UNIVERSITY OF SOUTHAMPTON

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# DESIGN FAULT FEEDBACK, AN INFORMATION TECHNOLOGY STUDY INTO WAYS OF USING PAST EXPERIENCE OF FAILURE TO IMPROVE DESIGNS

by Brian Lewis Smart

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I keep six honest serving men
(They taught me all I knew);
Their names are What and Why and When
And How and Where and Who.

Rudyard Kipling

UNIVERSITY OF SOUTHAMPTON

ABSTRACT

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DESIGN FAULT FEEDBACK, AN INFORMATION TECHNOLOGY STUDY INTO WAYS OF USING PAST EXPERIENCE OF FAILURE TO IMPROVE DESIGNS

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This thesis examines the use of past experience of equipment failure in the design process. Indexing and analysis techniques are developed to feed back this experience to designers. The design process is examined and the designer´s information requirements considered. The use of natural language terms is examined and a model of their use for indexing terms is proposed. A large database of historic records were examined covering some 35000 failures, mainly mechanical in form. These were classified and indexed by an expansion of the Feature Analysis technique PITFA proposed by PITTS. The set of terms used in the index has been examined and compared with the models proposed. The index was combined with numeric analysis of the failures to produce an Experience System providing a series of weighted outputs to users. This information is intended for use in Reliability analysis, Design Reviews, Fault Tree analyis and Failure Mode and Effect analysis.

The concept of Failure Characteristic for design features and elements is proposed and values obtained for the elements analysed. The dichotomy between Failure Mode and Failure Effect is also addressed. A revised approach to these terms is proposed and has been used in this work.

The system developed was tested in practice with case studies. The actual results are discussed and recommendations made for further work.

Details of the models, feature analysis of failure and the reasoning behind it are given in the appendices, as are the index database, the thesaurus, failure characteristics and failure occurrence rates.

CONTENTS

## INTRODUCTION, BACKGROUND TO THE PROJECT

'...If you or I had to pay for our TV sets to be serviced every week to keep them working, we would not give them house room!...

The above quotation is taken directly from a lecture given by Dr W J Willoughby of NASA to a branch of the IEEE in the 1970's. The lecture was recorded and has been subsequently shown repeatedly to interested parties in the US and UK at Defence Industry seminars on improving product design and reliability. In the early 1970's it became apparent that the reliability of military products was so poor that if the trend continued, upkeep and support costs would consume the entire defence budget within one to two decades. As a result a number of initiatives were implemented in the US and the UK to improve military product reliability whilst at the same time reducing the 'Through-Life' cost of ownership. A major area was the improvement of product quality by various methods. These included revised testing methods and financial guarantees/penalties for achievement of specified reliability goals. The electronic field is notable for the work of the Department of Defense, in particular at Rome Air Development Centre (RADC) in the USA and the Ministry of Defence (MOD) in the UK.

1977 saw the first UK National Reliability Conference at Nottingham, and there has been a gradual increase in work in this field throughout the ensuing years. There is increasing cooperation within the EEC in this area and this is evidenced by the cooperative work on the CODUS facility at the University of Sheffield.

Much of the work on this study into Design Fault Feedback was funded by the MOD under the Military Vehicle and Engineering Establishment (MVEE) project 7506 with the University of Southampton. The source data used is related to engineering equipment in use with the Royal Engineers. As a result some of the results have been disguised, and certain domains of the original database have not been published. Nevertheless, the published database and information contained in this thesis are sufficient to stand alone and be used as a design tool.

Due to the original requirements of the MOD sponsoring organisation, it was intended from the start to restrict this study primarily to the mechanical engineering aspects of design. Hence aesthetic, electrical, chemical, and civil engineering aspects etc will not be addressed. However, instances will be given to show how the various points made can be transcribed to another engineering discipline.

CHAPTER 1

## 1.1 DESIGN FAULT FEEDBACK, WHERE TO START?

In recent years there has been a growing interest in the use of failure records as a source of engineering information. The main drive in this area has come from management where there has been a need for accurate information on maintenance costs and spare parts stockholding needs. There has also been some interest in the use of this data in design, but here the emphasis has been on safety prediction, accident prevention, and laterly reliability.

As a result there have been several cases of data stores being generated to provide this information service. There has been some collation, classification and analysis of these records. Some of the results have been made available in the various professional publications.

In the United Kingdom, noted sponsors of this work have been the United Kingdom Atomic Energy Authority (UKAEA) and the Ministry of Defence (MOD). This sponsorship has provided the National Centre for Systems Reliability (NCSR), the Army "FORWARD" system, the RAF Maintenance Data Centre (MDC), and the NAVY Maintenance Data Centre (NMDC).

Their aims have been directed to "Good Housekeeping" by improving maintenance and reducing operating costs. However there has been some design feedback to manufacturers. The work has comprised the compilation of files of maintenance and failure records and data of spares and stock holding levels. The NCSR files were originally founded to give accurate information on the safety of Nuclear Installations and as such were used as proof to justify various safety claims in this industry.

## 1.2 ORIGINS OF THE ROLE OF THE DESIGNER

To see the origins of this data gathering it is necessary to examine the evolution of the designer and the design process. Going back many years to the era of the water wheel and similar machinery, the machinery of the time was designed and built by the craftsman. They were responsible for the total creative process, the conception, design, and manufacture of the item. They were the engineers of their time. As time progressed the role of the designer became more specialised, and the design function became an independant role. For example by the late 1700's, as is evidenced in Trevethick's records, there was a clear distinction between the two roles. The drawings and specifications of Trevethick's designs produced by the draughtsmen are vastly different from Trevethick's sketches and instructions from which they worked. [1.1] This trend, of the engineer/designer being removed from the physical work, has long been established by Civil Engineers [1.2].

## 1.3 THE DESIGNER'S BACKGROUND AND TRAINING

Until recent years, designers and draughtsmen have normally come from the progression of apprentice to craftsman to draughtsman to designer. This progression ensured that the designer had a good basic grounding in the practical aspects of his trade within his own industry. As a result, designs contained a wealth of practical experience and know-how obtained at first hand by the designer. In recent years, due to many factors, there has been a change of emphasis in the background of the designer, No longer do the more able students become apprenticed. There is a trend for designers to be people with high academic attainment and limited practical experience e.g. University Graduates.

## 1.4 THE DESIGN TEAM

In the last decade there has been a move towards the use of Project Design Teams. Whilst there are many advantages to be gained from this particular management structure it does lead to the isolation of the project team. There is a consequent reduction in the crossfeed of information between projects. This has been commented on with some concern [1.3]. It has also resulted in the reduction in size of specialist teams working on one aspect of a company's product. These teams are divided between the projects, with a resulting dilution of capability and a certain amount of duplication of effort.

## 1.5 DESIGN AS AN ACTIVITY

Design is, in essence, an Information Processing Activity. Designers gather information on ideas, natural phenomena, processes, materials, standard geometries, mathematical models, and a host of commercially available standard and special components. The designer gathers facts and opinions and uses these to create his own individual design. With the modern drives for economy and cost effectiveness, there is increasing pressure on the designer to work to narrower but more accurate safety limits. As knowledge increases there is a trend towards increased complexity to give a more accurate solution to the problem posed. Countering this is the conflicting requirement of simplicity, to reduce overall costs and improve reliability. A design may be revolutionary, in that it is a complete departure from the normal pattern of designs in that field. It may be an evolutionary design in that it is a development of some existing idea or product. The designer seeks to exploit particular attributes of the various elements which he uses in his design. Some of these attributes may be the result of interactions between certain elements and features in the design.

## 1.6. MEASUREMENTS OF THE DESIGNER'S PERFORMANCE

Given that the design does what is intended of it, then the designer's performance can be judged in two ways.

(a). By the cost effectiveness of the design.

(b). By the reliability of the design.

Designers are expected, in general, to improve either the quality or the performance, or reduce the cost of the new creation when compared with the existing product. For a given performance, a good measure of the quality of a design is its reliability, and this can also be used as a measure of the designer's performance. Unreliability is thus the error signal in the design process. At present there is no standardised way of feeding back this error signal, the knowledge of failures, to the designer. The nearest function to this feedback is the experience contained in the Design Standard or Code of Practice, and the statistical record of failures in reliability databases.

## 1.7. DESIGNERS' EXPERIENCE AND PRODUCT RELIABILITY

There is no magic formula which can be used to improve the reliability of any product. Reliability is only achieved by painstaking attention to detail. An experienced designer has a much higher chance of producing a reliable design than an inexperienced designer, as he is more aware of the problems and pitfalls experienced in the design process. It is this awareness of the problem areas and the ability to weigh the risks involved that singles out the skilled designer.

In general this awareness comes from a designer calling on his own experience. This may be the result of practical experience of both success and failure of designs either personally or through the experience of immediate colleagues. Alternatively it may come from an external source such as lectures or articles in technical journals.

## 1.8. DESIGN AND RELIABILITY, THE CURRENT SITUATION

There have been two principal directions in which the reliability field has developed, stochastic and analytic approaches.

### 1.8.1. THE STOCHASTIC APPROACH

The stochastic approach to Reliability Engineering measures the 'Status Quo' using failure data from known discrete elements or components. Mathematical models are used to analyse known statistical data from standard production items. The information is then used in 'Parts Count' and 'Parts Stress' analysis. The former uses a default stress condition and analyses the design using standard values of failure rate for all the components. It is a special case of the Parts Stress model. The 'Parts Stress' model analyses the effects of various stress levels in the individual components on the overall reliability of the design. Stress levels can be varied to reflect the given design conditions. Both models can be tailored to reflect the design situation with various shaping factors used in the analysis to take account of different duty and environmental conditions. The electrical component failure rate models are statistically based and generally use a variation of the Arrheneous equation. The models are intended to give an accurate assessment of the reliability of the product. However, it would appear from current investigations that the models are not sufficiently developed to give more than an order of magnitude answer [1.4].

This approach is seen particularly in the Electronic Industry where the technique is to divide the design into discrete elements for which operational failure data is available. The configuration is then varied until the new arrangement gives the required reliability prediction. The accuracy of this technique relies heavily on the following aspects:-

(a) The environment must be well defined.

(b) The duty is either controllable or predictable.

(c) The variety of elements in the assembly is limited, typically less than 100

(d) Large quantities of failure data exist for each of the different element types.

The system falls down when a new item occurs or a configuration is used which is completely different to any prior arrangement.

### 1.8.2. THE ANALYTIC APPROACH

In recent years there has been a change of emphasis, Reliability Engineering has begun to move from the 'past failure' to the 'future failure' type of analysis. Techniques such as Fault Tree Analysis [1.5][1.6] or Failure Mode and Effect Analysis [1.7][1.8] are becoming more widely accepted. The work of the MOD with the Committee for Defence Equipment Reliability and Maintainability (CODERM) and the UKAEA in the UK and the DOD (notably at RADC) in the USA has been notable for drawing these various techniques together. The change has been towards identifying the 'hazardous' elements in a design, i.e. those elements which put the product or user at risk if they fail. The techniques give a much more detailed analysis of the design with respect to failure. The engineer is forced to examine his design from a failure aspect. These specific techniques show where design efforts should be concentrated, and this management information is of increasing importance [1.9]. The overall effect technically is to improve the Reliability of the design and make it more fitted for its purpose.

With the trend towards the more analytic techniques it has become apparent that the subject is highly specialised. As a result the last few years has seen the advent of specialist cells e.g. Availability, Reliability, Maintainability (ARM) Cells within the MOD and the main defence contractors. Over a longer period the learned societies and academic institutions have also set up specialist groups (IEEE Reliability Group, CODUS Centre at University of Sheffield) and there is now an EEC initiative in this field. During this period there has also been a drive to improve education and awareness in this area. Courses are now run at a number of Universities and the MOD runs specialist in-house courses several times per year for its engineers and selected defence industry specialists.

There has been a distinct change to one of designers submitting their designs to a fairly formal analysis process by specialist groups that can go into much deeper and more complex analysis techniques, depending on the results at each stage of the analysis. The method of management, the phasing, the techniques used and the selection of these techniques are described in a number of sources e.g. [1.10] of which the DEFENCE-STANDARD-0040 series and the associated MIL-HANDBOOK-217 are probably the most widely known and referenced within the Defence Industry in the UK.

## 1.9. DESIGN AND RELIABILITY MANAGEMENT ASPECTS FAULT FEEDBACK LOOPS

A trend in the last decade has been towards the use of matrix management systems. Typical of this is the use of project design teams. The differences in project management and more traditional management are shown in figure 1.1.

Figure 1.1(a) gives, in block diagram form, the more traditional project team organization. The various design requirements are submitted to a common drawing office team under the command of a chief designer. All technical design aspects are considered within this team. Their output, the design drawings and full technical specification, is passed over to a common manufacturing facility.

In figure 1.1(b) the diagram has been modified to that of a more modern 'Matrix Management System'. The differences from 1.1(a) lie in the use of a discrete team for each design or product. The teams comprise a complete design and production group totally dedicated to that one product. Within each team there are specialists from the various disciplines. These specialists also belong to their own specialist groups. They will thus have divided loyalties between their team and these groups.

Figure 1.2 shows one project team from fig 1.1(b) and shows the basic process from initial requirement to actual use of the completed product. In this model any error signal 'theta' giving reliability information is lost.

Figure 1.3(a) shows a feedback of failure information to the designer. This is the situation in which a designer solves problems on his own design. Figure 1.3(b) shows the case where the failures are processed by a separate Post Design Services (PDS) Group. In this case all the experience comes to one group and they are then more able to correct design errors. Unfortunately this system cuts off the flow of experience to the designer.

Figure 1.4 shows a typical system used in electronic engineering where the design is examined and changed by a Reliability Engineering group prior to production. This is similar in form (but not in function) to the Value Engineering groups which are sometimes used in the design chain.

Figure 1.5 shows the Terotechnology Technique where selected cases are fed back to the designer. This technique relies on the designer being made aware of problems by very detailed case studies. It assumes an initial drive to seek improvement in the specific problem area and is not tailored to detailed but global topics. The information fed to the designer is totally dependant on the Terotechnologist and therefore does not allow the user (the designer) to 'Browse' effectively.

It is generally recognised that the cheapest time to alter a product is at the design stage. Figure 1.6 shows a general model for carrying out alterations to a product at this stage. The design review shown may be biased to value engineering, reliability, or performance for example. This design review is an effective logic gate at which the designer's performance can be judged for a minimum of cost and minimum of time penalty. If information on problems of manufacture and use are fed into the design review 'logic gate' then this will achieve the aims of the Reliability Engineer and the Terotechnologist.

A technique has evolved, particularly in the Defence and Aerospace Industries, of carrying out design reviews with the use of copious checklists. These have proved quite effective, but no checklist can possibly cope with all the possible permutations and combinations of failure types and events.

## 1.10. THE POOLING OF EXPERIENCE, CORPORATE FAILURE RECORDS

No one designer can possibly gather sufficient experience to cover every eventuality. Between themselves several designers may well be able to cover most problems. In any organisation, if all information of part failures is placed in one common data store, then this store of failure records could be used by the designers as an extension of their own experience.

## 1.11. CONVENTIONAL INFORMATION SYSTEMS INFORMATION SOURCES AND INDEXING SYSTEMS

Designers gather their information from a variety of sources. These will vary from lecture notes through to international standards. It is often very specific but will generally contain certain key documents, typically 'State of the Art' articles by the learned societies and information produced by component manufacturers. This information is the result of practical experience and theoretical knowledge,and is often presented in an easily digested form. There is generally a dearth of information on maintenance and failure experience. This form of information is particularly valuable within industries. It is the means whereby corporate experience can be transmitted to individual designers. Failure and maintenance information is normally in report form. To be effective, reports should be catalogued and indexed. Many firms catalogue their reports but meaningful indexing is rare. There are many techniques available for indexing documents and reports. The techniques most suited for any one application are dependant on the form of use, and the storage of the documents. The most commonly used systems are those typical of a library, namely the clustering of records, books, and papers under related subject headings. This system is particularly suitable for 'browsing' through the documents. Variations of this are also seen in company files where documents are often clustered under project or equipment headings. The principal drawback of these systems occurs when a document contains information which should be stored in more than one of the defined groups or clusters. In this event the document is either:-

(a) Stored in one of the relevant clusters.

(b) Stored in a cluster and a reference note placed in the other relevant clusters.

or (c) Duplicated and stored in each relevant cluster.

The technique of assessing a document through a combination of identifiers i.e. coordinate indexing, is now widely accepted as being the most flexible and accurate indexing technique [1.11]. It also enjoys the benefit of being the most suitable for use in mechanical indexing systems.

The work of Pitts [1.12],[1.13] has shown there is a need in this field for the use of a simple system, and Rix [1.14] has carried out a feasibility study of the techniques proposed.

# CHAPTER 2

# AIMS AND OBJECTIVES

## 2.1 OBJECT OF THE STUDY

This work has centred on the use of experience for design Fault Feedback. The work has followed on from the previous work of Pitts and Rix. Pitts proposed to use keywords or Features to index failure reports, i.e. the concept of PITFA, 'Product Improvement Through Feature Analysis'. Rix took up the indexing aspects of this work and looked into methods of indexing. He concluded that co-ordinate indexing was the most suitable method for this application.

The PITFA concept restricts indexing to features associated only with causal aspects of failure, the concept of indexing using all aspects related to failure is followed in this work. It is believed that this is an important extension to the original PITFA concept. Many failure records would only have sketchy information on either cause or effect or both. What may appear trivial or irrelevant in one case may be very important in another. This may not matter so much in individual cases but when taken in the round with all the other records it could become significant, the 'synergy effect' so often quoted in the context of information systems. The person indexing a set of records may not be looking for retrieval from a causal point of view. Often the records are indexed by personnel involved in user aspects and they may well only concentrate on the event and its effects. On the other hand the user of the system may only be interested in the effects of using specific features or perhaps on the effects of a specific environment or operating procedure, e.g. when carrying out a failure analysis on a specific design. Hence Cause and Effect, Mode and Frequency are all considered relevant and are encompassed in this study.

The present study has followed on from this prior work and concentrated in two main areas:

1. Examination of the structure, form, and content of experience type data retrieval systems. Such systems could be used to give greater access to stores of data records such as experience of historic (i.e. past) failures for use by designers in evaluating new designs and design options.

2. The development of specific techniques for the use of an experience data file in design fault feedback. This aspect would concentrate on the use of retrieval techniques to extract data as well as retrieve documents. From the previous work it is clear that such a system would use keywords, however it would also encompass the manipulation of data indexes and related data files which may be numeric, textual, or even pictorial.

## 2.2 THE MAIN AIMS

The studies main aims were:

1. To provide a sound theoretical basis for a structured indexing system for data retrieval, not just document retrieval.
2. To take an existing set of failure records and index them using keywords in a structured way; showing how the specific keyword index/thesaurus was developed.
3. To evolve techniques for use of the database and it´s related indexes and files in an experience system for use in product design.

To prove the concept, techniques were to be developed to show how a structured index of this kind could be used to improve design fault feedback. If possible, practical case studies were to be conducted in the field i.e. in the real design situation.

