip valve which was triggered by the passage of the butter block to the carton erecting station.

The system was sufficiently simple to meet the requirements of maintenance and price. The discs were hardened by deposition of chrome to prevent wear from the board, and polished to avoid scuffing the cartons. Allowance was made for the sag of the carton in the stack due to their intrinsic weight and this was found to be calculable.

Having decided to use vacuum cups to solve the erection problem it was then necessary to choose between making the movements of the cups purely mechanical or a mixture of mechanics and pneumatics.

A quick survey of possible schemes showed that the mixture of pneumatics and mechanics gave a more economic solution than the use of gear driven cams and links. However, this transgressed the philosophy of simple maintenance and outweighed the advantage of a lower capital cost. The decision on the method of drive was, therefore, deferred until both schemes had been drawn out and examined in detail.

In the purely mechanical scheme, A. Fig. 5 , the system was driven from the mechanical layshaft and required several cams and linkages, also considerable step up geometry was required to effect the quick opening action required. As a consequence, small degree of wear in pins, cam followers, etc., could have large effects on the positioning of the vacuum cups. This could be offset to some extent by the introduction of soak up devices, but to obtain effective action would mean large space requirements.

The use of a mixture of pneumatics and links, A Fig. 6, could result in very simple action with built in overtravel to allow for wear of the suction cups, pivot points and variation of board tolerances. Speeds and adjustment would be readily flexible and this inbuilt manoeuvrability could be a powerful tool on initial installation.

Due consideration of these detailed points led the balance of opinion towards the pneumatic system in spite of the desire for simplicity of maintenance. Replacement of cams, though simply understood, is a long and tedious business. Replacement of seals can be made a preplanned operation. It was, therefore, decided in this instance, to depart from the basic overall philosophy and adopt the pneumatic system.

In considering the use of suction cups for the erection of the carton it was realised that this would present distortion problems and could not be relied upon to give the final geometry required, i.e. a slightly oversquare presentation with all sides having a degree of flatness which would be within the clearance of the wrapped product and the internal dimensions of the carton.

It would be necessary therefore to add a mechanical follow through system which would finally position the carton after the suction system had opened it from the flat.

This naturally led to the reconsideration of an overall mechanical system, but the requirement of reliability prompted the continuation of a compromise solution between pneumatics and mechanics. A simple fixed geometry frame and a single clamp system, the latter operated pneumatically and triggered from the rising position of the suction cup was found to fulfil this need.

As the carton had to be erected on a turntable so that it could be rotated for transfer to the sealing mechanisms, the optimum fulcrum points could not be used. Once this was fully realised, it consolidated the choice of a pneumatic system with its greater degree of flexibility.

DESIGN TRIALS

During 1964-5, the feed and erection mechanisms were fully designed and built and a series of trials were undertaken using the available trial cartons. Both systems worked well during these trials and only minor modifications were called for.

In 1965 the machine was transported to New Zealand and territory trials commenced.

FINAL DESIGN

During territory trials the design ran into considerable difficulties due mainly to the non-representative cartons which had been forwarded and used for the shop trials.

During the shop trials in England, the carton feeding mechanism had functioned satisfactorily and appeared foolproof. It failed in New Zealand however, for one reason (viz) the inconsistency of the edge condition of the cartons when supplied in bulk. One carton in about 400 was found to have a bulbous edge instead of the semi-circle which had been assumed from the sample of carton given to the designer and used for trials. The bulbous condition was found to have come about from the way the cartons were palletised and strapped for transhipment between the carton making factory and the end user. However, for commercial reasons, the bulk distribution methods for the cartons could not be changed and the sorting of cartons to eliminate the defective cartons would have been costly of labour.

It can be readily seen, A Fig. 7, that the occasional bulbous edge could form a nesting action with the edge of the normal carton on either side and would thus prevent the action of the interrupted knife discs.

This not readily predictable snag was, in fact, a serious problem, since it rendered the utilization performance of the machine lower than desired. A small team of engineers/designers were flown out to New Zealand to provide an intensive, on the spot, reassessment. An important decision had then to be made in view of the contract aspects and the initial cartons supplied. It was agreed to re-design and produce the revisions required on site.

The result of this was a most simple and ingenious solution to the problem. In all the earlier proposals, the carton had been considered as a flat entity once the natural spring (or sag) of the board had been allowed for as a deficiency to be overcome. It had not occurred to the design team to consider this feature as a useful attribute which could be harnessed to the problem.

The final design is shown on A Fig. 8. The discs were removed and the stack was allowed to sit on four small ledges. The band conveyor was replaced by two endless chains carrying a pusher bar. Between the chains was mounted a simple vertically reciprocating suction device, which rose to the bottom carton, made its suction hold and when depressing drew off the bottom carton by springing it off the narrow ledges. This final solution was cheap, required little and easy maintenance, and made the edge condition of the carton no longer a limiting parameter.

This solution was subjected to considerable trials runs and proved very successful with only very minor modifications.

The carton erection mechanism also ran immediately into difficulties during the territory trials. The curvature of cartons in the flat was found on occasion to be quite exaggerated due to set occurring in boards drying out whilst strapped in bulk in storage and shipment, and the stiffness of the board on the scored creases was also found to vary widely. In some cases the curvature was S shaped due to the way in which the cartons dried out when stored in less humid conditions. None of these conditions had been apparent in the sample batch of cartons which the design team had used.

The net result was a failure of the suction cups fully to get hold of the carton surface in some instances. It was at first considered to be a simple matter to soften the rubber but following this precept it was found that with softer rubber the lips occasionally curled when the light scoring of the bends on some cartons made them very stiff and difficult to bend. A Fig. 9 shows the cup design and lists the factors to be considered.

The problem was referred to various specialist suppliers of vacuum cups but there was little true response as the quantities involved were too small for the computational effort, the die design and the type of mix, to be resolved as a viable proposition. There were also several thousand miles now between location and design base with extended communication.

The design engineers on site were therefore faced with a serious, apparently intractable, problem which had to be solved in a hurry. The solution came from a brainstorming (desperate) suggestion that the suckers used on car roof racks should be suitably drilled and tried.

In the words of the Chief Designer on site "Needs must as the Devil drives" and the idea was tried and found to work. The suckers were a few shillings apiece because of quantity production and could be readily replaced on a pre-planned maintenance scheme. The design was now highly successful and after a season's running, the suction cups were still functioning satisfactorily.

No other major problems occurred with the aspects of the overall design described in this case history and following a final documentation they were considered to be successfully completed.

CONCLUSIONS

In the view of the author, this case history is one of the most interesting and valuable of those collated. It was not easy to separate the design of the components described from the overall machine design and it was only made possible by the very considerable assistance given by the leader of the design team concerned.

The case history exhibits an emphasis of resources on the later stages of the overall exercise: the trials and particularly the final design, becoming the major aspect.

The initial attempts at the solution were completed fairly quickly with the emphasis in building in flexibility for subsequent modifications on site.

Other interesting aspects were the informality of the operation once the territory trials were under way and the high efficacy of the team at this stage - due, presumably, to personal factors such as working under pressure, the desire to finish and return to the United Kingdom, isolation and, possibly, national pride. In addition, of course, to being much 'closer' to the hardware.

The initial designs of the feed mechanism produced a solution which met the known factors and yet had not produced the simplest and cheapest solution. It had been coloured by attempting to simulate a manual operation by automatic means and finding a simple answer which fitted and satisfied the known conditions.

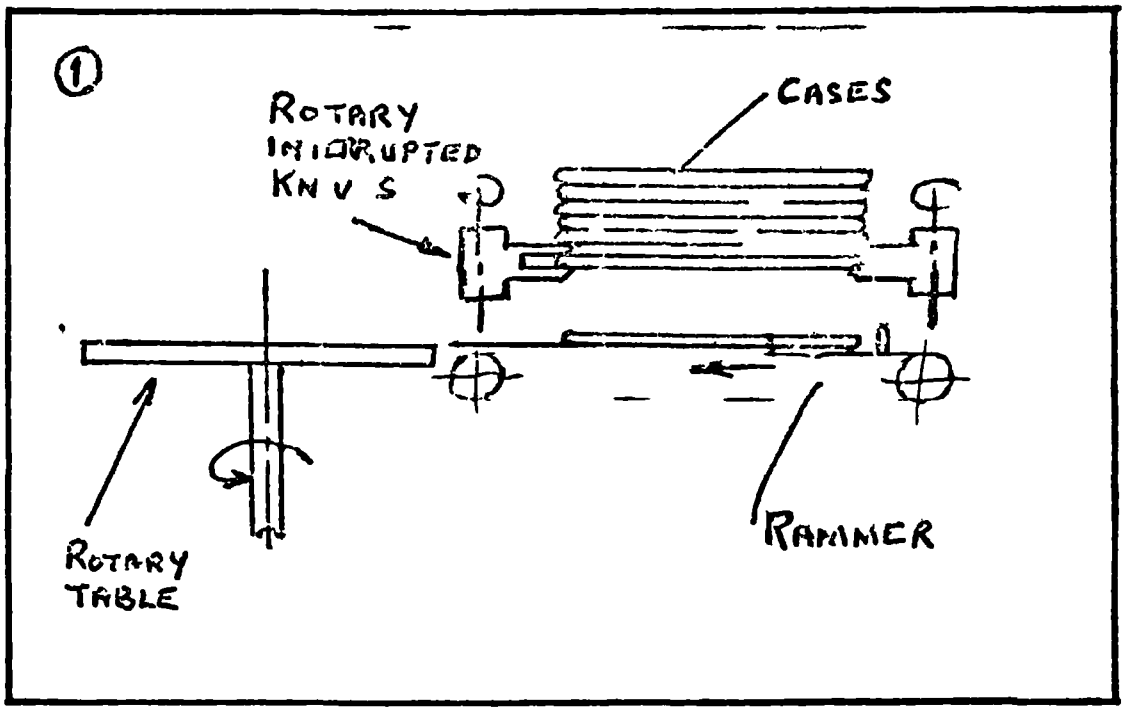
In the erecting mechanism although a successful design emerged, and with the size of carton involved probably one of the simplest solutions in operation today, there were several serious problems which were only overcome by fairly drastic modifications on site.

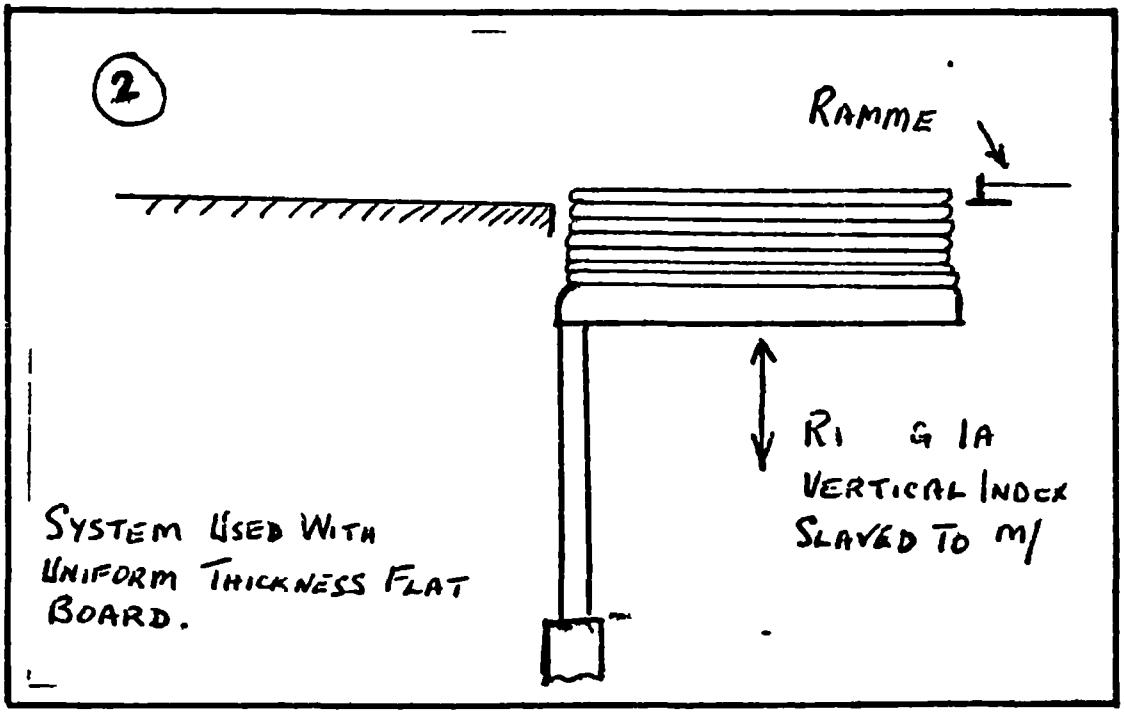
A conscious effort was made to use a systematic approach to design throughout the schematic phases but was not repeated to the same degree through all the various detail phases.

Should the approach have allowed for the Gaussian distribution which must occur in such things as carton production, or was it justifiable to have assumed that the sample units represented the ends of the spectrum of variation which could occur? In packing design practice it is universally assumed that product samples are representative.

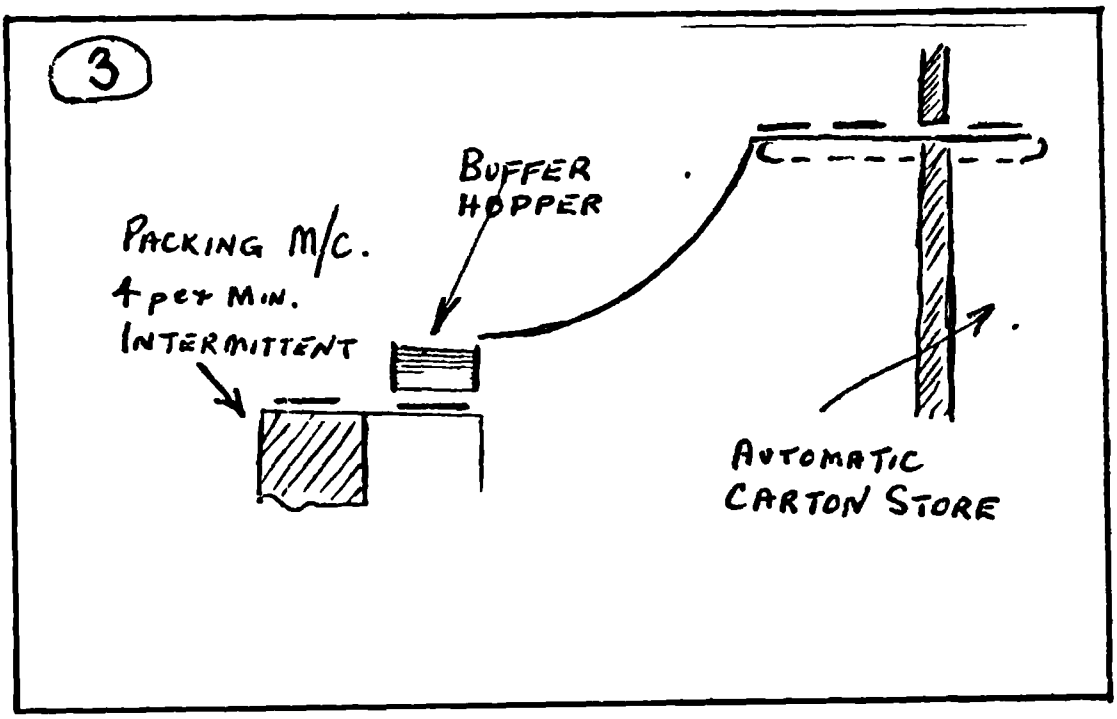
A further aspect of the use of a systematic approach was that in practice the case history resolved to the solution of detail problems. This probably illustrates the nature of a systematic process converging to a few intransigent problems, rather than emphasises the importance of general detail design.

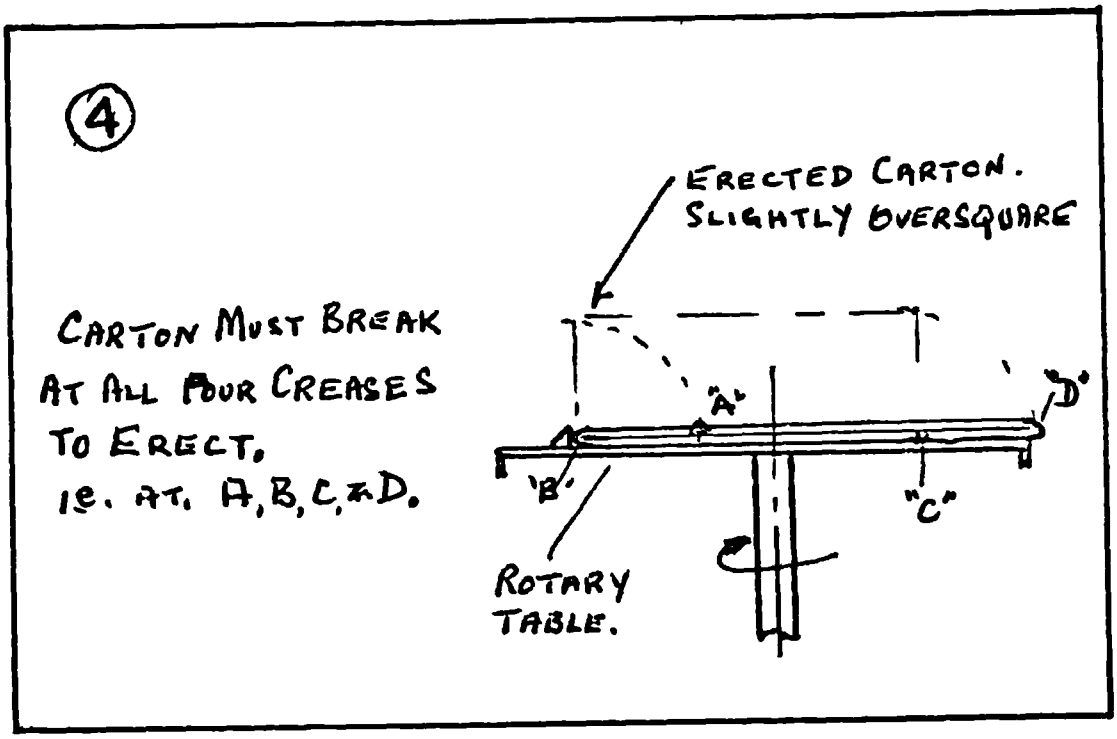
Although the final costs on site may have amply justified a deeper initial investigation stage, it is not certain that some of the imponderables would even then have been appreciated. Nor is it certain that the problems would have been solved as efficiently as they subsequently were on site.



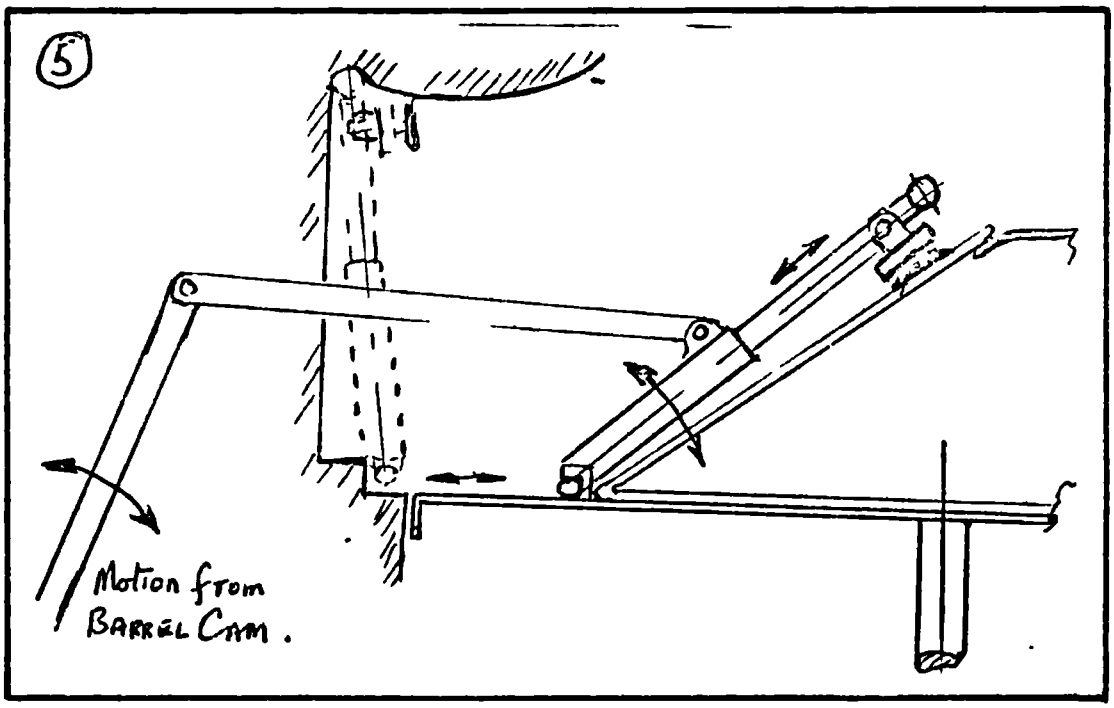


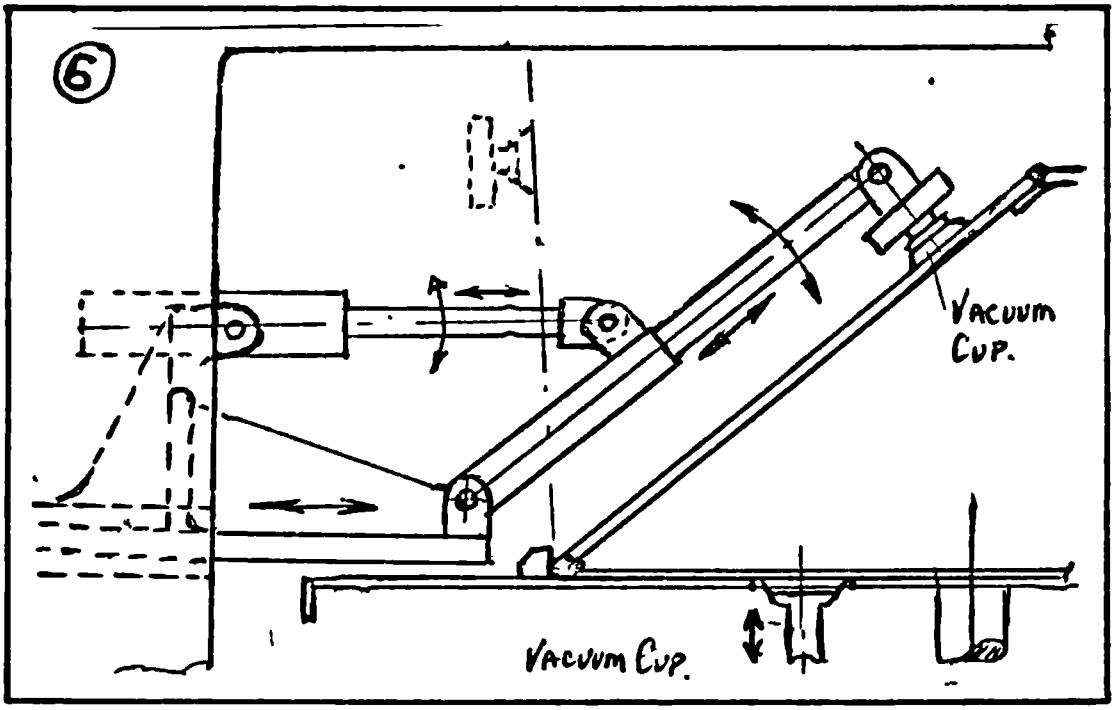
AFIG 1& 2 INITIAL DESIGN PROPOSALS



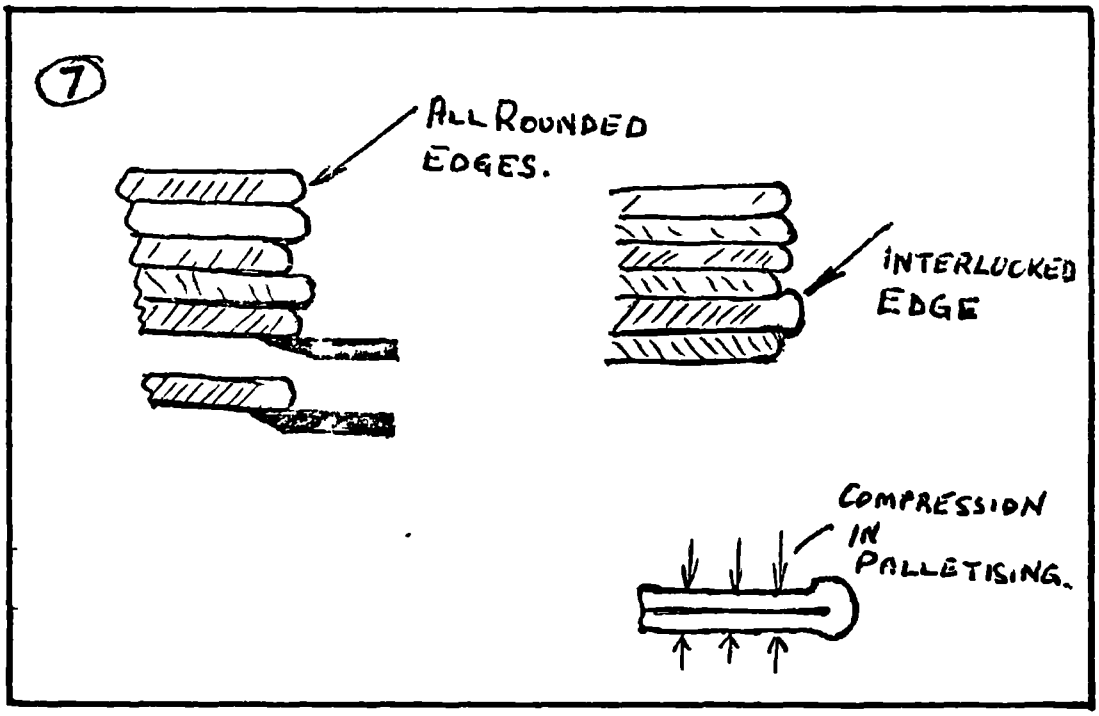


AFIG 3&4 DELIVERY AND ERECTION OF CARTONS

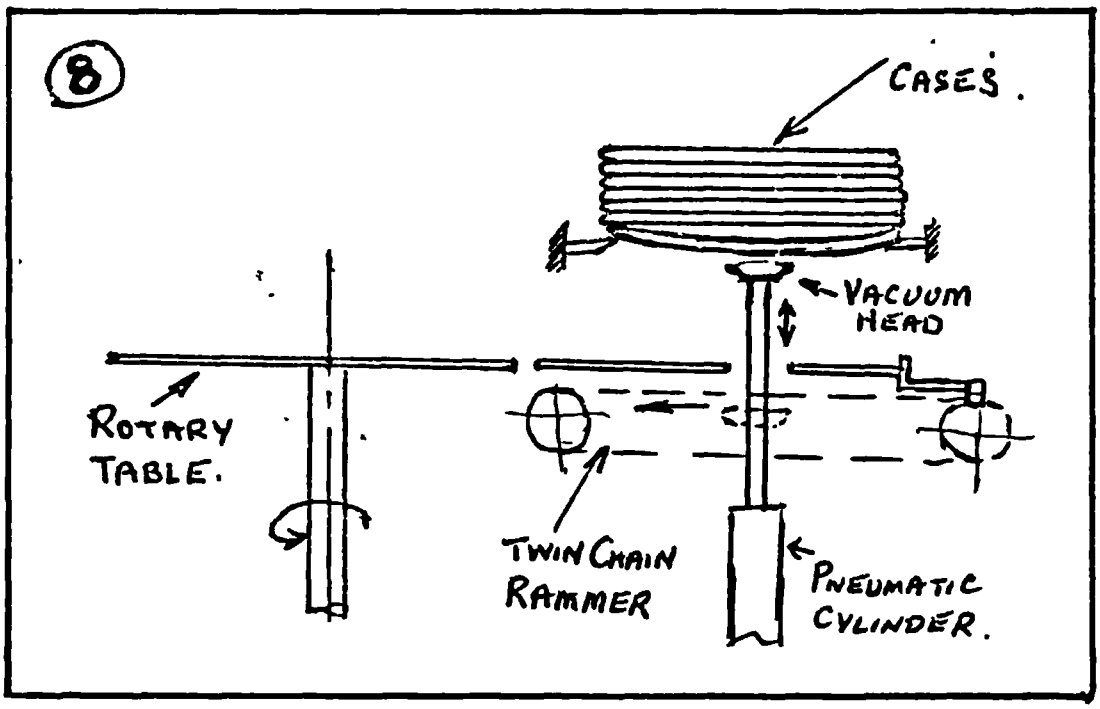




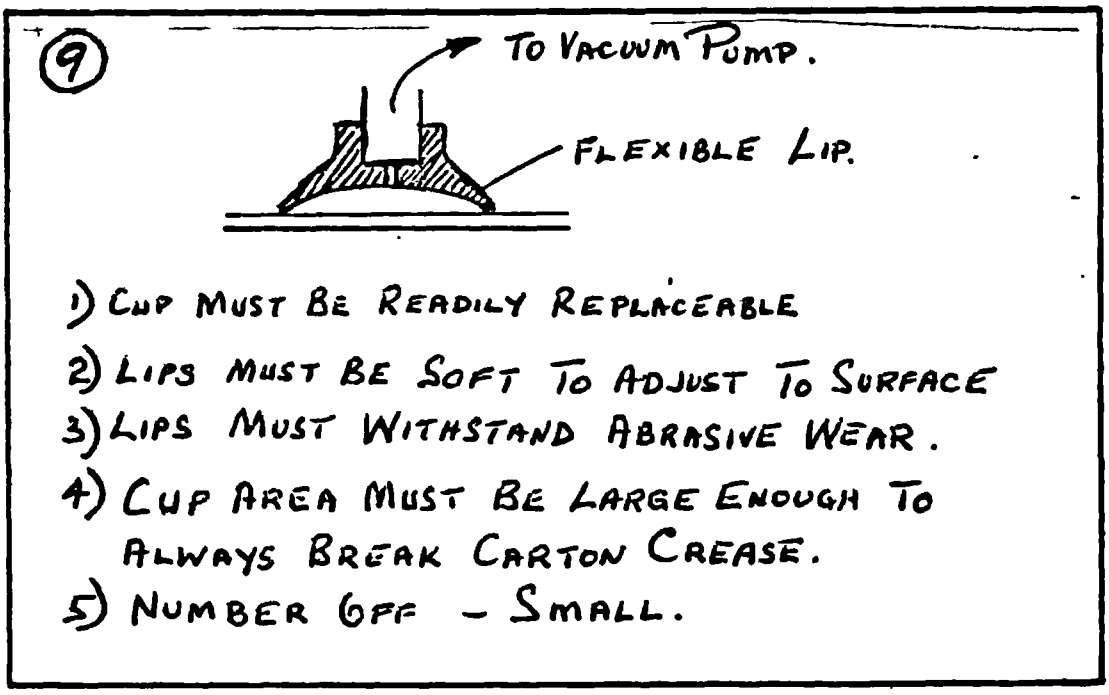
A FIG 5&6 ALTERNATIVE OPERATING PROPOSALS



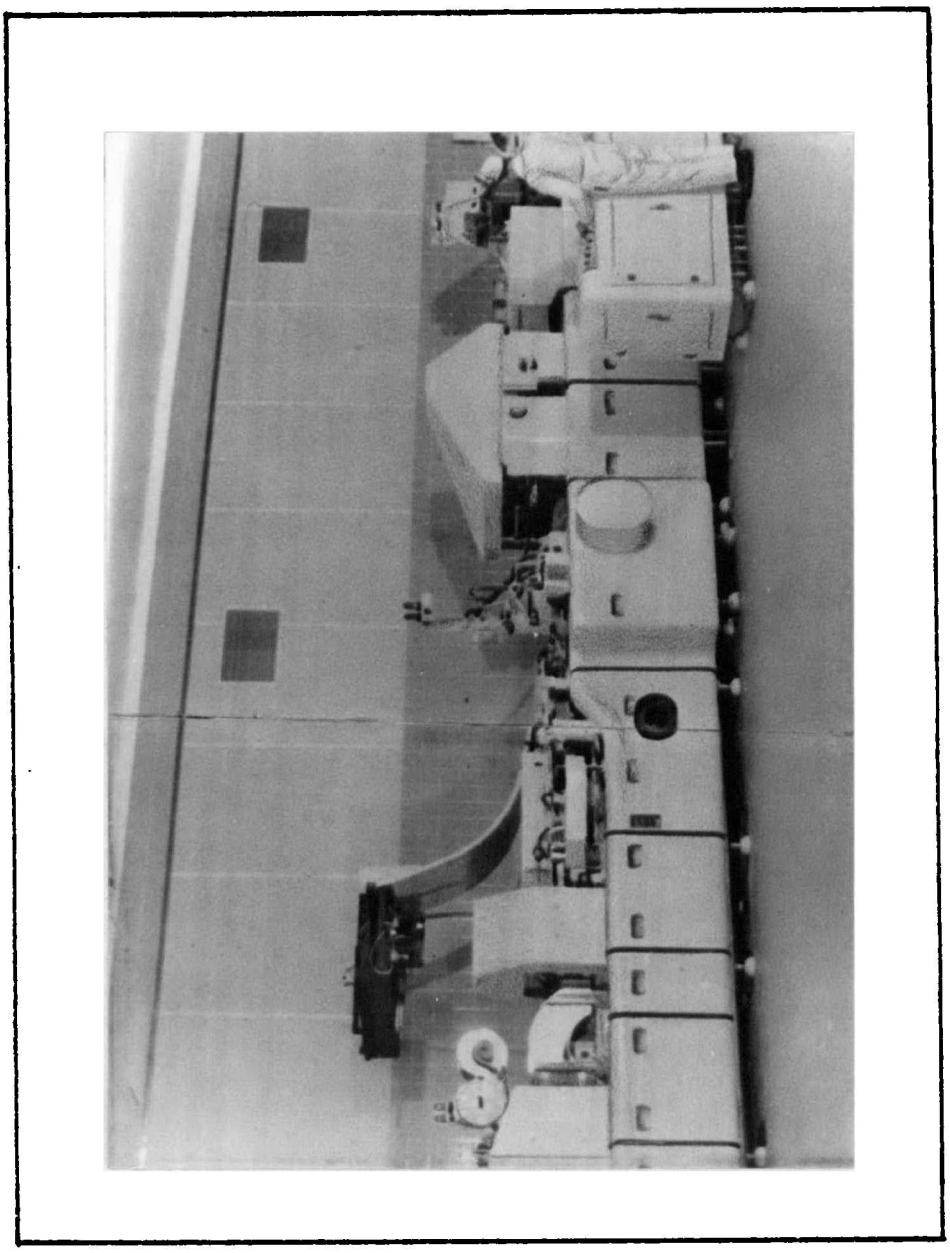
A FIG 7 CAUSE OF DESIGN FAILURE



A FIG 8 FINAL DESIGN PROPOSAL



A FIG 9 RUBBER CUP DESIGN REQUIREMENTS



A PLATE 1 THE FINAL DESIGN

CASE HISTORY B

GAS CIRCULATOR MOUNTINGS IN A NUCLEAR REACTOR

INTRODUCTION

This Design Case History is concerned with the Gas Circulator Mountings in an advanced Gas-cooled Reactor (A.G.R.) Nuclear Power Station. An important feature of this plant design is the use of a pre-stressed concrete pressure vessel as the integral primary pressure containment and biological shield. The pre-stressed concrete pressure vessel, although a relatively new concept, is not new to the A.G.R. reactor system, as this was a feature pioneered in the lat er stages of the Magnox reactor era.

This case history is an example of the common necessity for the integration of mechanical and civil engineering which is essential in the design of nuclear reactors and their primary containment. As the technical content of this case history is higher than that of any other case history studied it is necessary to include in this introduction a fairly detailed account of the technology involved, and in particular to describe the working of the reactor and its containment.

B Fig. 1 shows the concrete pressure vessel; a massive thick-wall structure designed to contain the reactor coolant gas at about 500 lbf/in^2. The main C.P.V. dimensions in this example are, 90 ft external diameter, with 12 ft thick walls and 21 ft thick flat end caps. These dimensions are determined from the optimum strength requirements of the vessel in order to adequately provide for the biological shield which in earlier designs necessitated a separate concrete shield outside a conventional steel pressure vessel.

Since concrete is not capable of resisting the significant tensile stresses induced by the internal pressure, the vessel is pre-stressed prior to operation into a state of substantial compression by high tensile steel tendons. In operation under pressure the vessel still remains in a state of considerable compression except for small regions of acceptable low tensile stress.

In contrast to the elastic growth of conventional steel vessels under internal pressure, the C.P.V. is elastically shortened in size even during the operating conditions. Furthermore, since creep under stress and temperature in concrete is significant, the vessel continues to contract by straining until reaching a steady state.

The inner surface of the C.P.V. is lined by a gas-tight mild steel membrane adequately lugged back into the concrete in order to strain with the C.P.V. without buckling. In areas where penetrations through the vessel are required, the liner is continued as penetration sleeves extending the pressure boundary.

Another requirement of the concrete as a structural material is that its temperature must be kept within reasonable limits and it is therefore protected against the direct heating of the reactor coolant gas which varies in this case from about 290°C at the bottom to 675°C at the top. This thermal protection is achieved by insulating the inner surface of the steel membrane with stainless steel foil packs, and providing a water coolant circulated through pipes embedded in the inner layer of concrete outside the liner.

The concrete inside surface temperature at present accepted is about 60°C which, being 40°C higher than the external ambient temperature, gives rise to a radial temperature gradient through the vessel walls. The thermal stresses thus induced in the C.P.V. cause further compressive strains on the inside surface.

The thin steel membrane and thin penetration sleeves offer very little stiffness to resist the straining of the large bulk of C.P.V. surrounding them and are therefore freely strained into compression which is only marginally reduced by the application of internal pressure.

In the long term, as the vessel creeps, the strains in the large steel liner and penetration sleeves reaches compressive yield. This problem presents complications where any structural connection is made into the C.P.V.

An added complication also arises when reactor components working at temperatures up to 700°C are required to be connected back into the C.P.V. Provision must be made to limit the heat flows into the C.P.V. thus avoiding local hot spots in the concrete. The major components supported from the C.P.V. are: the reactor core which stands on a grid structure which is supported by columns from the floor of the C.P.V.; the boilers which in this case are slung from the C.P.V. top, and the circulators which are supported off the C.P.V. side walls.

The gas circulators, which in this design are single-stage centrifugal type, are externally electrically driven with a drive shaft passing along a penetration. There are four circulators to each reactor and they provide the blower power to circulate the coolant gas through the reactor and heat exchanger circuit.

The temperature of gas passing through the circulator is 300°C. In the A.G.R. system the graphite core moderator is kept at cool temperatures by a re-entrant gas circuit directing the flow of the gas downwards through the core before passing upwards through the fuel channels, B Fig. 1. The heated gas completes the cycle by passing from the fuel channels at 675°C to the boilers or heat exchangers generating steam for the turbines.

The overall initially anticipated cost of a Nuclear Power Station of the type involved in this case history is £75m - £100m. The usual procedure is for the customer to issue an enquiry specification for the station and then for the interested consortia to prepare tenders.

These tenders give, and attempt to justify, all the important design features and the anticipated capital and running costs. They do not however include all the detail design studies, and are in fact a proof of 'ability to design' rather than a detailed statement of a proposed design.

Thus any feature of the overall design, such as the gas circular mountings, are considered at two distinct stages. The pre-contract stage when overall parameters such as size, number off and location are being decided, and the post-contract stage - not always reached of course - when the detailed design exercise is undertaken.

THE PROBLEM

This design case history is concerned with the design of the structural units on which the gas circulators are mounted.

Positioning of the circulators results from an optimisation of the reactor plant layout and C.P.V. design. At this stage consideration must be given to the primary design requirement that the circulators must be mounted so as to facilitate easy removal to the outside of the vessel for routine servicing. Provision of four large permanent penetrations in the vessel for this purpose, has considerable influence on the C.P.V. design.

For instance, room inside the concrete for optimum positioning of the pre-stressing tendons is severely limited by the numerous penetrations which pass through the walls and end slabs. This is particularly relevant when attempting to achieve a simplified tendon arrangement comprising essentially of horizontal hoops and straight vertical tendon groups. In this case a penetration would impose unusable voids created by the shadow of penetrations projected in the vertical and horizontal directions. It is therefore desirable to position as many penetrations within projected shadows of each other and in achieving

such an arrangement large circulator penetrations tend to dominate the choices available.

These are only some examples used to illustrate the optimisation of the circulator positioning which must be considered in relation to the optimum reactor plant layout to give the smallest possible overall plant size for a given reactor power output. The very small relative cost involved in mounting the circulators imposes categorically the decision that the design solution must not restrict the freedom to reposition the circulator within the overall plant.

STUDY OF THE PROBLEM

In preparing design proposals for submission with the tender the stated aim of the design was to mount the gas circulator cartridge in a prescribed position onto the pre-stressed concrete vessel and to satisfy the following requirements:

(1) Provide a means for removal of the circulator cartridge as one single unit.

(2) Ensure a gas tight seal as part of the pressurised envelope of the primary reactor containment.

(3) Take account of the strains and distortions resulting from attachment to the C.P.V. and ensure the structural stiffness is compatible with the concrete.

(4) Limit the local flow of heat into the concrete vessel so that local concrete temperatures do not exceed 60°C.

(5) Provide adequate strength in the support to resist:

(i) Circulator gravity loads.

(ii) Internal pressure loads.

(iii) Stresses due to temperature variations.

(iv) Loads transferred by virtue of connection into the concrete vessel.

(v) Gas exit discharge loads from the circulator diffuser.

(vi) Torque loads reacted in the mounting resulting from an assumed fault condition of bearing seizure.

(6) Attempt to give minimum interference to pre-stressing tendons which had previously been positioned local to the circulator penetration. It was

noted that the tendons in this area were found to give a significant contribution in obtaining a satisfactory C.P.V. design, at a time when the anticipated penetration diameter was smaller than finally required. The effect of having to remove tendons can be appreciated by considering that each pre-stressing tendon unit has a working load of a fraction under 1000 tonf.

Initially not all of these requirements were fully appreciated as can be illustrated by examination of the first design proposal. In fact several of these design requirements were formulated from an appraisal of the acceptability of the first design.

As described above the design concept was prepared at the time of the complete station tender when little effort could be devoted to the finer details, and it is also probably relevant that the first design was prepared by mechanical engineers who lacked the specialised knowledge of the civil engineering aspects.

INITIAL DESIGN - PRE CONTRACT

The first design proposal, submitted with the tender, is shown in B Fig 2. It involves a bolted flange ring of large cross section located within the penetration tube, it is stiffened by radial webs and cast into the concrete vessel side wall. In consideration of the effect of strain imposed by concrete deformations, the behaviour relative to penetrations in the vessel should be examined in further detail.

If the penetration sleeve is considered to be situated in the mass of concrete which is subject to stress, then the penetration hole will constitute a stress concentration and there will be an associated strain concentration. One example of this effect analysed in detail by the design team was the case where the field stresses in the concrete are assumed equal bi-axial. It was also shown that the steel hoops inherent in the penetration sleeve partially resist the local strain concentrations, reducing the stress concentration in the concrete, in the same way that a nozzle provides compensation at a hole in a conventional steel vessel.

This hole reinforcement can also be provi ded by reinforcing bars set in the concrete round the hole. The large flange mounting ring initially proposed would give a substantial reinforcing to resist concrete strains, but unfortunately the large radial outwards force exerted by this ring is highly concentrated local to the inner corner. A serious fault in this design is that the ring would, therefore, shear off the corner of surrounding concrete.

Another defect was the lack of a graded heat path to the cool heat sink, causing the ring and surrounding concrete to be subject to excessive temperatures. This in turn aggravated the previous fault by virtue of the thermal expansion of the ring causing even larger loads to be applied to the surrounding concrete.

LATER DESIGN SOLUTIONS - POST CONTRACT

The tender for the nuclear power station contract was submitted by firm B in January 1965 and the station contract was awarded in September of the same year. Having thus provided satisfactory proof of ability to design, the Company then proceeded to undertake the more detailed design studies.

The appraisal of the first design enabled the design requirements to be more strictly defined and as a result of this the following, more realistic, proposals were made:

(a) Radial Keyed Scheme

This scheme proposed to retain the heavy flange mounting ring and to radially key it to a smaller ring located within the penetration sleeve. In this way the circulator mounting flange is located, by the radial keys, to the C.P.V. with end stops to resist the axial thrusts. This layout provides freedom for relative expansions between the ring and C.P.V. The disadvantages with this design were:

(i) A great difficulty in providing a gas seal across the two ring sections which move relative to each other.

(ii) The guarantee required to ensure freely moving surfaces for the 30 year period of plant life.

(iii) Undesirable heat conduction paths to the concrete.

Although these problems were purported to have been solved by another nuclear design group by whom a patent was taken out covering their particular design solution, the impression of unnecessary design complexity ruled out this proposal.

(b) Direct Flexible Structural Connections

The accommodation of differential movement between components is not an uncommon problem in reactor engineering design. In these cases it is more often considered desirable to achieve this connection by means of adequately flexible structure,

as opposed to sliding surfaces which must be guaranteed for 30 years life.

DESIGN ANALYSIS

A study of the second of these proposals led to a clearer understanding of the problem, and of the predictable behaviour of the type of structure involved.

The stresses resulting from differential movements between components can be defined as secondary or self limiting since minor distortions satisfy the relative movements which cause the stress to occur. Secondary stresses therefore satisfy an imposed strain, as opposed to primary stresses which are in equilibrium with external loads. Within reasonable limits of secondary strain exceeding yield the presence of secondary stress does not affect the capability of the structure to carry superimposed primary stress. This principle was used to evolve the design of the circulator mounting, using a flexible shell to mount the heavy flange ring remote from concrete distortions.

When a hoop near the equator of shells in the form of cylinders, shallow cones, and spheres is locally strained the distortion is localised, and sections remote by a length exceeding $2\pi/\lambda$ will not distort.

Where $\lambda = \sqrt{\frac{1 - \nu^2}{R^2 t^2}} = \frac{1.285}{\sqrt{Rt}}$

and R and t are radius and thickness respectively and ν is Poisson's ratio.

The form of these distortions is a rapidly damped deflection curve such that at a distance of π/λ away from the strained section, the effects are negligible.

DESIGN DEVELOPMENT

In the light of this analysis and the fuller appreciation of the problem which it afforded, the possible design solutions shown in B Fig. 3 were proposed.

The merits of these designs in relation to the prescribed requirements can be listed as follows:

1) Circulator removal is simply accomplished by removal of the flange ring bolts and withdrawing the cartirdge through the penetration on a simple arrangement of rails.

2) The gas containment is provided in a conventional shell with a conventional gasketed flange seal.

3) Distortions imposed by the concrete strains are localised to one end of the shell at the connection into the vessel, and the flange ring is structurally isolated from these effects.

4) The length of the shell provided for isolation of the ring also serves as an ideal low-sectional-area conduction heat path which can be simply insulated. Thus restricting the heat flows into the concrete as shown in B Fig. 4.

5) An ideal structural form is provided to resist the primary loadings defined. Secondary constraints are remote, for example, for the same reason that the concrete imposed strains are isolated from the flange ring, the thermal expansion of the ring is sufficiently remote not to be restrained by the concrete vessel.

FURTHER ANALYSIS

In assessing the shell design solutions shown in B Fig. 3 it is apparent that scheme (c) differs structurally in that the shell is internally pressurised whereas the other two cases are externally pressurised. The penalty for cases B3a and B3b is that the shell thickness has to be slightly increased to ensure adequate buckling strength. In order to appreciate the implications of the shell thickness on secondary stresses detailed analyses were undertaken to investigate thermal stresses, pressure discontinuity stresses and stresses induced by concrete strain, which are of principle interest at the junction of the shell into the concrete. These effects can be summarised by showing that an increased shell thickness would have the following effects:

(a) Reduce ~~Increase~~ the shell wavelength in proportion to $\sqrt{t}$ where 't' is the shell thickness.

(b) Increase secondary thermal stresses in proportion to $\sqrt{t}$.

(c) Decrease pressure discontinuity stresses in proportion to 't'.

(d) Have no effect on secondary stresses due to concrete strains because these are shown to be independent of the shell thickness.

(e) Increase the heat flow into the concrete, which in turn further affects (b).

These effects illustrate generally the factors which were accounted for in the dimensional optimisation, which included also the primary stress requirements and the slightly differing stiffness properties for the various types of shell geometry.

At this stage it was found necessary to eliminate the turned back cylindrical shell design, B Fig 3c, due to a requirement which was not fully defined. This difficulty arose when the length of the circulator cartridge unit was increased and with this design could no longer be manoeuvred between the outside face of the vessel and external building steelwork. In any event this design did have some theoretical disadvantages in that secondary strains due to the separate effects described all proved to be additive.

DESIGN SOLUTION

Having followed a course of design evolution based on a particular structural understanding, it was not surprising that in this case the final evaluation was concerned basically with only two very similar solutions, i.e. the spherical, B Fig. 3a, and cylindrical, B Fig. 3b, shells joining the mounting ring into the C.P.V. The spherical shell mounting had the advantage that the local pressure thrust loads could be taken deep into the concrete. This was considered important because the concrete around the circulator penetration was already highly stressed, this being a zone of stress concentrationed around the hole.

Some small scale steel model tests were carried out in which the collapse mode of the spherical shell under external pressure was investigated. These tests also included exaggerated high strains to simulate the imposed concrete strains at one end. The results showed that the shell and ring could be plastically deformed to an extreme shape without breach of the pressure containment. An added safety feature was that in the extreme of progressive collapse the ring would be stopped from moving outwards by the stepped ledge in the penetration sleeve, i.e. a fail safe condition.

A conical shell was considered as an alternative to the sphere, but it was found that the continuation of this form of shell into the concrete fouled existing tendon positions. These considerations led to the spherical mounting shell design as the final chosen solution.

FINAL THEORETICAL EVALUATION

The theoretical aspect of the final design was then subjected to an intensive analysis. The result of the analysis in this case was well assured by the implication of

concepts used to form the structure. However some problems still remained, in particular a study of the permitted level of acceptable secondary strains.

A simplified understanding of this problem by analysis indicated that the secondary bending stress in the spherical shell due to a concrete strain ε_c is simply given by:

$$\sigma_b = 1.92\ \varepsilon_c E$$

Now the concrete strains (ε_c) approach that of yield in mild steel (e.g. yield $= \sigma_y/E \doteq 1000 \times 10^{-6}$ in/in) so the bending stresses due to the concrete compressing the shell approach twice yield. This is slightly exaggerated because the steel shells forming the penetrations act as reinforcement and partially resist this straining to about 75% of the yield in steel.

The other significant component of the secondary bending stresses in the shell results from the temperature gradients and was additive to that imposed by concrete strains. Discontinuity bending stresses due to the pressure were not so significant and anyhow induced an opposite bending action. This characteristic was not present in the turned back shell design previously eliminated for practical reasons.

The combined secondary stresses were therefore meridional bending which were greater than twice yield, and hoop membrane stresses just below yield. For such combined stresses it is usual to assess the onset of yield to some criteria such as that proposed by Tresca (maximum shear stress theory), which states that yielding occurs when the difference in principal stresses (sometimes defined as stress intensity) reaches yield. The secondary stress intensity, due to concrete strains in this case, is therefore approximately three times yield (i.e. the algebraic sum of hoop and bending stresses) and this is further increased by the temperature gradients.

To say a secondary stress is several times yield is somewhat fictitious since it implies stress remains related to strain proportionally above yield. What we really means is that if a secondary strain is imposed it can, for convenience, still be related to stress by the Youngs modulus for the purpose of stating the magnitude of that strain.

The implication of secondary strain cycles above yield may be considered by the diagrams BI, BII and BIII. Consider a secondary strain greater than yield to be imposed but not greater than twice yield[BI]. Assuming ideal plasticity (no strain hardening), the imposition of strain (ε_1) will cause yielding and the stress strain relationship will be as shown along the line 0 to A. If the strain is then removed, the stress follows the

line AB to give a residual stress σ_2 of opposite sign. Subsequent applications of a strain (ε_1) will then cycle on line BA elastically. This behaviour is often termed shake-down to the elastic conditions.

Considering now the application of a secondary strain greater than twice yield B11 In this case removal of the strain (ε_3) would cause reverse yielding at D giving a residual stress equal to yield of opposite sign. Repeated application of the secondary strain (ε_3) would then cause further yielding at C, and all subsequent strains would produce progressive plastic strains by cycling round the loop BCAD.

This is the basis of allowing secondary stress intensities up to twice yield such that shake-down to elastic conditions is assured on repeated straining. This criteria is the basis of the limits set in the American Nuclear Pressure Vessel Code when dealing with secondary stresses.

However, in this design case it will be noted that the total secondary stress intensities were approximately three times yield, which would appear to exceed this shake-down limit. But in studying the make-up of the stresses it will be appreciated that only the stresses due to pressure and temperature gradients will ever be cycled in operation. The major proportion of stress arising from concrete strain is permanently imposed and would never be cycled, giving a stress strain relationship as shown in diagram BIII.

The design was therefore considered acceptable wh ere in this case secondary strain due only to pressure and temperatures are ever removed, and within these limits elastic shake-down along line BA will occur when only these strains are cycled.

Further practical design considerations were concerned mainly with the optimum length of the mounting shell. Obvious savings in construction time would be achieved if the ring distortion after pre-stressing could be minimised so that any further machining of the mounting faces was unnecessary. Furthermore an ideal requirement would be to allow the circulators to be mounted in position at the time of pre-stressing the C.P.V.

These questions were raised at a time when a shorter length of shell was being examined in order to clear proposed pre-stressing tendon positions situated around the penetration stop. A shorter length of shell would have a direct effect on the ring distortions. This problem was examined in more detail by carplex computer analyses, made necessary because a unique solution was not available for short length shells

terminating at a stiff structure. This work showed that for the final design, the extent of stress in a shorter shell was extended over all of the length, but only very small distortions occurred at the ring. These predictions showed that if the vessel was pre-stressed with the circulator in place and the circulator subsequently unbolted, then only 4 thou. radially inwards movement of the bolting face would occur. This movement resulted mainly from ring rotation. These conclusions have yet to be proven in practice.

PRODUCTION (MANUFACTURE)

Following initial studies of this very complex problem the design feasibility was considered to have been satisfied and in 1967 the final detail design was put out to tender. The final analysis which was required to prove the high integrity of the design continued in parallel with manufacture.

The manufactured unit consisted of the ring, spherical shell, and part of the penetration ring reinforcement in the membrane, as one welded fabrication. The extent of this fabrication is generally that part of the penetration shown shaded in B Fig. 5. This unit was shop fabricated and stress relieved as one complete piece before connection to the rear portion penetration sleeve. Each complete unit comprising circulator mounting and penetration was delivered complete to site and then welded into the C.P.V. membrane, after being accurately set to suit the alignment of the circulator drive. These fabrications were built in Italy, this choice being based on the need for supply at an early date because of the dependence on associated plant.

A final evaluation of the site construction problems was made which influenced further small design modifications. These concerned mainly the concreting around the penetration following final positioning. It will be noticed in B Fig. 3b that radial gussets had been provided to stiffen up those parts of the shell embedded in the concrete where the loads were transmitted into the C.P.V. It was subsequently anticipated that these gussets would impose cavities likely to induce air locks when concreting and suitable vent holes between compartments were suggested to overcome this problem. However the need for these gussets was eventually analysed in some detail and they were shown to be an unnecessary design refinement. These gussets were therefore deleted prior to manufacture giving a much improved profile for concreting, ensuring sound concrete in this important region.

At the time of writing the mountings have been made and installed but the reactor has not yet been operational.

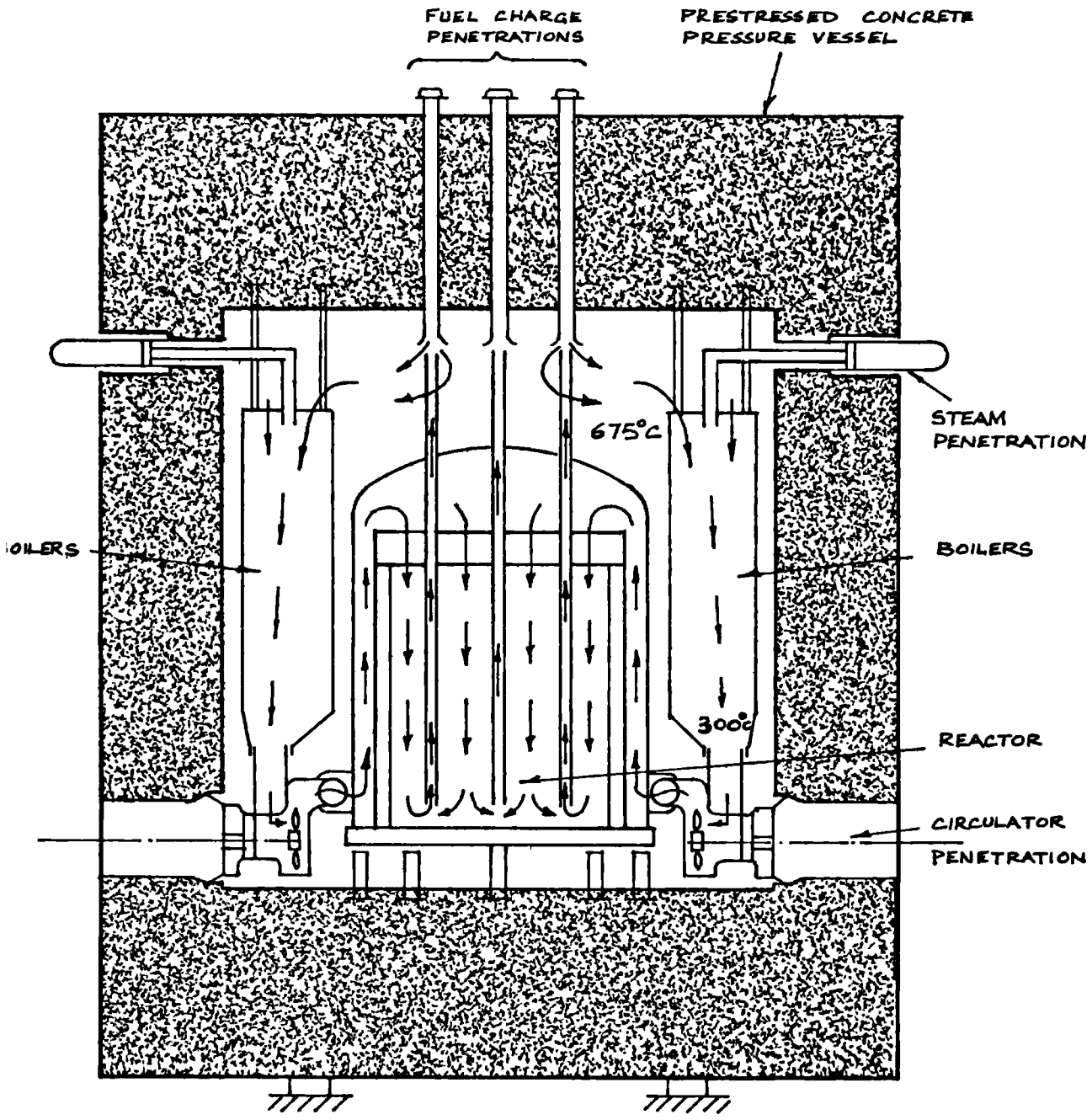
CONCLUSION

This design case history is unique in that it has an element of pre-contract and post-contract design, is very technically complex and exhibits strongly the process of understanding the problem only by attempting and analysing solutions.

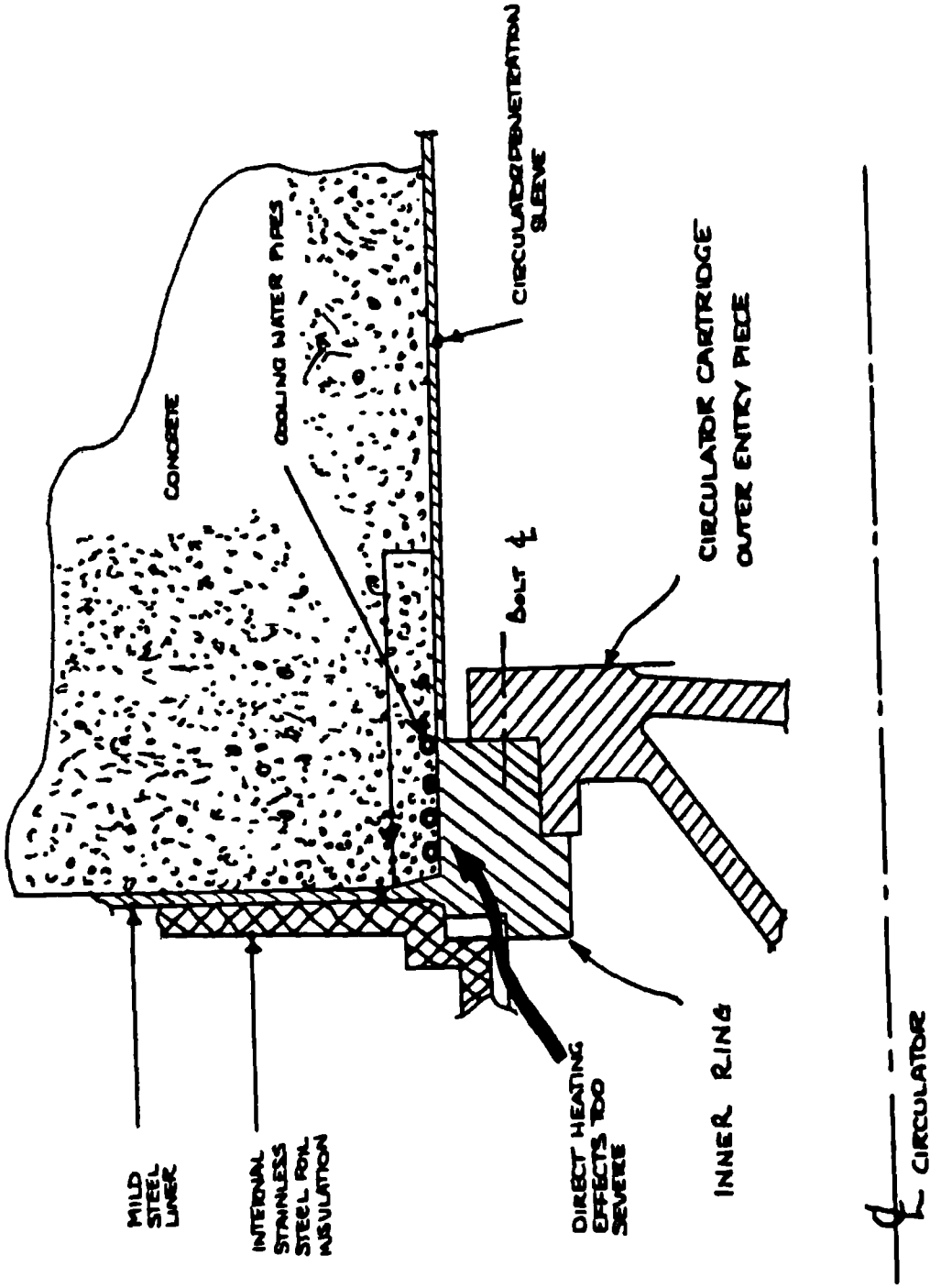
For this reason it is difficult to decide when the various stages in the design process commence and finish, although all the stages are identifiable.

Another unique aspect of this case history was that cost was of little importance to the designer. An overall cost for the circulator mountings having been set at the tender stage, the designer was soon aware that his proposals were well within this stipulated figure. In all subsequent studies he could therefore ignore cost as an important factor. He was, however, subject to severe constraints on reliability because of the very limited accessibility to most components in the design once the reactor has become operational, and also because of the importance of very high integrity gas containment. The latter restraint related to statutory requirements and the licensing authority, and in fact secondary containment on C.P.V. penetrations became a requirement on all later A.G.R. stations.

In the view of the author the designers in this case history were working under the most extreme conditions of all those studied in the field work. The level of complexity, innovation and technical difficulty involved were all extremely high. In addition to this the consequences of being wrong were very serious and the problems of integrating for a long period, several different design teams, specialisations and organisations housed in numerous different sites were enormous. Moreover the design was a one-off exercise where the need to build in modifiability conflicted with, and became subservient to, the need to submit a very competitive tender.

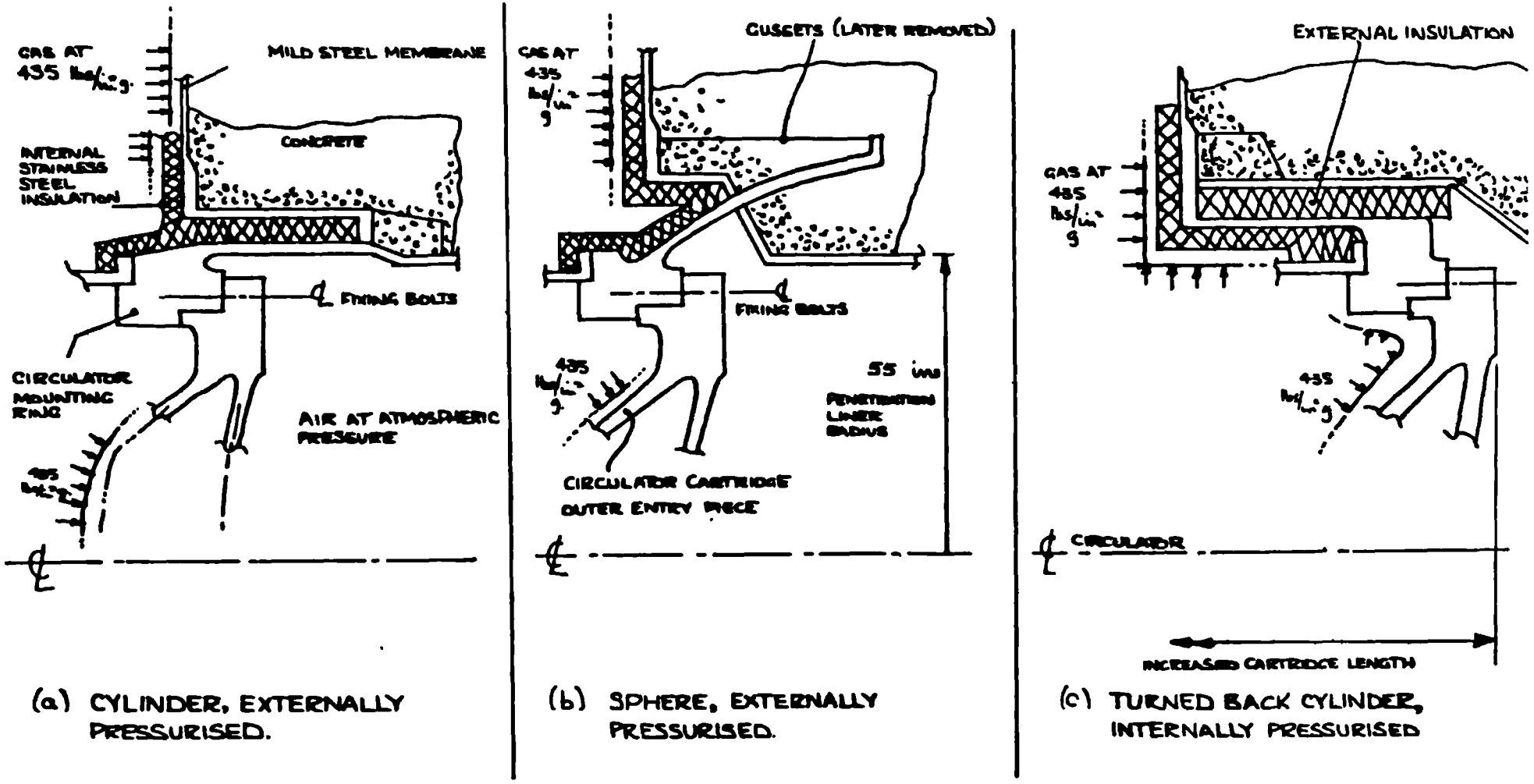


B FIG 1 A.G.R. REACTOR LAYOUT



BFIG 2 FIRST DESIGN PROPOSAL

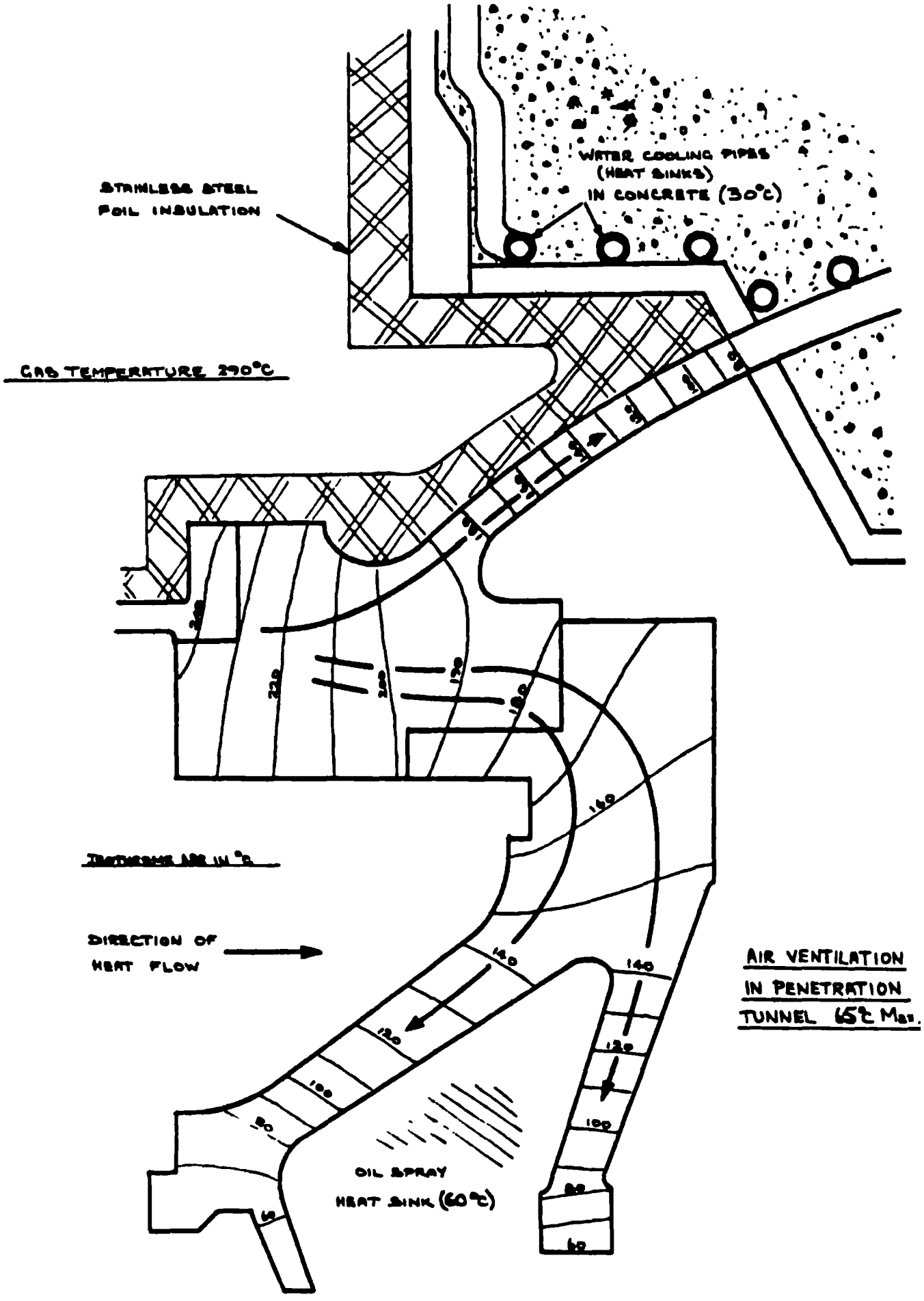
B FIG3 ALTERNATIVE DESIGN PROPOSALS



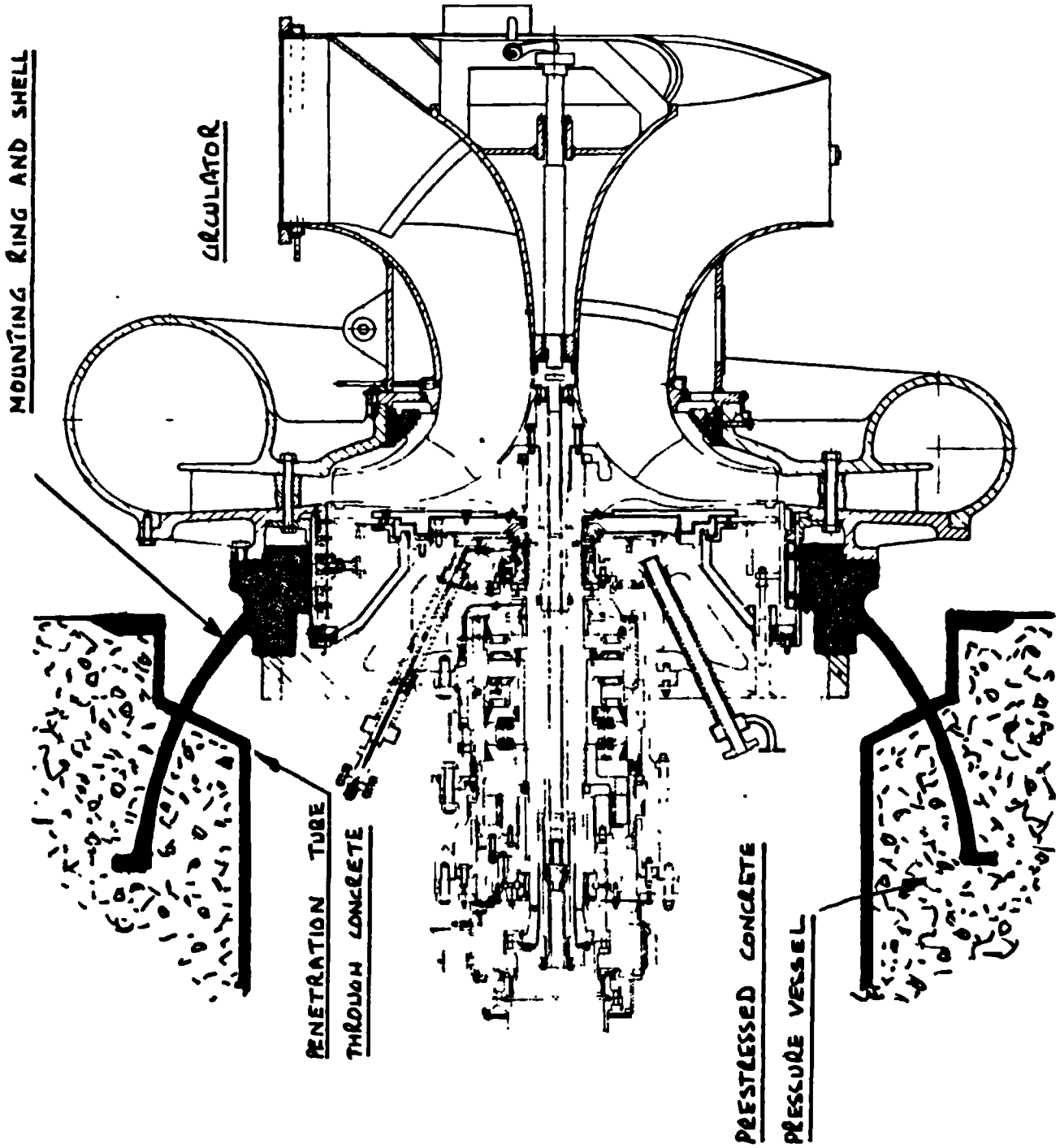
(a) CYLINDER, EXTERNALLY PRESSURISED.

(b) SPHERE, EXTERNALLY PRESSURISED.

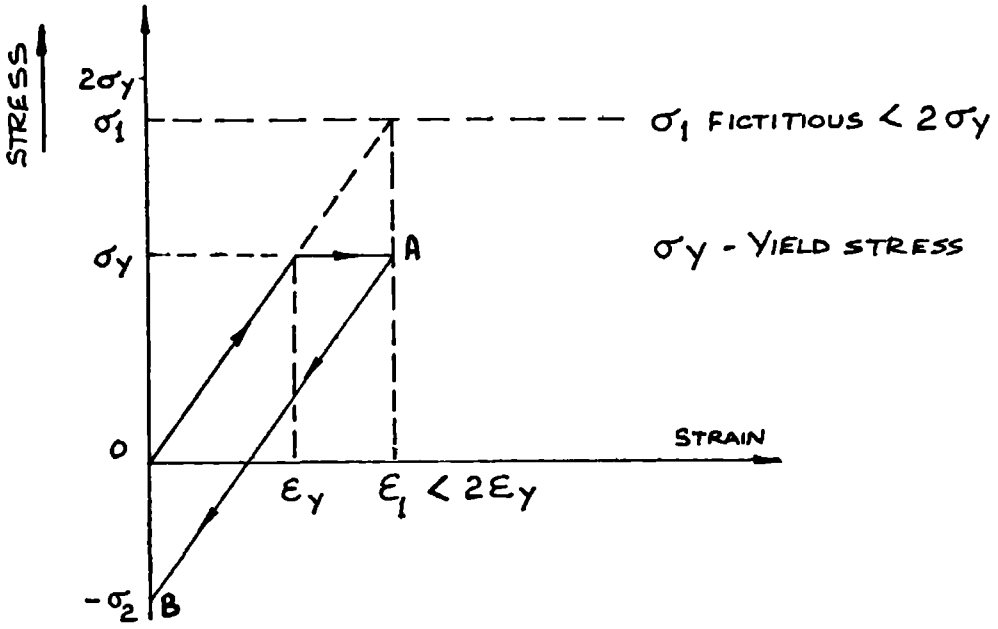
(c) TURNED BACK CYLINDER, INTERNALLY PRESSURISED



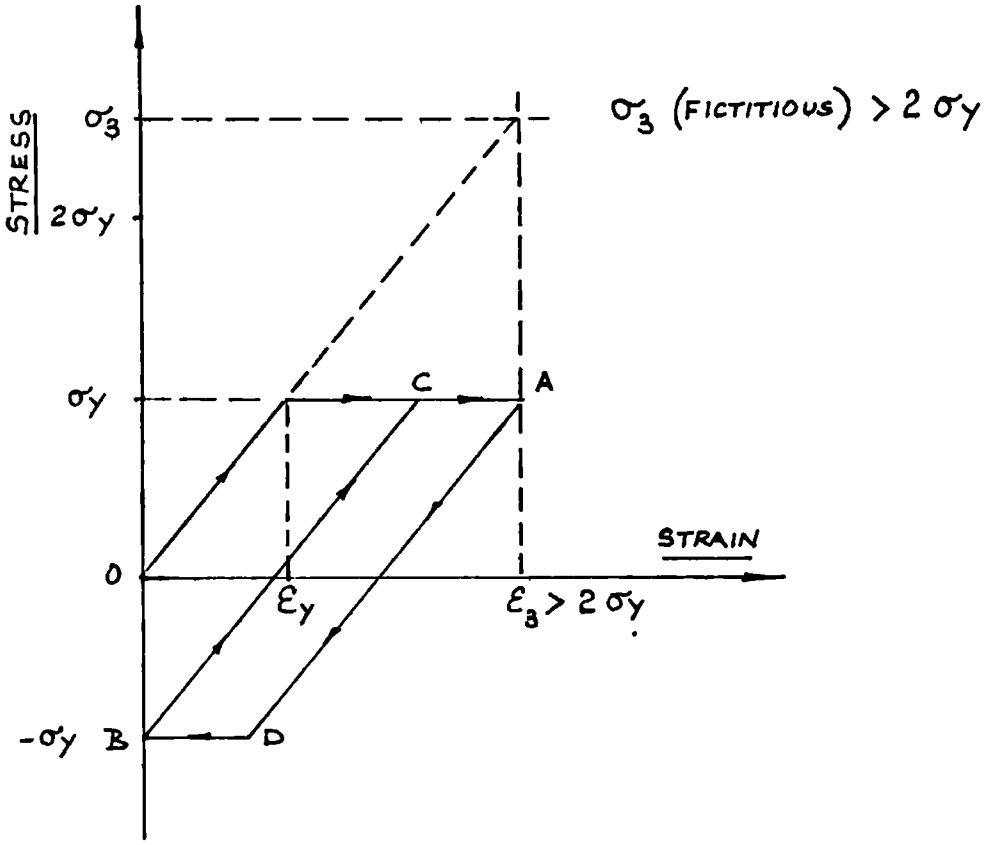
B FIG4 RESULTS OF DETAILED ANALYSIS



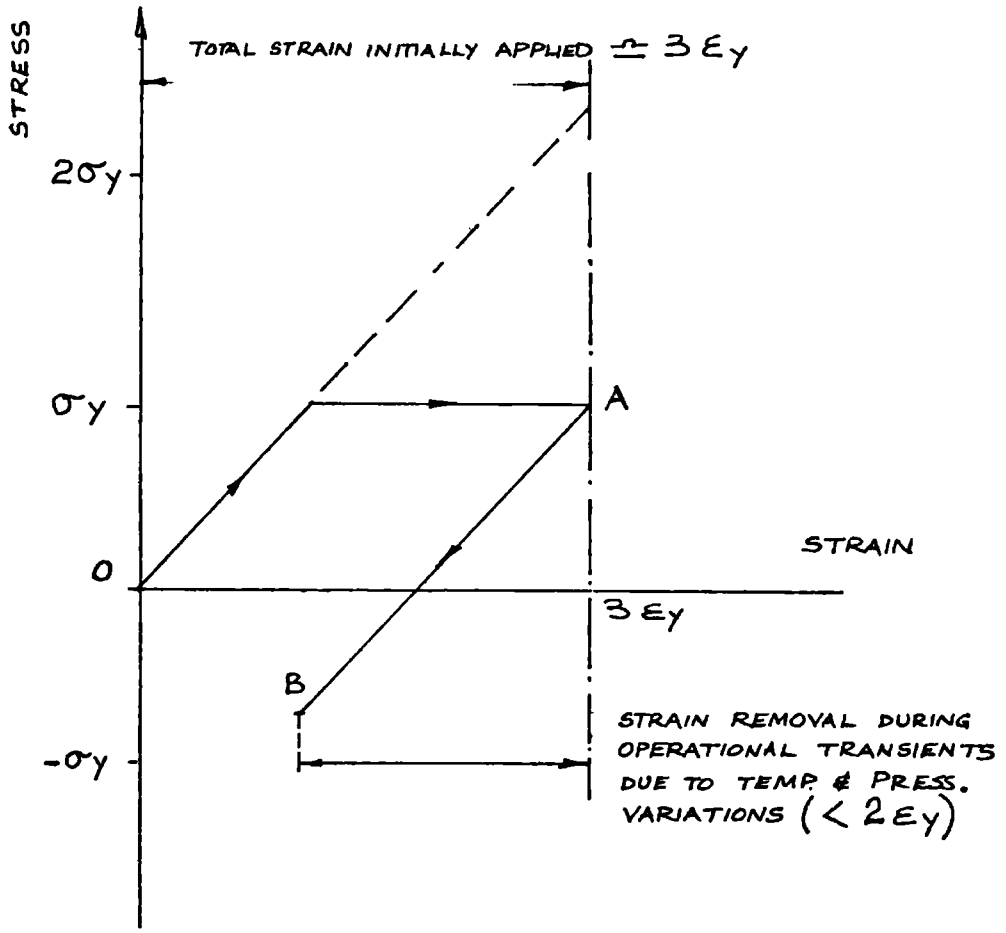
B FIG 5 FINAL CIRCULATOR ASSEMBLY



B DIAGRAM I $\varepsilon_y <$ SECONDARY STRAIN $< 2\varepsilon_y$



B DIAGRAM II SECONDARY STRAIN $> 2\varepsilon_y$



B DIAGRAM III SECONDARY STRAIN ≐ $3\varepsilon_y$

CASE HISTORY C

THE INTRODUCTION OF PLASTICS MOULDING PANELS IN THE DESIGN OF AN IMPROVED STENCIL DUPLICATOR

INTRODUCTION

The antecedent to the duplicating machine with which this case history is concerned was first produced by firm C in 1953. It proved competitive throughout the world in its several versions - manual and motor driven - for over 10 years, C Fig. 1.

One of the important features of a duplicating machine is the system of feeding the paper to the printing rollers. The rising price of paper during the life of the earlier machine had led to the need for a more versatile feeding system in order to cope with some of the inferior quality paper which was being used.

In 1963 the mark III model A was introduced; although this had a new improved type of feed a number of problems arose in the field and early in 1964 the following specification was given to the design team.

1. To completely restyle the machine within the parameters of existing proven mechanisms.

2. To protect or fold the feed board in the restyling thus eliminating one of the major problems in the mark III model A.

3. The feed table to cater for the wide range of paper sizes now in use internationally.

4. To increase the speed of the machine for the home market from 150 cpm to 160 cpm. Machines exported to the U.S.A. are set to a maximum speed of 180 cpm before leaving the factory and in some cases the speed is increased by the agent to 200 cpm.

5. The motor to be contained within the machine - in some very early models the motor was in the cabinet on which the machine stood and was connected through a drive shaft - and be easily removable for servicing.

6. The controls to be basically the same but their arrangement and detail design to be reconsidered.

7. To reduce the weight of the machine considerably below that of model A (115 lbf) and to make provision for lifting by hand.

8. The selling price to be within £5 of competitors machines.

9. To comply with all known national and international safety standards.

10. The appearance to be improved since the sales department had stated that the old fashioned appearance of the model A was slowing down sales.

11. A target date was set for marketing the new machine it was in fact aimed at the Office Equipment Exhibition of 1965 and the overall cost of the development, including design and tooling, was limited to £100,000.

The model developed from this brief was model P, C Fig. 2, and this case study is concerned with the plastic side panels which were designed for it.

THE PROBLEM

"The basic shape of the model P was decided in the Work s Director's Office using a side elevation of model A, some string and a few drawing pins". C Fig. 3 shows the drawing made as a result of this meeting.

At this stage the company's Industrial Design Consultant was called in and a number of different designs were prepared. The shape and size of the side machine covers in these proposals made it impossible to consider using deep drawn pressings as used in the model A and the only practical alternatives were die castings or plastic mouldings.

The earliest machines produced by firm C had used cast metal side covers, and a considerable amount of skill in designing and producing thin walled castings had been accumulated within the company. In order to reduce cost and weight, castings had slowly been replaced by sheet metal pressings as the duplicators were developed and improved.

Pressings still suffered the disadvantage that several operations were necessary after the deep drawing e.g. trimming, piercing, welding, surface finishing and labelling.

Because of this and the importance of appearance and weight, it was decided to consider seriously the use of plastics materials for the side fairings. The company at this time had no experience of plastics materials other than the use of phenol-formaldehyde compounds for small components in the existing machines.

The design problem with which this case study is concerned therefore became the selection of suitable plastics material, and the design of the side panels to be made in it to satisfy the overall brief.

THE FIRST STEPS

Three parties were involved in the problem from the early stages in Summer 1964, firm C, a specialist plastics company, and the industrial designer who was being used as a consultant on the overall appearance of the model P.

The first step was to investigate those plastics materials which might be suitable, and to set their properties against the requirements of the brief.

The main factors considered by the firm at this stage were:-

1. Strength. The material would have to have good impact resistance in order to withstand the rough treatment to which it would be subjected during shipment to all parts of the world, and during use.

2. Thermal Stability. The extreme conditions occur during transportation and storage overseas and field studies suggested maximum and minimum temperatures of 140°F and -40°F.

3. Water Absorption. An important factor in some overseas countries and also in ships holds during transportation.

4. Chemical Resistance. The chemicals in the inks and cleaning fluids employed in the duplication process, chosen plastic would at least have to be resistant to these chemicals.

5. Flame Resistance. Certain standards authorities had fairly rigorous requirements on the flame retardant properties of materials to be used in factories and offices.

6. Price. The cost per component was not to exceed that of the steel pressings previously used. The company had specified also that the cost of the tools for all the plastic mouldings on model P should not exceed £25,000.

7. Appearance. The colourability, texture and colour fastness of the material were obviously important factors.

In consultation with the material suppliers and moulders, factors such as mouldability, flow rate and shrinkage were also being considered.

A 4 - 5 month study of possible materials resulted in Acrylonitrite Butadiene Styrene (ABS) being selected as the most suitable. The range of materials considered, and the designer's comparison in terms of the most important factors, is given in C Figs. 4a,b,c and d.

At the end of this study it was agreed, that: "ABS has the right mechanical properties, gives a good finish and is economically right for the project. The moulding properties of this material also prove to be quite attractive".

INITIAL DESIGN

The initial design involved further consultations between the parent design team, production department, particularly to designers - the buying department, the industrial design consultant and the material suppliers.

The industrial design consultant was responsible for the final shape of the panels but the firm C team carried overall responsibility for matching the functional and manufacturing aspects of the brief. Some preliminary layouts were produced by the industrial designer at this stage and agreed in principle, the final detail design would obviously depend upon the method chosen to manufacture the panels.

Vacuum forming was originally considered as a method of manufacture with the main attraction that tooling would be cheaper than most of the alternatives.

This was eventually discarded because brackets or bosses would have to be attached to it after it was formed in order to be able to fix it firmly to the body of the duplicator. The apertures in the panels for the controls would also have to be machined after forming. Neither of these problems could be overcome without radically altering the design concept.

The fact that the choice of detail design would be restricted and the desired rigidity would be difficult to achieve, were other factors which led to vacuum forming being abandoned in favour of injection moulding.

Even when injection moulding was selected as the most suitable process several problems remained to be solved.

The main problems involved achieving the overall stiffness, providing for the apertures and the means by which the panels would be attached to the duplicator.

DEVELOPMENT

The rim round the front outside edge of the panels was adopted as a means of achieving the overall stiffness, C. Fig. 5.1. Unfortunately if manufactured as shown in this figure the bulk of material in the rim would cause sink marks which would spoil the finish on the component at a point where it was most noticeable.

After some consideration of possible alternatives - two of which are shown in figures 5.2 and 5.3 but were abandoned because they would be dirt traps in practice - it was decided to adopt the design shown in 5.4. This concave corner not only reduces the possibility of an exaggerated sink occurring but also has the advantage that any small sinks which do occur will not show. It was also considered that this shape would enhance the overall appearance of the panels.

The problem of the apertures was finally solved by providing moulding tools with sliding cores in these areas. Although this obviously added to the complexity, and hence cost, of the tools they were still able to be produced within the stipulated budget.

The main problem here lay with the tool-makers and in this respect the designers were very dependant upon the advice they received from these specialists.

Integral bosses were moulded on the inside of the panels to attach them to the body of the duplicator. The problem of sinks occurring on the surface of the panels, due to the drastic changes in cross section at these bosses, was overcome by locating them where the surface sinks would not be seen.

As has already been indicated in this case study firm C's design team was organised to work in close co-operation with other specialists. It also had the advantage that there was very close liaison between the design and development departments, the prototypes were in fact built in a large workshop next to the design office and the design team were intimately and continuously involved in all the development work.

A prototype of the complete machine was constructed and tested and the development section were faced with the problem of producing a plastic mock-up of the panels. This was fabricated from ABS sheet and rod and was painted to give the quality of finish expected in a moulding, C. Fig. 6.

The prototype when complete was used to finalise the design of the machine and for a formal Value Engineering study.

No major modifications to the panels arose at this stage but changes in the body of the machine - mainly involving the operating mechanism, - entailed some minor design changes, in particular to the side panel fixings.

Demonstrations and transportation trials also took place during this period. These led to several major design changes in other plastics components on the machine but the ABS side panels were satisfactory in all respects, C. Fig. 7.

FINAL DESIGN

Final detail drawings of the panels were passed to the moulders in the Spring of 1965 and the first few production machines were completed in time for the BEE exhibition in October 1965. Full scale production started in January 1966 and since then many thousand machines have been produced.

One major problem which arose after detail design was finalised and production was started was the fire safety requirements for the Canadian market. These requirements are the most stringent which have to be satisfied by the model P and the ABS side panels were not acceptable because of their flame - retardant characteristics.

After several possibilities were investigated the problem was overcome by spraying the inside of the panels with an asbestos, fire resistant, coating.

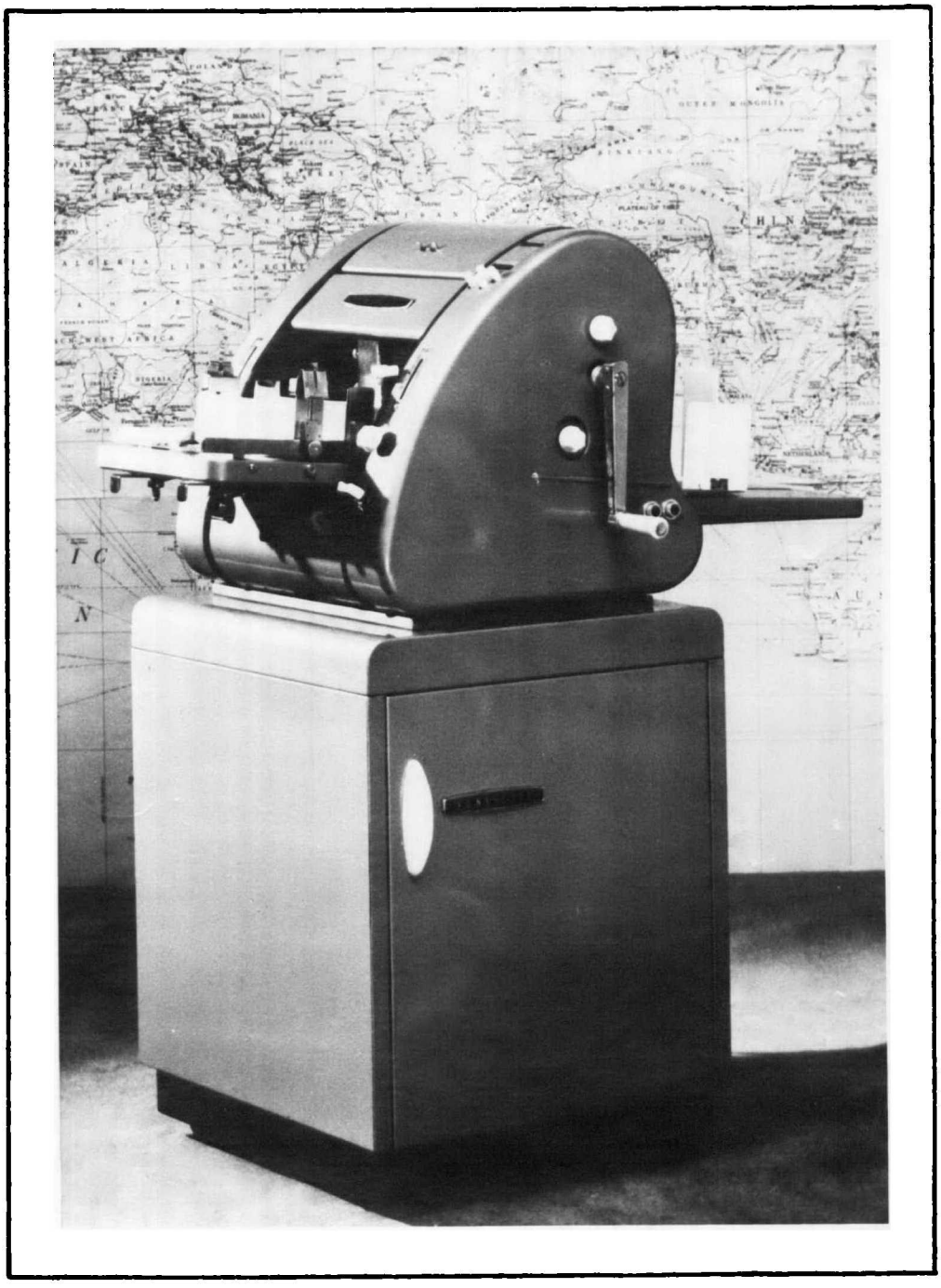
CONCLUSIONS

This design case history is one of the most successful of these studied by the author. There are several features of the design, and the design organisation, which appear to contribute to this.

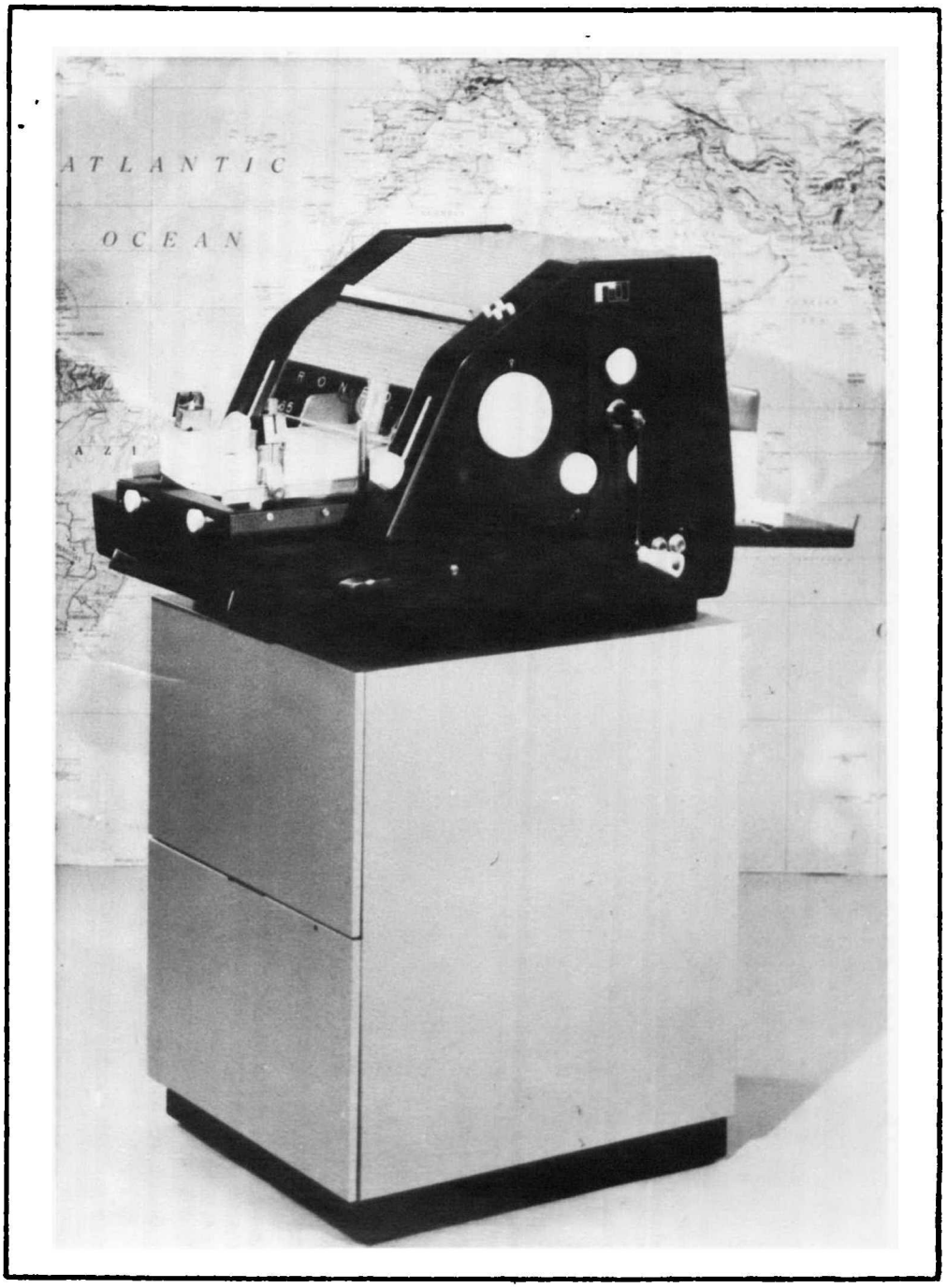
The first is that the design was basically an extrapolation of an existing design. Although the designer was faced with challenging problems of innovation using new materials, he was, nevertheless, working in a framework which was familiar. Because of this it was possible for management to ensure a detailed and realistic brief and to monitor progress.

The second important feature was that the organisation was such that it ensured complete and continuous communication between the designer and his sources of information, i.e. management, specialists, production and other departments. The fact that the central design organisation was adjacent to the development shops and the works, and that the designers were given ready access to both, was an impressive example of this.

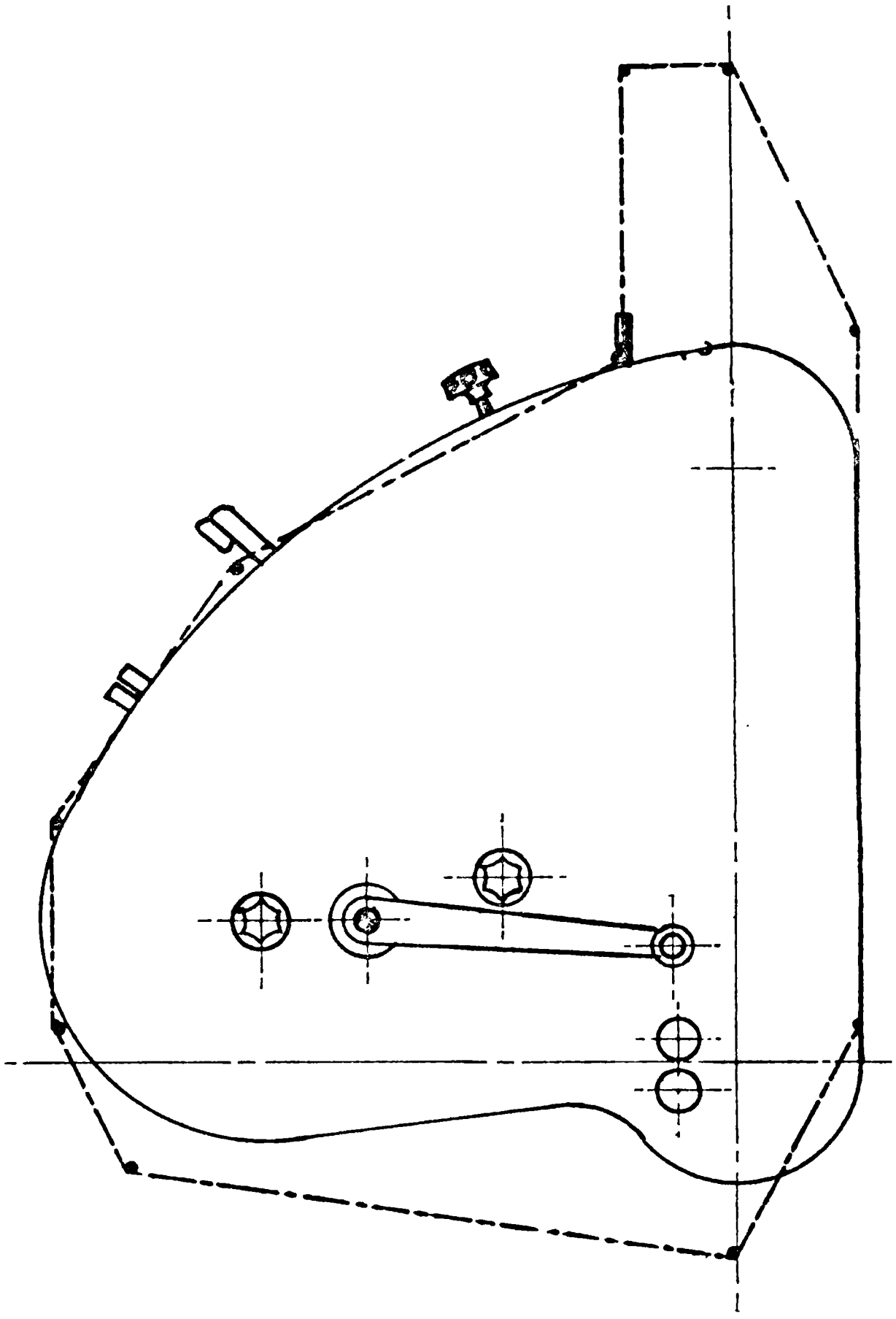
The final factor was the presence of certain key personnel at management and other levels who were responsible for controlling and leading the design effort.



C FIG 1 THE ORIGINAL MODEL

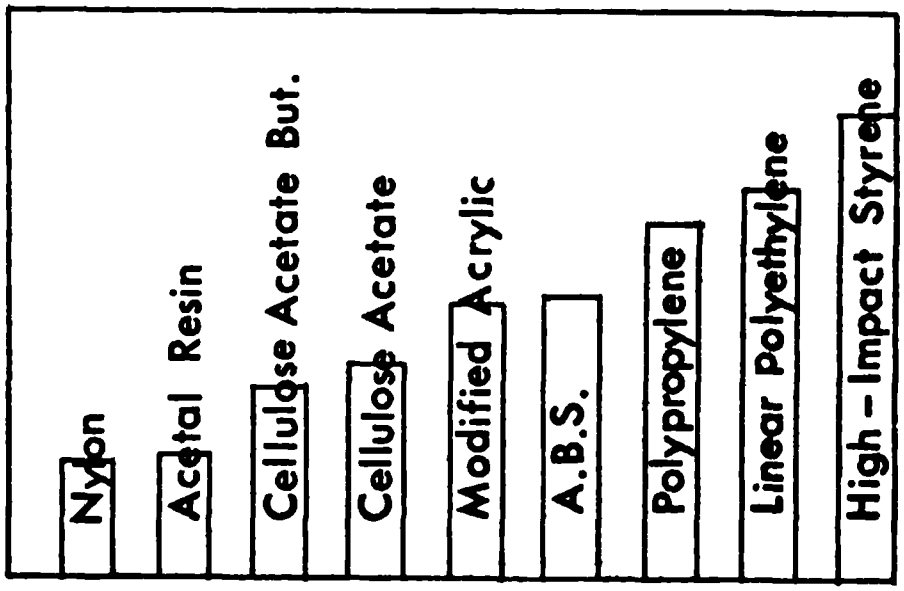


C FIG 2 THE NEW MODEL

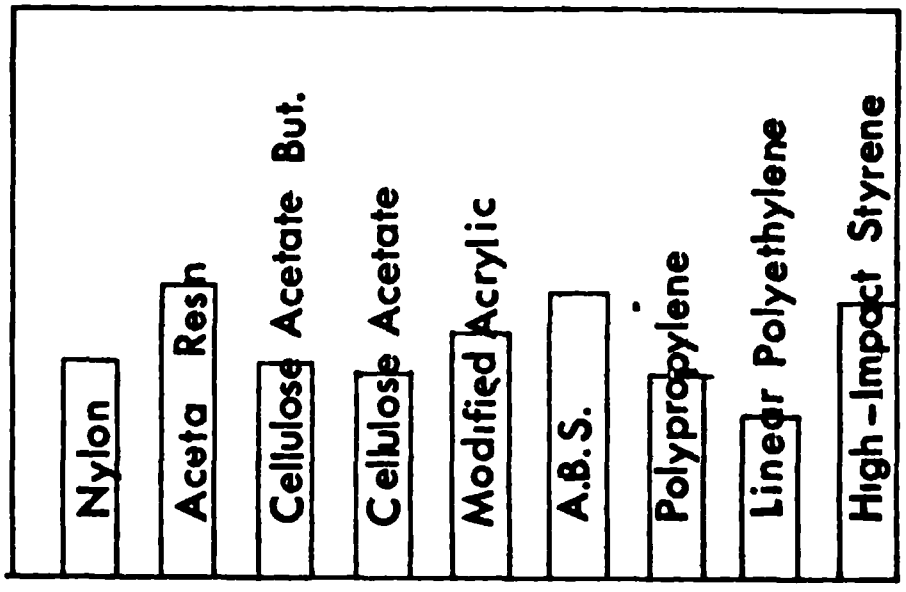


C FIG 3 THE BASIC SHAPE

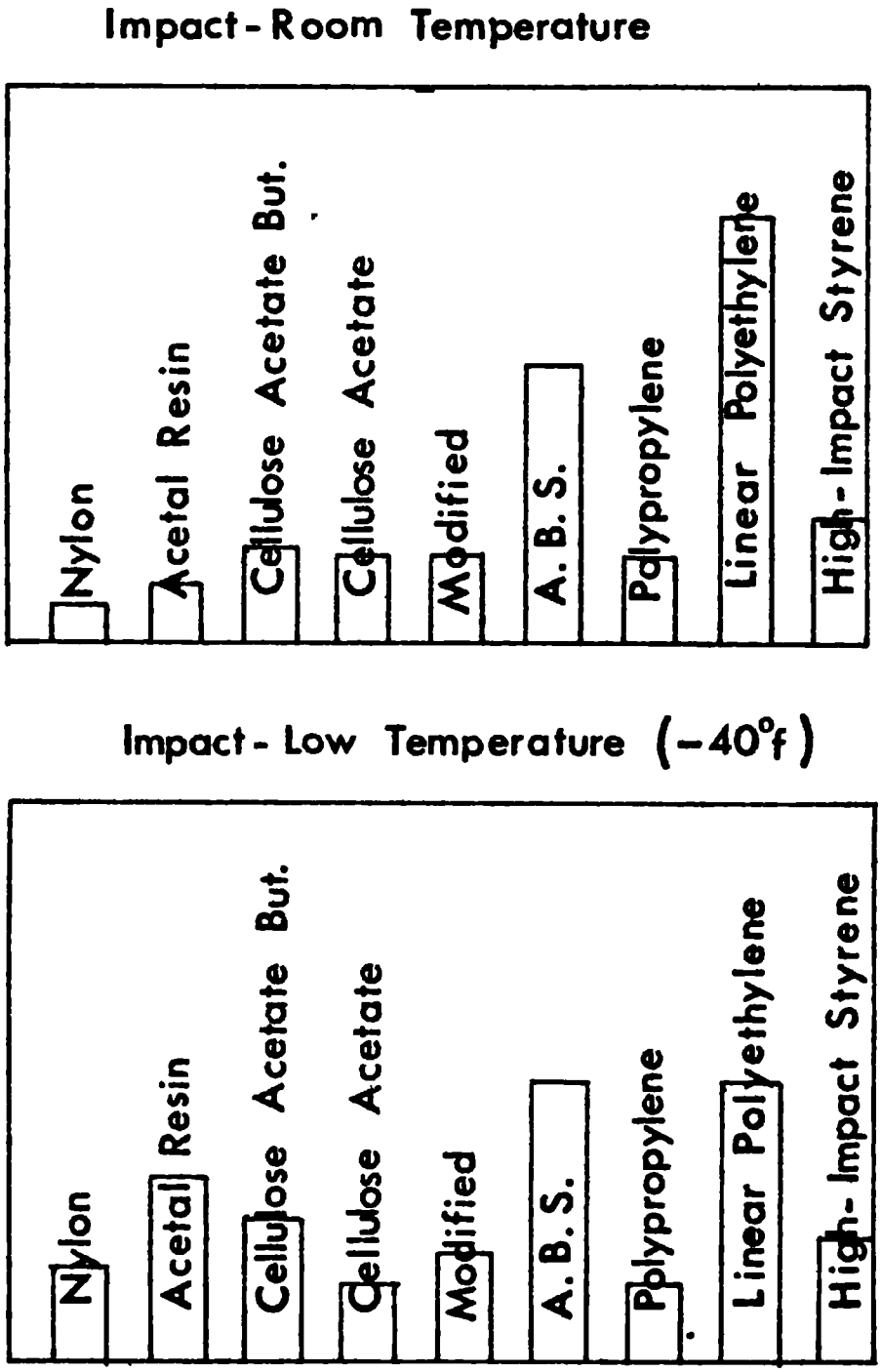
Cubic Inches - Cost Comparison



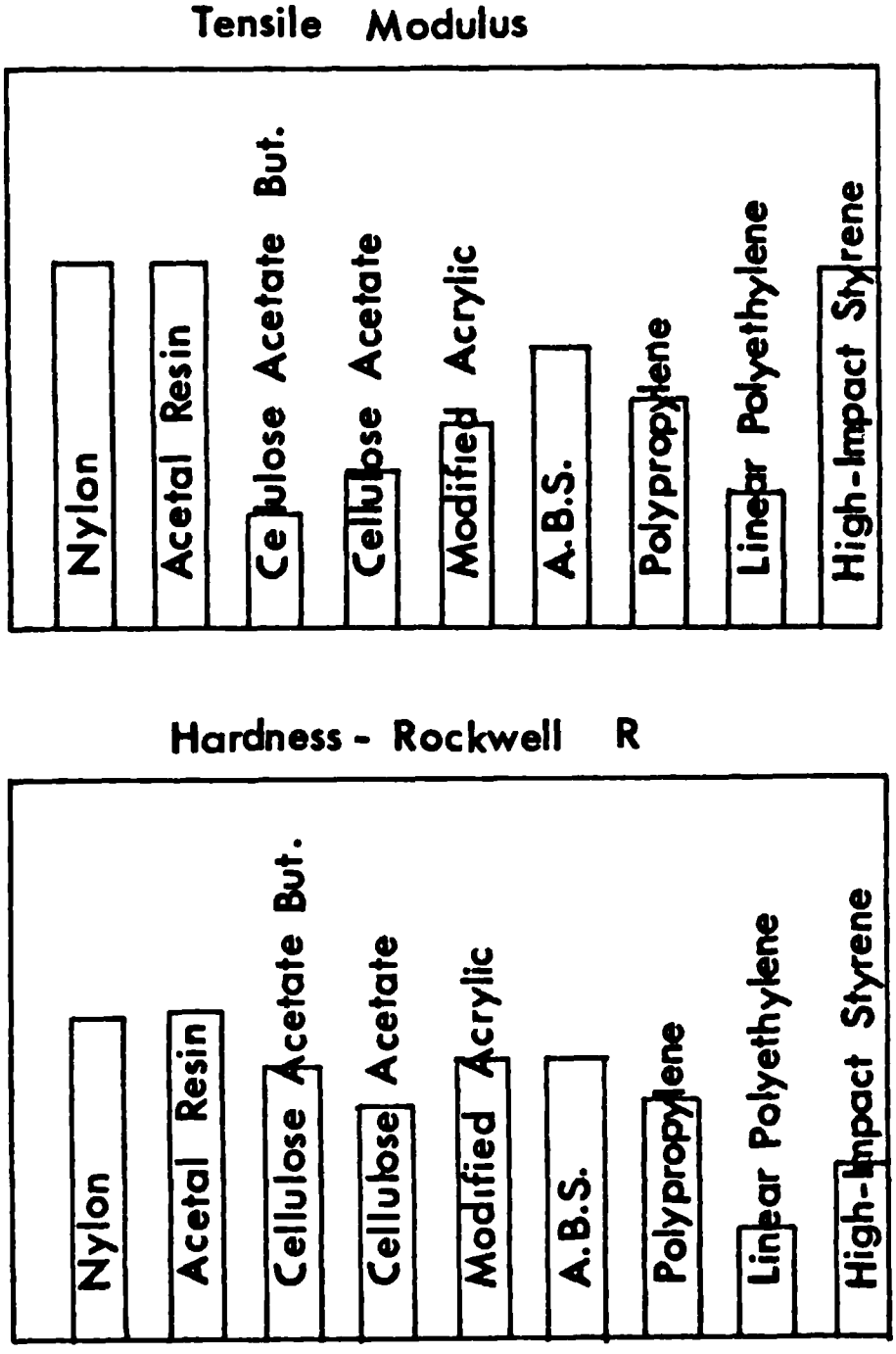
Heat Deflection Temperature 264 PSI



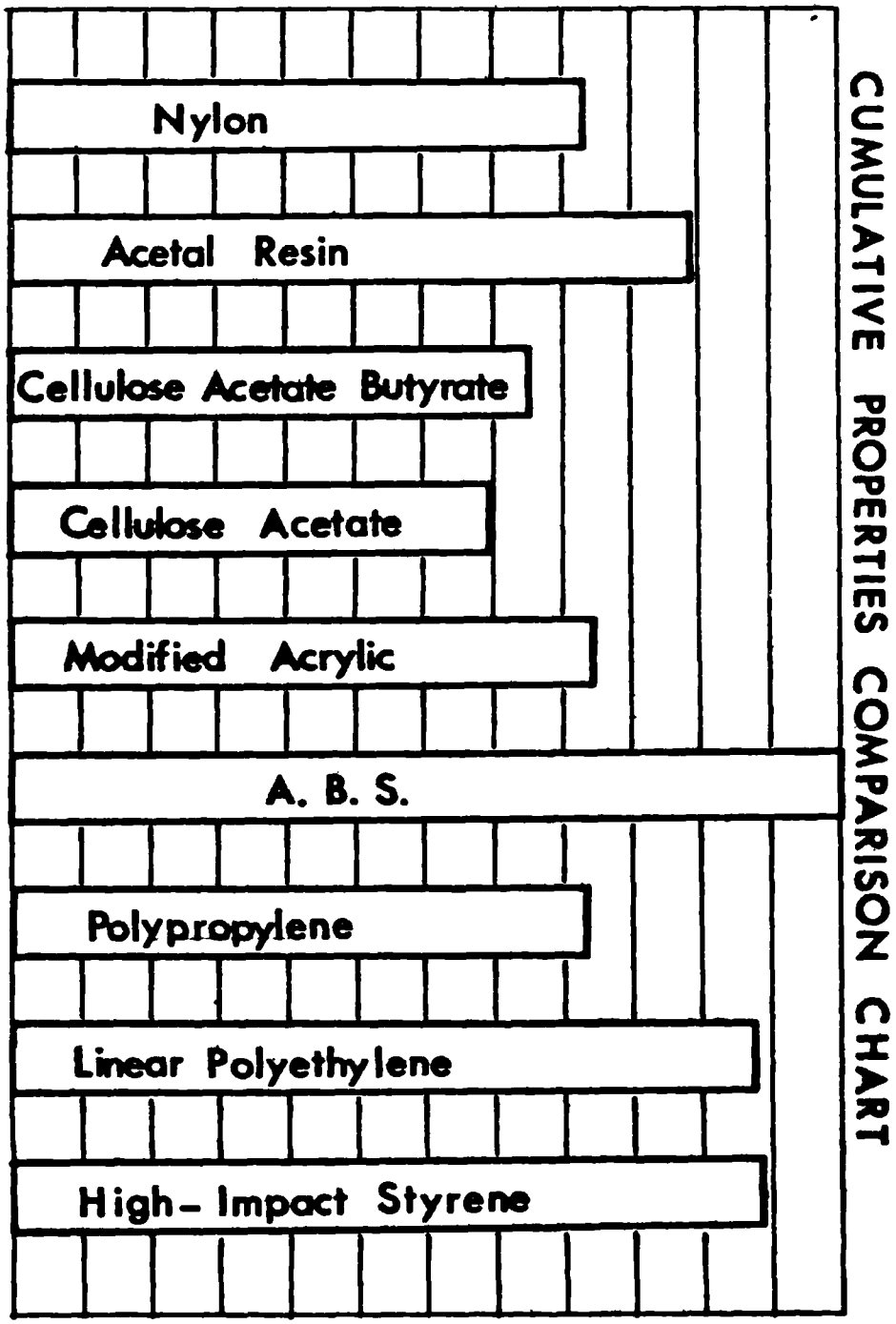
C FIG 4a COMPARISON OF PLASTICS MATERIALS



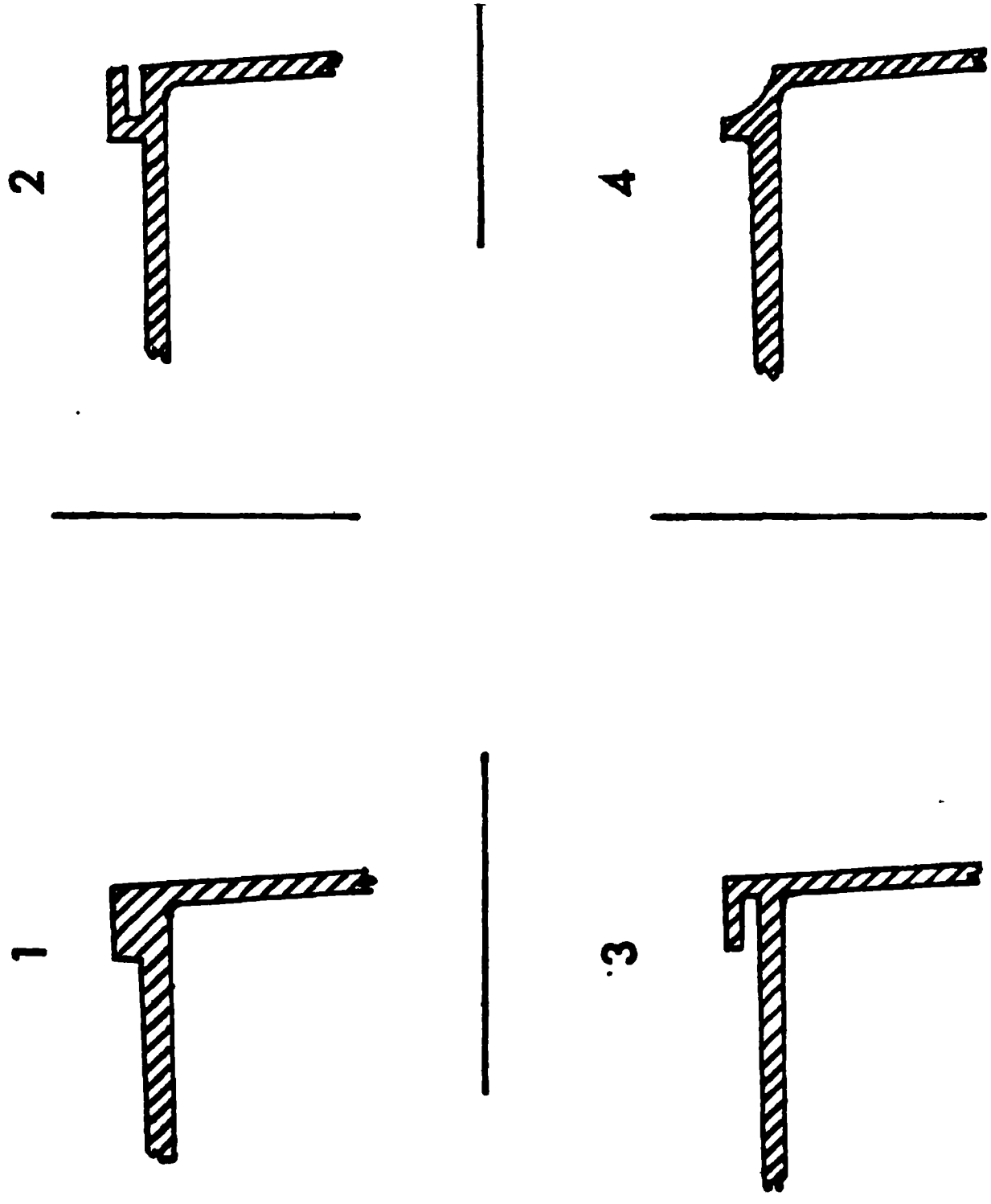
CFIG 4b COMPARISON OF PLASTICS MATERIALS



CFIG 4c COMPARISON OF PLASTICS MATERIALS

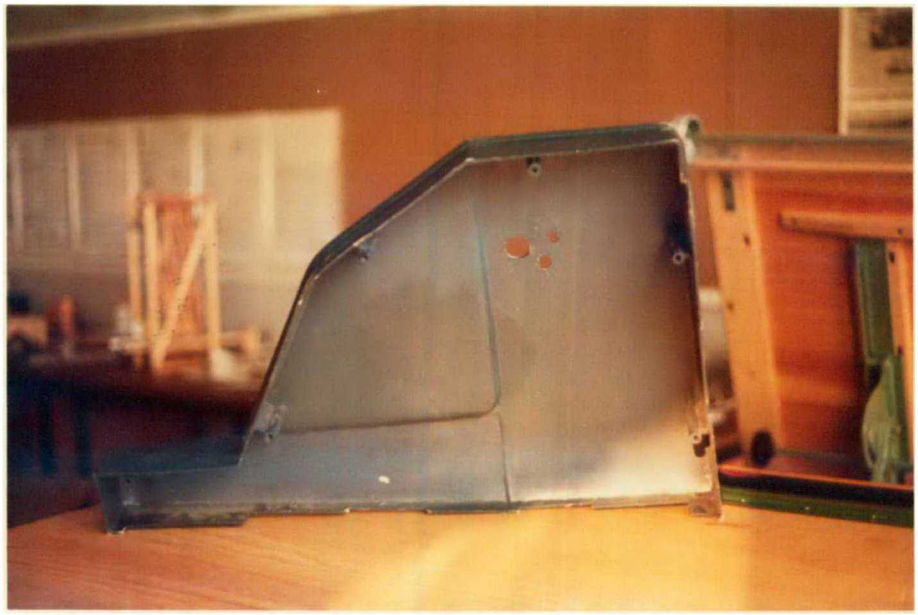


C FIG 4d COMPARISON OF PLASTICS MATERIALS

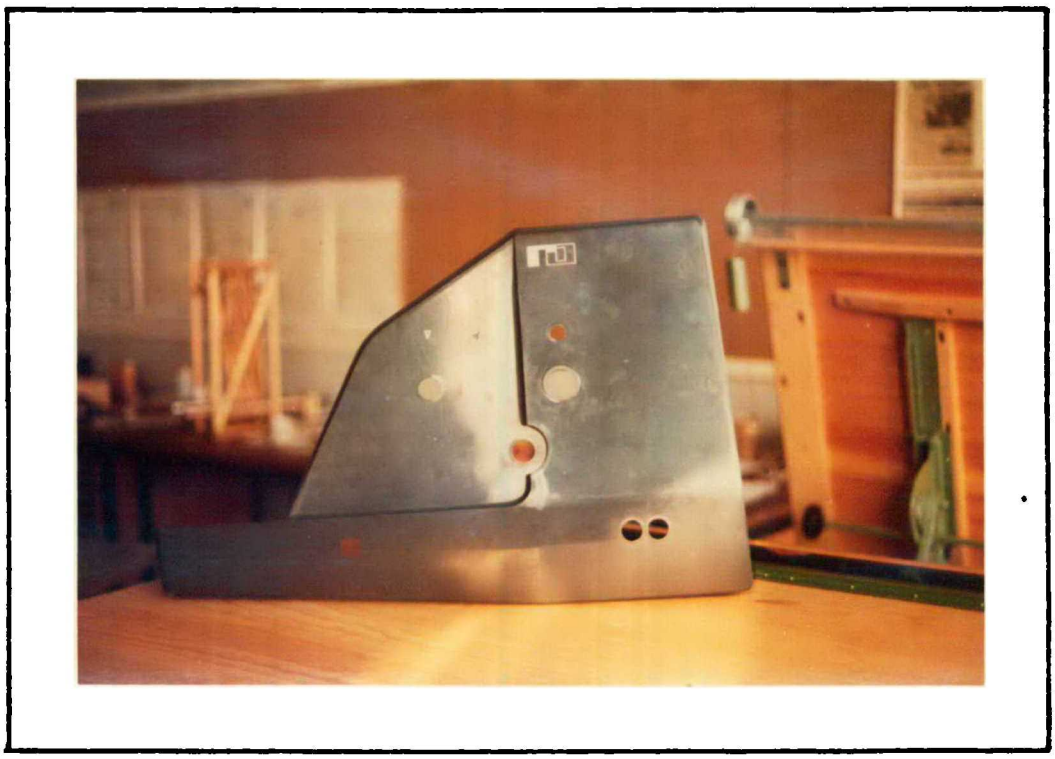


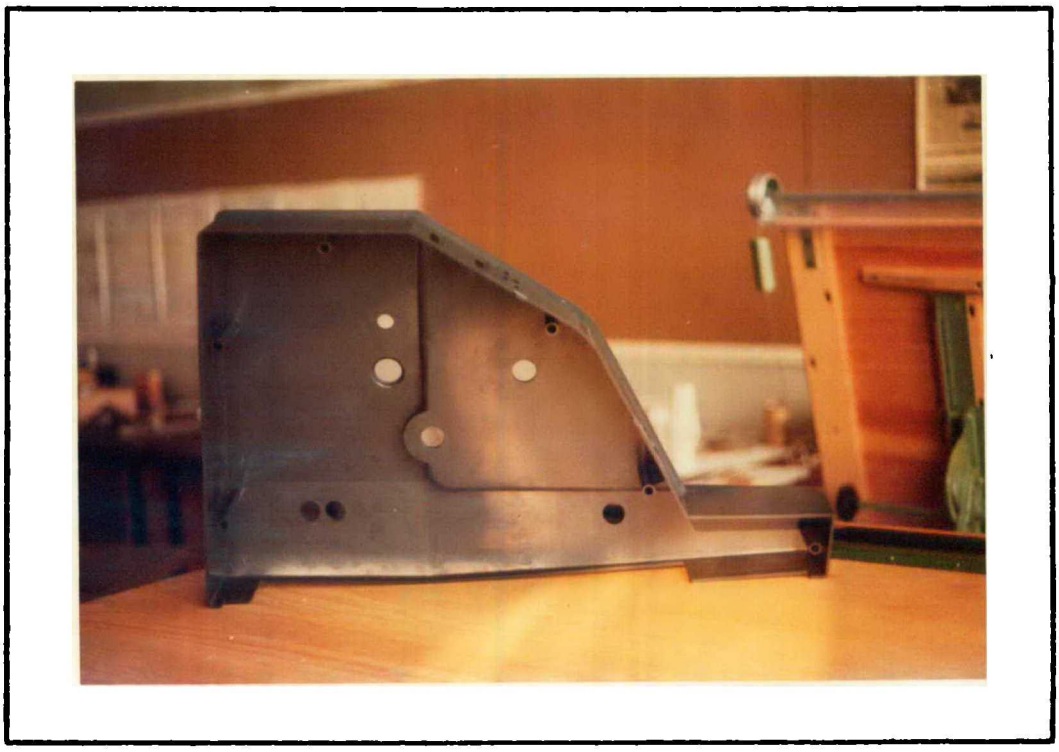
C FIG 5 DETAIL DESIGN FEATURE





CFIG6 PROTOTYPE PANEL





C FIG7 THE FINAL DESIGN

CASE HISTORY D

TEMPERATURE CONTROL VALVE FOR THE EQUIPMENT CONDITIONING SYSTEM ON AN AIRCRAFT

INTRODUCTION

The modern high speed military aircraft carries a considerable amount of electronic equipment. One of the requirements in the design of the Vertical Take-Off and Landing aircraft, involved in this case history was for an air conditioning system to control the environment in one of the equipment bays; in particular to prevent the equipment from overheating.

This case study describes the design of the temperature control valve, which forms part of this air conditioning system. The exercise is basically one of extrapolation since similar systems had already been designed and proved for earlier aircraft produced by firm D.

The design organisation in which this valve was produced has changed during the long period - 5 years - during which it was designed and developed. Moreover several other organisations and design teams were involved at different stages.

However this design case study was collated in conjunction with a member of the firm's design team who had been closely connected with the design from its original inception to its final acceptance.

THE CONTEXT OF THE PROBLEM

a) The complete equipment conditioning system

The conditioning system is required to remove 2½-3 kw of heat from the equipment bay under a wide range of ambient and flight conditions. To satisfy this requirement it was estimated that about 30 lb/min. of air would need to be bled from the engine, representing a loss of about 70 hp. This air is cooled by means of a heat exchanger and expansion turbine cold air unit and is then delivered at a controlled temperature.

In 1962 a specification for the system was drawn up by the firm listing the following parameters:

1. Description of Function.

2. Performance Requirement - Temperature of air supplied to the equipment bay to be maintained at $30^{\circ}C \pm 3^{\circ}C$. during all operating conditions.

3. Environment in the equipment bay. This covered acceptable air flow rates, vibration limitations and contamination by fluids.

4. Working Life - Stipulated as 3000 hours.

5. Reliability - This was given in terms of acceptable M.T.B.F. (Mean Time before Failure) and M T B D (Mean Time before Defects).

6. Weight - This should of course be kept to a minimum.

7. Space - To be kept to a minimum.

The main differences between this brief and that for earlier similar designs produced by the firm were the new requirements to be satisfied during zero forward velocity and vertical flight conditions, and the increased emphasis on weight saving. The aircraft geometry, and therefore the system layout would also be different.

The specification outlined above was prepared in the light of experience with earlier S.T.O.L. aircraft which had flown, and considerable development work which had been carried out by the firm for earlier conventional aircraft systems.

b) Factors affecting the design of the temperature control valve

In order to appreciate fully the problems involved in the design of the temperature control valve, it is necessary to describe the main features of the original proposals for the equipment bay air conditioning system.

Figs. 1 and 2 are diagrams of the complete systems used in the aircraft and initially constructed as test rigs. Hot air from the engine compressor at about $350^{\circ}C$ and 150 p.s.i. was to be fed to a heat exchanger and cooled by ram air. It was then to be passed through a restrictor to provide constant flow and pressure and then via a shut off valve, to either a turbo fan cold air unit, or the temperature control valve.

The cold air unit reduced the air temperature to about $15^{\circ}C$, it was then to be mixed with the hot air from the control valve to give the required amount of air at about $30^{\circ}C$.

The amount of hot air fed to the mixing chamber was to be controlled by the temperature control valve from a bi-metal sensing element in one of the equipment bay supply ducts.

An essential feature of the final design, compared with that for a conventional aircraft, is the provision of a system to ensure a supply of coding air to the equipment bay during hovering.

No separate specification was prepared for this valve since the overall features such as weight, space and environment were covered in the overall brief and the exercise was one of developing an existing design, rather than starting from scratch.

The company policy was of course to be cost conscious, but not to "sacrifice engineering to economics".

This design case study therefore covers the development redesign and proving of a temperature control valve and its sensing element within the design specification outlined above.

INITIAL DESIGN

The first design to be considered is shown in D Fig. 3. This was originally developed by another member of the group for one of the firm's earlier aircraft.

D Fig. 3 also shows a diagram of the sensing unit, which consists of a bent bimetal element cantilevered at one end with the free end covering an orifice. As the temperature in the sensor unit rises the orifice is opened. Since the orifice is connected to the top fitting on the control valve the pressure in the upper chamber increases with the temperature of the sensor unit.

This increase in pressure forces the flat valve plate down towards its seating thus reducing the flow of hot air.

Although this valve had proved satisfactory for earlier aircraft its development potential was limited by its low capacity and the use of a rubber diaphragm.

The first V.T.O.L. design was developed from the design described above and is shown in D Fig. 4. It was originally developed for a V.T.O.L. aircraft but was not pursued because of a government decision in 1964 to cancel the project.

On the temperature control valve, D Fig. 4, connection C leads to the variable orifice in the temperature sensing unit and the pressure in the right hand chamber - the control chamber - is therefore controlled by the temperature of the air in this unit. As this temperature drops the control chamber pressure rises and the valve poppet is moved to the left thus increasing the supply of hot air, via connection B.

Some of the hot air from the inlet A is bled through the piston shaft via connection C to the sensing valve and thus provides the high pressure air to operate the piston.

The sensing unit, D. Fig. 4, which is inserted into the delivery pipe, comprises a cantilevered straight bimetal element in contact with an adjuster which is used to vary the temperature setting of the unit.

This design had the following new features compared with the first proposal:

1. The rubber diaphragm was replaced by a piston.

2. A compensating piston was introduced to balance the inlet air pressure in the main valve poppet.

3. The flat plate valve was replaced by a profiled poppet valve to improve the outlet flow/travel characteristics and to reduce leakage.

4. Should there be a leakage, or failure of the sensor, the valve fails in the closed safe position.

5. The bimetal sensor is adjustable.

DEVELOPMENT OF THE DESIGN

The testing and development work was carried out in two parts: investigation of the valve characteristics prior to the prototype design and the overall evaluation of the system.

The two critical characteristics of the valve which were being investigated were the design of the control orifice in order to give satisfactory pressure drop characteristics and the bimetal element load/temperature behaviour.

D Fig. 5b shows a diagram of the rig used to investigate the effect of orifice clearance on the pressures in the control valve.

D Fig. 6a shows the results of these tests and the nominal orifice clearances as a function of temperature. These results are very satisfactory as they demonstrate that over the widest range of inlet pressure the system remains sufficiently precise and sensitive: the change in control pressure for the overall valve travel is consistent and less than 4 p.s.i. throughout. The insert of D Fig. 6a shows how this sensitivity represents a temperature variation of $\pm 2°C$. about the nominal settings of 30°C.

D Fig. 5a is a line diagram of the rig used to investigate the force at the orifice acting on the bimetal strip. The load characteristic curve is shown in D Fig.6b. The operation of the complete rig system is indicated in D Fig. 6c where the dotted lines indicate how the air temperature will vary with the inlet pressure for the metering orifice and control orifice combination. These results are obviously within the limits given in the design specification. The characteristics of the bimetal element were supplied by the manufacturers.

The prototype valve was built in the company's experimental department - where minor design modification, drawing errors etc. were discovered and remedied - and was tested with the sensing unit, as a separate component.

As a result of these initial tests the following problems were established:

1. The control valve was unstable, the piston tended to hunt due to turbulence at the outlet poppet valve.

2. The volume of the control chamber was too large and tended to act as a pneumatic spring increasing the instability of the valve.

3. When the end cap D was screwed on it slightly distorted the body and caused the piston to seize.

4. The end cap was made of a weldable stainless steel, the body of S80 and the piston was a bronze. At higher temperatures the different thermal coefficients of expansion of these materials caused the pistons to seize.

At this stage the work on the valve was taken over by another part of the group but before the problems revealed by the tests could be resolved the contract was cancelled.

In October 1965 Firm D considered the valve for use in its current aircraft (version E) and the control valve and temperature sensing unit were redesigned, D. Fig. 7, to embody the following improvements suggested by the earlier tests:

1. A skirt was added to the poppet valve to give a less turbulent flow.

2. The volume of the control chamber was reduced.

3. The valve cap was redesigned and the materials used for it and the body and piston were made more compatible.

Further ground tests were undertaken on two prototype valves, one series of tests investigated the characteristics of the separate valve and the other studied its behaviour as part of the overall conditioning system.

The former tests were satisfactory and only very minor modifications were necessary but the system tests revealed the following major difficulties:

1. The bimetal element resonated under the high velocity and turbulence of the air flowing past it and this caused the control valve to hunt severely.

2. When the valve was opened rapidly due to a sudden drop in temperature of the sensed air the rush of hot air through it caused it to seize.

These problems were both serious and their discovery at this late stage in the programme could have adversely affected the whole project programme. It is of interest to note that neither of these difficulties could reasonably be expected to have been foreseen and could only have been revealed by extensive rig testing.

FINAL DESIGN

The final design was basically as shown in D Fig. 7 but by selectively increasing the size of the bimetal element it was possible to prevent it vibrating without altering its temperature-displacement characteristics, the vibration problem was also alleviated by modifying the air ducts adjacent to the sensing element. The outer casing was added to reduce external heat loss and prevent the sudden local changes in temperature when the valve opened; this and careful selection of materials and tolerances overcame the problem of control valve seizure.

The design was proved on the test rig before it was fitted to prototype aircraft for flight testing: D Fig. 8 shows the layout of the installation in the aircraft.

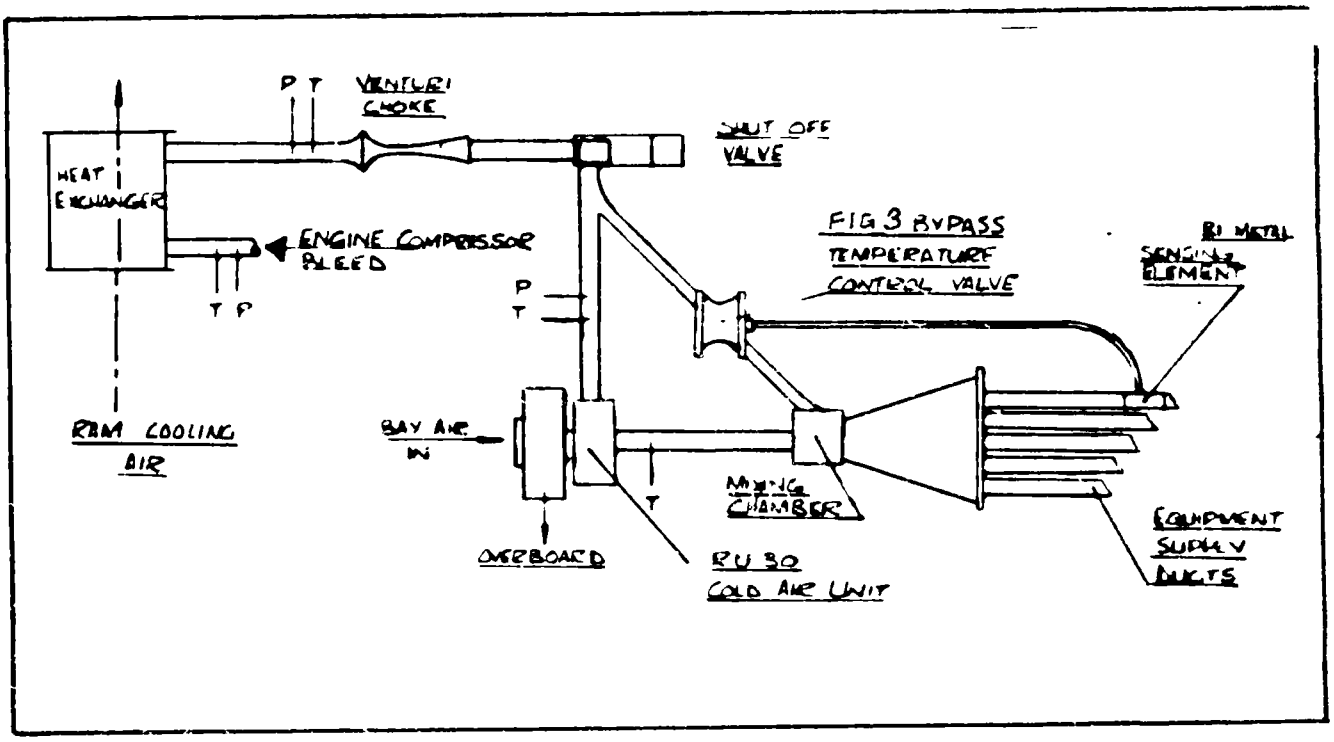
The flight tests showed the valve to operate satisfactorily through the complete flight envelope.

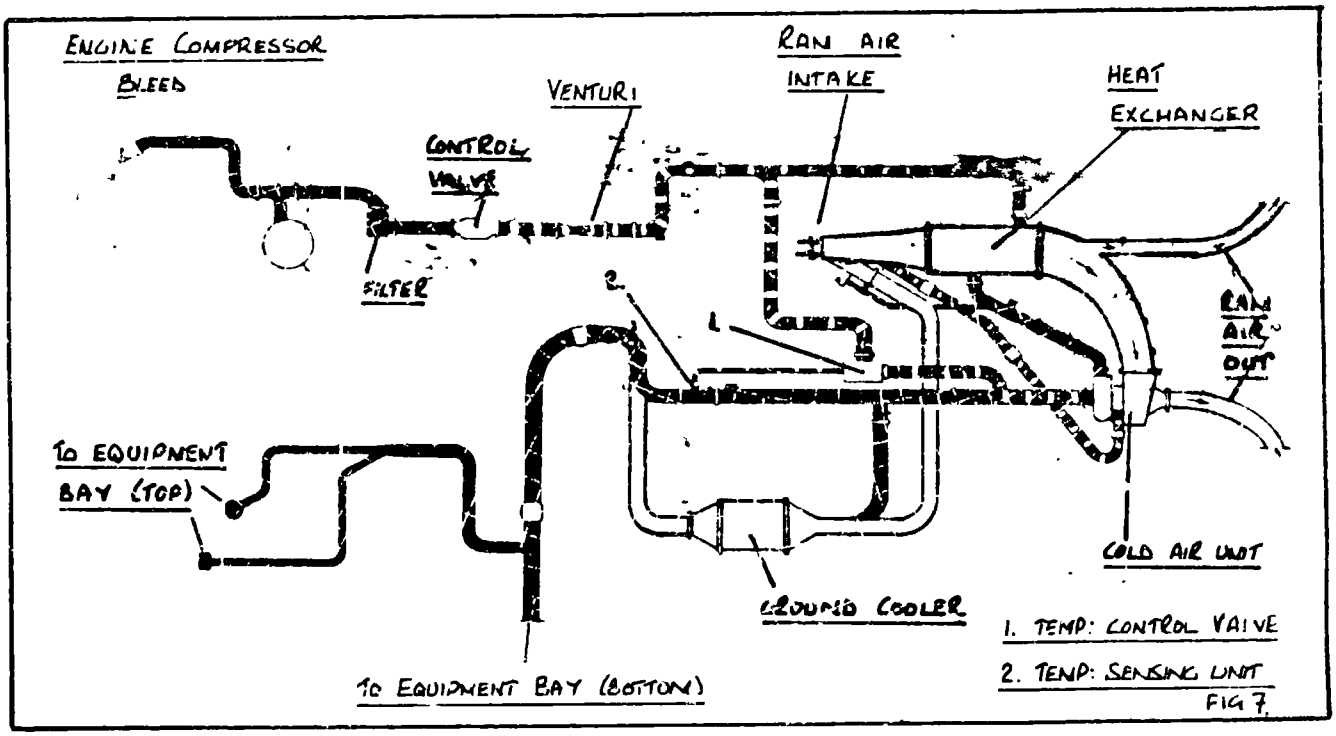
CONCLUSIONS

The aircraft on which the temperature control valve is a component has proved to be uniquely successful; it is the first operational jet V/STOL aircraft and is considered to be the first of a new and important generation of civil and military aircraft.

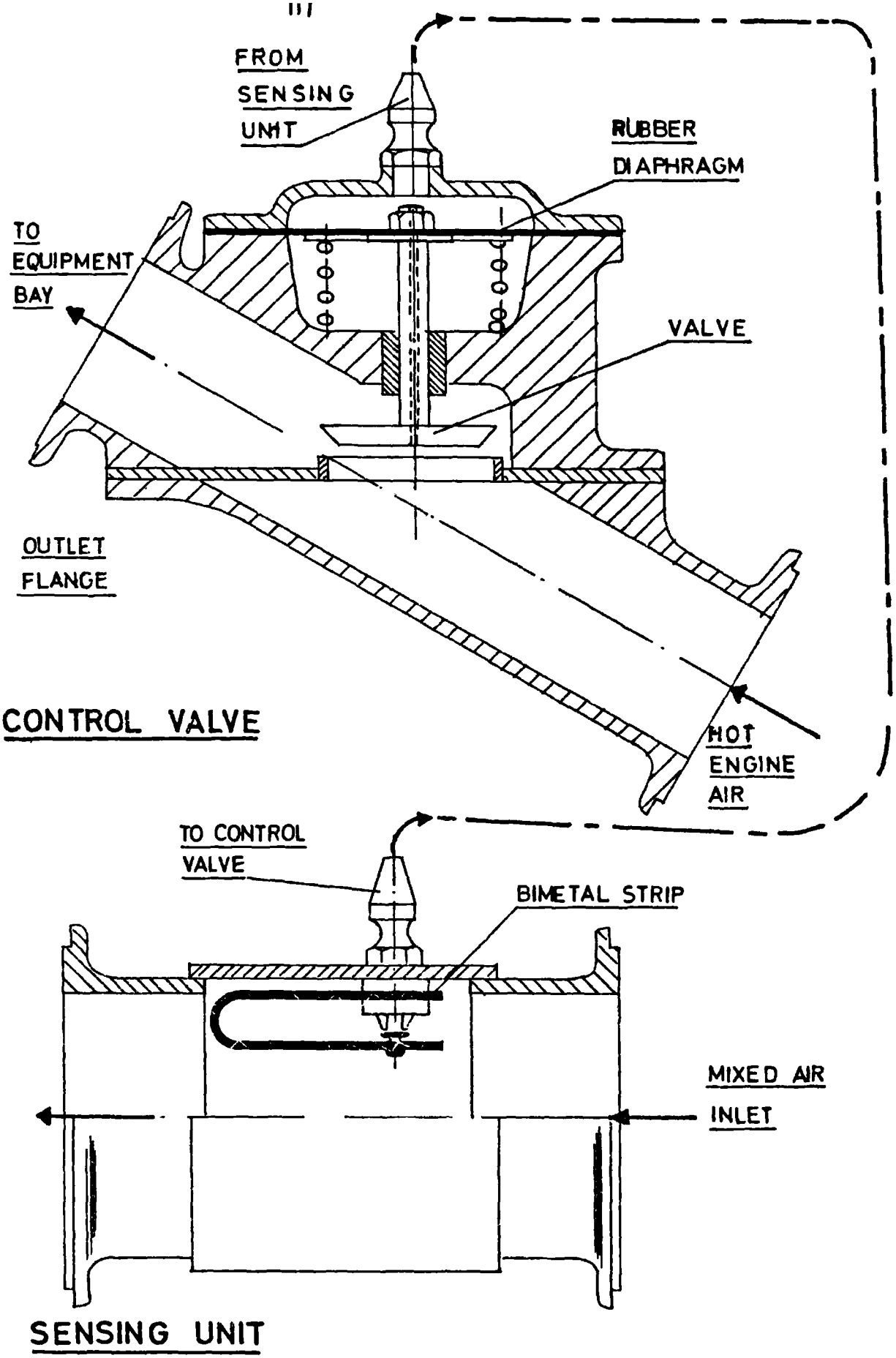
The design case history unfolded over a period of several years and was interrupted and redirected by several important policy changes bought about by political, rather than technical, decisions.

The exercise was predominantly one of adaption, rather than innovation, although some of the constraints imposed by the hovering characteristics of the aircraft, involved novel problems and solutions. The design exercise was predominated by the need to refine the product in order to satisfy the prime requirements of safety, reliability and weight. This refinement was achieved by means of extensive and elaborate development tests, and in the event this approach proved to be critical in revealing the unpredictable and intransigent problems.

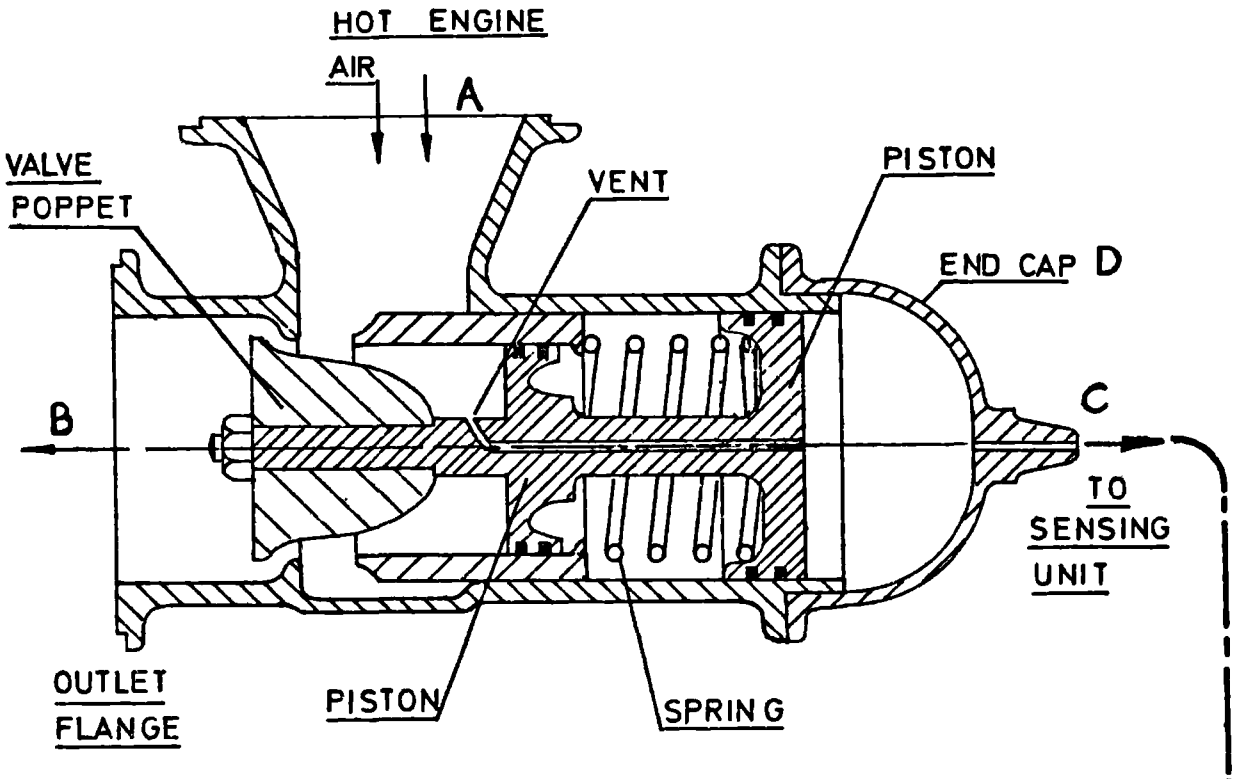




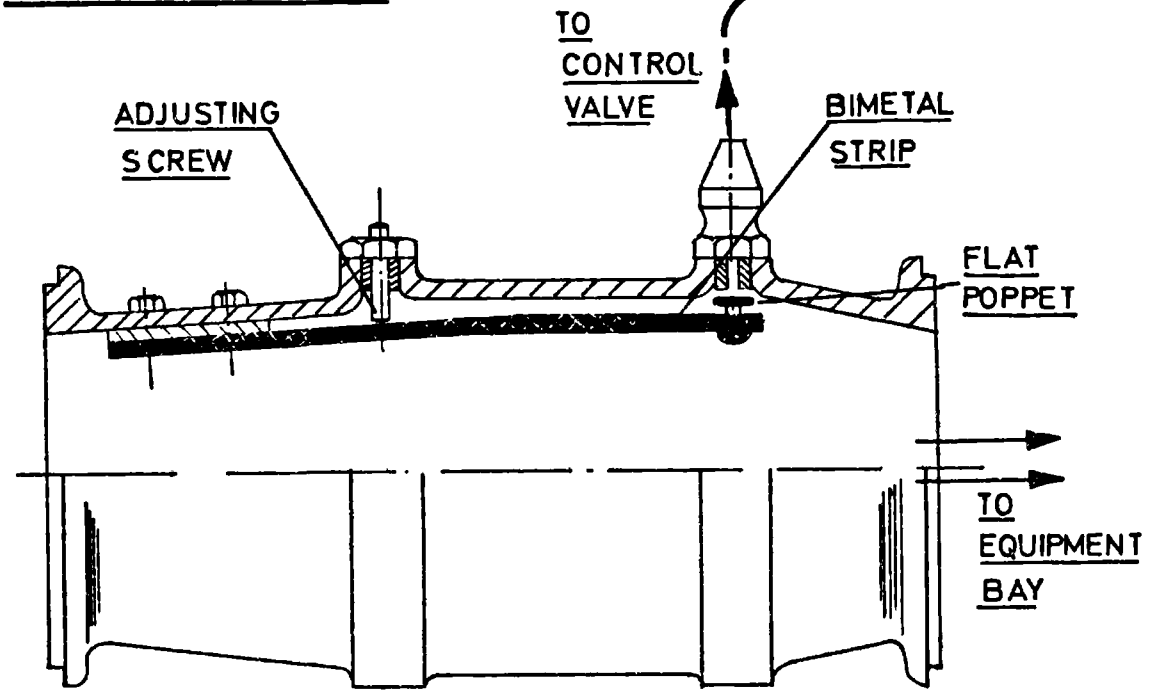
DFIG 1&2 THE CONDITIONING SYSTEM



D FIG 3 THE FIRST DESIGN



CONTROL VALVE



SENSING UNIT

D FIG4 THE SECOND DESIGN

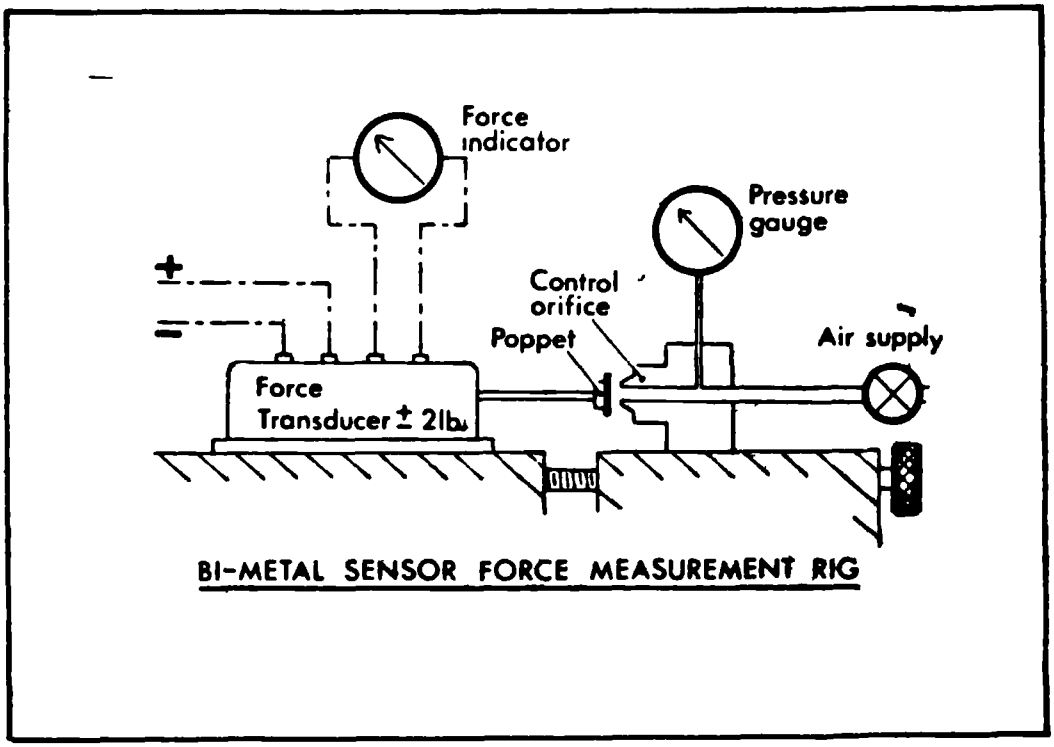


FIG 5a

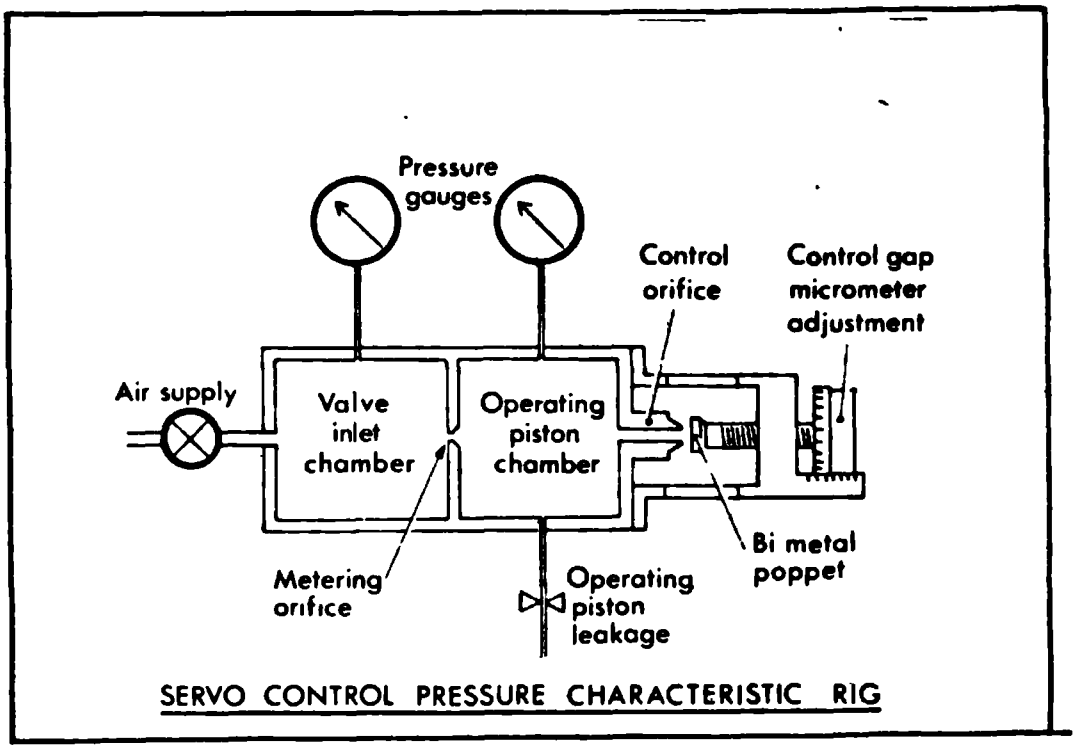


FIG 5b

D FIG 5 TEST RIGS

FIG 6a CONTROL ORIFICE PRESSURE DROP CHARACTERISTICS

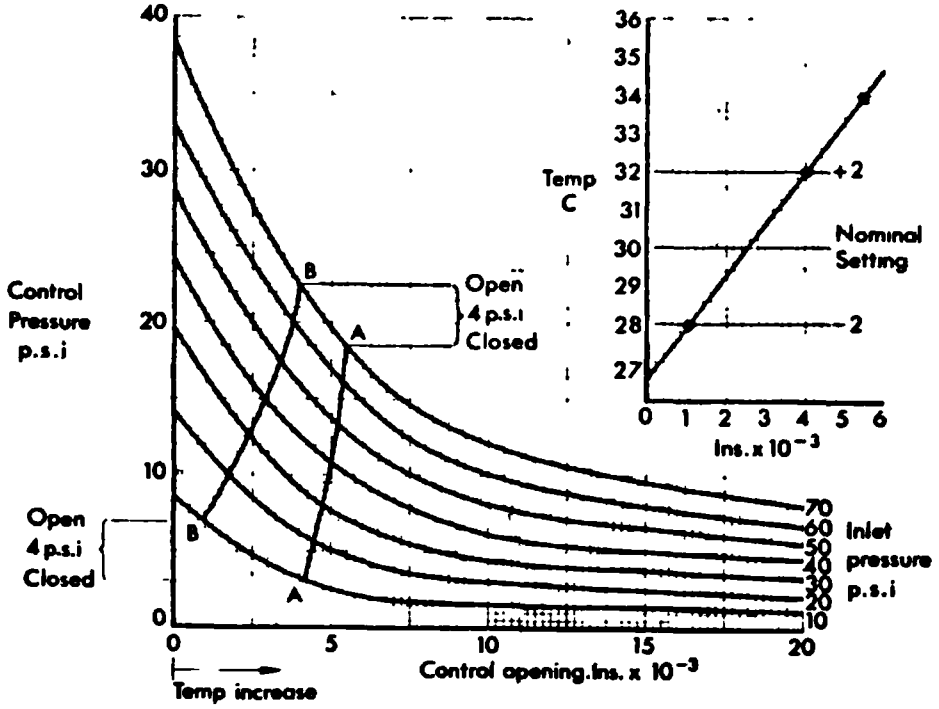


FIG 6b LOAD CHARACTERISTICS

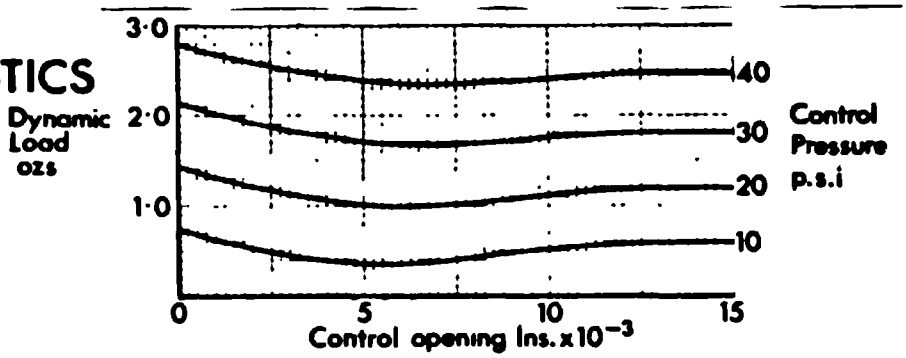
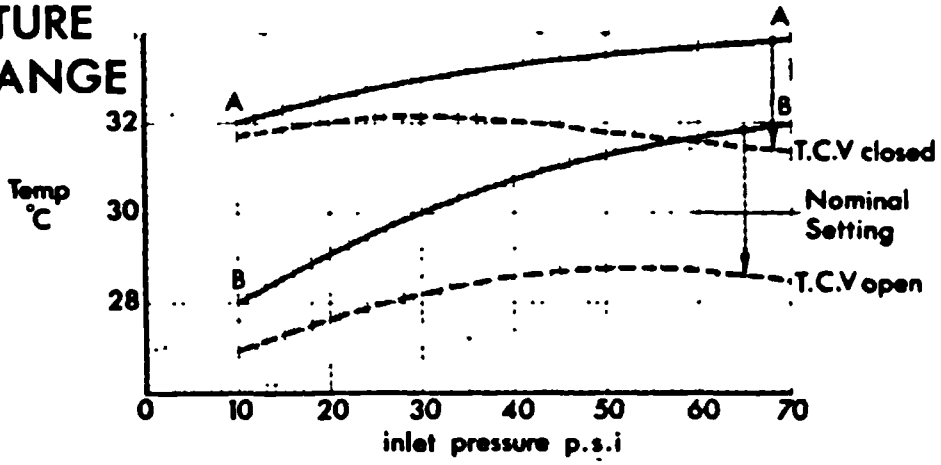
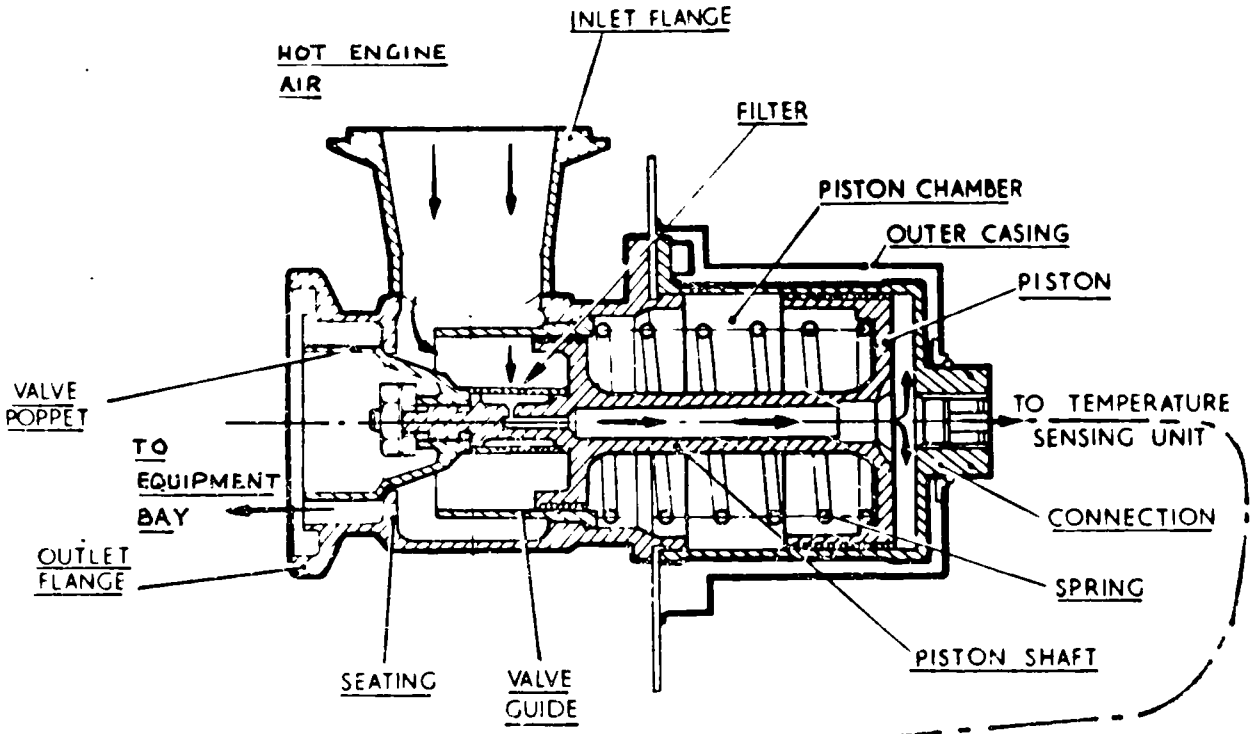


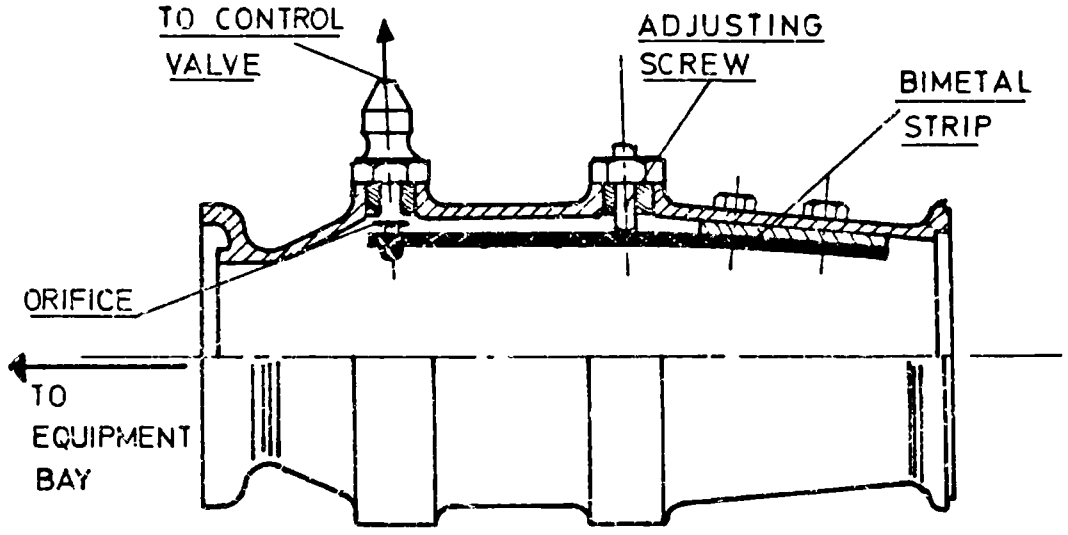
FIG 6c TEMPERATURE CONROL RANGE



D FIG 6 TEST RESULTS

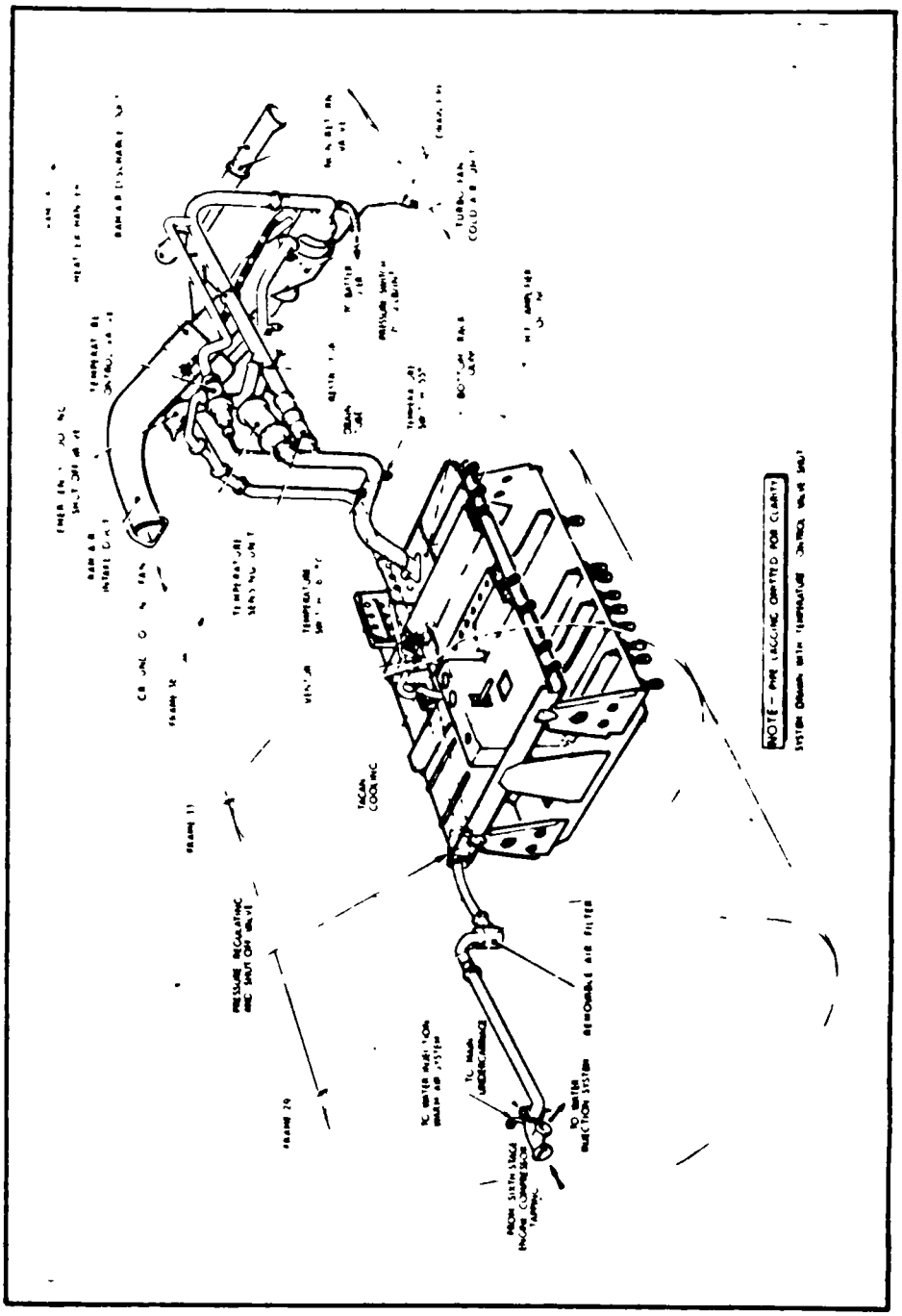


CONTROL VALVE



SENSING UNIT

D FIG 7 THE FINAL DESIGN



D FIG 8 THE AIRCRAFT INSTALLATION

CASE HISTORY E

THE AIR CONDITIONING SYSTEM IN A PRIVATE MOTOR VEHICLE

INTRODUCTION

When planning the introduction of a new model Firm E stipulates the date on which full-scale production will start and the price at which the model will be sold.