From these initial aims a basic plan was formulated comprising some seven discrete subsections:

1. Expand the basic concept of PITFA preferably along the lines suggested by Rix.

2. Study and develop the techniques necessary to produce a structured index, showing the theoretical rationale behind such a structured indexing system. The use of words in language was clearly of importance in this respect. A preliminary survey of library systems and other work related to language structures and models of their construction and use was needed, as was any work related to the mathematics of the use of language.

3. Apply the techniques so developed to the creation of a basic thesaurus for the indexing of a given data set. A trial data set had been identified for use as a vehicle for this part of the work. The data set in question was in active use and would therefore provide active feedback for the study. The practicalities of creating a thesaurus would be explored and aspects such as cross checking with repect to synonyms and homonyms would be covered.

4. Take this thesaurus and use it to create an index of the data set showing how the thesaurus was modified and refined in practice. As this index would clearly be of direct benefit to users of the database it would also ensure that the study did not drift away from a realistic practical study into an interesting but useless piece of work. By use of an active system practical problems would be highlighted and refinements could be observed.

5. Analyse the index thus produced and check if it conforms to the pattern predicted by the theoretical analysis. Examine any variations from the norm and find the reasons for these variations. The original model could be tested against the index for such aspects as precision, recall, and frequency of use of words. Comparisons could be made with respect to alternative systems or models.

6. By use of a pilot study, develop techniques showing how the index and it´s associated data set of records files, and related data can be used in a practical situation such as a design review. Typical topics to address could be Fault Tree Analysis, Failure Mode and Effect Analysis, and other failure analysis aspects. Survey how these techniques could be used with known methodologies to improve Reliability. Analyse how the study interfaces with these known methodologies, and how one could expand the benefits of the study. Examine any possible unforseen outcomes and look at the possible implications in both the narrow context of the study and also the wider context.

To summarise, the basic objectives of the study were to lay down the ground rules for the creation of a data retrieval system for indexing failure reports, to create such a system and show how it could be used with the related set of data in the real world for Design Fault Feedback.

## CHAPTER 3

## Design, memory processes, aspects of conception, the designers information requirement, language and semantics.

### 3.1 INTRODUCTION, CONCEPTS OF MEMORY PROCESSES

To understand how a designer thinks and the basic thought processes that are set in train during the design process must involve some study into the basic mechanisms of the mind. How does one solve a problem? How does one conceive a new design or idea? There are many theories but in truth no-one has yet determined the full problem solving process.

Endel Tulving [3.1] produced a model of long term memory, he divided it up into two types, episodic memory and semantic memory. The first deals with personal experience, transient events, the second deals with facts. The question was raised as to whether there were separate memory systems for verbal and non-verbal processing. In fact much is only verbal in as much as the material is presented verbally and the subject responds verbally. What is stored is the experience and the response is what is conjured up by the verbal material. For example, if a craftsman is told to harden a piece of steel to a 'straw' colour, the command is a simple verbal instruction but the resulting actions are very complex. It is clear that there is considerable 'redundancy' when reading and using language (the term is synonymous with predictability in the applied psychology sense as opposed to the reliability sense). Language is redundant in the sense that successive words are not equally probable and are not statistically independent. Sentences and phrases have a basic content (subject - verb - object etc.). For example 'the' is almost always followed by an adjective or noun, adjectives tend to precede nouns, pronouns tend to be followed by verbs. The subject matter will also constrain the selection of words available and used. As a result there is a tendency for each word to be predictable on the basis of the surrounding words. It is therefore possible to infer meaning without the full set of words. Knowledge is a series of hierarchical networks of relationships which are all intertwined and intermeshed with various cross links and common nodes. The various concepts used do not rigidly define the different categories but are more loosely determined. Problems occur when items lie on a category boundary, the item could appear to be in either, e.g. problems with the word canary - colour?, bird?, island? informer?

Atkinson and Shiffrin [3.2] produced a model of the memory process which gives a useful basis on which to work, (figure 3.1). According to Baddesley [3.3], the mind tends to access memory via some form of semantic coding, thus enabling a fine detailed level of recall. Research into long term memory has tended to focus on the 'levels of processing' and has moved more in the direction of factors governing retrieval from long term memory.

## 3.2 VISUAL IMAGERY

A particular focus of interest has been the topic of visual imagery. From a series of studies [3.4], [3.5], [3.6], [3.7], it appears that visual imagery is spatial in nature rather that purely visual. Also it seems that placing a heavy load on the general processing capacity interferes with visualization, presumably because it makes heavy demands on some central component of working memory, (this is analogeous to the heavy demands on computer graphics processing on computer CPU's). However there would appear to be little difference between imageable recall and abstract recall. Apparently the memory holds encoded concepts rather than an actual verbal or graphic image, also our visual imagery system is spatial in nature rather than purely visual. As a result it would seem that there is little to be gained by using a graphical image when a verbal image is readily and easily available. Hence wherever possible, textual descriptors would seem to be preferable for presenting information from an information system, particularly in view of the data processing advantages. This does not mean that the user will necessarily hold and use the information in textual/verbal form, e.g. rectangles, circles, triangles are simple descriptors for simple shapes, but paraboliods, exponentials, asymptotes, catenaries describe more complex functions.

When considering the use of natural language, it can be shown by statistical analysis of text that the frequency of occurrence of words is inversely proportional to the precision in meaning. Many words could be stripped from a text and yet the reader could still understand the basic message. It can also be shown that combinations of a few words can cover a very large number of meanings, for example 7 terms could be arranged to cover up to 5000+ different events. However the difficulty for a user would lie in the interpretation of those 7 terms to return to the original event. It is clearly easier to use more terms but at the same time use a thesaurus to cross link and expand the original descriptor to cover a wider span of associated meanings. The mathematical basis to the use of textual descriptors for indexing is set out in Appendix A.

## 3.3 PROBLEM SOLVING THEORIES AND PROCESSES

How does one solve a problem? There are many theories but in truth, no-one has yet determined the full problem solving process. The GESTALT theory of problem solving [3.8] hinges on the notions of insight and structure. Insight into a problem occurs after a period of cogitation, not as a result of simple trial and error, though this may have a bearing on the eventual insight. It reflects the ability of the problem solver to see and understand the structure of the problem. It relies on the ability to focus attention on the core of the problem and the inner relationships involved, also to be able to organise and reorganise those relationships in order to fill in the missing information. A response to a problem based on insight tends to be well retained and transfers well into a new situation. Hence the value of experience to a designer.

Mathematicians distinguish between heuristic and algorithmic methods of problem solving. Heuristic techniques are often the fastest and most useful but they do not guarantee a solution. Algorithms will always give an answer, though the number of steps through the algorithm may in some cases be excessive for practical use, and in other cases there may not even be an algorithm. These differences will be touched on in the following text.

There is no single algorithm for choosing which method to adopt when trying to solve a problem. Polya [3.9](1957) distinguishes four well known phases:

1. Understand the problem; determine the goal, the data given, and any general constraints or conditions.
2. Devise a strategy for solution; collection of data and relating it to the problem, production of a plan of work.
3. Execute the plan of work in a methodical way.
4. Review the method and solution.

Morrison [3.10], makes an interesting point when defining the problem, 'It is characteristic of a true need that it can be expressed without mentioning any possible means of fulfilling it'.

When a design team is set a problem, be it a new product or a change to an existing product, they will tend to approach the problem in defined and structured way. This can often be described by Fig. 3.2.

Within this design process the designers will examine the problem posed, gather information that is available from a variety of sources, standards, documented procedures, standard cases and past experience both personal and of others. This data will be sorted and collated and any missing information identified. Figure 3.3 shows how the use of existing data is interlinked. The list as shown is clearly not exhaustive, neither are all the cross links shown as this would make the diagram far too complex and confusing. The links between Standards Organisations and their various procedures is obvious, as is the link with standard text books on the various topics.

The personal experience of the designer will encompass training, and any personal experience of manufacture and use of various products, as well as actual design experience.

A designer will conceive a solution to the problem using the basic engineering building blocks that are well defined and have predictable parameters, e.g. I beams, angle bars, flat bars for structural engineering; rollers, cams, springs, shafts, bearings for automotive engineering. Each of these items will have a set of known parameters including including known failure modes under known conditions.

When these basic blocks are brought together they do not always behave exactly as expected, particularly under transient load conditions. These transient effects will occupy much of the designers time once the basic case stressing and analysing has been completed. The basic case analysis will be completed using known solutions prepared from standard texts (wherever possible). Some aspects of interaction between the different items will be known, some will not. For example in pressure vessel design, the effects of access openings or pipe connections on the vessel can be examined and predicted using well defined methods with a high degree of confidence. However the slamming loads on a speedboat are less predictable as they will vary depending on the sea conditions and the skill and nerve of the operator. Under these latter conditions the experience of the designer and his information sources come into play.

There are many instances in engineering where designs are based on empirical formulae. These formulae are produced from experimentation and practical experience, they are only valid within the limits of the original work and should therefore not be extrapolated beyond these limits. However there are many cases where such an extrapolation has occurred with disastrous results. Typical examples are to be found in bridge design [3.10].

In many cases, the use of deterministic algorithms is not a credible option due to the complexity of the designs under analysis. To compensate for this, the usual method is to use simulation modelling such as using Monte-Carlo or similar techniques. Under these circumstances the designer should be aware of all the various factors which could or should be included in the model.

### 3.4 FORMAL DESIGN PROCESSES

If one takes the normal Defence Industry design/creation process Fig 3.4 (and left hand side of Fig 3.2), then the design team will produce experimental rigs, test beds, even pre-prototypes during the feasibility stage. These models will be used to test, prove or produce amongst other things the various empirical relationships which will be used in the final design. They are used to confirm the basic concept to investigate 'grey areas', and try out various ergonomic and other factors. This process of experimentation is expensive and, prior to embarking on such a task, much use is made of information and literature searches to pre-empt any 're-inventing the wheel' activity.

At this stage, be it from 'Brain Storming' or other techniques, the designer will have some concept of the possible (even probable) design options open/available. Hence any search will be geared towards information related to these pre-conceived options.

This is also a stage at which information on past failures will be of great benefit. With this information the designer can see the problems which have occurred in the past with specific elements which are under consideration and take account of them in the design. Information on the effects of the intended environment and any similar previous applications will also be welcome.

The designer is driven by two main questions:

What am I doing?

Why am I doing it?

These two questions are amplified in Kipling's famous poem 'I had six honest serving men...' [see frontisepiece]. What do designers need to know? The simple answer is that they need as much information as possible about any aspect related to the problem they are tasked to resolve, and any item, element, feature, function, process or thing that they may use in resolution of the problem. To be of maximum benefit the information should be sorted and presented in readily digestible form. The list of such information is endless, but from considerations of reliability it is clear that aspects related to failure are most important. In particular the features of a design which are susceptible to failure.

Because the designer will be searching for information on specific elements used in the design and of specific features incorporated, the data retrieval system or information system should be geared to enable the designer to access the data using familiar terms. It is clear that if the information can only be accessed by a term which the designer would not normally use then some form of Thesaurus will be required. In some cases the information may be in graphic form, either in graphs, nomograms or similar charts or in diagrams e.g. the stress concentration effects of notches [3.11] or the mode of buckling of a beam or plate.

When carrying out literature searches a designer will often 'browse' through the abstracts thrown up by a computer search of the database to become more aware of as many aspects as possible related to the subject of interest. During this browsing process certain documents will 'catch the eye' and be followed up by retrieval and reading in greater depth.

Diagramatic and graphic information is not as easily accessed. This tends to be gathered into standard reference texts e.g.[3.12][3.13][3.14][3.15] which the designer will consult for information on objects similar to that being considered.

In many designs the designer will not attempt to go to such exhaustive detail. This may be due to the design being a 'one-off' and/or the cost involved not being considered worthwhile either from the design or the manufacturing aspects. Under these circumstances the designer tends to 'play safe' by using large safety margins and conservative design techniques.

Obviously designers will recall information from a variety of sources in many different forms. It may be in toto, or in summary form, e.g. the conclusions of a report, or an abstract, or in analysed form such as algorithms or as statistics, or even in diagramatic form. Each will have its own place in the overall scene, however designers all have their own likes and dislikes. Hence one designer may prefer to use textbooks for the bulk, if not all, the source data. Another may use a predominance of articles and charts.

For maximum effect, any information system to feed back failure information should be able to present the information in different ways. The obvious ones from the foregoing discussion are textual, diagramatic and stochastic. Others may well be apparent but these three methods would seem to be main avenues of communication, they are addressed in the following chapters.

CHAPTER 4

## 4.1 INFORMATION RETRIEVAL SYSTEMS/EXPERIENCE SYSTEMS

Objectives of information retrieval systems are to allow the exploitation of the information contained within the original data or document sources. For document retrieval systems, firstly it should be possible to identify and locate a document with only a limited knowledge of it's contents. Secondly information techniques should facilitate the exploitation of information for purposes other than those for which the information was originally intended. For example, a failure report on a particular equipment may have been written to ensure that future users of the equipment did not experience the same failure condition by use of particular operating techniques. However, this information may well be used when considering future replacement equipment or for some other application.

The techniques of information retrieval were for a long time those of the card index and printed index. These are satisfactory for simple applications but suffer a number of limitations. Because they are primarily manual in operation they are limited by the clerical effort that is available to operate them. There is a definite economic trade off between size and cost of operation and this is not very difficult to reach even in a small system. They are also limited in the flexibility of use.

The first mechanised aids to improving the situation were the introduction of punched cards. These came in the form of optical coincidence cards, edge notched cards, and other punched card systems. They allowed the user to combine multiple term enquiries in a relatively simple manner. From discussions with past users of such systems it is apparent that these techniques were always awkward to handle and often resulted either in a pile of cards on the floor or bent knitting needles (used for selection) or a frustrated enquirer giving up the task of writing the various document references down and leaving in high dudgeon. The sorting boxes of several such systems were seen in the Military Establishments during this study. Not one had ever been used extensively, despite a few dedicated adherents to the technique. The general experience was that the memory span of the record keeper had proved 'more than adequate and a *----* sight faster than this box', hence the systems had, without exception, fallen into dissuse.

The advent of cheap computing power has given a tremendous boost to the information retrieval scene. It requires relatively simple computing operations and with the advent of low cost storage devices it has come into its own. It offers the user an easy way of combining search terms interactively and will also produce printed output. It also offers the ability to process information in a variety of ways and when dealing with a large store of past experience, if handled and processed effectively, it can be expanded into an Experience System, sometimes referred to perhaps erroneously as an Artificial Intelligence System. Probably its most useful attribute is the ability to provide printed output which can be sorted by the machine as requested, e.g. in alpha sort, or weighted sort.

## 4.2 MATHEMATICAL MODELS OF INFORMATION/EXPERIENCE SYSTEMS

The formal study of Information Feedback in the form of Experience Systems has only developed as a scientific discipline in the last decade. It is still a young discipline and its theoretical methods and formulations are still the subject of considerable debate. A key issue in that debate is the choice as to which among the various mathematical approaches is the proper vehicle to describe the phenomenon of Artificial Intelligence (AI). Among those propounded are control theory, information theory, fuzzy set theory, and catastophe theory. The first two are approaches at the fundamental theory level, the latter two are more at the phenomenological level.

Control theory has a natural appeal because of the structural similarity of experience systems to the problems seen and addressed in control engineering. Within the context of this study, a control process (design) has an objective (creation of a reliable product). During the design process deviations from the original objective are measured (the error signal) and corrective action taken through a feedback loop. In practice the situations encountered in design and manufacture are extremely complex and the ability of the designer to effect corrective action is very uncertain. Nonetheless the structural analogy is valid and some limited success has been achieved by applying the concepts of control theory to experience feedback systems.

Information theory also has a natural appeal, but for quite different reasons. It is not that there is a simple structural analogy, information is the fundamental quantity involved in the process of design fault feedback. It is the most pervasive aspect of the whole process. It is gathered in the form of incident reports, maintenance reports, design queries and other methods peculiar to the particular organisation involved. This information is noisy in that there is a great deal of extraneous data, it is corrupted by false records, false analyses and false data, it will decay in time as both time itself and other data change both the effect and the relevance of the particular piece of information. Information is the basis of all design decisions, and despite noise and corruption is the essence of the directives from the designer to the manufacturer and user.

Fuzzy set theory has been employed to express the inherent imprecision that is characteristic of most experience systems. One of the widest used techniques in reliability engineering is the use of stochastic analysis to predict probability of failure. Foremost in these is that described in the American DoD MIL HANDBOOK 217, but there are a number of others which use essentially the same technique but with different databases e.g. [4.1] [4.2]. In addition, much use is made of historic data. A further expansion in this area is the use of Monte Carlo modelling techniques, relying on past data for the shaping and scaling of the sampling algorithms used. The main thrust in this area has come, not surprisingly, from the military and aerospace industries.

Catastrophe theory has been introduced, largely on an ad hoc basis, because certain sudden changes in product reliability that are related to the design process appear to resemble certain catastrophes as defined by Thom [4.3]. It seems only to have been introduced when there is a specific case clearly defined e.g.[4.4][4.5]. It does not yet appear to have been introduced on a general basis, though it has been suggested as a tool for reliability analysis work [4.6].

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**4.3 TEXTUAL ASPECTS**

With any information retrieval system using documents containing textual information it is desirable, in fact necessary to have some form of document location system which uses textual descriptors. For a system to operate on an experience database containing records of past failures the indexing and searching system must relate to aspects of failure and design features relevant to the failure. The following chapter sets out the basic rationale of the set of indexing terms created during this study to index such a system.

To be effective, it is preferable that any feedback of failure information should be via an organised system such as a formal information system. The operation of such a system can be divided into two clear domains, the creation of information and the dissemination of information. The dissemination of information is a standard feedback process and can be either positive or negative in form. It can therefore be modelled by the standard feedback models, such as an error servo system. This was clearly shown in chapter 1 where various feedback models were discussed.

With positive feedback the designer is building on a previously successful outcome and produces 'more of the same'. With negative feedback he is reacting to an error signal, the information of past failures or of trials and experiments, and is trying to correct and minimise these errors. In general the design process will be found to contain a mixture of both positive and negative feedback. Many known techniques, procedures and natural laws will be used to give positive feedback. The designer is directed to use set rules and methods. Information will be provided in a variety of forms, tables, charts, algorithms, techniques. All will be the result of prior knowledge and experience of the organisation/person giving the directive. Similarly the designer will draw on his own experience and that of his colleagues and the sponsoring organisation.

It is a truism that one 'learns by one's mistakes' and an obvious source of data to expand a designer's experience are failure records. If failure records are gathered from a wide number of sources then the user of this pooled information benefits from the corporate experience of the whole. This effectively widens his own experience to encompass the personal 'experience of failure' of the various design teams whose products are detailed in the whole.

The information should be stored in an easily and readily retrievable manner, catching the readers eye, and giving an awareness of the main aspects. The system should be able to emulate the 'browsing' technique in that the relevant aspects of the problem posed are easily highlighted, preferably in some sort of order of importance. A typical example is the contents page of a book, or the abstract of an article or report. The system should 'catch the readers eye' and give an awareness of the relevant problem areas.

PITTS has concentrated his studies on the use of keywords or features as the indexing medium. He has looked at the advantages of indexing with respect to the designer of new equipment, namely his PITFA concept. RIX has also looked at this area and examined the impact of classification, coding, and coordinate indexing. He concluded that coordinate indexing was the best form of indexing for use of historic data in the design situation.