Time factors are established from previous experience on similar models and cost targets are established from current production model costs, planned reductions, value analysis reports and analysis of competitors' design costs.

Although these objectives may be set up to three years before production starts, they must be rigidly adhered to and the designer must therefore operate within these imposed constraints on time and cost.

Additional constraints of function and performance which have been established early in the model programme are also imposed on components and systems.

An overall programme is then drawn up, aimed at achieving the production target date; each system and component is integrated into this master programme.

Working within this framework the designer must supply all necessary designs and information on processes, tools and materials to ensure that:

a) prototype build, test and development may be completed;

b) pre-production build and validation test programmes are completed;

c) full-scale production starts on the scheduled date; and the objectives of performance and cost must also be satisfied.

This case history concerns the design of the air conditioning system for the new model.

The overall objectives given by Engineering Management to the design team were:

a) design, build and test a prototype fresh air, heating and defrosting unit in 7 months for the new model range;

b) performance to meet latest Company targets;

c) the unit to cost no more than the previous model system and be simple to assemble on the line.

The study of these objectives in more detail, the sub-problems which arose and the final statement of the problem are covered in the next section.

THE PROBLEM

Initial discussions were held between the Departmental Manager and the Project Leader in May 1961 and the main aspects discussed were timing, resources and performance. No procedure existed within the firm from which to draw experience in designing heating systems, although the experience of the parent American company and other models were available. Previously the suppliers of heating systems had been asked to submit designs to suit a particular vehicle and the Company's own design teams had not been involved directly.

a) Timing

In order to achieve the target date, it was agreed that a team of three designer/engineers should be involved led by the Project Leader, who would be responsible for completing the project within the scheduled time. The first task was to establish liaison with other design areas that were affected by the design of the heating unit. The three members of the team took part in these initial contacts which enabled a list of additional design requirements to be drawn up. These were:

Department	Requirement	Areas affected
Body	Minimum depth of draw in centre of Wind-shield Panel Air intake at centre of cowl top.	Windshield, Dash and Instrument Panel
Styling	Controls integral with unit	Location and appearance of control head

Department	Requirement	Areas affected
Chassis	Clearance between clutch pedal (R.H.D.) and accelerator pedal (L.H.D.) to heater case	Foot control and handbrake
Engine	Water hoses on right-hand side of engine	Dash panel and matrix water pipes
Manufacturing	Simple assembly operation	Line assembly
Purchase	Suppliers' existing production techniques to be utilised	Source of supply Design for conventional materials and construction methods
Electrical	Maximum current draw 50 watt	Fan motor and fan design

Other aspects of the overall design were ahead of the air conditioning design by as much as six months and the design team were therefore able to obtain layout drawings of the engine installation, body structure and pedal arrangements at this stage.

At the end of the first week in May 1961 a detailed work plan was drawn up, E Fig. 1, which allocated specific responsibilities to each member of the team. This shows that of the seven months allocated to the project, the first five were to be design and the last two were to involve development by rig and car tests.

This plan also allocated specific responsibilities to each member of the team and indicated how the design work was to be paralleled by the task of acquiring additional data to support the design activity.

Fortnightly design co-ordination and timing meetings were held throughout the project. These meetings were chaired by the Executive Engineer with design responsibility for the new vehicle and were attended by the Project Leader.

b) Performance of the Air Conditioning System

Since the team had no direct previous experience of the design of Air Conditioning Systems, the required performance was established as a result of discussions with management and marketing and from information obtained on existing comparable designs.

The required performance was finally established in terms of the following "in vehicle" performance targets:

Heating

The vehicle interior shall have an average temperature of 80°F with 0°F ambient after testing at 20 m.p.h., top gear, for 60 mins with fan on. Performance at 40 and 60 m.p.h. with and without fan on shall not fall below this temperature target.

Air outlet tmperatures must be fully controllable between maximum heat setting and ambient air temperature.

De-icing

The prescribed deposit of ice after a 14 hour soak in a cold room shall be cleared from the screen within 30 mins of starting the engine and running at fast idle in an ambient of 0°F.

Location of tempeature measuring points, soak periods, etc. are also specified.

Having established a working programme to match the required time factors, and completed a fairly detailed study of the problem, the next stop was to break the system down into its components and attempt to establish performance targets and initiate design on each one.

FEASIBILITY STUDY

At this stage it was decided that a full analytical treatment of the problem, although desirable, was not possible because the time available was too short. An empirical approach based on experimental test work and simple calculations was decided upon and this was reflected in the work plan.

In carrying out this analysis the air conditioning system was considered to be made up of the following basic elements:

I Air Inlet
II Blower
III Heat Exchanger
IV Air temperature and distribution regulation
V Heater case

E Fig. 2 shows a schematic arrangement of these five elements for a car with a water cooled engine. Previous experience from an investigation into the air flow requirements of heating and ventilating systems, and data gathered from a literature survey, enabled some requirements to be established for each of these components in order to satisfy the required overall system performance.

It was decided that by locating the air inlet at the base of the windshield, to achieve maximum ram effect, there would be no need to use the blower above 40 m.p.h.

In order to achieve satisfactory air and temperature distribution to the rear of the car, the blower should deliver 100 cubic ft. per minu e at a vehicle speed of 20 m.p.h. The blower fan should also be large to minimise noise and either an axial or centrifugal design could be used and still satisfy the current draw requirement.

The Heat Exchanger would utilise existing production techniques and be of tube and plate fin construction. In order to keep the flow rates low but water velocities in the radiator high, and the hoses on one side of the engine, it was decided to use two water passes.

The Temperature Controller was required to provide fast response to change in control setting and a passenger head temperature 15°F below the feet temperature. It was therefore decided to adopt an air blend system to proportion hot and cold air. It was decided to use existing production facilities for the Heater Case which would be of sheet metal construction. A rough estimate of the sizes of various elements was made in order to have some basis for considering different approaches in the next design stages.

In order to achieve low resistance to flow, it was calculated, and based on previous experience, that 40 sq. in. of free area of air inlet were required and that the air passages should be of maximum cross-sectional area in the space available.

A 5 in. to 6 in. diameter fan was required for the blower in order to satisfy noise requirements and a 3 in. diameter 50 watt motor would be needed.

Previous test data indicated that the Heat Exchanger should have a face area of 36 in^2, a depth of 2.75 in. and 16 fins per inch. Simple calculations showed that to meet a target of 80°F in a 0°F ambient and an assumed heat loss from the body of 1.4 BTUs/min per °F temperature difference a heat input of 250 BTUs at 100 cfm would be required. To achieve this heat output an air temperature rise of approximately 140°F would be required. With an engine thermostat set to crack open at 180°F and to maintain circulating water at this temperature, this meant a radiator designed to achieve a thermal ratio of 0.77 (i.e. the temperature rise of the air as a ratio of the extreme temperature difference between entry air and entry water).

Test reports of heater matrices in current production were examined and, from the assumption that face area is proportional to dissipation for a given thickness and fin density, a rough estimate of size was obtained. A graph of matrix thickness against thermal ratio gave an indication of the thickness required to produce the air temperature rise.

The size of the Heater Case was determined from the need to contain in it the heat exchanger, fan air passages and air control flaps.

Additional information required to complete the design was listed and one engineer had the task of supplying this information at the time it was required. He also undertook to check on the validity of the assumptions made at this stage. These include the total resistance against which the fan would operate; the engine water flow through the system at 20 m.p.h. in top gear, (1250 rev/min); a verification of the matrix performance and body loss coefficient assumptions, and the water drainage requirements.

INITIAL DESIGN

Draughting work commenced with a full-size layout which assembled relevant details of the engine, the body panels, the pedals, handbrake, and windshield wiper locations.

This, when completed, was used as an underlay over which various ways of disposing the basic components were evolved. Five variants were produced within the four weeks allowed. Each scheme was completed in sufficient detail for costing analysis, based on existing studies, and for engineering discussion. Only the costs to produce the various sheet metal cases and assemble the units, were estimated at this stage.

Three variants contained the fan, matrix and air blend or temperature control flap within the engine compartment, an air distribution box being mounted on the inside of the car. An obvious advantage of these extemally mounted designs was the low noise potential obtained by keeping the fan remote from the passenger space. Disadvantages were high assembly and sheet metal costs and failure to meet the objective of minimum draw on the windshield panel.

These three extemally mounted designs were evolved by modifying existing designs in an attempt to simplify the operation and number of controls, and to improve assembly techniques.

A novel solution involving an internal mounting concept was developed from the need to achieve the cost targets. It was realised that to produce a system with a 25% increase in heat output the solution would need to be compact, contain less parts, have a simple control system and a reduced number of assembly operations.

These objectives, in combination with that to keep the depth of draw in the windshield panel to a minimum, provided the need to seek an unconventional solution. A centre line section through the windshield panel is shown in E Fig. 3. Once the arrows indicating a possible air flow path had been sketched in and a surface created from the bottom of the panel to the windshield opening, the essential parts of the design quickly followed, E. Fig. 4. This development proved to be a major breakthrough in the design exercise. A full-size layout of this idea was used to examine problems of water penetration and the method of mounting the motor. The resulting design proposal is shown in E. Fig. 5.

An alternative arrangement with the windscreen air outlets emerging from the side of the case (shown by dotted line) was also completed.

The five layout drawings, together with cost information, were presented to the Chief Engineer with design responsibility for this system and representatives from other affected areas. The recommendations to continue design work on the unit illustrated in E Fig. 5 and build a prototype were accepted.

Cost breakdowns of the target unit had confirmed that a possible area for cost reduction lay in the simplification of controls, reduction in the number of parts and reduced assembly costs.

Mounting the controls on the unit had not only reduced direct costs but had simplified the assembly since the system could be adjusted prior to fitting into the vehicle.

DESIGN DEVELOPMENT

Sufficient information was not available to proceed with the detailed drawings of the components. Test rigs were built and new test and measurement techniques were established.

Long and short term procurement items were identified, as were those items which would be built within the firm's own facilities and those that would be obtained from outside sources. An example is shown below:

Where possible, the long term items were detailed first. This schedule also confirmed that the initial timing plan could be contained.

Part No.	Name	Source	No. Off/ Assy	Time to complete - weeks		
				Detail Design	Manuf.	Std. Item Purchase
X/1234	Heater Matrix	XYZ Ltd.	1	1.5	6.0	
X/1235	Fan	Firm E	1	2.5	4.0	
X/1236	Electric Motor	ABC Ltd.	1	Order	-	3.0

In discussing the function, control and linkage system for the two lower flaps it became clear that one flap would serve just as well and provide obvious cost saving although it would not be possible to select warm toe and cold screen. This was considered

acceptable and became a significant step in producing a satisfactory solution to the overall and detailed design problem, and E Fig. 6 shows how the required functions were met with two flaps. A further cost saving was made by locating the motor support directly onto the heater case. This obviously reduced line assembly time and unit assembly costs.

The design, E. Fig. 7, was now sufficiently advanced for a cost and weight analysis to commence. Liaison with the suppliers started with discussions of this layout. Copies were handed over for their considered comments.

Progress on the experimental side now enabled the operating point for the fan to be specified. Tests had also shown that water flow, above the critical 1 gal/min. level could be expected, E Fig. 8, and that the estimated body loss coefficient could be a little lower than estimated.

Fan design calculations were carried out by hand, based on a standard series of aerofoil sections and conventional design theory. Prototype fans were made from resin bonded glass fibre hand lay-ups and tested for performance.

The final detail drawings, those of the control head assembly, were completed in August 1961 nine weeks after starting detail design.

PROTOTYPE TRIALS

It had been decided to modify an existing vehicle to accept a prototype heating unit to carry out the vehicle trials. Rig tests were also being undertaken at this stage on another prototype; both were built in the firms workshops. The rig tests showed the air flow to be 10% below the target of 100 cfm. To overcome this the volume of plenum chamber was increased by 20% and the water guard panel was reduced in height below the fan centre line. These modifications were effective in achieving the target air flow.

The rig tests also revealed a problem in achieving a reduction of air outlet temperature proportional to the movement of the temperature control lever. This effect is shown in E Fig. 9 where the air temperature at the toeboard outlet is barely affected by opening of the temperature control flap, but is accompanied by a rapid fall in screen outlet temperature.

Modification to the control flap which throttled air flowing into the bypass duct and lowering the air offtake point of the windshield outlet duct alleviated this problem.

The affected drawings were modified and all prototype drawings were rechecked prior to issue, together with a parts list, to the department responsible for production release. The Production Release Department checked drawings for conformity with Company practice and raised Design Release documentation used to control the timing, purchase and manufacture of production quanitites.

Sets of drawings were issued to two suppliers of heating units for the manufacture of samples based on their production methods.

Cold room tests, using the prototype unit fitted to the modified vehicle, were used to check the de-ice performance and this proved successful. The vehicle was also equipped with a prototype engine and the windshield air outlets were of fish tail design carried over from an existing model.

Heating tests were also carried out in the M.I.R.A. wind tunnel. E Fig. 10 shows that although the target performance was met at 20 miles/hour with the fan on, the "ram only" 40 miles/hour condition fell short of 80°F. (Results are corrected to 0°F ambient). The cause was identified as poor air flow distribution to the rear foot wells. A deflector, made in cardboard, was fitted to the lower outlet of the heater unit and repeat tests showed an all round improvement in foot well temperatures. The target performance for this test condition was thus achieved and an additional part was designed in the form of a plastic moulding; the drawings were then issued.

These two types of tests covered the area of uncertainty of the design for no one could predict precisely how the air would flow over the windshield glass and along the floor of the vehicle, and this could only be examined by means of the vehicle trials.

The programme of work to this stage was completed within the alloted period of seven months.

TERRITORY TRIALS

Later a trial to confirm that satisfactory performance could be achieved in low temperatures was requested. A vehicle, together with one member of the team, was sent to Northern Sweden in December 1961. Subjective appraisals and measurements of performance on a fully engineered prototype vehicle were carried out. It was a successful trip, thoroughly enjoyed by all who took part, in which work on the heating system was combined with engine carburettor tuning. Slow engine warm-up was cured by fitting a thermostat with a closer leakage tolerance.

The field trials also exposed the problem of high noise levels when the top flap was set in the mid-position. This had not been observed in previous test work because it had been masked by the noise of the air flow test rig. Moreover the flap had not been set in this position during wind tunnel tests, in which only maximum performance settings were used, and there had been no previous experience from which the trouble might have been anticipated.

Subsequent analysis of the noise spectrum showed the major content of the noise to coincide with blade passing frequency and to be caused by the proximity of the top flap to the fan blades and their matching vibration characteristics.

Detail development and design work on the fan, the fan housing and mounting reduced the noise somewhat, but not to a completely acceptable level. This was to be expected as we had "designed in" a fundamental fault. The solution was to adopt the palliative of fitting a two-speed blower switch which was acceptable since the high speed setting was only required in extreme conditions. It was therefore unlikely that the critical fan speed would be selected at the same time as the critical flap position. The decision to live with this problem was taken because the design achieved all other performance requirements at a cost more than 20% below the target figure, and no time was available for a fundamental redesign.

It is interesting to note that subsequently the two-speed blower became a sales feature in this model!

FINAL DESIGN

The final design modifications were completed and incorporated in January 1962.

Liaison with the suppliers had been maintained since the issue of the drawings, and samples were received three months later. Both differed slightly from our design and from each other. A period of rig tests with these units were followed by a series of tests in a fully engineered prototype vehicle to ensure that the samples matched the performance of the prototype unit in all respects.

Each company submitted cost details and that offering the lowest price was accepted by the Purchase Department.

This supplier built sufficient samples to fit into all prototypes and to meet component durability test requirements, e.g. cycling of control system, electric motor durability. The detail design work on these units was undertaken by the supplier.

All test work during the vehicle prototype and pre-production phase was done by our Test Operations area who submitted test reports to the engineer requesting the work.

Two final tasks for the design team remained, one required an Engineering Performance Specification to be written in terms of rig test results and against which production samples could be checked by Quality Control. The other task involved preparing a draft patent application which was subsequently applied for by our Patents Office.

CONCLUSIONS

This design case history was one of the most successful of those studied by the author. It achieved the major objectives set by Management in terms of time, cost and performance.

It was also the most closely controlled of all the case histories, the constraints imposed upon the design team, both external and internal, being more comprehensive, formal and rigorous.

The exercise involved an element of innovation for the design team since, although the product was familiar, the company had no previous internal experience in the field. One aspect of the work was, therefore, that it increased the "in house" knowledge of the design of an important component of the motor car.

A further aspect of the work was that it forced the development of new measurement and test techniques, and exposed the limits of the company's knowledge and experience in the field concerned. In this sense the technical content was high.

The author was also interested to note two important instances of 'break-through' in the process. The first involved the decision to house all the components as one unit inside the passenger space and the other was the realisation that only one flap was required to select the air outlet positions. Both of these ideas came, not as a result of sudden inspired insight, but, rather, as the result of a logical approach towards a solution.

After completing this design and development exercise, work was continued on fresh air ventilation systems. Once the question "Could the new heating system be adapted to provide a basic fresh air ventilation system" was asked, the answer was obvious. A three inch diameter outlet in each side of the case above the matrix, E Fig. 6, provided a source of forced fresh air. The modifications to the unit and to a vehicle, which, in addition to extra outlets at the ends of the facia panel, included a body air extraction system, showed that a reasonable degree of fresh air ventilation could be achieved.

These new developments were embodied in a later change to the model and they were also used in a new model range which is in current production; the basic heating system was also extended to meet the requirements of a new range of vans and trucks. These indications of development potential can be regarded as a further measure of the success of the exercise.

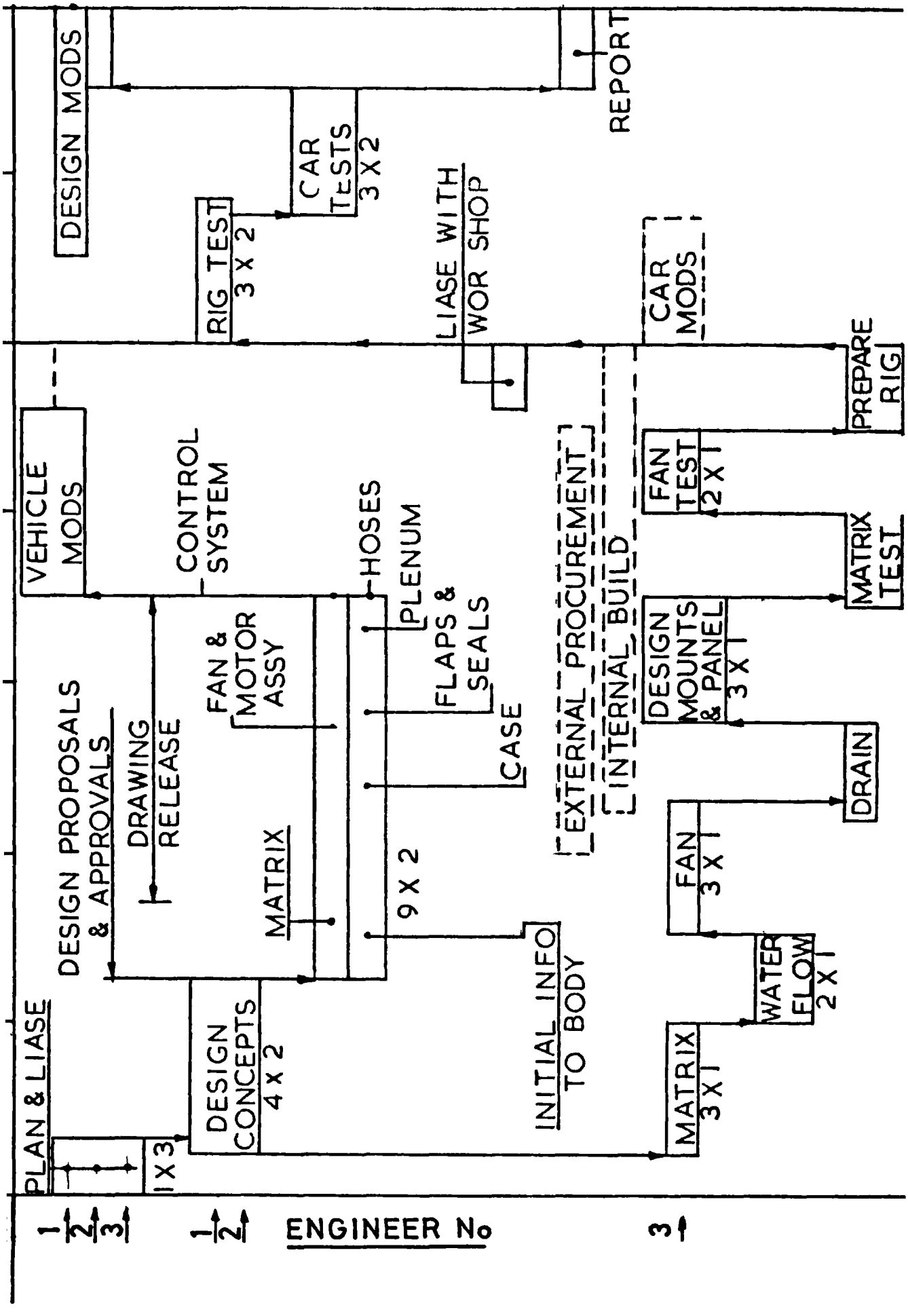
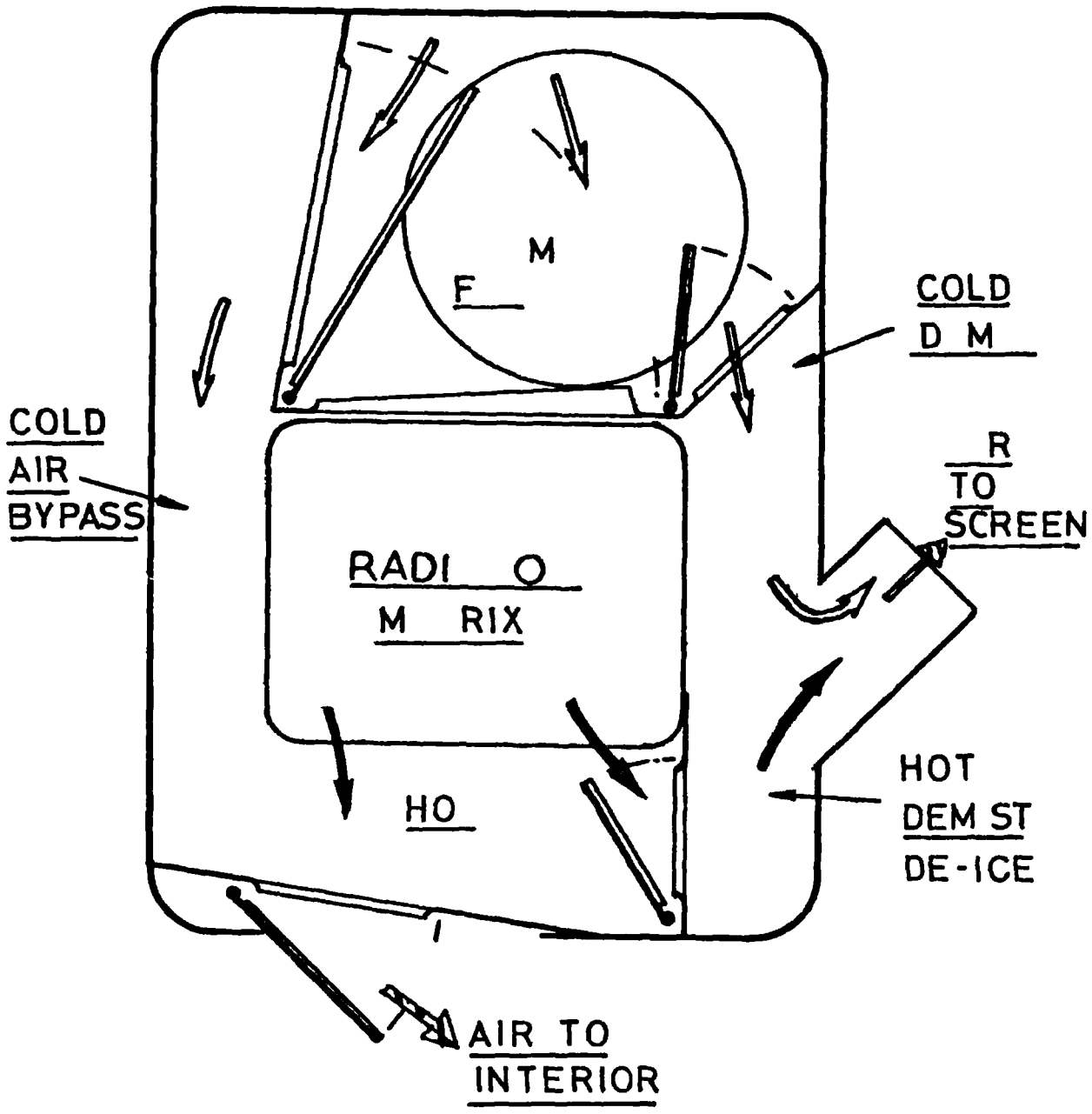
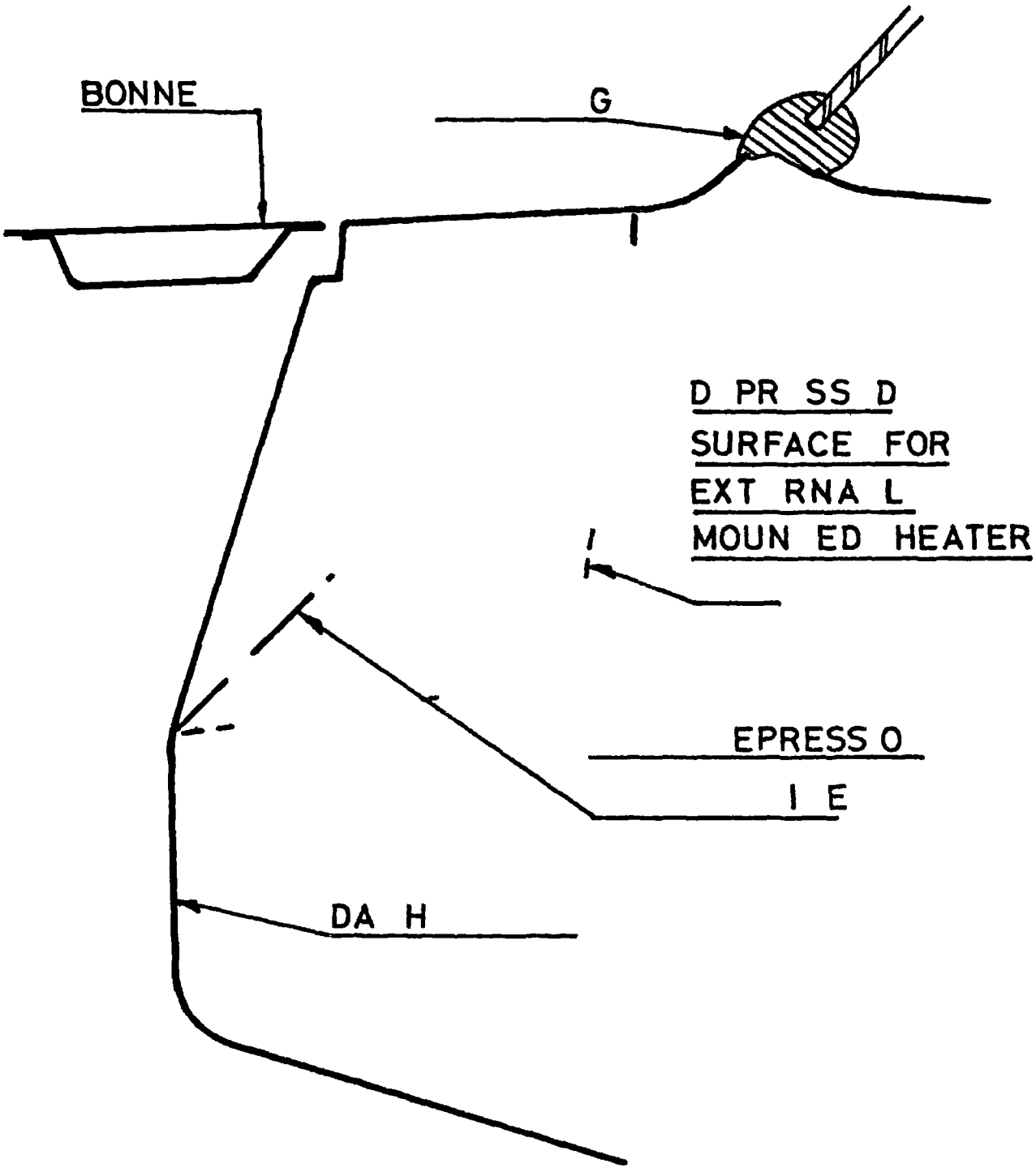


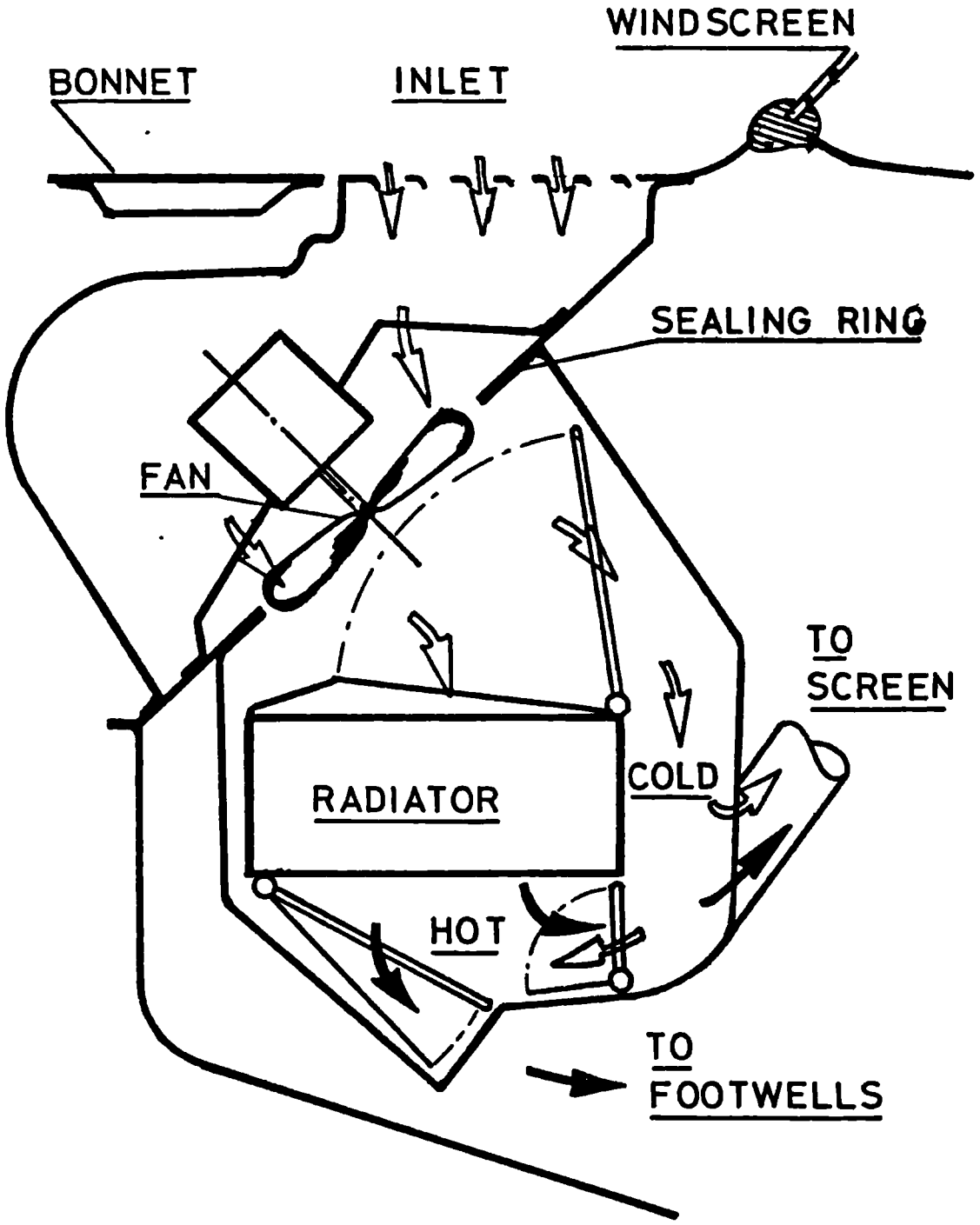
FIG1 DESIGN PROGRAMME



EFIG 2 TYPICA SYST M WITH AIR BLENDING

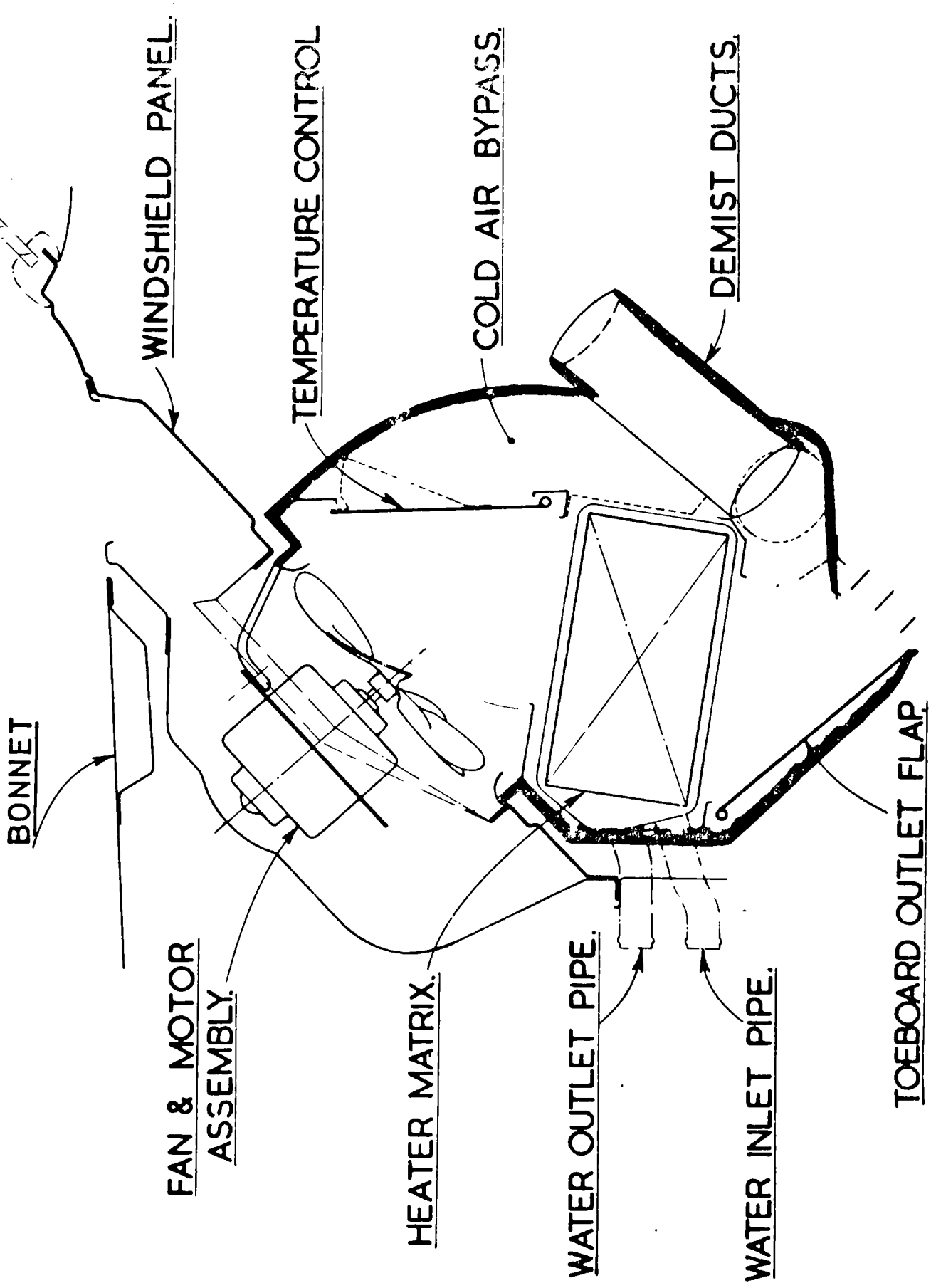


E FIG 3 SECTION A O CENTRE LINE



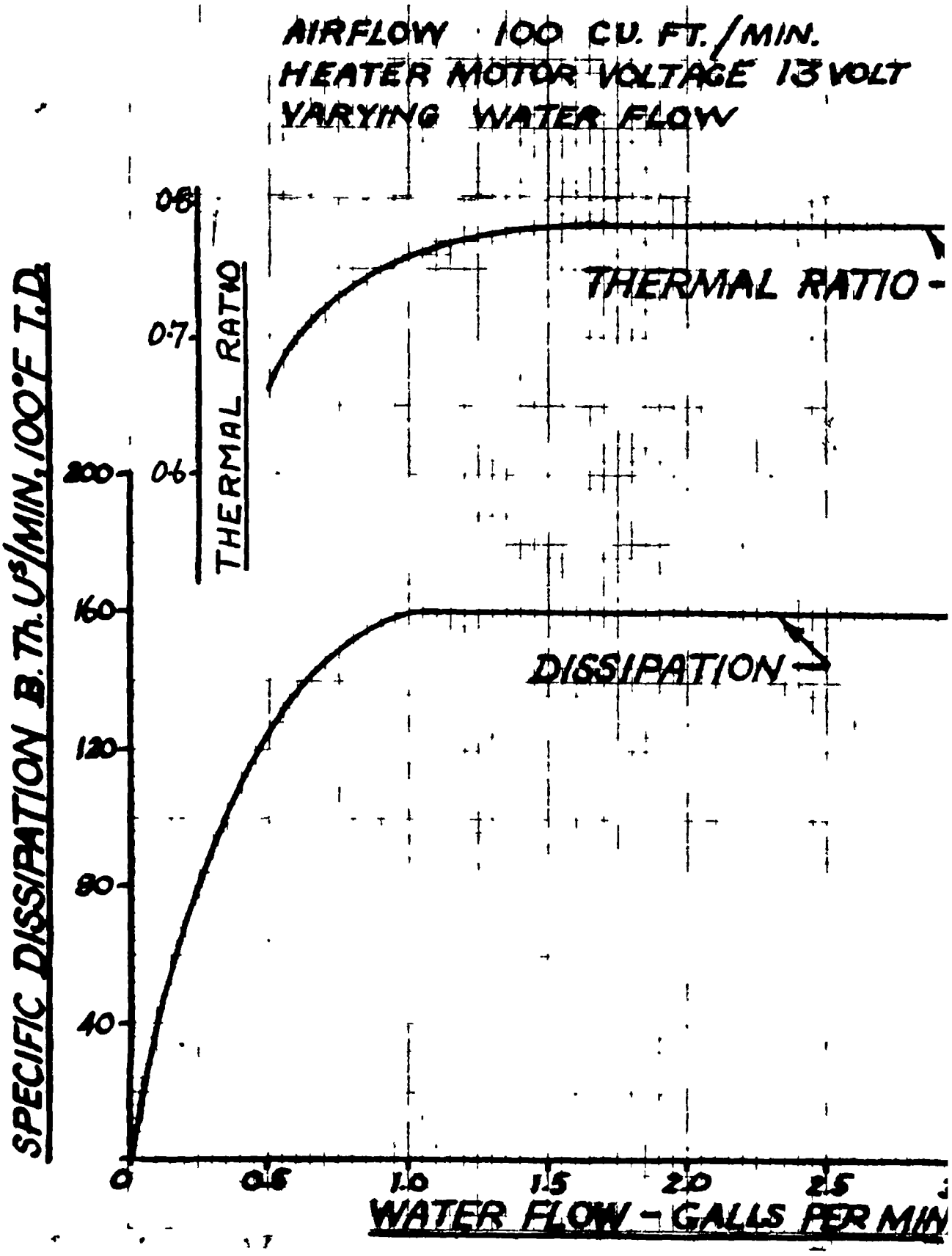
EFIG4 LAYOUT OF INTERNALLY MOUNTED UNIT

EFIG 5 DESIGN OF INTERNALLY MOUNTED SCHEME



E FIG 6 TWO FLAP DESIGN PROPOSAL

EFIG7 FINAL DESIGN - METHOD OF OPERATION



EFIG 8 PROTOTYPE HEATER - RIG TEST RESULTS

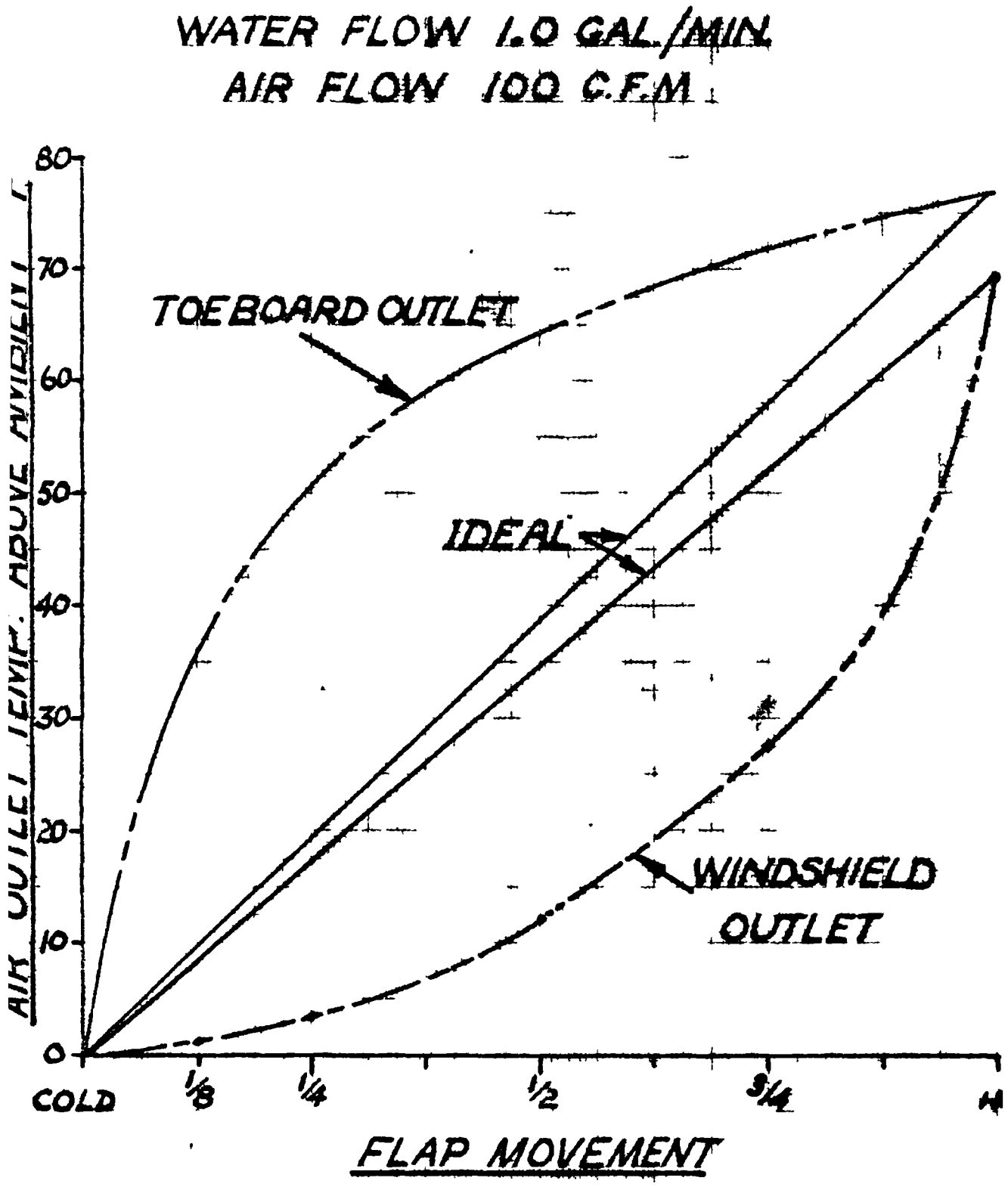
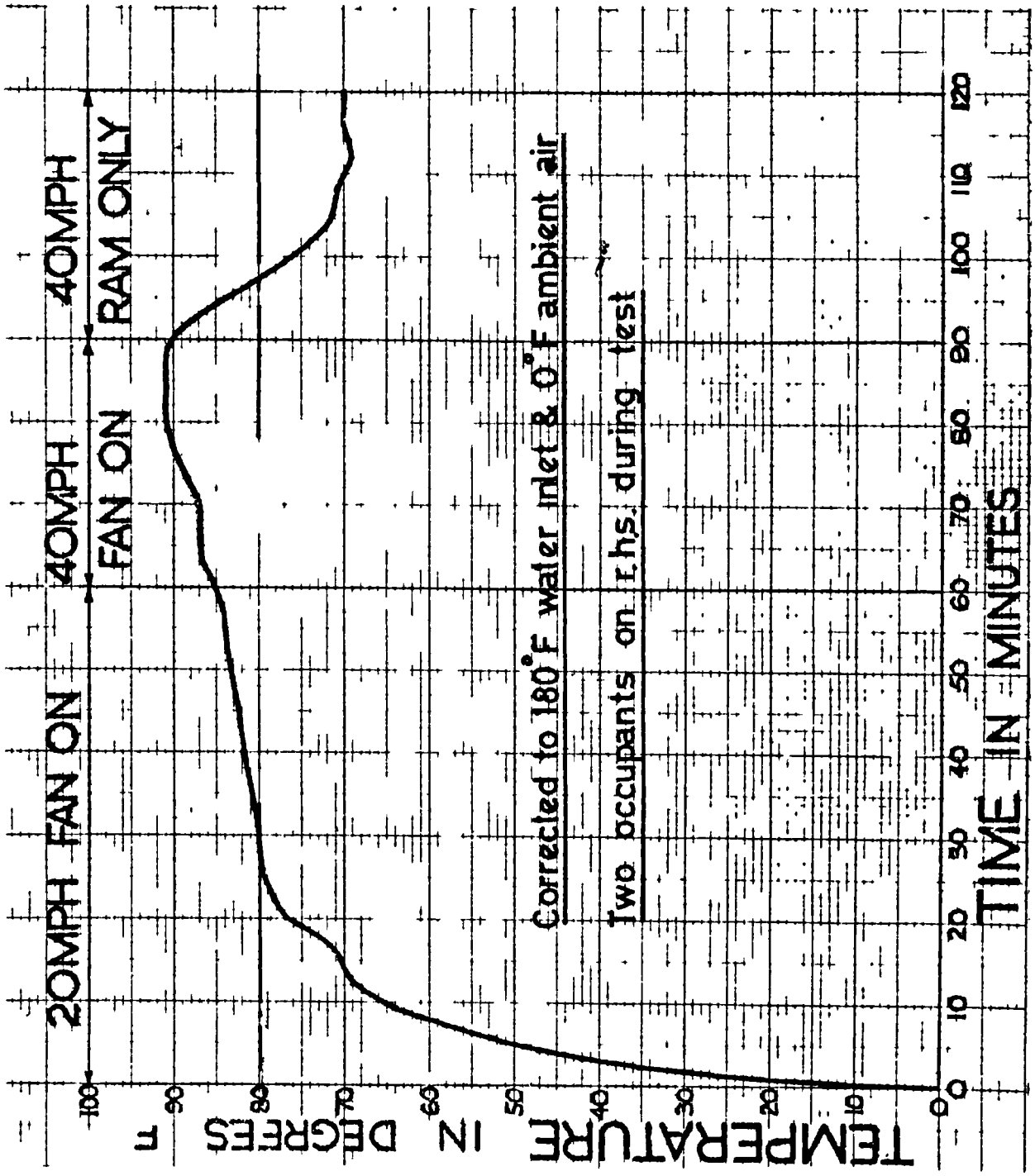
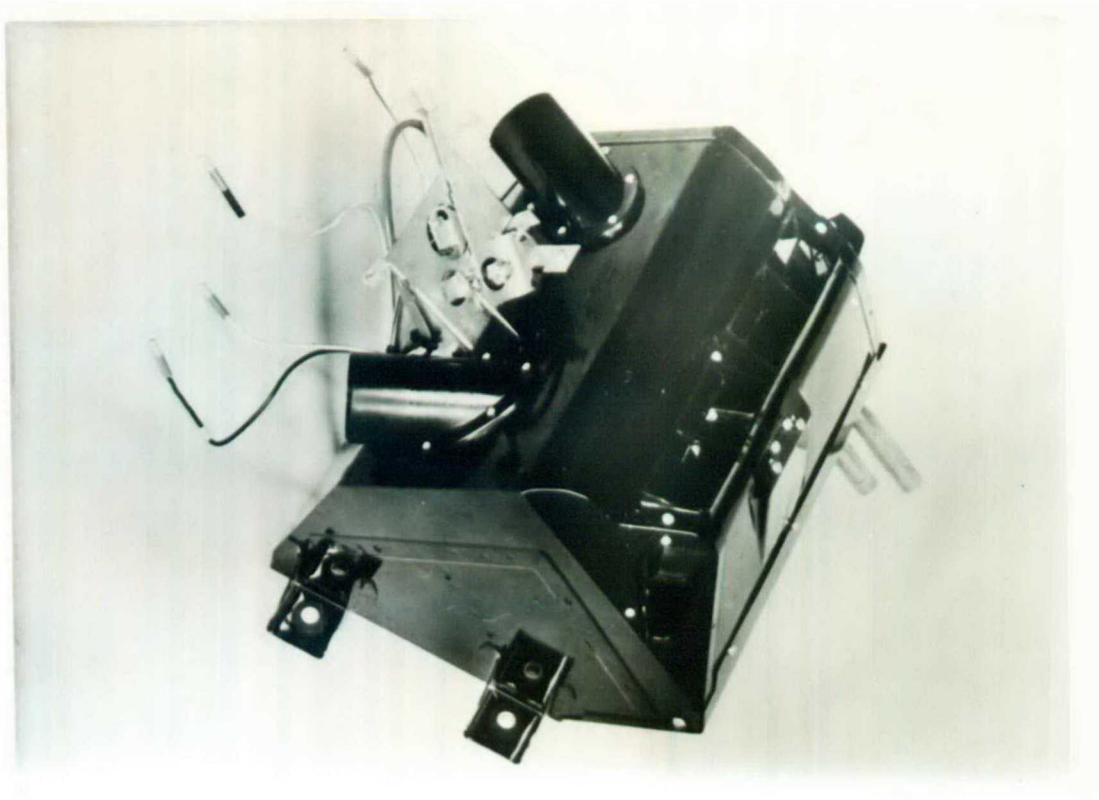
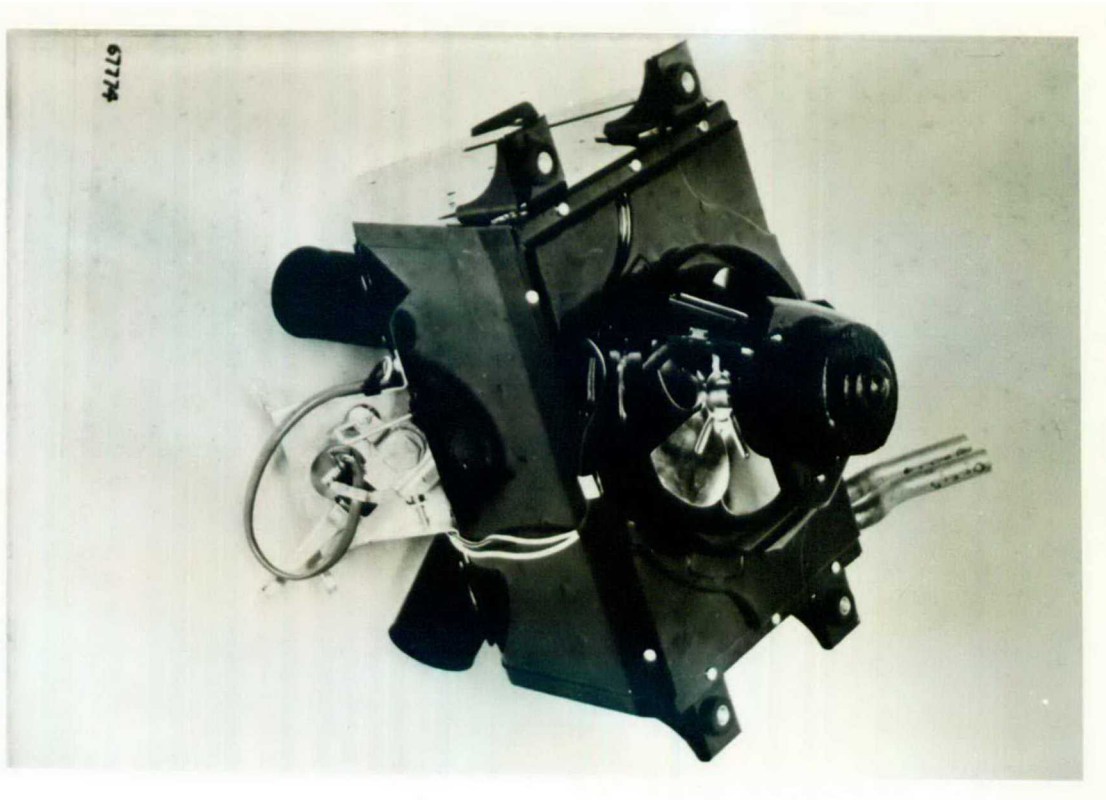


FIG 9 PROTOTYPE HEATER - PERFORMANCE



EFIG 10 MEAN INTERIOR BODY TEMPERATURE





EPLATE I THE FINAL DESIGN

CASE HISTORY F

REACTION CONTROL VALVE USED IN S/V.T.O.L. AIRCRAFT

INTRODUCTION

The S/V.T.O.L. aircraft designed and manufactured by firm F is stabilised in jet borne flight by a reaction control system; this is a spider of lightweight ducting within the structure feeding air from the final compressor stage of the engine to the extremities of the aircraft, F. Fig. 1. Control is achieved by opening shutter valves at the end of this ducting; these valves are linked to the normal aerodynamic control surfaces and work in the same sense.

The engine nozzles are rotated by shafting and chains, powered by an air motor, F Fig. 2. An auxiliary gearbox in the system drives a linkage which operates a shut-off valve in the ducting off-take from the engine compressor. This linkage and valve ensures that the engine bleed tapping is closed with the engine nozzles in the aft (conventional) position, and that the valve opens progressively as the engine nozzles are rotated downwards. The valve is open sufficiently to pass full flow at an engine nozzle angle of 20° down from the horizontal. It is this valve that is the subject of this case history.

THE PROBLEM

The design of the shut-off valve was first examined during the design definition of an earlier aircraft, version A, in the period 1958/59. The requirements then defined can be summed up as follows (not necessarily in order of priority):

The shut-off device must:

(1) Be simple

(2) Be reliable

(3) Withstand engine compressor delivery pressure

(4) Withstand engine compressor delivery temperatures

(5) Operate at high pressure and temperature

(6) Have a low pressure drop at design mass flow

(7) Shut off air when the engine nozzles are aft

(8) Ensure that air is available whenever jetborne flight (below 150 kts) is likely, i.e. by the time the nozzles are 30° down

(9) Have a small movement from fully closed to fully open

(10) Fit in the space between the engine compressor casing and the (decided) run for the reaction control ducting

(11) Have a low leakage rate when closed, to obviate wasted engine thrust

(12) Be accessible

INITIAL DESIGN

The design philosophy which was evolved as a result of the study of the problem remained unchanged throughout the life of version A and its derivatives versions D and E.

The requirement for simplicity and reliability led to the choice of a mechanically controlled system rather than hydraulic, pneumatic or any mixed systems, all of which were considered less reliable, and more difficult to test.

A butterfly type of valve was also opted for because it was basically simple, relatively cheap, could satisfy the operating requirements of pressure temperature and leakage and could be accommodated in the limited space available.

It was also decided to satisfy the requirements for valve operation by linking it to the engine nozzle drive system. The geometry of this linkage, shown in F Fig. 3 was to play an important part in subsequent design decisions on the butterfly valve.

The linkage was designed in concert with the engine nozzle drive system, and it drove the butterfly valve as the engine outlet nozzle rotated. At a 40° nozzle angle the valve was 90° open and was kept open as the engines nozzle continued to rotate to the fully vertical position. These valve characteristics are shown in F Fig. 4.

The estimated engine pressure and temperature at maximum rev./min. at sea level are shown in F. Fig. 5. The valve would be required to operate only during stationary and low speed transition to horizontal flight - up to the 200 knot curve, and would be closed at conditions between the 200 knot and 620 knot curves.

The valve diameter was determined from the permitted outlet dimensions in the engine and the size of the ducting it was to feed. Flow calculation on the reaction control system had already shown that 4 inch diameter ducting was required, the flow splitting two ways - forward and aft. A nominal $4\frac{1}{2}$ in. diameter butterfly valve was specified and to a first approximation the pressure drop across such a valve when 5° from fully open is only 0.9 lbf/in^2 at the design mass flow of 12 lb/sec.

A vigorous specification for the valve was then prepared since it had been decided that the detail design and manufacture would be sub-contracted.

This specification was issued during 1959 and the first valves were delivered in mid 1960.

Specification for $4\frac{1}{2}$" Butterfly Valve

1. Introduction.

This valve is required to provide control of an air bleed from the canannular combustion chamber to a pair of vertical stabilization jets.

2. Design Requirements.

2.1 The valve shall satisfy the general design requirements of DES.1. As this unit is a Class 1 casting it must also adhere strictly to the more stringent requirements for Class 1 parts specified in A.P.970, Volume 1, Part 4 with particular reference to Chapter 406, Leaflet 406/1.

2.2 The valve bore is to be nominally $4\frac{1}{2}$" diameter.

2.3 In order that the unit shall be as light as possible the length of the valve body is to be kept to an absolute minimum.

2.4 The upstream side of the valve is to carry a 6" diameter bolting flange drilled with mounting holes on a $5\frac{1}{2}$" p.c.d.

2.5 The downstream flange is to incorporate the standard 20° cone angle and is to be spigotted to provide a register in accordance with S.D.M.250.

2.6 The drive spindle of the valve is to emerge from a simplified end fitting for connection to the customer's own actuating linkage.

3. Working Pressures and Temperatures

3.1 In the closed position the maximum pressure at the valve inlet will be 186 p.s.i.g.

3.2 With the valve fully open the static pressure will be in the order of 130 p.s.i.g.

3.3 The through air temperature will be 450°C maximum.

4. Flow

The maximum air flow through the valve will be 12.5 lb/sec. with a static pressure of 130 p.s.i.g. at the valve inlet.

5. Acceleration

The valve shall be capable of withstanding an acceleration of 13 g in every direction.

6. Vibration

The valve shall satisfy the vibration requirements of DES.1 for equipment mounted in the power plant region.

7. Ambient Temperature

Maximum : 140°C

Minimum : -60°C

8. Leakage

With the valve in the closed position the leakage is not to exceed 10.0 S.C.F.M. under the following conditions:

Inlet Pressure - 186 p.s.i.g.

Outlet Pressure - 14.7 p.s.i.g.

Air Temperature - 300°C.

The result from this specification was a conventional stainless nickel-iron butterfly valve, F. Fig. 6, with carbon bearings, and the valve disc skewed to obtain a complete sealing ring without having to pass through the spindle. The sealing ring was retained in the groove, at one point, by pins. End float to allow for differential expansion was obtained by shimming.

This valve was fitted to the first version A aircraft, and to the four subsequent aircraft. Version A carried out tethered hoving flights in October 1960, and the first free hover in November 1960. Full transitions from jet-borne to wing-borne flight were completed by September 1961, and during that time it was established that the design of the valve was unsatisfactory.

DEVELOPMENT

The major difficulties encountered were that the piston ring extruded from its groove at high mass flows - on one occasion this caused the valve to jam - and the operating torques were high.

An additional complication at that time was that the suppliers of the auxiliary gear box had specified a maximum output torque equivalent to 212 lbf.in. at the butterfly valve in the closed condition. Measured valves were found to be as high as 200 lbf.in.

A temporary solution was the removal of the ring. This increased the leakage from an actual 8.0 c.f.m. to 260 c.f.m. at 150 p.s.i.g. and 20°C. Removal of the piston ring reduced the operating torques to around 130 lb-ins at 150 p.s.i.g. but this torque was entirely due to the pressure load on the valve disc and the high friction in the carbon bearings and did not include the aerodynamic torque on the valve.

In addition, minor troubles existed. Valves were found to be distorted when supplied, and defects were experienced with the shimming and end float.

Then followed protracted negotiations with the sub-contractor. As a result of these negotiations the company decided to design and manufacture their own butterfly valve. The main reasons for this decision were:

(a) Firm F did not like the price of the bought out valve and estimated that they could produce cheaper.

(b) The technical back-up of the sub-contractor (at that time) gave the firm little confidence that satisfactory modifications could be incorporated.

(c) The company were already pursuing a policy of manufacturing the remainder of the reaction control system. This being a new and untried primary flying control and vital to the safety of the aircraft, it was considered that complete responsibility should be in the hands of the contracting authority.

(d) There was, in the firm's design office, a specialist designer in mechanisms who was confident that the firm could make a satisfactory job.

Thus in mid 1962 the firm's own design team commenced work on the detail of the valve.

REDESIGN

The design exercise now became much more time conscious since the valve was to be fitted, initially, to the 6th prototype aircraft and subsequently to the nine version D aircraft ordered by the air forces of the United Kingdom, the United States of America and the Federal Republic of West Germany. This limited the time available for design, development, manufacture of the aircraft unit and test to approximately 12 months. The first design had to be the right design - or at the worst right enough.

The basic conditions for the design of the valve in addition to those of function and cost which had already been specified, were that it must be installationally interchangeable with the original butterfly valve and it must not be like the sub-contractors' valve.

Firstly, design conditions were reconsidered. Estimates for the engine due in 1964 gave the following pressures and temperatures at sea level, temperate conditions.

Ambient Temperature, °C	-10	+15	+30
620 knots Pressure, p.s.i.g. Valve closed Temperature, °C.	285 420	255 447	234 464
200 knots Pressure, p.s.i.g. Valve working Temperature, °C.	189 356	181 400	174 425

It is interesting to compare these figures with those given for the same engine two years later, when test bed results were available.

Ambient Temperature, °C.		-10	+15	+30
620 knots Valve closed	Pressure, p.s.i.g.	257	219	198
	Temperature, °C.	404	430	446
200 knots Valve working	Pressure, p.s.i.g.	173	157	145
	Temperature, °C.	349	379	394

The other major change in parameters that also necessitated consideration was that the reaction control bleed flow was now fully variable, from leakage past the control valves up to 15.0 lb/sec constant bleed; this increase from 12 lb/sec was due to the increase in weight of the aircraft. Thus the valve would be required to open against varying pressure drops which would depend upon the opening of the reaction control valves at any time during the 'nozzles down' movement. This recognition of operating torque varying with mass flow became an important aspect of the development tests.

It was decided that to obviate the problem of having to pass the sealing ring through the centre of rotation, the valve disc proper would be placed below the spindle. This necessitated a spherical bore, and a disc that was wedge shaped in cross section. The spherical bore was necessary as the projected radius increases as the valve is opened, until the disc diameter is level with the pivot. One fall out from this apparent penalty on manufacture is that the valve remains at closed clearances over a portion of its initial travel, (in fact some 10°). This in turn gave considerable saving on jigs, tooling and assembly.

The outlet diameter is, however, reduced. This was overcome to some slight extent by increasing the inlet diameter, within the existing geometry, by .060" which gave an outlet diameter of 4.40", a decrease of 0.1" in the original size. Friction loads were minimised by supporting the spindle in needle roller bearings suitable for operation at 450°C. luckily such bearings were available, F. Fig. 7).

Previous development work on the reaction control valves had shown the suitability of silicone based molybdenum disulphide lubricant at high temperatures, and greaser nipples were provided for this purpose.

Leakage past the bearings was to be contained by a single split piston ring. Shimming controlled the end float. The valve sealing ring was retained in place by fitting it into an 'L' shaped groove, and secured by a riveted bottom plate, F. Fig. 8 .

The ring was made from DDT.719, a chromium-molybdenum cast iron alloy, and the disc and body in Firth Vickers 520 stainless steel, a material with good mechanical and fatigue properties which can also be cast and welded.

The design tolerances were such that the ring expanded out against the stop annulus in the disc, and just touched the bore, at ambient temperature. As the disc expanded more than the body, due to differential temperatures, the ring collapsed back into the groove, still providing good sealing.

The shaft was of Nimonic 90 providing high hot strength; thus the shaft diameter and hence the disc thickness could be kept to a minimum to reduce obstruction to flow. The piston rings sealing the rolled bearings were of the same material as the main sealing ring - DDT.719. Rings of this material were already in use elsewhere on the aircraft, and in particular one size was suitable for the bearing sealing rings.

The disc was secured to the shaft by two taper pins. Free fit bearings had been decided upon, and the shaft was considered to be simply supported, i.e. maximum bending moment at the centre. Thus, the pin holes were put at points of small bending moment. The pins were secured by peened over nuts. All parts were to be stress relieved before final machining.

Thus lessons learnt from the original valve had been incorporated, viz, restrained piston ring, low friction bearings with high temperature lubrication, stress relieving to avoid distortion, and sufficient end float to allow for maximum thermal expansion.

The design exercise had commenced in July 1962, and detail drawings were given to the shops at the beginning of October in the same year. Three units were ordered at this stage, the first was for the Development Department and the others were for the first version D aircraft and the engine test bed. The first unit was delivered in February 1963, the components having been machined from the solid and fabricated; although casting was envisaged as the production method in the event of large production orders.

FURTHER DEVELOPMENT

The terms of reference for development were quite clear. Aircraft build programmes were such that the machining of further units would proceed concurrently with testing. Thus, no major design change was possible, and modifications must be such that they could be done retrospectively.

Preliminary testing took three months and the important results were:-

(1) The valve was satisfactory on hydraulic pressure to 450 p.s.i.g.

(2) Leak rates were approximately 120 c.f.m. (8.8 lb/min) at 160 p.s.i.g.

(3) Opening loads were excessive; 200 lb-ins at 70 p.s.i.g. to 500 lb/ins. at 180 p.s.i.g., all at ambient temperature. The ring was scoring the valve body - unacceptable.

(4) Rounding off the edges of the ring did not reduce torque loads or stop the scoring.

(5) Running at 320°C produced opening torques of 450 lb-ins, at only 60 p.s.i.g. - unacceptable.

(6) The test unit had not been stress relieved and 0.007" ovality had developed. The valve was remachined true and re-assembled without a piston ring.

(7) Torque loadings were measured without the ring, and were still high, 280 lb-ins at 180 p.s.i.g. a 45% reduction on those with the ring fitted. Leak rates, however, were excessive, 65 lb/min. at ambient temperature and 180 p.s.i.g.

(8) The ring was replaced, and successively shimmed out to establish a satisfactory clearance, cold, such that the ring was just clear at maximum pressure.

(9) Hot running at this condition produced high loads and scoring.

(10) Hot loads were still excessive with the valve open, thus the bearing rings were giving trouble. Strip examination confirmed there was pick up and scoring in the bearing housing, and on the shaft where these rings operate.

(11) The tight fit of the shaft in the butterfly disc caused pick up between the surfaces when trying to strip the valve for modification.

As a result of this preliminary test work it was decided that:

(1) Piston rings must be of a material that did not pick up and score with stainless steel.

(2) The finish of the spherical bore must be improved, to reduce high loads when ring touch did occur, e.g. not worse than 8 micro inches.

(3) Tolerances on the valve disc and main piston ring should be altered, such that the ring just touched at the estimated temperature differential between disc and body. Measurements had shown that this was unlikely to exceed 200°C.

(4) Tolerances on the bearing sealing rings, shaft and bearing ring housings should be altered to ensure no possibility of an interference fit at estimated differential temperatures.

Attention was turned to copper and its alloys for the main piston ring. K-Monel and beryllium copper looked the two best runners, and advice was sought from the Copper Development Association. They confirmed that beryllium copper had already been used for piston ring applications in high temperature environments in recent nuclear work. Two choices were available, Normal (or 2½%) beryllium copper, and Low (or ½%) beryllium copper. The ½% was chosen as it exhibited more stable strength characteristics at high temperature, although it had a lower U.T.S. after heat precipitation treatment than the 2½% (54 Tons/in^2 as opposed to 85 Tons/in^2).

The piston ring manufacturers were consulted on the basic ring design; they had little to offer but recommended a spherical nosing. They were also of the opinion that the original sealing ring material, used in an annealed condition, would be satisfactory.

All dimensions were recalculated on the basis of a 200°C differential, and the test valve re-machined. Sealing rings and piston ring were redrawn and rings of both materials made by the piston ring supplier; the valve was re-assembled and back on test in mid-July. It was fitted with a low beryllium copper bore piston ring and annealed DTD.719 sealing rings.

Further tests showed that at ambient temperature, opening torques were down to 120 lb-ins. but these torques increased to 220 lbf.ins. at 350°C. Examination showed that pick up was still taking place with the DTS.719 roller bearing sealing

rings, but although there was evidence of rubbing of the main ring no scoring had taken place. The sealing rings were changed for beryllium copper rings and again at 350°C operating torques had reduced to below 160 lbf.in, despite the poor condition of the sealing ring bores. The development department considered the results satisfactory, and the recommended design changes were passed to the drawing office at the end of July, two weeks having elapsed.

Drawings incorporating all the recommended changes were issued by the middle of September. Development testing on reaction control nozzles, proceeding concurrently, had highlighted problems with the grease lubrication of bearings at high temperature and proved the effectiveness of dry lubrication treatment; by this time the lubrication nipples had been removed and a specification for dry molybdenum disulphide treatment drawn up.

The required torques to hold the valve at any opening were now measured on the test valve, at various upstream pressures and with the maximum mass flow. This was necessary to ensure that the maximum allowed torque at the drive gear box was not exceeded. The valve was mounted in a duct system fitted with a down stream restriction that produced the required non-dimensional mass flow.

These torques are shown on F. Fig.9. Factoring the torques by the gearing of F Fig. 4 produced the gearbox torques, as shown on F. Fig. 10, for the most adverse pressure conditions. These torques were well within the permitted maximum.

The first aircraft unit arrived for test at the end of November, nine months and one week after development had started. A very proper gestation period!

Within the next month three units in all were put on test. It was found that another increase in clearance was necessary on the shaft sealing groove, and following this modification hot operating torques were down to between 25 and 50 lbf.in. The design was considered finalised by the end of 1963.

FINAL DESIGN

During the next fifteen months a total of 14 valves underwent a simple acceptance test before fitting to the aircraft. Some were rejected due to high operating loads and in all cases this was found to be due to manufacture outside allowed tolerances. Drawings were raised in issue to clarify doubtful points, and special gauges produced to check alignment. At maximum pressure and temperature leak rates

varied between 2 lb/min. and 9 lb/min. (27 c.f.m. to 120 c.f.m.) and opening loads varied between 10 and 60 lb.ins.

Clearance Testing

The design could not be considered cleared until further testing had shown the unit had a satisfactory life. To this end, the following tests were undertaken:

(1) Ultimate pressure test.

(2) Fatigue testing in the open and closed con dition. This was done using hydraulic pressure impulsing to a factor of 10 on the required life.

(3) Examination of aircraft butterfly valves used on the engine test beds. Here they were working in the correct environment. By November 1964 one valve had run for 690 hours on test bed engines, with 1000 valve operations.

(4) Endurance testing of the valve in a complete, rig-mounted, reaction control system, to 500 flying hours. The system was working at correct pressures, temperatures and flows.

Tests 1, 2 and 3 above were satisfactory.

The endurance test showed two things:

(a) The beryllium copper piston ring oxidised badly.

(b) Fretting corrosion was taking place between the non rotating - and unlubricated - parts of the valve.
Examination of aircraft units showed that these defects were exaggerated on the endurance test valve, and no design action was taken on the Version D valves. All clearance tests were complete by May 1965.

VERSION E DESIGN

In February 1965, work started on a development of the version D aircraft with an uprated engine, to enter R.A.F. service early in 1969. Six development aircraft were to be built, followed by the production version at the end of 1967, this aircraft is referred to as version E.

The first four development aircraft were to have butterfly valves to the version D standard. The fifth and sixth development aircraft would have the production

version of the butterfly valve. Thus the production version was required by the Spring of 1967.

No defects had been reported back from version D flying, and it was known that the valve was capable of meeting the slight increase in operating conditions. Therefore, no major design change was proposed. The design for production did, however, include the following features:

(1) Body and valve disc to be made from castings.

(2) Piston ring material changed from $\frac{1}{2}$% to $2\frac{1}{2}$% beryllium copper to reduce oxidation.

(3) Mating parts to be vacuum blasted, to 25 to 30 micro inches, and given an anti fretting treatment of molybdenum disulphide.

(4) The two pin fixing of the valve disc to the shaft to be replaced by a single pin fixing. This was the result of the change in disc design and a new concept of stress analysis of the assembly.

The first drawings for the production version were issued in February 1966. Then followed the process of obtaining satisfactory castings from the casting manufacture, this entailed the sectioning and detailed inspection of sample castings until the Inspection Department were satisfied.

The first production type unit was manufactured and handed over for test in March 1967.

The reaction control system used for version D design clearance testing was modified to the development aircraft standard, and run at the new conditions for the equivalent of 250 flying hours. Included in this system was a version D type butterfly valve with the new material piston rings and the anti fret treatment mentioned above. These tests commenced in September 1966, finished in December 1966, and proved the efficacy of the modification.

Production acceptance testing of the new valves showed no major problems, the only design change found necessary was to increase the clearance between the shaft and the valve body to eliminate occasional touching, this was instructed in May 1968.

Fatigue tests were done on the unit, once again to a factor of 10, and showed a satisfactory fatigue life equivalent to 13,000 hours of flying.

The casting unit was incorporated in the production reaction control test rig, in March 1968, and the system run at representative pressures, flows and temperatures. By the end of 1968 the system had run for 1000 flying hours and the valve showed no defects.

A rig was built to enable the operating characteristics of the valve to be measured. The change to a casting had altered the profile of the disc, and it was necessary to check the aerodynamic torques produced. This time, torques were measured whilst opening the valve, against varying back pressures, at a velocity of 260° per second.

These tests were done in April and May 1968, and showed that at the maximum pressures and flows expected during take off and landing the maximum allowable gear box torque was still not being exceeded.

Thus, by the time version E was delivered to the R.A.F. in the Spring of 1969, the bleed shut-off valve design had been proved satisfactory.

CONCLUSION

In this design case history the technical content, the novel aspect of the work and, perhaps most of all, the high possibility and serious consequences of an error, appear to justify the emphasis on design by development.

The designer who compiled this case history is in fact a member of the Development Section in the firm and it is significant that he should have such a comprehensive knowledge of the complete design exercise. A considerable part of the firm's specialised knowledge appeared to be acquired and disseminated by the Development Section who tended to act as consultants to the design office during all stages of the project.

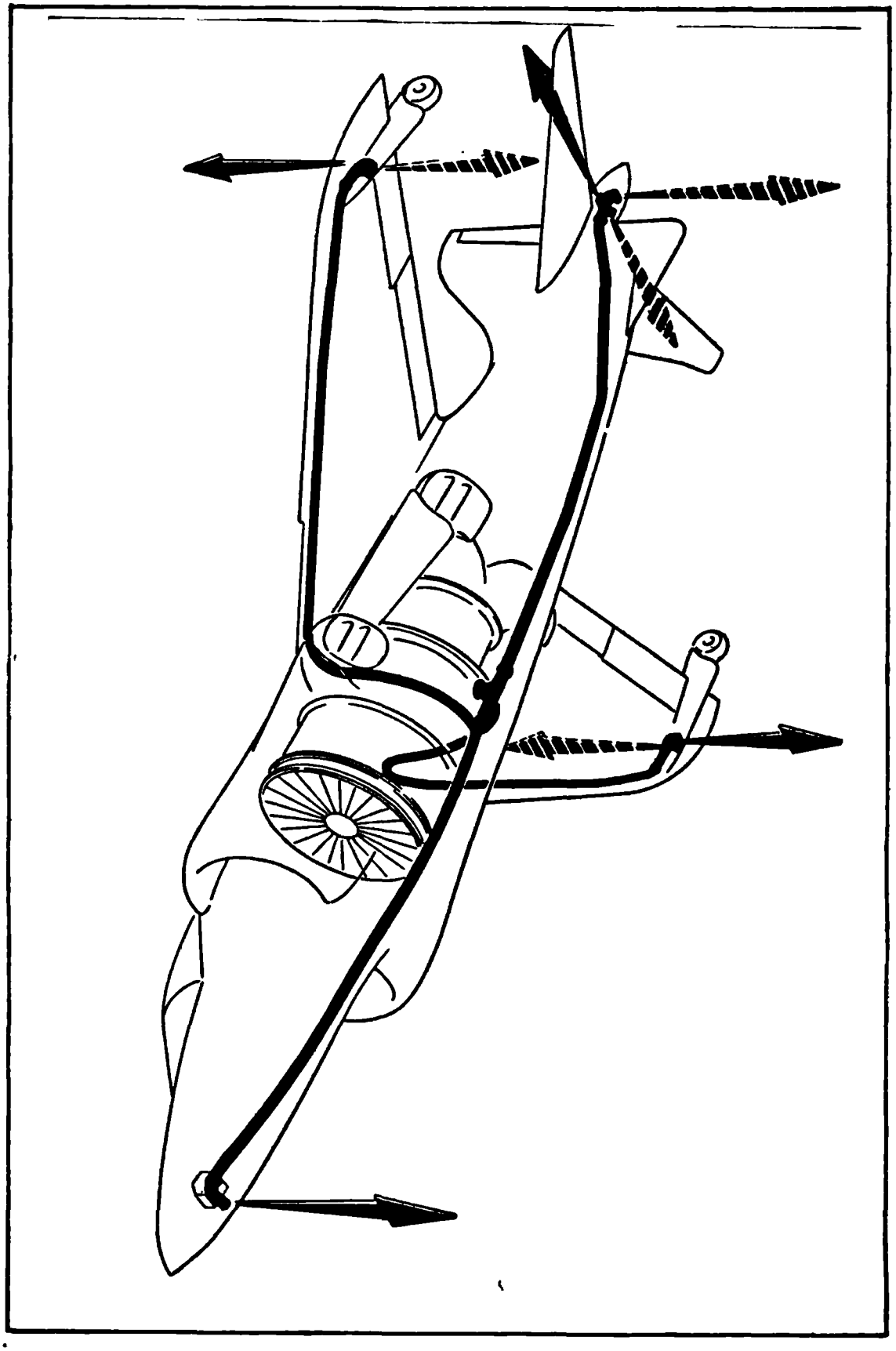
The constraints applied to the design in this case were predominantly technical and related to the need for satisfactory functioning of the valve. It was not until the redesign stage when the political and economic factors had changed, that the design team became much more time and cost conscious - and even then these factors still remained subservient to function and reliability.

The organisation of the design effort appeared less formal than the comparable case history recorded in the motor-vehicle industry. Although both exercises were

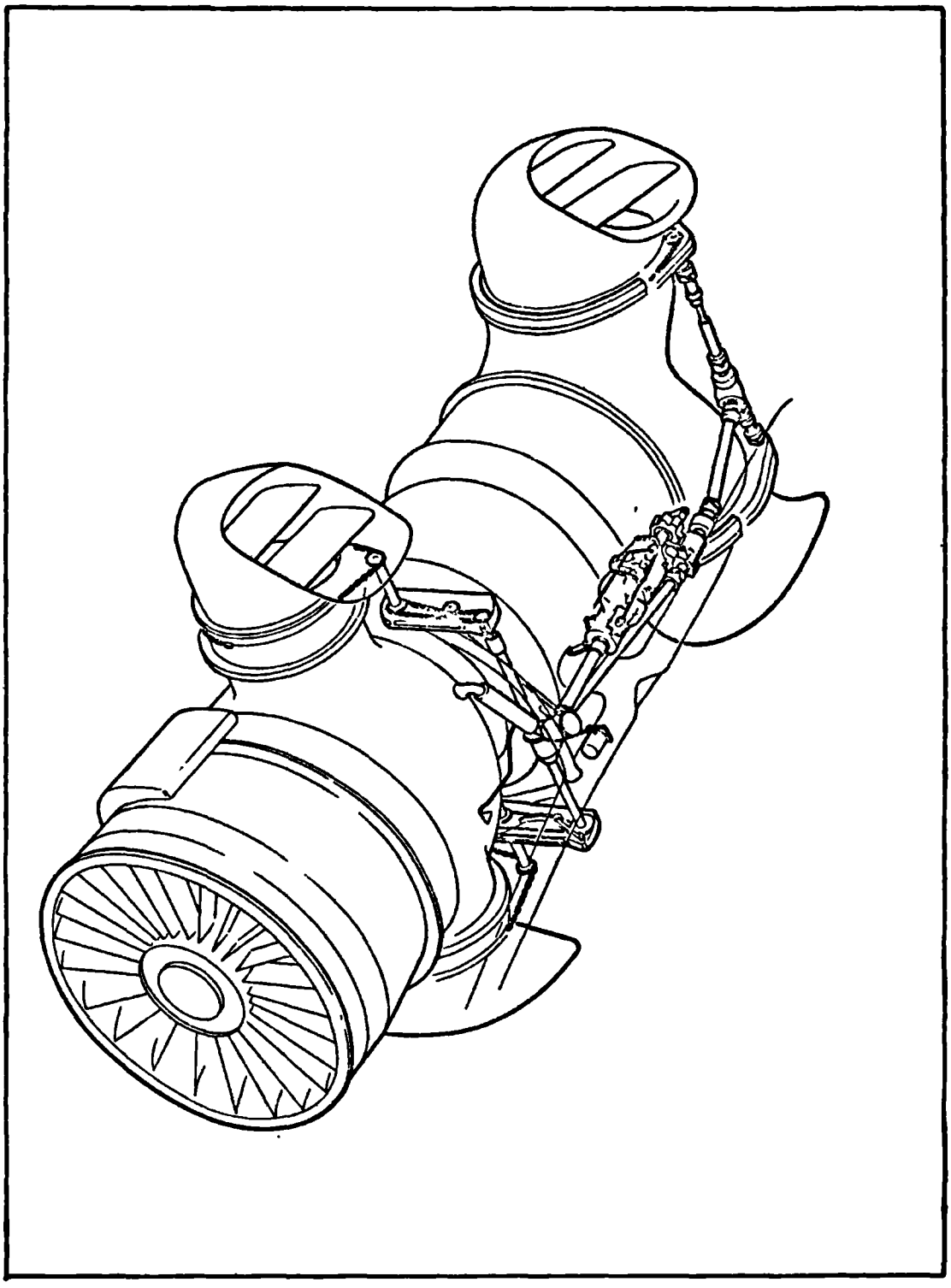
concerned with producing a correct solution before mass-production commenced the unpredictable political and economic situation, which had considerable effect on management decisions in the Aircraft industry made it difficult to set and achieve realistic overall project targets.