The problem is one of access to a set of data, and from an indexing aspect can be regarded purely as one of Recall and Precision. However, from an experience system aspect the problem is wider. The system should ideally tell the user all that it can about the topic being addressed. It should not only tell him what he wants to know but also what he needs to know. It should give 'awareness' of all the aspects involved. The form of output and the method of its presentation is therefore of considerable importance.

There are a variety of ways that records are stored and used. They may be in strict chronological order, or in clusters or groups, or in numeric or alphanumeric order. Each system will have its own advantages and disadvantages, its advocates and detractors. If one were using a specific set of documents repeatedly on a topic, and when accessing the documents they were generally recalled and used as a group, then it will obviously be better if they are all held as a group in one file of documents. It may be that this file is best kept in chronological order, but it could also be that sub grouping of the documents into topics could be of greater benefit. The method will depend on the users of the documents, the way they work, the uses they put the documents to, and a host of other parameters. The users may be interested in financial aspects, or planning a particular task, or a specific aspect of the design or development.

Despite the various problems related to the way the documents are packaged in the filing system, it is possible to implement an effective indexing system using a modern computer system. With such a system a user could locate records which may have been grouped in a different file cluster to that in which the bulk of the recalled data was held.

### 4.4 THE PITFA APPROACH

PITFA is an acronym for 'Product Improvement Through Feature Analysis' and is the name coined to describe a particular technique for using failure data in design. With this technique, reports of failures are analysed, and the features of the design which caused the failure are represented as keywords to index the particular report. The index can be used by designers to locate any reports relevant to their enquiry. They first construct a simple 'search profile' of their needs and then search the files for reports with index profiles that match their original search profile.

systems e.g. body punched cards, where the amount of data is limited and the number of users is small. It is also suited to large data systems, normally in the form of computer held data stores.

The technique involves the examination of the various reports of an incident by a specialist who then selects what, in his opinion, are the main features of the report. These features are then used as the keywords to index the report in a database.

To obtain information from the system the user would consult the index and search for occurrences of the topic/features they are interested in. Having found these occurrences they would then select the reports they are interested in/wished to see. These would then be drawn from the archived data files/records.

PITFA as originally conceived, would only contain keywords related to cause of failure. These indexing features would then be used in searching the database. The intention was that the user would not be confused by features relating to the effects of failure.

### 4.5 EXPANSION OF PITFA TO COVER CAUSE AND EFFECT

If the record index only contains features related to the cause of a problem/failure, then if the indexer does not spread the net wide enough, many relevant records could be missed by users of the system. One of the main aspects of this study which addresses this point is the expansion of the PITFA concept to cover both Cause and Effect. Thus the record for a particular document could contain keywords related to both cause and consequence.

Users of the system would be able to look for particular features and could discover the various failure modes and effects associated with this feature. Such an expansion of the PITFA system would turn it into an Experience System.

## 4.6 DESCRIPTIVE FEATURES-LOGICAL CREATION

There are some terms which if used would present very little difficulty in interpretation e.g cylinder, cube, aluminium, gold. However, other terms may well either confuse or raise further questions for clarification. For example the actuator for an aircraft control surface, this may be electrical or hydraulic in operation or purely mechanical. It is therefore of crucial importance that any set of features are carefully checked to ensure that such anomolies can be dealt with, either by further definition or by the operation of the information system. Even so, it may eventually come down to relying on the users basic engineering knowledge and common sense. When indexing a report using a feature indexing technique such as PITFA, the indexing terms can be selected in either a "Top Down" or "Bottom Up" way, or both if sufficient terms are used. Principally one should aim at the user, therefore cause and consequence will both be relevant as enquirers will be interested in what failed, why it failed, and any effects of the failure. Looking at the causal aspects first, and using Kipling [see frontisepiece] as a well known design guide, the enquirer is interested in what failed, why it failed, when did it fail, where, how and who was involved. This would give a minimum 6 terms, though for completeness it is likely to be more. Details of the rationale and the concept behind the various features and other descriptive terms used are given in Appendix C. A specific point which has been addressed in this appendix is the use of the terms Failure Mode and Failure Effect. These terms are not clearly defined in the literature, they are generally defined in an incestuous relationship [4.7]. A more precise definition is offered and has been used in this work.

To analyse a large store of failure records takes time and effort as well as experience. Failure analysis is a specialist area and a number of texts have been produced giving detailed analysis of specific cases e.g.[4.8], [4.9],[4.10]. The learned societies place considerable emphasis on this aspect of engineering [4.11]. One regularly sees reports of investigations in their journals e.g. New Civil Engineer, Marine Engineers Review, and also in trade journals such as Aviation Week. Appendix D gives details of some of the factors which must be considered when analysing a failure report.

Considerable effort was expended during the creation of the set of indexing terms which are described and listed in Appendix E. Users were surveyed at different stages in the process and the listings and terms used were shaped to suit the requirements of the various designers in the MVEE Establishment. As the system was to be a practical tool for use by these designers it was illogical to attempt to produce a 'whiter than white' system that satisfied academic needs but did not give the users what they required and hence would fall into disuse. The system that evolved was therefore shaped with these users in mind. It therefore contains a number of jargon terms that are peculiar to this design group. Where possible these have been backed up by more readily recognised terms but in the process there has been some degradation of the information content transferred. A single term in the database can give a tremendous amount of information to an aware user, and this has been the case with this system. One would expect a similar situation with other systems used by dedicated teams of designers, however, if a system is to be used in the general domain then this particular feature will need addressing during the indexing process.

## 4.7 STOCHASTIC ASPECTS

When reporting a failure it is rare for the report to contain complete details of the time and duty history of the item or equipment. It is also rare for it to contain complete detail of the quantities involved. No doubt the numbers of a particular equipment failing and the total number held could be elicited. However when it comes to such detail as 'how many rivets failed in the aircraft and how many are used in its construction?' it is apparent that this level of detail is not available.

The best that one can hope for is such detail as X of these equipments are held on the inventory and Y failed within the scope of the report. This is not a tenable position for a true statistical analysis but it is the best that can be achieved from many data sources. There are few data sources that can give better detail than this, the nuclear industry is a noted example which can. Even such sources as the US MIL-HDBK-217 mechanical data source material has been of this low level of accuracy in the past.

Such data can however give a ranking of occurrence. It is primitive and is, from an information sense, both noisy and subject to corruption as not all the information is available and the data could well be erroneous.

Notwithstanding the above comments, when taken in the round, with a large database when the complete spectrum of signals/reports/datasets are integrated, the noise will be diminished in value and the underlying trends should become apparent. These are what the designer needs to know, the trends and the relative importance of a specific aspect. With this information other design techniques can be brought to bear on the topics highlighted by the experience system analysis.

With any complex analysis system using and combining data from a multitude of sensors/inputs, e.g. modern military command and control systems, at the present day level of analysis the software is such that, if left to 'free run', the resulting answers will often be wildly inaccurate. This is expected of such a system as is proposed in this study. The normal mode of operation is for such systems to be run interactively with the user weeding and selecting the data which it is required to analyse. The sensored data is then processed by the system to give, hopefully, a better and more relevant output to the user. Appendix B describes in detail the various search probabilities, some 16 in all, which can be manipulated though not necessarily quantified to give a measure of precision and recall.

### 4.8 PSEUDO STATISTICAL APPROACH

With an experience system, a user will be presented with a large number of choices by the system. To help users of the system, a form of ranking or weighting of the data output is desirable. To fulfill this need, a pseudo statistical approach has been adopted through the use of recorded occurrence rates. These are then analysed and used to give a variety of guidance information. The occurrence rates were used in several different ways to weight the output to the user. The methods are described below.

1. Simple occurrence rate (F1); a count of the number of times that the relevant term occurred in the index. This was used to give the total number of records in the system which were indexed with the relevant term and hence an indication of the relative 'nuisance value' to the system. It also gives a primitive measure of the volume of information available.

2. Time and Equipment related occurrence rate (F2); a combination of the number of times a term occurred with a particular equipment. This gave the total number of records for a specific equipment which occurred with the relevant term. It is a finer measure than F1.

3. Number of items failing per record, numbers of equipment involved, time span of analysis (F3); this gave a measure of the occurrence of failure, (note: NOT the specific failure rate). Actual calculation was:

$$F3 = \text{Sum}((Ni/Ne)\text{per record})$$

for the given time span
i.e. between set calendar dates
where Ni = numbers failing per record
and Ne = total numbers of that equipment owned

4. Cumulative value of F3 divided by time (F4); this gave a relative measure of the observed occurrence rate of the particular feature in the overall design scene. It is analogous to the failure rate used in reliability calculation but is not a rigorous measure. It cannot be defended statistically but it is believed to be as good a measure as the existing mechanical failure rate values in some published literature [4.12],[4.13]. In view of the paucity of information in this area, the values obtained from such an analysis are offered for use within the confines of MVEE as a 'best estimate' when no other value is available.

## 4.9 FAILURE CHARACTERISTIC

One set of information which the system can extract is the occurrence of a failure in all equipments of a particular type that are held in stock (within a set reporting time frame). This would be evidenced by a value of one or more for F3 above. Figure 4.1 shows the typical output for such an analysis of a particular feature when taken over the total database for all equipments listed. This has been called the Failure Characteristic in this study. It is of particular importance to the designer when it is apparent that a total failure of the relevant design feature has occurred. Such a trend may become apparent on other equipments with this feature and this will have a bearing on a number of areas. It is stressed that the designer should be alerted to such a catastrophic Failure Characteristic.

The chosen design feature may be sensitive to a variety of things but the designer should ensure that safety factors selected and design configurations used are adequate and the design is not working close to a condition in which it may fail. It would be prudent to arrange some form of testing during manufacture to guarantee that such a condition will not occur, e.g. by proof testing of lifting equipment and pressure vessels, over-voltage checks on electrical equipment, overpressure tests on pressurised systems. It should be bourne in mind that proof testing may not be totally adequate. With a catastrophic failure characteristic testing to destruction of an initial sample may be required to confirm that the proof test levels selected are both adequate and effective.

Such a failure characteristic is, in effect, a catastrophe type of phenomenon. Analysis of the total records in such an experience system could well aid in identifying features with such a characteristic and the associated driving factors related to the failures. Conversely if the failure characteristic indicates a stable form, figure 4.2, then this could also affect the design, manufacture, and test philosophy. Providing such a characteristic had been tested to a set level successfully, then the total output need only be sample tested in a non destructive way to give a high confidence in the product. A total analysis of this form has been carried out on the database and the results of this analysis are given in graphic form in appendix G. The concept itself is treated in more detail in appendix D.

CHAPTER 5

# CREATION AND OPERATION OF THE DESIGN FEEDBACK SYSTEM

## 5.1 INTRODUCTION

The following chapter gives a summary of the actual work carried out under this study to create an Experience System. Examples are given of the application of the system and the earlier systems created in the process of its development.

## 5.2 THE INITIAL DATA SOURCES

Apart from the initial literature surveys (which are looked on as a mandatory task) carried out with the assistance of the on line DIALTECH search facility at Orpington [5.1], the first subsequent task was to search the MVEE files and find what data was available and readily accessible. There were several areas of suitable data, the most promising were the manufacturing problem reports for the Medium Girder Bridge, the repair records for a Tank Bridge, and the Royal Engineers (RE's) failure reports held for the period 1954 to 1976. These latter reports were the Royal Engineers Technical Service reports (the RETS reports).

The first source, the RETS files, contained the basic failure reports, which were of a standard MOD format, analysis reports on the problems, study reports and other investigation reports. These might vary from electron microscope work to chemical analysis to special field trials and even to extracts from court martial reports.

The second area examined was the series of records and reports from the manufacture of the various components of the military Medium Girder Bridge (MGB). This had been designed and prototyped at the establishment and was in full production with a contractor. The reports from the MGB were in the form of manufacturing concession requests and production permits. They concerned cases where the production process had gone awry to a limited extent and the manufacturers had requested that the item be accepted by the user but perhaps with caveats as to the equipments use. Typical concessions would be for holes bored slightly oversize on a low stressed part, or perhaps a machined lug slightly undersize. Production permits would typically involve the use of an equivalent but different material to that specified in the drawings.

The third set of records examined were the repair records of one of the series of Tank Bridges that had been designed at the Establishment. These contained reports from initial inspections carried out on receipt at the repair agency. The equipment had been shipped back after initial examination from field units ('Back-Loaded'), for repair by the main contractor dealing with this work. Other notes reports and records were included to give a comprehensive picture of the damaged item and the work involved in refurbishment.

Reading through these three series of records gave a basic background and understanding of the overall scene. It also gave insight into the organisational aspects and viewpoints of the various equipment designers, analysts and users of these records.

## 5.3 ANALYSIS AND CODING

After reading all these reports and talking to the engineers and designers (the system 'users') about their use of historic data held within the establishment, a sample of less than 200 RETS reports were analysed and coded up with keywords. Of necessity the keywords would not all be features relating to failure. The report number and some form of equipment descriptor was required, and possibly the sub-unit descriptor. This would enable the users to enquire 'how many failures have occurred on equipment X or Y in this environment etc'. This initial sample set was then discussed with the users and the comments noted. The response was rather muted and generally sceptical of the aims and objectives declared.

A similar exercise was carried out on the MGB reports but in this case the coding up of the reports was carried out using descriptor codes for the various concession types. There were some 14 descriptors for the features, 32 different items, and 'accept with caveat'/'accept'/'reject' qualifiers for the records. For these records a punched card system was tried and nearly 50 cards were punched up for the records, of which the first 360 were recorded on the cards. Apart from needing good eyesight, the system would need the patience of a saint to use it regularly, for example if a mistake were made then the card will not give the correct output and should be replaced. When it is considered that there are 1200 locations on each card used and the probability of human error is of the order of 1 in 2 to 3 orders of magnitude [5.2], the problems are obvious. However, it did locate and highlight problem groups that the staff were unaware of. The features used to identify the manufacturing problems are listed in table 5.1. Further details are given in [5.3].

The problems of transcription from the punched card back to the actual record numbers required was tedious. In this day and age the punched card system is now totally unacceptable and a computer would be used to much greater effect. However, the system did demonstrate the principle worked. Records were found and problems collated in a way that simple searching of the records would not achieve. Thus the design group carrying out rectification work had a tool which located previous faults of a similar nature and which would ensure that concession ´sensoring´ was consistent. The problems identified were all of a manufacturing nature and were therefore of limited interest to the new equipment designers.

The next stage was to examine the problems which had occurred on one equipment in service. The complete repair records were available for one of the types of bridge used by the RE´s. There were several hundred records covering a number of years. These were examined and some 22 features identified for indexing. The bulk of the repairs related to repair or replacement of damaged items, however there was a large block of repairs which involved the replacement of missing parts. Details of the features and their occurrence are given in table 5.2. Further details are given in [5.3].

Figures 5.1, 5.2, 5.3 and 5.4 show the layout of the bridge and the terms resulting from feature analysis of the design. This feature analysis was carried out to give some comparison and possible checks on correlation between the manufacture and repair analysis and the In-Service aspects covered in the RETS reports.

A further set of the RETS reports were read analysed, and an index of features and other keyword descriptors was produced for a total of over 500 records. A limit was set of 6 or less keywords per record. The keywords were listed in alphanumeric order and the revised list of keywords, now totaling some 425 words, was circulated and discussed with the engineers and designers at MVEE. The use of general terms for several linked/similar terms was not liked. Users found difficulty with this. They felt that it was too restrictive and was too 'academic' an approach to be of practical benefit. The index listing was held on the MVEE computer at Chertsey and operation was generally in 'batch mode' via a remote terminal at MVEE Christchurch. 'On line' operation was extremely slow, for example a demonstration run arranged with 'high priority access' taking an hour to poll three commands. This mode of operation was therefore unworkable. Example searches were carried out at designers request on a number of topics. An example is given below.

During routine checking of failure reports, a report was examined of a failure to a bridge during training. The particular failure concerned an extension beam which is used to bridge the initial gap and act as a pilot structure to support the bridge whilst it was moving into position, see figure 5.5. This item had, like the rest of the bridge, been thoroughly tested during acceptance trials. After examination it was decided to classify the failure as a random failure probably caused by mishandling during training. As a final check the database index was searched for any previous occurrences of a similar nature. Surprisingly the search, which was a precise search (equipment AND (item 1 OR item 2 OR launch)), threw up 11 records, see table 5.3. On checking the records it was clear that there was a common thread running through several of the records. After investigation it was found that during 'productionising' the drawings of the item in question, the spacing of particular stiffeners had been changed from a carefully calculated spacing to an even spacing. As a result the production versions had an inherent weakness. Action was taken to replace the relevant units as soon as was practical and temporary operating instructions were issued in the meantime. Further examples of these searches are given in [5.4].

### 5.4 DEVELOPMENT OF ANALYSIS FACILITIES

Searching for data on the MVEE computer (an ICL 1903T series machine) was both primitive and time consuming. In view of the difficulties experienced with this system it was decided to use the University facilities and create a search routine using BASIC on the DEC PDP11. This proved more tractable and enabled a far more detailed and complex data analysis. The facilities produced are akin to many that are currently available on relational database systems. They are generally described by Boolean logic functions, sort functions, and algebraic functions. The primitive flowcharts for the routines are given in Appendix H, together with a listing of some of the routines.

The basic Boolean logic type of activity that was used in the study, can be used on any normal commercially available relational database. The various combinations and search logic that can be used is effectively endless. It is therefore believed that the search patterns used and the results obtained are of no great interest to most readers. What is of interest is the way the data is structured and how the output can be manipulated by the various techniques developed.

The first facilities developed to use the record index were simple Boolean logic search routines. These gave a listing of all records with the requested indexing pattern. The listing was in order of occurrence in the data file and could be provided in the form of a printout. The run was in 'batch mode' and the print out was delivered to the user in the normal way through internal post, or if necessary, by collection from the terminal room.

## 5.5 WEIGHTED OUTPUTS

This procedure was then enhanced by inclusion of calculations which gave various search statistics such as number of records found, percentage of the total database recalled, and total occurrence of specific terms. These simple statistics gave enquirers a feel for the relative 'nuissance value' of a specific feature. They helped users to order their priorities and focus on the more important aspects highlighted. Table 5.4 shows the enhanced information available for the previous example.

A practical case study was carried out using the system on a new design, the Combat Support Boat. This is a general purpose workboat used to transport men and material. It's other main function is as a workhorse for bridge building in the form of a tug to push and pull floating units etc. This was being designed and built by a well known contractor with a considerable reputation in the boatbuilding field.

The design was carefully analysed and a list of descriptive features produced. The list of design features was rationalized to conform with the known keywords in the index. By examining the occurrence of the various features it was possible see which had been the most often reported and hence order the priority of search. This is seen in table 5.5 in sorted order.

When one looks at the features listed and examines the design it is apparent that several of the more commonly occurring features were linked into subsystems within the design. Searches were then carried out to find previous occurrences of problems with similar design elements and features.

The search process is essentially an interactive one and the list of records produced by each search has to be scanned to 'weed' the irrelevant records, or if the list is too long, to select additional search terms to refine the search. The resulting set of records were then checked to see if there were any common themes that would be of interest or relevant to the proposed design. One such search concerned surface treatment of the aluminium structure. The detail that emerged was well known within certain sectors of the Establishment, but it was useful background knowledge that may well have not been available to the chosen contractor.

A second area that was highlighted concerned the control mechanisms used, a system of sheathed cables more commonly known as 'Bowden' or 'Morse' cables. These are frequently used for vehicle braking systems and there were a number of records which indicated that this was a problem area. The design problem is twofold.

Firstly, if sheathed cables are coiled through more than a certain angle then the effect is the same as coiling a wire or cable around a bollard. With such an arrangement the slightest friction in the system will prevent movement in the same way that a large ship can be moored by a rope to a bollard. The mathematics involved in such a design calculation are simple and readily available in standard texts.

Secondly, the use of such a cable system in a workboat is open to the corrosive effects of a marine environment. One equipment in particular had experienced considerable trouble with such a cable brake system. In addition the Failure Characteristic analysis indicated that this was a design feature with a catastophic Failure Characteristic, i.e. if the design was not correct, the possibility was that there would be a failure of the complete production batch. The records contained details of a design solution to the problem that was suitable for the new design.

The officer concerned found that the printed listings were most useful in locating problem areas. They were easy to use and gave an immediate feel for the problems. He also noted that the contractor was much more amenable to changing the design when presented with factual proof of past problems. Tables 5.5, 5.6, and 5.7 give details of the various sorted lists. Only the first page has been given, not the full detail as this runs to several pages in each case. Examples from this case study are given in [5.5].

## 5.6 REASSESSMENT

After several trial runs of the system and comments from users that a particular record had not been located by the search routine, it was decided to expand the number of keyword fields. The records were rechecked and the limit on the number of keyword fields was doubled to 12. Further records were analysed and the index was expanded to cover 627 records. On carefully checking the index it was found that the maximum practical number of keywords was 10. The odd one or two records that exceeded this were truncated to this limit. These records covered a total of 35000+ failures. The full index set is held in number form, and this full data set is listed at Annex F.

The revised number of keywords had now risen to 523 words, including a number of jargon words requested by the users at MVEE. Additional data was added in the form of statistics on the number of items failing and the total sample size (or stockholding) in each case. All records were examined and the failure mode defined (in line with the definition given in Appendix C). These changes transformed the original index into a form of experience database.

## 5.7 ADDITIONAL FACILITIES

As a consequence of the above reassessment of the system, a need was seen for some form of output to help in fault analysis of the new designs. an obvious aid from such an experience database was help in creating fault trees. The problem was examined and two main areas of assistance were seen:

1. Help in defining the various modes of failure and the effects of these failures.
2. Help in displaying the failure characteristics (see Appendix H) of the chosen elements.

Routines were then developed to produce these outputs for the user.

The failure modes and effects data routine has been developed as an interactive routine and the output is in the form of lists of features relevant to the failure of the chosen design feature, item, or equipment. The procedure is relatively straightforward, though perhaps a little long-winded. The enquirer starts with a list of design features and equipment descriptors. The search routine then lists the various failure effects experienced with these features and lists the design elements and features which occurred within the records found. By selecting the elements and features which are relevant to the design in question, a series of branches and levels of a fault tree can be created. The process is clearly an interactive one and it is likely that it will be of most benefit to specialist reliability and failure analysis groups.

The failure characteristic output has been produced as a series of diagrams created from the output of a global analysis of the database. The analysis takes a considerable amount of computation and is not a realistic analysis to use as a normal on-line activity. The diagrams are given in toto in Appendix G, however some of these diagrams are not really relevant as not all the keywords analysed are design features and would not have such a characteristic. The relevance of the analysis to the features is easily discerned by inspection. The figures have been included for completeness however, should they be required for any reason - for example by other workers.

A further output, though contentious, was the calculating of a so called 'failure rate' for the different elements and features listed. How this is calculated is detailed in chapter 4. The proposition is clearly untenable from a purely statistical viewpoint. In terms of a base figure for reliability calculations however, the values given are better than nothing and may well suffice as a 'first estimate' when none is available, and this has proved to be the case as the data has been of use within the MOD for such analyses. The results of these analyses are tabulated in Appendix E part 2.

The weighted outputs were one of the most cost effective aspects of the system. The outputs from a modest size equipment analysis could be prodigious and the weighting terms gave clear guidance as to the most common problems and the most troublesome areas. Without this the users would be presented with reams of output to claw through and the probability is that the system would fall into disrepute due to the shear time involved. In addition the failure characteristic gives guidance as to the safety factors and testing requirements for the different elements and features in the proposed design.

The system acts as an aide memoire to a skilled designer, but for a young inexperienced designer it gives a wealth of knowledge on which to draw. It will act as an in-service training aid for newcomers to the team, giving an immediate awareness of the major problem areas.

### 5.8 COMPUTING RESOURCES

Through the period of the study a number of different computing facilities have been used. The initial index was created on the ICL 1903 computer at MVEE. The search facility analysis of the index using weighting terms was carried out on the ICL 1903 and the University DEC-PDP11-44. The production of the failure characteristics and 'failure rate' outputs was also done on a PDP11. The fault tree creation routine was attempted on a Hewlett Packard HP2749 with limited success, transcribed to a VAX 750 successfully, and laterly has been put on to an IBM PC using an integrated software package 'Open-Access'. Though this has taken a considerable amount of effort, the basic analysis concepts would appear to be reasonably robust. The main problems would seem to arise due to the size of the database. As yet, there are only limited operating instructions for users, and this is a clear shortfall.

CHAPTER 6

# DISCUSSION AND CONCLUSIONS

## 6.1 INTRODUCTION

We have seen in the previous chapters how the whole concept of information feedback has been expanded from the initial concept of an indexing system for a set of reports into one of feeding back basic information which is of benefit to the user. The structure of the use of words in natural language was examined and a mathematical model postulated, this was then proposed for the structure of the indexing terms and hence the structure of the associated index.

## 6.2 EXPANSION OF PITFA

The original PITFA concept was taken and amended in the light of the perceived information needs of the users. This resulted in the expansion to cover basic aspects such as identity of items and equipments, and the ability to examine the consequences of failure (the effects) as well as the causal aspects.

When the wider information scene was examined it was clear that the system was effectively moving towards an experience system. The main drives in past experience in the design and in particular the reliability field was the use of failure analysis in both FMEA and FTA. Information was also needed for event and hazard analysis.

It was evident that effects of failure and operational aspects would need to be included in the index. This was done and keywords developed to cover these aspects. A consequence was the refinement of the description of failure modes.

## 6.3 MEMORY RECALL, TEXTUAL OR GRAPHIC DESCRIPTORS?

From research in the behavioural sciences field, the problems of text versus graphic descriptors would appear to be mainly artificial. As stated in chapter 3, memory recall relies on concepts rather than images or text. There are a number of cases in the literature where graphic images have been given to describe a design feature and then within the text they are given a textual descriptor e.g. [6.1]. It is clearly possible, given enough descriptors, to describe almost all of the elements in a design by textual descriptors. In fact it is difficult to conceive a feature which cannot be so described.

The main problem arises when considering the use of code descriptors to cover complex shapes. The trial indexing exercise carried out on the concessions and production permits would appear to support this. The work showed how a number of simple textual descriptors could be used to describe and index a large body of reports which would often be described by graphic or code means. Some 36 major defect types were covered and 360 reports indexed using 14 different descriptors. The problems covered were in the main typical of the type normally covered by graphic descriptors. The use of textual descriptors did not prove a problem and it would seem that this is the normal case. Therefore the use of textual descriptors was adopted as the main descriptive mechanism. It was considered that the benefits, particularly with respect to processing, outweighed the disadvantages.

## 6.4 CREATION OF THE THESAURUS

The thesaurus started with a number of preferred terms, it was expanded to encompass a whole series of terms that seemed relevant to the reports being indexed at the time. It was then refined to cut down duplication of meaning between terms. This duplication and the associated cutbacks were checked with the users and it was found that the cutbacks had been too severe. The final thesaurus was therefore expanded to a limited extent to cover the words requested by the users who had expressly requested a number of special terms including jargon.

The thesaurus was structured into 6 main groups, equipment/item descriptors, design, manufacture, delivery, use, and failure effects. These groups were split into a number of subgroups making 16 in total. Many features were applicable to a number of groups as can be seen in Appendix E. In addition to these groups there was the separate group of items and equipments. This was required to enable normal use of the records for specific activities related to the individual documents.

During the initial stages of the creation of the thesaurus the users were surveyed for their views on synonyms and homonyms. Examples were given and opinions sought. The returns were all in favour of ignoring the problem. The general consensus was that as they would be involved in the weeding process anyway, they would prefer to use terms that they were familiar with even if there was some overlap in meaning or in the terms describing an event or feature. This view supports that of BLAGDEN [6.2], with his comments on the example BIG END see HIGH + LAST, taken from previous papers. It was felt that this should be addressed at a later stage as the index grew and the implications became more apparent. In the event it has never proved to be much of a problem as the users have been able to weed out the overlapping areas. As the system grows it may prove troublesome but the indications to date are that it does not warrant any major effort.

## 6.5 CREATION OF THE INDEX

The index was produced in a number of iterations, the end product being shaped to suit the end users rather than keep to a rigid 'Ivory Tower' academic approach. The result has been a measure of blurring in the use of some indexing terms and a certain measure of overlap in meaning. This has been countered by use of more than one term to describe specific features when required. Inevitably this creates noise and corruption in the 'clean' data set. Some noise and corruption is to be expected in the system and the level created by this variation from the ideal is accepted as necessary in a practical system. Each document had its own number and these were allocated sequentially in chronological order.

As the index has been shaped for a specific organisation the use of jargon terms and generic terms has been used extensively. This is directly contrary to the known recommendations of many indexing agencies [6.3] [6.4], but has been justified by the specialist application. It is also supported in some measure by BLAGDEN [6.5], who recommends that such systems are shaped specifically to the users' requirements, and SVENONIUS [6.6]; both recommend the use of narrow terms to improve precision.

## 6.6 COMPARISON WITH THE MODEL PROPOSED

Despite this use of jargon, the index itself and the distribution of use of the terms used would generally appear to conform to the mathematical model proposed. This can be seen in figure 6.1 where the cumulative occurrence is plotted against the frequency of use of the terms on a Weibull plot. The graph would appear to be in two parts with shape factors of approximately 0.7 and 1.3. The mean shape factor is approximately 1, i.e. the underlying distribution would seem to be an exponential distribution as predicted.

Comparison checks were made with the Maintenance Data Centre (MDC) thesaurus at RAF Swanton Morley. This relates to a similar application in the aircraft world. Occurrence data was obtained and the plot of the occurrence rate in the MDC files is seen in figure 6.2. As can be seen, the distribution is exponential. Both these findings support previous work by TOMA [6.7] on the Euratom Thesaurus. They are at variance with the oft quoted Bradford-Zipf distribution [6.8].

Assuming that the exponential model is valid, then this can be used as a guide to show when a term is being used too frequently. In the case of this system, the most frequently used term was the name of a specific piece of equipment. As this took up 29% of the records, the number of indexing terms used to index a report on this equipment should contain sufficient terms to keep the frequency of occurrence in balance and to give sufficient precision in recall, i.e. at least 4 more terms in this case. In fact it is most likely that 6 or 8 terms would be used to give the indexing definition required.

## 6.7 USE OF JARGON

When an index is being used by a specialist organisation as in this case, the use of jargon is a very efficient way of transmitting information. Take one of the specific terms used in the index, MGB, this is a high strength aluminium alloy structure and a number of points are known about it in the design group. By stating the equipment name, with one or two exceptions, one is immediately aware of the material content and a number of ancillary processes and procedures used in its construction. It is a welded aluminium structure that has been fabricated from a high strength aluminium magnesium zinc alloy and has been described by KENT [6.9].

The generic family of material used on this equipment has well known corrosion problems under certain conditions e.g. exfoliation corrosion of similar materials in the aircraft industry [6.10]. In this particular case, the treatment to cure the problem is well known in the establishment and the manufacturing process is therefore expected and implicit. However, an unaware user of the system would totally miss these points especially as there are no reports held within the RETS files of problems in this area. Such information would have to come from a literature search, prior knowledge, or some other source.

Similarly with the use of fairly simple terms. The use of 'weld' for example. Welding is an extremely complex process, there are many forms and methods of welding, Figure 6.3 is a feature tree for welding terms. It is quite clear that there are many terms which would be needed to qualify this single term if one wished to transmit a lot more information. If this is done then the model moves into the domain of conditional probability which was touched on in chapter 3, this examined the way the mind works and memory recalls both things and concepts.

Use of jargon has another advantage. As the system grows, the number of reports recovered for each search will grow unless the search is made more specific. The use of jargon terms will be extremely useful in refining searches under these conditions. It is therefore believed to be beneficial to include them for this reason. Unaware users would not use them and would therefore not be confused by them in the first instance, only on checking the output would they see the association with their search. When this occurs they would then be able to check on the meaning of the term in the thesaurus and refine their own search to suit.

This implies that when jargon is used, the first application in the index should also contain the various implicit terms that the jargon conveys. Such a procedure would effectively embed the thesaurus into the index, and this would aid in the system use. An alternative is to have an embedded routine which does this but is transparent to the user. In this case, the wider search coverage would increase the level of noise to users. To counter this would entail a more precise search definition to eliminate the additional data when this was not required, or a multi staged search procedure as is used in the standard 'on-line' search facilities at Dialtech.

## 6.8 RECALL AND PRECISION

Many researchers have addressed the problems of the relationship between recall and precision, most notably CLEVERDON [6.11] in the Cranfield experiment. The aims seem to be to achieve some relationship that will ensure high precision and high recall. As the two terms are inversely related it would seem that this is an impossible task. It would therefore be better if the problem could be cicumvented.

Taking an approach from another information processing area, namely military command and control, it would seem that the most effective way to overcome the problem is to use human censoring of the data. This would entail the user weeding the output as it is generated, i.e. an interactive system, and this is the approach which has been adopted in this case.

If sufficient terms are used in the initial indexing, then this is a fairly straightforward task. How this is done will depend on the volume of the records found in the search. When there are large numbers of reports found then an occurrence count can be used to indicate the relative rank of the features, (the Pareto approach - the important few and the trivial many [6.12]). The search would then be refined to encompass the most important terms and the search repeated to give a smaller set of records. When satisfied that there is an adequate but not excessive number of reports the user then reads the set of index terms for each of the reports and further weeds them if necessary.

Throughout the process the user is continually being updated with information and is made aware of all the various features and elements which have occurred within the overall data set. This process is useful in itself to pass simple information from the system to the user. This process comes into its own as the data set becomes very large and the system indexes a large store of records.

## 6.9 DESIGN PROCESSES AND METHODOLOGIES

A number of design methodologies were examined to find how past experience was fed back to the designer [6.13] [6.14] [6.15] [6.16]. Despite the various claims by the different proponents there was a great deal of similarity between them. Checklists figured in a considerable number and there is clear benefit in structuring the analysis process in this way, particularly when very complex issues are concerned or when one aspect is of major importance, e.g. safety in nuclear installations. In this respect the system could well be used in shaping specific checklists aimed at the design in question. Reviewers could analyse the design, obtain a listing of relevant features, and then amend the basic checklist to reflect the problems seen by the system.

Whichever method is propounded, the use of existing information is fundamental to the process, and the use of past historic data on failures is encompassed within this information. Whether this is processed and presented in the form of design standards, standard cases and texts, or other means is irrelevant. The method proposed in this work is one of the ways that this prior knowledge can be fed back to the designer.

With the increased drive to greater efficiency in design and production of products, in the shape of lower costs and increased reliability, the use of reliability improvement design tools will increase. This is clearly seen in the defence industry with the various initiatives and directives produced in recent years. In this respect the techniques of Reliability Analysis, Fault, Event, and Hazard Tree Analysis, and those of Failure Modes and Effects Analysis are becoming even more important.

The techniques developed in this work are specifically aimed at users of these techniques and should give help in the basic analysis of the systems under scrutiny. By the very nature of the topic it is expected that the work will often be carried out by specialists or with the background help of specialists either directly involved or through training schemes for the designers.

The techniques are particularly relevant to the design review process and it is expected that they would be used by review teams. This would appear to be an area of great benefit. The use in reviews is not restricted to the formal review process but it is also recommended for the designers own reviews.

## 6.10 FAILURE CHARACTERISTICS

The identification and production of item failure characteristics is seen as a step forward in the overall knowledge of failure. The concept of catastrophic failure characteristics is seen as important, particularly in the way designers should approach the use of such elements in designs.

The philosophy of their testing is also important and techniques should be used which are relevant to such a characteristic. Much effort is spent in testing items and equipment and it is believed that a rethink in the test mode philosophy may well be warranted in the light of such characteristics being defined. For example the long burn in or soak testing used in testing high reliability IC's may well be irrelevant when their life could be dependant on transient voltage effects rather than age or infant mortality aspects. Such a characteristic would indicate high stress rather than endurance as a better test method. This is already seen in the mechanical world with proof test of lifting equipment and overpressure tests on hydraulic equipment.

An interesting point of note was the great similarity between the experience of the two systems. The most commonly occurring features were the same for both lists (MDC and RETS) and roughly in the same order. It would seem that there could be some questions asked and lessons learnt from this. For example why does a cement mixer or a road roller exibit similar features of failure as a modern combat aircraft? Is it a fundamental property or are we training designers and engineers incorrectly?

## 6.11 INFORMATION NOISE

A number of workers have commented on the noise in information and retrieval systems e.g. BLAGDEN [6.17], KONIGOVA [6.18]. If one considers how many terms are involved in indexing systems it is apparent that a measure of the system noise would be the probability of the terms occurring together purely due to their occurrence rates. This could be compared with the actual occurrence rate between terms.

Initially it was intended to carry out such an analysis but when this was closely examined, it was rapidly seen by some simple calculations that the analysis was impossible. To carry out such an analysis would have taken of the order of 1000 years of CPU time on the MVEE 1903 machine! There are over 500 terms and the possible number of combinations is vast. On re-checking it is apparent that a simpler measure of the noise, though not an absolute measure, would be the probability of combined occurrence of the features that do occur together. When this is calculated and compared to the actual occurrence it gives a measure that can be used to rank the various combinations. This has been done in some of the examples.

## 6.12 TESTING AND SAMPLING

A number of surveys were carried out and many times during the study the different techniques proposed and the uses of the system were discussed with the end users. The survey sample size was small in absolute terms, though in relative terms of the total number of expected users it was a large coverage. Virtually every active designer in the unit was asked for opinions at some stage during the study. The results were used to shape the information system which subsequently evolved.

The first of these was responsible for the change in emphasis from use of the concession and production permit records to use of the in-service records. These were seen as more relevant to new design work and also of wider coverage. Having concentrated in this area, the users were again consulted on the keyword index. Some design features were added but a considerable number of jargon identifiers were also included at the users request. After the move to the University computer the users were again consulted on the method of operation. Throughout the whole period of the study, the feature index was revised (as opposed to amended), twice for indexing terms, and the thesaurus three times, (not including the gradual expansion due to addition of extra terms as the index expanded).

The index was converted into an experience database by the addition of the sample size and number of items failing. The output from this final arrangement has been used subsequently in a number of analyses. Unfortunately they cannot be published with the main study findings due to security considerations and they have not been included.