The design was very restrained with respect to space, size and weight; these factors affected not only the initial design but also the redesign "Any design modifications tend to 'snowball' due to the limited space available".

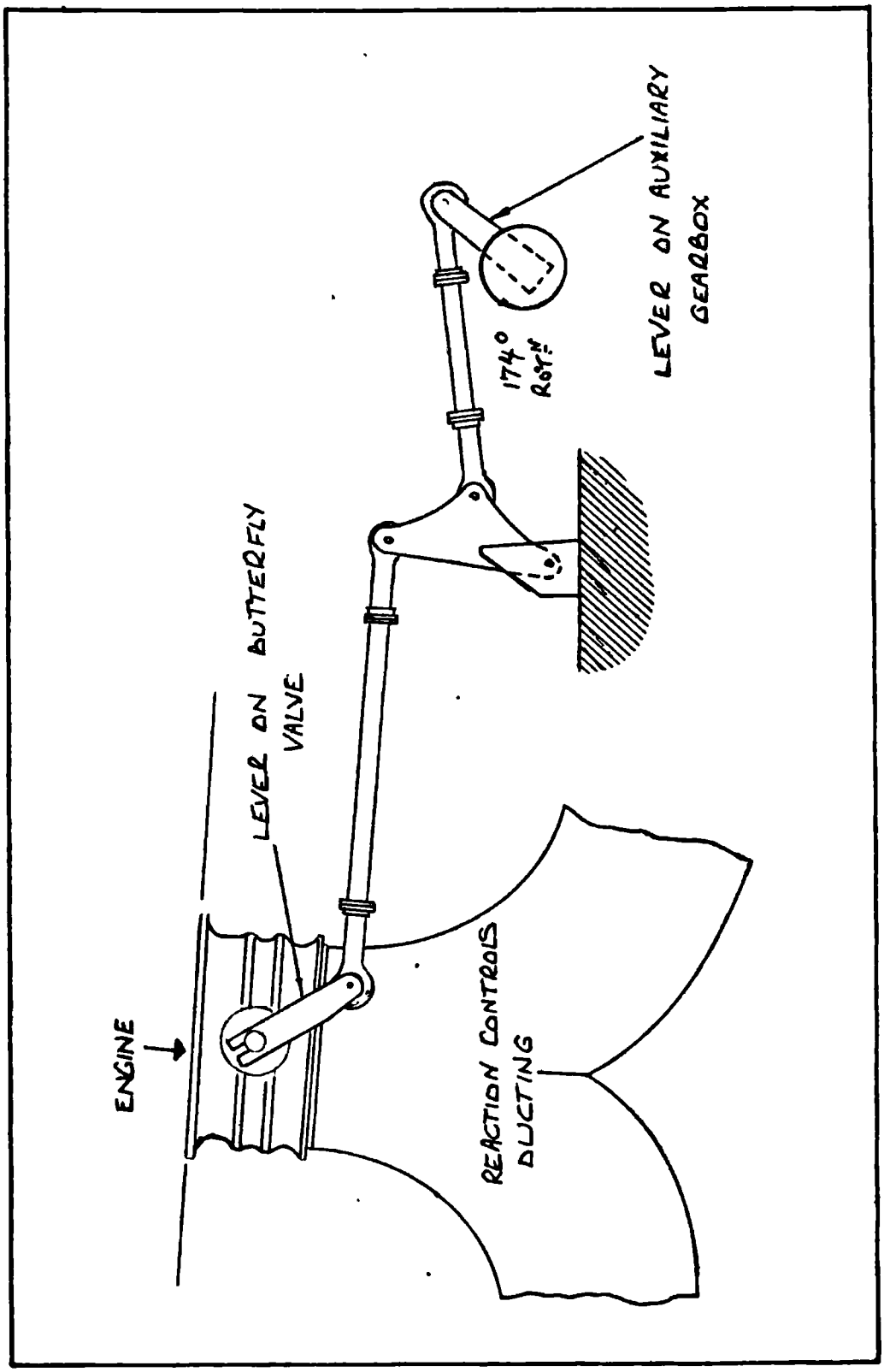
The success of the emphasis on the first two stages of the design exercise, in order to produce a satisfactory design for the production version, was illustrated by the very minor changes required for version E, and the relatively short trouble free per'od in which it was produced.



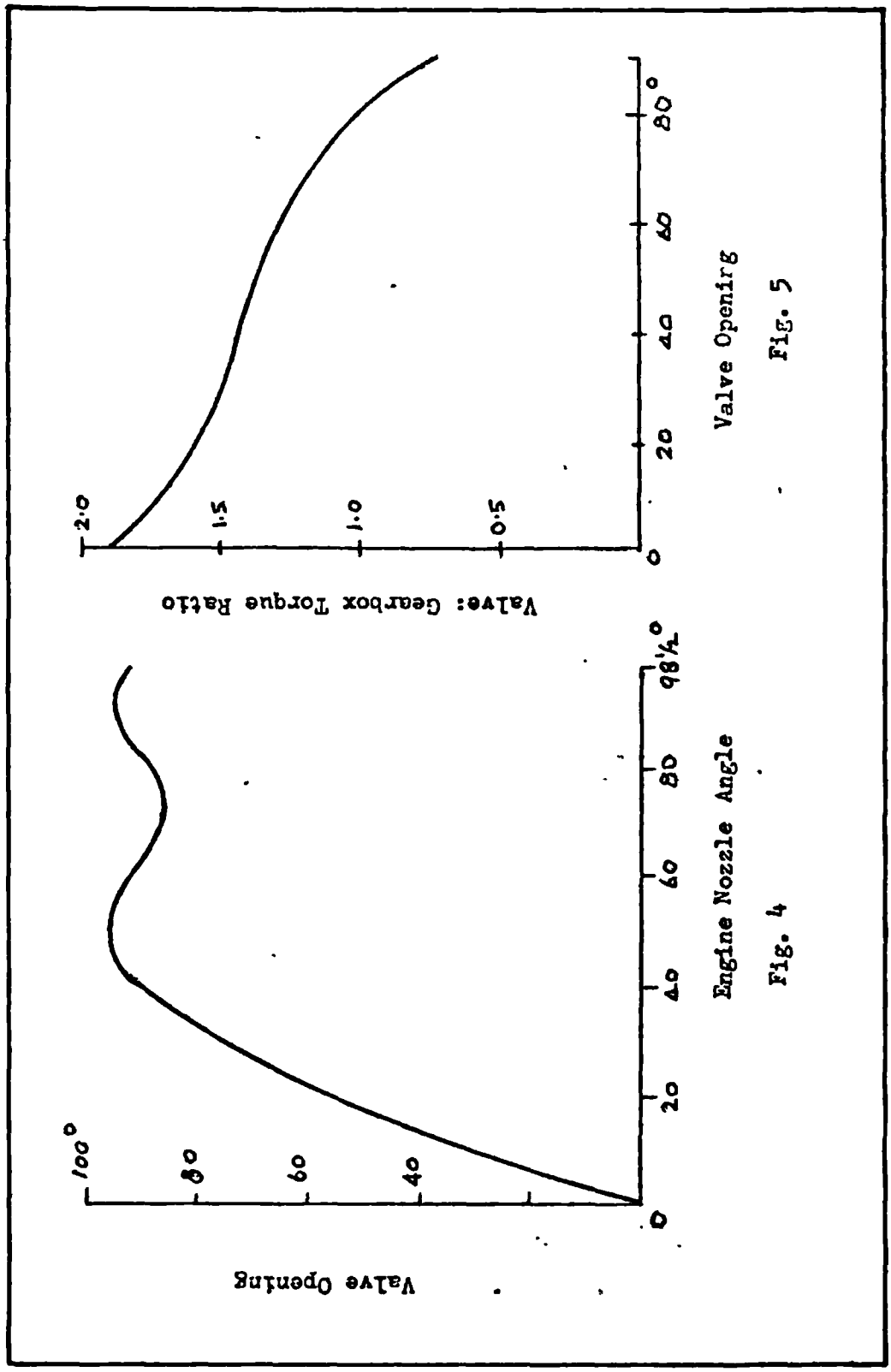
F FIG 1 REACTION CONTROL SYSTEM



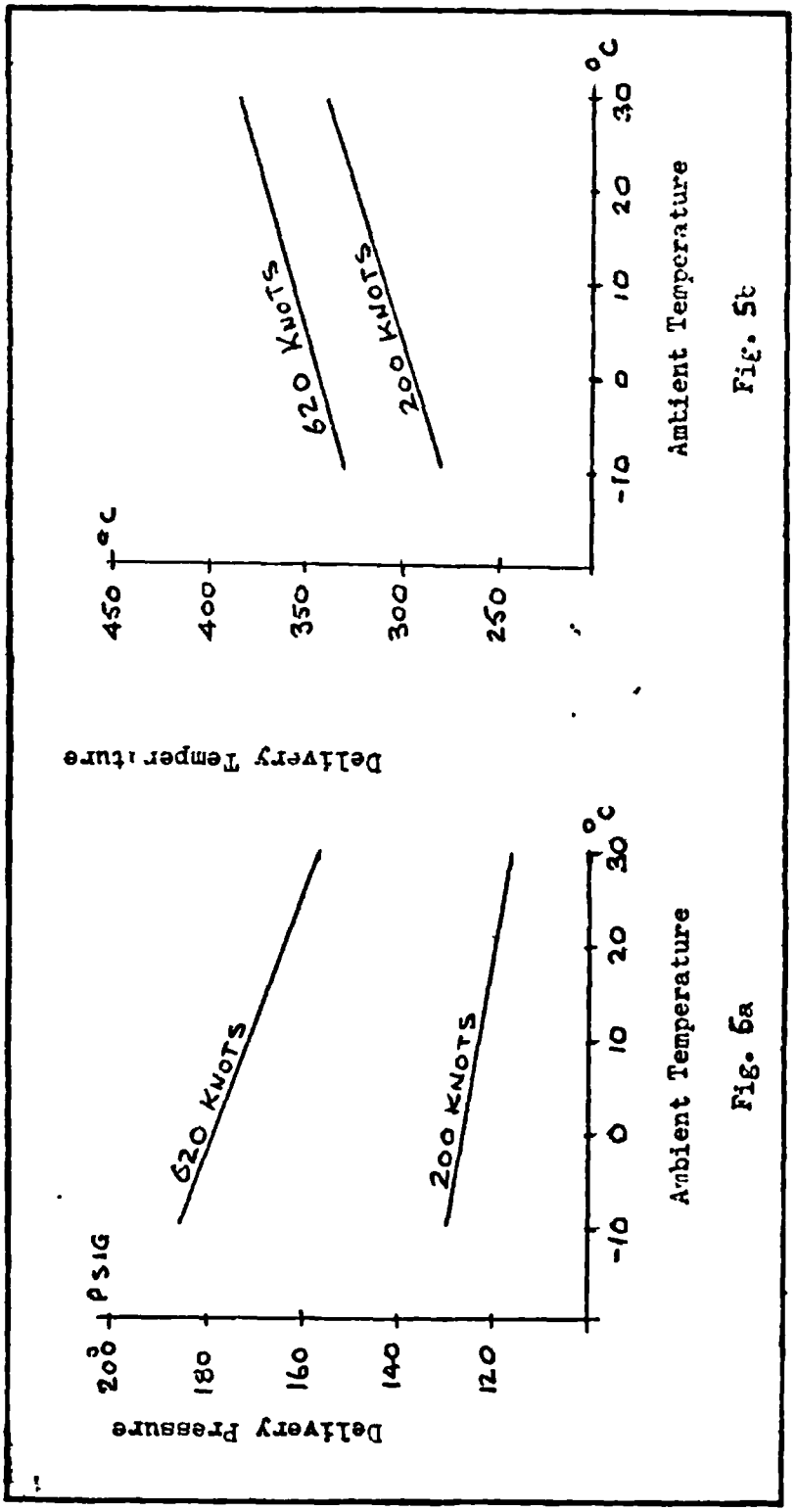
FFIG 2 NOZZLE ACTUATING SYSTEM



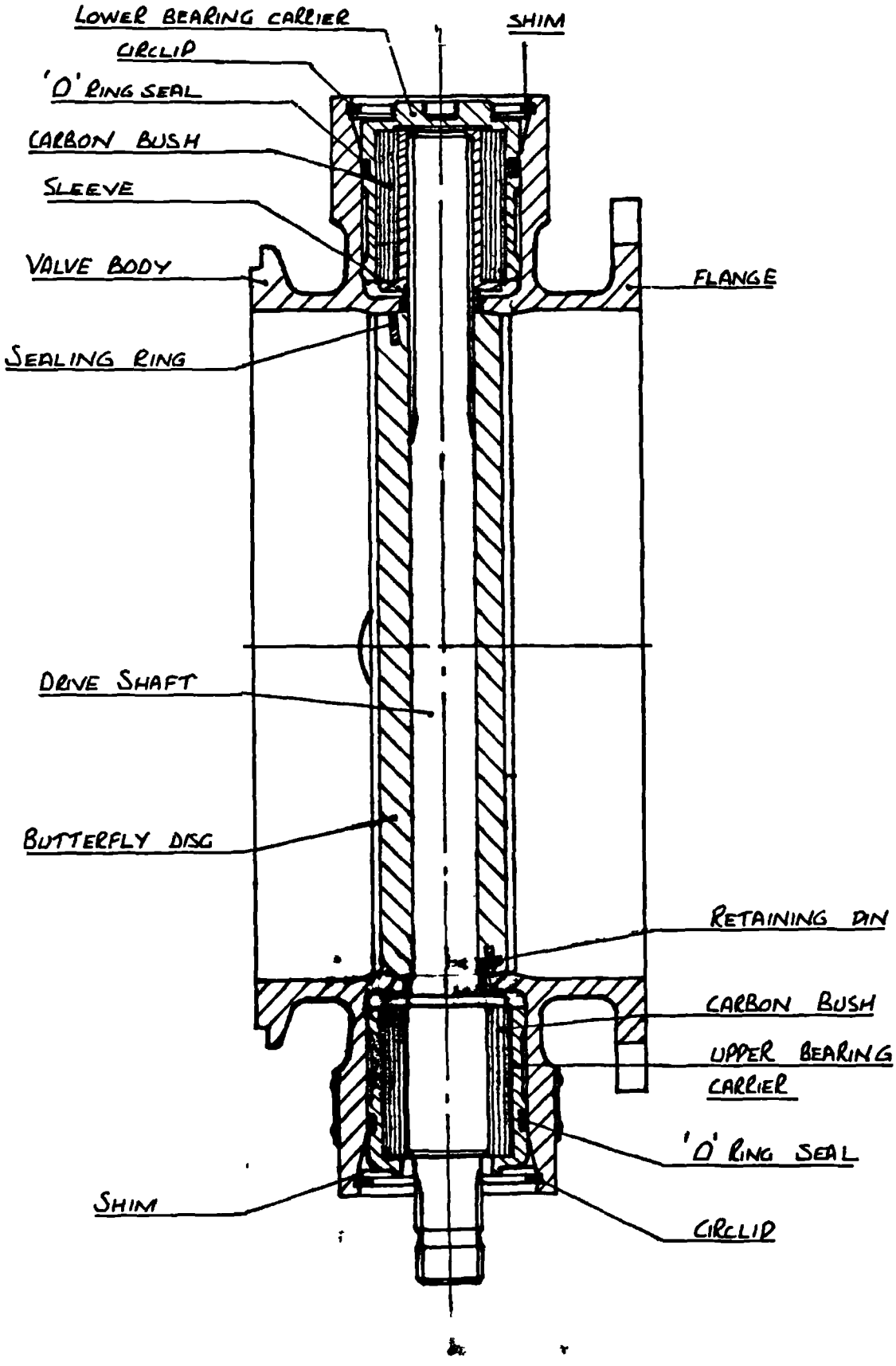
FFIG 3 VALVE OPERATING LINKAGE



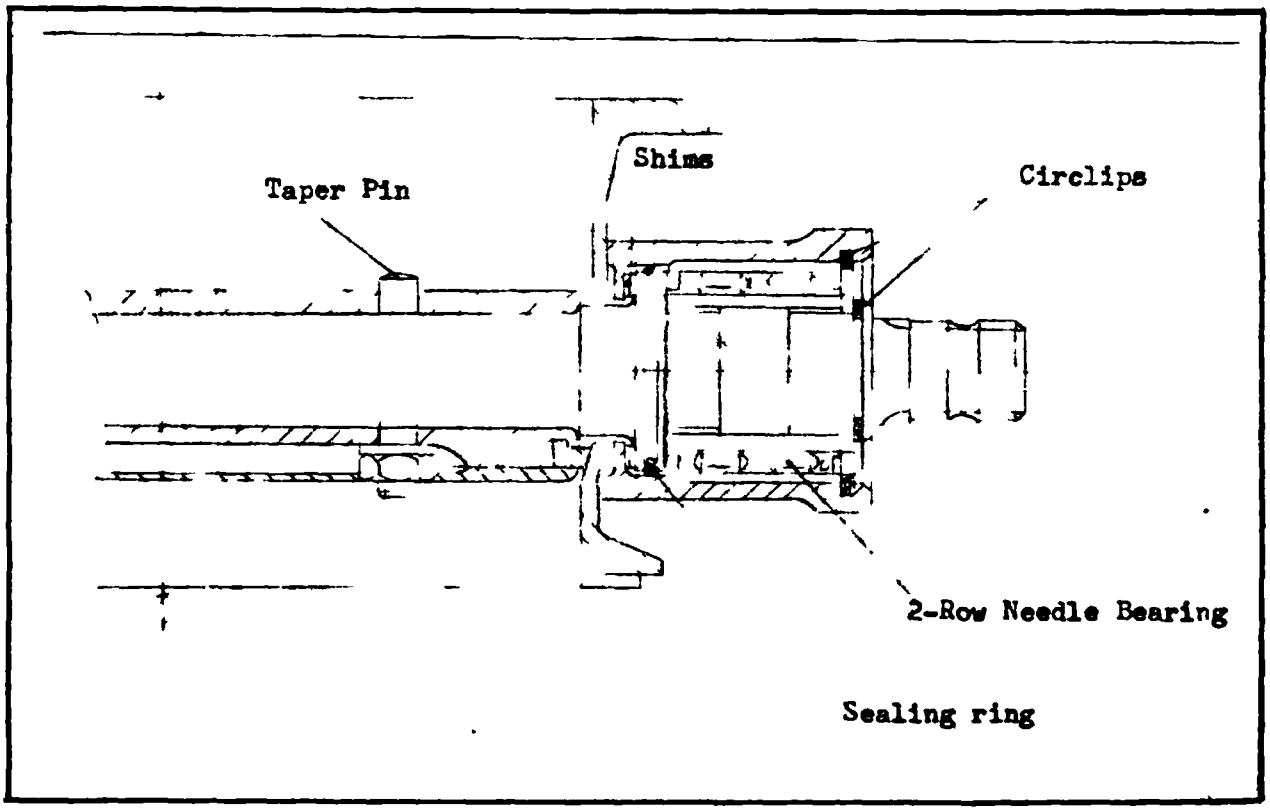
FFIG 4 BUTTERFLY VALVE CHARACTERISTICS



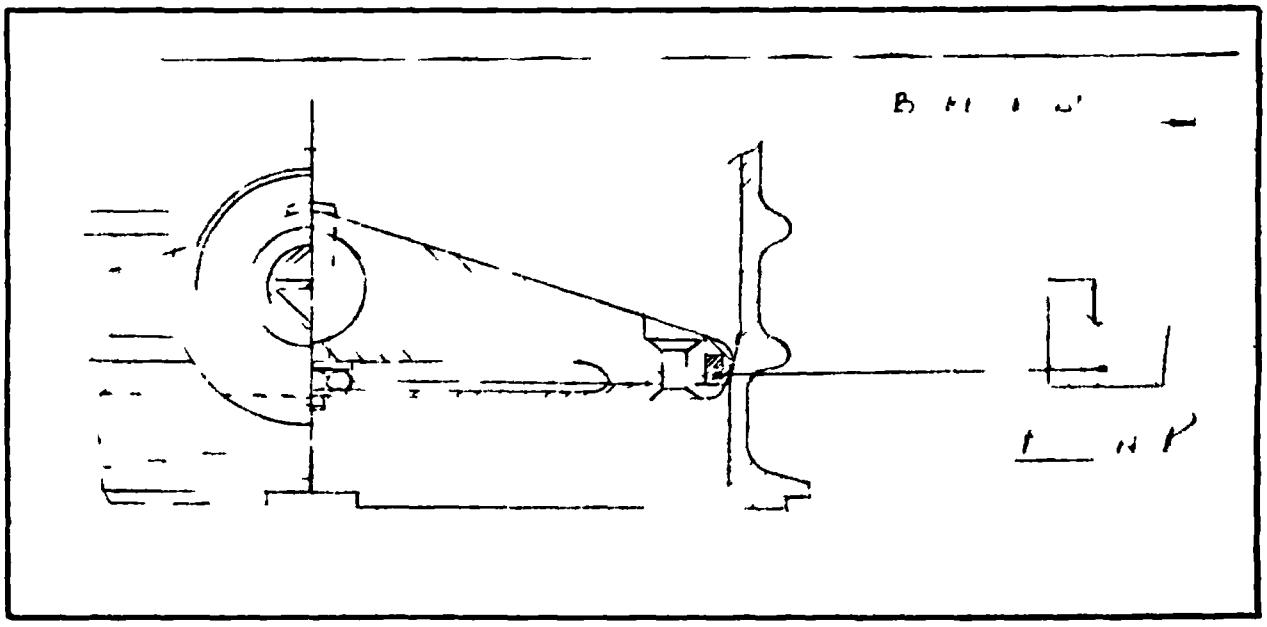
FFIG 5 ENGINE DELIVERY TEMPERATURE & PRESSURE



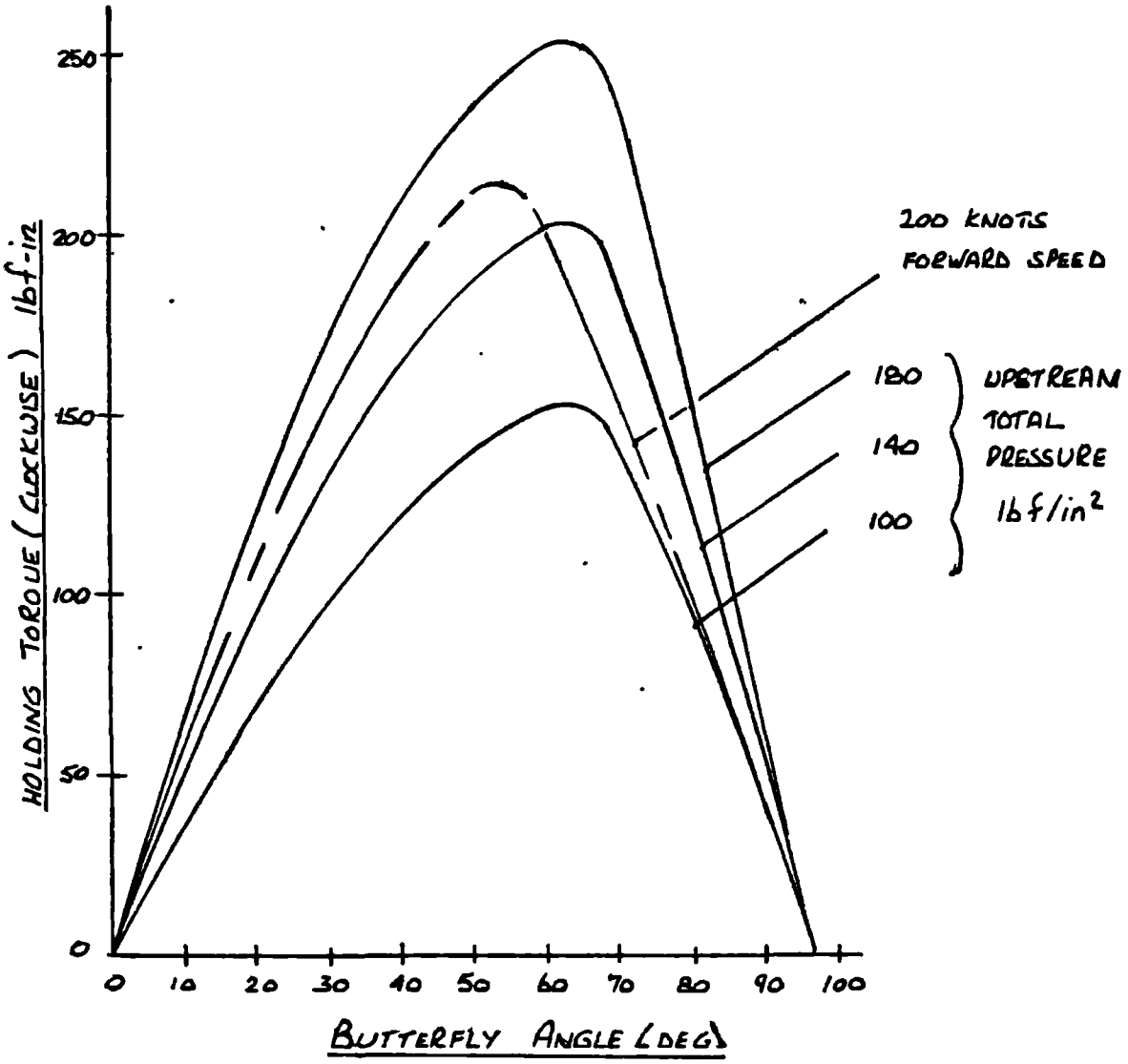
FFIG 6 PROTOTYPE BUTTERFLY VALVE



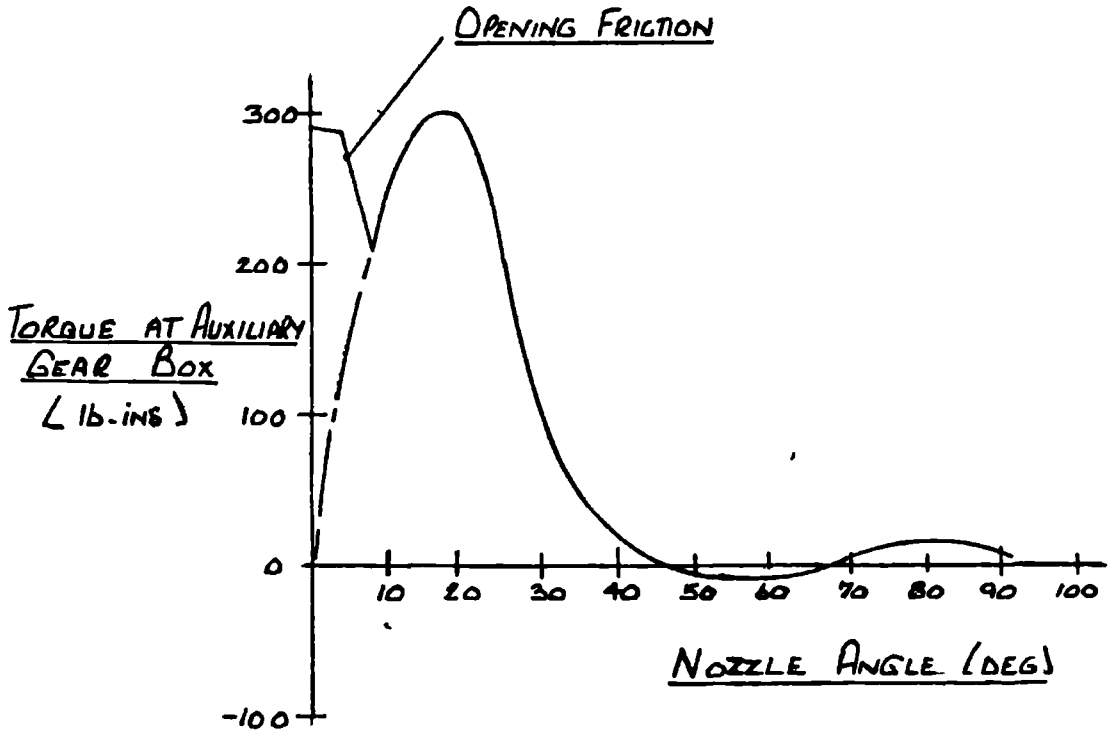
FFIG 7 SHAFT BEARING DETAILS



FFIG 8 VALVE DISC AND BODY DETAILS



FFIG 9. REQUIRED TORQUE AT VALVE



FFIG 10 REQUIRED TOROUE AT GEARBOX

CASE HISTORY G

WIRE STRIPPING AND CUTTING ATTACHMENT

INTRODUCTION

As part of its training system the Engineering Training School of firm G presents design problems to its student engineers; these problems are often presented by the production department of the adjacent factories which manufacture the firm's products.

One of these problems involved the design of an attachment to facilitate and speed a process involving the assembly of the computer back plates into which printed circuit boards are plugged.

A stage in this assembly involves connecting with insulated wire several thousand pins which project from the back of the steel plates. On the assembly line this work is carried out by female labour who connect the pins according to a wiring diagram, using conventional hand strippers, cutters and wrapping gun.

To ensure an electrically sound reliable connection a $1\frac{1}{2}$ in. length at the end of the wire is stripped of insulation and inserted into a hole in the nose of the gun; a second hole in the nose is then placed over the pin and the gun is operated. The barrel of the gun then rotates tightly twisting the wire 6 - 8 times around the pin.

As the wires are not all of the same length it is not possible to pre-cut and strip the wire, and each length is therefore cut and stripped to suit between each wrapping operation. To facilitate this the operators are each provided with a work bench on which the gun and stripping tools are conveniently placed; the cutter is a special tool with length gauges attached so that $1\frac{1}{2}$" of wire is stripped every time.

However the repeated lifting and replacing of the different tools required for stripping cutting and wrapping caused some fatigue, and controlled the output. There was, incidentally, no financial incentive on the operators to improve the rate of production.

This case history concerns the design and development of an attachment for stripping and cutting the wire which could be conveniently operated and would be

attached to the wrapping gun.

THE PROBLEM

The problem was presented to the designer concerned by his supervisor in the form of outline notes prepared by the production shop supervisor. The designer was also presented with details of an earlier incomplete attempt which had been made to solve the problem but which had not proved very successful.

The brief had been prepared by the training section in consultation with the relevant production department and the designer was encouraged to contact the production department direct and to study the problem first hand.

A provisional assessment of the problem also established the following parameters which affected design decisions but were not listed on the original brief, no attempt was made formally to record these additional parameters.

(a) The method of stripping should give a clean cut on the insulation in order to produce tidy reliable connections.

(b) There must be no damage to the wire.

(c) The attachment to the gun should be as light as possible.

(d) The prototype design should be capable of manufacture within the organisation.

(e) The attachment to the gun should not foul adjacent pins when one pin is being wrapped.

(f) The attachment should be mounted so that it did not obstruct the operator's view of the pin being wrapped.

INITIAL DESIGN

G Fig. 1 shows a sketch of the designer's first proposal. It consists of a simple stripper mounted on the side of the gun barrel with a cutter operated by the trigger finger.

The wire is fed from a coil suspended above the operator and its end is lightly gripped between the cutter blades using a finger of the hand holding the gun to operate the lever. The other hand is then used to grip the wire and pull it down into

the slot in the stripper blade until the insulation is cut. The operating lever movement is then completed to cut the wire and an additional pull then strips off the insulation. The stripped wire is then placed in the nose of the gun for wrapping as before.

The spring loaded barrel on which the stripper is mounted enables the stripper to retract as the gun is placed over the pin to be wrapped.

The stripping operation is simplified when a second wrap on a length of wire is being made since the stripping tension is then applied by pulling the gun against the wrapped pin rather than by using the other hand.

The following initial tests were undertaken by the designer to prove the basic features of his design:

1) The 'V' notch stripper blade was tried in the workshop using a piece of spring steel cut with a hacksaw blade. These tests showed that the stripping proposal was feasible. It satisfied the requirements of a clean cut of the insulation and no damage to the wire, moreover it was simple to make, involved no moving parts and was easy to operate.

2) The cutter design was in fact developed by trial and error tests. The geometry of the finger operated lever was arranged as a compromise between convenience of operation and the magnitude of the forces involved. An alternative method of cutting, using two blades hinged at a point, rather than one fixed blade and one rotating on the barrel, was also tried but proved too cumbersome and complex.

A test of 1000 cuts using the stipulated wire showed that sloppiness developed between the blades, this led to some design improvements which were incorporated in the next stage of the design process.

DEVELOPMENT OF THE DESIGN

a) The first Prototype

In the light of the tests which had been carried out - and using some components from the earlier design - a prototype was produced. This was done either from rough sketches by verbal instruction or by the designer himself.

The cutter-lever component was redesigned to include the features suggested by the tests. The fixed cutter blade was spring mounted using a spring circlip and the moving blade, incorporating the operating lever, was redesigned to simplify manufacture

and facilitate operation.

Aluminium was used wherever possible in order to reduce the weight of the attachment but for the main shaft - which acts as the bearing for the rotating cutter - Nylatron G.S. was used.

The prototype attachment was then tested on the production line.

b) The second Prototype

The trials of the prototype involved several of the operators each of whom was asked to use the new design for a suitable period. The designer himself controlled these tests and noted their results.

These tests showed that the stripping and cutting attachment produced a considerable saving in time on the operation. They also, however, led to the following design modifications:

1) The operating lever was redesigned so that it was more easily operated by the smaller hands of the female operators, and the mechanical advantage was improved.

2) The cutter blade contact pressure was reduced in order to decrease the finger pressure required to cut the wire.

3) It was discovered that the operators always gave an initial twist to the wire by twisting the gun when it was first placed over the pin. With the attachment fitted to the gun this movement often led to an adjacent pin being damaged by the stripper. This serious disadvantage was overcome by reducing the stiffness on the spring and fitting a round nosed screw into the end of the stripper rod. Further tests showed that this was satisfactory and that if the stripper contacted another pin the stripper was deflected and the pin remained undamaged.

4) The spring which rotated the cutter to its original position was redesigned to give a suitable load and the slot in the barrel which limited its movement was replaced by a large diameter hole. This reduced the friction and the override movement thus preventing the operator's finger from slipping off the lever onto the gun trigger. It also simplified manufacture and reduced cost.

5) The stripper blade was bent back at about 30° to the vertical to give a pull parallel to the barrel, to force the wire into the 'V' notch and to facilitate the stripping operation.

As a result of these tests the first prototype was modified and a further series of trials was planned by the designer to be carried out by the operators.

FINAL DESIGN

The final design incorporating all the features established in the trials is shown in G Fig. 2 and Plates G1, 2 and 3. An initial production of 12 attachments was made and tested in production, followed by a batch of 100.

As the gun is for internal use no attempt was made to improve the appearance of the attachment and the detail design is based on a production of 100 within the works. This is indicated in the method of making the stripper blade, the springs and the barrel, all of which can be produced easily using existing facilities within the organisation.

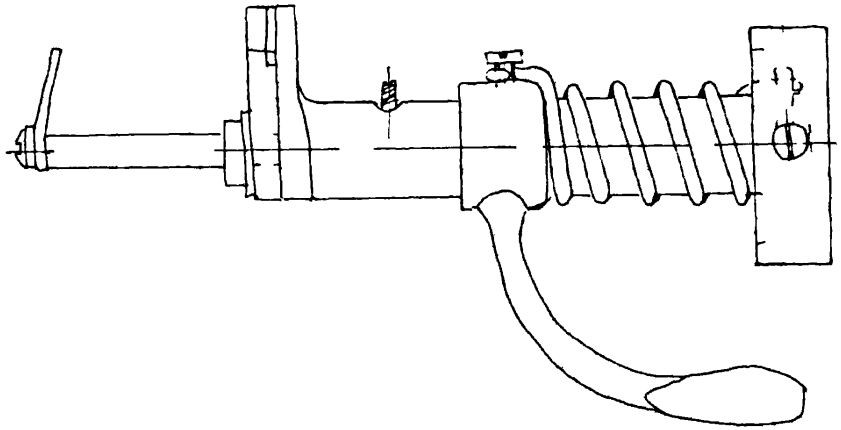
A patent to cover this design has also been applied for.

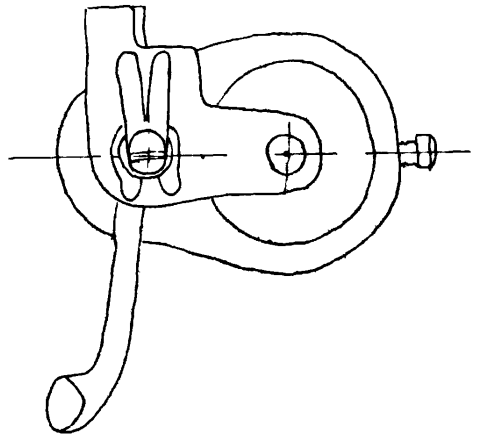
CONCLUSIONS

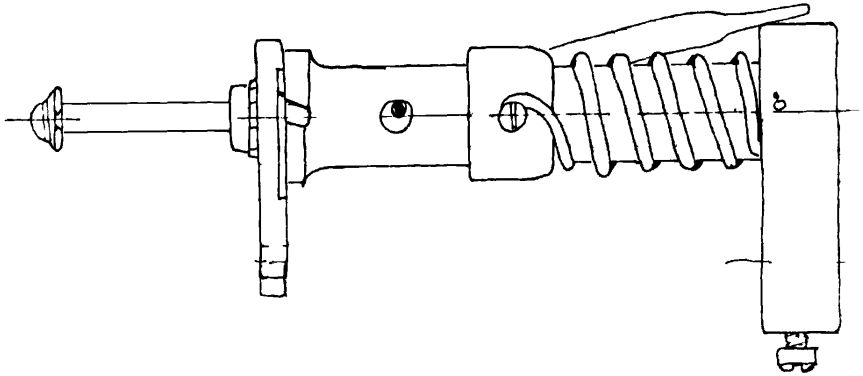
This design exercise illustrates the importance of tests and trials in revealing unpredictable aspects of the design. The initial small scale tests to investigate the configuration of the blades, and the field trials which uncovered several serious disadvantages of the initial design, were critical to the success of the exercise.

The proximity of the production line and design offices greatly facilitated the planning and undertaking of the operator trials and ensured direct and complete communication between the designer and the operators.

The complete exercise occupied the designer concerned for 4 months during the latter half of 1968.







C FIG FIRST DESIGN PROPOSAL



G PLATE 1 THE FINAL DESIGN

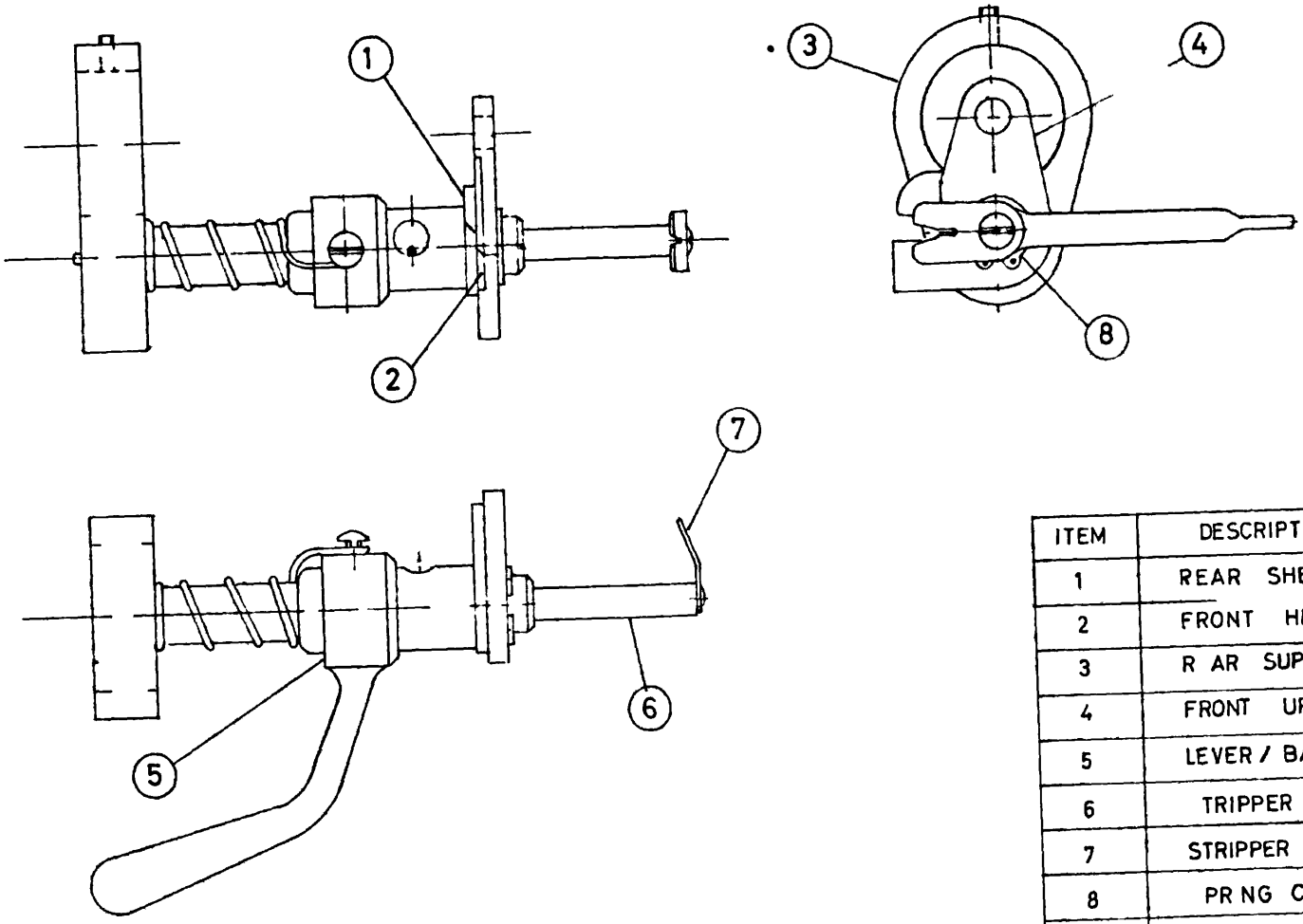
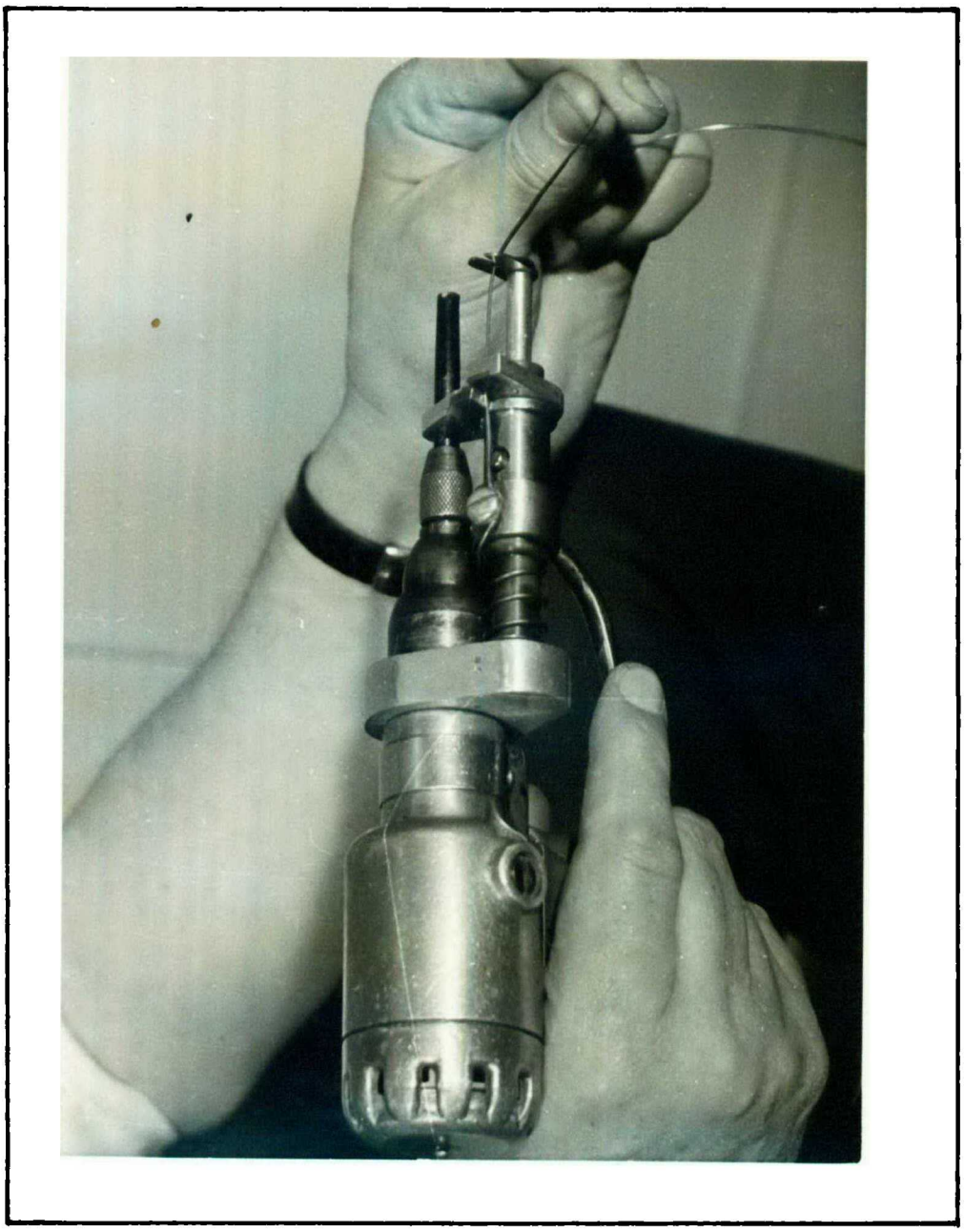


FIG 2 FINAL DESIGN PROPOSAL FULL ALE

ITEM	DESCRIPTION
1	REAR SHEAR
2	FRONT HEAR
3	R AR SUPPORT
4	FRONT UPPORT
5	LEVER / BARREL
6	TRIPPER ROD
7	STRIPPER BLADE
8	PR NG CIRCLIP



G PLATE 2. THE DESIGN IN OPERATION - 1



G PLATE 3 THE FINAL DESIGN IN OPERATION -2

CASE HISTORY H

MACHINE FOR ATTACHING PLASTIC SEALS TO GLASS BOTTLES ON A PRODUCTION LINE

INTRODUCTION

This case study concerns the design of a special machine for attaching plastics seals to bottles of export gin on a main bottling production line in firm H.

The special export bottle design, which had been produced to exploit the English image, had been very successful and it had proved necessary to consider a greater degree of automation on the bottling lines in order to satisfy the increased demand.

In the existing production line the plastics seals were fixed by hand and the designer's brief was to design a machine to replace the four female operators involved, and to attach the plastics seals at the full production rate of 60 per minute.

The author worked during this case study with all the members of the design team involved and in particular with the designer directly responsible. This designer was at the time completing the final industrial phase of his engineering Diploma course and undertook the initial part of this design exercise as his final year project supervised by the author.

The project was started in April 1968 and this case study was collated over a two year period. Although the design exercise was partly an extension of previous work, the technique developed to deal with the plastics seals was novel and the exercise finally became one of innovation rather than extrapolation.

THE BRIEF

The original brief, given verbally by the Chief Engineer in October 1967 was: "To design a machine that will automatically fix the plastics seals to bottles : fast enough to keep the production lines in full use - approximately 60 per minute".

In addition the designer was told of two ideas which had been put forward as possible part solutions but not developed. These are discussed in detail later.

ESTABLISHING THE PROBLEM

As he was new to firm H, the designer spent some time absorbing the background of the problem by studying the production lines, talking to the operatives, and discussing the previous attempts at solutions. In this way the following rigorous limitations, and the decisions made because of them, were recognised. The rigorous limitations represent those constraints which could not be altered.

(i) Bottles - a range of capacities using the large size seal.

(ii) Seals - the investigation was initially to be confined to the large size seal, which was to remain in its present form and could only be changed as a last resort.

(iii) Mode of attachment - to retain the use of hot melt adhesive of existing specification which had proved to be best suited for this application.

(iv) Application of glue - To employ the xyz system which was the most successful and consistent method to date, of applying the above mentioned adhesive.

(v) Seal handling - To continue with, but if necessary redesign, the vertical stacking magazine system.

(vi) Bottle handling - To employ a standard conveyor chain, and to investigate an existing system, and bottle location, as mentioned in the original brief, H Figs. 1 and 2.

(vii) Glue 'Open-time' - Time between application of glue and application of seal was to be limited to 10 seconds.

(viii) Quality control - The seal to be affixed no less effectively than if put on by hand and no adhesive to be visible. Seal must be in correct position, correctly orientated.

In addition to the rigorous limitations controlling design decisions, the following factors were established which appeared to be less stringent and could be relaxed to some degree.

(i) Position of machine in production line - Need not necessarily be the first process but a very important design consideration, H. Fig. 3.

(ii) Method of dispensing seal - One method suggested in original brief to be further investigated but not a rigorous limitation.

(iii) Power and control - Electrical and compressed air supplies both available.

(iv) Degree of automation - Initially hand loading and unloading of bottles. Hand loading of filled seal magazines; remainder fully automatic.

(v) Operators - may be either male or female.

(vi) Cost - to be monitored and kept to a minimum.

(vii) Time - Prototype running by Christmas 1968, if possible.

(viii) Maintenance - Regular maintenance to be kept to a minimum. Major overhauls can take place to suit company policy.

A more detailed study of all these contraints made it clear that the machine should be sited at the start of the production line where the bottles would be hand loaded. It was also clear that an efficient and reliable mechanism for dispensing the seals was the major sub-problem involved.

FINAL PROBLEM STATEMENT

Establishing the understanding of the problem as outlined above had taken several weeks, and the following statement of the problem was agreed with the customer early in 1968.

(i) The main requirement is for an automatic machine which will affix large size seals, taken from a vertical magazine, to bottles being carried on a conveyor.

(ii) The bottles will be angled in supports so that the seal space is in a horizontal plane.

(iii) Adhesive will be applied before the bottles reach the seal dispenser.

(iv) The required output speed is 60 per minute.

(v) An intermittent motion conveyor of existing design is to be utilised.

(vi) The major problem to be solved is to find a method of handling the seals and dispensing them - one at a time onto the bottles.

(vii) The finished design is required to reduce significantly the number of operatives on this section of the production line, and existing standards of quality control are to be at least maintained.

(viii) Adhesive, to attach the seals to the bottles, is to be supplied by an existing design of hot melt glue ejector.

INITIAL DESIGN PROPOSALS

Having studied and stated the problem in detail it was commercially desirable to proceed with the design process and seek solutions to the stated problem. Although it was recognised that other factors would emerge which would alter, or add to, the established problem statement, it was considered that sufficient background information had now been acquired to allow viable proposals to be made. Moreover it was realised that further information and problems would best be discovered through initial design proposals.

The Seal handling problem

As stated in the previous section the major design problems which had emerged to date,were to achieve efficient techniques, or mechanisms, for handling the seals and for dispensing them onto bottles. It was therefore to these problems that the designer first turned his attention.

The two problems of handling and dispensing the seals were obviously dependant. As it was not realistic to leave the dispensing problem until the handling problem had been solved, the latter was tackled in the assumption that the seals would be available packed uniformly in a cylindrical magazine.

The existing magazine and the machine to fill them were felt to be unsuitable for adapting to meet the requirements of the present brief; the major reasons being that that seal orientating machine was not efficient nor reliable enough for the new conditions, and the magazines were very cumbersome and of insufficient capacity to be economic.

Clearly, a different approach was called for and, after consultations had taken place between the Chief Engineer at Firm H and the makers of the seals, it was suggested that an aluminium extrusion could possibly be used as a magazine tube. Furthermore the nature of the moulding process was such that the seals could easily be loaded into such a magazine.

A sub-contractor specialising in aluminium extrusions was then approached on ıe subject and confirmed that he could produce a suitable aluminium extrusion for a ıagazine. The seal makers then undertook to supply seals packed in such magazines as ›quired.

The problem of handling the seals was thus eliminated - rather than solved - nd in order that the design work could proceed a one-off copper magazine was manu- ıctured to the required profile, H. Fig. 4.

he Seal dispensing Mechanism

By eliminating the handling problem the major problem had become the lispensing mechanism and the following possible solutions to it were considered, H. Fig. 5.

(a) Air separation, forcing seals through retaining spring clips.

(b) Thin wedges forcing seals through retaining spring clips.

(c) Retaining members operated by contact with the bottle.

(d) Using the adhesive strength of the adhesive to pull a seal out through a spring retained member.

Method (a), H. Fig. 5a, would have required very powerful, carefully ›ositioned and directed air nozzles, if positive results were to have been achieved. This method would also require considerable experimentation in order to achieve any ıuccess.

Method (b) was intended to be a more positive version of method (a) with the ıir jets replaced by wedges which would force the seal through the retaining spring :lips. H Fig. 5b shows such a system. The wedges would be actuated by small air :ylinders or solenoids. It was felt that this method had possibilities, a definite advantage ›eing that it could be arranged to press the seal firmly into the glue.

Method (c), H Fig. 5c, shows a diagram of a system working on this principle. The obvious disadvantage of this method is the chance of bottle breakage and the effect hat variations in bottle size might have on its operation - the tolerances on bottle dimensions are quite wide.

Method (d), H. Fig. 5d. This method was suggested as a solution at the time ›f the original brief, and its full potential was to be investigated. It involved employing he adhesive strength of the glue to pull one seal from the magazine through spring ·etaining members.

The adhesive would be applied to the bottle prior to it reaching the seal applying station so that the adhesive was in its most tacky condition. The seal magazine would then be lowered so that the bottom seal contacted the glue, where it would pause. When the seal magazine was raised the seal would remain on the bottle.

It appeared to be quite simple and possess the potential for rapid repeated operation.

It was concluded from this assessment of possible solutions that, because of its simplicity, method (d) could most easily be tested, (using rough model techniques). If it proved successful it would be developed but if not then further investigation of methods (c) and (b) might take place. If any other possible solutions were forthcoming these too would be given full investigation.

INITIAL TESTS

Clearly, the only way to assess method (d) as a design solution was by the construction and evaluation of a rough model. It was felt that this would consume a minimum expenditure of time and money and would provide some assessment of the imponderables involved.

The construction of a very simple test rig was started in February 1968. A short length of the copper magazine tube already mentioned was obtained and fitted with a brass ring and three retaining arms.

At the current stage of the design it was not necessary to be concerned with the actual methodsby which the seal magazine would be raised and lowered or by how much. These would be decided later if the method showed promise. Therefore, after the magazine had been loaded with seals, it was clamped in a vertical position in a vice. A bead of glue, at the correct temperature, was applied to a bottle and it was allowed some seconds before being brought into contact with the seal at the base of the magazine. After some two seconds the bottle was withdrawn vertically downwards.

After some experimentation with the adjusting screws, the exact curvature of the retaining arms, together with combinations of springs and weights on top of the seal stack, and the time delays, the method was made to work repeatedly.

It was found from the experiments with this model that ten seconds might have to be allowed between applying the glue and affixing the seal; this could be catered for and would only affect the overall lengths of conveyor required. However, it was

also found that up to two seconds pause might be required while the seal is in contact with the bottle, before the magazine is withdrawn. This would have the effect of limiting the machine to a performance of 30 per minute, but was reckoned to be capable of improvement with further experiment.

The exact curvature of the retaining arms could be optimised quite easily by trial and error. The spring strength was found to be proportional to the weight of seals and no particular difficulties were envisaged if the stack of seals was to be lengthened for actual use.

It appeared that this method had possibilities, but would require a fair degree of refinement, development and testing, before it was fully acceptable.

As a result of these tests it was decided to produce a complete design based on the proposals outlined above and to undertake further development on a more elaborate test rig. In view of the imponderables involved, the need to make progress with the design and the experience acquired to date, this appeared to be the most effective and economic method by which to proceed.

DEVELOPMENT OF THE FIRST DESIGN

The building of the test rig enabled the intermittent motion conveyor to be tested and associated functions, such as the timing of operations and safety features, could also be devised and tested.

The drawing board work which followed in order to complete the testing was classified approximately under the following headings:

1) Design of main frame including conveyor and intermittent drive.
2) Design of gluing station.
3) Design of seal dispensing station.
4) Design of methods to link all the processes and functions producing an integrated system.

How these were achieved and the effects they had on each other are described briefly in the following sections, since an appreciation of the problems involved is necessary in order to understand the design of the seal attaching machine.

The design of the main frame was evolved from the earlier design of an intermittent motion conveyor which had been undertaken some years before the current project was started. The gluing station was also designed by adapting an existing unit. Both these designs were undertaken by a designer/draughtsman who was familiar with the earlier proposals.

The design of the seal dispensing station which is the prime subject of this case study, was the only one within the exercise as a whole about which there was very little real knowledge or experience. The test rig was intended to overcome the nescience of this seal applying problem and test the proposed solution.

The designer started to work on the seal applying station by thinking about the general layout, raising two main queries:

1) How is the magazine to be raised and lowered and by how much?

2) How to provide for magazines to be changed when empty?

The answer to the first question was straightforward. The use of a linkage from the main drive motor was discounted because it would have been unnecessarily complicated, and therefore an independent method of operation was required.

The use of pneumatic cylinders was favoured in preference to electrical methods because of their ready availability and ease of fitting and control. Their response to signals was also felt to be rapid enough for the job. The vertical travel of the magazine was not critical but was kept to a minimum so that the fastest speed for the overall operation could be achieved. Investigations showed that air cylinders could be ordered with any stroke, and also that it was a simple job to shorten the stroke of an existing cylinder.

The various layouts illustrated in H Fig. 6 were considered. Solution 6a was initially rejected because of the chance of the slider locking. However because the other solutions (6b, c and d) were all felt to be unnecessarily complex for a rig, solution 6a was eventually adopted.

The answer to question 2 required careful thought. The detail drawings and sample length of magazine tube had not been received from the makers at this time, but the capacity of each tube was expected to be approximately 600 seals. Therefore, the minimum time between changes of magazine (i.e. at 60/minute) would be 10 minutes.

This made it important to provide a simple method of changeover, an automatic change-over system being an essential future development if the machine proved successful.

It was obvious that some refinement of the rough model was required in order to provide this facility, and a few rough sketches were made in an attempt to achieve this. The major change which had to be made to the design was to devise some method whereby the magazines could be joined to the seal dispensing head, because the mechanism shown in H Fig. 9 could not be attached to the magazine every 10 minutes.

After several attempts the solution shown in H Fig. 7 was produced. An adapter was fitted to the full replacement magazine and a rectangular wedge inserted to prevent the seals from dropping out. The adapter and magazine were then fitted onto the real dispensing head in place of the empty assembly.

The completion of this concept enabled the layout drawings to be finished in mid 1968.

The final aspect of the initial design was the method of control and interaction of stations and the essential features to be incorporated in the control circuits were:

1) As the conveyor stops the seal magazine must be lowered and the glue ejector fired. These operations could occur simultaneously.

2) Immediately before the conveyor restarts the seal magazine must be raised.

The desirable features were that:

3) No adhesive should be fired if there is no bottle present.

4) The machine should stop automatically if the seal magazine is empty.

The circuit design closely followed current and industrial control system layout. Switches triggered by the main drive motor operated air cylinders controlling the glue ejector and the seal unit.

Requirements 3 and 4 were met by means of photocells which cut off the air supply if a bottle was missing or the seal magazine was empty.

When the circuits had been assembled and fitted to the test rig, they were tested. It soon became apparent that the conveyor was not indexing constantly because the inertia of the conveyor chain and bottle carriers was taking it past the stations.

In an effort to prevent this a second air cylinder was positioned to act on a second conveyor sprocket triggered from two additional swtiches operated by the constant speed motor. The first switch triggered the cylinder to eject its piston and engage with the second sprocket and the second switch released this locating system. This was intended to engage the conveyor positively and prevent cumulative errors due to the overriding described above.

A measure of success was achieved with this system and it eventually reached 60 indexes per minute.

It was now possible to test the remainder of the control arrangements all of which functioned satisfactorily once the switches had been correctly set to give suitable timing, and the restrictor valves on the air cylinders adjusted to give satisfactory operating speeds.

The full scale tests were then prepared for.

FULL SCALE RIG TESTS

As soon as the sample of the aluminium magazine tube had been received, the seal head and adpator were completed and fitted to the test rig. A fully loaded magazine was fitted and the machine was readied for full scale tests in September 1968.

The first tests were concerned with the gluing unit, and involved adjusting the thermostats until a correct adhesive temperature was achieved at the nozzle. Once this had been achieved and the bottle carriers adjusted the gluing unit was found to fire satisfactorily onto the centre of the seal space although the size of bead was possibly too small.

During preliminary runs of the conveyor and tests of the control system, it became obvious that due to the weight of seals in the magazine tube, a stronger spring was necessary to prevent seals falling through the arms. When this had been fitted the seals could not be pulled through the arms by the adhesive, when the magazine was nearly empty. A large mass (relative to the weight of seals) was placed in the top of the magazine to try and keep the spring force required fairly constant. This improved the operation slightly but the action was still not reliable.

By varying the conveyor speed (the drive motor was a variable speed "NICO" D.C. motor) it was possible to vary the time between applying the adhesive and operating the seal dispenser.

Satisfactory seal dispensing was not achieved at a speed greater than 25 per minute and was not consistent.

The conclusions drawn from these tests were therefore:

1) The seal dispenser was not satisfactory under full scale operating conditions. The reasons for this were:

   (a) The 'improved' design of seal head did not allow sufficient room for the arms to release seals, see H Fig. 8a.
   An attempt to overcome this by modifying the arms also failed to produce good results due to the predominant difficulty of ensuring correct adhesive conditions, see H. Fig. 8b.

   (b) The ideal conditions of the adhesive could not be achieved at the required speed, with the existing station spacing.

2) The magazine itself was satisfactory.

3) The method of reloading was effective and simple to operate.

4) The problems of indexing the conveyor had been lessened but speed was still limited.

5) All the controls worked satisfactorily.

6) The gluing unit required detail improvements (it was also a prototype unit) but when working reliably would be suitable.

FURTHER DEVELOPMENT

Following the full scale test rig tests an assessment of the design and progress to date was made.

The major problems outstanding were the seal dispensing mechanism, the details of the conveyor design and the satisfactory operation of the glue dispenser.

The design of a reliable seal dispensing mechanism was the main responsibility of the designer and the trials had established that this was the critical design problem.

The conveyor design was not considered to be sufficiently near to satisfactory not to be a critical problem.

Messrs. XYZ accepted responsibility for developing their glue dispenser to give reliable and improved results.

The failure of the initial design proposal for the seal dispensing mechanism was directly attributed to the lack of positive operation and the existence of too many variables. The method of presenting the seals to the dispensing mechanism via the magazine was successful however, and so ideas for a more positive mechanism were sought.

By this time, October 1968, the designer had resumed his full time studies at College, but was timetabled six hours per week for project work.

During this initial period a new design of seal head which he produced had been built and tested at the factory. It was based on one of the earlier proposals, H Fig. 5b, and used three retaining springs and three wedges; the latter were designed to force the bottom seal through the three springs as it contacted the adhesive. This proposal was not immediately successful owing to the difficulties of producing a mechanism to operate the wedges simultaneously and further problems were caused by the seals not lying exactly horizontally in the seal head, causing the wedges to crush the seals on occasions. Much of this work was done on a 'suck it and see' basis in the company's workshops.

At the same time the designer was experimenting independently with mechanisms on a "Meccano" model. This model was not particularly successful except that it demonstrated very clearly that it was extremely difficult to operate simultaneously and precisely three members located symmetrically around the magazine. It was therefore decided to change to using only two members in future design proposals.

This decision, which was made during a progress meeting between the designer and the author, subsequently proved to be a very important one.

The type of mechanism envisaged would release the bottom seal, while retaining the next, and then force it onto the adhesive, thus making the operation more positive, and leaving room for manoeuvre in subsequent development. For example, problems of conveyor speed and glue condition would have far less control over the success of the design.

The mechanisms which were considered to be adaptable for this were:

1) A type of escapement which would always hold the second seal when releasing the first, see H Fig. 9a.

2) A single ratchet mechanism to release the bottom seal and catch the next one, see H Fig. 9b.

Proposal (1) was the more positive of the two but would have been difficult to produce and operate be cause of its small size; it was also difficult to achieve a claw geometry which would satisfactorily retain and release the seals.

Proposal (2) was a simpler conception and although less positive than (1) still offered room for manoeuvre. There being no problems with size of the mechanism, it was decided to progress with design proposals on this method, reverting to proposal (1) if it proved unsuccessful.

THE SECOND DESIGN PROPOSAL (Mk. II)

The major features of the Mk. II design and the points of departure from previous proposals are listed below:

(a) Two retaining members were used instead of three. This considerably simplified the control and operation of the mechanisms.

(b) The bottom seal was retained by plates underneath it rather than the less positive spring retainers.

(c) The bottom seal is released onto the glue and may even be forced down onto it - thus the problems of carefully controlling the timing, glue temperature and clearances between the members and the bottle are all alleviated.

H Fig.10 illustrates how the design operates. The first diagram shows the magazine being lowered with all the seals retained. The second shows the retaining arms opening to release the seals so that they drop a small distance onto the glued bottle. The travel of the magazine is arranged so that at its lower limit the retaining arm can be returned in between the first seal and the second (as shown in the third diagram). This applies a small pressure to the first seal and allows the magazine to be withdrawn leaving the first seal on the bottle.

Because the fitted seal stands proud of the seal recess on the bottle, no interference occurs between the retaining members and the bottle as was experienced in the previous unsuccessful design proposal.

It was decided that the mechanism to achieve the cycle of operations outlined above could best be found using rough model techniques, and the first problem to be overcome was to devise a system which only operated when the magazine was lowered.

A rough model was constructed to test this idea and is shown in plate 1. H Plate 1a represents the magazine being lowered and 1b the retaining arm being opened by the cam at the top of the arm contacting the peg on the ratchet arm, thus releasing a seal. H Plate 1c shows the arm having closed again and 1d shows the retaining arm pushing the ratchet arm out of the way on the return stroke of the magazine.

The mechanism functioned entirely satisfactorily and it was decided that this warranted the building of a working full scale model. This is shown in H Plate 2 and was used to finalise the geometry of the operating members and ratchets and other imponderables. It incorporates a section of magazine tube mounted on a vertical slide. The seal dispensing mechanism is mounted on wooden blocks on either side of the magazine. The model, although rough, was built so that as many variables as possible could be investigated.

The model showed convincingly that this was a positive method and repeatedly dispensed individual seals onto a specimen bottle. One difficulty was experienced on the model caused by the retaining plates becoming distorted through contacting the bottle. This was overcome by recessing the plates into the magazine so that they were protected.

The mock-up showed that this proposal was obviously feasible and was also instrumental in firm H deciding to build a full scale unit and test it on the existing test rig.

A working drawing was prepared, with critical dimensions taken directly from the rough model.

The unit was completed and fitted to the test rig early in 1969. A modification to the control circuits was incorporated so that the seal head would only be lowered, and a seal dispensed, if a bottle was present.

When the unit had been fitted, and carefully set up it was found to operate consistently and give no trouble. H Plate 3 shows the complete test rig before after it was prepared for final production trials.

TRIALS OF MK.II DESIGN

Full scale trials of the Mk.II design were delayed due to the repeated faulting of the gluing machine. However it was agreed that its reliability under prolonged working conditions could best be determined by running the machine in parallel with one of the production lines.

In order to do this a number of modifications and refinements were deemed necessary both for safety reasons and as a result of tests so far carried out.

It was realised that it was now no longer necessary to have the gluing and seal applying stations widely separated, it was decided to close them up to only two indexes apart, i.e. 18 inches. This enabled the overall length of the machine to be reduced by an equivalent amount and meant that the inertia of the conveyor was also reduced allowing the machine to run at higher speed.

In preparation for production trials, the conveyor was fitted with guards where necessary and all wiring was made safe.

The gluing unit was returned to the makers for further repairs and it seemed likely as the major cause of trouble until replaced by a more robustly constructed unit. Replacement, unfortunately, would be extremely expensive.

No further modifications were made to the gluing station as such but a small heater was arranged, to warm the seal space of incoming bottles, at the previous adjacent index position. The heater directs heated compressed air onto the seal space in an attempt to equalise bottle temperatures, and remove any moisture.

On test the seal dispenser functioned very satisfactorily, and a production rate of over 45 per minute was achieved. In all trials the seals were fixed accurately and firmly to the bottles. The main problems involved were with the gluing station, and this held up further work on the machine and its introduction into production.

THE FINAL DESIGN

With no major design modifications to the seal dispenser the machine was used successfully in production during the early part of 1970. The whole machine functioned satisfactorily except for the gluing station which hadbeen subjected to considerable redesign by the manufacturers.

CONCLUSIONS

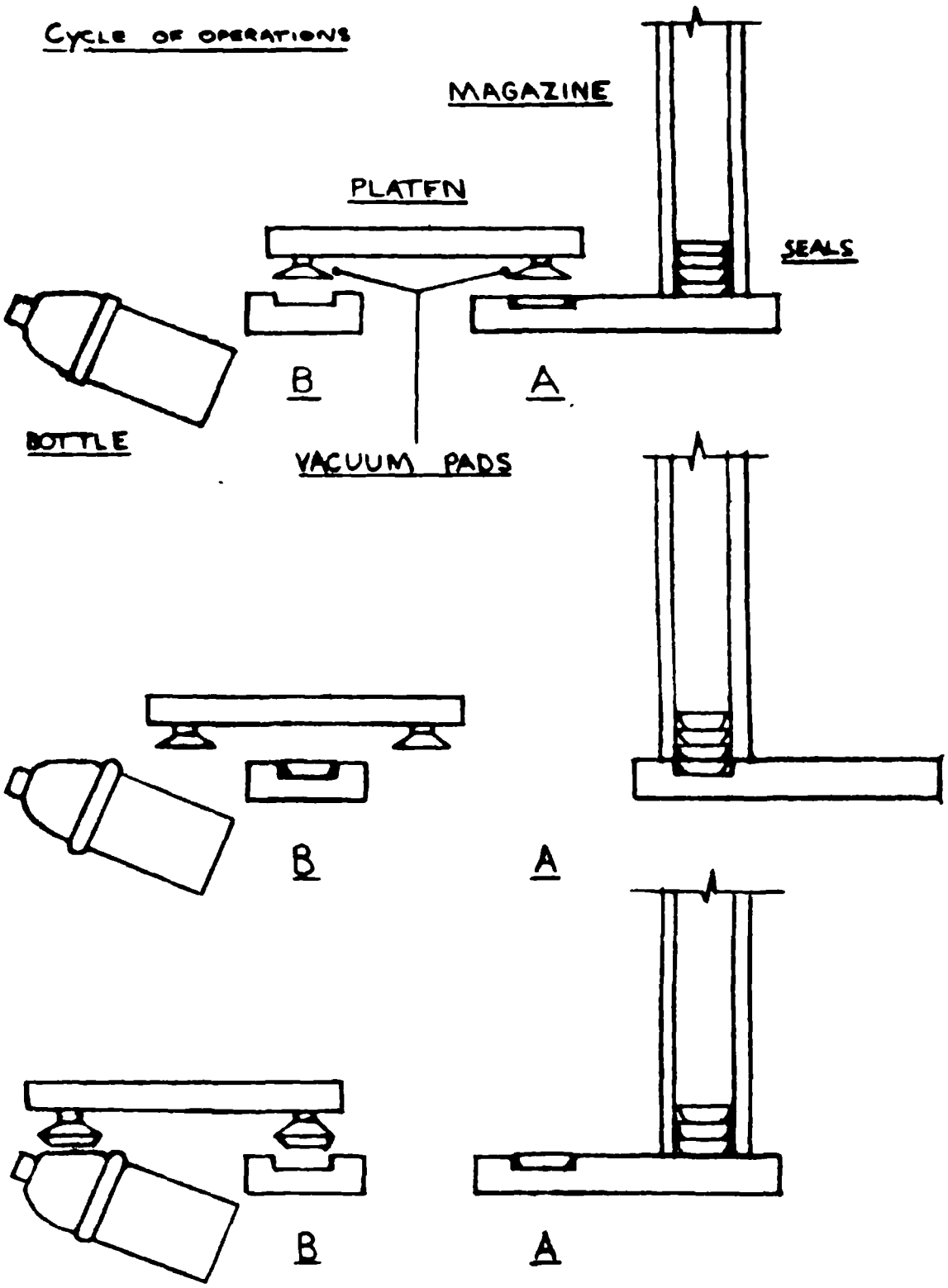
This case history was eventually very successful. The constraints and pressures

applied to the engineering designer in a totally commercial environment were not present in this case but the hardware which evolved was of real value to firm H.

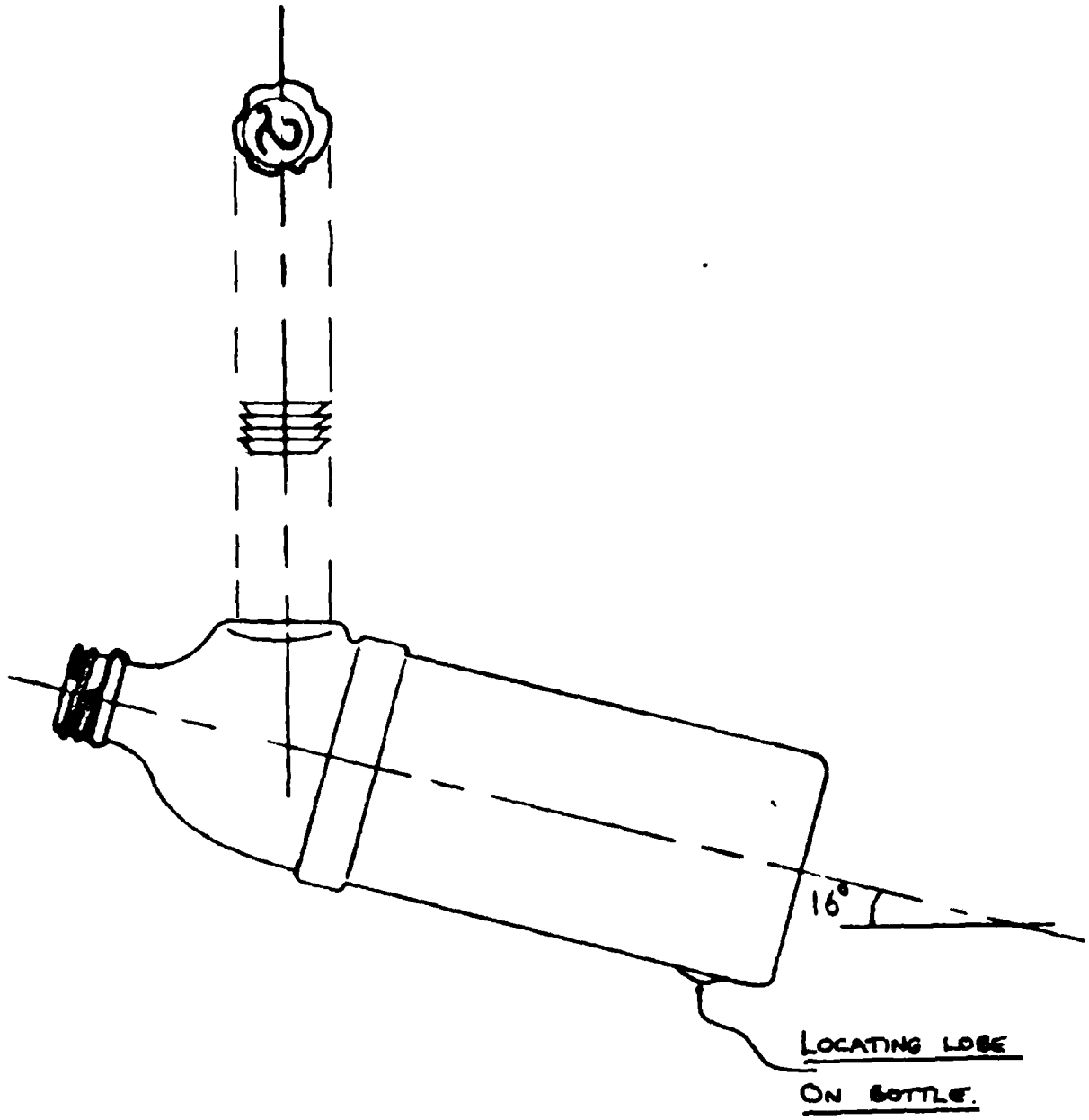
An important aspect of the exercise was the emphasis on the use of physical models as a means of assessing and overcoming the imponderables such as glue behaviour and plastic seal stacking characteristics.

The elimination - or sub-contracting - of the seal handling problem was important to the success of the design, whereas the sub-contracting of the gluing station proved very unsatisfactory in that this aspect eventually became the major unsolved problem.

The student was subsequently employed by firm H and is now a project leader in their design team.