The problem of examining the product one has created is a difficult one. In this case having indexed all the reports it is difficult to maintain an objective view of an example search. It is of obvious benefit to have an unbiased user test the system. This was done with the study of the Workboat previously described. Surprisingly the officer responsible for this project found the outputs from the index and associated statistics of most benefit. The actual records were hardly checked. It seems that the team took the short cut of consulting the officers from the other project when the system highlighted areas of concern. The statistics and associated weighting factors resulted in a number of design aspects being revised.

## 6.13 CONCLUSIONS

The object of the present work was principally

(a) to examine the form and content of experience type data retrieval systems and create such a system using the PITFA technique of Feature Analysis.

(b) to develop specific techniques for the use of an experience data file of failure records to improve the reliability of new designs.

A secondary objective was to validate the concept by carrying out case studies using the system that had been created.

It was found that expanding the original PITFA concept to include both cause and consequence descriptive features markedly improved the overall utility of the system. The addition of simple statistical type data, namely occurrence of failure and sample size gave additional information which could be used to weight the output and help the users to structure their use of the system. The benefit was such that some users only used the system search listings and weighting outputs. They did not locate or use the original source data reports.

The use of graphical descriptors in an indexing system does not appear to be of such benefit as was originally thought when compared to the use of textual descriptors. It was found that the frequency of occurrence of terms in the textual indexing system conformed approximately to an exponential distribution as predicted.

When the main users of an indexing system are specialists it would seem that despite certain drawbacks, they prefer to use unrestrained textual terms, rather than the artificially constrained terms recommended by some information processing specialists. With such a system having access only by limited users, the use of specialist and jargon terms would seem to have definite advantages.

By using some simple associated statistics it is possible to produce considerably more information feedback than with a simple index.

The outputs of the system developed have been of benefit in reliability analysis and failure analysis. The concept of a 'Failure Characteristic' has been proposed for use in reliability and design analysis.

## 6.14 RECOMMENDATIONS FOR FUTURE WORK

There are many obvious directions in which this work could be extended. There is a need for further investigation into the concept of the Failure Characteristic. Similarly the aspects on failure mechanisms need further investigation and possible incorporation into the system.

The statistical relevance of the failure occurrence rates calculated should be checked against verifiable data and the order of error measured to give an indication of its accuracy. To this end the whole system should be more fully tested under rigorous conditions.

The prospect of a direct application of catastrophe theory to reliability theory offers fruitful scope for further theory and experimentation.

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A.3 Munday A.J., Farrar R.A.,(eds), An engineering data book, MacMillan, 1979

D.1 Carter A.D.S., Mechanical Reliability, MacMillan, 1972

D.2 Williams T.R.G., Discontinuity fatigue curves, Ph.D. Thesis, University of Southampton, 1972.

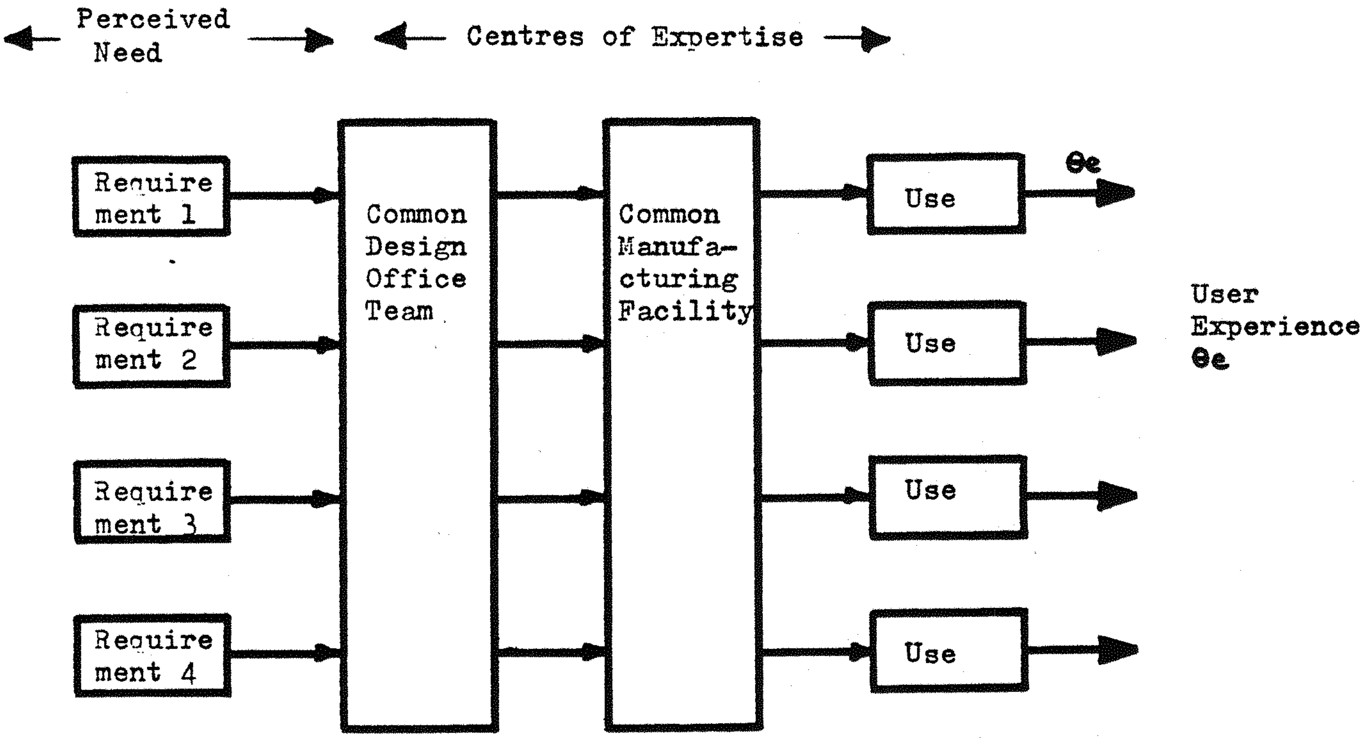



FIGURE 1.1 (a) TRADITIONAL SPECIALIST ORGANIZATION

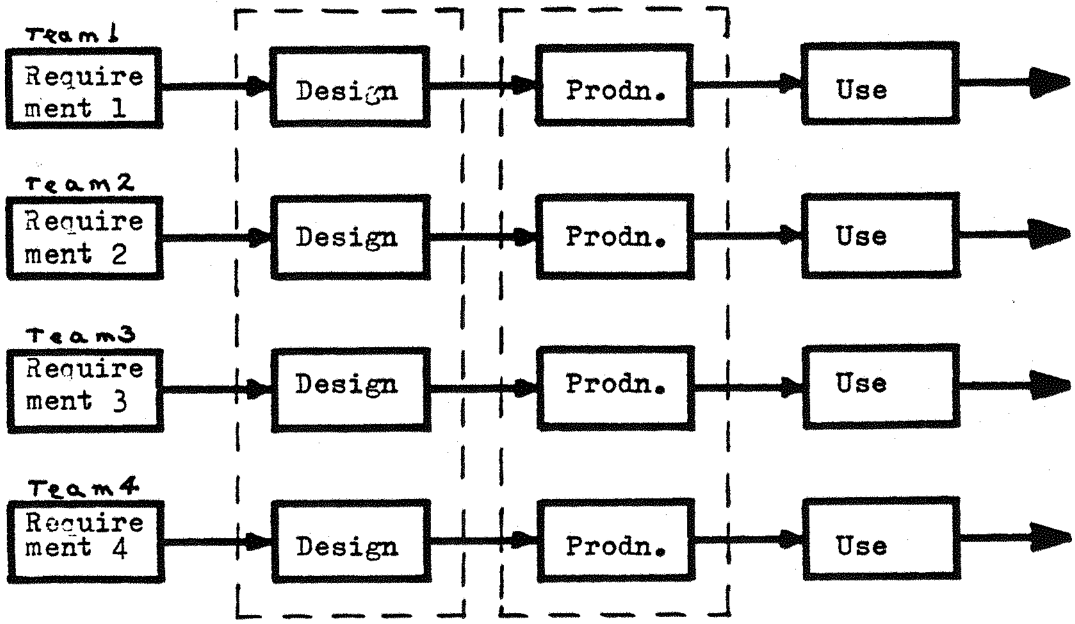



FIGURE 1.1 (b) MATRIX MANAGEMENT SYSTEM

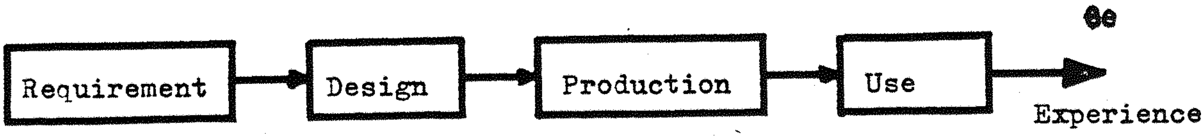



FIGURE 1.2 BLOCK DIAGRAM FOR ONE PROJECT TEAM

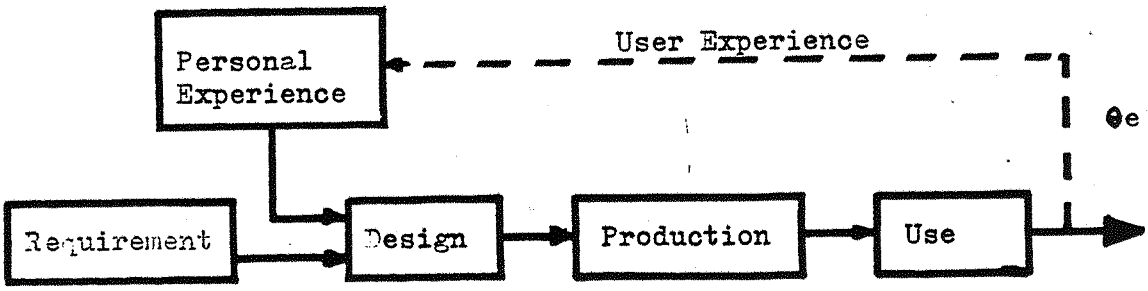



FIGURE 1.3 (a) SINGLE TEAM WITH FEEDBACK (θe) TO THE DESIGNER

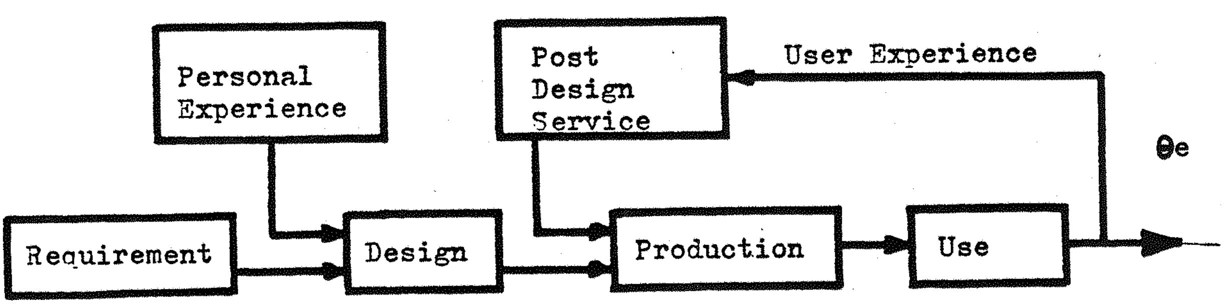



FIGURE 1.3 (b) SINGLE TEAM WITH FEEDBACK (θe) TO POST DESIGN SERVICES (PDS) UNIT FOR ERROR CORRECTION

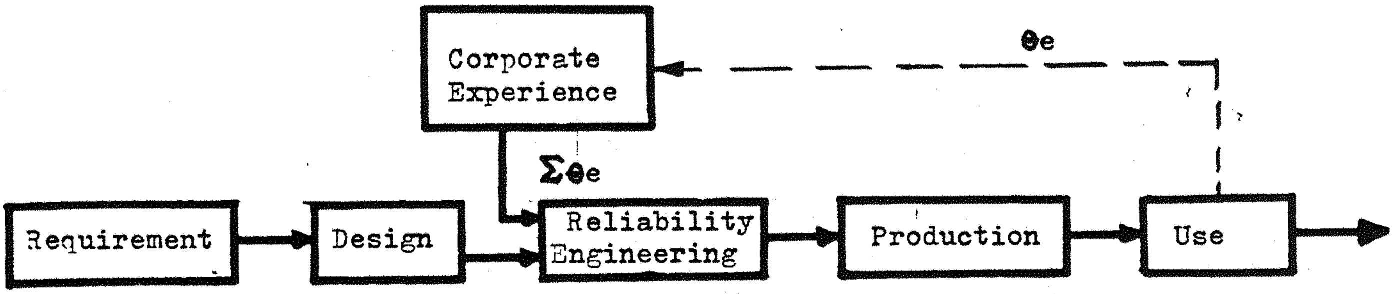



FIGURE 1.4 PROJECT WITH RELIABILITY ENGINEERING GROUP CHECKING DESIGNS PRIOR TO MANUFACTURE

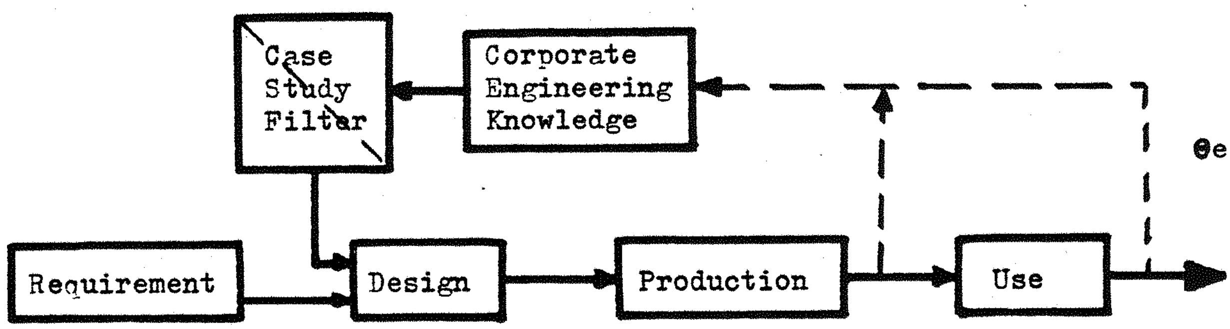



FIGURE 1.5 TEROTECHNOLOGY FEEDBACK MODEL

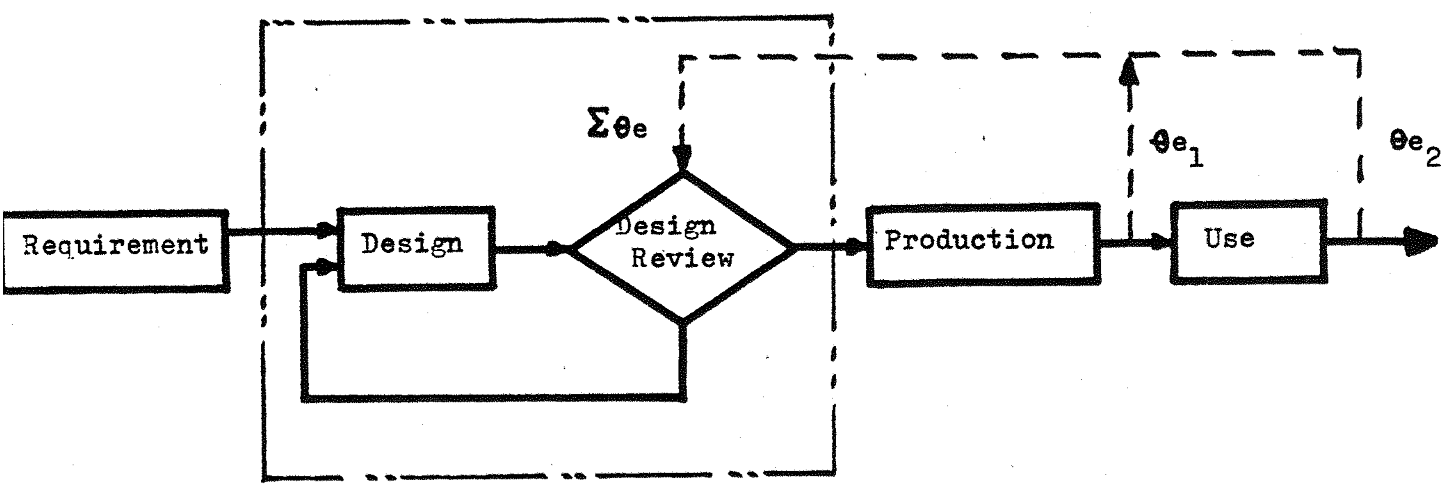



FIGURE 1.6 DESIGN REVIEW FEEDBACK MODEL

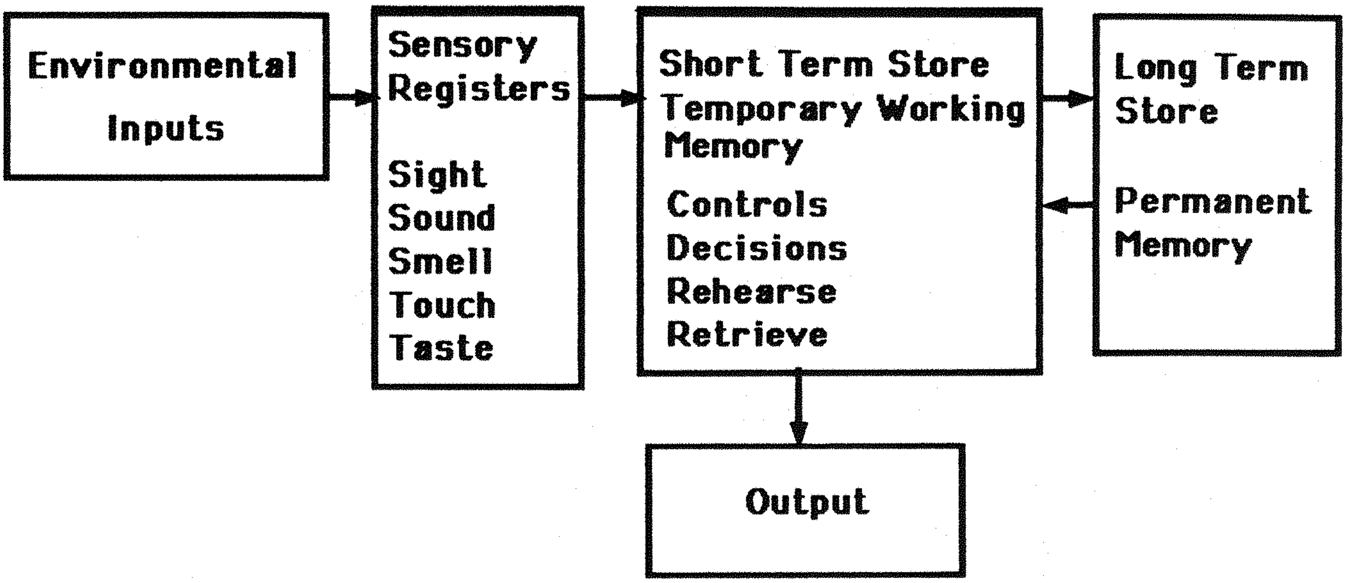



Figure 3.1 Memory Process Model
(after Atkinson & Shiffrin [3.2] and Baddeley [3.3]