H FIG 1 EARLIER DESIGN PROPOSAL



H FIG 2 LOCATION OF BOTTLE AND SEAL STACK

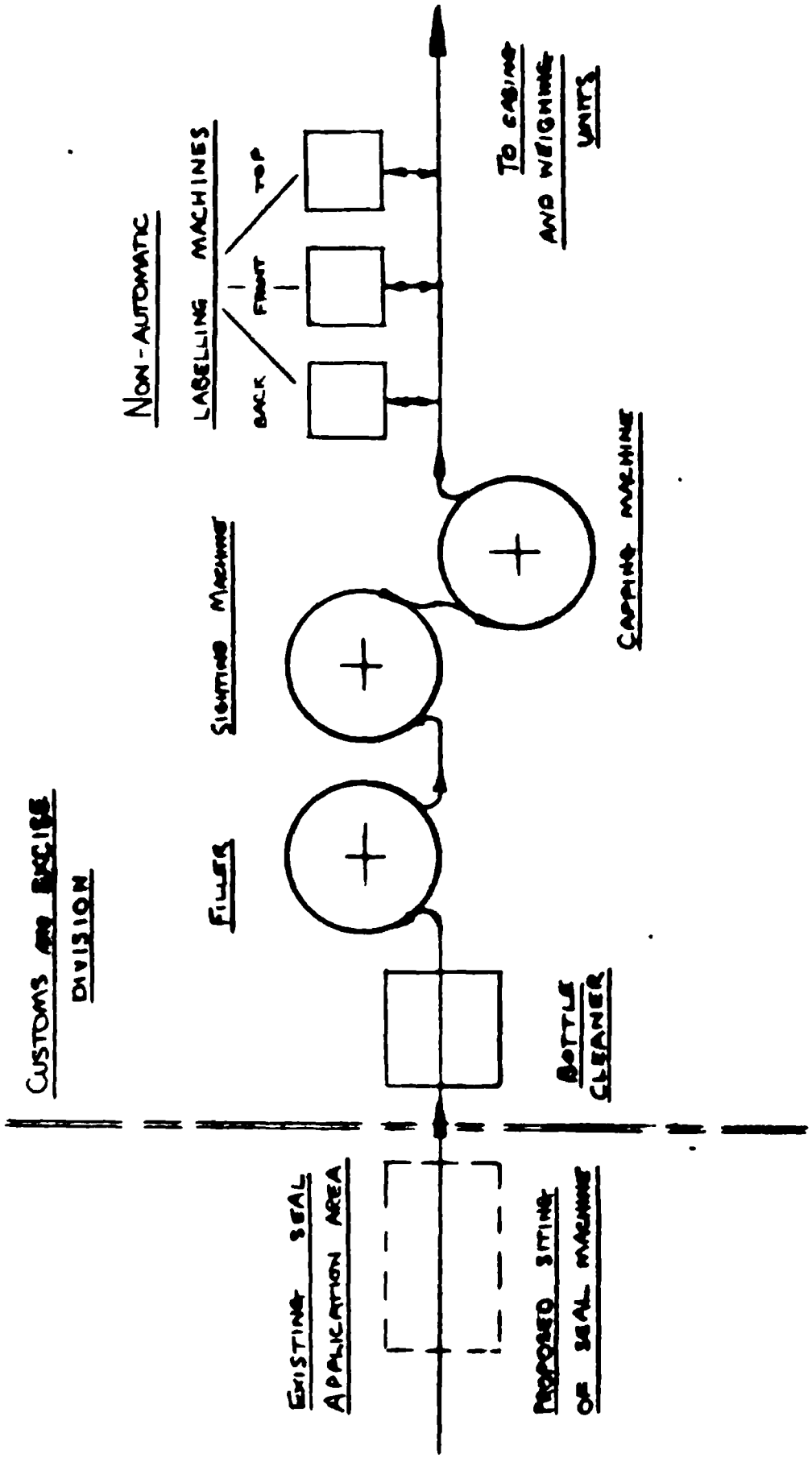
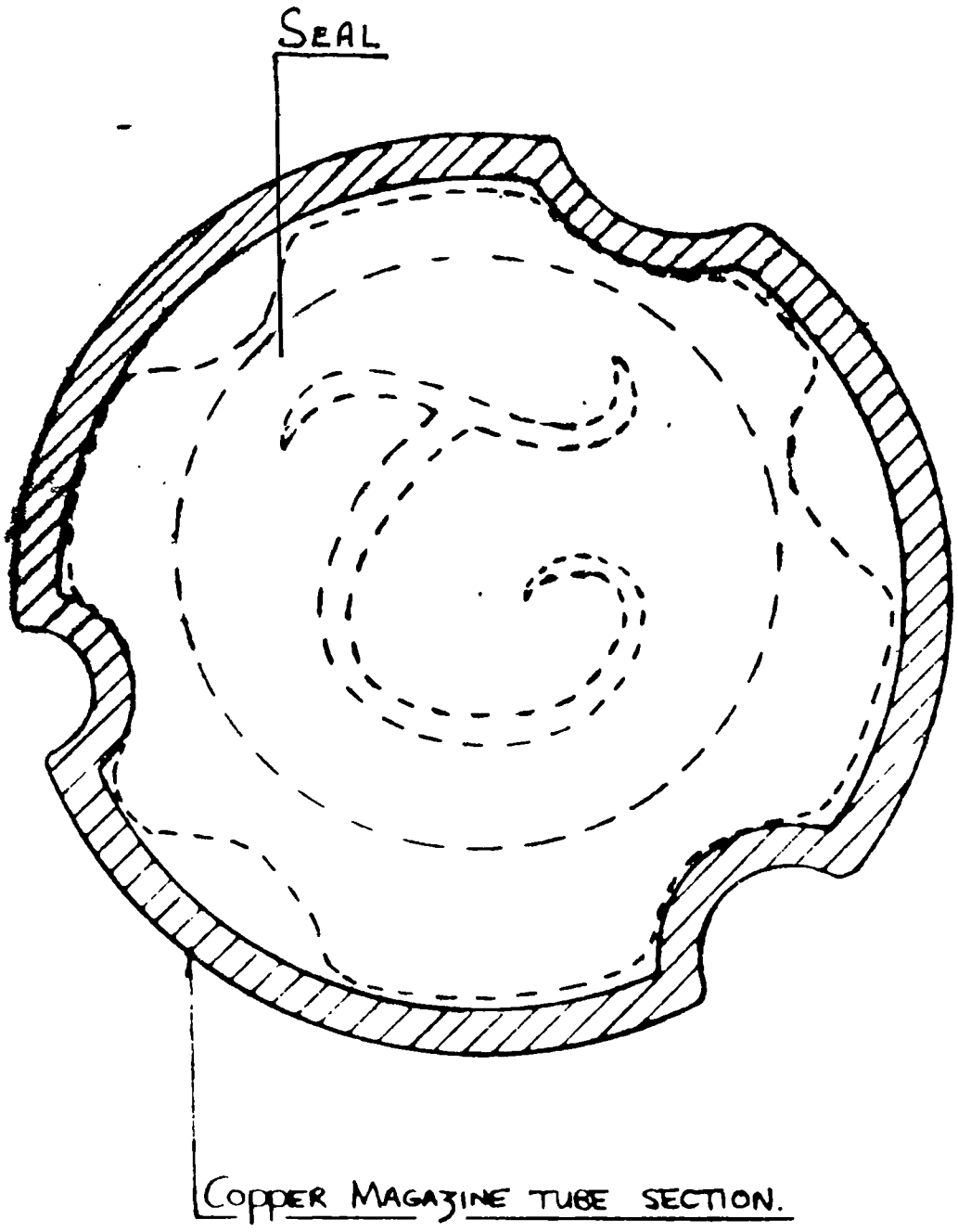


FIG 3 FLOW DIAGRAM OF BOTTLING LINE



H FIG 4 ONE-OFF SEAL MAGAZINE

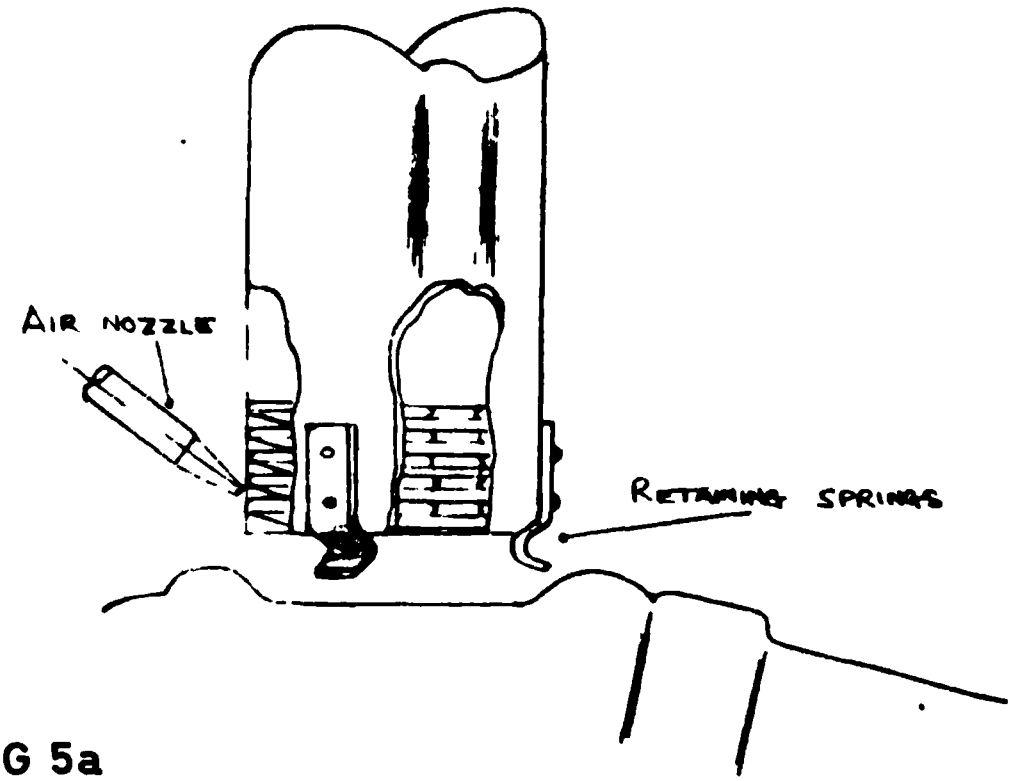


FIG 5a

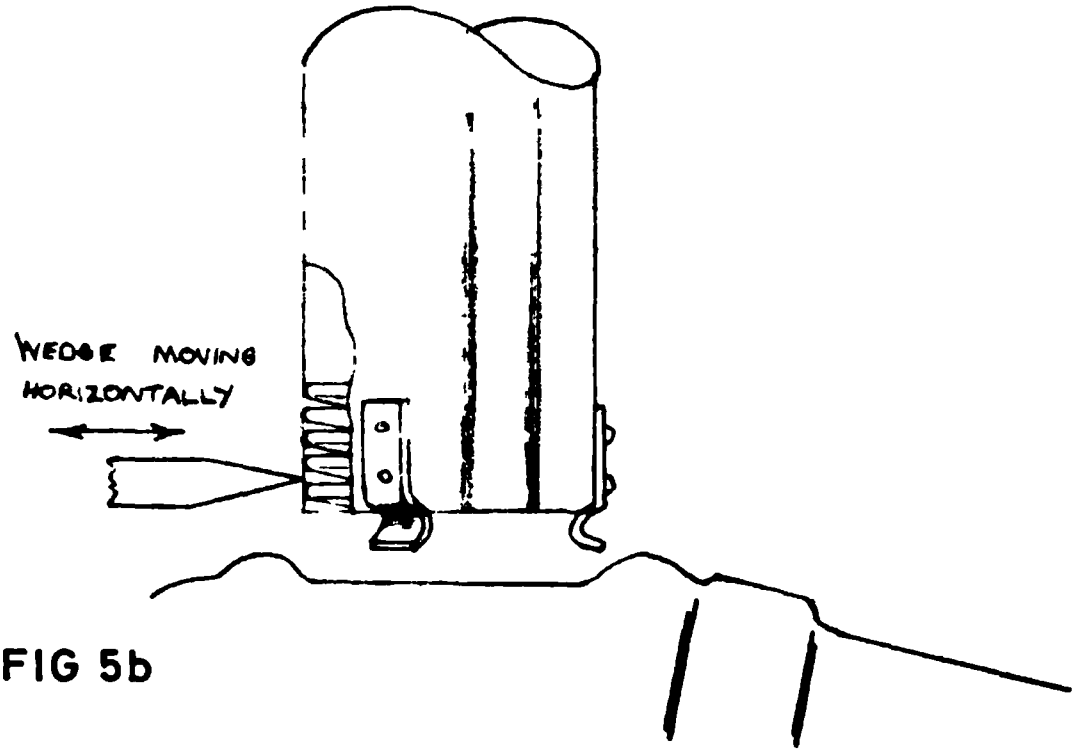
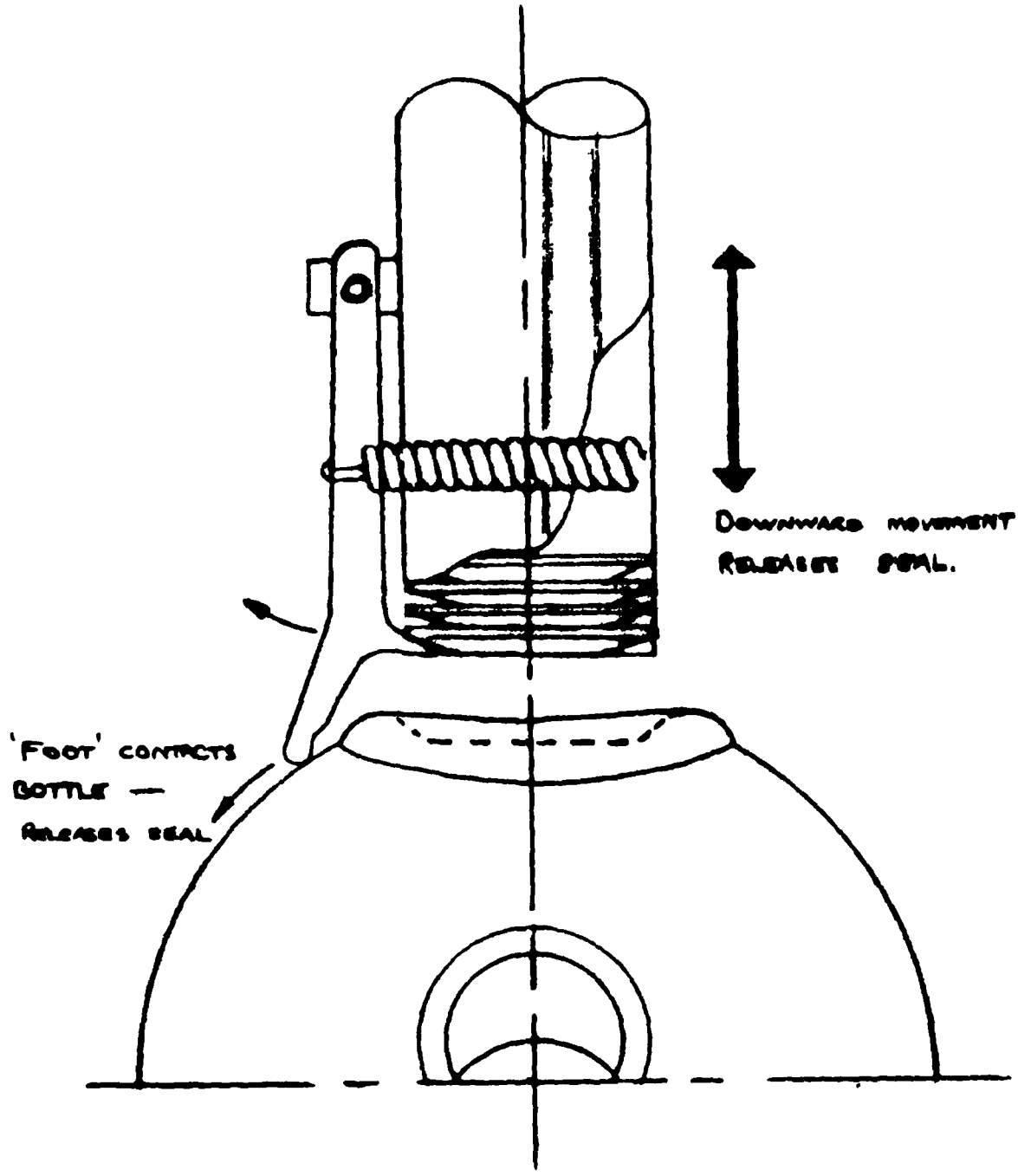
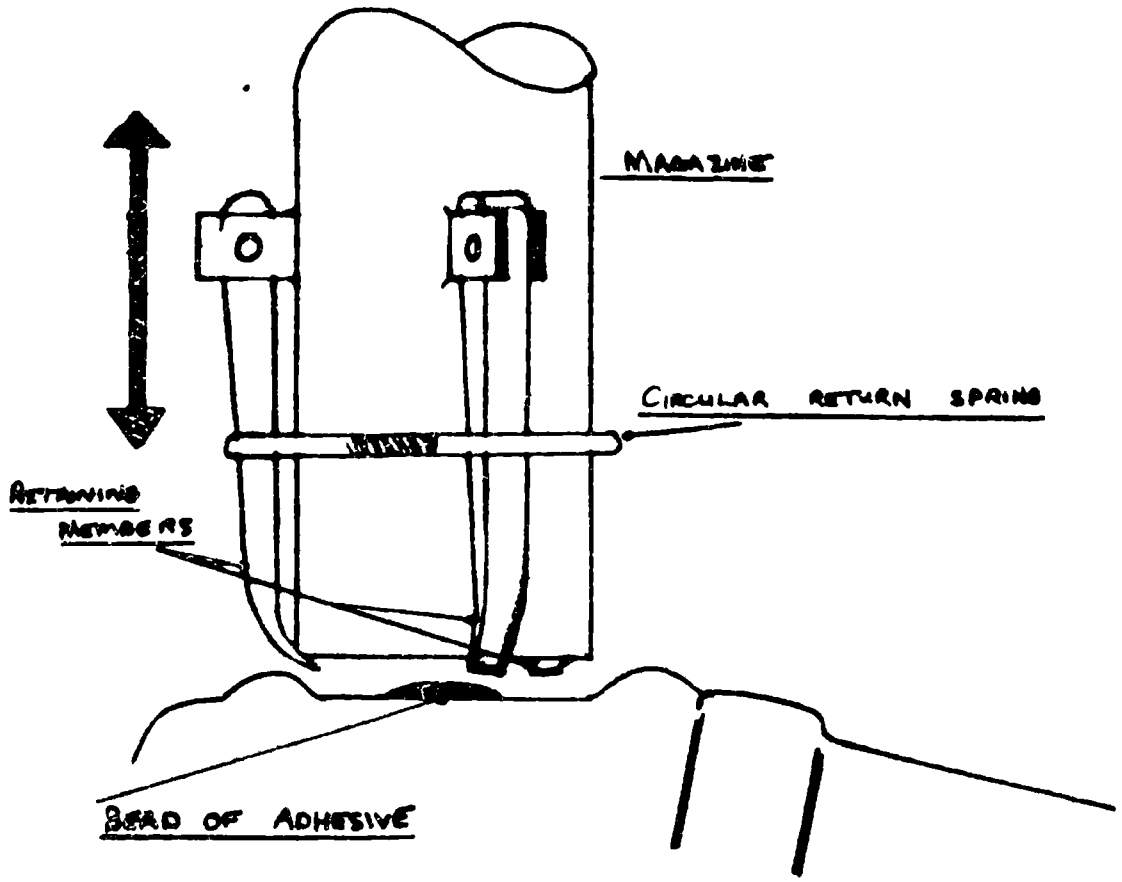


FIG 5b

H FIG 5a,b SEAL DISPENSING PROPOSALS

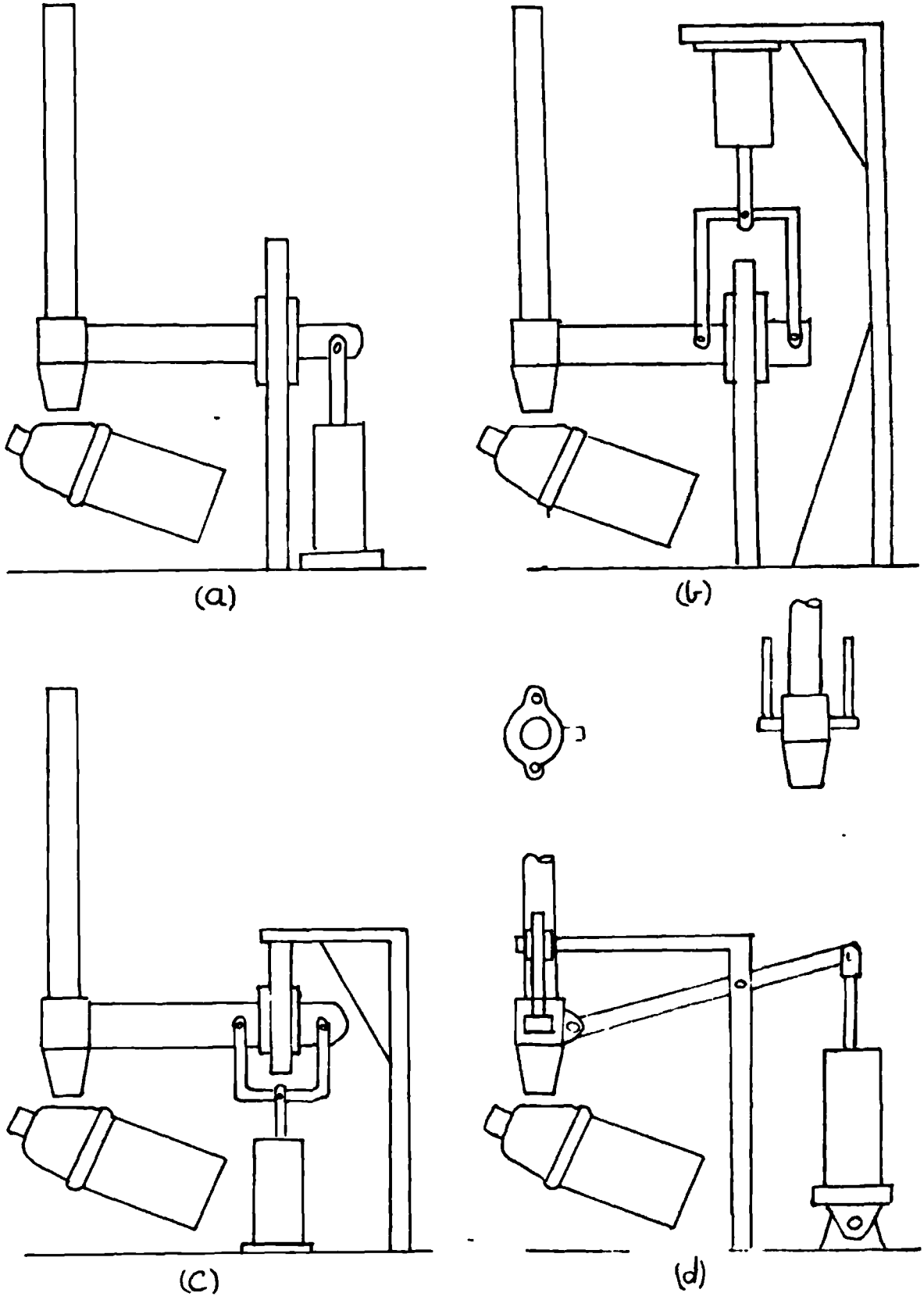


H FIG 5c SEAL DISPENSING PROPOSALS

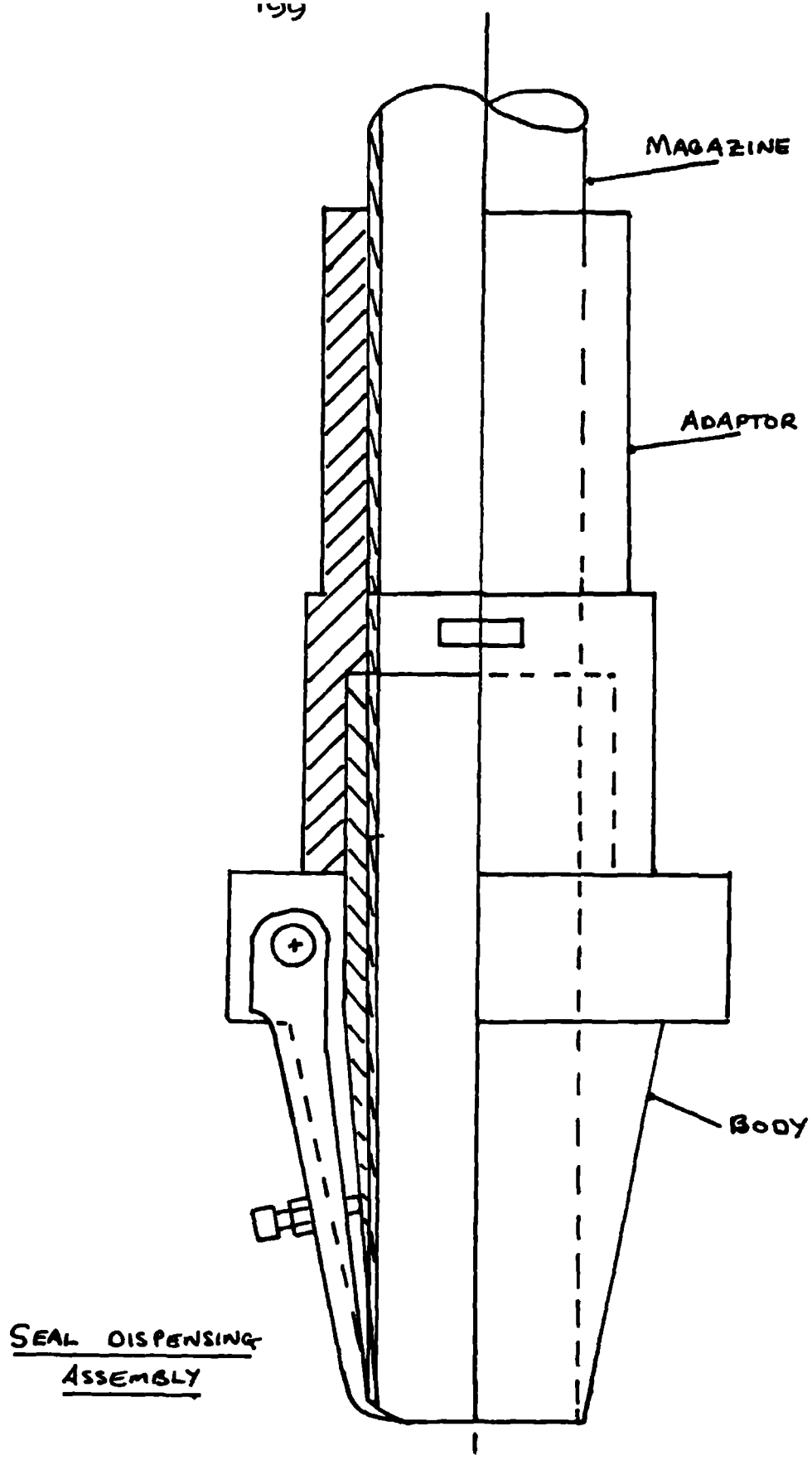


WHEN THE MAGAZINE IS LOWERED THE BOTTOMMOST SEAL CONTACTS THE ADHESIVE. THE MAGAZINE PAUSES, ALLOWING THE ADHESIVE TO STICK TO THE SEAL, AND IS THEN RAISED LEAVING THE SEAL RETAINED ON THE BOTTLE.

FIG 5d SEAL DISPENSING PROPOSALS



H FIG 6 SEAL DISPENSING STATION - PROPOSALS



HFIG7 MAGAZINE CHANGING - SOLUTION

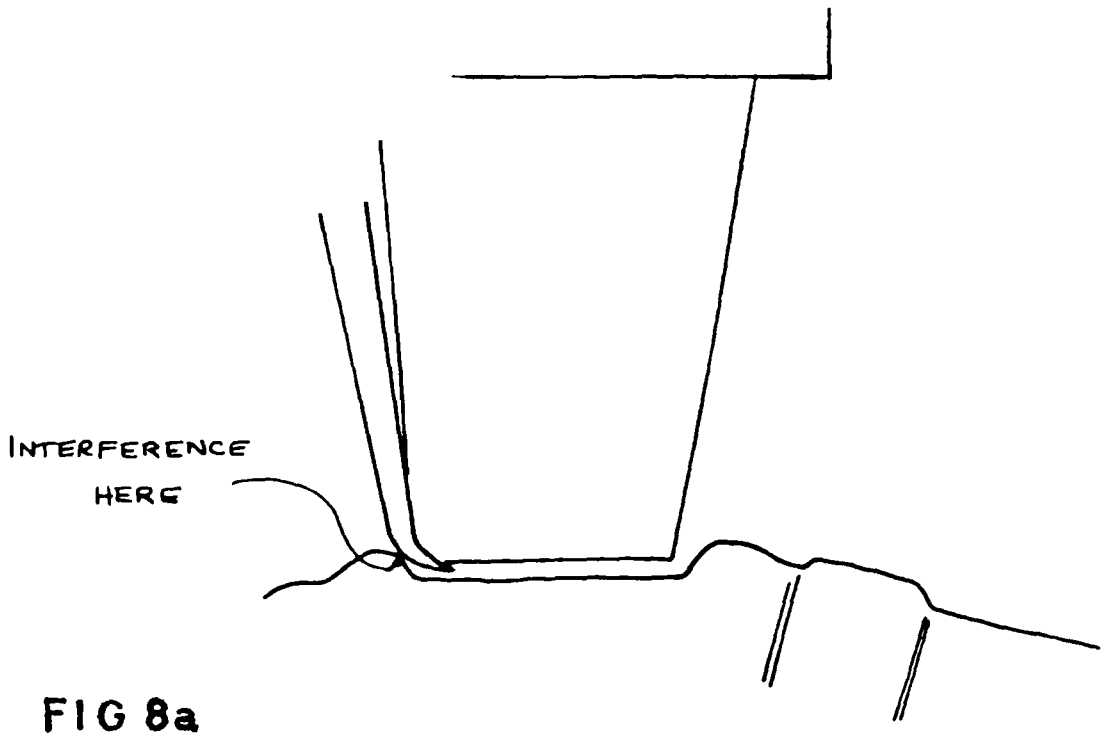


FIG 8a

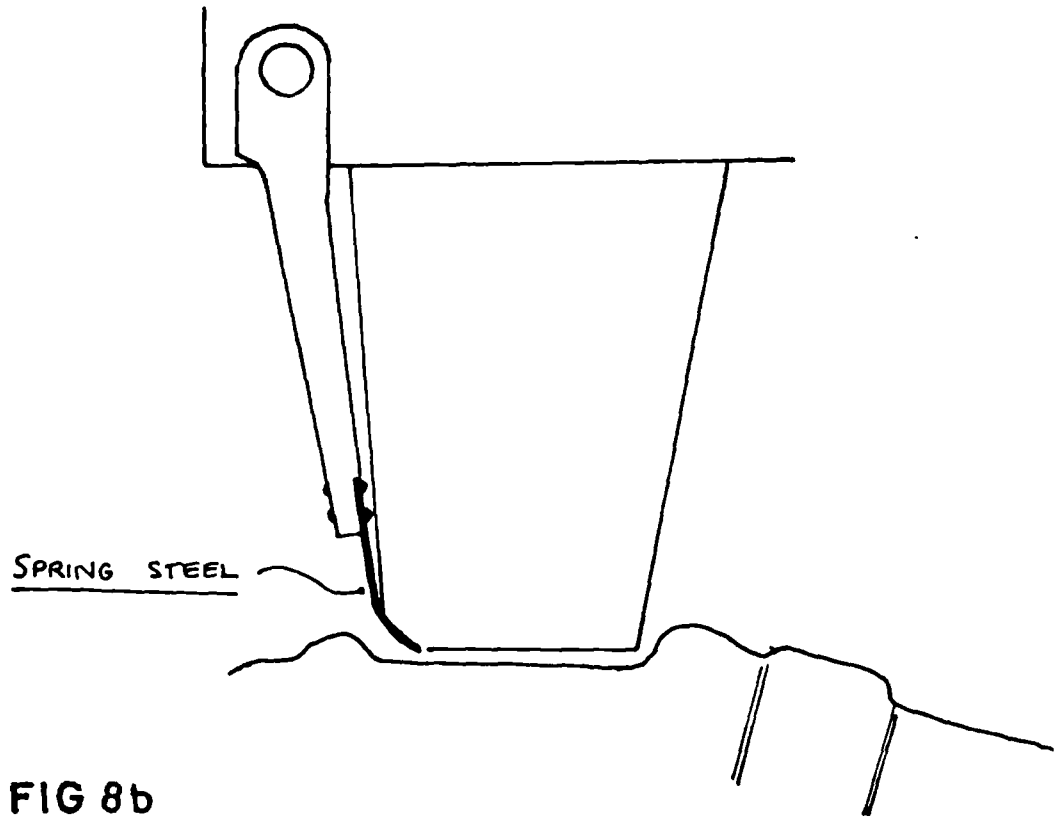


FIG 8b

H FIG 8 SEAL DISPENSING HEAD - REDESIGN

SCALE 5:1 APPROX.

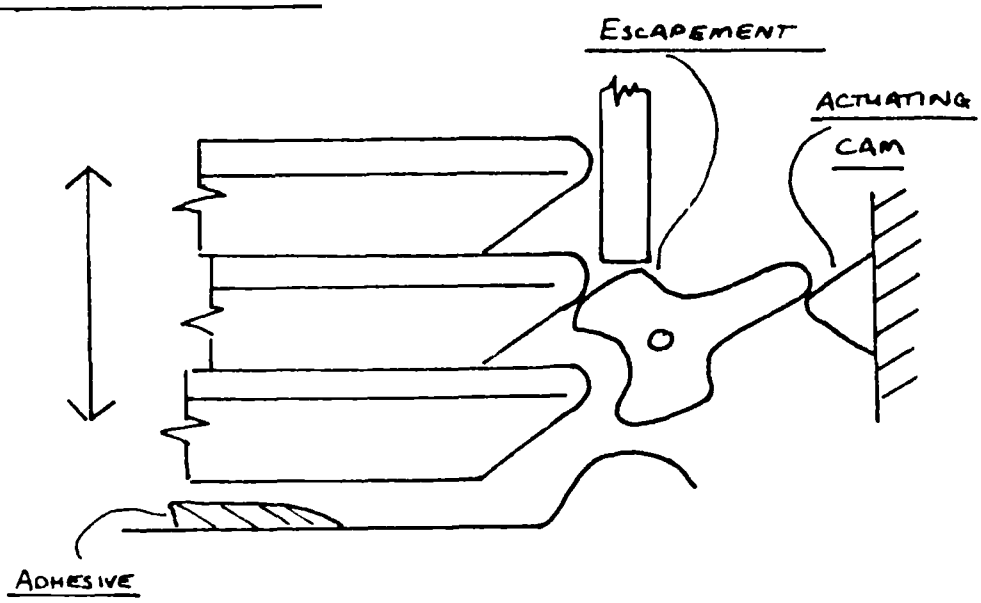


FIG 9a

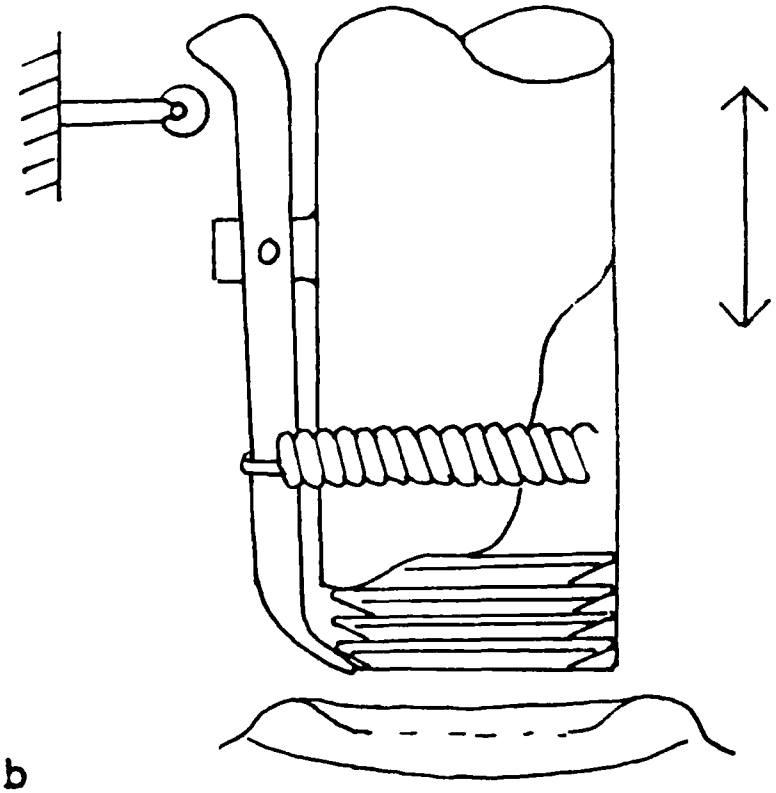
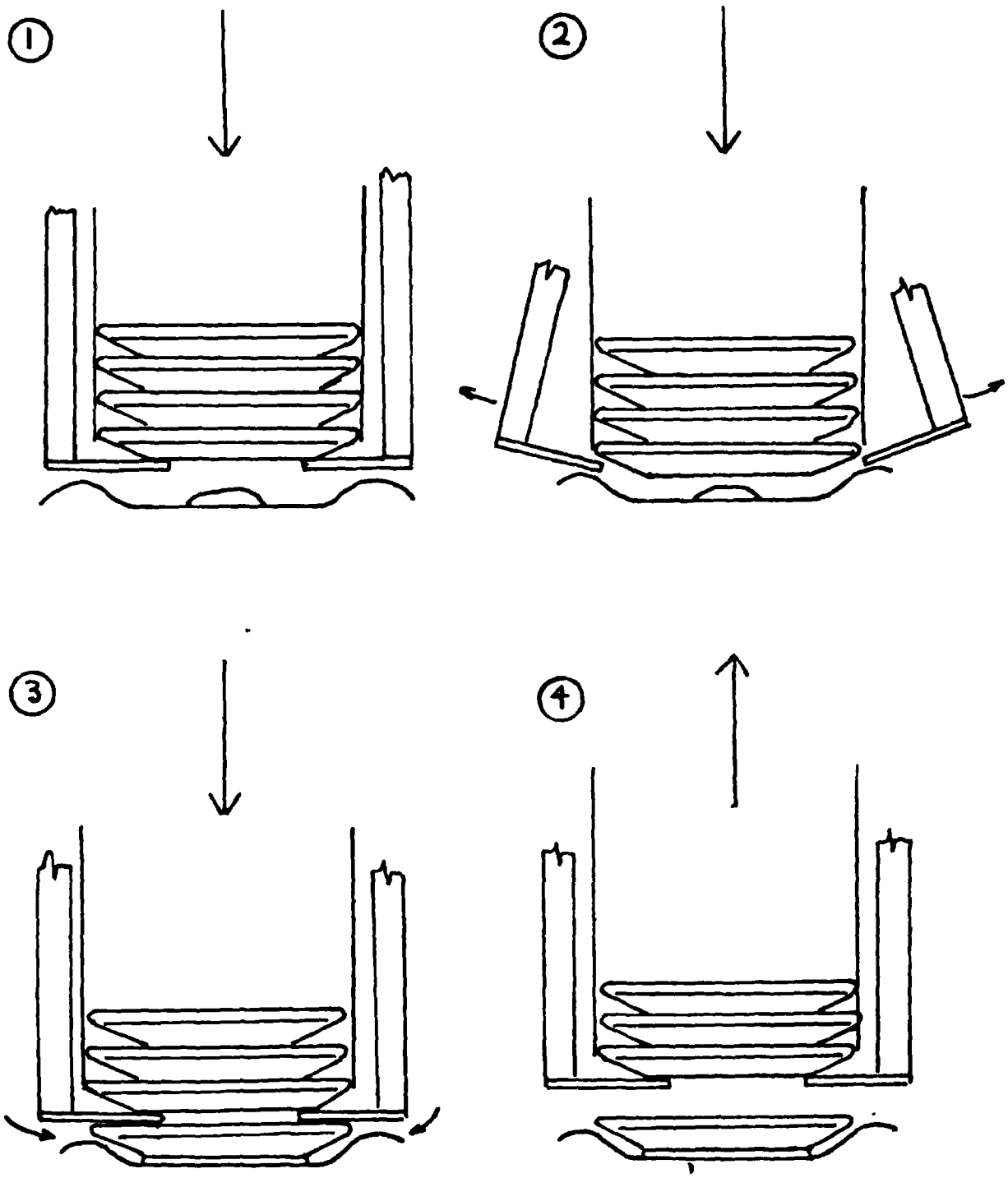
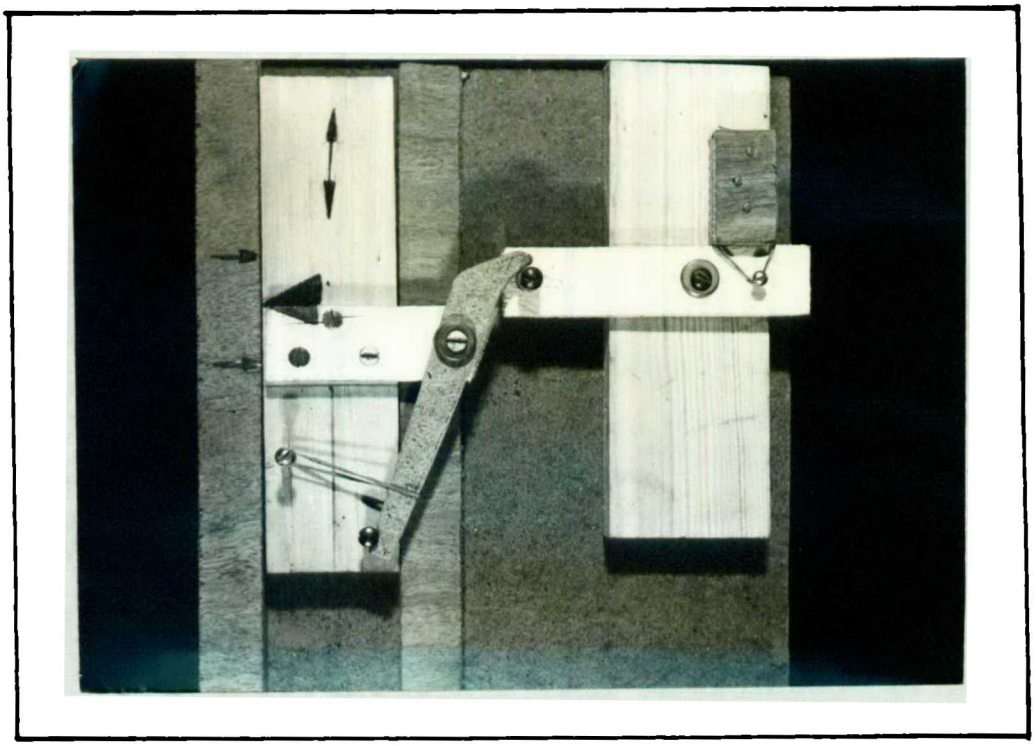


FIG 9b

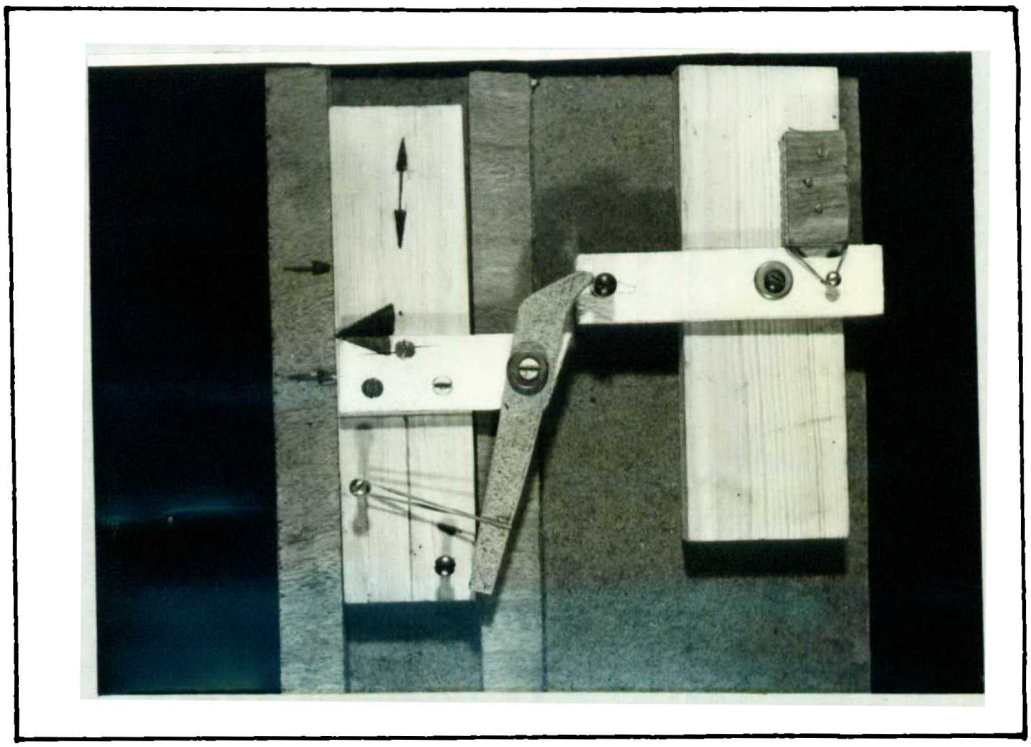
H FIG 9a b SEAL DISPENSING HEAD - FURTHER PROPOSALS



H FIG 10 SEAL DISPENSING HEAD - FINAL DESIGN

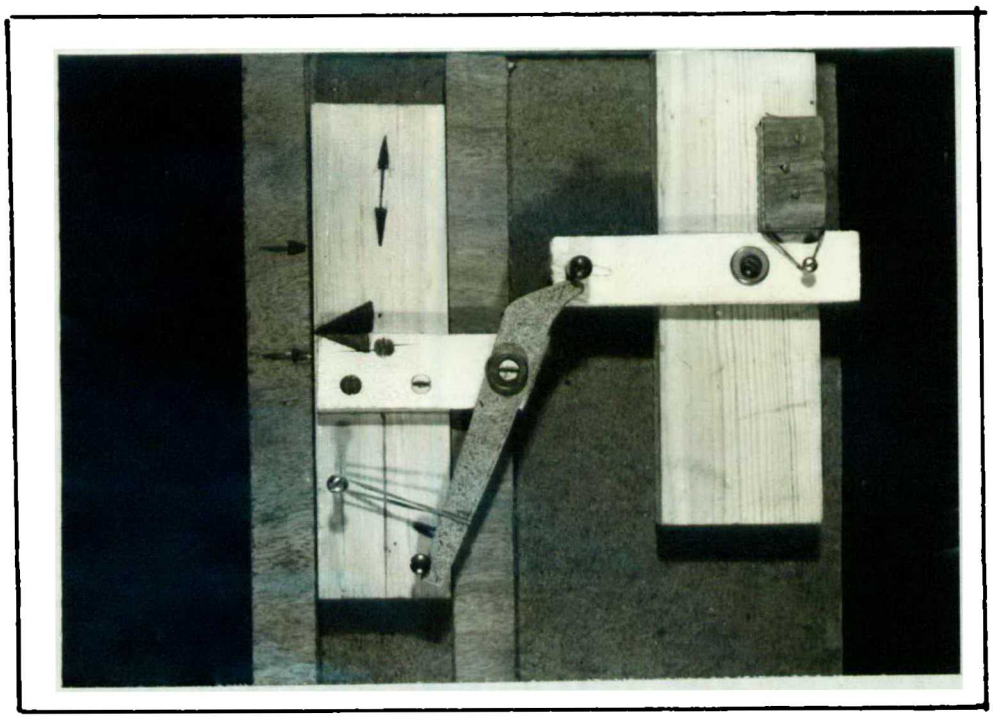


a) Plate lowered

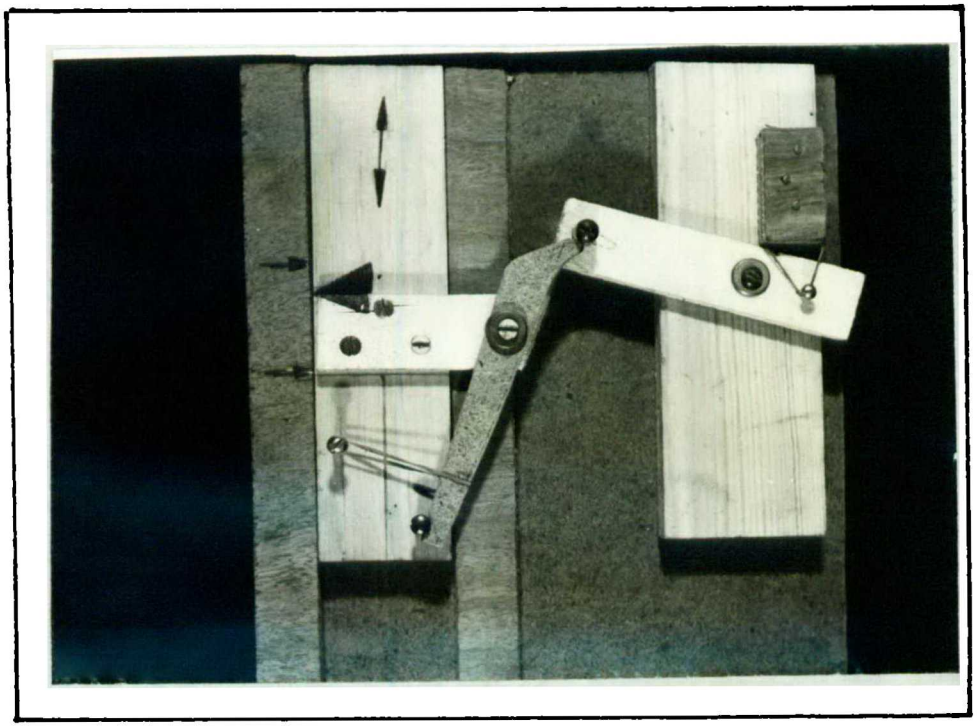


b) Seal released

HPLATE1 SEAL DISPENSING HEAD - MODEL

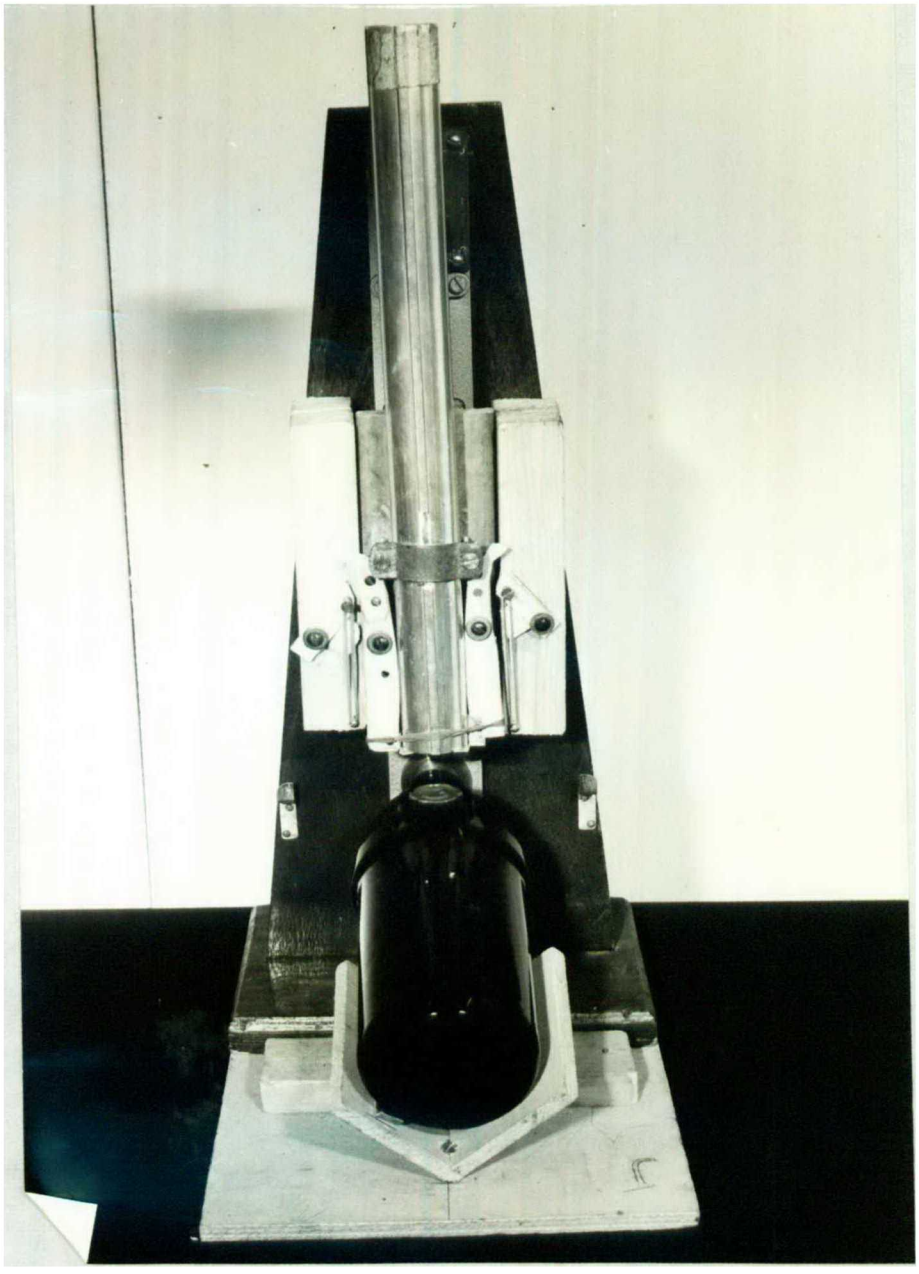


c) Second seal retained

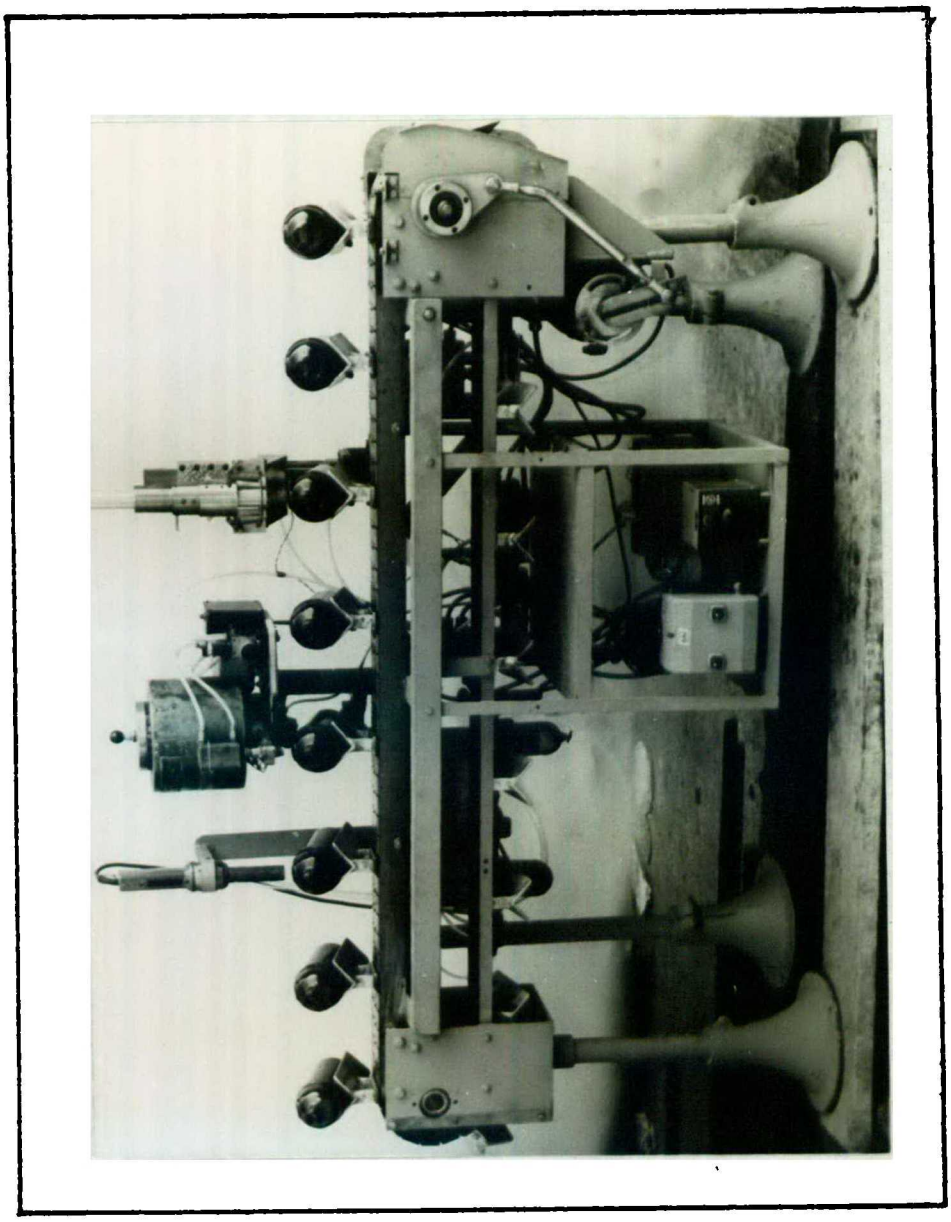


d) Return stroke

HPLATE 1 c d SEAL DISPENSING HEAD - MODEL



H PLATE 2 SEAL DISPENSER - WORKING MODEL



HPLATE 3 THE FINAL DESIGN

CASE HISTORY J

SUPPORT STRUCTURE FOR GRAPHITE MODERATOR IN NUCLEAR REACTOR

INTRODUCTION

Firm J was one of the first consortia formed in the United Kingdom to design and construct commercial nuclear power stations. The design team, of which the author was then a member, commenced work early in 1957 on the design of a 500 MW Graphite moderated station.

As this was one of the first commercial nuclear power stations to be built, and the only previous experience available at the time was from the much smaller experimental plant, the design was an exercise in innovation rather than extrapolation. Some guidance was available from the prospective customer but this was limited by commercial considerations as several other consortia were competing for the same contract.

Because of the novel type of problem and the newness of the design organisation, the development of the design was far from straightforward.

The main features of the final design proposal submitted by firm J described a graphite-moderated carbon-dioxide-cooled reactor using finned Magnox cans for fuel elements containing Uranium fuel; it is contained in a large spherical pressure vessel $3\frac{1}{2}$ in thick and 61 ft in diameter constructed of fusion welded carbon manganese steel and supported on a 25 ft diameter cylindrical skirt, J Fig. 1.

The pressure sphere is mounted inside a large cylindrical reinforced concrete biological shield 70 ft in diameter by 80 ft high with a side wall 10 ft thick and a top $11\frac{1}{2}$ ft thick. The main cooling gas ducts, stand-pipes and other connections to the vessel from outside pass through this biological shield, this is also shown in J Fig. 1.

The graphite moderator core is made up of numerous machined graphite blocks locked together to form a cylinder 30 ft high and 24 ft diameter.

The weight of the moderator, about 2500 tonf, is transmitted to the top of the inner skirt by means of the support structure, and then through the skirt to the foundations.

This case history is concerned with the design of this moderator support structure. The author was personally involved with this design from the initial concept to the final detail drawings which were prepared after the tender had been accepted by the customer.

HE PROBLEM

Initial work on the design of the moderator support structure consisted of a series f feasibility exercises which investigated several possible design solutions. The design rief was far from settled since the parameters such as working pressure, temperature, skirt ize and moderator design were still subject to change.

However sufficient information was available to enable realistic studies to be :arried out, an assessment of the dominant factors to be made and some possible solutions stablished.

The design parameters which were used for these initial design exercises are listed elow.

The initial brief

The initial brief given to the design team was of necessity vague, and subject to modification as other related design began to finalise. However, the following parameters were presented.

1) A support structure for the graphite core which would be about 50 ft in diameter, 25 ft high and weigh about 2500 tonf excluding levelling plates and self weight. One only to be constructed per reactor - 2 reactors per station.

2) To be contained within the reactor pressure vessel.

3) The life of the plant to be 30 years minimum.

4) The initial design to be undertaken at firm J's headquarters and to be approved by the customer and main contractor.

5) The initial design with full supporting reports, to be completed in 12 months.

6) Construction to be undertaken by the main contractor either at their works or on site.

A closer study by the design team ascertained the following additional factors which would affect the design.

7) The structure would be inaccessible during operation.

8) The structure must be sufficiently rigid, to prevent excessive distortion of the core. Precise values or acceptable displacement were not available until the core design was finalised, but a slightly concave deflected shape is more satisfactory than a convex shape since it prevents the graphite blocks from falling apart.

9) Adequate flow paths for the cooling gas to the core channels through the structure must be provided.

10) The structure would be subject to an environment of about 200°C at 250 lbf/in^2 pressure and a high level of radiation.

11) The accuracy and finish were not critical except where the structure was to be compatible with adjacent parts of the reactor structure.

12) Cost was to be minimised but was not more important than function, safety and reliability.

13) Stress levels to be to the relevant code.

INITIAL DESIGN PROPOSALS

The first design proposals undertaken early in 1957 were based on a concrete pressure vessel with the graphite core supported directly on the foundations. The support structure was to consist of a series of support columns "tree trunks"; at their top end they carried levelling plates on which the moderator stood and their lower end was mounted on, but insulated from, the foundations. Each column was to be hollow and the CO_2 would flow through holes in the column walls before passing up through the fuel channels in the graphite blocks.

Some form of roller bearing was envisaged at the top of each column, to allow for thermal and load induced incompatibilities.

This proposal was considered only until November 1957 when company policy was changed and the concept of a steel pressure vessel contained in a concrete biological shield was adopted. (It is interesting to note that current designs as illustrated by case history B in this work, use this composite concrete pressure vessel - biological shield concept).

The new proposal consisted of a spherical vessel supported by a skirt attached to a forged reinforcing ring around its equator with the moderator support structure slung from this ring, J Fig 2. The original proposal for the spherical vessel was based on conventional

techniques used for similar, but much smaller, tanks in the chemical plant industry (Horton spheres) as many of the design team involved had experience in this industry.

This proposal appeared to have the advantages that the gas flow paths were clear and some previous experience in this type of configuration was available. The latter advantage proved to be very limited however since the enormous increase in size, pressure and temperature compared with existing designs virtually invalidated the application of previous work.

This proposal was finally rejected for the following primary reasons.

(a) The size of core which was evolving as the overall design parameters were finalised meant that the vessel, in order to accommodate it, would be much bigger than had originally been envisaged or was in fact possible due to the restriction of only being able to weld up to $3\frac{1}{2}$ in thick plate on site.

(b) In order to achieve the required stiffness for the support structure, which was supported only at its periphery, it was obvious that an extremely cumbersome structure would be necessary.

The next development was the proposal that the vessel be supported on an intermediate cylindrical skirt and that the support structure should be supported on an inner extension of this skirt, J Fig. 3. This would mean that the weight of the moderator core would be transmitted directly to the foundations, and the only stresses which it would induce in the vessel would be local secondary stresses due to the strain incompatibilities at the vessel-skirt junction. Although the prime factor in deciding skirt diameter would be the stresses induced in the vessel at this skirt/vessel junction, initial studies were undertaken to investigate the optimum position of the skirt in order to satisfy the support structure requirements. These feasibility calculations varied from the very approximate first attempts to much more rigorous studies culminating in a precise computer analysis.

Another factor which had to be allowed for at this stage was the need to provide for the entry of the cooling gas into the vessel through the 5'6" inlet ducts. On the basis of all this work a compromise was sought in order to fix the skirt diameter, and design effort continued on the design of the support structure which was to be used with this latest proposal.

Sketches of the main proposals for the support structure configurations which were considered at this stage are shown in J Fig. 4.

The first was a square 'egg-box' grid, J Fig 4a, of deep 1 beam members circular in plan and supported on a concentric circular support cylinder. Initial investigation of this design showed that it would need to be very deep in order to provide the required stiffness and adequate gas flow paths. It had the advantages however that it would not present any very difficult manufacturing problems and it could also be designed to match the square array of fuel element channels in the moderator core.

It is interesting to note that when the first 'egg-box' structure was designed for the Calder Hall experimental Nuclear Power Station a draughtsman put on his drawing 43' - 6" DIA GRID. The two words subsequently became joined and to this day structures of this nature to support graphite moderators in nuclear reactors are known as 'diagrids'.

A further proposal was the radial 'spiders webb' array shown in J Fig 4b. This had the advantages that it gave good radial gas flow characteristics and its radial symmetry also facilitated some aspects of analysis and construction. On the other hand, however, it had the serious disadvantage that it could not easily be made to match the square configuration of fuel element channels, and in fact masked some of them.

Several Warren girder versions of the egg box design were also considered and led quickly to a geodetic three dimensional space structure made up of 6in o/d tubular sections welded to large spherical forgings at each nodal point. One of these proposals is shown in J Fig. 4c. This design initially appeared to be very promising as it satisfied the requirements of rigidity, gas flow paths and matching with the fuel element channels. The design was rejected however because of the manufacturing difficulties, particularly those involving the manufacture and assembly of the large nodal forgings.

The next step was to consider combining the best characteristics of two of the designs. The possibility of superimposing a shallow egg box grid on top of a deeper radial spider-web configuration, J Fig. 5a, was considered. This could be made to satisfy all the requirements of rigidity, gas flow and channel matching but presented construction and compatibility problems. It was from this proposal that the final design was developed. The original idea to combine the radial and square configuration was retained, since it had exhibited obvious advantage, but the design was modified to simplify the concept, J Fig. 5b.

In this proposal the 'egg-box' grid is retained in order to provide matching with the fuel channels, and the overall stiffness and gas flow characteristics are improved by introducing radial support struts from the top of the inner skirt to the grid periphery. A peri-

pheral ring was introduced at the strut/grid junctions in order to increase stiffness and ensure more uniform load distribution and displacements. A similar ring was also introduced, for the same reasons, at the top of the inner support skirt.

During the early months of 1958 a preliminary tender had been submitted by firm J to the customer. The aim of this exercise was to consolidate the proposals made to date, to assess the competence of the design team and to establish contacts with the customer's assessors.

THE DESIGN SUBMISSION

The tender submitted to the customer in March 1959, consisted of a description of the design proposal and supporting calculations.

a) The Design

The moderator support structure submitted in the tender is shown in J Fig. 6. It consisted of a circular floor formed by a square array of vertical I section girders 36 in deep over the central area tapering to 12 in deep at the periphery. The floor was supported on the inner skirt of the pressure vessel by 12 sloping struts 12 in outer diameter and 2 in thick, equally spaced around its periphery, and by 16 vertical pillars 12 in outer diameter and 1 in thick. The struts were spaced to avoid the gas inlet ducts and the pillars to match the grid girders.

Two box section rings, one at the periphery and one on top of the inner skirt, linked the structure together.

b) Outline of method of analysis:

The analysis submitted with the design proposal was intermediate in that, while it was by no means a first estimate, it could be improved and in fact considerably more work would be undertaken if the tender was successful.

The analysis was sufficiently detailed and reliable however to support the submission and prove its feasibility. It consisted of rough initial estimates followed by successively closer and more refined approximations.

This technique was customary at the time with such a highly redundant structure before suitable computer programmes were readily available.

:VELOPMENT OF THE DESIGN

In May 1959 the customer forwarded Tender Comments to firm J, the following ›ints were raised on the moderator support structure.

1) The specification of the steel to be used should contain less than 2lb of Aluminium per Ton and the details of the chosen specification should be given.
   This was agreed by firm J.

2) All welds in the diagrid were to be 100% crack detected before and after stress relief.
   This was agreed by firm J.

3) Provision should be made in the design for relative movement between the diagrid and the skirt.

Firm J requested that discussions on this should be held at an early date, they felt hat it was not necessary to provide for such movement since the skirt was sufficiently lexible to carry these movements along its top.

A supporting calculation showed that the stresses induced in the skirt were as ollows:

a) Direct compressive dead weight stress - 4200 lbf/in^2

b) Secondary stress due to displacement of the structure, this would be relieved by creep and plastic deformation 9000 lbf/in^2

c) Thermal stresses 6700 lbf/in^2

A letter from the customer in September 1959 agreed to accept the firm's proposals hat no provision need be made for relative movement between the diagrid and skirt.

In October 1959 detailed drawings of the diagrid structure were submitted to the :ustomer. At this stage one of he main contractors to firm J became involved in the lesign since they were to be responsible for its construction.

In the meantime a computer programme had been written by the design team of 'irm J analysing the floor grid and this gave realistic and acceptable values of displacements, ›oth in magnitude and variation. Since the programme was novel and had not been checked ›n any other structure it was decided that two steps should be taken.

1) A similar programme, which had just been written by an independent group in a University should be used to check the firm's programme; this was done and the results were satisfactory.

2) A model should be built which could be used to check theoretical results from the programme against measured values. It was also foreseen that this model could be used for a study of the matching of the floor grid to the columns and struts via the two ring beams.

This work was undertaken in a University; the model was not made to scale as its aim was to verify the computer programme and to assess the effect of the ring beams and associated structure.

In November 1959 the customer approved the detail design with only a few minor queries on the type of weld used in some parts of the structure, the need to vent hollow sections for gas escape during welding and for complete sweeping of air during commissioning. Other queries were raised on the method and timing of the manufacture of the structure.

MANUFACTURE

During the early part of 1960 the problems listed above were resolved in consultation with the main sub-contractor and the customer. Final sets of detailed drawings were forwarded to the customer and the insurers before the end of 1960, and construction was started by the sub-contractor on site, J Plate 1.

Further design changes were made at this stage as the detailed analyses were completed and as a result of closer consultation and co-ordination between the design teams of firm J and the sub-contractor. Most of these changes involved minor detail design but one important modification was the elimination of the lightening holes in the grid members - compare J Fig. 6 and J Plate 2. This was done as a result of an investigation into the shear deflection of the members and their lateral stability. As a result of this change the CO_2 flow paths through the structure had to be reconsidered but were proved to be satisfactory.

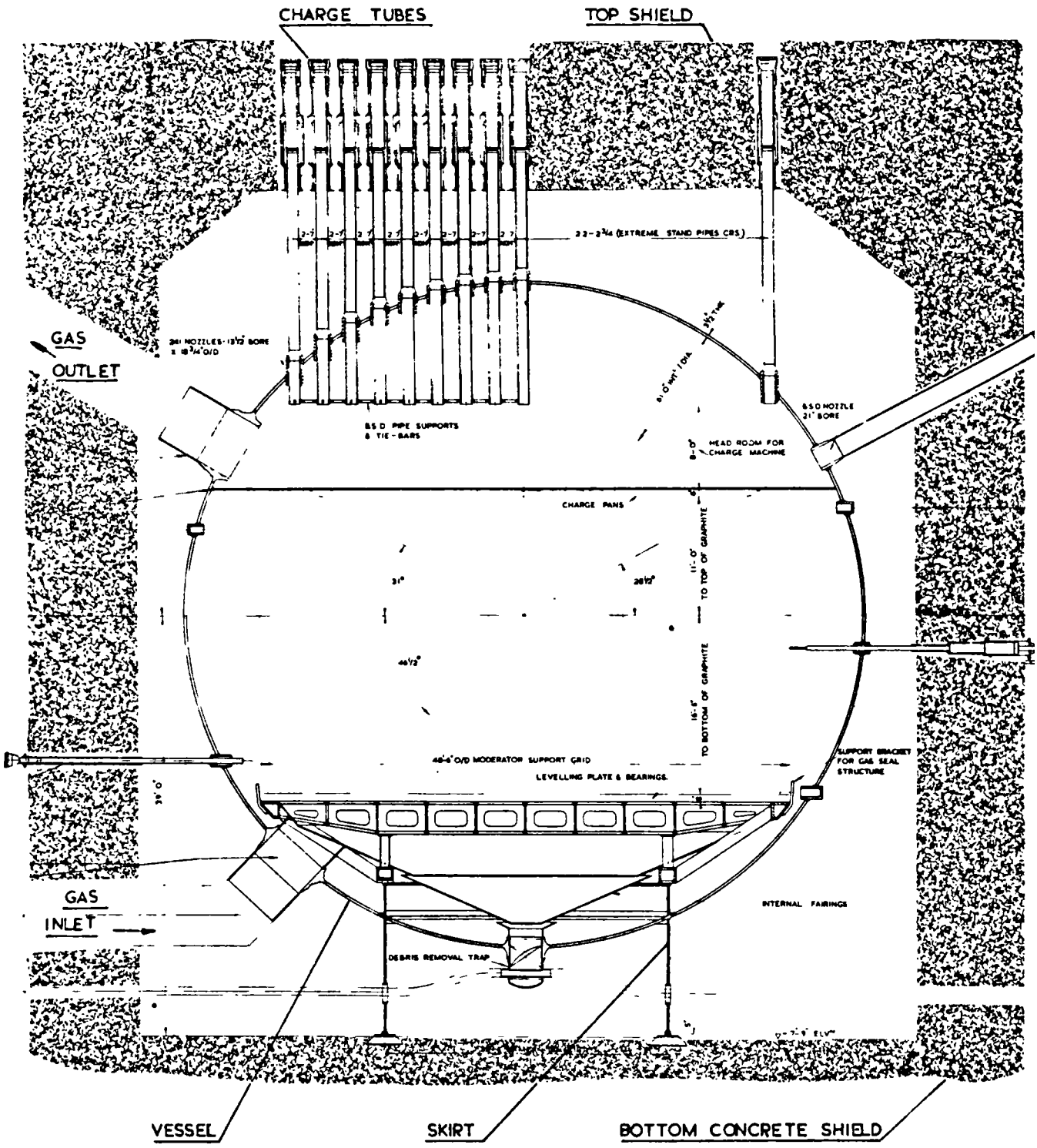
Construction was nearing completion in June 1961, J Plate 2, and the grid was lifted into place in the reactor vessel in November of the same year. J Plate 3 shows this operation and the Goliath Crane and special ring beam fixture which were used for handling the grid and other heavy components.

The Nuclear Power station was commissioned in 1963 and the grid has performed very satisfactorily to date.

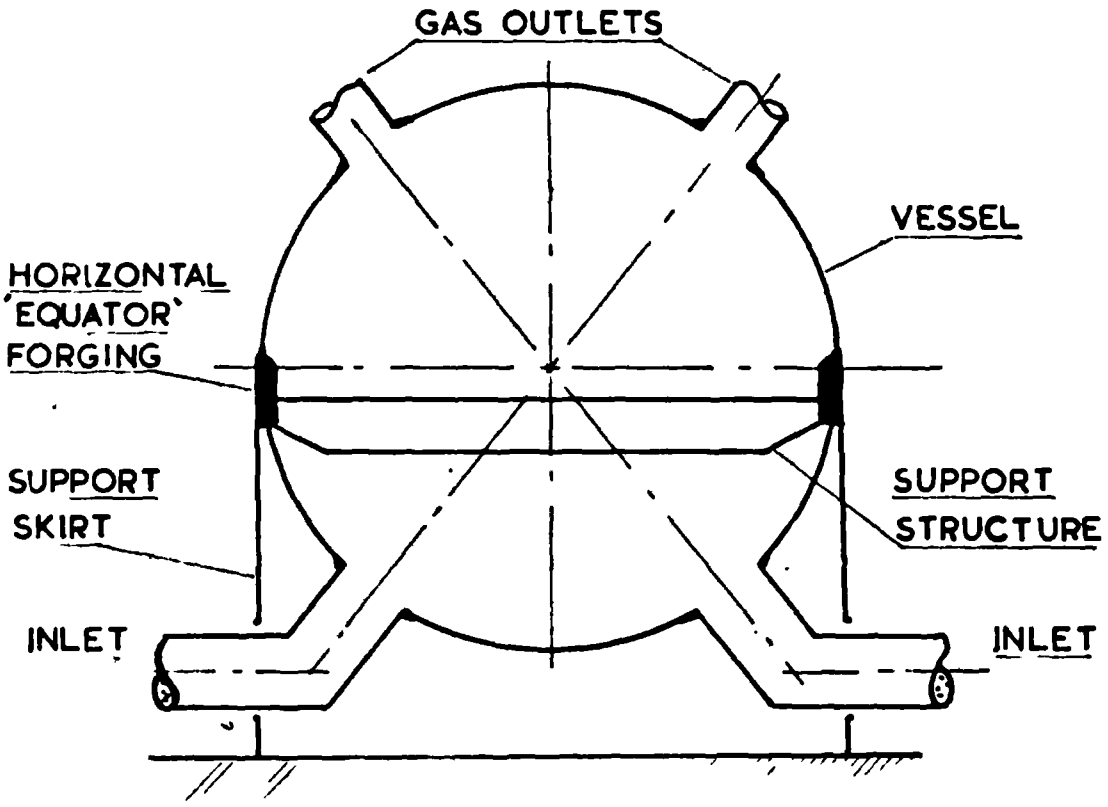
CONCLUSIONS

This design exercise lasted for more than four years and was near to one end of the spectrum of design situations. It was innovatory, technically complex, large and complicated. It was also administratively difficult in that it involved various design, manufacturing and research teams and the coordincation of several disciplines, for example mechanical engineering, civil engineering and mathematics.

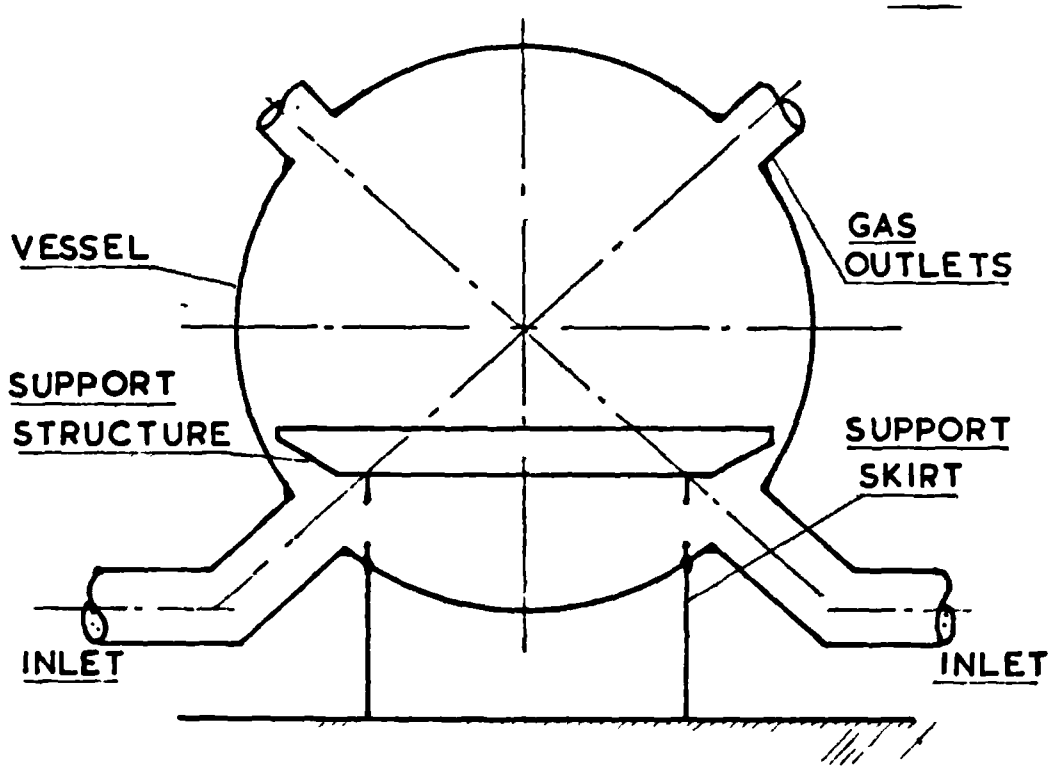
There was a strong element in this design exercise of the team proving its ability to produce a satisfactory solution before committing itself to the final detailed design exercise, and related to this the important role played by the customer who acted as both adviser and controller.



JFIG1 REACTOR DESIGN LAYOUT

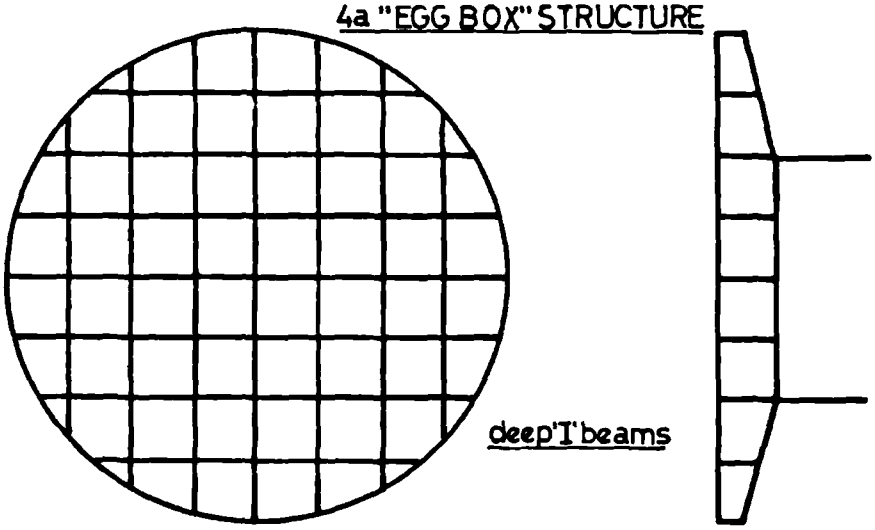


JFIG 2 FIRST DESIGN PROPOSAL



JFIG 3 SECOND DESIGN PROPOSAL

4a "EGG BOX" STRUCTURE



4b "SPIDERS WEBB" STRUCTURE

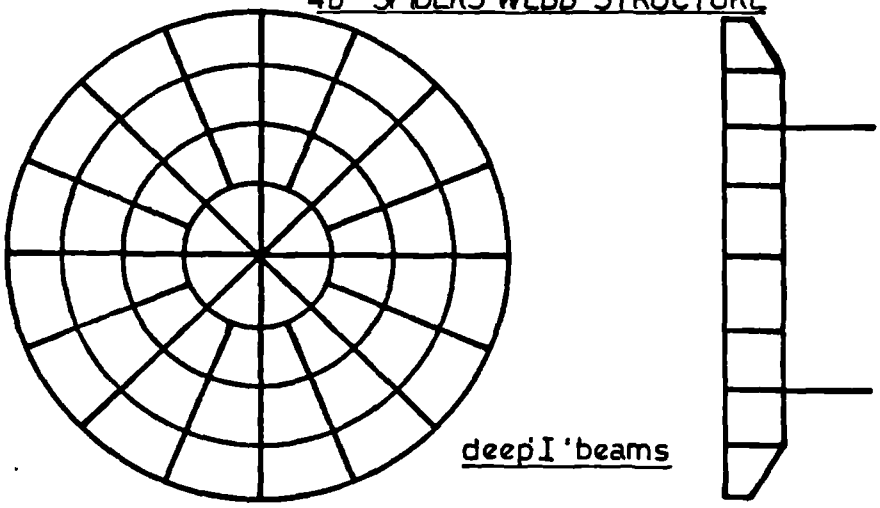
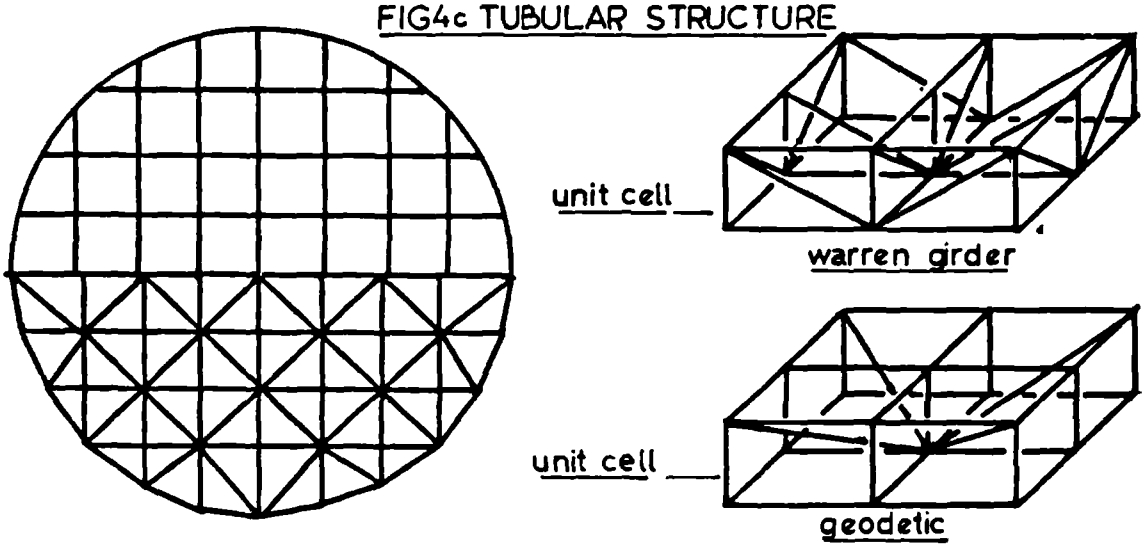


FIG4c TUBULAR STRUCTURE



JFIG4 SUPPORT STRUCTURE INITIAL PROPOSALS

FIG5a COMPOUND STRUCTURE 1

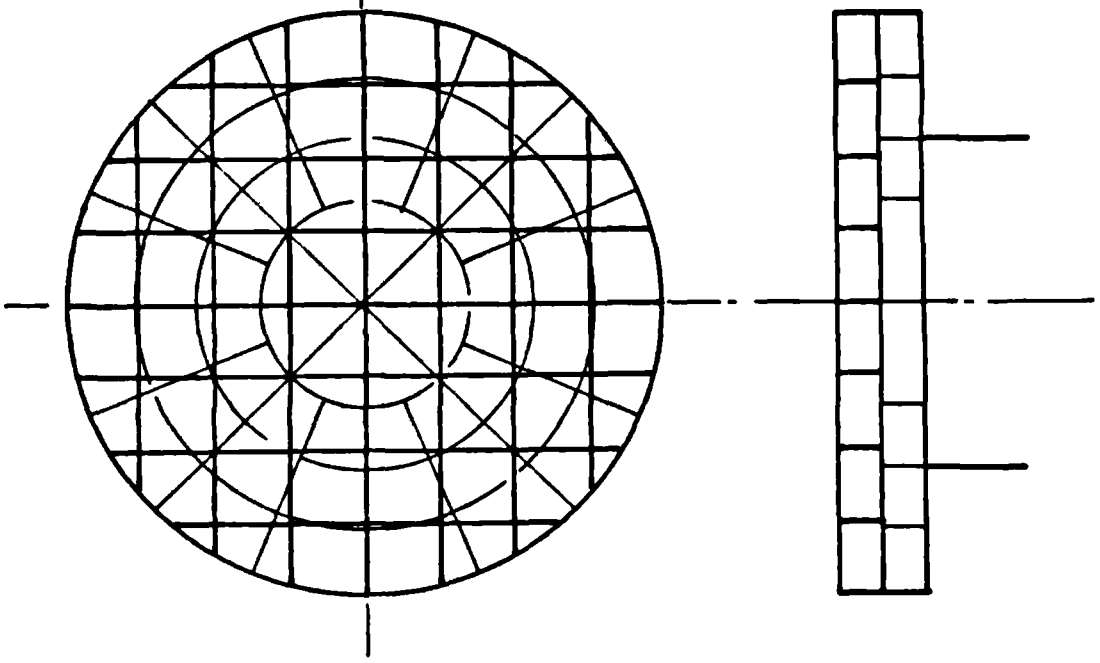
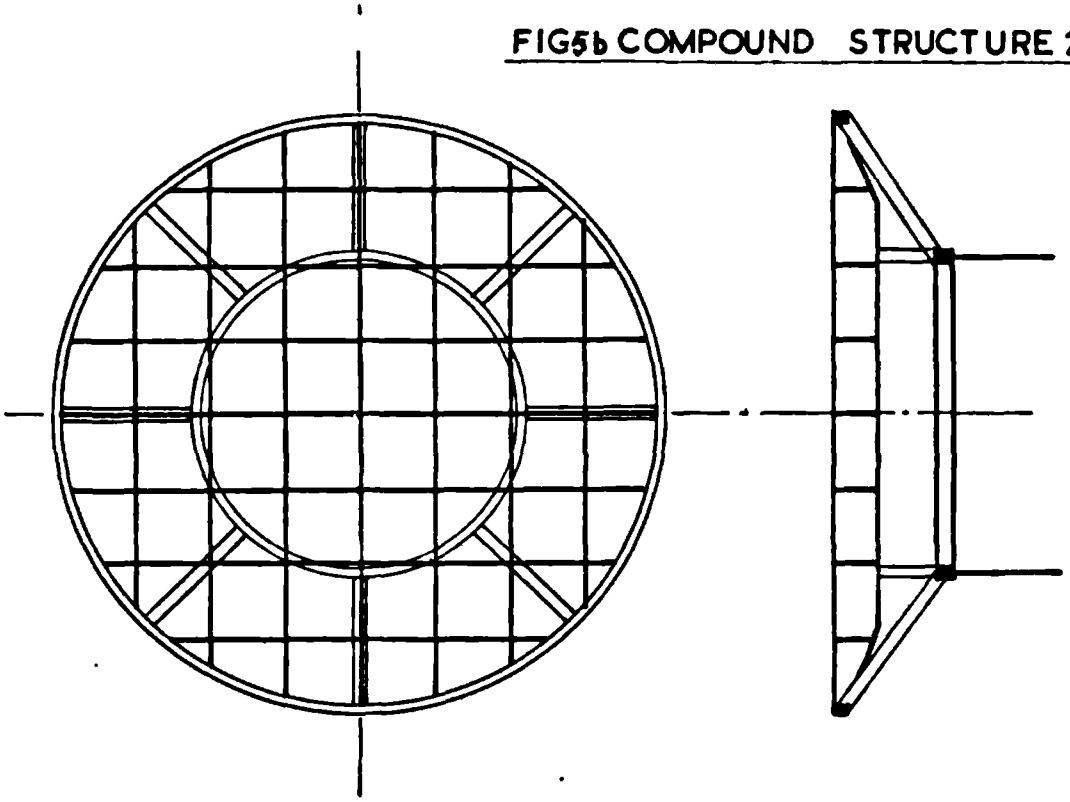
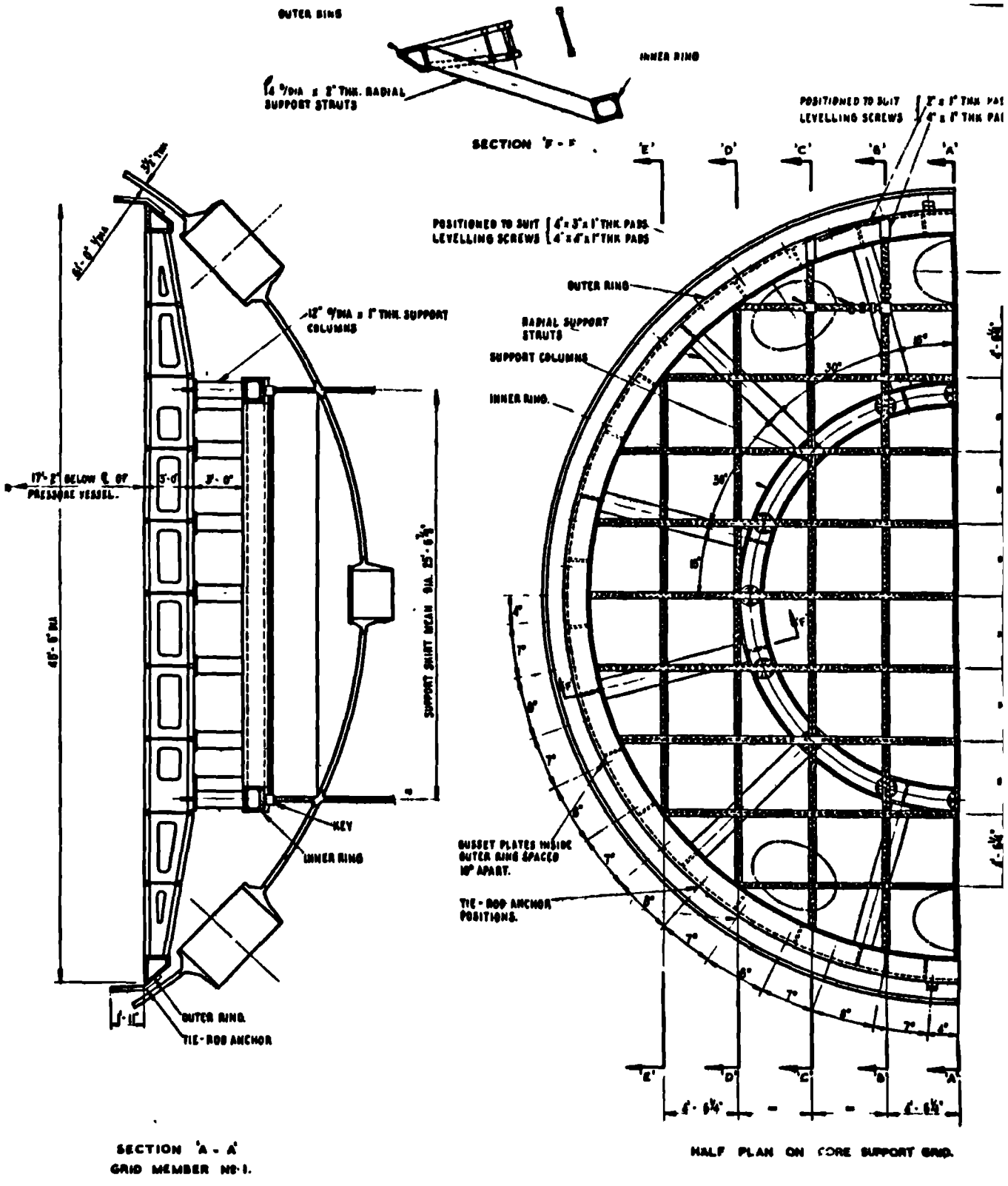


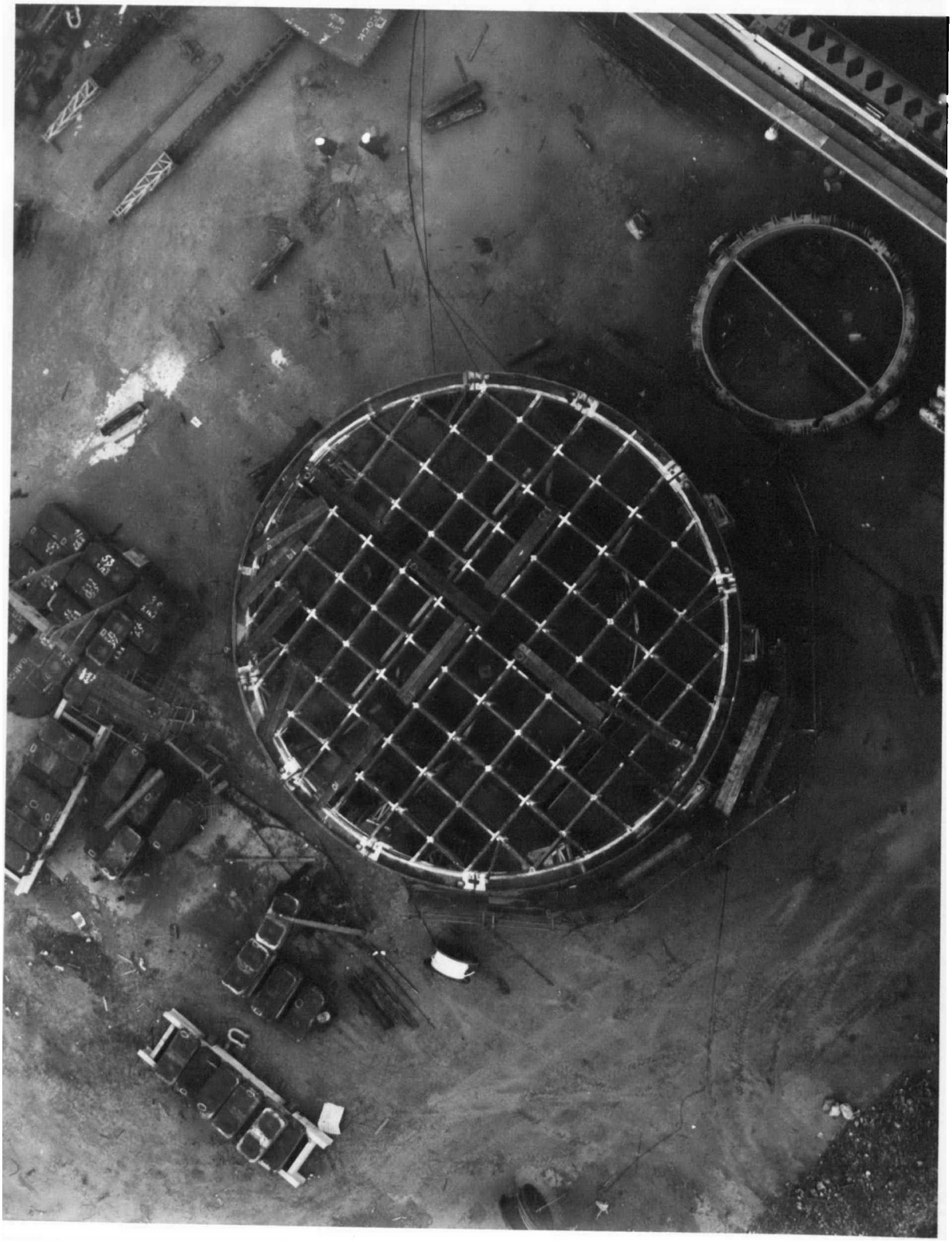
FIG5b COMPOUND STRUCTURE 2



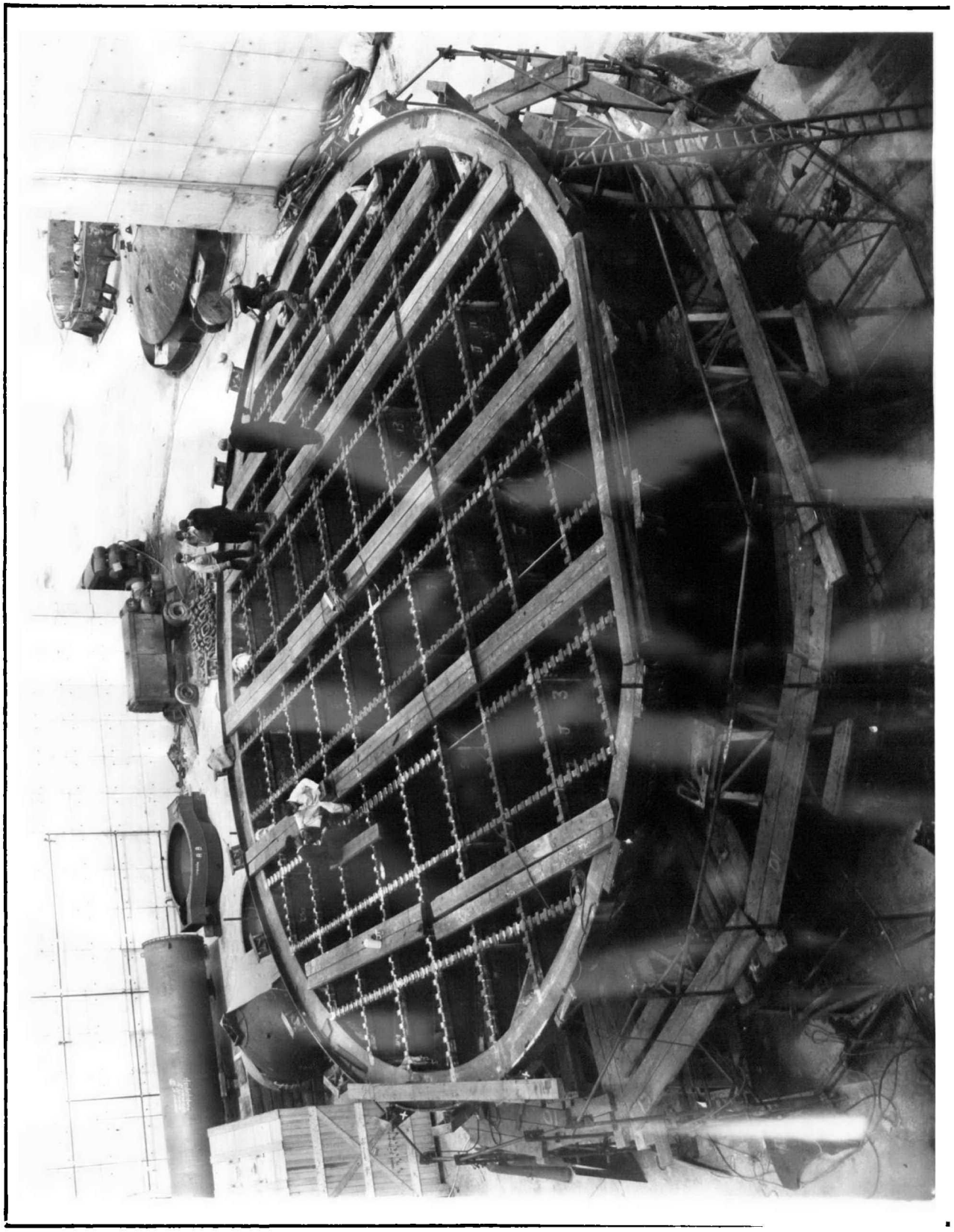
JFIG 5 SUPPORT STRUCTURE FINAL PROPOSALS



JFIG 6 SUPPORT STRUCTURE FINAL DESIGN



J PLATE1 CONSTRUCTION ON SITE



J PLATE 2 NEARING COMPLETION 21·6·61



J PLATE 3 LOWERING INTO POSITION 19·10·61

CASE HISTORY K

BEARINGS FOR MODERATOR SUPPORT STRUCTURE IN NUCLEAR REACTOR

INTRODUCTION

The contract to build an Advanced Gas-cooled Reactor (A.G.R.) Nuclear Power station was awarded to firm K in September 1965, the tender having been submitted in January of the same year. Preliminary work on the site started in October 1965 and the first reactor was planned to be commissioned in July 1970.

The station consists of two reactors with a combined output of more than 1300 MW. The reactor design is based on a graphite moderator which is CO_2 cooled and is contained in a cylindrical concrete pressure vessel, K Fig. 1. The moderator and its support structure are also enclosed by an inner steel pressure cylinder; the top end of this cylinder is domed and the bottom end is welded to the peripheral ring of the moderator support structure. A skirt attached to the underside of this peripheral ring forms part of a seal with the floor of the concrete pressure vessel to complete the pressure enclosure. The design of this seal provides for strain incompatibilities with the C.P.V. arising mainly from thermal gradients.

The double containment of the moderator described above is an important characteristic of the A.G.R. concept, providing - among other things - for greater control of the cooling gas leading to an improved performance.

The moderator support structure, K Fig. 2, which is circular in plan consists of a square grid of 18 in deep plate beams connected around its periphery to a box section ring. It is supported on 36 columns arranged symmetrically in octants and generally positioned in concentric circles with one other at the centre. The design criterion for the moderator is acceptable displacements; the slope of the top surface of the structure must be controlled carefully in order to give acceptable stresses in the moderator graphite and limitations on block tilting. In the first instance it was assumed that the degree of rigidity necessary to achieve this would give low stress levels, and this was to be confirmed later by a comprehensive analysis.

The peripheral ring of the support structure is mounted on the 20 outer support columns which are continued as flanged tubes grouted into the floor of the concrete pressure vessel and react the upward thrust of the gas loading.

The moderator is made up of machined graphite blocks; it is approximately 34 ft high by 27 ft in diameter and weighs 1123 tonf.

Vertical movement of the structure relative to the concrete vessel, due to loading and thermal expansion, is provided for by allowing a break in the charge path between the stand pipes and charge tubes. Relative radial movements are also allowed for in the circulator gas inlets. The horizontal movement between the support structure and the floor of the concrete pressure vessel is catered for by introducing radial rollers between support structure and its supporting columns. These rollers must be designed to carry very high loads in the adverse environment with a sufficiently low coefficient of friction to ensure acceptable horizontal load at the top of the support columns.

This case history attempts to record the design of these roller bearings. It is to some extent retrospective but since the design had not reached the erection stage when this work was started, and all the personnel and documentation were readily available, the author felt confident that his record would be complete.

THE PROBLEM

The tender for the station was submitted in May 1965, at which stage the major design decisions for the reactor had been made although not all the details had been finalised.

In the tender the need for moderator bearings had been recognised and they had been provided for. The experience gained with the previous design had enabled a rough but reliable estimate of feasibility and cost to be undertaken and an outside contractor, experienced in large roller bearings for bridges, had been contacted to confirm the conclusions reached by firm K. At this stage the cost of the bearings was so low compared with the overall tender price that a detailed design study was not justified.

When the station contract was awarded to firm K it was necessary to finalise the design details. The preliminary work on the bearings was undertaken by firm K but sub-contractors were sought for the supply of the bearings and pads. The contractor for the major items including the moderator support structure and the columns on which the bearings were to be mounted had already been decided. The assembly

and erection of the bearings was also to be sub-contracted. Thus the detail design of the bearings proceeded in parallel with other related design exercises on the part of firm K and several sub-contractors.

The factors affecting the design of the bearings which were considered at this stage are listed below, many of them were based on previous experience of an earlier design.

1. Loading

1.1 Vertical load

This would be the load during construction, the dead-weight load when the reactor was built but not operative, and the combined dead-weight less pressure load during operation.

The construction load would depend upon the construction programme and would include the support structure, the pressure cylinder, core restraint cylinder, discharge platework, the C.P.V. top head steelwork, the boiler temporary support and any other structure required during assembly.

1.2 Horizontal load

The requirement here was that the horizontal load on top of the support columns should be minimised. These columns presented several problems involving thermal insulation between the reactor and the concrete pressure vessel and it was considered inadvisable that they should also be subject to high bending stresses as a result of transverse end loads.

Inftially it was considered that the horizontal load would be only radial, due to rolling friction and the relative thermal movement between the grid and the concrete. The need to minimise the horizontal load meant that whatever the final design of the bearings a suitably low coefficient of friction was essential.

1.3 Load cycling

Some provision would have to be made for this.

2. Environment

The roller design would have to withstand the rather extreme environmental conditions underneath the reactor - Temperature, Pressure, Atmosphere (nature and contamination) and Radiation would have to be considered.

3. Cost

Maximum availability consistent with economic design was written into the enquiry sent to interested suppliers. A sum had already been allocated to the bearings in the tender price.

4. Size

The height of the bearings (rollers plus bearing pads) had to be carefully controlled. The overall design philosophy demanded that the reactor height be minimised, this meant that the height from the moderator support structure surface to the concrete floor was restricted and not subject to change.

The length of the bearings was more flexible and could be modified to satisfy the loading requirements.

5. Life of rollers

To be 30 years since this was the life over which the station was amortised.

6. Delivery to site

To be agreed with supplier. Details of protective coatings, packing for transit and during erection, matching and numbering to be covered.

7. Assembly on site

Details to be discussed with sub-contractors. Method of assembly and preparation for assembly would be likely to affect the design.

8. Time factor for delivery

To be related to construction programme for station.

9. Acceptable inspection and control by interested Authorities and Insurance Companies

STATEMENT OF THE PROBLEM

In January 1967 an enquiry was issued by firm K to three organisations which were capable of, and interested in, supplying the type of bearings supplied. By this time the design had begun to finalise, the detailed analysis of the moderator support structure had led to some important changes which had in turn affected the design of the bearings. The enquiry of January 1967 was for 72 bearings (two reactors): in addition to legal aspects including methods of delivery and payment it also listed the detailed working conditions.

In February 1967 representatives of firm K made visits to some of the suppliers

in order to settle certain queries on the enquiry and at the same time to assess the competence of the sub-contractors to supply bearings to the required standard.

Apart from difficulties of interpretation - two of the suppliers were from overseas - the following points were clarified.

1) The bearings as originally conceived would not carry a side force.

2) Tests would be carried out to proof load the bearings and to establish their coefficient of friction.

The tenders from the three sub-contractors were received during February 1967, and the process of comparison and assessment started immediately.

A price comparison was undertaken based on the cost of the bearings, delivery and duty; further changes for design and development, site supervision, inspection and maintenance were also assessed. As a result of this comparison and the reports on the competence of the sub-contractors one was recommended. Furthermore detailed discussions then took place on the design of bearings proposed by this supplier.

The details of the submission and the subsequent discussions which finalised the details of the design of the bearings is given in the following sections.

THE PROPOSED DESIGN

The design proposal submitted in the successful tender was based on the type of roller bearing shown in K Plate 1. It includes the pads, roller bearing surfaces and keys. The keys are a standard design feature and are incorporated to prevent 'wobble' as the rollers move. Two diameters of roller 125 mm and 150 mm were offered with six different lengths. These were designed to cope with the quoted loads and movements at the various positions.

The end bars are a standard feature of such designs and are designed to ensure that the rollers cannot roll completely out from between the pads. This could happen it a displacement cycle occurs with the pads opening up and moving relative to each other.

DEVELOPMENT OF THE DESIGN

At a meeting at the beginning of April 1967 between firm K and the sub-contractor, the following points affecting the initial design were raised:

1. Loading

The maximum working load on the bearings was now revised and increased. The new figures were 200 tonf on the inner 16 bearings and 300 tonf on the outer 20 bearings. This was due to changes in the erection programme which required that additional weight would be carried by the bearings for about 6 months during the construction period - there would, of course, be no movement of the rollers at this maximum loading condition. Moreover during normal operation the load carried by outer bearings would be very small or even zero.

The contractor confirmed that the design could be modified to cope with the new requirement by lengthening the rollers without increasing their diameter and hence the overall height. It was also agreed to design two standard bearings rather than six, and that this would help to maintain costs.

2. Friction Coefficient

The importance of an acceptably low value of the friction coefficient was emphasised by firm K. They requested that tests using the rollers and their bearing pads should be undertaken to measure the load to start movement, i.e. the initial coefficient. This was agreed by the bearing sub-contractor.

3. Bearing design

The following design parameters were also finalised.

1) All bearings to incorporate a radiused aligning feature in a direction parallel to the roller axis, in order to avoid the difficulty of providing two perfectly parallel surfaces between which the bearings would be positioned, K. Fig. 4.

2) The width of the top bearing plates was fixed as 8 in for the inner bearings and 12 in for the outer.

3) The inner bearing overall height to be within 425 mm and the outer to be within 367 mm.

4) The final overall height of each bearing to be confirmed by firm K as a result of a site survey. The contractor would then machine individually the packing pieces to suit.

5) All bearings to have a base plate of min. width 12 in to be drilled with four $1\frac{1}{8}$ in dia holes, suitable for 1 in bolts.

6) All bearings to include 'keep plates'.

7) The contractor stipulated a flatness for the plates between which the bearings are to be positioned.

The contractor was requested to submit a revised design and tender as a result of these discussions.

The revised design, K Fig. 4, was incorporated into the revised tender submitte during April 1967 and a letter of intent to place a contract with this supplier was despatch early in May.

The next stages in the development of the design involved minor discussions on the design calculations, inspection procedure, material testing and construction programr Tests on the friction coefficient and the corrosion characteristics of the materials were also planned and agreed.

The contract was signed in October 1967.

DESIGN MODIFICATION DUE TO SIDE LOAD

At this stage in the design it was found necessary fundamentally to reconsider the design of the main steel pressure vessel. This involved a tangential, rather than radial, gas flow into the vessel, this flow being deflected by large inlet cowls around the vessel. This resulted in a very significant turning moment being applied to the pressure vessel and it was decided in December 1967 to investigate the possibility of the bearings reacting this turning moment. The proposal was that the load should be transmitted from the grid to the columns via the key and keyways in the rollers. Initial calculations showed that the load along the axis of each roller would be about 15 tonf.

A meeting was arranged at the end of December 1967 in order to discuss the proposals in detail with the bearing sub-contractors.

At this meeting it was explained to the sub-contractors that due to the gas loading during operation the grid above the rollers tended to rotate. Calculations showed that this moment could be reacted by an axial load of 18 tonf on each of the outer 20 rollers, it was pointed out that this load would only be applied during operation when the vertical load on the rollers would be zero and there would in fact be a 1.5 mm gap between the roller and pad. Other transient conditions combining vertical and axial load had been considered but did not constitute a design case. The combination of rolling with the axial load did, however, need to be considered.

A scheme was then proposed by the sub-contractor which involved the

following modification to the outer bearings:

1) Increasing the dimensions of the key and grove to enable the axial load to be transmitted through them, subject to a preferential fit-up in erection.

2) Introducing a radius on the end of the rollers to accommodate tilting.

3) Shear bolts holding the end bars in position to counteract the twist of the bearings around a vertical axis. This twist is caused by the friction forces along the keyways as the rollers move outwards radially. These friction forces produce a turning couple about the vertical axis.

4) Introducing shear bolts and plates to attach the bearing pads to the grid above the rollers and the support columns beneath them.

It was agreed that a detailed scheme, with supporting calculations, should be prepared by the bearing sub-contractor. It was considered that the delivery date would not be affected. The revised design was completed by the sub-contractor early in January 1968 and a contract variation order was raised to cover the redesign and change in price.

In early March a further meeting was held to finalise the modified design and to discuss progress in manufacture. Detailed design alterations to prevent fouling of end plates on assembly, and the use of existing holes were agreed and a revised production was finalised which would enable the rollers to be delivered to site on time. It was agreed that a drilling jig should be made by the sub-contractor for drilling the holes for the shear bolts in the bearing pads and that this jig should then be forwarded for use on site.

THE FINAL DESIGN

During the period in which the geometry of the bearings had been finalised other work had been proceeding. The corrosion tests were underway and the friction tests had been planned. Discussions had also taken place on the method of erection of the bearings leading to 'Principle Statement' being prepared by firm K in conjunction with the sub-contractor responsible for erection.

Contractors were also approached for the design and manufacture of a special purpose machine for grinding the pads on the grid to which the upper bearing pads would be bolted.

In April 1968 a query was raised by firm K on the use by the sub-contractor of

a mild steel key against a hardened steel roller in view of the axial load on the rollers. The sub-contractors replied that the very low coefficient of friction obtained on similar bridge rollers meant that the wear on the keyway would be negligible. This was considered unsatisfactory by firm K as there would be no lubrication of the rollers in operation and it was conceivable that the roller and key might 'freeze'.

In July 1968 the friction tests were completed giving satisfactory results on the distortion of the rollers and the coefficient of friction. These tests were witnessed by firm K representatives and the insurers.

At this time a meeting was arranged between firm K and the sub-contractors to discuss the friction and wear problems on the rollers. Two important points were discussed at this meeting.

The first was the effect of the CO_2 atmosphere at high temperature. Work done had shown that for unlubricated couples in this environment it was beneficial to use unlike materials of similar hardness rather than a soft/hard combination as in general practice. The contractors replied that the slow sliding between the roller face and key under the 18 tonf load was not significant. They quoted comparable bridge loads which had behaved efficiently.

The second point, raised by the contractor, was on the reported tilting action of the roller under zero vertical load which would be produced by the axial load. This they felt would lead to line contact, between the key and roller.

It was agreed that firm K would investigate both these points and report back. Some discussion also took place at this meeting on the protective coating to be used on the bearings during transit.

Further discussions took place during July and August 1968 - they were mostly concerned with problems related to construction. The supply of drilling jigs, the drilling of additional holes and the protective coating for transit were discussed and agreed. Firm K and the bearing contractor also agreed to prepare a statement justifying the choice of key material and the friction force between the key and roller.

Further problems from site were raised on the allowable angle through which the self-aligning pieces could be rotated and the parallelity of the keyways. In November 1968 the maximum angles with which the radiused aligning features on the bearings would have to cope were measured on site and found to be greater than the 1^{o} limit recommended by the sub-contractor. This was due to the slight distortion of the support grid around its periphery. As this figure was in excess of that quoted by the

bearing sub-contractor, they declared that it was unacceptable. The situation was much worse on the outer bearings because of the large radius on the aligning feature.

Further study of the sub-contractor's submission showed, however, that they had based their calculations on the assumption of a point load system which was unrealistic and severe. After discussion the sub-contractors agreed to revise their calculations and subsequently showed that considerably increased angles (up to 4°) could be catered for or, alternatively, at the previously imposed angles the acceptable loads could be increased.

At the end of November 1968 firm K and the sub-contractor submitted their case to the customer on the acceptability of using the bearings to carry side load. The sub-contractor pointed out that they had used their bearings on a bridge in Holland in which they were subjected to a maximum side load of 20 tonf and a vertical load of 500 tonf. The movement catered for was 250 mm resulting from a temperature variation of $35^{\circ}C$. After six years' operation in a sea atmosphere there was no sign of damage or corrosion to the bearings, keys or keyways. Firm K pointed out that in the present design the radial movement of the grid occurs during transient conditions and that as the system is at half pressure during warm-up the side load is reduced to about 9 tonf, the down load will also be less than the maximum design load. The only other occasion when movement will occur is on shut down, in this case the temperature difference, and hence the movement, will not be so great and there will be a down load combined with the reduced side load to prevent excessive wear on the keys and keyways. Thus there was no possibility of a situation arising where the keys were subjected to a maximum side load during movement without a veritcal load being applied.

An executive progress meeting was held at firm K in mid-November to review the following aspects of the design and progress with erection:

1) Roller ratings
2) Tests to be undertaken on Rollers
3) Erection tolerances
4) Flexibility of columns and grid
5) Foundation movements
6) Grid and column machining
7) Column loads
8) Further work

This meeting was critical in many respects; the most significant changes were that the organisational aspect of the design was changed giving overall responsibility to

one of the companies 'troubleshooters', and it was decided to draw up and issue a detailed specification restating and clarifying the design requirement. This would enable all the problems so far encountered to be considered and where possible solutions to be embodied in redesign of the outstanding bearings and modification of those already supplied.

This specification was issued in December and a copy was forwarded to the bearing sub-contractor. The critical loading cases were stated as:

Proof test

Cold start-up

Normal operation - new vessel

Normal operation - old vessel

ERECTION

The first set of bearings was delivered to site during December 1968. Early in January 1969 a query was raised on the design of the dowels locating the bearings into the grid. These dowels had been designed to a German standard which did not satisfy the relevant U.K. standards for use in a Reactor.

To overcome this a design modification was introduced involving a slight increase in the size of the existing dowels, a change in material and the insertion of an extra dowel.

The tolerances to be achieved by grinding the lower face of the grid had been relaxed by firm K since the erection contractor had found it impossible to achieve the required limits in the time available.

Although this did not present serious problems in the tangential direction, owing to the radiused slip pads, it did cause considerable difficulty in the radial direction. If the top surface of the column and the base of the grid were not perfectly parallel in this direction the grid would rise or fall as the bearings moved out radially. This would redistribute the load and could cause excessive stresses in the structure.

At this stage the erection of the bearings became critical to the construction programme and the design philosophy and detail were subject to very close scrutiny by the erection and coordinating teams within the company. As the date of erection of the bearings approached a detailed study of the ramifications of the change in construction programme, and the resulting increased loads on the bearings, was continued. An analysis of the column design and the grid structure suggested that the outer columns should be

erected to an 0.008 in limit and the inner columns to an 0.004 in limit. Further studies on the distortion of the concrete vessel and the flexibility of the ring beam were also initiated.

Further problems began to arise as the first sets of bearings were inspected on site, surface finish and tolerances on some dimensions were not considered satisfactory. In particular the matching of the upper pads to the radiused tilting pads and the keyways into the bearing pads.

At a meeting with the bearing sub-contractors they emphasised that firm K had paid for, and been supplied with, bridge bearings, not precision bearings.

A letter from the customer queried certain aspects of the design philosophy including the effect of the environment, the wear between the pads and keyway and the number of thermal cycles on which the design was based. The allowable stress used in the dowel design was also queried and an amplification of the erection statement was requested.

It was agreed that an associated firm should undertake certain machining operations on the bearings in order to achieve the required accuracy on overall height, keyway parallelity and tilting pad matching. A further meeting with the contractors responsible for erecting the bearings clarified the outstanding points on technical and administrative aspects of the erection schedule.

Following discussions with the customer it was agreed to increase the size of the bearing locating dowels to give an acceptable stress level. This work was to be carried out by the associated firm and at a meeting in January 1969 the new design proposals were approved.

At the end of January a statement was issued by the troubleshooter in firm K which outlined the design and erection philosophy. This statement included the first formal attempt to define the overall design problem and listed the prime reasons for positioning the Moderator Support Structure very precisely as:

1) To ensure correct distribution of load.
2) To accommodate the thermal expansion.
3) To ensure an adequate torque restraint system.
4) To ensure satisfactory matching and operation of the main gas seal outlets, diffuser and fuelling machine nose mounting.

The main features of the erection proposal were that pan jacks were to be placed on the top of each column and the grid lowered on to them; using these pan jacks

to level the grid to a fixed height relative to the gas inlet datum, the column gaps would then be measured for height, parallelity and tolerances.

Calculations had shown that in order to ensure that the load on any column during erection does not exceed the acceptable loads it was necessary to locate some of the outer bearings vertically to ± 0.003 in. Tests on the vertical flexibility of the outer ring on the grid had shown that a vertical load of 7.35 tonf applied at an outer column position was necessary to produce a vertical ring deflection of 0.001 in at that position and this ring flexibility had been used to investigate the effect of variations in the column loads.

By using the computer programme to investigate the effect of variations in column loads it had been ascertained that the optimum condition occurred when the innermost columns were set 0.040 in high, the intermediate columns were set 0.030 in low and the outer columns were at datum. Allowable tolerances on these settings would then be 0.008 - 0.012 in.

It was considered that this arrangement gave the most realistic combination of acceptable loads and realisable tolerances. It must be remembered that the severest loading case occurred during erection and that the operating loads were less critical.

The design proposal was to build in some means of adjusting the bearing settings to these close tolerances and also to monitor the actual loads during erection. If the loads became excessive a proposal for by-passing the column was in reserve. The basis of this philosophy was that the design should not be controlled too rigidly by the erection loads.

Tests were carried out at the laboratories of firm K to establish how best to monitor the loads on the bearings and to check the load displacement characteristics of a bearing assembly. At the same time the design team was preparing drawings stipulating the required tolerances and indicating how they should be achieved and measured.

Early in March 1969 a procedure was established for delivering the bearings as they arrived from the sub-contractor and modifying them to take the new dowels, and to satisfy the new tolerance and surface finish requirements. The matched bearings were then forwarded to firm K's laboratories where duplicated strain gauges were fitted to the rollers and each bearing assembly was calibrated.

The laboratory tests showed that all the small gaps and malalignments in the bearing assembly were taken up by fairly small loads and the subsequent load-displacement characteristics were monitorable and consistent. It was anticipated that all this work would be covered in the original firm K cost estimate for the supply and assembly of the bearings.

FINAL PROPOSALS

The final design and erection proposals had evolved from the rigorous study of the situation as erection day approached. This was considered reasonable since with a large one-off operation of this type, where many of the factors controlling design and erection were not ascertainable or foreseeable at the initial design stage, a late review and revision is inevitable.

The final proposals, which were put to the customer at a meeting during May, included a detailed Method Statement of the installation schedule plus a proposal to provide for the monitoring of the column loads during erection.

A proposal for additional support at some of the column positions during erection was also presented with a very detailed analysis of the loading in the support columns under all the erection and operating conditions given in the Method Statement. All these features, and in particular the manoeuvrability engendered by monitoring the loads and providing for shims, were key factors in obtaining approval of the final proposals.

During March 1969 a Variation Order was issued by firm K to the bearing sub-contractors covering the additional work to be undertaken to cater for the design modifications. Calculations showing that the load-accentricity effect on the columns, and the thermal cycling effect on the wear between roller and key, were unimportant were forwarded to the customer.

In April the load sensing system to be used on site was finalised and agreed with the customer. An Appendix to the Principles Method Statement was issued to cover this. The proposal involved a series of strain gauges attached to the ends of the rollers. To achieve the required sensitivity a rosette of four gauges was fitted to each end of every bearing roller using the Brazilian Concrete Cylinder Test method. For long term reference a pair of Demec points was fitted to the top and bottom main plates. Each bearing assembly of roller main plates and slipper block was to be instrumented and calibrated at firm K's laboratories prior to despatch to site.

In May the customer formally accepted the revised Principle Method Statement covering the installation of the bearings and grid; although a query was raised on the calculation of the eccentricity effects this was satisfactorily answered by firm K.

On site during this period a serious problem had arisen involving cracks in the grid ring beam welds directly above the rollers. This had caused the date on which the grid was to be lowered to be postponed and had lessened the urgency on the bearing erection.

Work continued on the erection with several minor problems of dowel hole matching and matching between the grid and the columns.

INSTALLATION OF THE BEARINGS

The author made several trips to site during August and September to witness and assist with the setting up of the bearings and the final jack-down of the Moderator Support Structure.

Several problems arose on site due mainly to the lack of matching between the grid and the support columns. The pads on the underside of the grid were radially displaced from the centre line of the support columns, and the holes in the peripheral ring of the grid, in which the restraint bolts were to be fitted, were circumferentially displaced from the matching holes in the outer bearing support stools. Both these problems were cleared by the Design Department of firm K.

The very close tolerances called for in the bearing erection drawings were achieved on site using a Hilger Watts theodolite with a Taylor-Hobson telescope and special attachments.

All this work was done in the reactor under clean conditions. As outlined in the detailed Method Statement the philosophy was to locate the moderator support structure in a datum position and then to measure very accurately the required shim thicknesses on each bearing to ensure correct final location. The inner bearings would be set higher by 0.040 in. than the outer bearings so that the load they carry is greater - since the structure and columns can accommodate this - but the variation between adjacent columns should be restricted to 0.012 in. on the inner columns and 0.008 in. on the outer columns.

By the end of September 1969 the problem over lamellar tearing in the structure welds had proved not to be serious and had been overcome and the support structure had been lowered to less than 3 in. from its final position.

During jackdown when the shim thicknesses were measured it was discovered that some of the shims would be less than 3/8 in. thick, and the contractors for this work then stated that they could not machine shims to the required accuracy if they were this thin.

One method of overcoming this problem was to interchange the slipper blocks to give the required minimum shim thickness. This had the disadvantage of possibly

invalidating the overall bearing calibration of load against strain gauge reading.

In view of the programme urgency it was decided to change the slipper blocks to allow the work to proceed, but before doing so it was confirmed that the Demec readings would give some indication of the loading and the strain gauge readings would also be of some value since the slipper block to top-pad fit had been re-machined after delivery and was therefore reasonably consistent.

The decision was to some extent a gamble on the belief that due to imponderables such as column flexibility, grid behaviour and friction loads - all of which had been assessed pessimistically - the loads on the bearings would prove to be sufficiently low to prevent further work from having to be done.

In October 1969 the grid was lowered on to the bearings and the strain gauge readings and clearances were recorded and reported to the Design Department, where the two main aspects studied were the vertical load on the columns and the horizontal torsional load to be expected.

The following points arose with respect to the vertical loads on the outer columns, K Fig. 5.

(a) The total load was 1350 tonf compared with a measured load, from the Tangye jacks used to traverse the grid, of 980 tonf and a theoretical load of 865 tonf.

(b) Two of the loads were unreliable having been estimated from the Demec readings since the strain gauges at these stations were inoperable.

(c) The strain gauge readings were not very reliable since they were calibrated before the slipper blocks were changed. Moreover there had been higher than expected discrepancies between readings at each end of the bearing rollers, due possibly to the 0-0.003 in tolerance on the flatness of the bearing pads.

On alaysis of these detailed results it was agreed that the strain gauge readings were obviously exaggerating the column loads. However calculations based on the most pessimistic interpretation showed that the loads on the outer columns satisfied the conditions laid down in the Method Statement: the maximum erection load was 273 tonf (column 32) compared with an acceptable load of 300 tonf and under the other critical condition , hot shut down, the maximum column load was 181 tonf compared with an acceptable load of 200 tonf.

The horizontal loads were also analysed following the measurement of the clearances between the keys and keyways. The maximum gap was 0.008 in and calculations allowing for the column lateral flexibility - in parallel with the retaining bolts - showed that in the worst possible case only one of the rollers might not transmit some of the torsional load. The maximum column load in this case was 17 tonf and this gave a factor of safety of greater than 3 on the acceptable side loads on the columns.

In view of the above and the facts that time was critical and the grid was found to be located very accurately, it was decided not to attempt to readjust the shims in order to produce a more even distribution of load, but to proceed with the erection of the core.

It was agreed however that the loads would be continuously monitored - the Demec readings would become more reliable as the loads increased - and the effect of shim adjustment would be investigated in more detail on the second reactor.

On this basis the erection was satisfactorily completed by the end of the year.

CONCLUSIONS

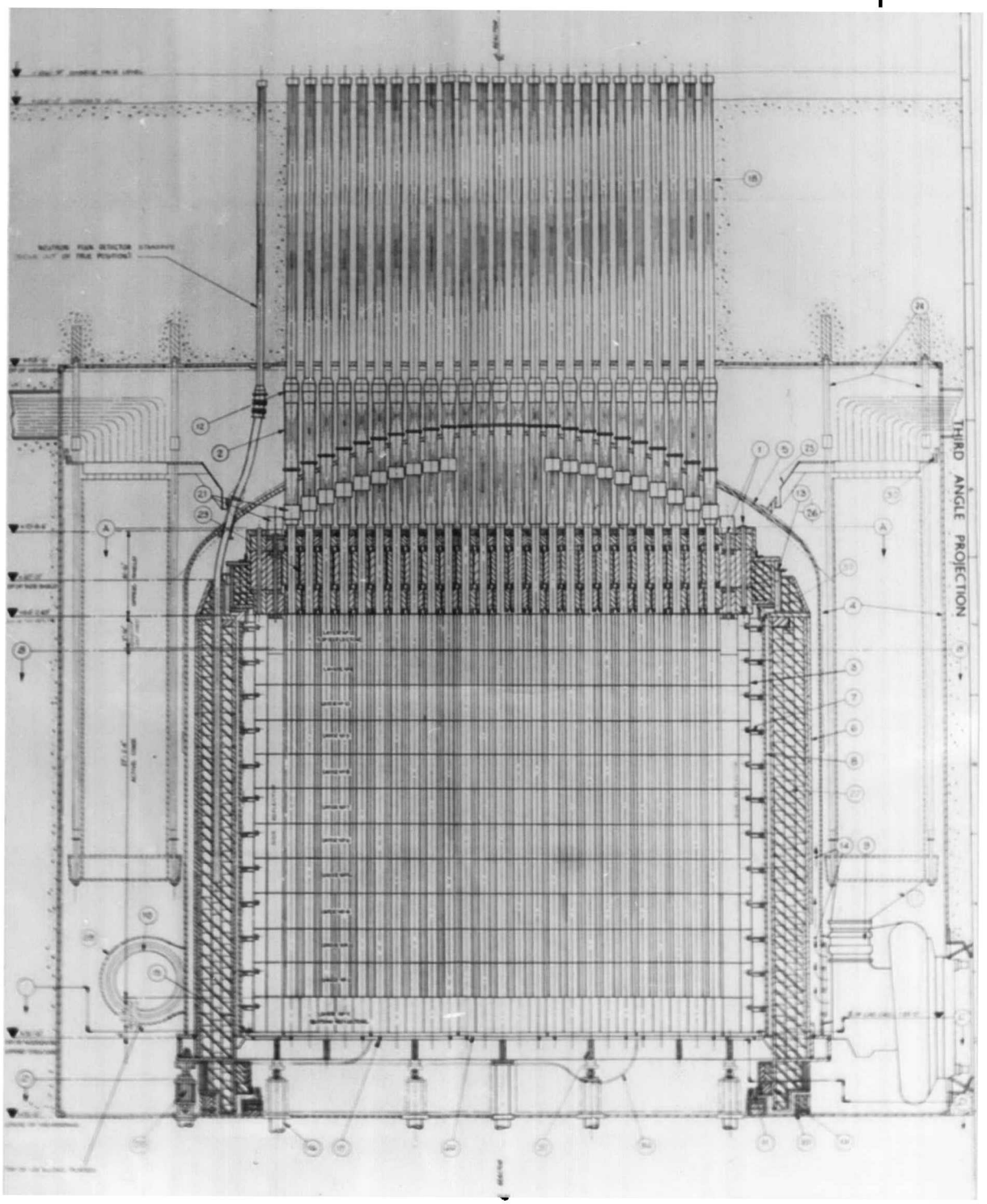
During the early part of 1970 fundamental reorganisation of firm K took place and the author's detailed knowledge of the design of the bearings, from the original concept to final erection, became of some value.

As erection continued the difficulties experienced and overcome in erecting the first set of bearings was valuable in setting up those in the second reactor. Monitoring of the loads was continued using primarily the Demec facility.

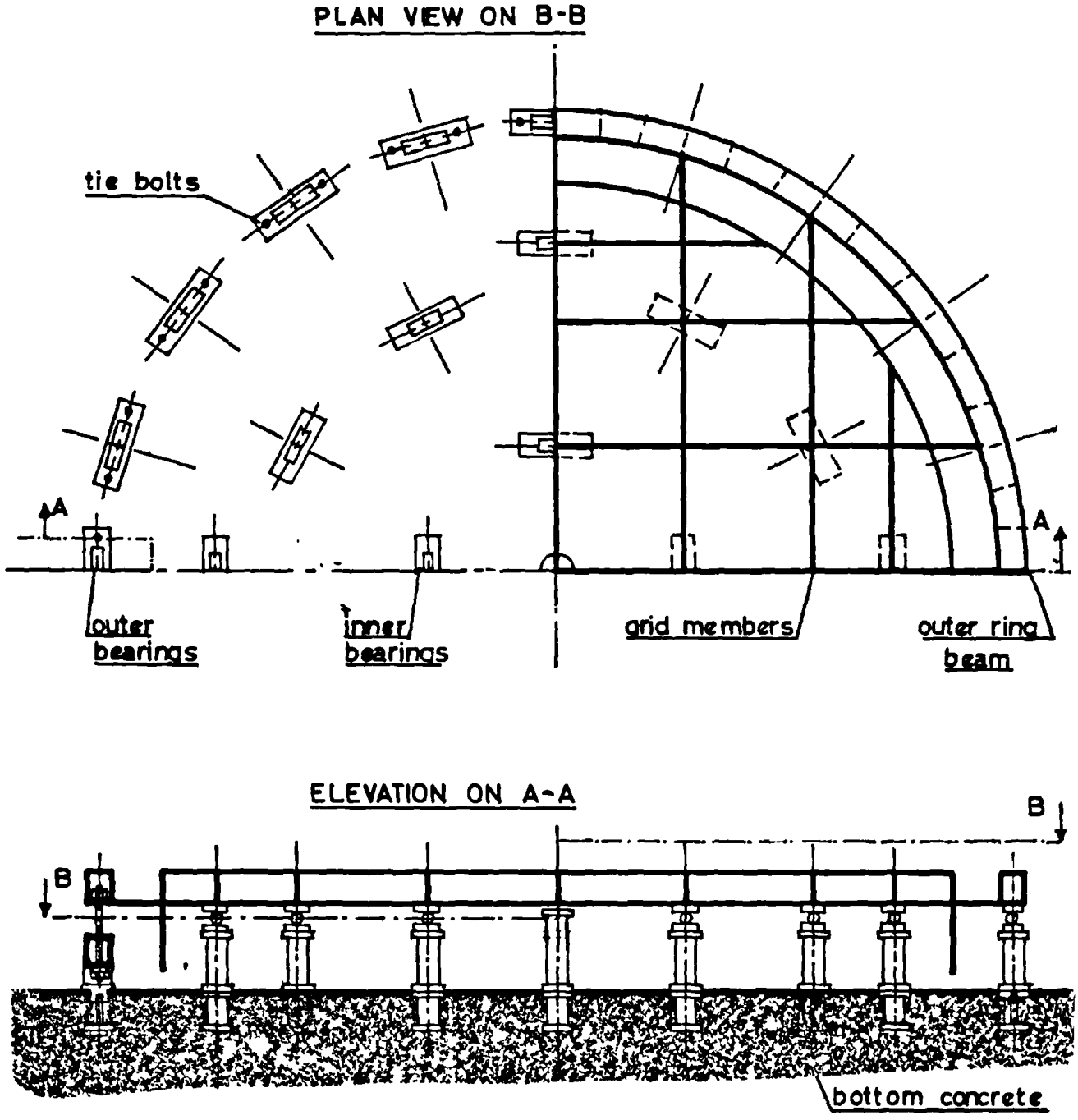
Major problems encountered with other aspects of the station caused considerable delays on the erection programme and changes of personnel in firm K and of sub-contractors.

These changes however involved no significant modifications to the bearing design and erection concept which was subsequently used in the second reactor.

The conclusions on the difficulties experienced by the designers in case history B also apply to this case history.

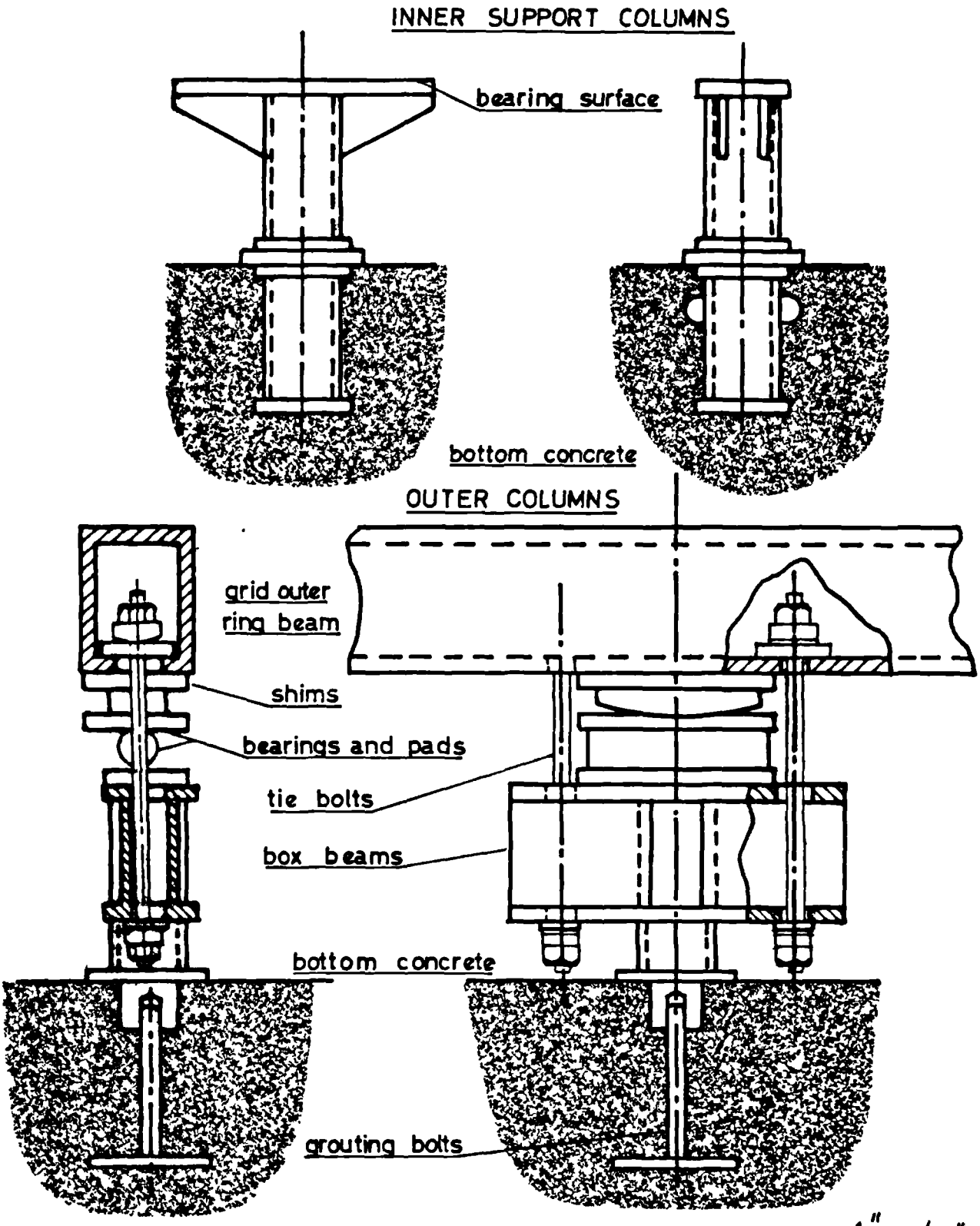


KFIG 1 G.A. OF REACTOR CORE



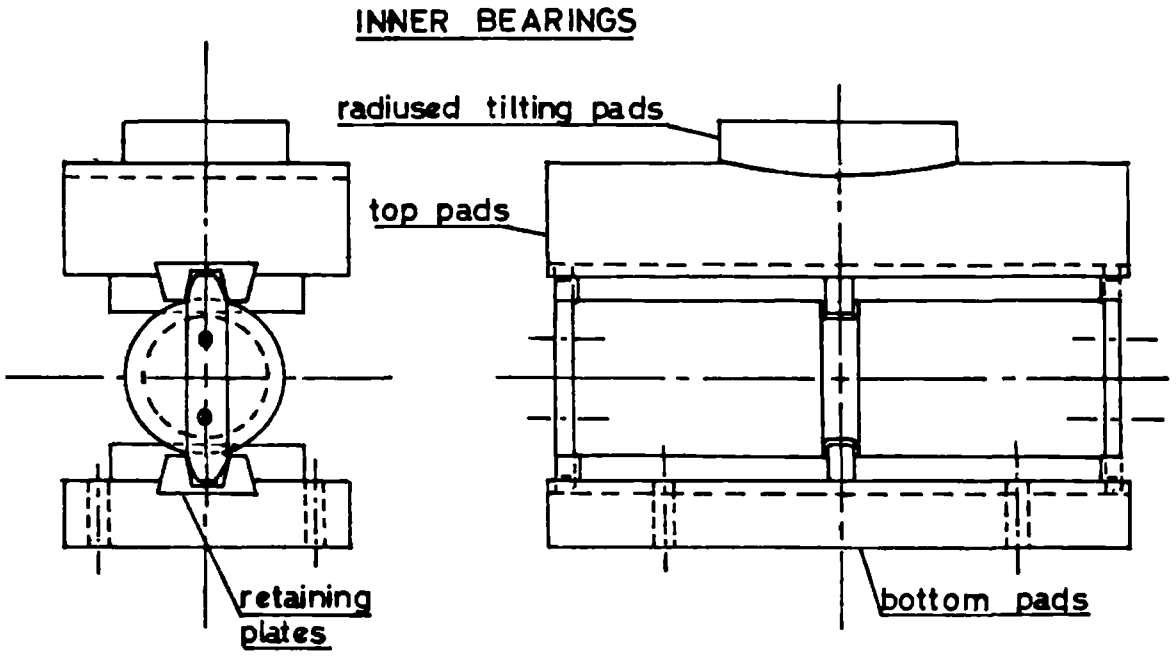
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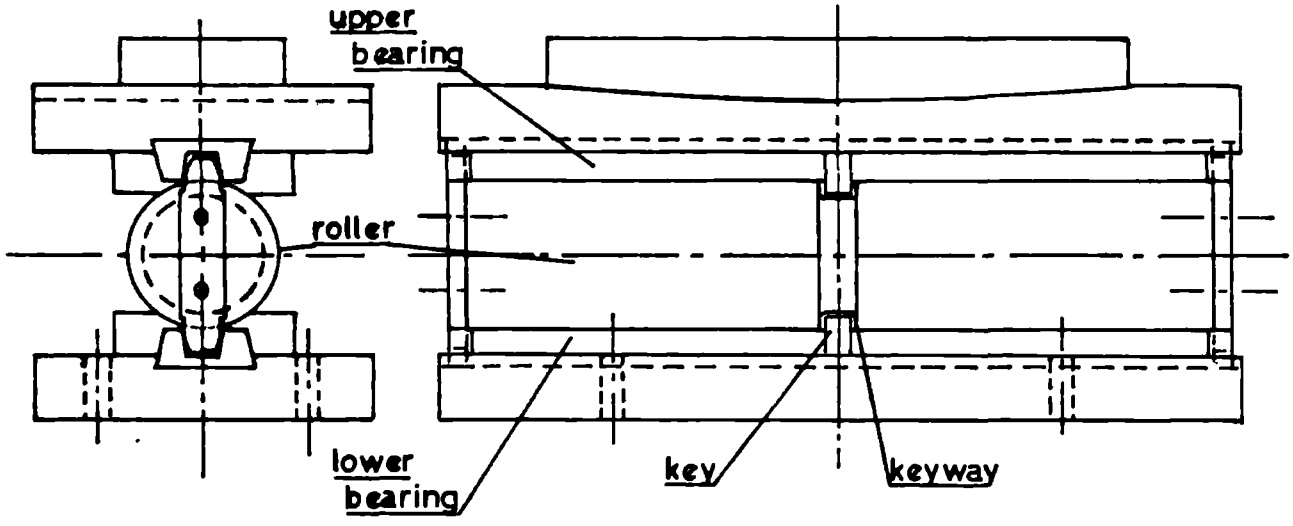
KFIG 2 SUPPORT STRUCTURE AND COLUMNS



KFIG 3 SUPPORT COLUMNS

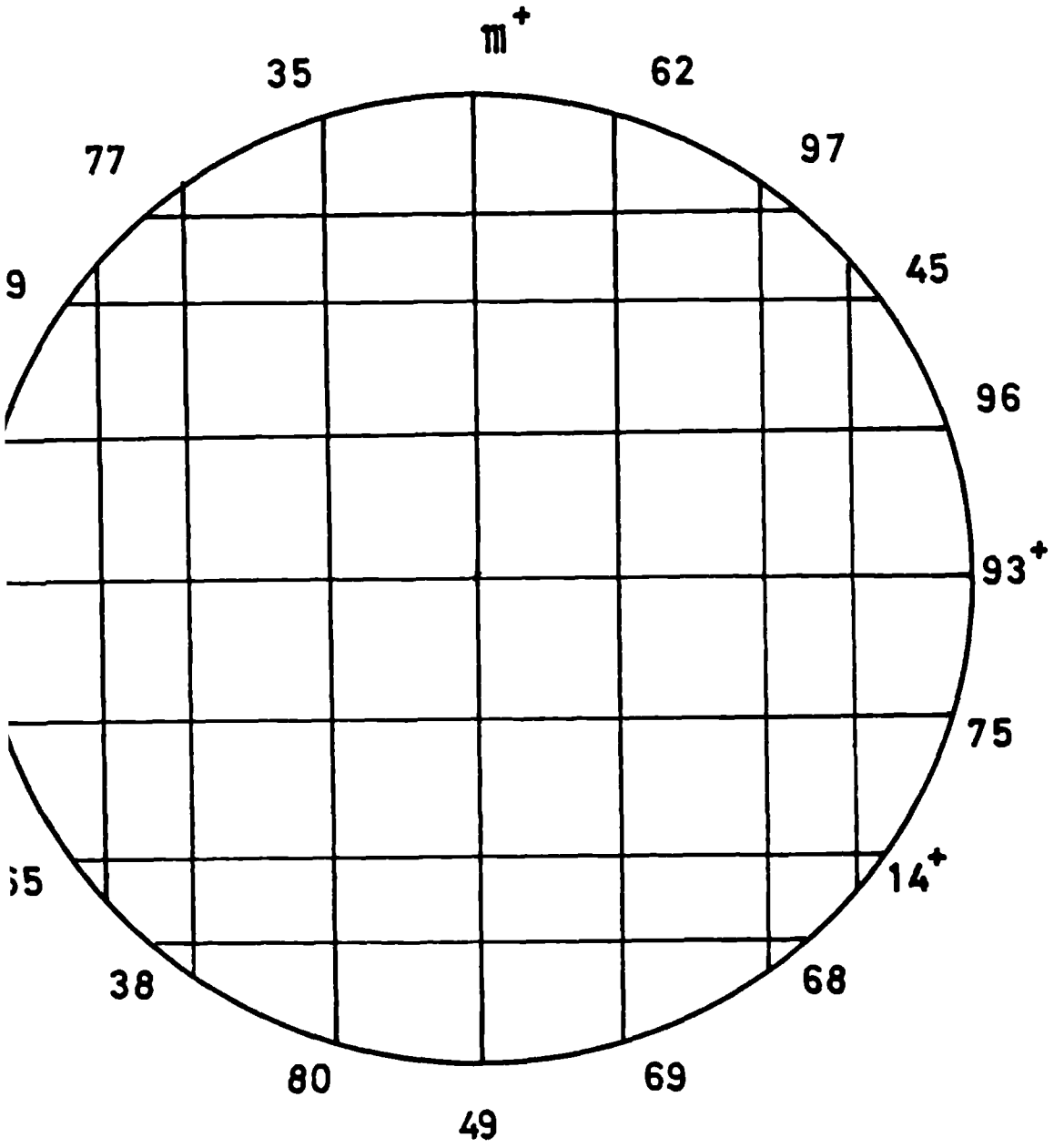
SCALE ½" = 1'-0"





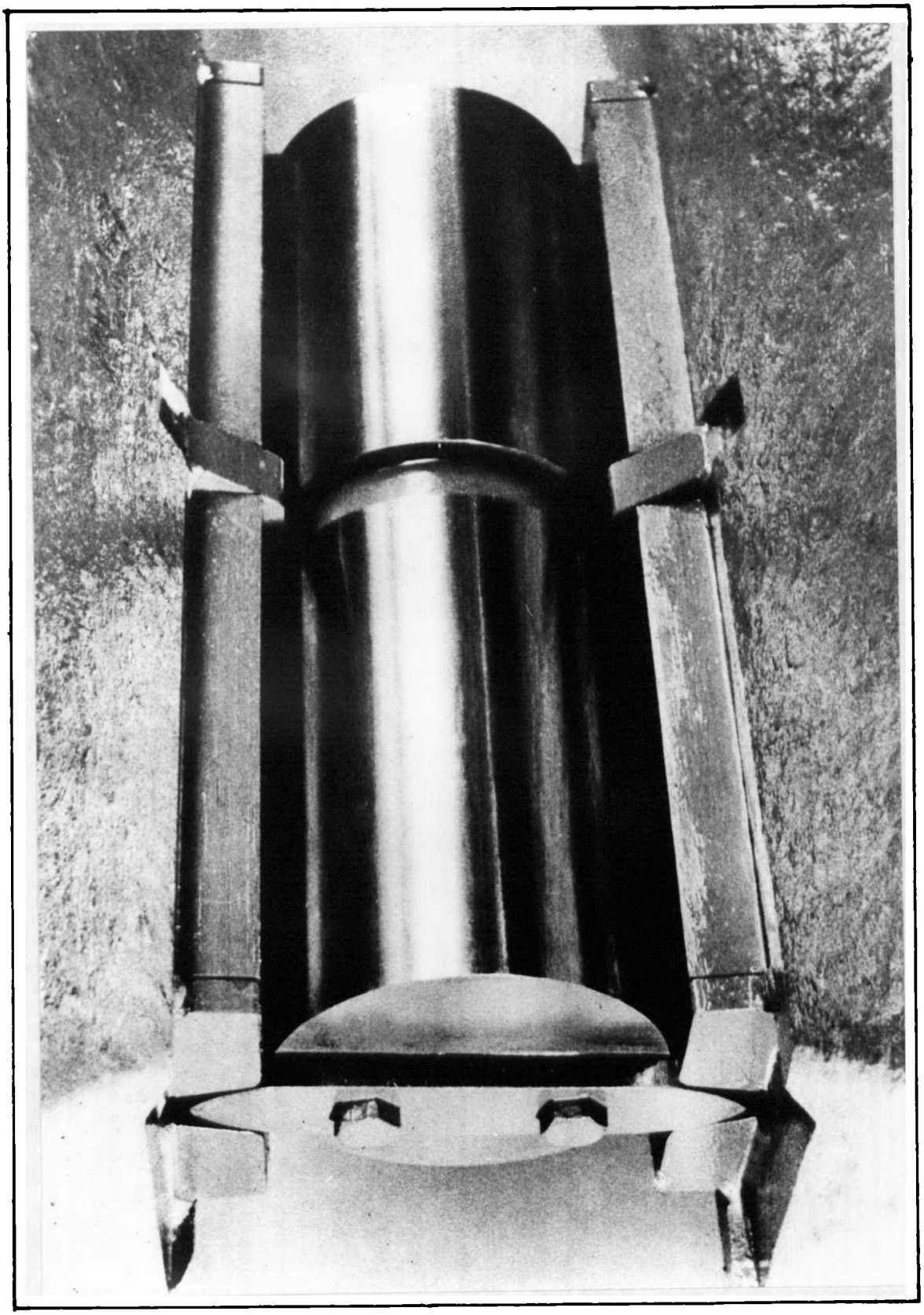
SCALE 1" = 200mm

KFIG 4 FIRST BEARING DESIGN PROPOSAL



Demec reading Total load - 1378 tonf

5 LOADS ON OUTER COLUMNS AT JACKDOWN(tonf)



K PLATE I TYPICAL BEARING DESIGN

CASE HISTORY L

SEWING MACHINE TWO-FENCE FOOT

INTRODUCTION

An aid to production in commercial dress design is the 'fenced' sewing machine foot, L Plate 1. This special foot enables a uniform seam to be sewn neatly, accurately and quickly by semi-skilled labour, but only permits one seam width to be selected for a given foot, as the distance from the needle to the fence is fixed. This case history covers the design development and production use of an improved foot incorporating two 'fences' either of which may be selected.

The work was undertaken by the author as a design consultant working with the managing director of firm L who commissioned the project for use in his technically advanced fashion production workshop.

THE BRIEF

The brief was originally presented to the author early in 1969. Although no firm statement of the problem was presented the following list of factors was made by the author immediately after the first meeting:

To design a sewing machine foot with two fences 8mm and 16mm from the needle with a means of selecting either fence or no fence as required during operation. The limitations on the design being:

1) The fence should be able to be easily moved longitudinally relative to the foot.

2) The fence selection should be able to be made conveniently during the sewing operation.

3) The fence spaces need not be precise.

4) The design must be reliable with little maintenance.

5) Space limitations were severe, allowance had to be made for operators' fingers and additional special equipment.

6) The design to be simple and cheap.

The design was to be for a new XYZ sewing machine which had been ordered by firm L and was to be modified and automated to provide a novel and advanced sewing unit.

The designer's lack of previous experience in this field was recognised as a serious disadvantage. However, the availability of the considerable experience of the managing director and the accessibility to his production facilities meant that the necessary information would be readily available. This in fact suited the designer who felt that the successful design of a product of this kind was sensitive to the operators who will use it, and that they should be used as much as possible in its development.

INITIAL PROPOSALS

The initial attempts by the designer to produce a solution involved a fundamental assessment of the problem. It was decided that the basic problem was to provide an adjustable stop for the material a given distance from the needle.

The possibilities considered were as follows and are illustrated in L Fig. 1.

1) A stop attached to the machine bed rather than to the shoe.

2) A sliding, spring-loaded edge to the shoe which could be moved towards or away from the needle.

3) A shoe with a single fence, the whole assembly being movable.

4) A double fence shoe with a mechanism for selecting either or no fence.

All these possibilities, had given rise to related problems on materials, shoe design and operator requirements which necessitated a further visit to firm L for additional information. A delay over the supply of the XYZ machine had also occurred and was holding up progress.

As a result of this meeting the following decisions were made.

1) The initial design should be based on the existing sewing machines so that most of the problems could be established and solved before the XYZ machine was available.

2) A stop attached to the machine bed rather than the shoe was already in existence and had not proved satisfactory.

3) The special shoe with a sliding spring loaded edge did not appear to be a feasible proposition on the basis of cost or satisfactory operation in factory conditions.

4) A movable shoe was a possible solution with minor difficulties over rigidity and needle location.

5) The double fence shoe with a selecting mechanism appeared to be the most suitable proposal on condition that the mechanism could be simple enough to satisfy the overall cost requirement. The managing director had one valuable suggestion to make on this proposal, which he clearly favoured.

The designer now felt that he had sufficient information and feel for the problem to attempt a design. It was recognised that there would probably be several prototype designs before the final solution was evolved and that most of the real proving would be done with the operatives.

FIRST DESIGN MK 1

The decision was made to concentrate on the double fence design and to adopt aspects of the movable shoe proposal if suitable, or revert wholly to it if necessary.

The Mk 1 design proposal is shown in L Plate 2, no detail drawings are available, it was made from rough sketches and verbal instructions from the designer.

The design consists of a channel into which was fitted a spring fence. A cam lies under the fence near its attachment screw and on turning this cam the spring is forced through the slot in the shoe to provide the necessary fence.

This model was used to test the idea on an existing machine and the following notes were made.

1) The rear of the channel fouls a thread cutting attachment. This is not a serious disadvantage and can easily be overcome by moving the cutter.

2) The front of the channel has very slight clearance on the needle holder; this should be remedied.

3) The design works well and positively. A layer cam and redesigned spring will make it even more positive and give further room for development.

4) No serious problems appear to occur with the operatives. The model is easy to use and does not cause any obstruction.

5) The handle shape is not critical and can be finalised later.

6) The rigidity of the assembly on the machine shaft needs improving.

On the streng th of this apparently successful trail it was decided to proceed with the Mk II version.

SECOND DESIGN MK II

The drawings produced for this model are shown in L Fig. 2 and a photograph in L Plate 3.

Two springs are fitted between the channel section. A rod underneath the springs has a filed section which is such that on rotating the rod either or neither spring projects though the corresponding slots in the shoe. The assembly is bolted rigidly to the machine shaft, a grove in the side of the channel preventing any relative movement.

The drawings and the design were explained in detail to the fitter who was to make the model, and as a result of this an error in the spring development was noted and corrected before the component was made.

The manufacture of suitable springs proved very difficult with the limited resources available but the design was made to work satisfactorily in spite of this. A calculation on spring stresses had shown them to be high but a comparison with the existing fixed fence foot showed this to be much worse. Moreover the new design of spring would not be under any strain when it was not being used.

The Mk II model was tried on an existing machine during August 1969 and the following notes were made:

(a) The shortened length of the channel improved clearance, and although a thread cutting device was near to the side of the channel, this could easily be moved.

(b) The operating lever moved through 180° and this was not satisfactory since it was in the way of the operator's fingers in the extreme position.

(c) The rigidity of the assembly on the foot shaft although improved was still not considered satisfactory.

(d) The springs were not suitable in that they were not sufficiently resilient but a satisfactory shape was developed from them.

In October 1969 a trial was run on the other aspects of the XYZ machine - all the working parts having arrived and been set up. This trial was not very successful since the pneumatic system which had been used did not react quickly enough.

It was decided, however, to proceed with the special two fence foot for the machine, although of course, the delay in the other aspect of the work lessened the urgency on this.

THIRD DESIGN MK III

In November 1969 firm L decided that the work undertaken so far on the automated machine did not indicate that it could be satisfactorily completed to programme, they therefore arranged for the work to be continued by another company, although the design of the two fence foot was still to be the respansibility of the author.

An inspection of the XYZ machine showed that a major factor had been overlooked in its design. In spite of a written request from firm L the spacing between the needle and foot shaft was not the same as on existing British machines. This meant that a modification would be necessary before standard feet could be used. It was agreed that this should be done since all existing attachments were based on this standard. The author produced a proposal for this modification.

The Mark III design is shown in L Figs. 3 and 4 and L Plate 4. The main improvement over the Mk II design is the redesign of the cam to give selection of either fence in a 45° movement of the operating handle rather than a 90° movement. This led to the complication that since the cam was no longer self locating in the fence down position some system of locking it had to be introduced. This was effected by means of a spring loaded operating shaft with two locating pins. Although this has the disadvantage that the operating shaft needs to move axially it was considered that this would not be a major disadvantage.

The length of operating lever and the handle were designed so that the component could be used on the XYZ or existing machines. The spring design was finalised and was shaped to be used on either a fixed or pivotted standard sewing machine foot.

The equipment was to be attached to a standard foot shaft, rigidity of the assembly being improved by screwing the circular shaft into a vee notch.

The Mk III design was presented to a small manufacturing firm at the end of November and they submitted a tender for the manufacture of three off which was accepted by firm L. The author maintained contact with the manufacturers whilst these three prototypes were made.

During manufacture it was agreed that the cam should be locked in position by means of a spring loaded ball locating into a plate on one end of the cam shaft. This had the advant ages that there would be no axial movement of the cam shaft and by increasing the spring strength the retaining torque could be adjusted during trials.

An influenza epidemic closed the factory producing the springs during the first part of December and since these were the items controlling the manufacture of the Mk III version the work on the initial three shoes was delayed.

A minor drawing error was discovered after the first set of springs had been made but a subsequent error by the spring manufacturer - producing the wrong handed springs - enabled the drawing error to be corrected when the replacement springs were produced.

FINAL TRIALS

In January the author collected one of the Mk III feet from the manufacturer and fitted it on standard sewing machine at firm L.

The appearance, location and function of the foot was very satisfactory but the following minor points were noted:

1) The spring loaded ball did not provide sufficient torque to retain the cam in the forward(16mm seam) position, particularly when a sewing machine with a high level of vibration was used.

2) The profile of the vertical face of the springs did not match the bed of the machine and also projected too far forward for small radii seams to be sewn.

3) The spring profile was in error by about 3mm.

4) The lateral fit between the springs and the shoe which depended upon the shaft dimensions, was in error by about 2mm. This however was not serious and to some extent alleviated the problem outlined in (1) above.

All these difficulties had been foreseen by the author and by grinding the springs - which had been made slightly oversize - and adjusting the cam load the foot was made to work very satisfactorily.

It was agreed that the foot would be left on trial for at least a week before the final drawings were made.

FINAL DESIGN

In February 1970 the author visited firm L where, as a result of the trials, it was agreed to modify all three Mk III versions of the foot which would then be given protracted trials in the workshops before a production batch was ordered. This would also enable a version for the XYZ machine to be finalised when the modified machine was delivered.

The only modificationswhich had arisen as a result of the few weeks trial, in addition to those mentioned above,were the need to increase again the retaining torque exerted by the spring and to correct the lateral matching of the foot and springs.

On returning to the manufacturer with the first version it was discovered that the shaft which had been used to ensure the lateral match between the foot and the springs, was slightly oversize and as a result the Vee notch was too deep. As the three prototypes would be used on several types of machine it was decided to use a packing washer to achieve a satisfactory match.

The Mk IV model, shown in L Figs. 5 and 6 and L Plate 5, embodies all the modifications listed above plus a more elegant thinner design of operating handle which was to be bent to give additional finger clearance on the XYZ machine.

CONCLUSION

On delivery of the three Mk IV shoes in April 1970 two were immediately fitted to existing machines and the third was fitted to the new XYZ machine. These models have proved very satisfactory and have formed an integral part of the XYZ advance sewing machine concept.

The success of the final design in this exercise was due in large to the accessibility of the prime sources of information; the special expertise of the managing director of firm L and the opinions and experience of the operatives. A further important factor was the recognition by the author that several imponderables would only be revealed and assessed by means of the trials and that it was therefore important to build modifiability into the earlier designs.

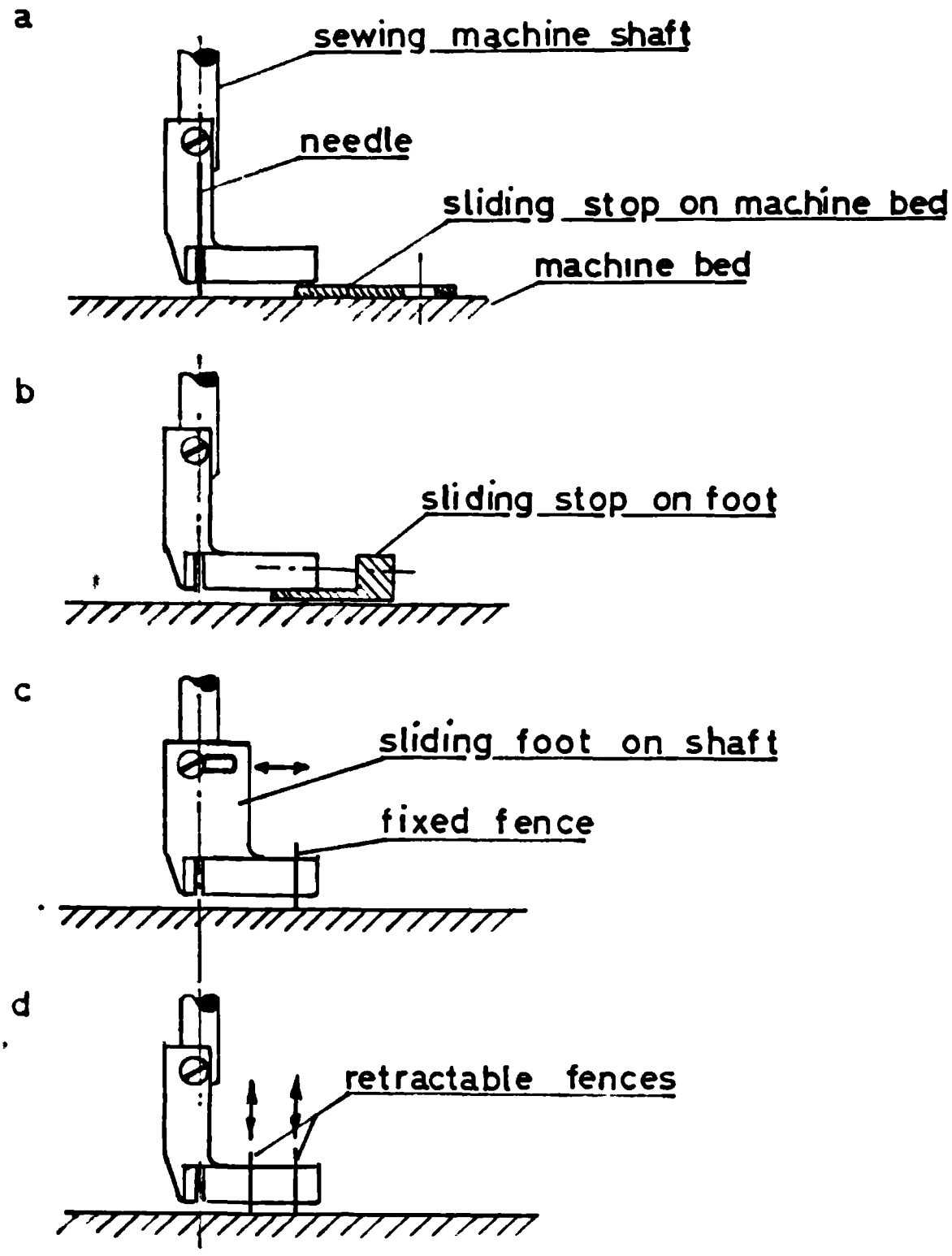
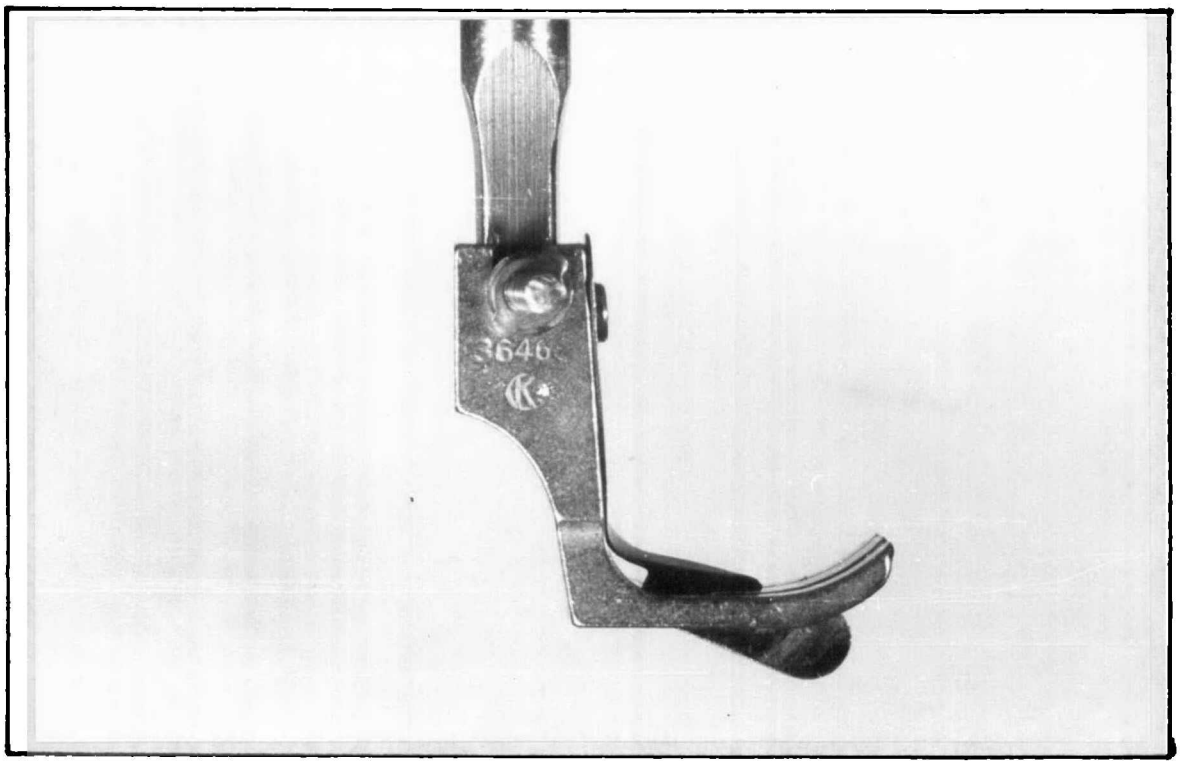
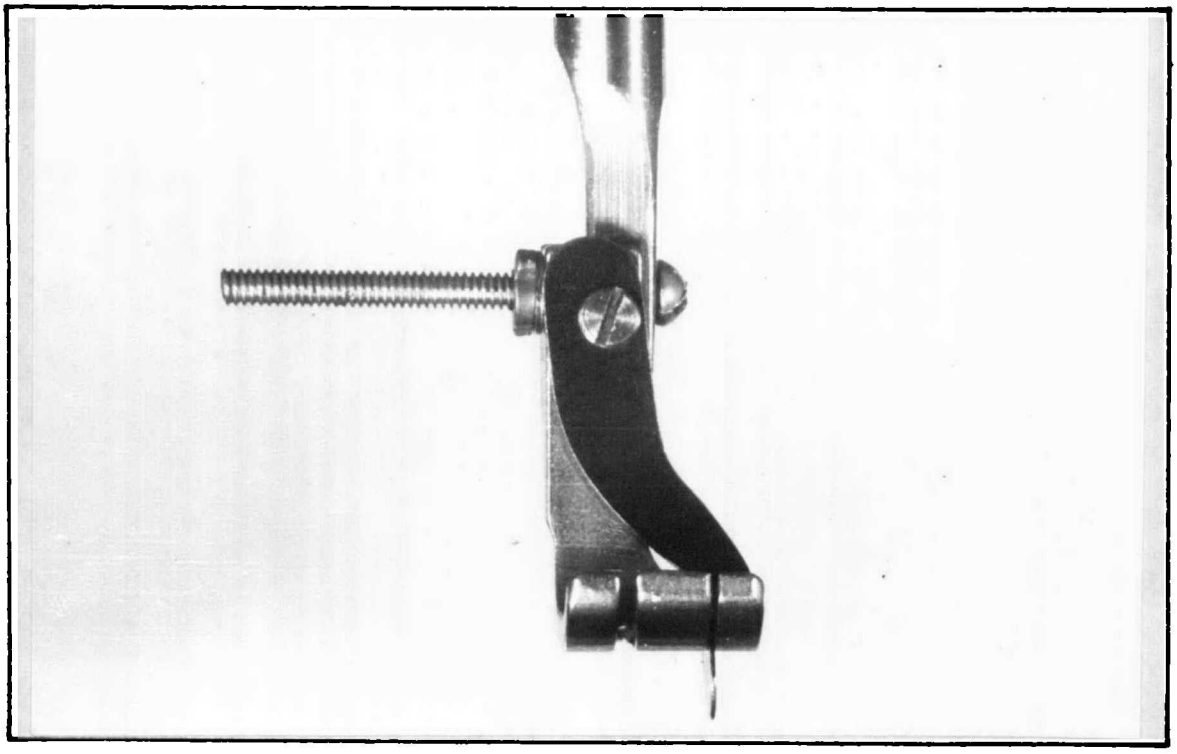
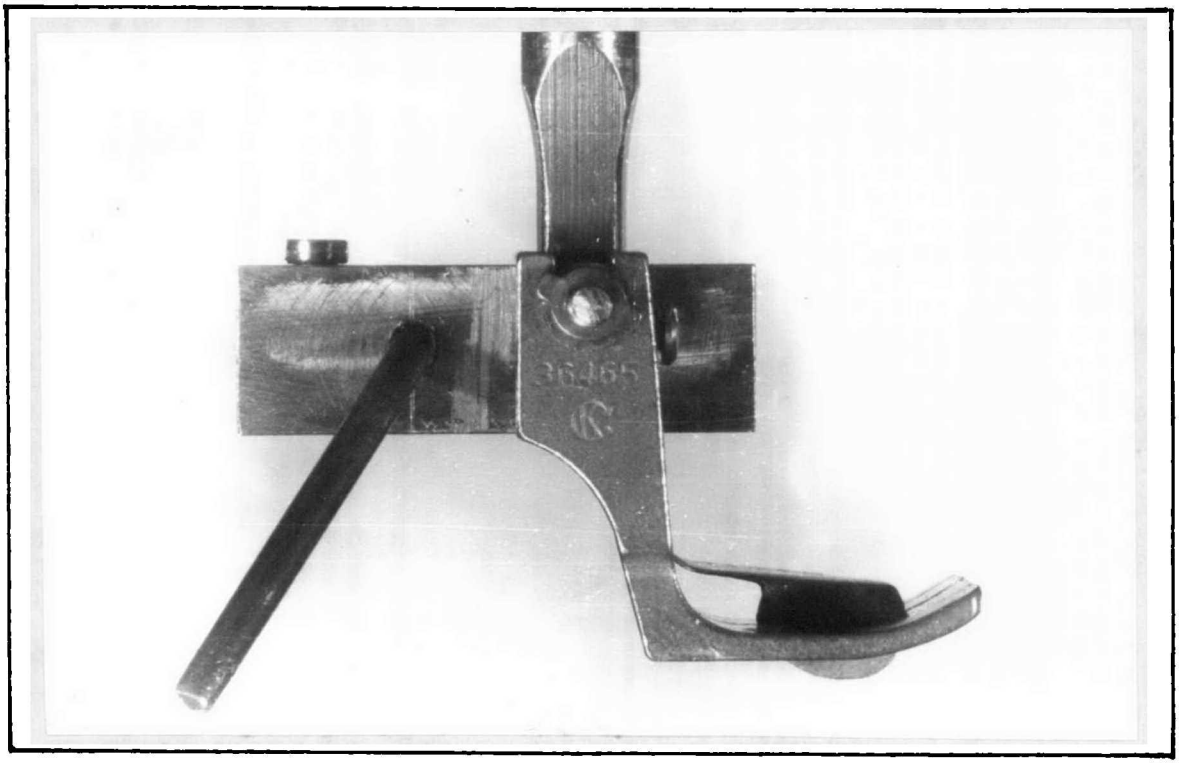


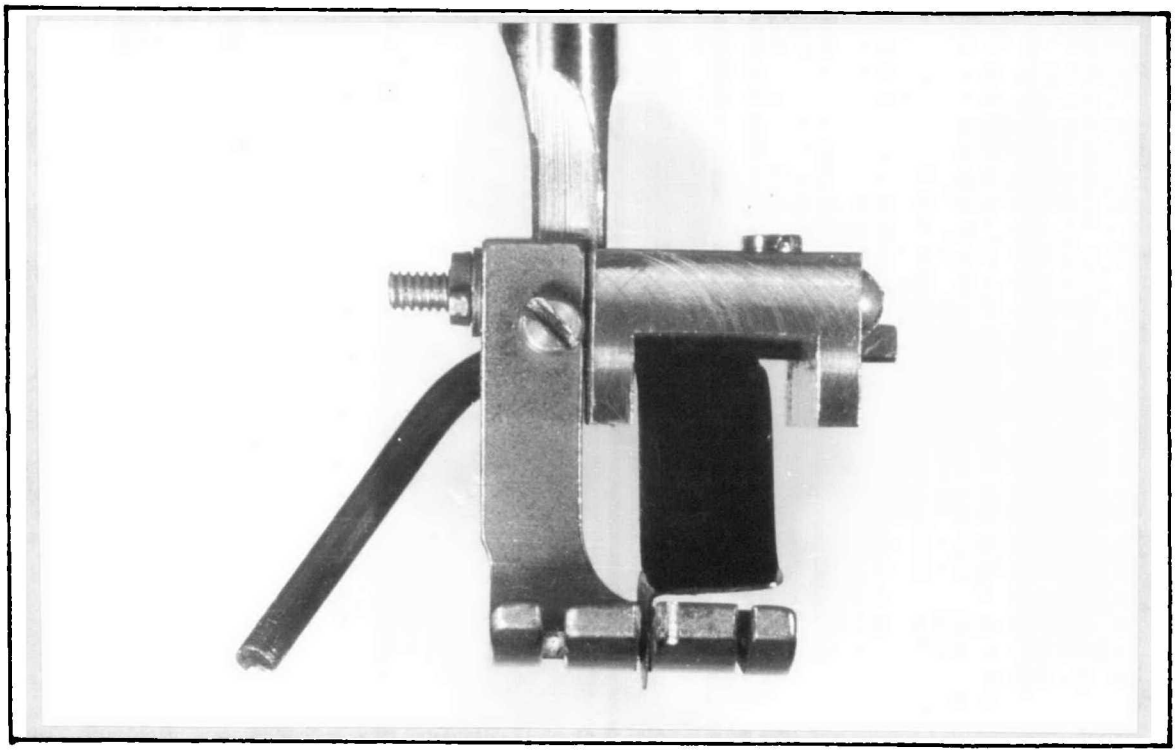
FIG 1 POSSIBLE SOLUTIONS





L PLATE 1 EXISTING DESIGN

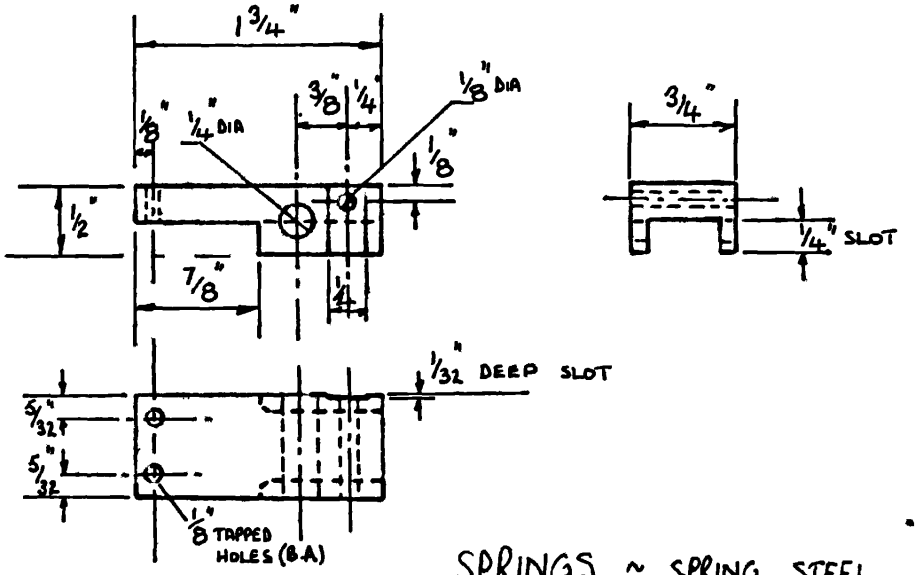




L PLATE 2 THE MK I DESIGN

L FIG2 THE MK II DESIGN

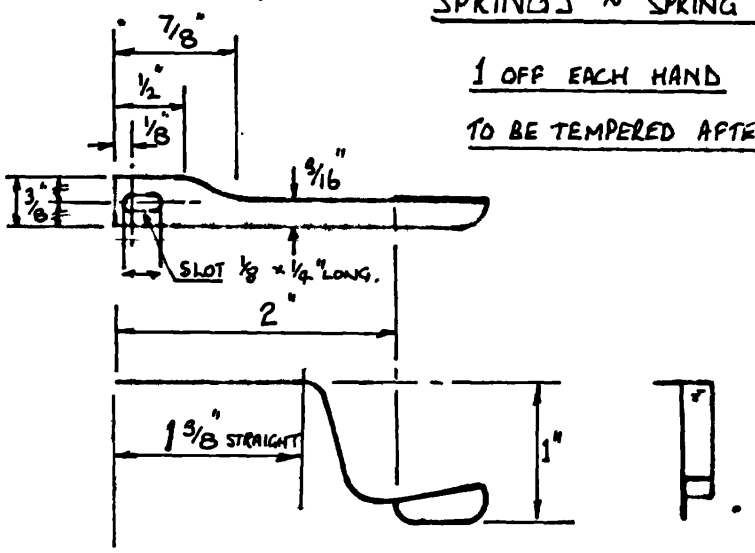
BLOCK ~ MLD STEEL ~ 1 OFF



SPRINGS ~ SPRING STEEL

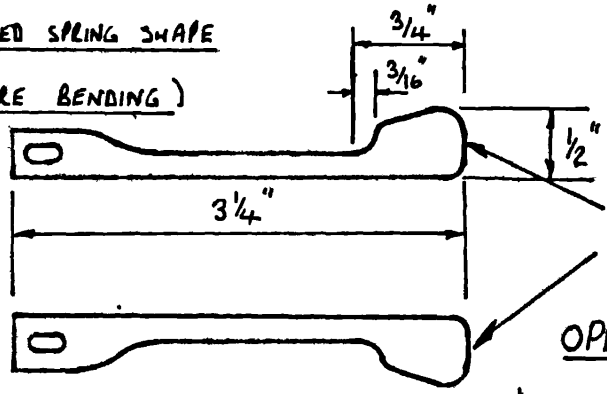
1 OFF EACH HAND

TO BE TEMPERED AFTER SHAPING



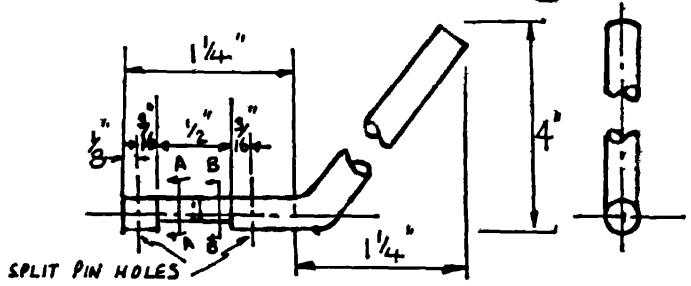
DEVELOPED SPRING SHAPE

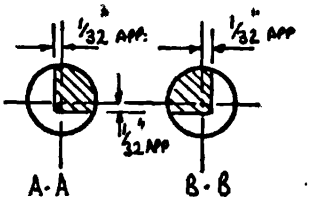
(BEFORE BENDING)



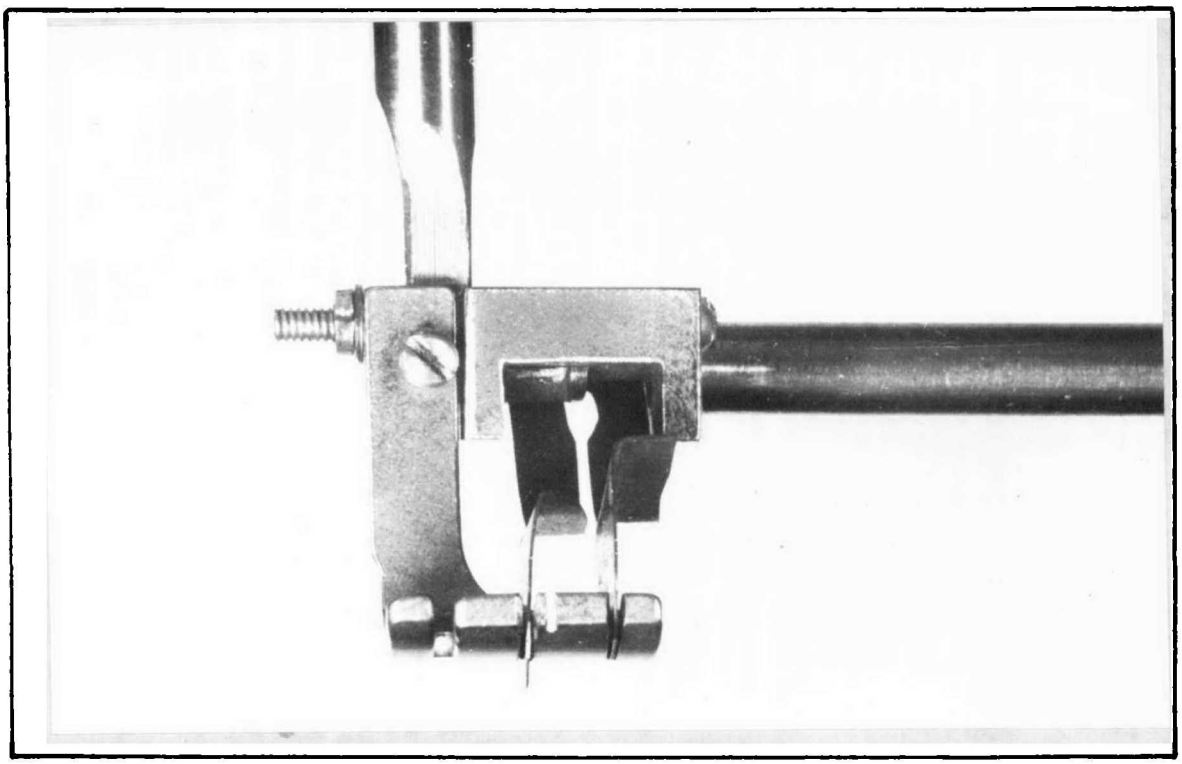
ONE-OFF EACH SPRING

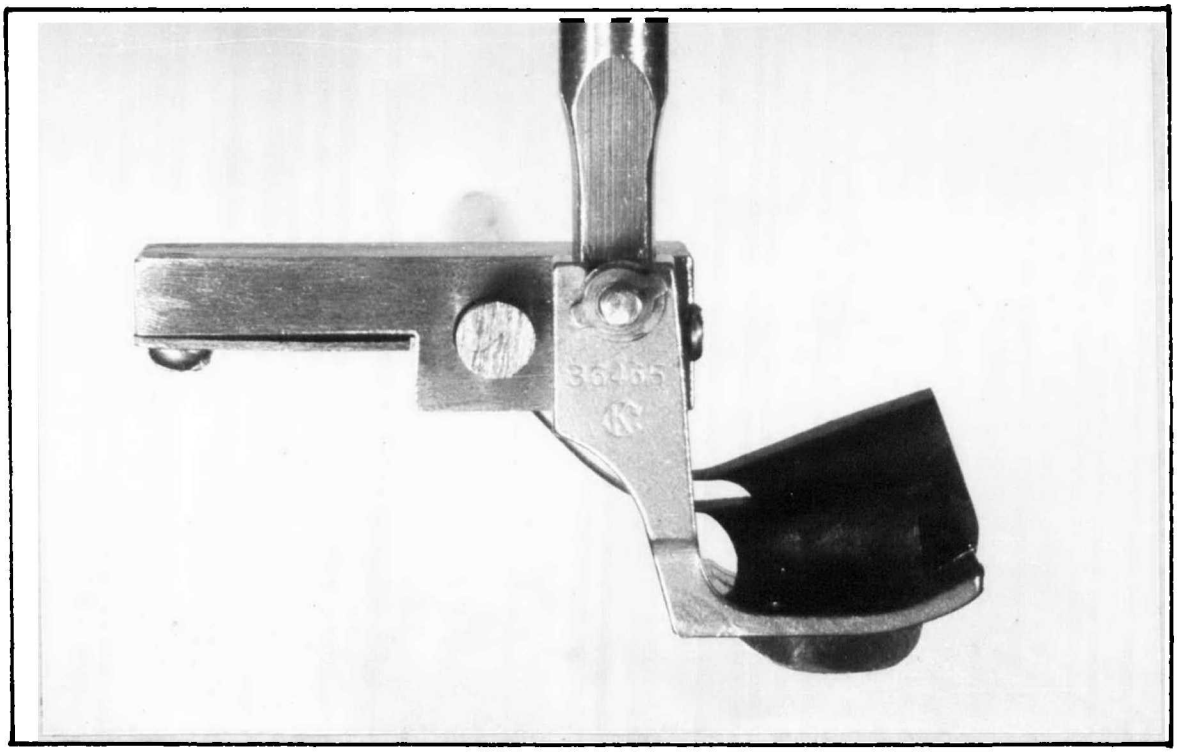
OPERATING ROD 1/4" M.S.