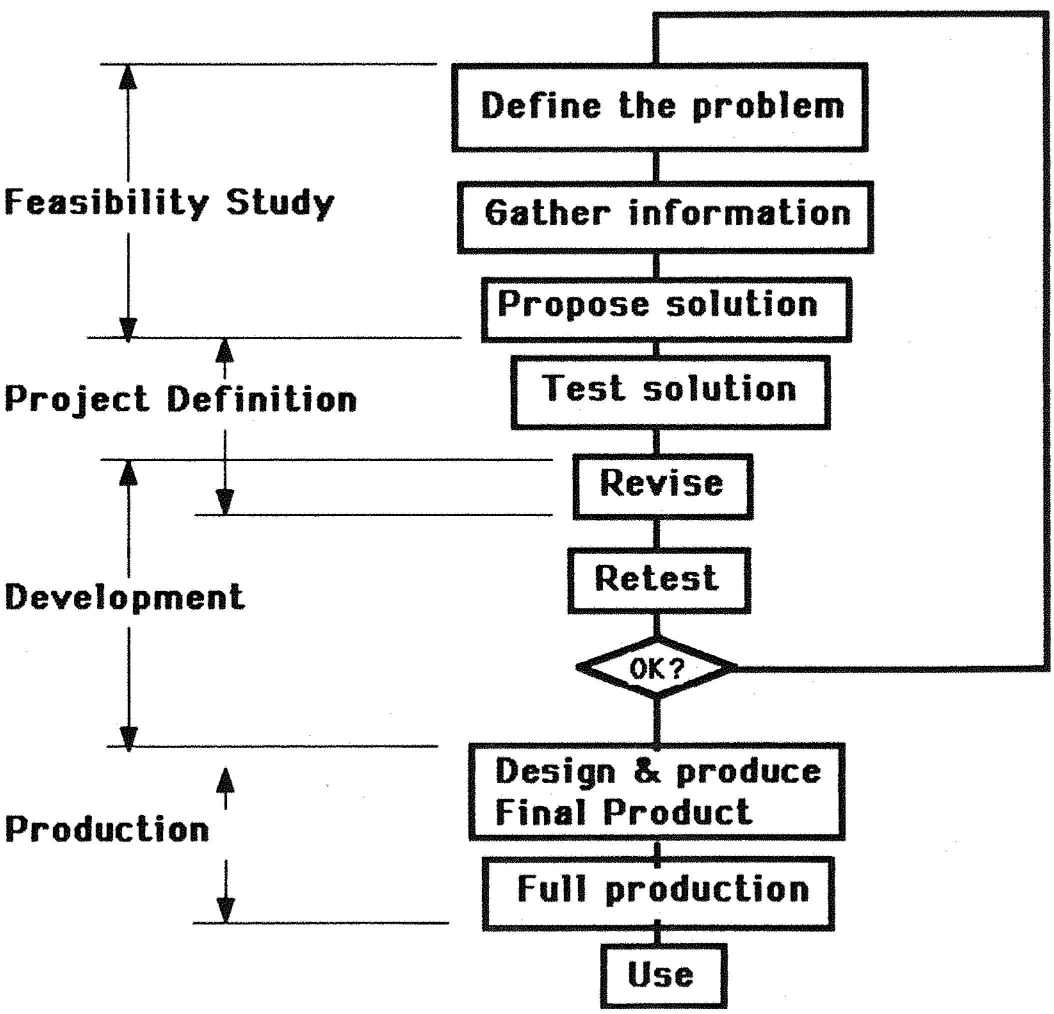



Figure 3.2 The Design Process

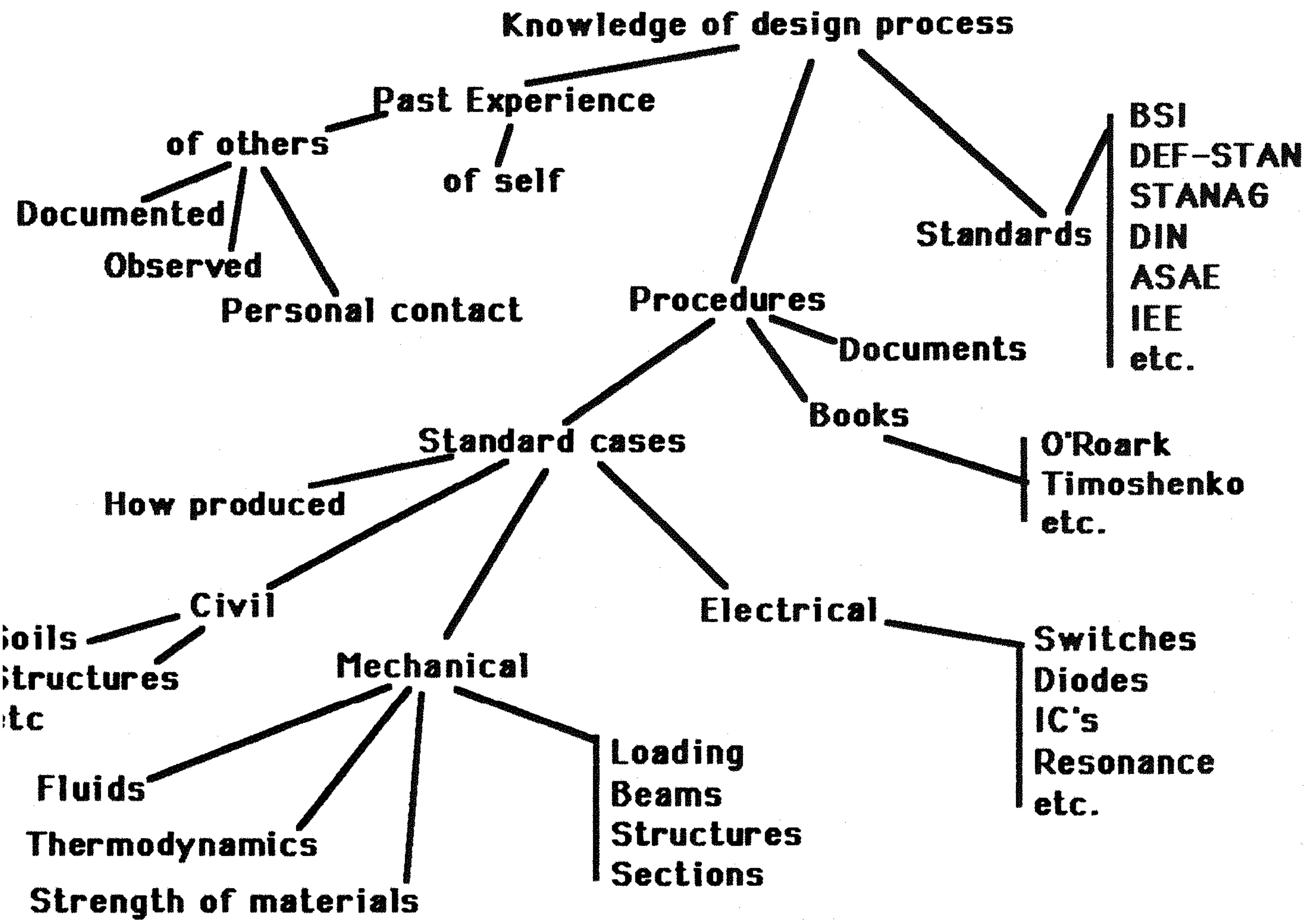
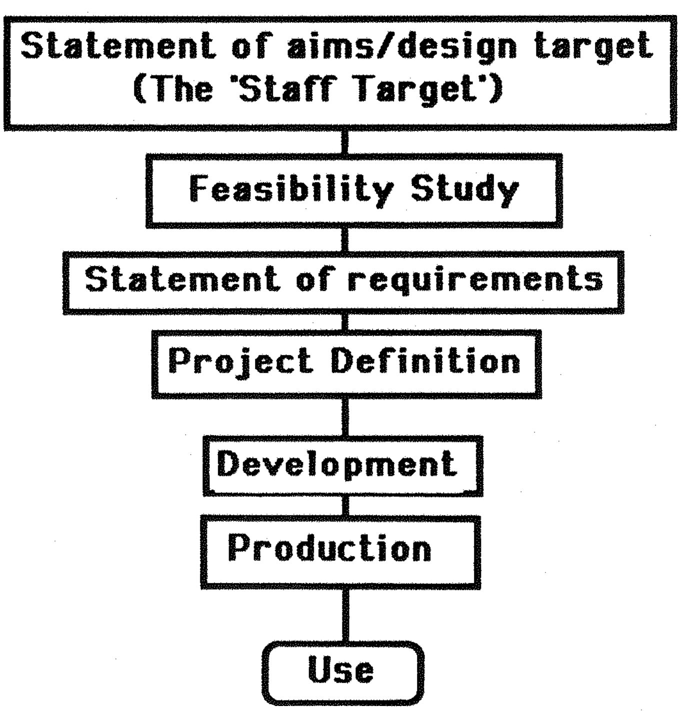
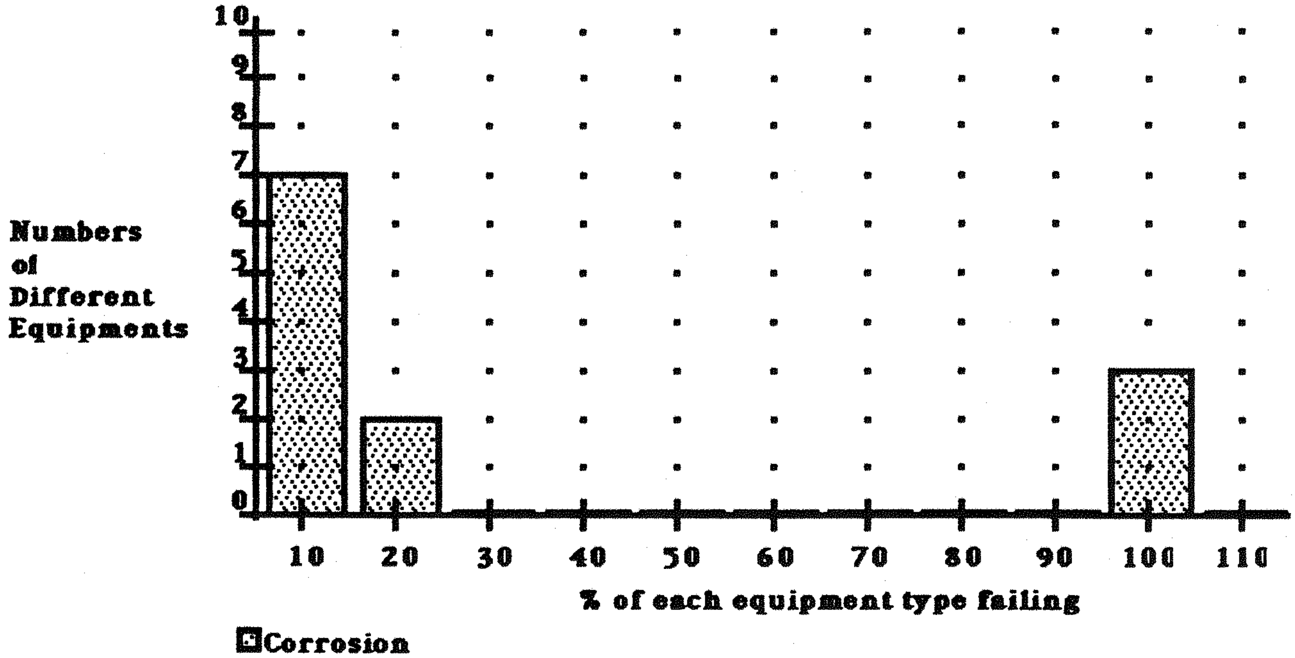



Figure 3.3 How a designer recalls past experience

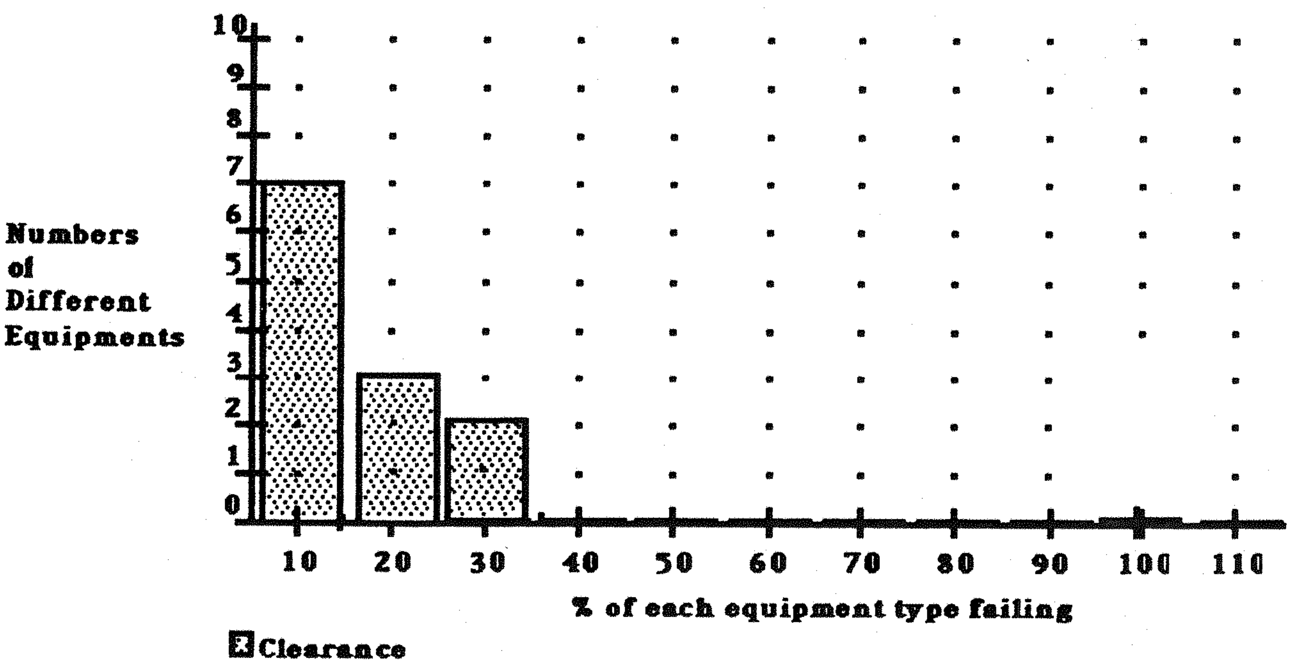



igure 3.4
he normal Defence Industry
esign and Creation Process




# Figure 4.1

**Example of a catastrophic failure characteristic**




# Figure 4.2

**Example of a stable failure characteristic**

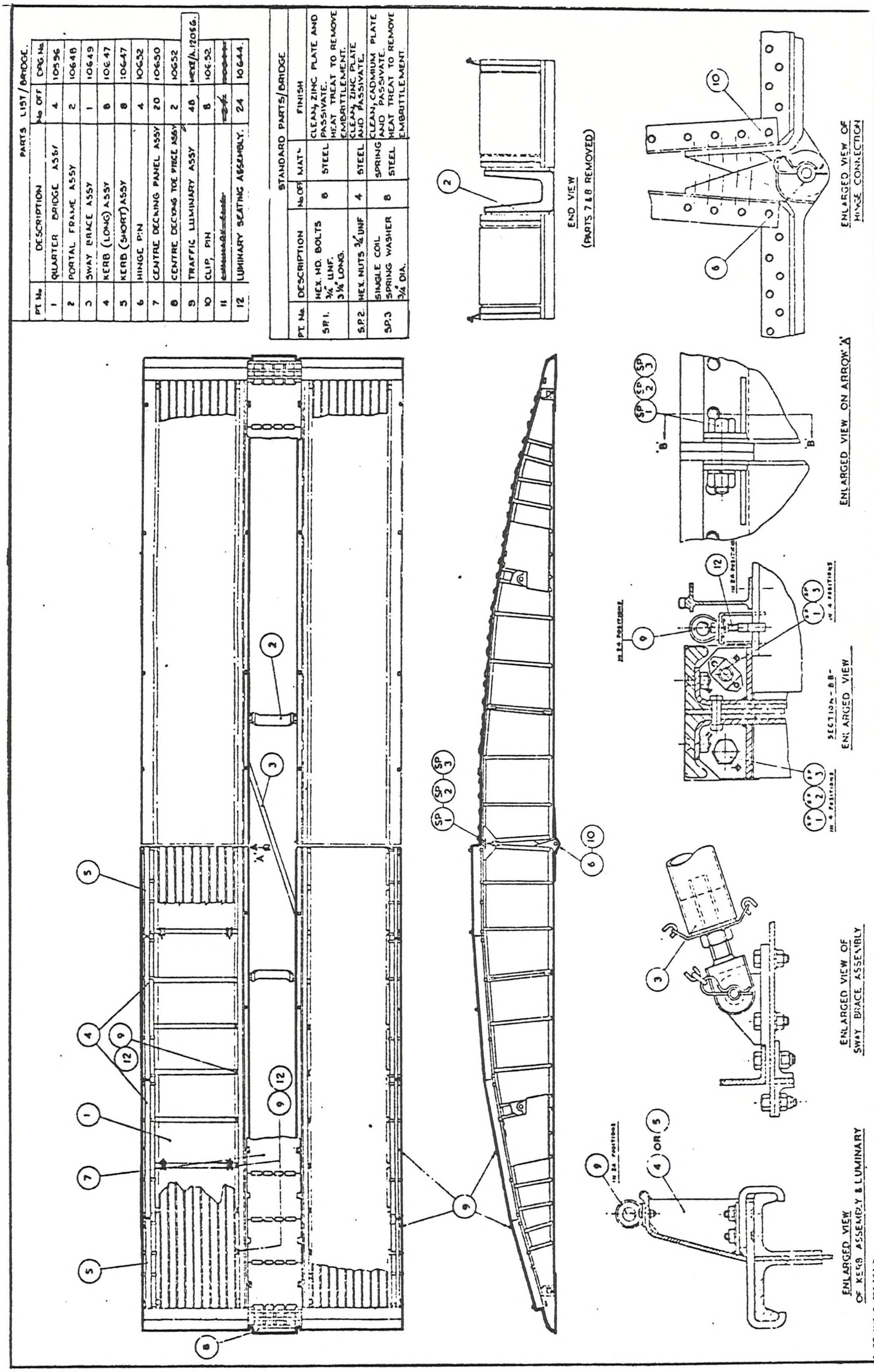



Fig. 5.1 No. 6 Tankbridge - General Arrangement

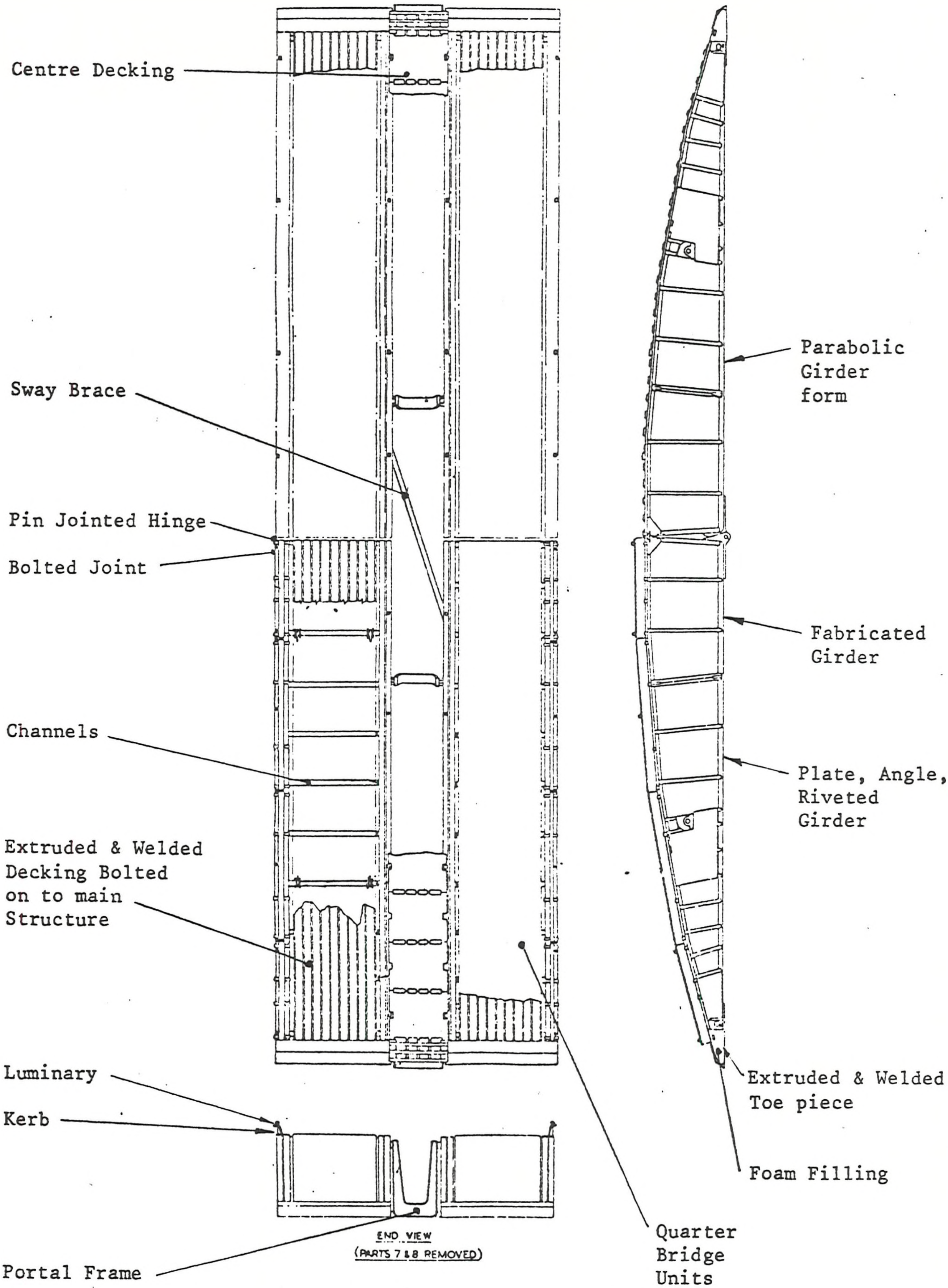
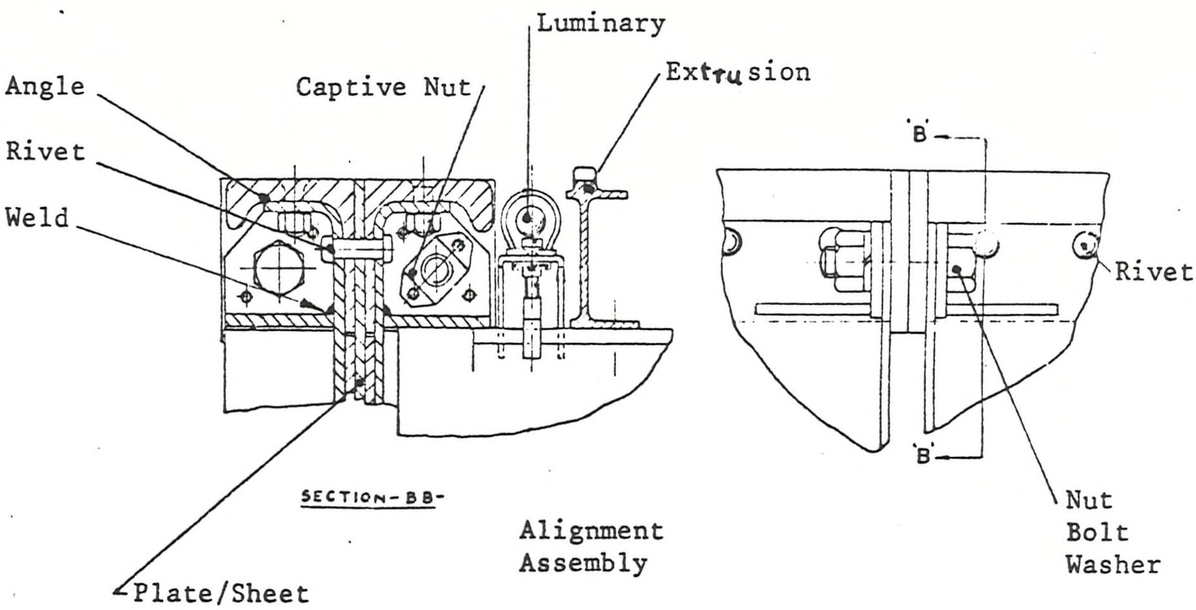
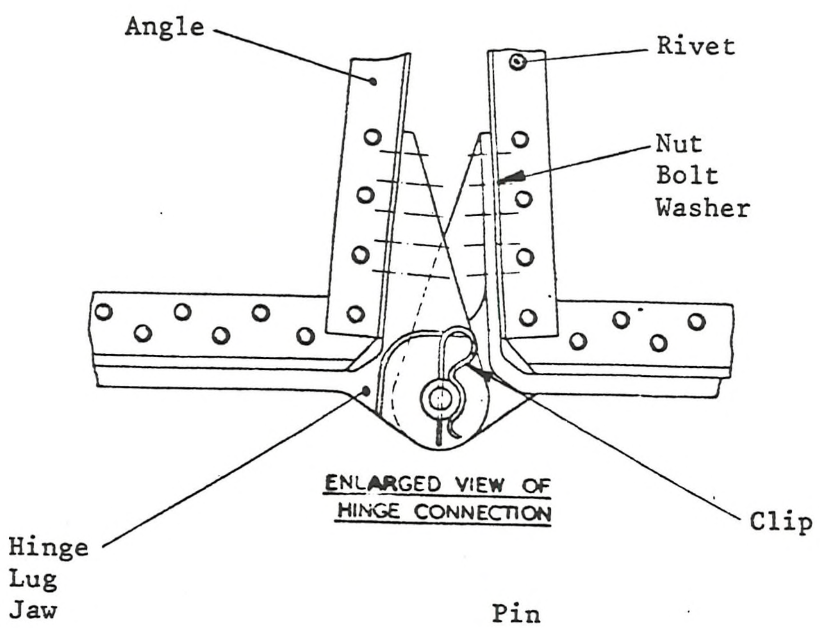