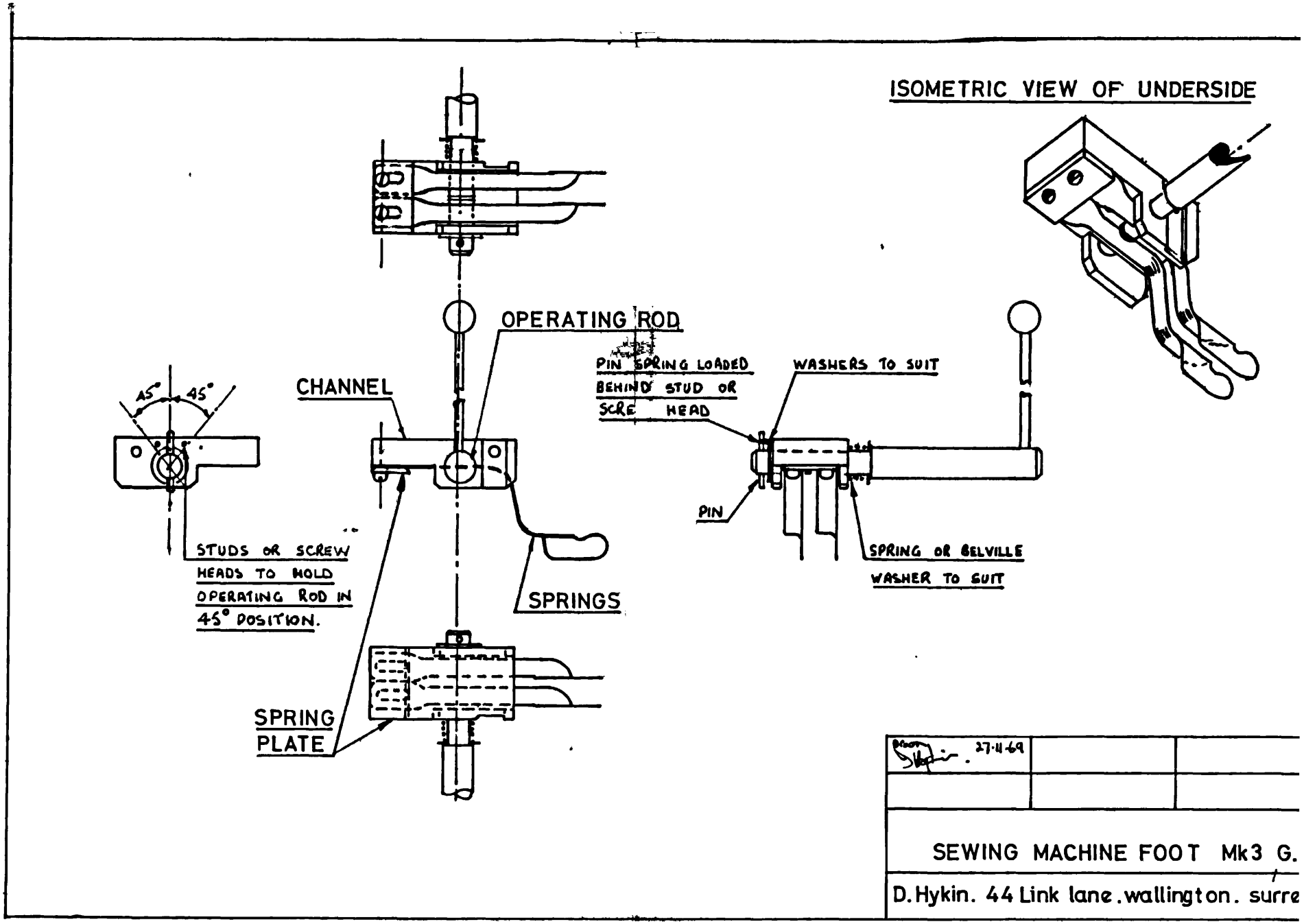


DETAIL OF ROD CROSS SECTIONS (DOUBLE SIZE

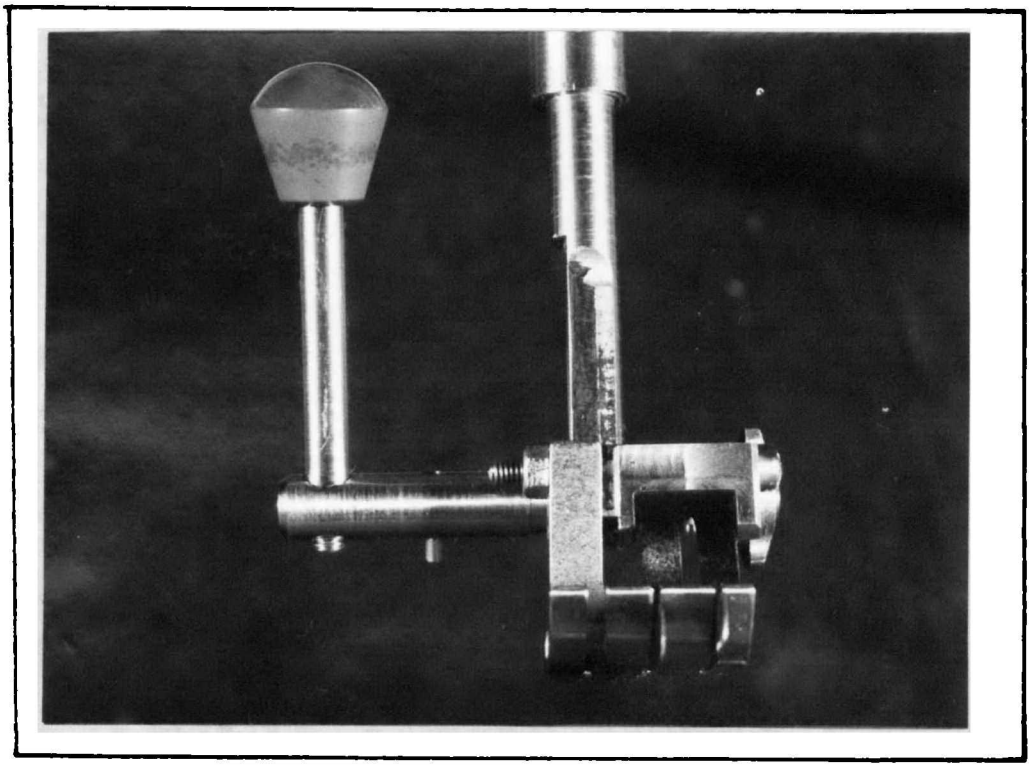


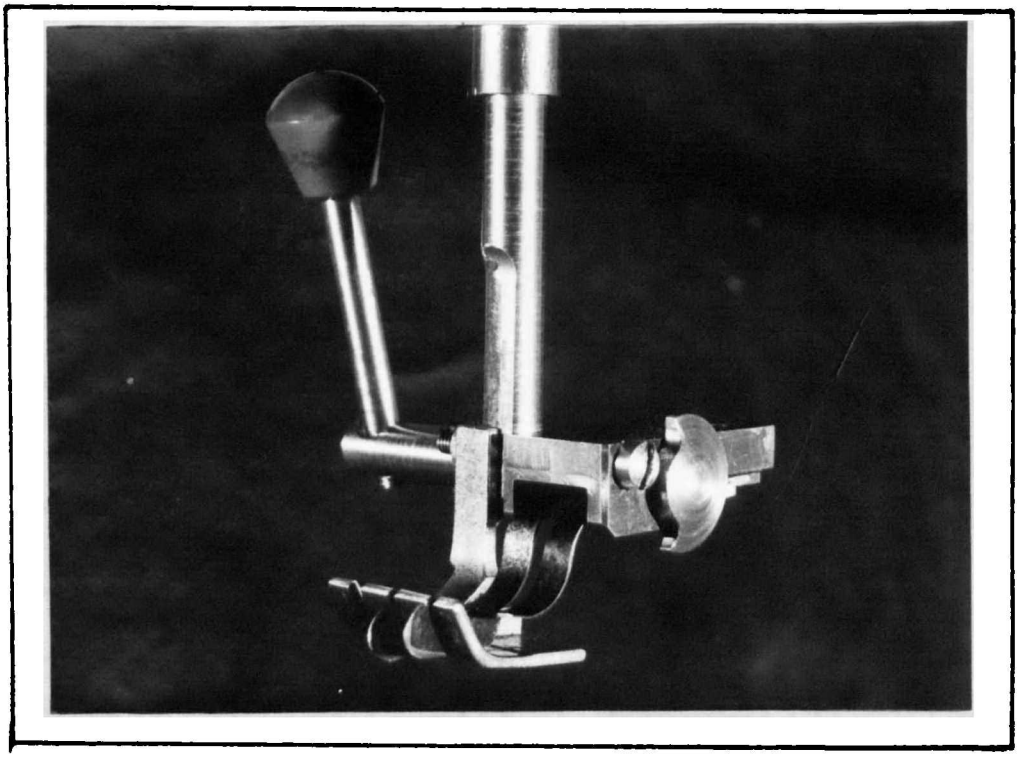


L PLATE 3 MK II DESIGN

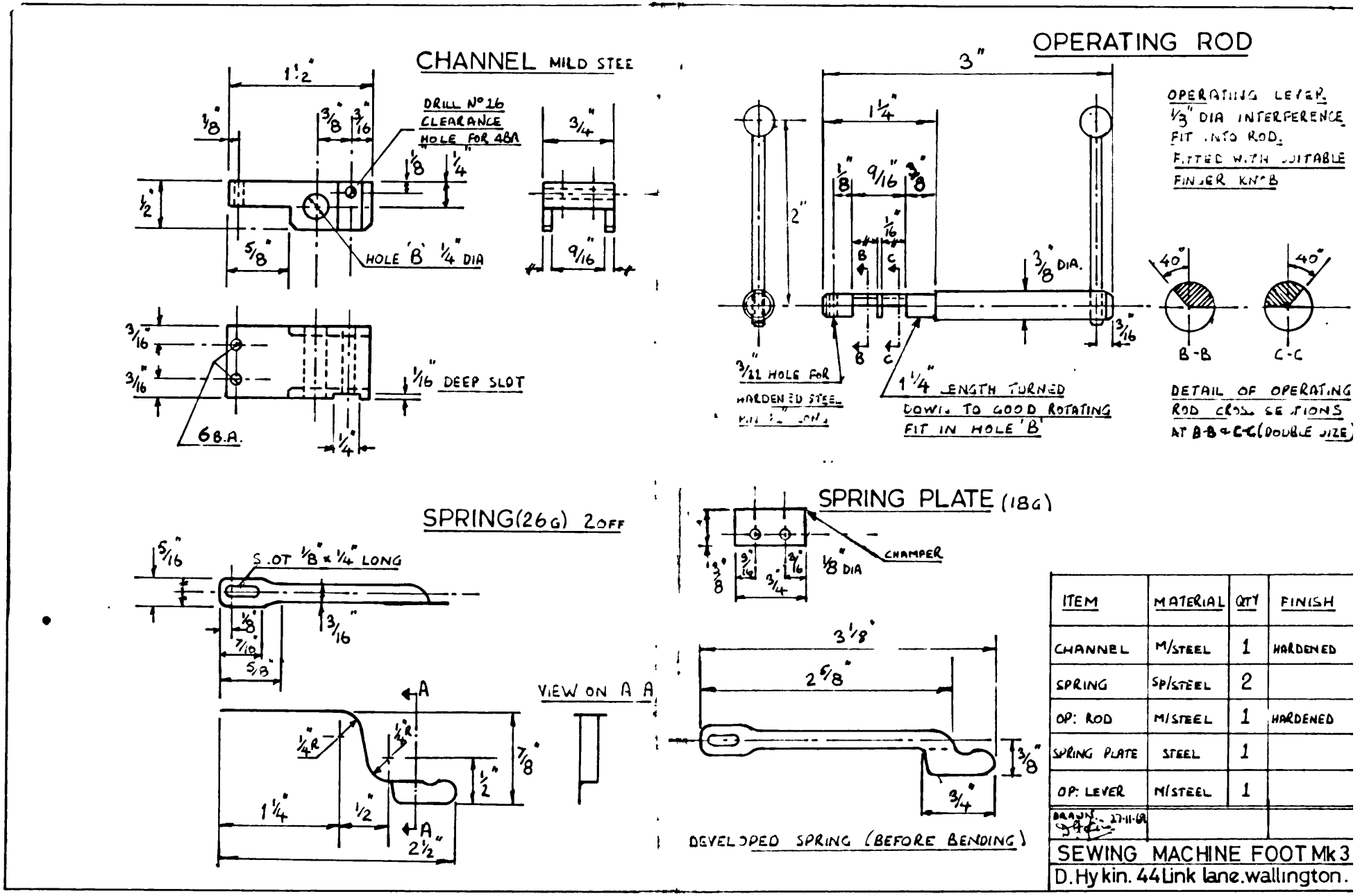


LFIG3· THE MK III DESIGN





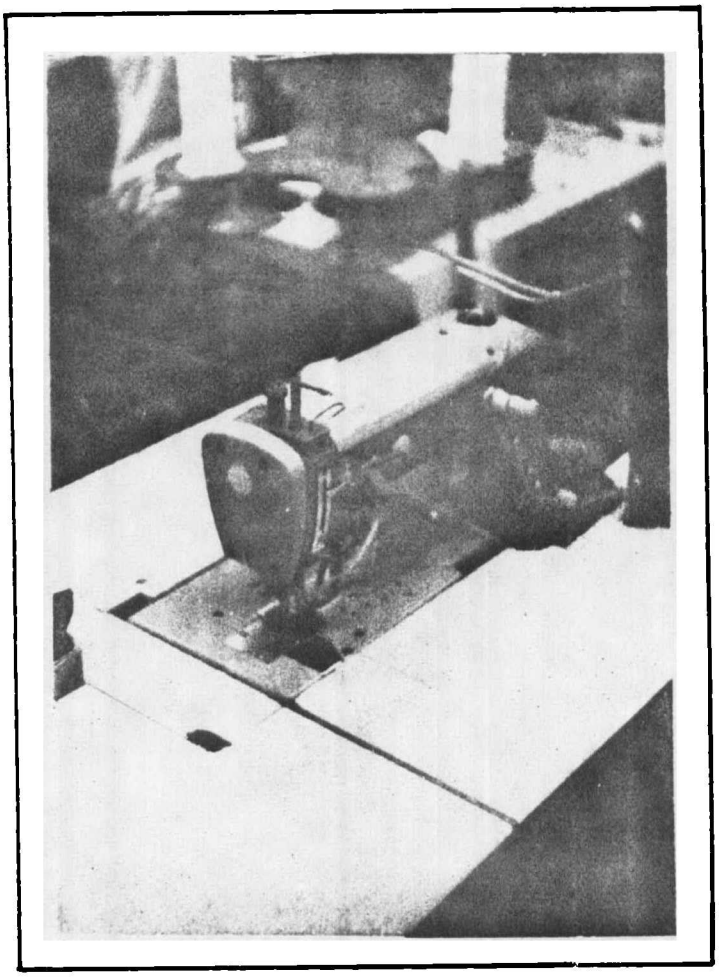
L PLATE 4 MK III DESIGN

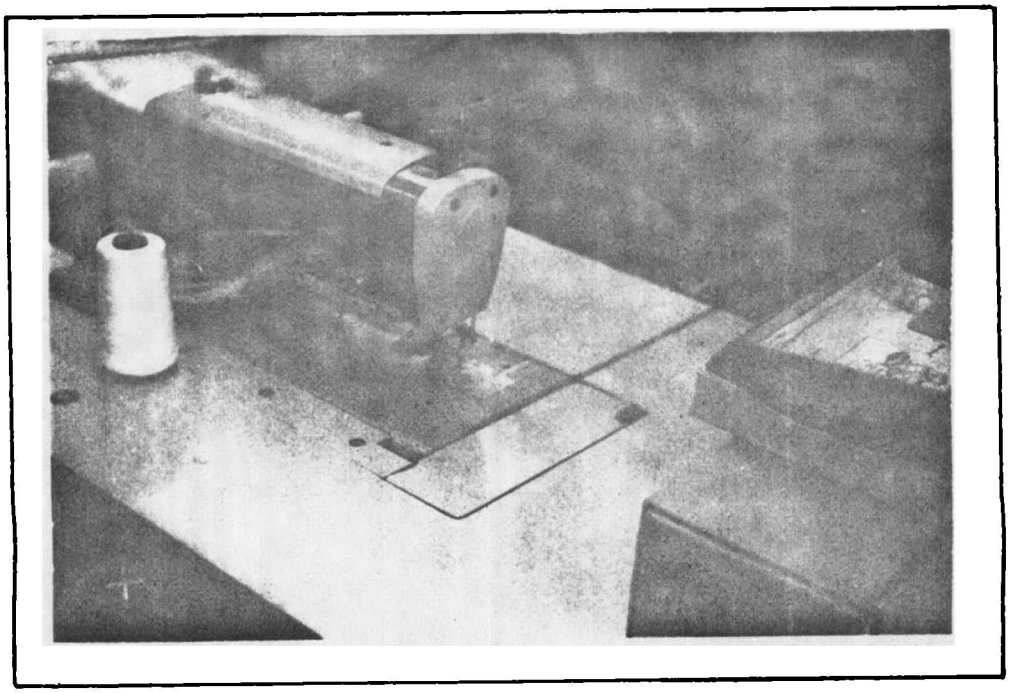


ITEM	MATERIAL	QTY	FINISH
CHANNEL	M/STEEL	1	HARDENED
SPRING	SP/STEEL	2	
OP: ROD	M/STEEL	1	HARDENED
SPRING PLATE	STEEL	1	
OP: LEVER	M/STEEL	1	
DRAWN DH 27-11-69			

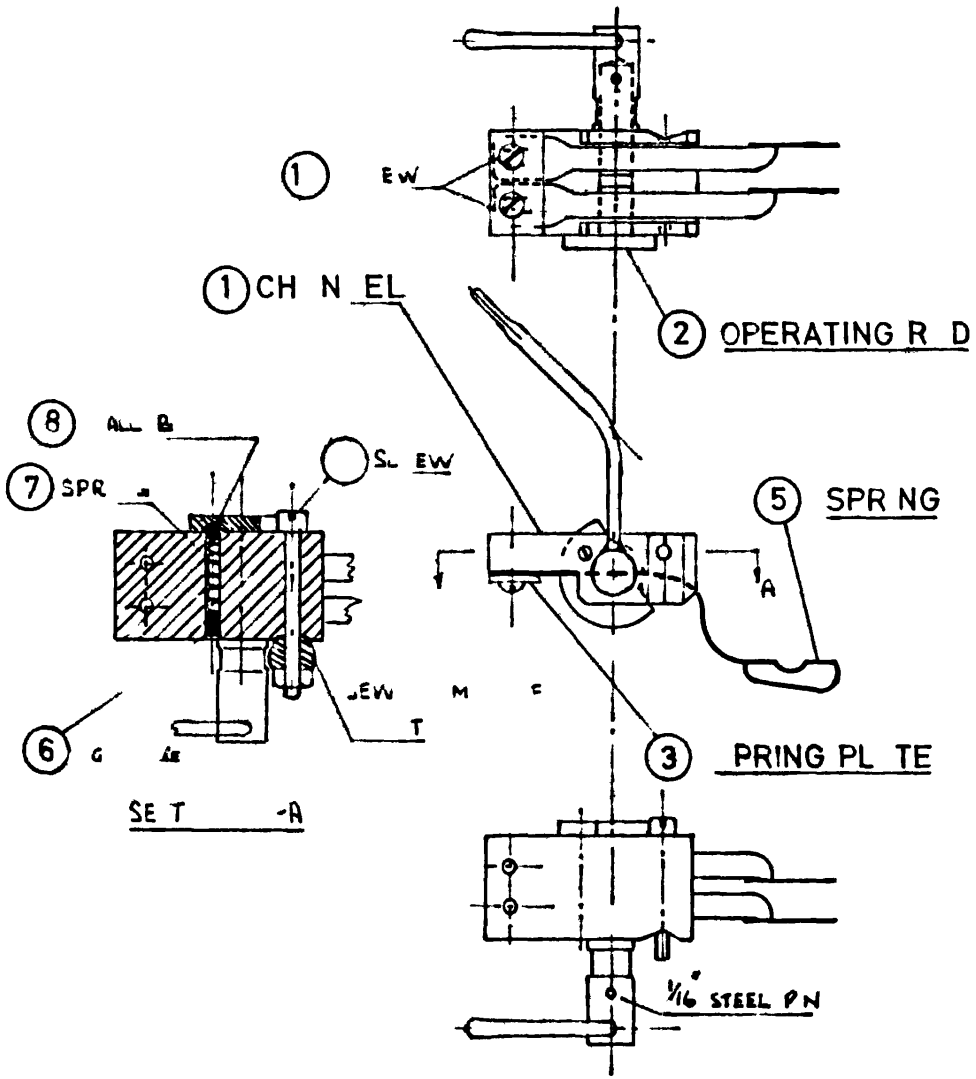
SEWING MACHINE FOOT Mk 3
D. Hykin. 44 Link lane. wallington.

LFIG4 THE MKIII DESIGN

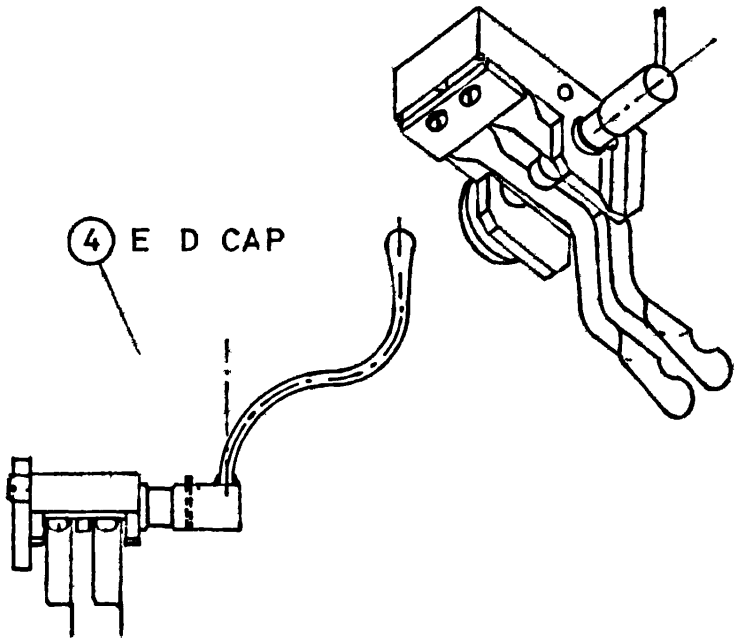




L PLATE 5 FINAL DESIGN



ISOMETRIC V EW CF UNDERSI E



Ref T Comp N NT DRAWI G B 11 FOR I EM		
Dd. 27.11.69	Dd. 6	
SEWING M CH N FO T Mk4 BS/		
D. Hy . 44 Link l ne, Walli gton, S		

L FIGS MK IV DESIGN

PART III

THE ANALYSIS

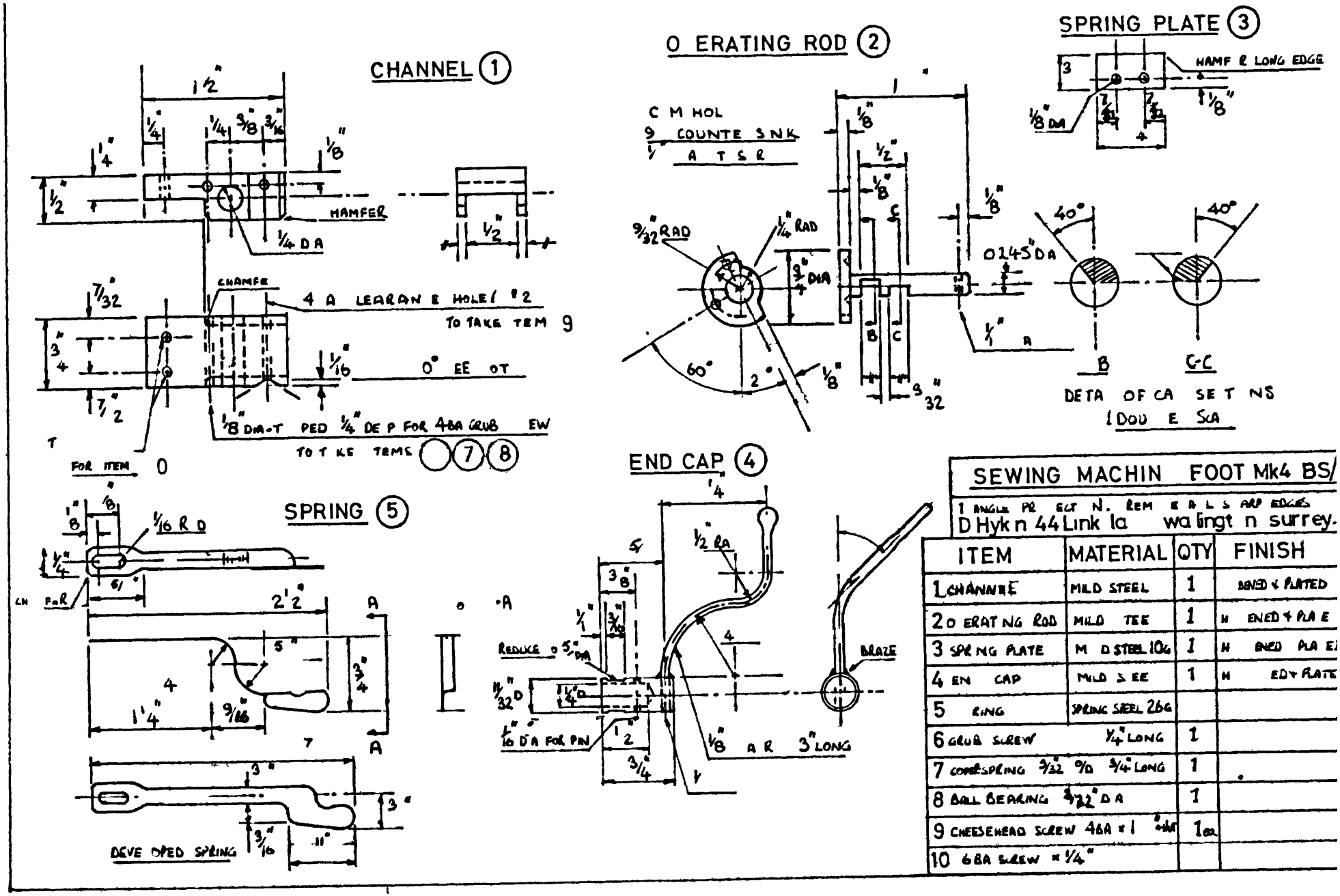
ANALYSIS OF THE CASE HISTORIES

ENGINEERING DESIGN - THEORY AND PRACTICE

INTRODUCTION

Part III is concerned with the analysis of the output from the field study. In the first section the case histories are analysed individually and collectively in the light of the accepted hypotheses of design structure and strategy; following this an attempt is made to categorise and group them. In view of the unprecedented nature of parts of this analysis they are presented chronologically so that the reader is more able to assess their reliability and validity.

The second section compares the design exercises encountered in the engineering industry and recorded in Part II with the theoretical descriptions reviewed in Part I.



SEWING MACHIN FOOT Mk4 BS/

1 ANGLE PR ECT N. REM E A L S ARP EDGES

D Hyk n 44 Link la wa lingt n surrey.

ITEM	MATERIAL	QTY	FINISH
1 CHANNEE	MILD STEEL	1	BNED & PLATED
2 O ERAT NG ROD	MILD TEE	1	H ENED & PLA E
3 SPR NG PLATE	M D STEEL 10G	1	H ENED PLA E
4 EN CAP	MILD S EE	1	H ED PLATE
5 RING	SPRING STEEL 26G		
6 GRUB SCREW	¼" LONG	1	
7 COMPSPRING 3/32" O/D	¾" LONG	1	
8 BALL BEARING 3/32" D A		1	
9 CHEESEHEAD SCREW 4BA x 1		1ea	
10 6BA SCREW x ¼"			

LFIG6 MKIV DESIGN

THE ANALYSIS OF THE CASE HISTORIES

DESIGN EVOLUTION

The study of each case history in terms of the evolution of the design exercise indicated that a logical sequence of events was discernible in them all, although the nature of the stages varied slightly and the emphasis placed upon each of them varied considerably. A diagram presenting the results of this analysis is given in Fig. 14. The stages were readily recognised and identified by means of the objectives and emphasis of the design team at the time, and by other factors such as the obvious attainment of an objective or the making of a conscious decision.

Several possibilities were considered for naming the stages which were recognised, but the following notation was finally chosen because it matched their nature, was unambiguous and had already received some general acceptance;

1. Study of Problem
2. Specification (Statement of Problem)
3. Generation of Possible Solutions
4. Selection of Best Solution
5. Development of Chosen Solution
6. Detail Design
7. Trials
8. Final Design

It should be emphasised that Fig. 14 is more qualitative than quantitative but nevertheless it is considered significant that it indicates clearly an identifiable sequence of events occurring in all the design exercise, in spite of their diversity. The absence of certain stages from some case studies relates either to the organisation in which the design was evolved or to the nature of the product.

For example, the Aircraft Temperature Control Valve (case history D) was developed from an existing design and there was no question of selecting solutions from several possibilities, although there was considerable emphasis in this exercise on development and trials. In contrast to this, the bearings for the Moderator Support Structure (case history K) were initially selected from a wide range of possible solutions with no pre-conceived and selected optimum but once roller bearings had been submitted and accepted in the original tender this basic decision was never seriously questioned.

Moreover the fact that this was a large, one-off exercise precluded the use of prototype trials prior to finalising the design.

Each case history also exhibits the cyclic nature of design evolution and Fig. 15 attempts to show the extent to which redesign occurs and the steps in the design process between which it occurs. It illustrates clearly that some degree of feedback is present in all the design exercises but that the extent, and the steps between which it occurs, vary considerably. The arrows in this figure indicate the steps between which there is clear evidence of feedback of information causing some reconsideration of earlier design decisions. The position of these arrows on the vertical scale in each row indicates the importance of this feedback; an arrow near the top of the scale means that the feedback involved major reconsideration and redesign - as in the butter packing machine of case history A - whereas arrows near the bottom of the scale indicate that the feedback involved only minor design changes.

Having recognised that a logical sequence of events was present in all the case histories the next step was to search for the importance attached to the stages in each exercise. The initial attempts to achieve this, based on the eight stages listed above, were unsuccessful because it was not possible to decide with sufficient certainty and accuracy where or when a particular stage had ceased and the following step had started. This difficulty was overcome by grouping the eight stages into the three phases suggested by Asimov:-

Phase I - Feasibility Study including Study of the Problem, Preparing the Specification and Generation of Solutions

Phase II - Optimisation including Selection of Best Solution and Development to final prototype stage

Phase III - Final Design including Trials and Testing and Production documentation

By using this coarser, but more measurable, scale it was possible to make a reasonable estimate of the weighting in time and effort applied to each of the phases and this is presented in Fig. 16. This figure provides a realistic basis for comparing the case histories; it should be emphasised here that this weighting was checked on several separate occasions by the author and was confirmed in every case in discussions with the design teams involved. In those cases where the design effort remained constant and the timing was rigidly controlled, i.e. cases E, G and L the values quoted in Fig. 16

are considered to be accurate to within 5%.

A further check on this approach to weighting the design structure was to be found in Ref. 64 chart 7 which allocates typical distribution of costs in successful product innovations in the United States. This part of the reference is by no means rigorous and has had to be amended to match the variables presented in Fig. 16 and, as pointed out in Ref. 65, the reliability of these values depends very much upon where the boundary is drawn between production costs and development costs. However, accepting that they are illustrative only, the results are of the same order of magnitude and tend to confirm those produced as a result of the present field work.

A further opportunity to relate this analysis to an independent study is afforded by Ref. 5 in which Jones suggests the categories of design situation System, Product and Part. The relevance of this is that in each of the design situations listed by Professor Jones the phases of Feasibility Study, Optimisation and Final Design all occur but the emphasis on each is different. In the case of Product Design, with which the present work is mainly concerned, the weighting applied to the three stages is of the order of magnitude presented in Fig. 16. In case history A (The Nuclear Reactor Gas Circulator Mounting Structure) it was not possible to separate the Feasibility and Optimisation phases since the problem could only be established by attempting and studying a range of possible solutions. This exercise was predominantly one of problem seeking, rather than problem solving.

It is emphasised that the estimated weighting applied to each phase in drawing up Fig. 16 is based upon the separate design exercises, and there has been no attempt in this figure to compare their overall magnitudes.

DESIGN STRATEGY

Having studied the pattern of evolution of each case history the next step was to investigate the design strategy. Decision trees of the type presented by Marples were constructed for each case history. Two of these diagrams are shown in Figs. 17 and 18, they have been chosen because they are each representative of a different type of the evolutionary structure illustrated in Fig. 16,because the data included in them is both accurate and precise, and also because they demonstrate certain significant features.

The decision tree for case history J Fig. 17 shows how a policy decision external to the design team can radically change the immediate problem. It also illustrates how several alternative proposals can be considered in parallel, and how the final solution may be the result of a re-combination of some of these alternatives rather than the result of a linear progression. Fig. 18 shows the corresponding diagram for case history L, it also illustrates that work on several problems proceeds concurrently and that the process is not solely sequential; decisions are inter-dependent and one may retrospectively affect another.

Other important features which are also common to both these diagrams of design decisions are the importance of external decisions in controlling and punctuating the activity and the fact that although the level of uncertainty reduces overall as the design process progresses, this decrease is by no means uniform. An encouraging aspect of this series of diagrams was that the times quoted on them and the levels of progress achieved related closely to the values assumed in producing Fig. 16.

In Fig. 19 the same two representative case histories have been used to construct the basic decision networks according to Morgan[40]. They illustrate clearly the inter-related decision areas but do not show any chronological order of events, nor do they provide for radical changes in design or the combination of apparently unconnected areas. It is possible, however, that by expanding diagrams of this type as the work progressed the designer could produce an accurate, detailed and usable model of his design strategy.

CATEGORISING THE CASE HISTORIES

Whilst the case histories were being recorded the author recognised that certain factors were of major importance in each design exercise. These variables were easily identifiable and as it was suspected that they tended to determine the nature of the design exercises it was decided to use them in an attempt to compare and categorise the case histories. The factors considered are discussed in detail below and their use in comparing the case histories is shown in Fig. 20 in which a key indicates how evident the factors were in each case.

(i) Cost Consciousness

This heading covers those case histories in which severe restrictions were placed on the designer because of costs, either of the design effort (A and E), the final price or the running cost of the product (C and E). In other cases such as

J and L there is no evidence of cost being paramount and more important factors controlled the nature of the design exercise. Case history D, which was recorded in the aircraft industry, is an example of a compromise being sought between cost and other factors; it was agreed in this exercise that "Engineering could not be sacrificed to economics".

(ii) Time Consciousness

Some designers were forced to work to a very rigorous time schedule, for example case history E. This appeared to restrict the time that could be spent on each stage of the design process, discourage excessive recycling and limit the amount of problem formulation and solution seeking which could be embarked upon.

(iii) Other Constraints

Constraints other than cost and time were applied to the designer in several of the exercises, an example being the requirement to meet safety and other regulations; if the consequences of failing to satisfy these conditions were serious, then the necessity to produce a foolproof design became a prime factor. The case histories collected in the nuclear power and aircraft industries were examples of safety restrictions being of major importance in the design exercise, and the need to satisfy national and international factory and office regulations was a prime factor in case history C.

(iv) Detailed Brief

In some of the case histories the designer was presented with a detailed brief at the outset and the exercise became one of problem solving; although none of the case histories represented this end of the spectrum case histories C and E approached it. In other cases where the brief was limited or unreliable, problem seeking was an important aspect of the design exercise, as in case histories B, J and K.

(v) Quantity of Production being Designed For

As the case histories were collected it became obvious to the author that the nature of the design exercise was affected by the quantity of production for which the product was being designed. For the purpose of classifying the case studies, the following three categories were considered: Large Production (over 50), Batch Production and One-off.

(vi) Innovation-Extrapolation

The degree of innovation evident in each case study was considered to be an important factor. Case history J involved a totally novel design for which no

directly relevant experience was available, and exercise A was also considered to be innovative because, although previous experience and solutions did exist, very little of the information was available to the design team. Where the case history involved the extension of an existing design, the element of innovation was reduced and the exercise was classified as one of extrapolation; this has also been described as design by adaptation or evolution.

(vii) Technical Content

The level and nature of the expertise required to solve the design problem also appeared to be an important variable. For example, the structural analysis involved in the reactor grid design (J) was undertaken in the technical office and this analysis and a high level of metallurgical expertise formed the foundation of most of the subsequent design work. In contrast to this however in case histories G, L and H only the most elementary calculations and materials knowledge were required.

(viii) Probability and Consequences of error

If the probability of being wrong is high, or the consequences of error are grave, the designer is obliged to organise his programme to prevent mistakes and to cater for the imponderables: this may be done by an emphasis on analysis and development according to the importance of other aspects of the design study.

(ix) Complexity

Some case histories involved the recognition and study of a large number of related sub-problems. In these situations two types of design activity occurred simultaneously, one was the inventive and creative effort applied to solving the design problems, and the other the organisational aspect of co-ordinating and integrating the separate parts of the overall problem.

In reference 65 an attempt is made to measure complexity of design in the engineering industry by comparing a given product on a logarithmic scale with five "benchmark" products. It is recognised that this is not a precise method of measurement and it must be related to other functions such as the relationship between the design process, the product and its manufacture. Nevertheless the scale given in Ref. 65 is considered to be sufficiently precise for the present work and enables some indication of the levels of complexity in each of the case histories analysed to be assessed, Fig.21 shows this assessment. The values quoted in Fig.21 are those given by the design team or chief designer involved together with the author's independent assessment.

(x) Magnitude

The magnitude of each of the design exercises was assessed by calculating approximately the number of man years involved. The results of this assessment are shown in Fig. 22. This proved to be a more difficult variable to assess than was thought at the outset, considerable variations arose as the result of the intermittent nature of some of the exercises and the changes in the number of persons engaged throughout. These values were also discussed and agreed with the designers concerned.

(xi) Other Variables Recognised

Other factors which appeared to affect some of the case histories were also noted. These included the competition for the product in the market, the geographical location of the design team - particularly its distance from the manufacturing facility - the type of management structure and the manner in which the case history was collected.

As none of these variables appeared to be a controlling factor affecting more than one case history they were not taken into account in the categorisation, although they are discussed in section IV.

The variables listed and discussed above are obviously not the same for all the case histories and in those cases where more than one of them is dominant the compound effect on the nature of the design exercise is not readily identifiable. Although this list of factors is not exhaustive, it includes all the important ones likely to dominate the design situation and it is considered that the range of case studies recorded is sufficiently diverse to ensure that no major factor has been overlooked. It is interesting to note that no case study was recorded in which the functional requirement was not a prime requirement and this has therefore not been included in the list of factors in Fig.20.

THE NATURE OF THE DESIGN PROCESS RELATED TO THE CATEGORY OF THE DESIGN EXERCISE

The next step in the analysis was to attempt to relate the types of design process identified in the first step to the categories allocated in the second.

A study of figure 16 indicates the presence of two types of design exercise. Case histories C.D.E.F.G. and L have a common pattern of emphasis on the first two phases, whereas in case histories A.B.J. and K a greater weighting is given to the final phase. Case history H appears to fall between these two extremes; initially this was

considered to be either because the allocation of weighting was not sufficiently precise to identify less significant variations, or because this case history was slightly uncharacteristic in that although it was industry based the designer was completing a College sandwich course as described in Part II.

The pattern of feedback illustrated in Fig. 15 tends to confirm the subdivision suggested by Fig. 16. Case histories B, J and K exhibit a common pattern of significant feedback from the end of the feasibility study to the initial study of the problem, plus further feedback from the development stage at the end of the optimisation phase. Case history A does not appear to conform to this pattern; this case history - The Case Erecting Mechanism in the Butter Packing Machine - is predictably unusual in this respect in view of its unique political and geographical character. The feedback characteristics of case histories C,D,E,F,G,H and L are all common in that the emphasis is on feedback from the development and trials stages.

Thus the collective analysis of the case histories suggests that they fall into two distinct groups - the first C,D,E,F,G and L, and the second A,B,J and K. These two groups are characterised by the weighting applied to the first two phases in their design evolution and the type of feedback present. It does not appear to be possible to draw further reliable conclusions from this analysis. The boundaries drawn are not sufficiently precise to justify the deduction of more detailed premises, and it would be a mistake to do so. It is interesting to note, however, that the major fluctuation of effort appears to be in the initial phase of the process, i.e. the feasibility study, whereas the variation in the proportion of the effort applied to the optimisation phase is much less.

The next step in the analysis of the case histories was to relate the grouping outlined above to the categories of the design exercise indicated in Fig. 20 and the first significant feature is that, with the exception of case history H, the case histories in the first group (C,D,E,F,G and L) are noticeably more constrained than those in the second group. If the first six columns in Fig. 20 are considered to be those involving a constraint applied to the designer then the first group of case studies are clearly seen to be the more constrained.

In order to analyse this effect in more detail an attempt was made to measure it by allocating two points for positive evidence and one for possible evidence of a constraint. The points for the first group are then C = 10, D = 9, E = 10, D = 9, G = 7, L = 7 out of a possible maximum of 10. The corresponding figures for the second group are A = 5, B = 2, J = 3, K = 3. These are considered to be significant groupings particularly after the special circumstances of case history A, are taken into account.

It is interesting to note that using this points system case history H is allocated only 1 point. It was realised in retrospect that this relates to the fact that the designer was College based, the constraints imposed upon him were therefore unrealistic and the case history in this sense was unrepresentative. The fact that the analysis had revealed this unlooked for and unexpected result, which in retrospect can be seen obviously to be true, is considered to be an encouraging verification of the validity of the field work and the analysis.

This stage in the analysis was reached early in 1970 and the marked correlation between the design categories and the constraints imposed on the designer was considered to be very significant; the next step was to seek a more detailed appreciation of this relationship. Further comparison of figs. 16 and 20 showed that the only factor which is common to all the case histories in the first group is that they were for batch or mass production and corresponding all those in the second group involved one-off design exercises - no other factor exhibited this complete correlation.

In May 1970, the author was introduced to Ref. 58 in which Woodward presents the results of an empirical study of management organisation in British industry. An attempt had been made to classify the level of success of each of 100 firms studied and to relate this to the type of organisational structure employed by them. In the first analysis of the results no relationship of any kind was established - which was somewhat disconcerting for a group involved in teaching management subjects.

The group then attempted to 'describe, measure and combine' the technical variables controlling the type of organisational structure of the firms. Factors such as product range, project size, complexity, technical change and geographical location were all considered in turn. When eventually the production situations in the firms were categorised into unit, mass,batch or process, there was immediately seen to be a significant correlation between success and the organisational structure in each of these categories.

In one-off situations success tended to relate to a loose, organic organisational structure, whereas in process production situations a rigid, mechanistic type of organisation appeared to accompany success. Other organisational aspects such as the authority of the chief executive, the number of levels in the line of command and labour costs, also exhibited this link with success in each design situation.

Woodward's work was very encouraging because it was the first external check in the present work and it tended to confirm the significant relationship between the type of design process and the production situation which had been postulated following the analysis of the case histories. Moreover, a discussion at this stage with Professor Woodward

and members of her group endorsed the author's field study procedures and led to some suggestions for improving the methods of analysis.

No other significant correlation appears from the comparison of Figs. 16 and 20 - although it is possible to draw conclusions about a particular characteristic of one of the groups in no case is this characteristic excluded from the other group. For example, in all the case histories in the second group (A, B, J and K) there is positive evidence of the presence of a high probability of error. However, this cannot be said to be a characteristic peculiar to this group as it is also positively in evidence in case histories D and F.

Although an attempt was made to relate the type of design strategy involved in each case history to the design categories developed this part of the analysis was considered to be unsatisfactory because the descriptions of design strategy were unusable or the data collected were not suitable reliably to identify and measure any of them. It is possible that the strategy used by the designer cannot be related to any particular category of design and is primarily a question of personal preference, leading to the adoption of different strategies at different stages in the design evolution by each designer.

On the other hand it could be that a wider study of engineering design with emphasis on the strategies adopted will be necessary in order to reveal any significant relationships.

In view of this it was decided not to consider the detail of each design strategy involved but to study the nature of the organisational system to which they were related. The characteristics looked for were those listed in Woodward[58] and used to identify the mechanistic and organic types of organisational structure. It is considered that the ease of recognising these broad indicators and the author's degree of involvement in each case history justify this part of the analysis.

The results of this analysis are presented in Fig. 23 and it is emphasised that they are concerned with an overall impression of the characteristics of the system of organisation and relate only to the particular groups and design exercises with which the author was involved.

Comparison of Fig. 23 with Fig. 20 shows a significant relationship between the quantity being designed for and the system of organisation. The mass or batch production group of case histories (C D E F G and L) are predominantly mechanistic in character whereas the second group involving one-off products, exhibit more of the

characteristics of an organic management structure. Case history H was not considered for obvious reasons and case history A was not easy to categorise satisfactorily in this respect because of the fundamental differences which occurred between different stages in this exercise; a property which accounts for some other anomolies in Fig. 23.

It is possible that alternative groupings of the factors listed in Fig. 20 could be related to a larger number of case histories to provide further significant relationships of the type described above or could reveal some which were quite different. It is considered unlikely, however, that they would invalidate the significant relationship between the production quantity being designed for and the nature of the design process.

ENGINEERING DESIGN - THEORY AND PRACTICE

The individual and collective analysis of the case histories in the previous chapters provides the basis for comparisons to be drawn between the theoretical descriptions of the design process reviewed in Part I and the reality revealed by the field work.

The pattern of design evolution postulated by Asimov and the general body of literature appears to be supported by the empirical work. All the design case histories exhibited a logical sequence of stages progressing from the study of the problem to the final engineering statement of a proved solution. The iterative nature of the process was also evidenced by the amount of recycling and redesign imposed upon the evolution as it converged upon an acceptable solution. The level of uncertainty was also seen to be reduced as the problems became less abstract and more material and detailed.

Any of the hypothetical models which recognises this sequence of events, coupled with a cyclic progression through them, appears to be satisfactory. Asimov's detailed description of design evolution and the emphasis in it of recycling at every stage (Figs. 1 and 2) is considered to be one of the most accurate and comprehensive, although even this has the disadvantage that it does not appear to recognise either the wide variety of design evolution, or the frequency of major redesign, which were revealed by the present study.

The great diversity in notation, and in the importance given in the literature to the different stages in the design process, probably relates to the failure to recognise the variation in the structure of the design process with the category of the design - in particular the quantity being designed for-and related to this the personal experiences of the authors of the descriptions. For example it is particularly interesting to note that in the case of Stamper[34] and de Ferranti[37] the propensities of the authors relate to the production quantities involved, and their descriptions of design evolution are biased accordingly.

Fig. 24 shows the author's attempt at yet another description of design evolution which is intended to cover all the aspects included in the literature plus others revealed by the empirical work. It is based on the three phases in the design process and illustrates: the iterative nature of design evolution; the level and extent of redesign; the reduced level of uncertainty as the design progress from the general and abstract to the more detailed and material; and the difference in the resources applied to each phase.

The three phases have been chosen because the field work clearly illustrated their significance and how surprisingly easy they are to identify and isolate by means of such factors as the emphasis of the design team, the critical decisions which typically terminated and initiated them, and the location of the work. Examples of this are the necessity to submit a tender in case history J which forced the design team suddenly to change their emphasis from 'whether' to 'how', the trials in case histories D, E, F, H and L marking the commencement of the final design phase, and also the management control which directly or indirectly controlled many important design decisions in case history E.

The descriptions of design strategy reviewed in Part I are far less in accord with the results of the field work. The picture painted by most of the authors is of the designer consciously and steadily choosing tactics, making decisions and progressing inevitably towards an optimum - or at least satisfactory - solution. Some authors, for example Matchett[1] and Archer[38], imply that all the important properties of a problem and their relationships can be established early in the evolution, and the strategy is then selected and controlled within this comprehensive framework.

The current field work does not support this description. In case histories A, B and C, many of the important problems were not recognised - far less understood - until several solutions had been attempted and pursued to an advanced stage. Also, in every case history there are examples of external factors or decisions which radically affect the design process and over which the designer has no control; for example the government decisions in case history D, the management policy decisions in C and E and the customers change of mind in J. It is possible that in some fields of design, or in trivial or predominantly extrapolation exercises, totally formalised predictable strategies could be adopted but they appear to have little bearing on any of the recorded engineering design exercises.

Jones' classification of strategies[39] based on the 'pattern of search' is obviously highly idealised but can nevertheless be related to the current field work. For example, the formal comparison and selection of a plastics material in case history C represents a linear strategy, in case history J the simultaneous consideration of several possible support structures and their combination in the final design is a branching strategy, and the redesign of the temperature control valve in case history D is an adaptive, or even incremental, design strategy. All these examples confirm Jones' classification of strategies although none of them follows from 'a conscious selection of a series of methods to assist the designer'. Also as explained in the previous section the isolation and identification of any

of these types of strategy in the case histories was so rare that it was not possible to undertake a useful analysis of this aspect of the design process.

Marples 'decision tree'[13] appears to be an oversimplified model of design strategy, ignoring the considerable inter-dependence of design decisions and giving the impression of representing a conscious logical decision making technique. Its value appears to be in analysing the design process after the event rather than as an aid during it.

Morgan's 'network'[40 72], which expands as the sub-problems and relationships are identified, appears to present a usable method of establishing decision areas and the relationships between them, but it probably suffers the common defect that it is possible for the designer too easily to spend time on the method rather than the design.

Aspects of design strategy which were highlighted by the empirical work include the recognition that a problem can only be appreciated and formulated properly by considering possible solutions. Until the search has been pursued for some way the critical sub-problems which render a given solution practical or otherwise, cannot be identified. Moreoever, the pursuit through several unsuccessful routes, possibly in parallel, leads to a clearer understanding of the 'real nature' of the problem, although in every other sense it is time wasted. Parts of case histories A, G and L illustrate all these points.

Another aspect is the relationship between the designer and the manager, and the need for the designer to justify his proposals to other people; this appears to bias him towards those solutions which offer certainty rather than those which offer superiority. Also, the critical, apparently irreversible,decisions which divide the design process into a series of phases are not always taken by the designer; the more significant they are the more likely they are in most organisations to be taken by a manager or management group.

It is important to recognise that these critical decisions - which are often formal and tend to punctuate the design process indicating to everyone concerned that a stage has been completed and the emphasis changed - are not in fact irreversible but the longer they are accepted as such, and the decision developed, the more irreversible they become. The constraints of time, cost and other resources, which apply in differing degrees to all commercial engineering design exercises make it increasingly difficult to reconsider some of the critical decisions later in the process.

Whatever the strategy followed, and in none of the case histories was any particular formal strategy consciously selected, the designer is forced to chose between studying a wide range of possible solutions in order to improve his understanding of the problem, and his efficiency in not wasting too much time on inferior solutions. In order

to relate the review of design methodologies given in Part I of this thesis to the results of the field study, the following criteria for deciding when to use a design methodology were considered:

(1) Jones[41] states that a methodology can be usefully employed when 'large quantities of design information have to be sifted, the design team has clearly defined responsibilities, and considerable innovation - as opposed to extrapolation - is required.'

(2) Archer[42] is less specific in stating that a methodology should be adopted when 'either the consequences of being wrong are disastrous and/or the probability of being wrong is high.'

All the case histories produced by the fieldwork exhibited one or more of the characteristics listed above but in no case did the designer choose to employ any formal design methodology of the type described in Part I. The value analysis exercise in C and the cost and weight analysis in E are the only examples of a motoring methodology being employed and in both cases their use was imposed by management to control, rather than to assist, the design process. Although the comparison of plastics materials in C was a typical example of a design team attempting to formalise a mundane decision-making process, this cannot be considered as the serious application of a formal design methodology The design team in A adopted a 'systematic approach' in order to monitor and assist their progress but this was not pursued beyond the feasibility stage and was therefore only a systematic attempt at problem formulation; unfortunately it did not avoid the need for major redesign at the trials stage.

In spite of the absence of any significant use of a methodology, all the design teams expressed some dissatisfaction with their present way of doing things; during the field work the author was frequently asked "Are all the cases you are studying as chaotic as ours?"

The increased complexity and level of uncertainty in current engineering design problems which was discussed in detail in Part I has produced a recognisable need for improved methods of designing, but the evidence of the current field study is that, although on the whole the designer in industry is prepared to accept them, these methods have not yet reached him.

Between those who insist that design methodologies offer an instant panacea for all ills and those who declare equally vehemently that the proposals are only naive

nostrums, there appears to be a majority of practitioners in the engineering industry who are prepared to consider them seriously. In the author's view this stems from the fact that many practising designers recognise aspects of the formalised methodologies which relate to their own informal, or even unconscious, methods of working. For example check lists, priority allocation, family trees and decision networks are all procedures which many practising designers already use in some form. A somewhat cynical suggestion made to the author by one of the senior designers was that "Designers with open minds already use methodologies, albeit unconsciously, whereas those who might benefit from them have minds too closed to learn".

The confusion and pretentiousness of the terminology related to some of the methodologies is also unfortunate; the experienced practising designer is aware that papier mâché artefacts tend to acquire papier mâché terminology.

The author's experience of cases where a design team in industry has deliberately adopted and applied a design methodology - as opposed to having one imposed as a management tool - is therefore limited to second-hand information. None of these data has been recorded or documented in a way which makes a reliable assessment possible, the records are usually retrospective (certainly some of the charts which have been completed give this impression), no attempt has been made to measure the time spent on the method as opposed to the design, and no investigation presented in which the design produced by using a methodology is compared with a solution to the same problem obtained by conventional means. A further problem is that most of the methodologies have been produced and advocated by teaching or research establishments. Although this is to be expected - the practitioner is usually too busy designing under economic pressures to be able to study design - it has the disadvantage that the examples quoted to justify the use of the methods are often unrealistic or trivial. The unrepresentative nature of a firm-based student project demonstrated by the current field work highlights this problem.

It is considered that any proposed design methodology should satisfy the following minimum requirements in order to be credible to, and used by, the practising designer:

(a) It must match the design situation in which it is to be used either by being sufficiently adaptable to match a variety of situations or by being developed for use in a particular category of design.

(b) It should be a means of communication and provide a record of the process which is available to all those concerned. The information recorded should include assumptions made, the facts ascertained and the decisions arrived at during the evolution of the design.

(c) It must be flexible, so that it can cater for a wide range of problems and for changes which occur as the design develops.

(d) It must provide a converging, logical route to a satisfactory solution; although it will automatically pose a host of new questions the answers which the designer is forced, and helped, to find should lead to a reduction in the imponderables and the emergence of possible solutions.

In addition to these positive requirements there are certain characteristics which should not be present in any methodology:

(e) It should not involve the designer in time-wasting exercises related to the technique rather than the design activity, for example the collation and assessment of irrelevant information or elaborate data-processing.

(f) It must not inhibit his search for novel solutions by being too formalised - it should in fact aid good judgement and encourage inspiration, by preparing the ground for them.

(g) It must not be disproportionate to the situation in which it is to be employed. A minor problem should not be subjected to an elaborate methodology if the time taken, and all the possible solutions produced, cannot be justified.

A methodology will sometimes lead to a true and tried solution to an old problem; this is of course a justification of the method, but not of its use in the particular situation.

Additional advantages of any method which provides a guide through the design evolution, and a means of processing information and improving communcations, are that it enables more personnel to be usefully employed, provides an early and accurate assessment of resource requirements and can be used to control a particular feature of the design such as cost or weight. In the last case, and this was demonstrated by case histories C and E, a methodology may be a manager's rather than a designer's tool.

The current work suggests that, subject to provisos of the type listed above, any methodology which helps the designer to understand the process by which he designs, and which he can consciously use in order to monitor and motor his progress, would be of value, and would be welcomed and used by the designer in the engineering industry.

PART IV

COMMENTARY

THE CASE HISTORY APPROACH - ITS VALUE AND LIMITATIONS

THE RAMIFICATIONS OF THE ANALYSIS

GENERAL COMMENTS AND FUTURE WORK

INTRODUCTION

In commenting upon the results of this work the following aspects appear to warrant special attention: The value of case histories as a method of studying engineering design and the procedures to be adopted in collating, presenting and analysing the necessary data; the light which the analysis of the case histories has thrown on the engineering design process as encountered in reality and finally general observations on engineering design which arose as the result of this study but not specifically from the analysis of the empirical data.

THE CASE HISTORY APPROACH - ITS VALUE AND LIMITATIONS

The collection and analysis of empirical data is fundamental to scientific method but the practical work and interpretation of data are both selective processes guided by theoretical considerations. In attempting to relate theory and practice, particularly in a field as unquantifiable as the study of human behaviour, it is essential to ensure that the empirical work is not designed solely to substantiate preconceived hypotheses: T. H. Huxley's comment must remain valid i.e. "one of the tragedies of science is the slaying of beautiful hypotheses by ugly facts".

The main purpose of the field study was to provide empirical data against which existing theories could be tested and upon which new proposals could be built. The problems inherent in undertaking such work when the observer is part of the field study is discussed in detail by Cicourel[59] in relation to Social Science, which is closely allied to the present study.

The crux of the problem is the validity and reliability of the observer and his method. The dilemma is the choice between richness, revealed by intense participation, and objectivity obtained by non-involvement; it is accepted that seldom can these both be maximised. If the observer becomes too involved he may be valid but not reliable. He 'modifies and is influences by the context[60]', he adopts 'the group's way of perceiving and interpreting the environment, becoming blinded to many points of scientific importance'[61] Moreover his morale, interest and effectiveness may fluctuate with those of the group.

A further danger - and this was certainly experienced by the author - is that the group's activities may not permit recording until some time after the event; Vidich[62] claims that over-involvement causes 'The alteration of memory structures and prevents the observer from seeing cumulative change'. In contrast to this, if an observer is too detached he may be reliable but not valid. He may objectively observe and record the events which occur but he may lose validity because he is not accepted by the group and cannot therefore obtain the necessary detail of information, nor can he appreciate and assess the full significance of the events taking place.

Becker[63] suggests that the degree of involvement should vary with whether a hypothesis is being verified or discovered. To the author the need for the observer to appreciate the modus operandi, technology and language of the group with which he works appears to be paramount when studying technological and scientific behaviour. In

collecting and analysing data it is also important to ensure that the method of describing the work does not itself restrict and mould what is described, and to recognise that 'no property of data can be said to hold unless the methods of collecting and analysing them permit alternative properties to exhibit themselves'[60]. Great care should also be taken in extending the conclusions drawn from a limited area of study to a wider scale of activity.

In summarising the problem Cicourel proposes the following set of rules for seeking data in field research;

(a) The researcher should formulate as explicitly as possible what he is seeking to accomplish, his final conclusions may then be related to these initial aims.

(b) He should acquire all available relevant information at the outset.

(c) If possible the type of information sought in the field research should be understood and stated at the outset.

(d) A 'natural history' approach can be very helpful. 'Presenting the evidence as it comes to the attention of the observer as the problem under investigation is conceptualised and reconceptualised over time'. This not only provides a sequential method of stating and testing, restating and retesting hypotheses, but enables the reader to draw his own conclusions.

CASE HISTORIES IN THE STUDY OF ENGINEERING DESIGN

During the six years that this work has taken to complete there has been a deep national concern over engineering design; fostered, if not engendered, by the collapse of some of our traditionally leading engineering design organisations. A desire fundamentally to reconsider the use and training of engineering designers has led to a more rigorous approach to the study of engineering design in industry. A report of the Science Research Council (Ref. 45) has advocated more engineering postgraduate involvement at Ph.D. level into 'industrial research, design or even management techniques' and several projects[6.71]. have studied what designers do - rather than what they think they do, or did - how they are organised and what makes them successful.

The problems of method and measurement in this field are new and complex, but it is essential that a body of reliable empirical data is accumulated in order to establish and substantiate the fundamental concepts upon which a scientific approach to the subject

can be based. This data must be sought and recorded accurately and in the world of observables: intuitive, retrospective 'guestimates' are no substitute for hypotheses which can be repeatably verified experimentally.

The eleven case histories presented in this work are not sufficient in number to enable wide generalisations to be drawn but fortuitously they do appear to represent a wide spectrum of the significant aspects of the design process and they therefore offer an identification, however crude, of the 'flora' of the engineering design process. In advocating further work in this field R. A. Hunter in the written discussion to Ref. 6 states - "We have to start where we are. If this means working from the crudest, and hence most unreliable signals, the sooner we start the sooner we will have some feedback to knock the rougher edges off the crudities".

In studying a specialised and technical activity such as engineering design it is essential to ensure the validity of the observer. In all the case histories in the present work the author found it necessary to establish his technical competence and credibility in order to obtain the necessary cooperation and information. It was possible to achieve this without any effect on the design process in most cases, and in the few case histories where the author became involved he was never in a position to affect unduly the process under observation. Furthermore the 'natural history' approach and the continuous review of progress helped to ensure the author's reliability and validity as an observer. The opportunity in some parts of the analysis to check the work against external factors, and to discuss it on numerous occasions with the individuals involved, also helped to guarantee the data and the conclusions drawn from them.

THE CURRENT FIELD STUDY

In describing in detail the field study method adopted in this work, and the results obtained, it is clear that most parts of the 'recipe' recommended by Cicourel were adopted. The decision to use a 'natural history' approach by recording detailed concurrent case histories neutralised many of the problems of subjectivity and retrospective readjustment. The author's familiarity with the current literature in the field and his experience as a practitioner and teacher of engineering design enabled the study to be realistically restricted to the engineering design process - the procedure and strategy.

The limitations of the study were recognised at the outset; in fact early in the programme it was considered that the only useful outcome of the work might be the information it produced on how this type of field work should be undertaken and recorded.

However as the work progressed the discussions following the intermediate reports and papers, and several papers by other authors, all indicated how the field study could usefully be modified and its more ambitious aims achieved.

At the outset very little guidance on how to formulate the research programme, the method to be used, the variables to be measured and the techniques of measurement were available from the industrial sociologists or engineers - it was of interest to the author to note that his own original overemphasis of the technological aspect of the case histories appeared to be matched by the industrial sociologists avoidance of them. In the event the case history method of collecting the data appears to have proved satisfactory. Detailed concurrent case histories presented chronologically ensure that the significant data are recorded and, equally important, that the researcher and the reader have the opportunity to study assess and re-assess all the data and the conclusions drawn from them.

Important lessons learned from the present work were that too much information is as dangerous as too little; in particular the temptation to accumulate and absorb detailed technical calculations and justification statements must be avoided because it absorbs valuable time and interferes with more important and relevant data collation. The need at least to note the organisational structure and to record precisely the source and timing of decisions made, should be emphasised in any future research and also the need to record, in standardised diary form, detailed information on the dates of events, the number of personnel engaged, and the amount of time spent, on the design. Many of these factors were catered for as the current research progressed but it was not until the final analysis of the data was undertaken, and some of the important variables were identified, that the need for the types of information listed above, was recognised.

Another important aspect of the field study was the method of gathering the data, this varied from the total involvement of the author to the use of a key member of the design team as the main source of information. This appears to have had no effect on the data recorded, probably because all the case histories except K were recorded concurrently and the record of events was repeatedly checked with the personnel involved. In every case, however, it was essential for the author to achieve credibility and to remain aware of the need for objectivity.

At the conclusion of the work, copies of each case history, carefully rendered anonymous, were sent to each of the firms concerned to obtain approval to publish. This operation was also used to obtain further information from the design teams by means of a questionnaire, and for them to vet the final version for accuracy.

In the analysis of the data the identification and measurement of the variables affecting each case history was based initially on the existing hypotheses describing the design process. The stages in the evolution of a design were based on several earlier works, including the author's, and the coarser division of these stages into three phases was based on Asimov. The list of variables thought to control the type of engineering design process was original and arose during the collation, and from discussions following the submission of intermediate reports of the work. The attempt to quantify some of these parameters, e.g. magnitude, complexity, and level of constraint, is in no way precise, but it does suggest that some of them are amenable to quantification and how this might be achieved.

The data produced by the field study proved to be verifiable by cross-checking and comparison with other studies. For example the feedback characteristics of the case histories (Fig. 15), the weighting of the phases (Fig. 16) and the systems of organisation (Fig. 23) all related significantly, correspondingly and independently to the design categories (Fig. 20). Also the process of interpreting the case histories to produce these figures proved to be repeatable by the author on several separate occasions and was confirmed by the designers involved. It is possible that the redundancy of information initially collected by the author and the continuous review of the field study programme as it progressed, contributed towards the self-correcting property of the data.

It was also encouraging that when precise information was subsequently made available it supported the judgements made by the author during the analysis, as in the weighting of the phases of case history E given in Fig. 16, which was subsequently confirmed by E Fig. 1. The results and value of the analysis were also enhanced by those instances where the results were seen, in retrospect, to be realistic and even obvious. For example the features of case history A which were difficult to codify, the phases in case history B which were impossible to separate and the unusual characteristics of case history H which, it was subsequently realised, followed from its exceptional nature.

Finally the questionnaire sent out to all the designers with the final version of the case histories for their approval, proved to be a valuable aid in checking the assumptions made in parts of the analysis. In this respect it is also interesting to note in Fig. 21 the extent to which, in almost every case, the designer's estimate of the complexity of his design is noticeably less than that allocated by the author.

THE RAMIFICATIONS OF THE ANALYSIS

The new information provided by the analysis of the data is that the weighting applied to the various phases in the evolutionary process of engineering design varies significantly with the production quantity being designed for. Related features which vary in the same way include the system of design organisation, the level of recycling which occurs, the stages between which it occurs, and also the orderliness of the design process making the stages in it more easily distinguishable.

On one hand the mass produced exercise requires an emphasis on the first two phases of the design evolution - feasibility and optimisation - in order to produce a nearly right solution for the final design phase and production. Related to this is the need for a formal, rigidly defined system of control with a well developed command hierarchy.

The one-off exercise, on the other hand, is noticeably different in structure and organisation, it is less ordered and constrained and the phases in the design evolution are less easily separated. There is more emphasis on the final design phase and a prime aim appears to be to build manoeuvrability (modifiability) into the earlier design proposals. The unit-production exercise is also associated with a less formal and more adaptable type of organisational structure. The feedback exhibited by the one-off exercise confirms these conclusions. The considerable amount of feedback during the early stages when solutions are being generated is in fact the process of understanding the problem by attempting solutions, and the absence of any significant feedback after the detail design stage indicates that with this type of exercise it is not usually possible to reconsider the design too drastically late in the process.

The large proportion of the total effort applied to the optimisation phase in all the design exercises indicates that they all contain some element of design by development - the feedback characteristics displayed in Fig. 15 in fact confirm this - and in current practice it means that in every design some degree of manoeuvrability should be built in prior to the development stage.

Two recent publications have tended to confirm this new hypothesis. In Ref. 6 Wearne presents the results of a study of six case histories in engineering design and concludes that the significant factor influencing the organisation of design in the firms studied is the proportion of the design completed after becoming committed to sales. A study of the case histories in this reference and discussions with its author have ascertained that in all the case histories analysed this variable correlates to the one-off or mass production

situation. Moreover, the organisational tree diagrams in this reference appear to relate closely to Woodward's optimum organic and mechanistic types for the one-off and mass-produced situations respectively.

In reference 67 Woodward extends the work described in reference 58 and suggests that the key factor in the correlation between management structure and the success of a firm's operation may be the level of uncertainty involved, rather than the production quantity - although these variables are rarely independent in the design situation.

These two references, with the present analysis, therefore reinforce the view that in engineering design the type of design process and organisational structure vary significantly with the production quantity of the project being designed for. This is considered to be a very important topical discovery, from which it appears to follow that the personnel at all levels, from the designer to the operator on the shop floor, and their organisation and method of working, should match this dominant variable.

It is also considered important to note a negative aspect of the analysis, namely that all the other variables considered, including the level of innovation, technical content, complexity and size of project, appear to be insignificant in affecting the type of design process, except where they may be related to the production quantity.

The main results of this analysis are considered to be very relevant to the management, execution and teaching of engineering design. A more detailed and diverse study of the subject may modify this view and indicate other secondary and less obvious relationships. It is hoped that the guidelines established in the present work will encourage and assist such studies.

GENERAL COMMENTS AND FUTURE WORK

During the course of this field study several aspects of design in the engineering industry became apparent and, although they are not related directly to the stated object of the research, they are considered to be worth recording.

The importance of key individuals in each design organisation and the fact that they were usually closely identified with critical decisions in the process was quite common. On one occasion this type of man was described as "The one who decides when we are changing direction, and behind whom we all shelter when the wind starts to blow".

The reluctance of the designer to abandon an old idea was also evident in most cases. This was not necessarily an indication of stubbornness, pride or vanity, but a natural desire - often unconscious - to reduce, or at least not to permit an increase in, the level of uncertainty.

The atmosphere in which the designer works obviously affects his performance and his manner of working. Those mass-production situations which took place in large closely controlled environments were themselves well ordered and regulated. In the situations where exceptional financial and personal incentives were involved the design performance improved noticeably.

The value of working models as a direct aid to the designer, and as a means of explaining and 'selling' his proposals to other people, was convincingly and significantly demonstrated on numerous occasions during the field work. In case histories C, H and J the models which were built to demonstrate how a proposal would work proved to be important factors in the subsequent acceptance and development of the design.

The advantages and disadvantages of the design methodologies have already been discussed. In none of the case histories studied was there any significant formal use by the designers of either monitoring or motoring methodologies. In spite of this there appeared to be an acceptance that any procedures which helped to clarify the design proces and which would monitor, guide and assist progress through it, would be of value. It was acknowledged that a problem well formulated was a problem half solved and the need to record information and provide continuity was critical; any methodology which would assist in this without being too complicated and time consuming would be accepted and used.

The question of communication also appears to be critical, where designs failed to reach fruition, or errors were made, this usually occurred because of insufficient or incorrect information, rarely through incompetence; the most serious errors involved changes of personnel without the necessary transfer of information.

The technical content of all the case histories was very low. Only those exercises recorded in the nuclear power industry involved any very erudite knowledge or calculations - about 90% of all the work studied could have been undertaken quite competently by a good HND student of engineering.

The level of innovation was also low, several case histories involved new ideas and techniques for the design teams but few of them had a large or continuous element of novelty. Furthermore there were no truly creative 'Eureka' experiences, although there was one bisociative inspiration and several inevitable progressions towards an innovation.

Several areas appear to offer fertile ground for future work related to the current study. One possibility would be to collate another series of case histories in a range of design categories in order to list the repeatability of the analysis and to seek further, less obvious relationships. A parallel approach would be to investigate the 'grey' region between the extremes of design for mass-production and design for unit production. The present work throws very little light on this region but it is possible that the quantity being designed for has less effect on the nature of the design process and its organisation system than it has on the type of management structure as investigated by Woodward.

Design strategy obviously warrants further investigation with a field study designed to reveal the pattern and nature of the decisions made and actions taken. It is possible that an algorism of design strategy could be produced which combined the chronological decision tree of Marples with the inter-related decision areas of Morgan; this might take the form of Bond's ramified structure based on the major features of the problem and would be of value in understanding the design process and to the practising designer. Such a study would also concentrate on the details of the organisation system involved and relate them to the results of Woodward and Wearne.

The real value of design methodologies also warrants further empirical investigation. A series of case histories in which methodologies have been formally employed could be studied or an analysis made of the results of a common design problem tackled in a variety of ways. The possibility of relating methodologies not only to the stage in the design evolution which has been reached, as advocated by Jones, but also to the

category of design involved, might also be studied. Related to this is the gradual development of computer applications away from the routine and towards the more creative end of the spectrum of design activity.

In undertaking the field work suggested above the concurrent natural history approach adopted in the present work has been shown to be suitable if the researcher is able to prove his validity to the designers with whom he is working, but does not lose his objectivity by becoming too involved with their problems.

The analysis of the output from the present empirical work has important consequences for the teaching of design. The description of design evolution can be used with confidence as the basis for teaching and training engineers and as the context in which to introduce an account of the monitoring and motoring methodologies, their value and limitations.

Case histories have been collated and used in the United States for some years as an aid to teaching Engineering Design (References 68 and 69); they have, of course, been used for much longer for the teaching of law and business administration. They offer the opportunity to consolidate and expand more conventional theoretical work and also to develop flexibility of mind, increased understanding, and a means of teaching students about the incoherent, unpredictable and imponderable factors associated with design in the engineering industry. The author has been able to find only two instances of case histories being used for research into engineering design in this country and none in the United States.

At worst this work will have served only to clarify some intuitions concerning the nature of engineering design in industry, at best it may provide a pilot research programme, and significant conclusions on what variables to measure and how to measure them, upon which future work can be based. This in turn may provide the body of reliable empirical data upon which further rigorous and precise studies of the subject may be based. The accumulation of a body of reliable empirical data on engineering design in industry is essential in order to understand how the designer works and how his performance, education and training can be improved.

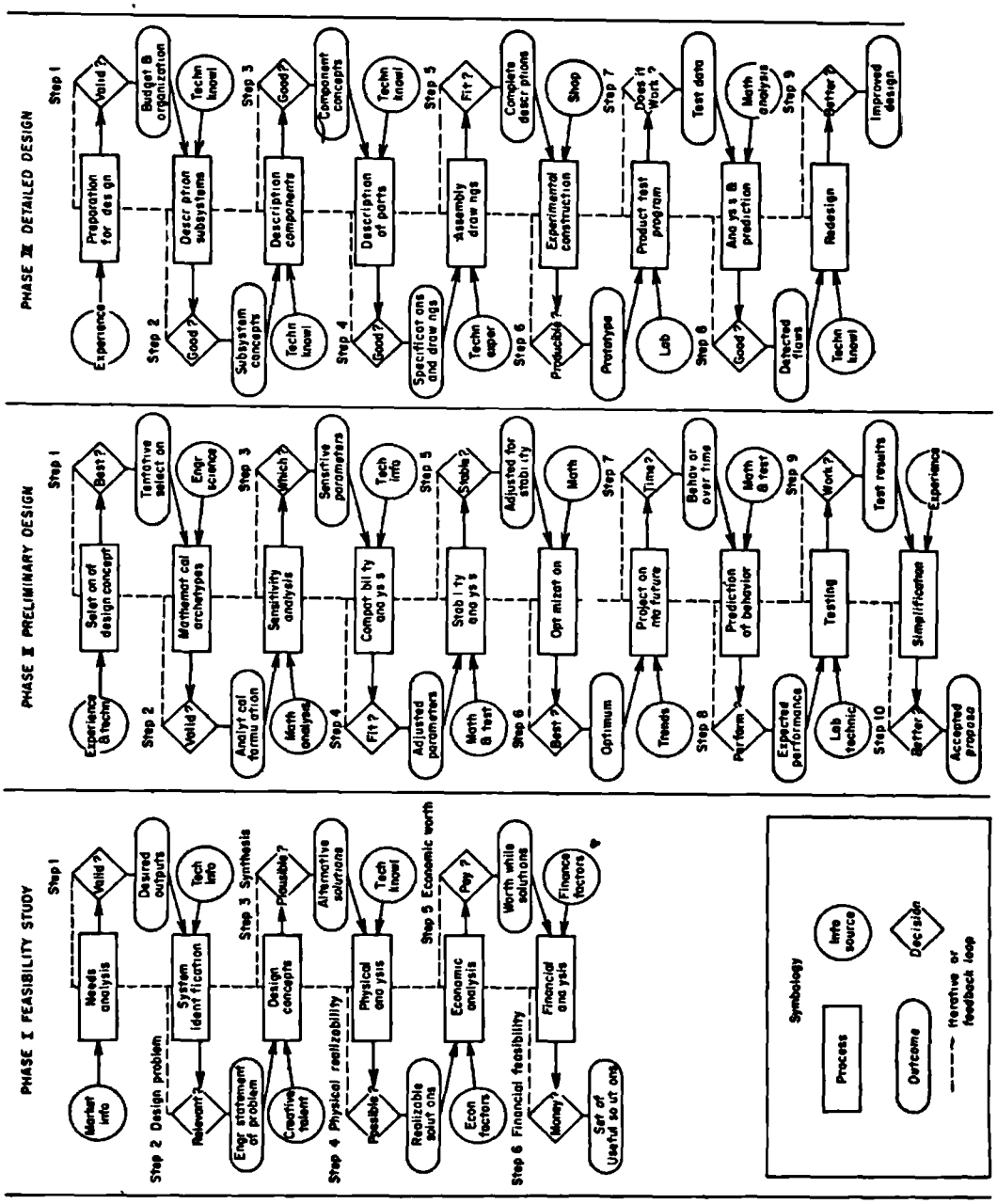


FIG 1 DESIGN EVOLUTION M.ASIMOV.

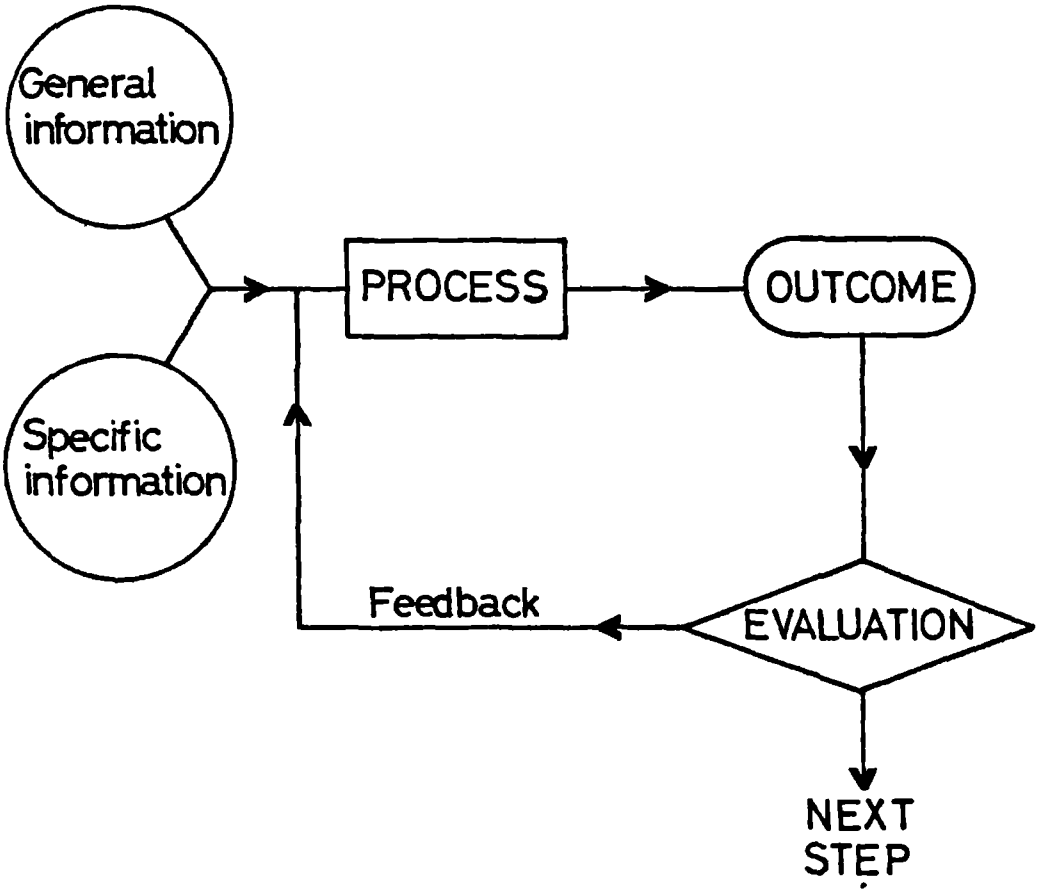


FIG 2 DESIGN EVOLUTION - UNIT STAGE - ASIMOV

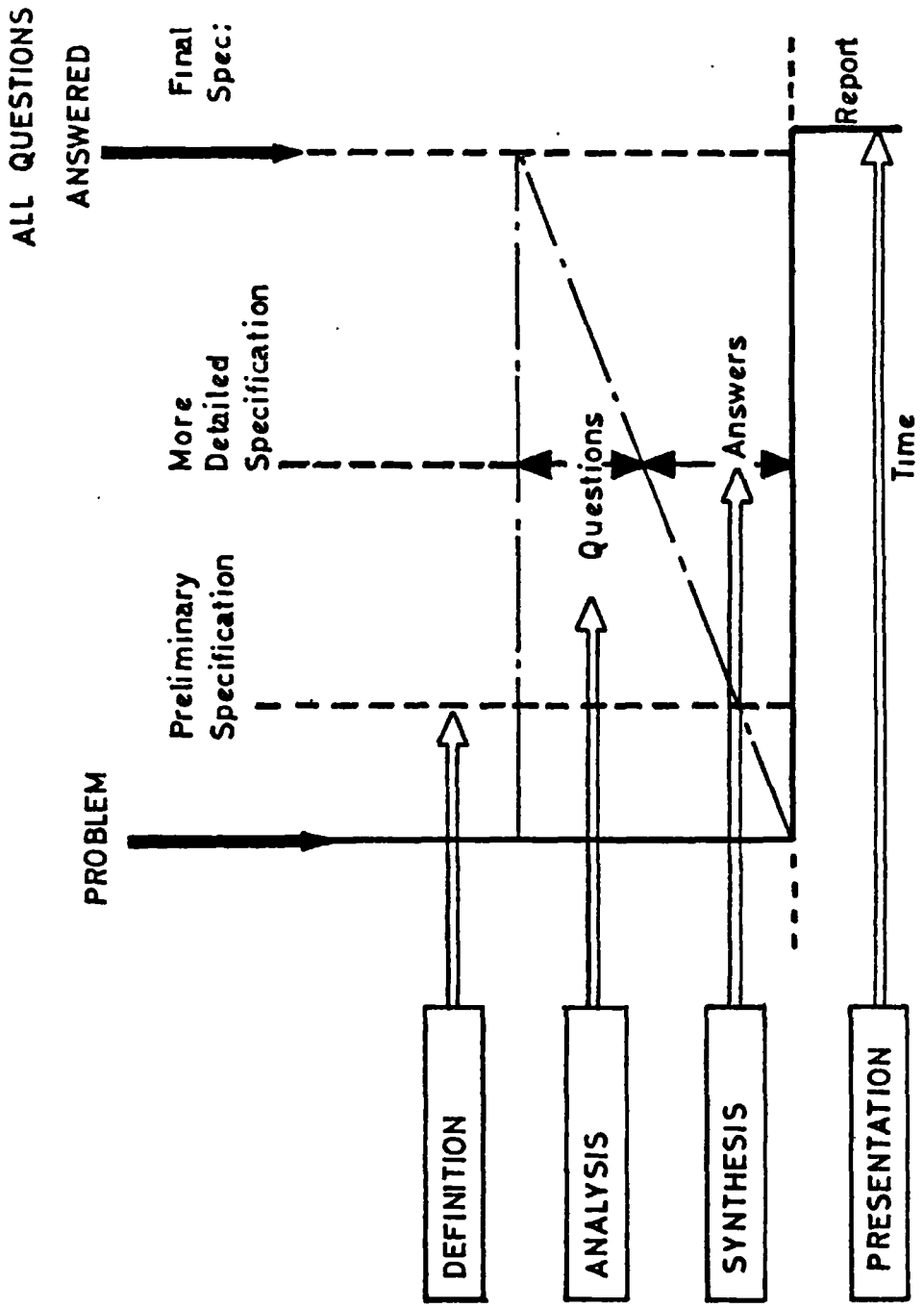


FIG3 THE MORPHOLOGY OF DESIGN K.NORRIS.

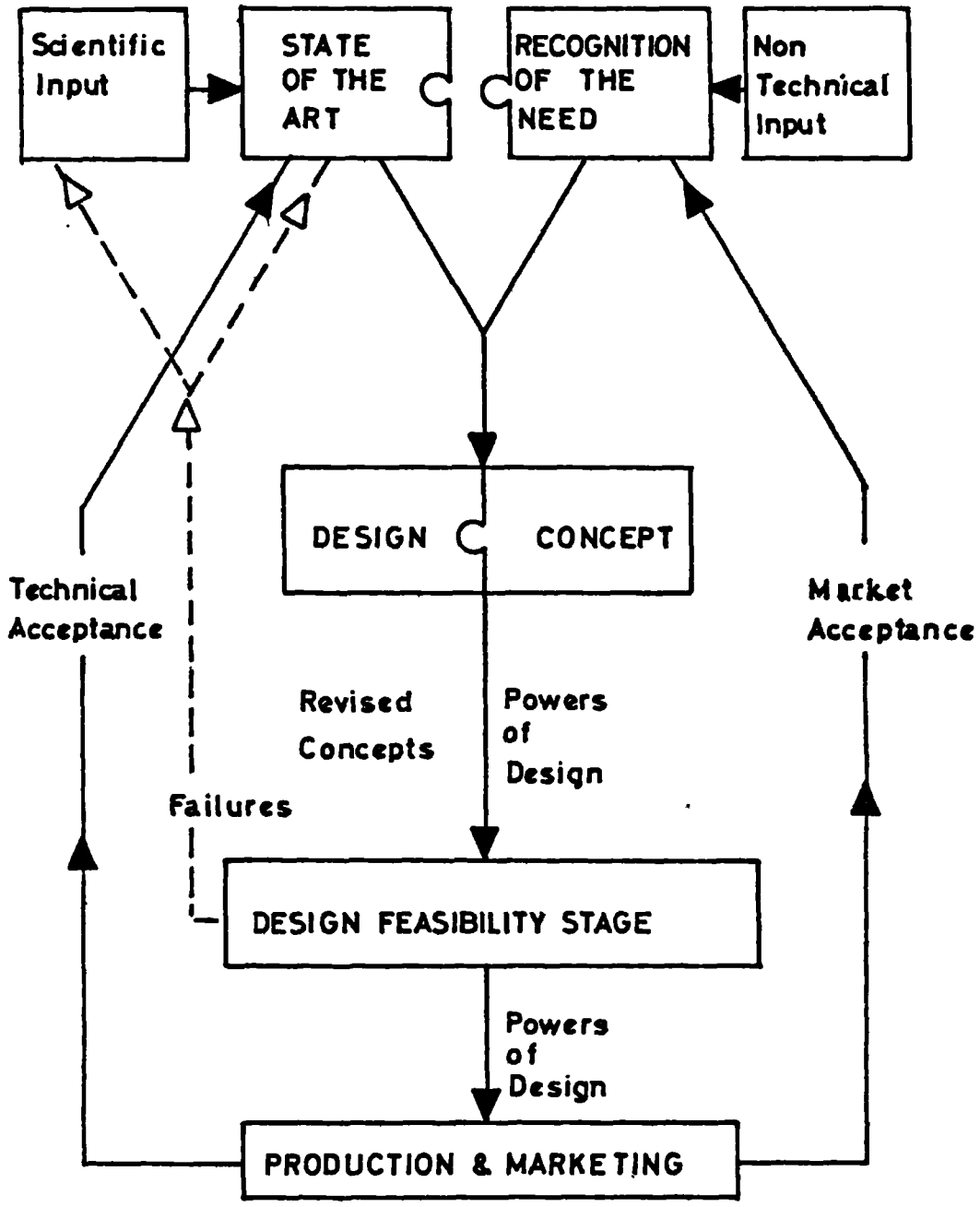


FIG 4 STRUCTURE OF DESIGN METHOD - R.J.McCRORY.

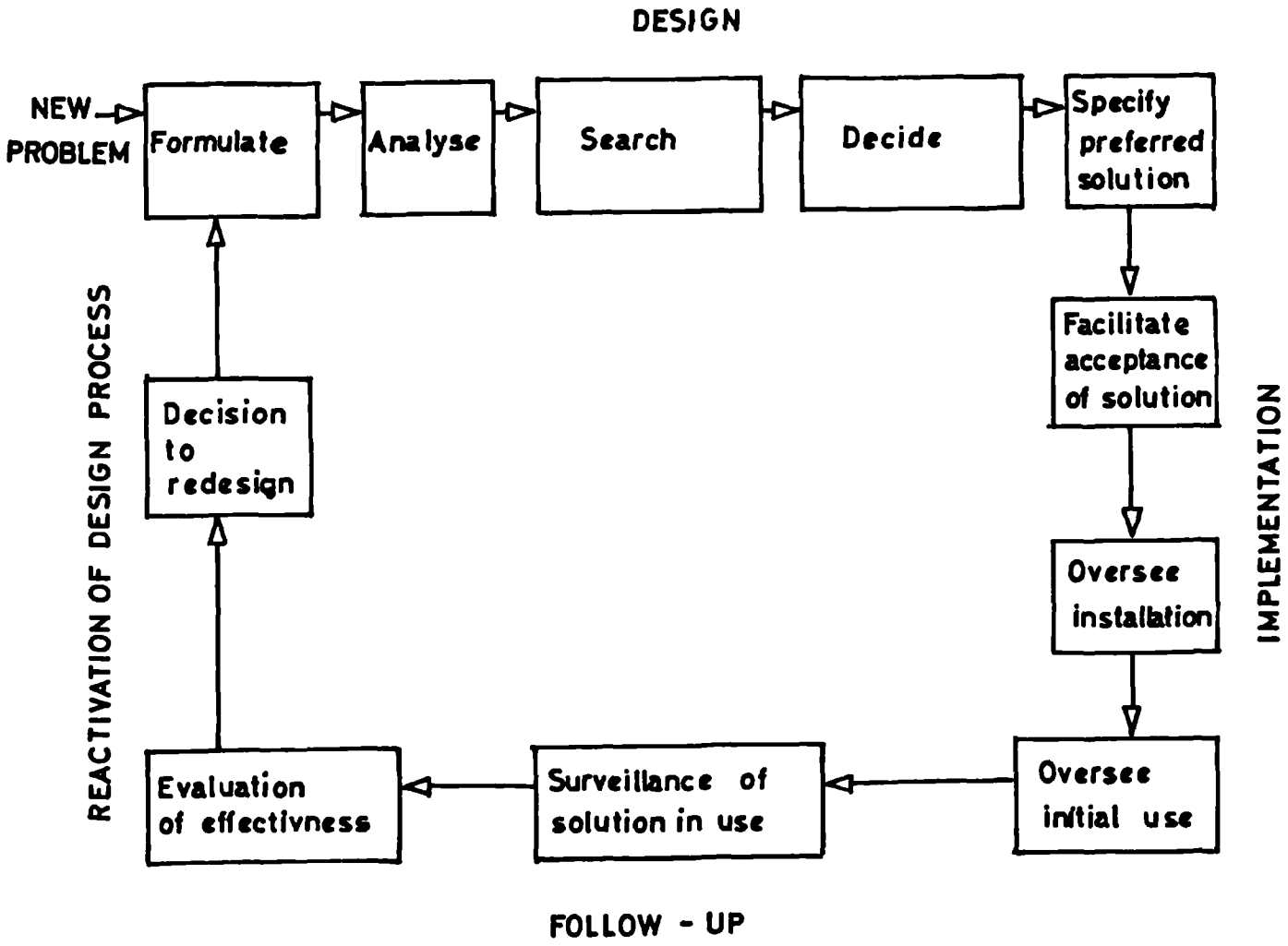


FIG 5 PROJECT LIFE - CYCLE - E.V.KRICK.

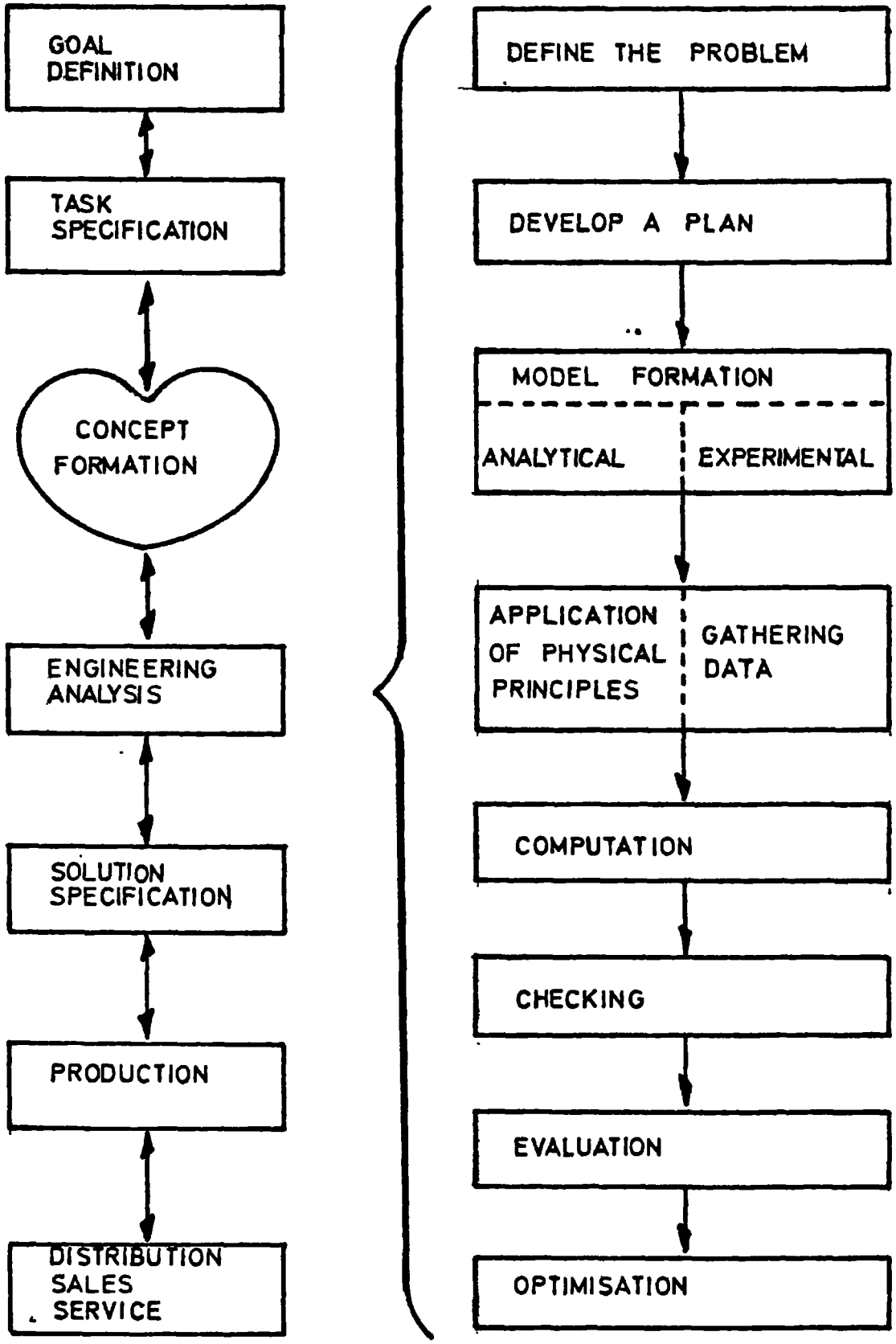


FIG 6 BLOCK DIAGRAM OF DESIGN PROCESS J.DIXON

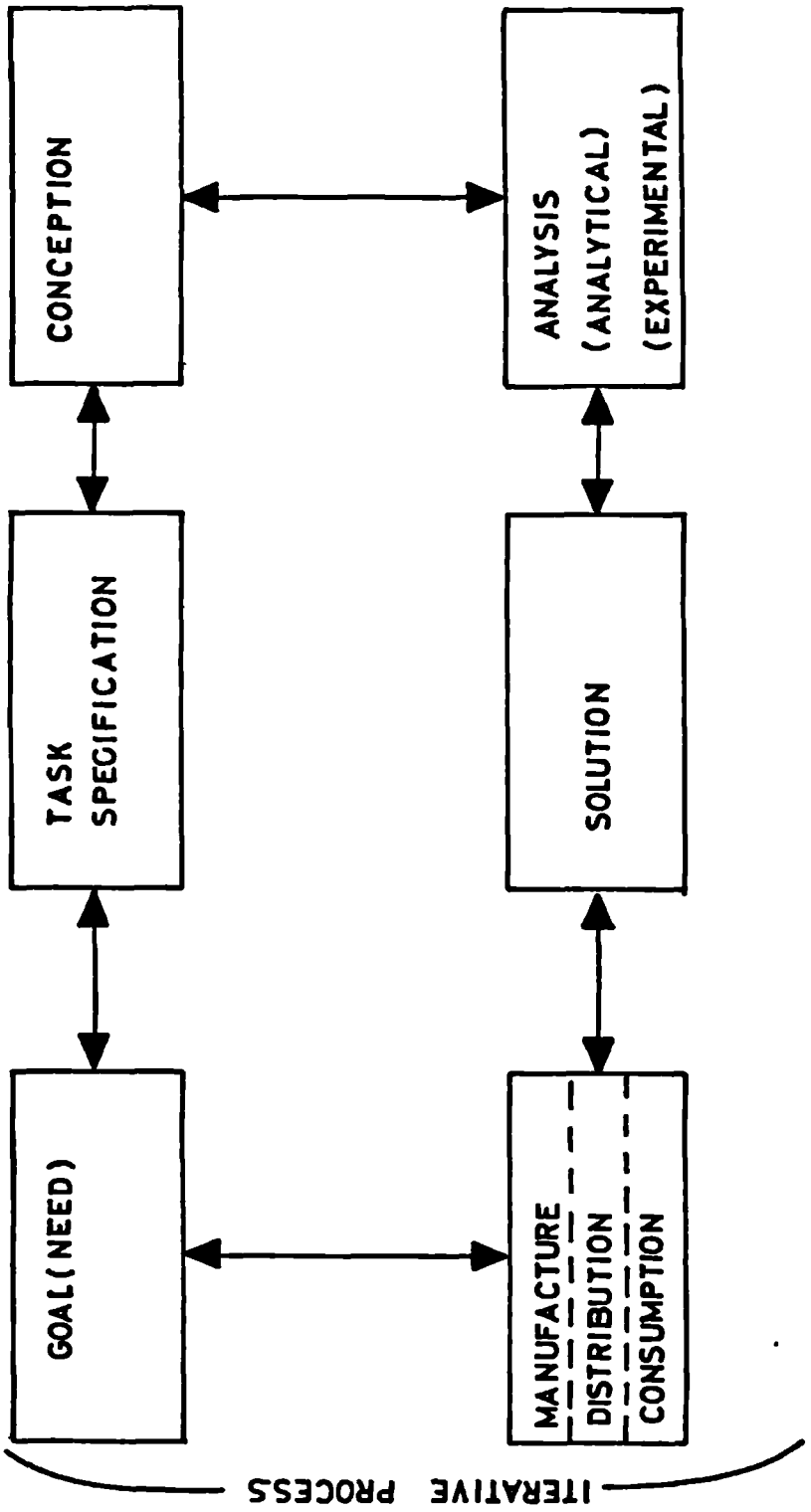


FIG7 PROJECT LIFE-CYCLE - P.H.HILL.

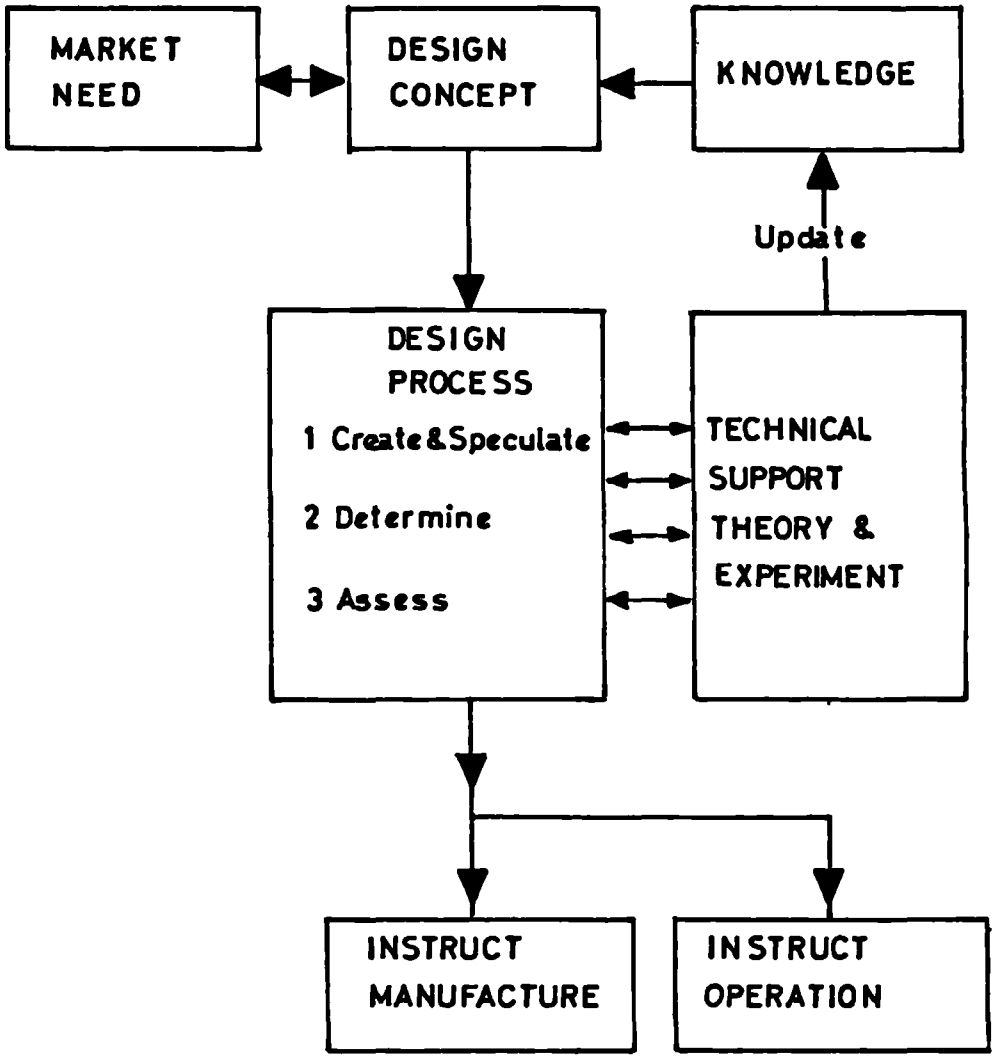


FIG8 PROJECT LIFE-CYCLE - J. STAMPER.

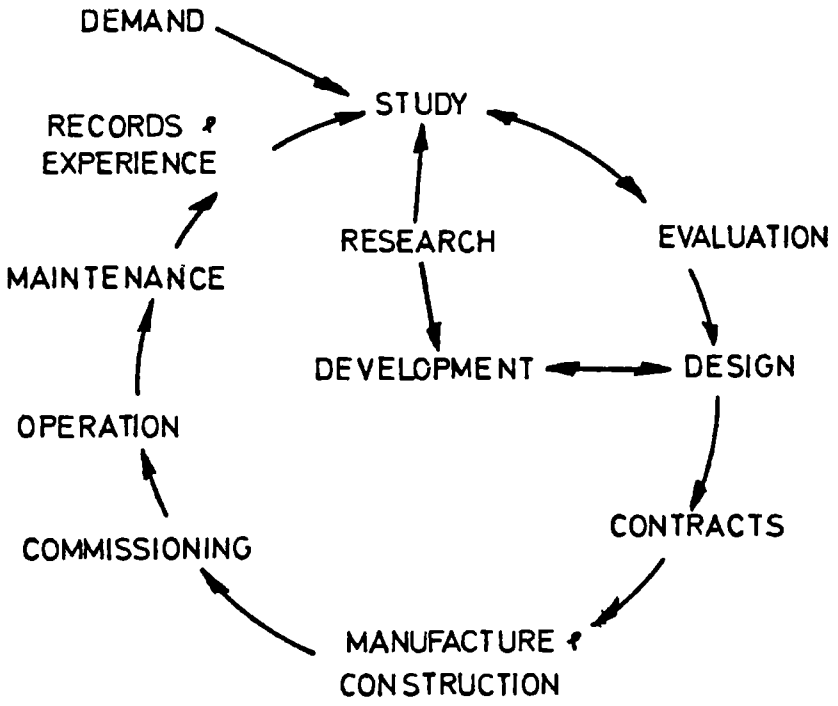


FIG 9a STAGES IN EVOLUTION OF A PROJECT

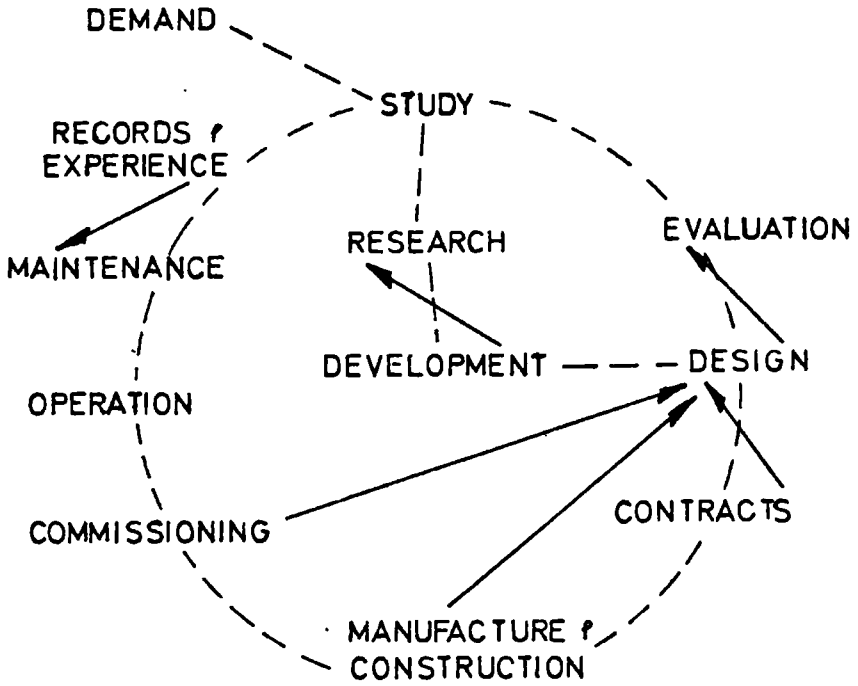


FIG 9b CURRENTS OF INFORMATION S.H.WEARNE.

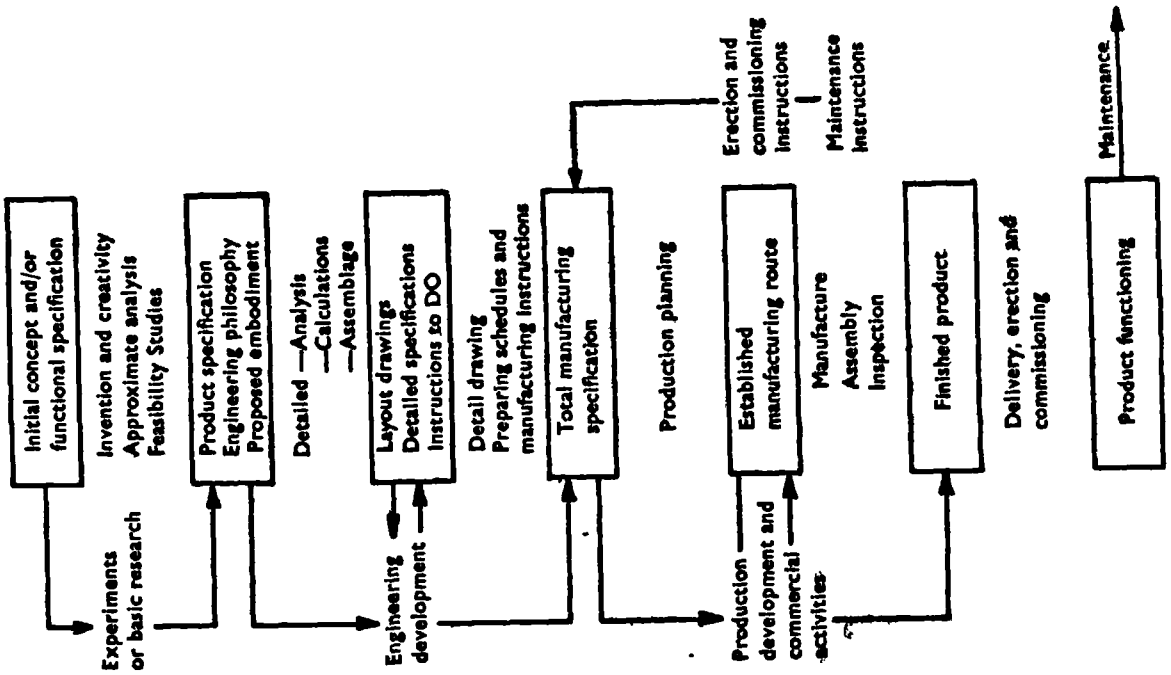


FIG 10 DESIGN AND MANUFACTURING STAGES

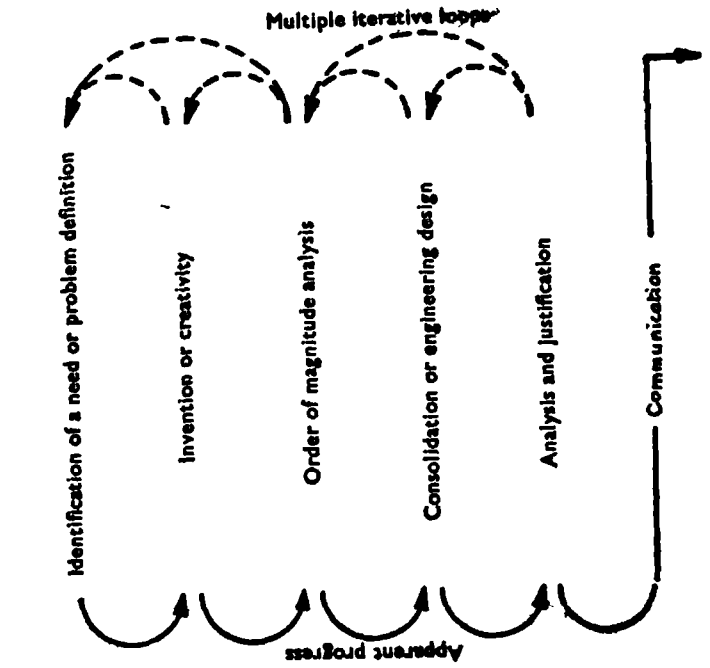


FIG 10 DESIGN STAGES C.RODWELL

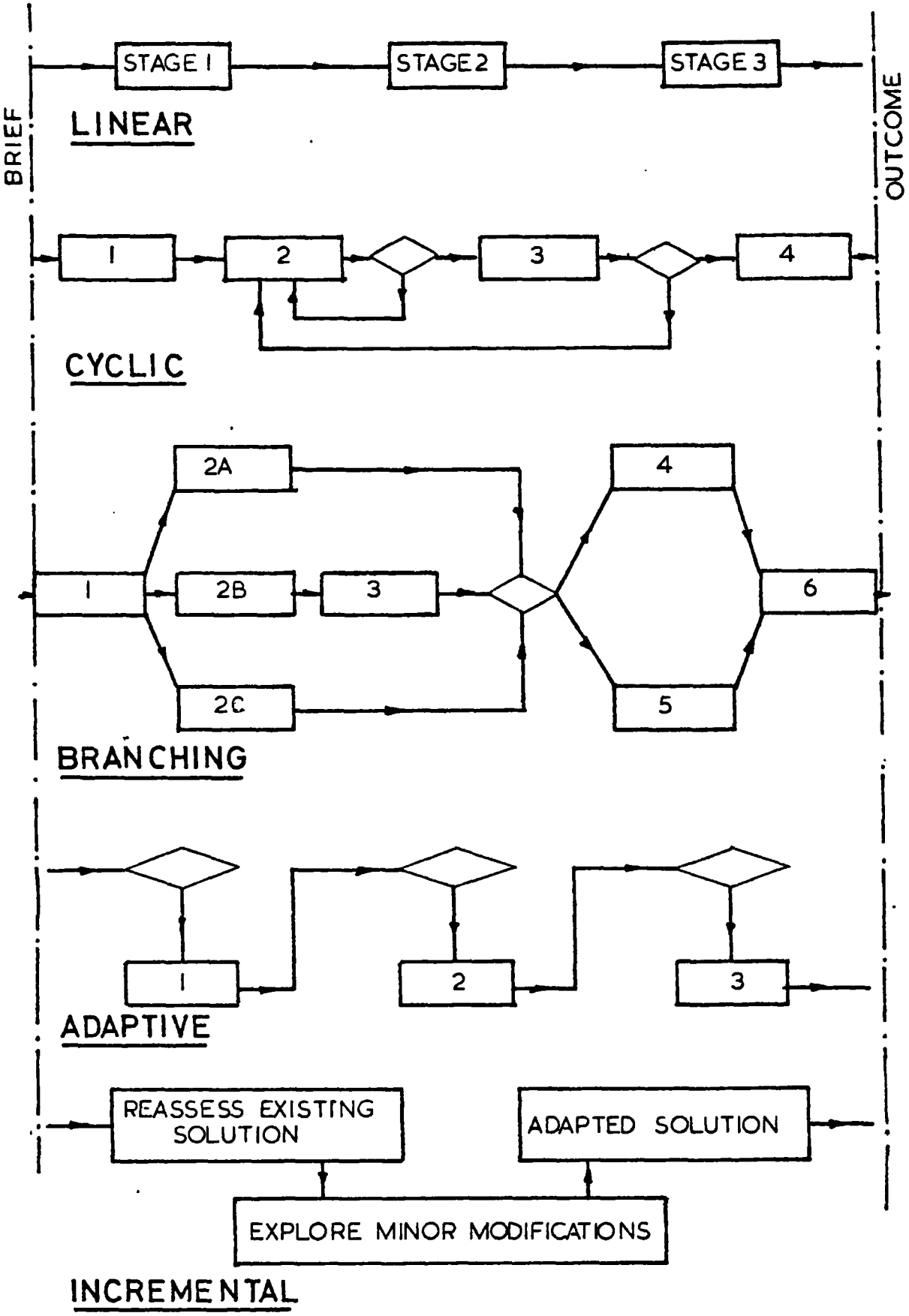


FIG 11 DESIGN STRATEGY J.C. JONES

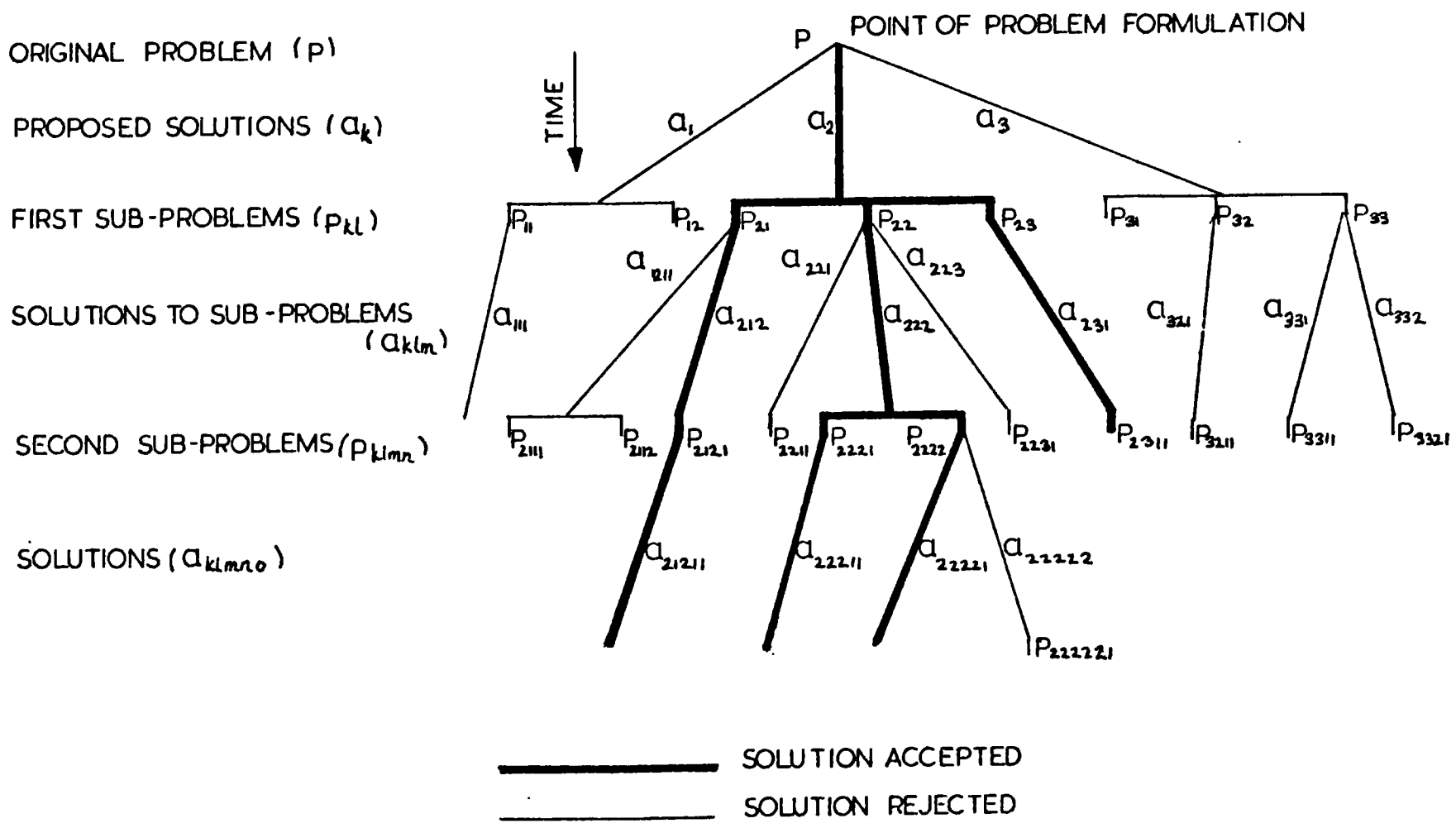


FIG 12. THE DECISION TREE L.MARPLES

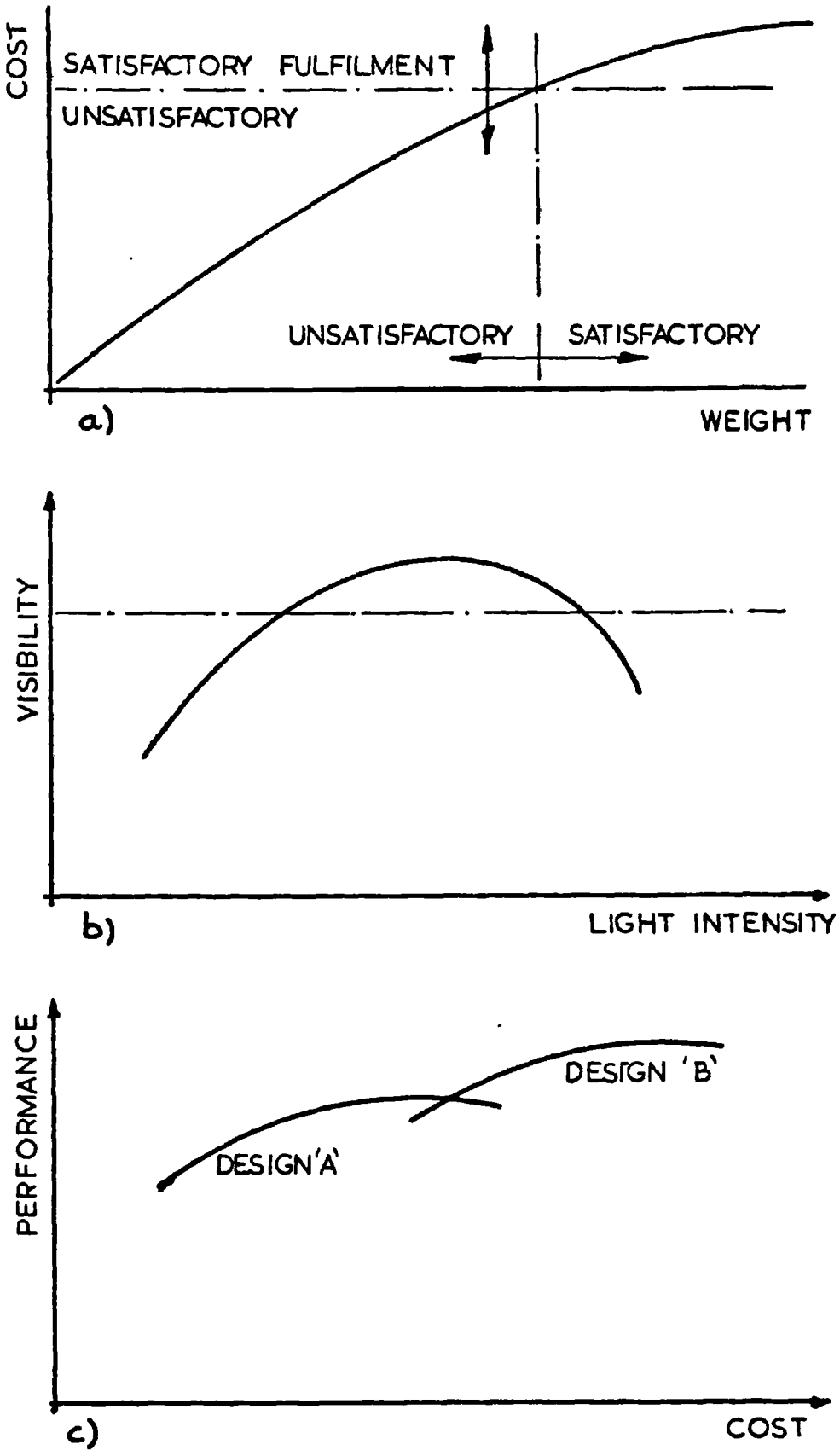


FIG 13 INTERACTION CURVES

STAGE → / CASE HISTORY ↓	STUDY OF PROBLEM	SPECIF-ICATION	GENERATION OF SOLUTIONS	SELECTION OF BEST SOLUTION	DEVELOPMENT OF CHOSEN SOLUTION	DETAIL & COMPONENT DESIGN	TRIALS	FINAL DESIGN
A	✓	✓	✓	✓	✓	✓	✓	✓
B	✓	•	✓	✓	✓	✓	•	✓
C	✓	✓	✓	✓	✓	✓	✓	✓
D	✓	✓	✓	•	✓	✓	✓	✓
E	✓	✓	✓	✓	✓	✓	✓	✓
F	✓	✓	✓	✓	✓	✓	✓	✓
G	✓	✓	✓	•	✓	✓	✓	✓
H	✓	✓	✓	✓	✓	✓	✓	✓
J	✓	✓	✓	✓	✓	✓	•	✓
K	✓	✓	✓	✓	✓	✓	•	✓
L	✓	✓	✓	✓	✓	✓	✓	✓

✓ STAGE IN DESIGN PROCESS POSITIVELY IDENTIFIED

FIG14 THE STAGES IN EACH DESIGN PROCESS

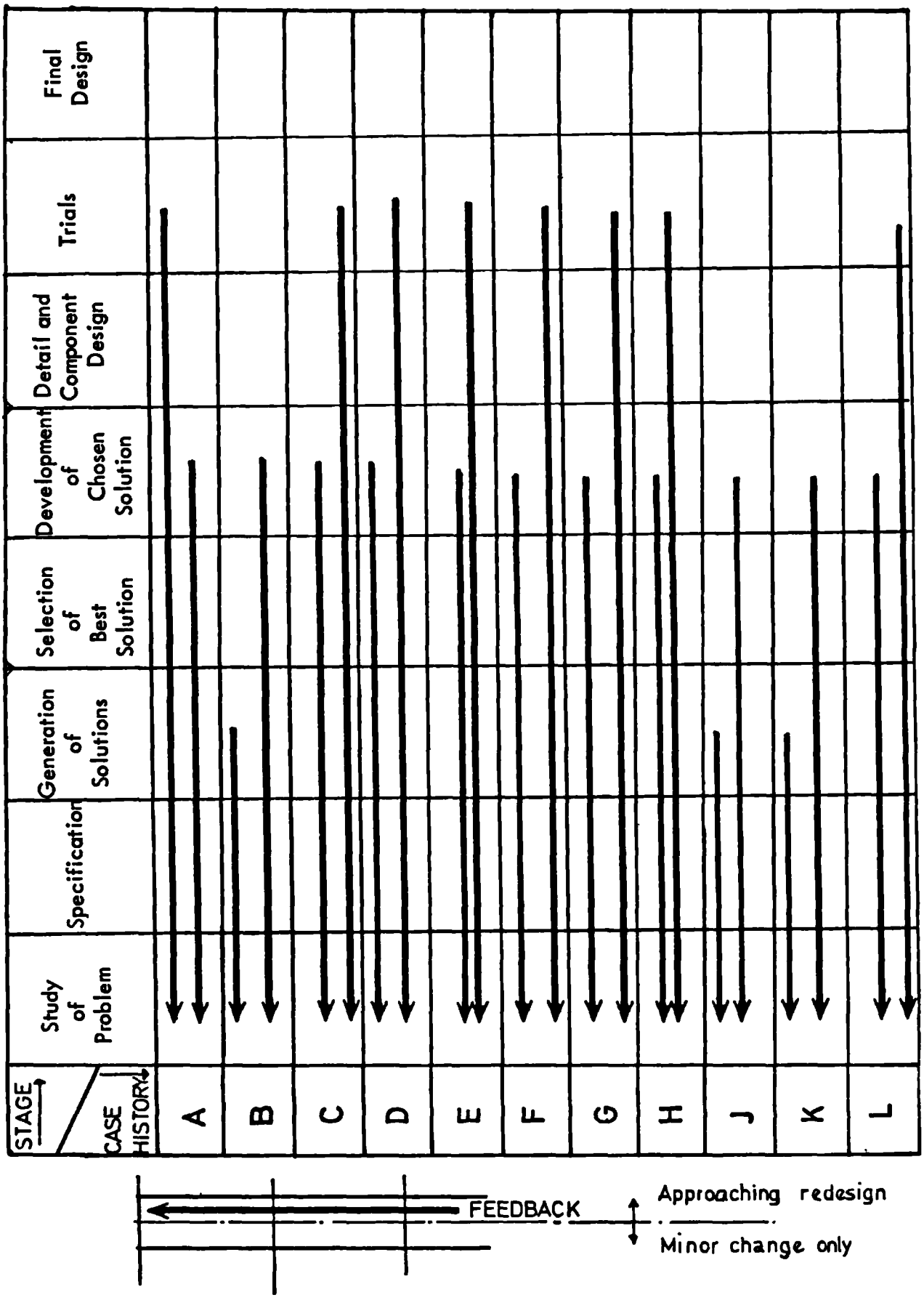


FIG 15 MAIN FEEDBACK IN EACH DESIGN PROCESS

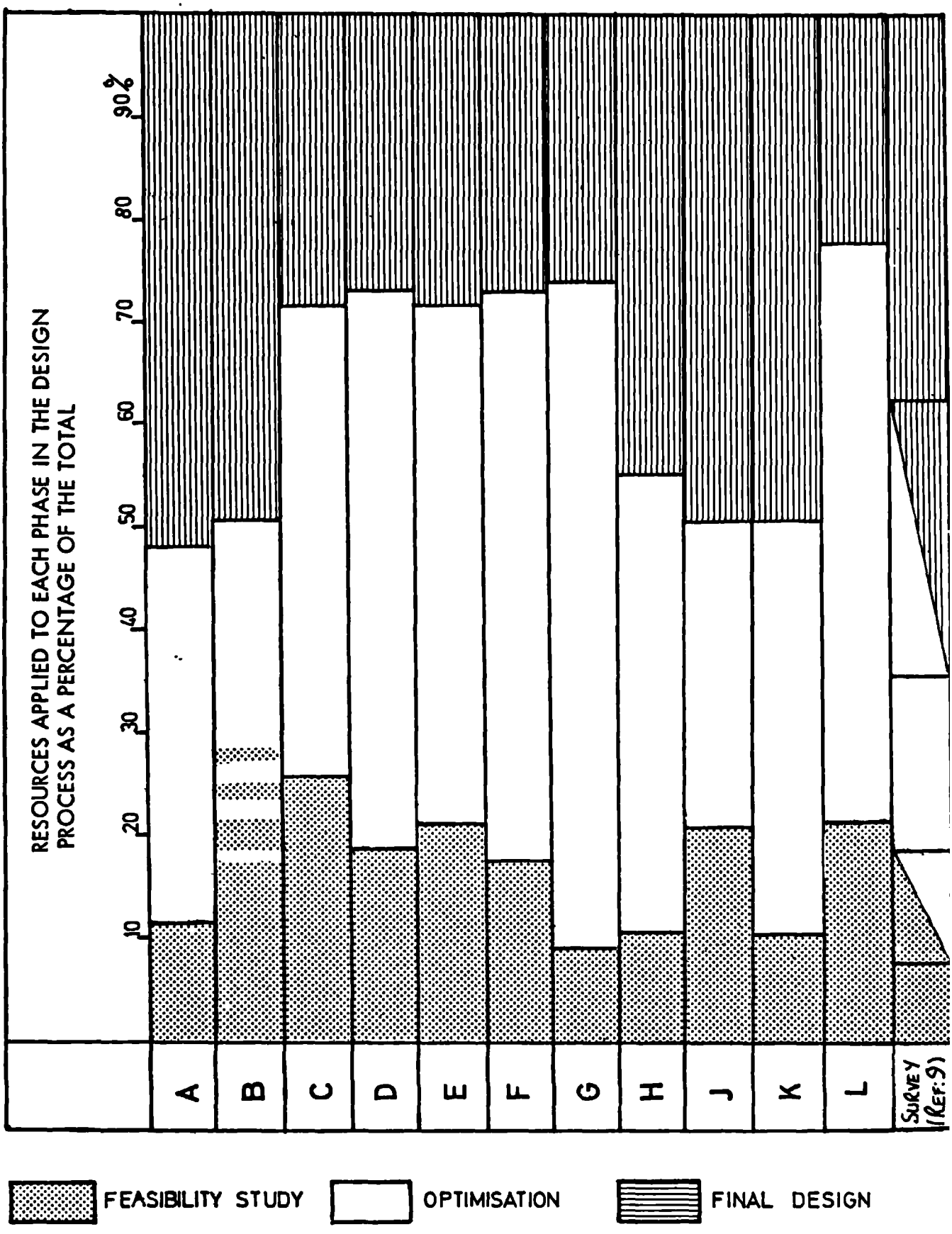


FIG 16 THE WEIGHTING APPLIED TO EACH PHASE

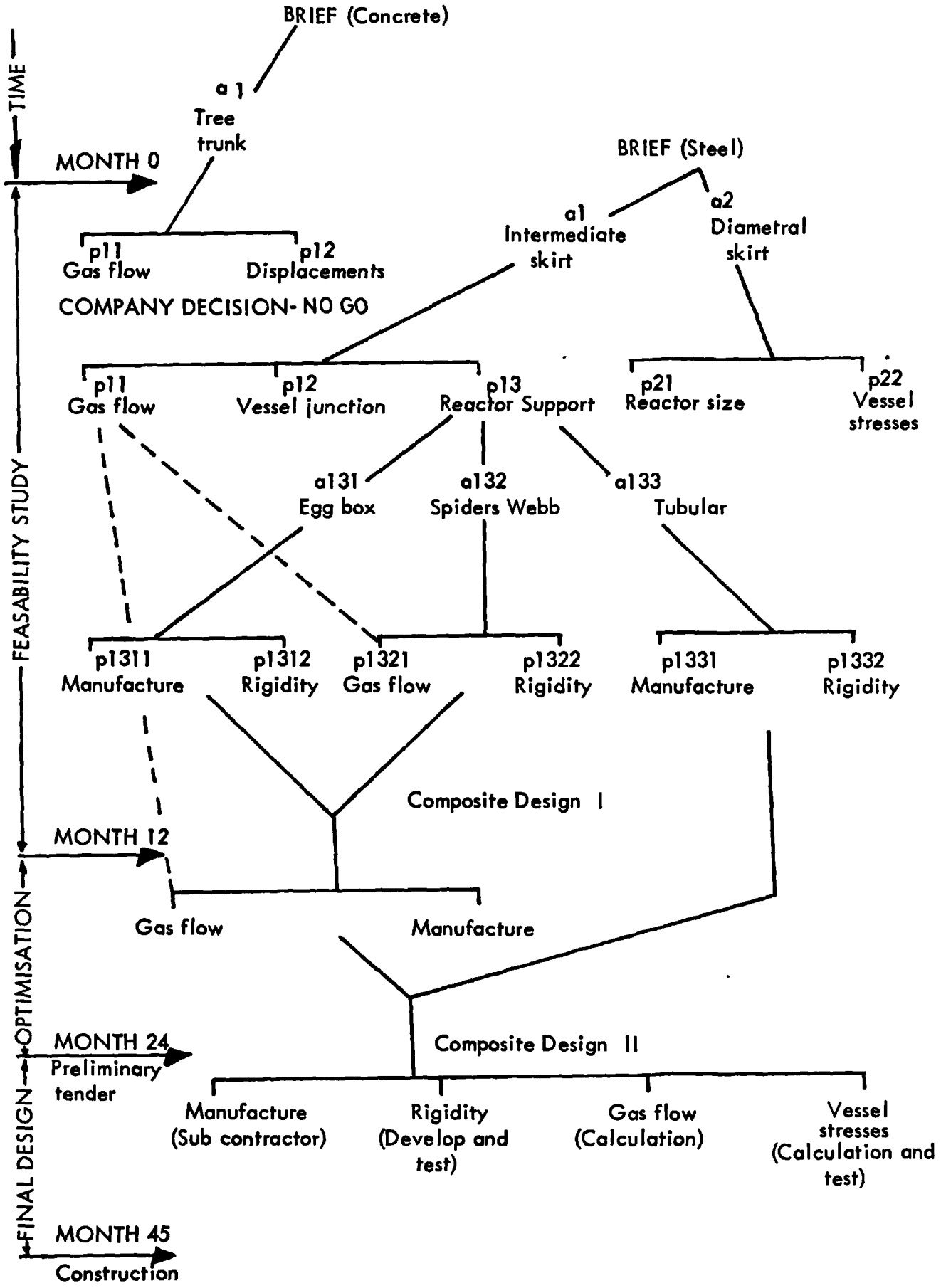


FIG 17 DECISION TREE - CASE HISTORY J

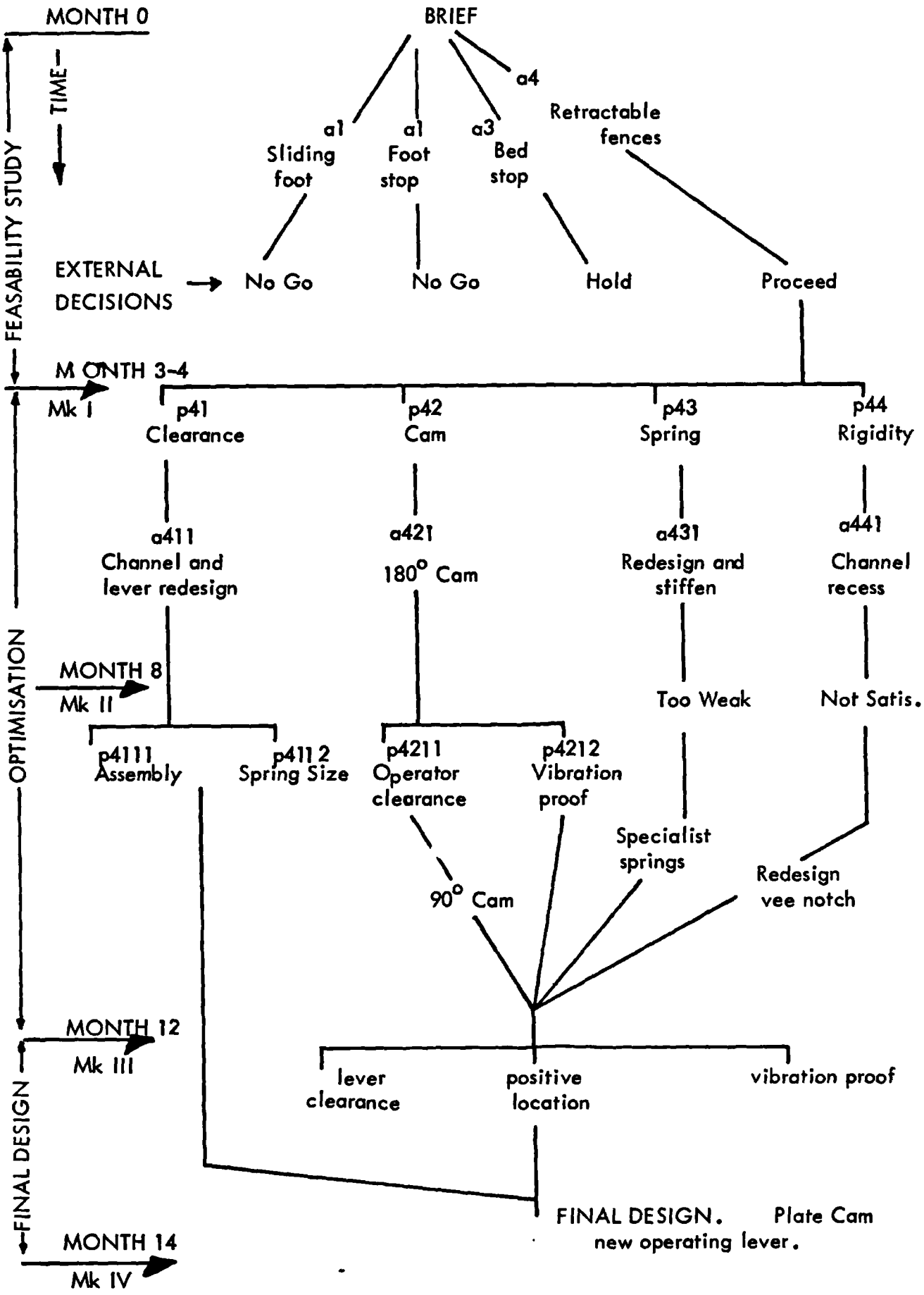
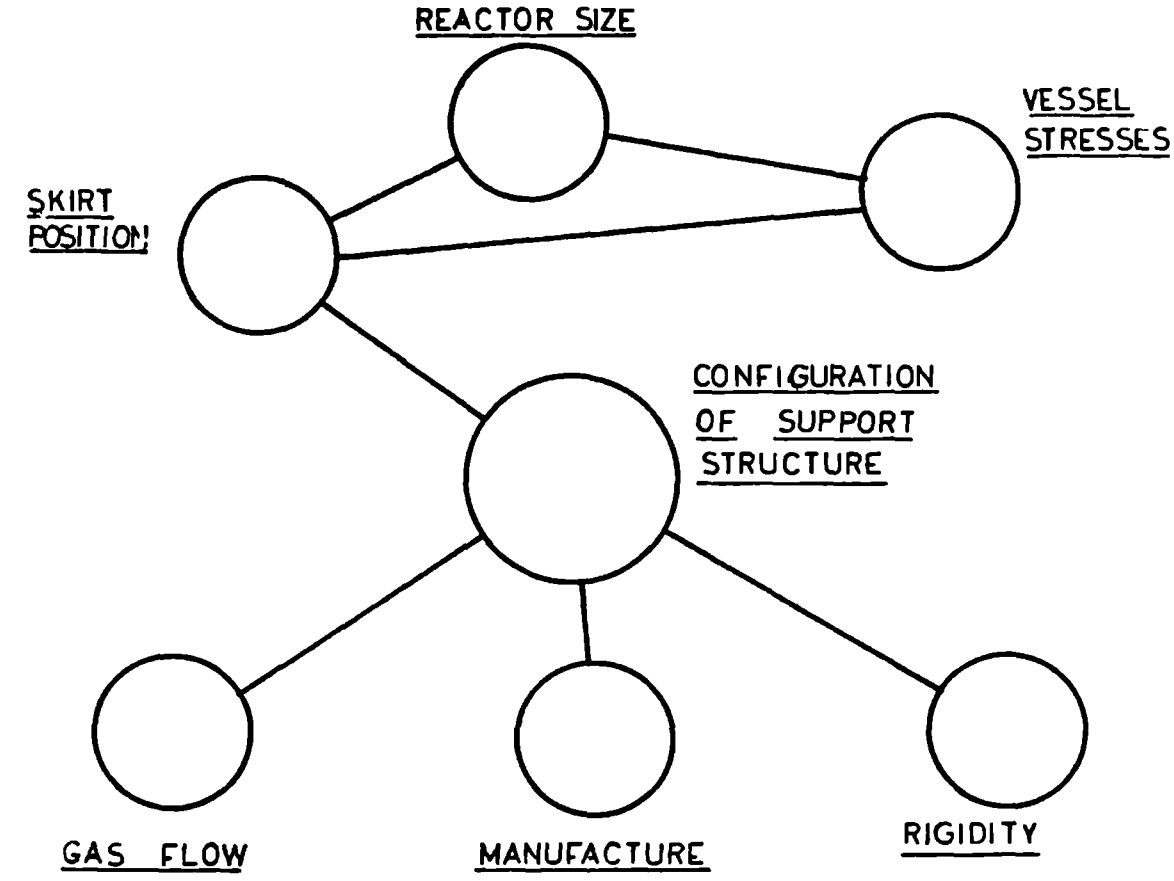
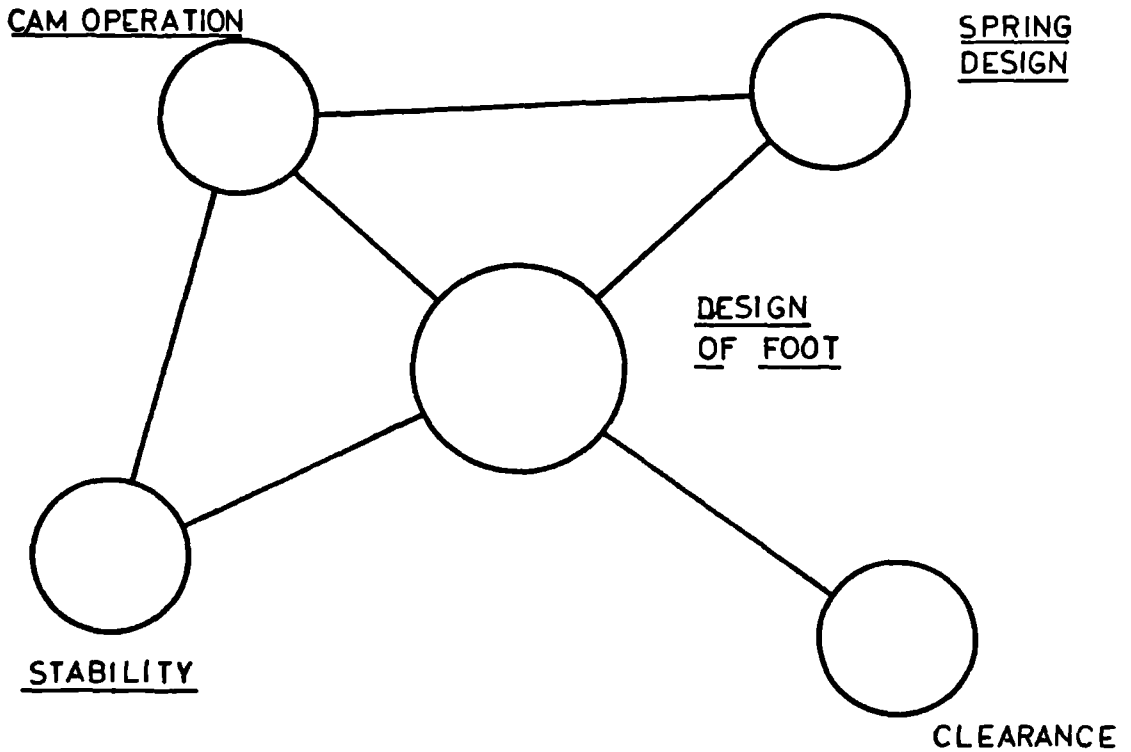


FIG18 DECISION TREE - CASE HISTORY L



CASE HISTORY J



CASE HISTORY L

FIG19 DECISION NETWORKS

FACTOR → / CASE HISTORY ↓	Cost	Time	Other constraints	Detailed brief	Production quantity: Mass	Production quantity: Batch	Production quantity: One-off	Innovation	Extrapolation	Technical content	Probability of error	Complexity
A	✓	○	○	○	•	•	✓	✓	•	○	✓	✓
B	•	•	✓	•	•	•	✓	✓	•	✓	✓	✓
C	✓	✓	✓	✓	✓	•	•	○	○	○	○	•
D	○	✓	✓	✓	✓	•	•	○	○	✓	✓	○
E	✓	✓	✓	✓	✓	•	•	○	○	○	○	○
F	○	✓	✓	✓	✓	•	•	✓	○	✓	✓	○
G	○	○	✓	○	•	✓	•	✓	•	•	○	•
H	•	•	•	○	•	•	✓	✓	•	•	○	•
J	•	○	✓	•	•	•	✓	✓	•	✓	✓	○
K	•	○	✓	•	•	•	✓	○	•	✓	✓	✓
L	✓	○	○	○	•	✓	•	✓	•	○	✓	•

✓ POSITIVE EVIDENCE OF THE PRESENCE OF THE FACTOR

○ POSSIBLE EVIDENCE

• NO EVIDENCE

FIG 20 FACTORS AFFECTING THE DESIGN PROCESS

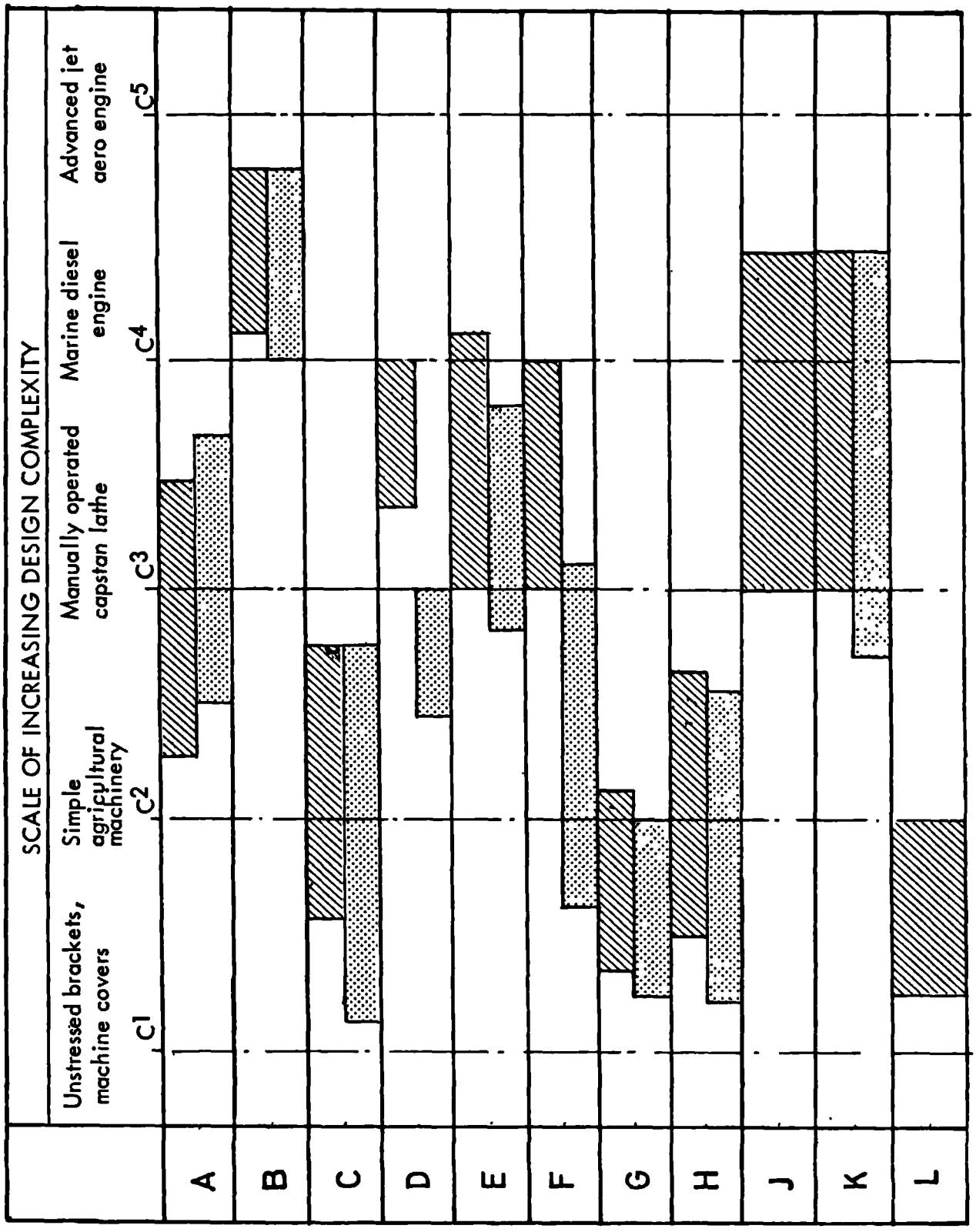


FIG 21 DESIGN COMPLEXITY

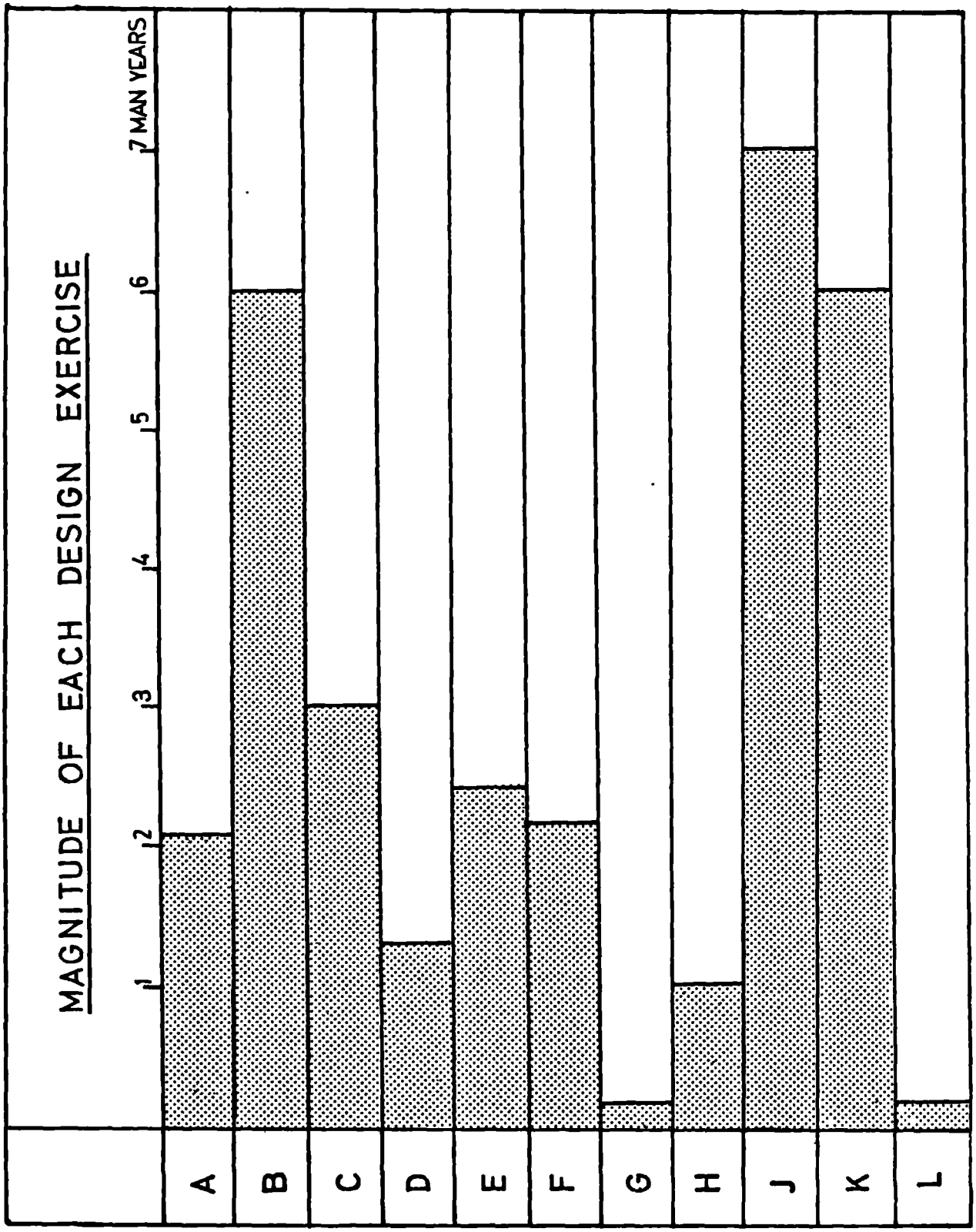


FIG 22 MAGNITUDE OF THE DESIGN EXERCISES

	MECHANISTIC							ORGANIC					
	Style formal	Instruction issued	Clear lines of command	Rigid structure & programme	Well defined duties	Style informal	Consultation the norm	Vague lines of command	Flexible structure & programme	Duties not clearly defined
A	○	○	○	•	○	○	○	○	√	○
B	•	○	○	•	•	√	√	○	√	○
C	√	√	√	○	√	•	•	•	○	•
D	√	√	√	○	√	•	○	•	○	•
E	√	√	√	√	√	•	•	•	•	•
F	√	√	√	○	√	•	○	•	○	•
G	○	√	√	○	○	•	•	•	○	•
H										
J	•	○	○	•	•	√	√	○	√	○
K	○	○	○	•	•	√	√	○	√	○
L	○	○	√	○	√	○	○	•	○	•

√ DEFINITELY CONSIDERED TO BE A CHARACTERISTIC

○ POSSIBLY A CHARACTERISTIC

• NOT A CHARACTERISTIC

FIG 23 CHARACTERISTICS OF SYSTEM OF ORGANISATION

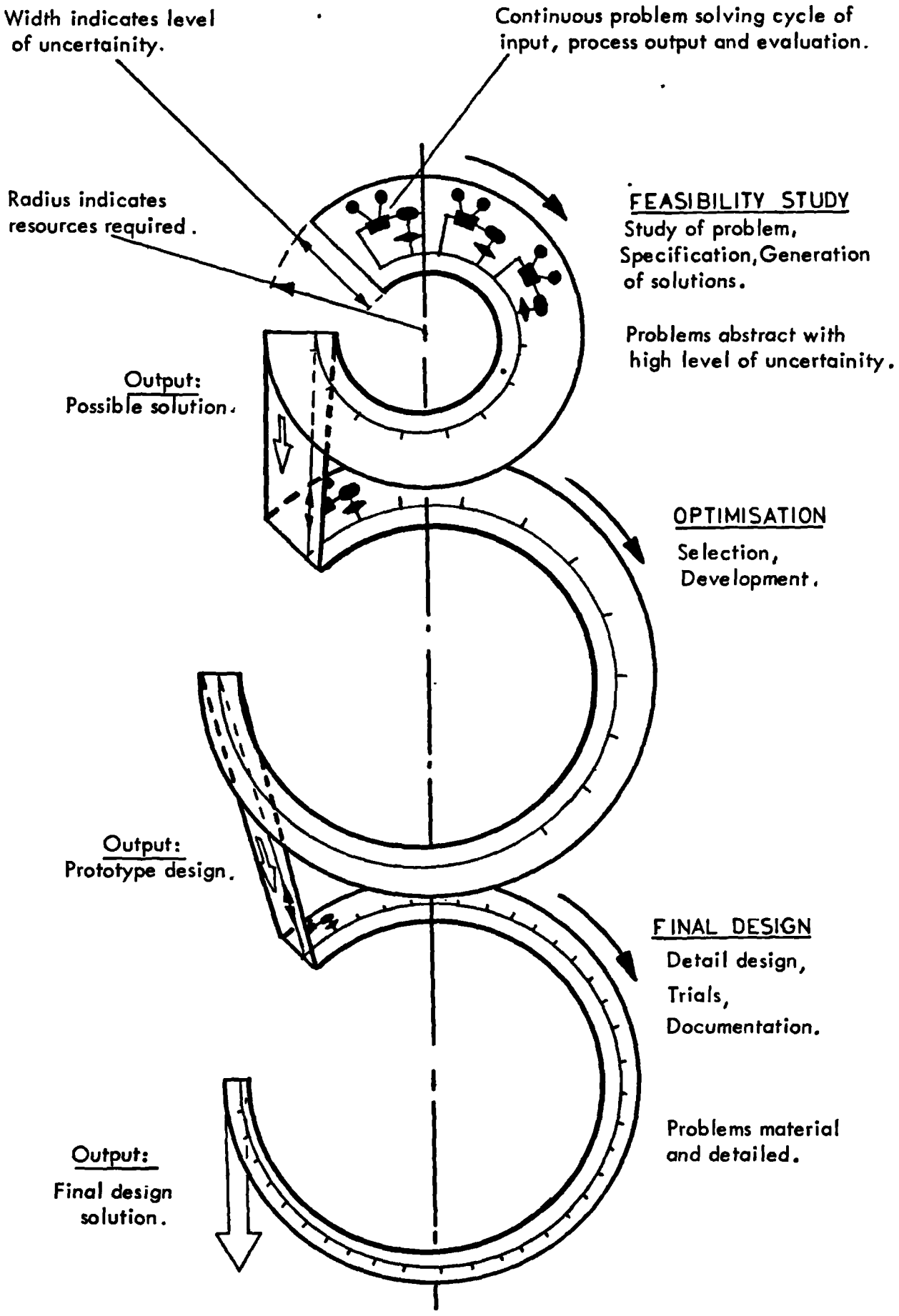


FIG 24 DESIGN EVOLUTION

b.

d.

a.

c.

PLATE1 MODEL OF THE DESIGN PROCESS

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