Fig. 5.2 FEATURE ANALYSIS

MAIN STRUCTURE



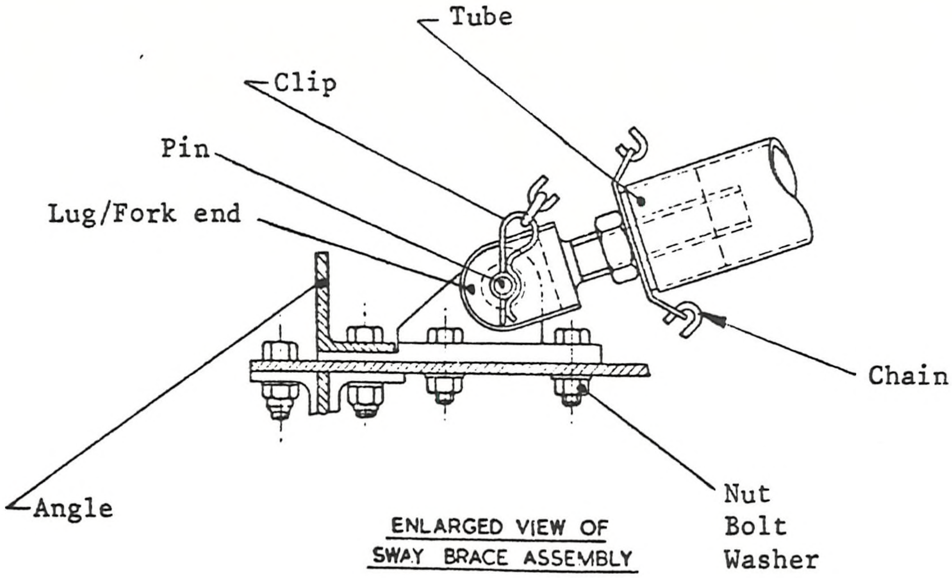

Alignment
Assembly




Alignment
Assembly

Fig. 5.3 FEATURE ANALYSIS

Details



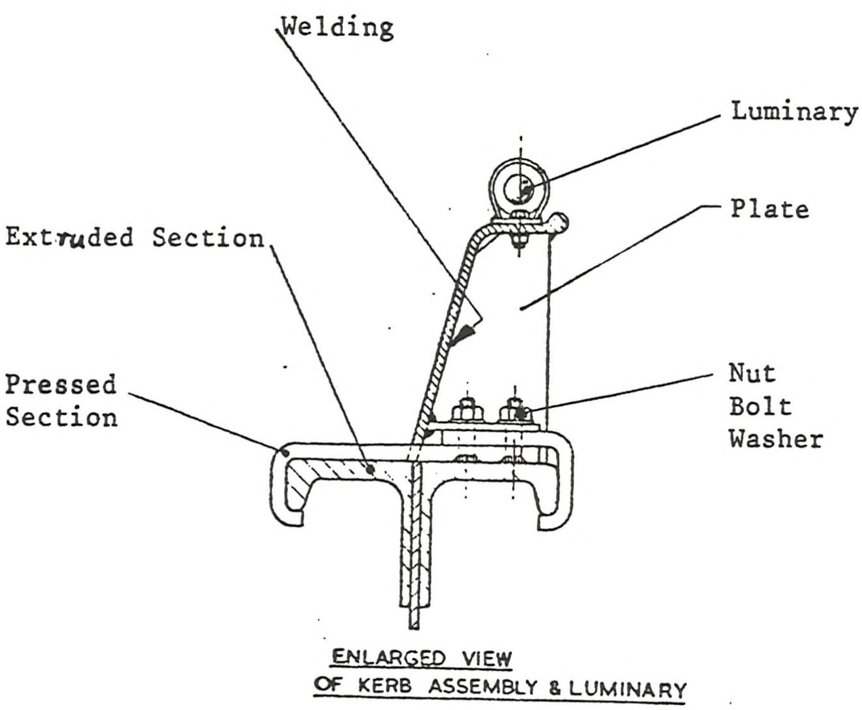




Fig. 5.4 FEATURE ANALYSIS

Details

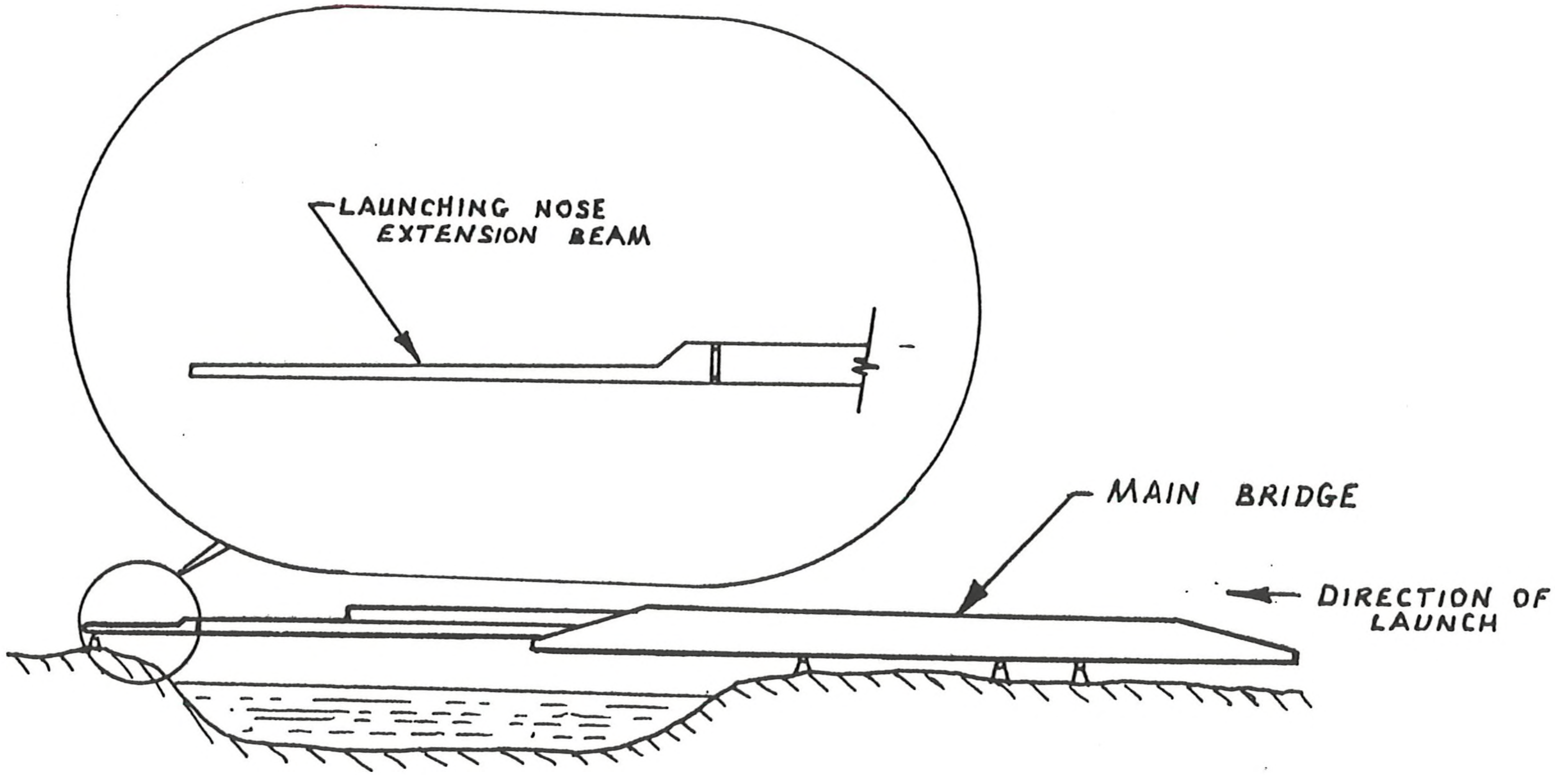



FIGURE 5.5 BRIDGE LAUNCHING PROBLEM

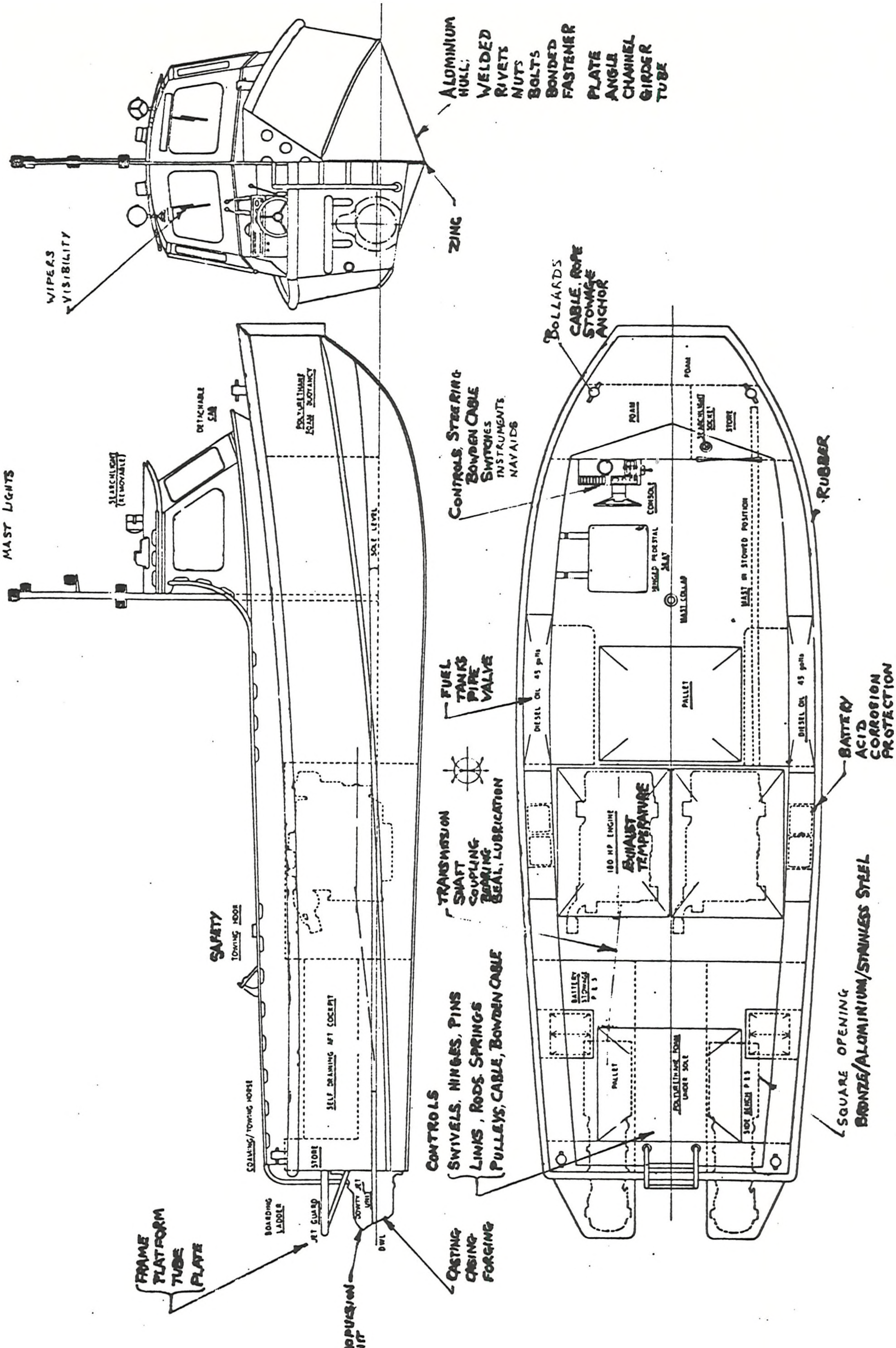



Fig 5.6 General Arrangement - Features

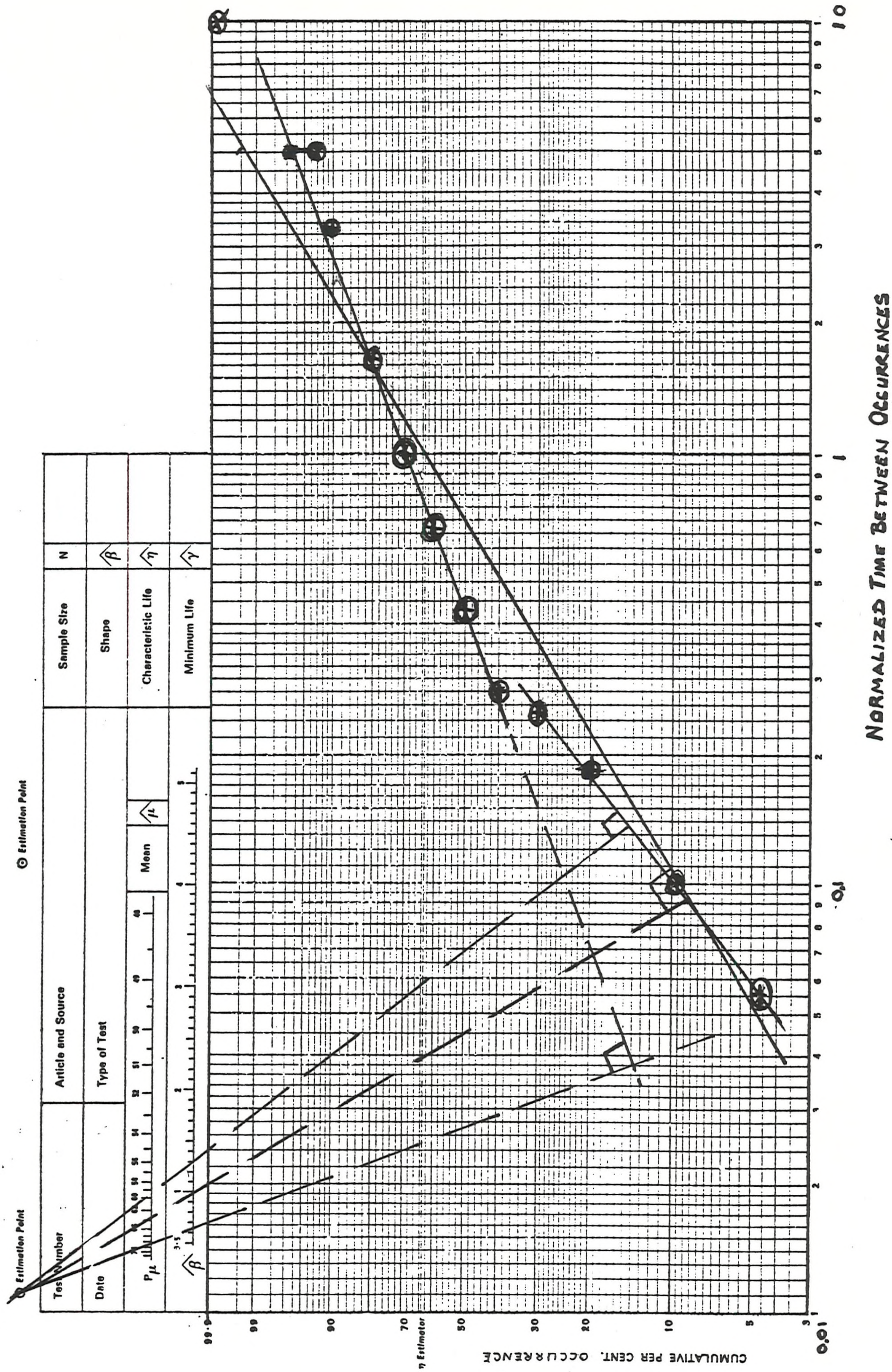
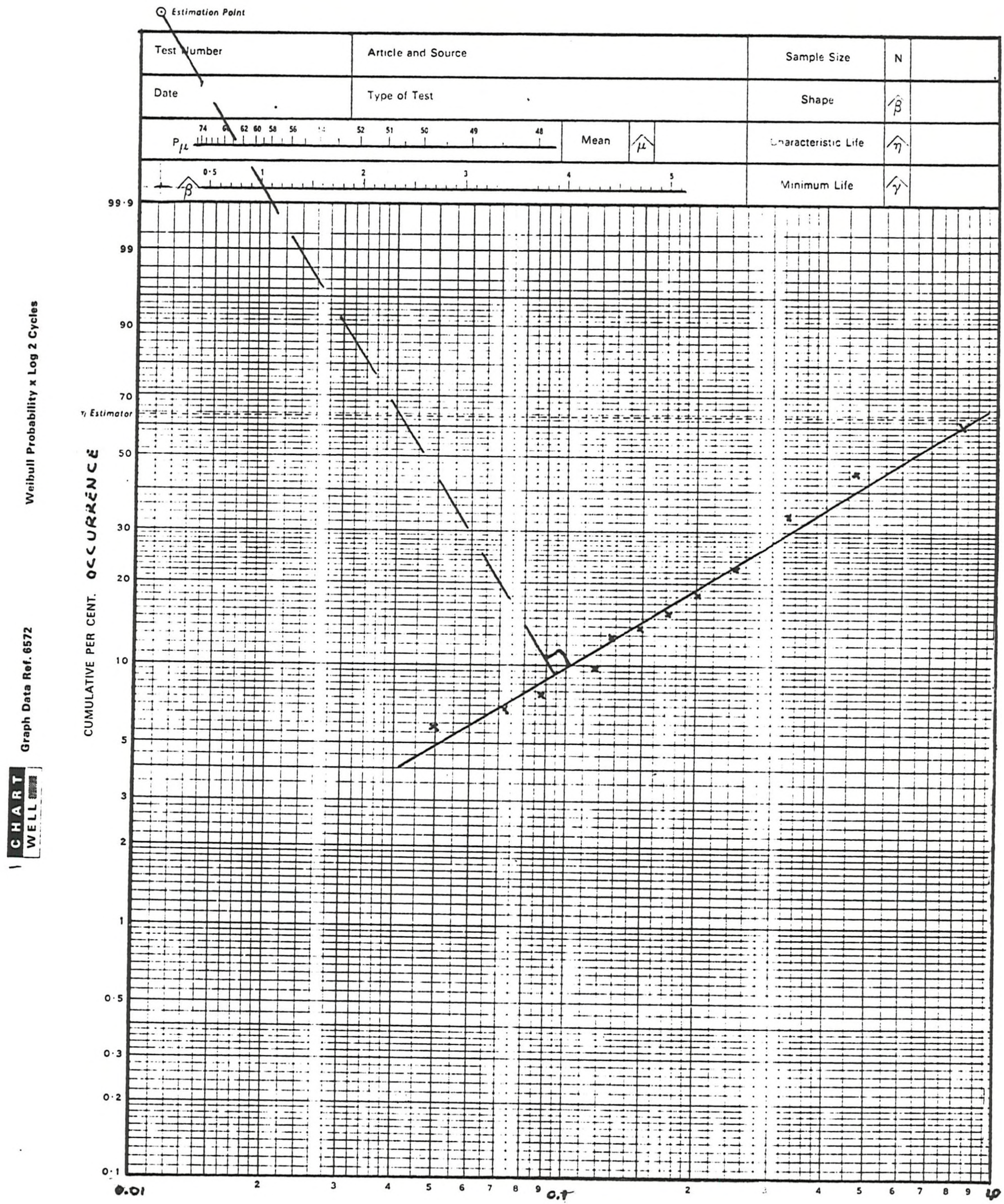



Figure 6.1 Keyword Occurrence of terms from RETS thesaurus in the report index




Normalized time between occurrences

Figure 6.2 Keyword Occurrence of terms in RAF MDC report index

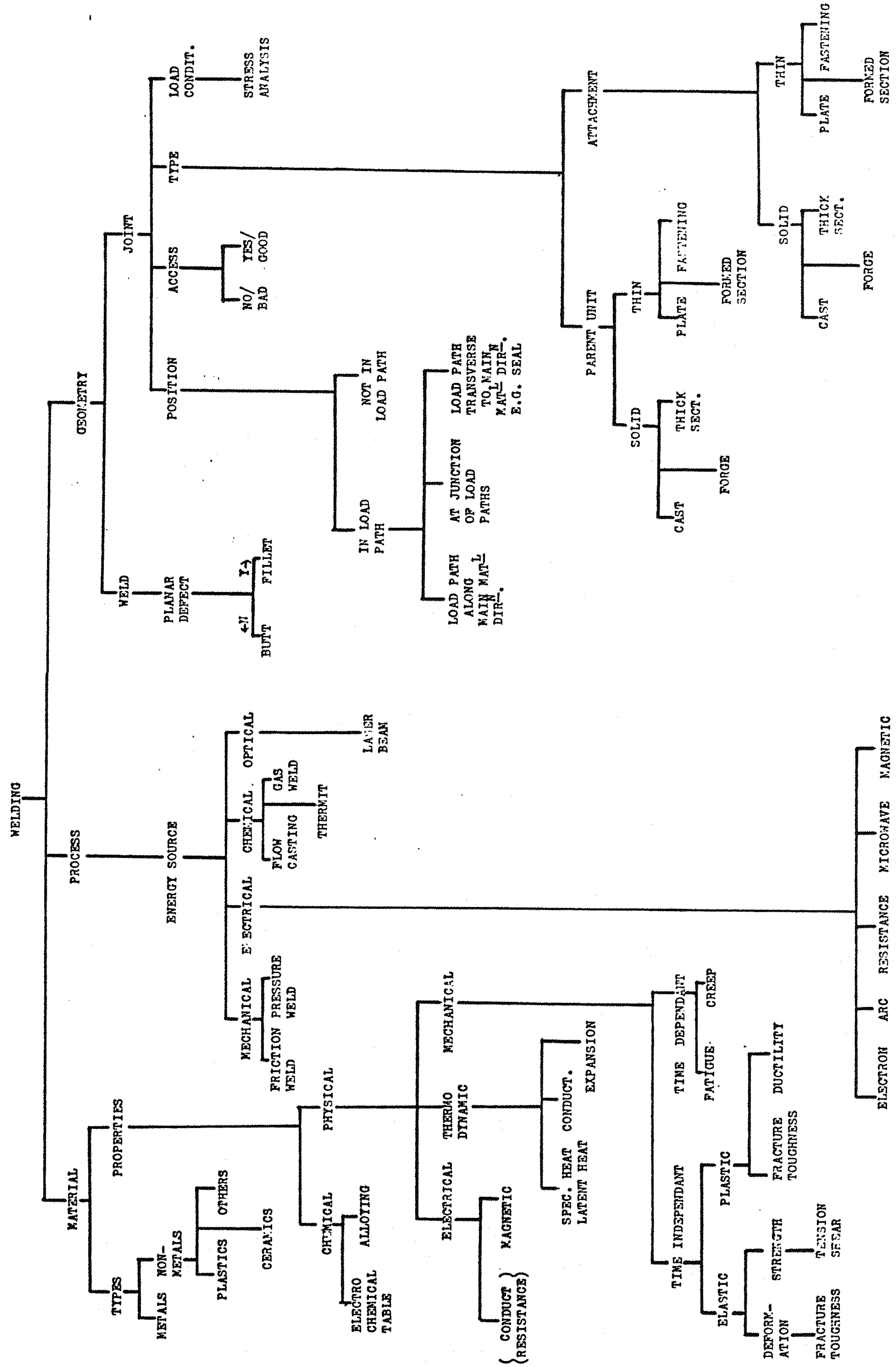



FIG. 6.3 WELDING FEATURE TREE

**Table 5.1**

| Feature | Occurrence | % Total |
|---|---|---|
| Dimension | 245 | 68 |
| Shape | 83 | 23 |
| Weld | 76 | 21 |
| Position | 65 | 18 |
| Material | 54 | 15 |
| Test | 40 | 11 |
| Miscellaneous | 36 | 10 |
| Replace | 32 | 9 |
| Missing | 32 | 9 |
| Repair | 29 | 8 |
| Surface | 11 | 3 |
| Attitude-/alignment | 11 | 3 |

**Table 5.1 Concessions and production permits**

**Features listed in order of occurrence rate**

**Table 5.2**

| Description | Occurrence | % total |
|---|---|---|
| Stiffeners | 221 | 53.90 |
| Fastenings | 165 | 40.24 |
| Deck & Blocks | 158 | 38.54 |
| Covers | 103 | 25.12 |
| Toes | 94 | 22.93 |
| Hinges & Joints | 67 | 16.34 |
| Portal Frame | 60 | 14.63 |
| Chords | 59 | 14.39 |
| Butt Plates | 42 | 10.24 |
| Launch Brackets | 38 | 9.27 |
| Panels | 34 | 8.29 |
| Bulkhead/diaphragm/transom | 25 | 6.10 |
| Boundary Member | 18 | 4.39 |
| Sway Brace | 8 | 1.95 |
| Corrosion | 5 | 1.22 |
| Lifting Eyes | 5 | 1.22 |
| Brackets | 2 | 0.49 |
| Tee End | 1 | 0.24 |
| Packing | 1 | 0.24 |
| | | |
| Replace | 410 | 100.00 |
| Clean/dress Burrs/buckles | 345 | 84.15 |
| Missing | 214 | 52.20 |

**Table 5.2 Damaged bridge repair analysis**

**Features listed in order of rate of occurrence**

**Search terms = (MGB AND (LN OR LNLR OR launch))**

| Report Number | Sub-Unit | Features rel | Features related to failure | | | |
|---|---|---|---|---|---|---|
| 954 | LNLR | Lightweight | Transit | Stowage | hole | damage |
| 957 | LNLR | Operation | assembly | productio | collapse | buckle |
| 958 | LN | Roller | acceptance | | | |
| 1007 | LNLR | weld | notch | overload | crack | buckle |
| 1030 | Frame | launch | location | shaft | splitpin | roller |
| | | assembly | aluminium | | | |
| 1131 | LN | girder | pin | clip | retainer | assembly |
| | | operation | | | | |
| 1181 | LN | pin | clearance | assembly | lashing | lift |
| | | operation | | | | |
| 1391 | LN | operation | crush | crack | | |
| 1394 | | assembly | launch | weld | fracture | |
| 1395 | | assembly | launch | operation | fracture | limitation |
| 1515 | LNLR | launch | operation | drop | buckle | collapse |

**Table 5.3 Listing of Search Output**

Table 5. PERS:TABLE5_3.FMD

Issue 1

Date 16- 3-1988 Search terms = (MGB AND (LN OR LNLR OR launch))

Time 13:51:35

| Report Number | Sub-unit | Features related to failure | | | | Features related to failure | | | Failure Mode | Effects | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 954 | LNLR | Lightweight | Transit | Stowage | hole | damage | | | M1 | hole | damage |
| 957 | LNLR | Operation | assembly | productiocollapse | | buckle | | | M1 | collapse | buckle |
| 958 | LN | Roller | acceptance | | | | | | M3 | | |
| 1007 | LNLR | weld | notch | overload | crack | buckle | | | M1 | crack | buckle |
| 1030 | Frame | launch | location | shaft | splitpin | roller | assembly | aluminium | M2 | | |
| 1131 | LN | girder | pin | clip | retainer | assembly | operation | | M2 | operation | |
| 1181 | LN | pin | clearance | assembly | lashing | lift | operation | | M2 | operation | |
| 1391 | LN | operation | crush | crack | | | | | M1 | crush | crack |
| 1394 | | assembly | launch | weld | fracture | | | | M1 | fracture | |
| 1395 | | assembly | launch | operationfracture | | limitation | | | M3 | fracture | limitation |
| 1515 | LNLR | launch | operation | drop | buckle | collapse | | | M1 | buckle | collapse |

| Feature | Occurrence in search | % occurr. | Failure Characteristic | Feature | Occurrence in search | % occurr. | Failure Characteristic |
|---|---|---|---|---|---|---|---|
| Operation | 6 | 54.55 | | acceptance | 1 | 9.09 | |
| assembly | 6 | 36.36 | C | aluminium | 1 | 9.09 | C |
| LNLR | 4 | 36.36 | S | clearance | 1 | 9.09 | S |
| LN | 4 | 27.27 | S | clip | 1 | 9.09 | S |
| launch | 3 | 27.27 | C | crush | 1 | 9.09 | |
| buckle | 3 | 18.18 | | damage | 1 | 9.09 | |
| fracture | 2 | 18.18 | | drop | 1 | 9.09 | |
| pin | 2 | 18.18 | C | girder | 1 | 9.09 | S |
| crack | 2 | 18.18 | | Lightweight | 1 | 9.09 | |
| collapse | 2 | 18.18 | | limitation | 1 | 9.09 | |
| weld | 2 | 18.18 | C | location | 1 | 9.09 | C |
| roller | 2 | 9.09 | C | notch | 1 | 9.09 | S |
| lift | 1 | 9.09 | S | overload | 1 | 9.09 | |
| Frame | 1 | 9.09 | | production | 1 | 9.09 | C |
| lashing | 1 | 9.09 | S | shaft | 1 | 9.09 | S |
| Stowage | 1 | 9.09 | S | splitpin | 1 | 9.09 | S |
| retainer | 1 | 9.09 | C | Transit | 1 | 9.09 | |
| hole | 1 | 9.09 | | | | | |

**Failure Mode**

M1 = Failure to 'do'
M2 = Failure to 'contain'
M3 = Below spec. failure

**Failure Characteristic**

S = Stable characteristic
C = Catastrophic characteristic

Table 5.[illegible] Features sorted by frequency of occurrence

18- 3-1988
00:32:39

**Table 5.5**
**Features ordered alphabeticaly**

| Feature | Occur. rate | Prob of occur in reports | Cum.% occur all equipmnts | Equiv. occur rate/10^6 hrs |
|---|---|---|---|---|
| access | 9.00 | 1.43 | 0.24 | 9.09 |
| accessory | 5.00 | 0.80 | 0.38 | 14.53 |
| adhesive | 14.00 | 2.23 | 1.25 | 47.68 |
| adjust | 4.00 | 0.64 | 0.17 | 6.60 |
| alignment | 10.00 | 1.59 | 0.42 | 15.98 |
| aluminium | 35.00 | 5.57 | 11.35 | 431.84 |
| anchor | 1.00 | 0.16 | 1.00 | 38.05 |
| angle | 2.00 | 0.32 | 0.10 | 3.91 |
| anode | 1.00 | 0.16 | 0.08 | 3.04 |
| assembly | 39.00 | 6.21 | 1.76 | 66.81 |
| attachment | 1.00 | 0.16 | 0.02 | 0.86 |
| attitude | 1.00 | 0.16 | 0.02 | 0.63 |
| bar | 6.00 | 0.96 | 0.15 | 5.85 |
| base | 3.00 | 0.48 | 0.11 | 4.27 |
| bearing | 33.00 | 5.25 | 2.40 | 91.33 |
| bend | 11.00 | 1.75 | 0.62 | 23.47 |
| boat | 4.00 | 0.64 | 0.03 | 0.99 |
| bolt | 17.00 | 2.71 | 2.91 | 110.61 |
| bow | 1.00 | 0.16 | 0.01 | 0.36 |
| Bowden | 7.00 | 1.11 | 1.09 | 41.37 |
| box | 9.00 | 1.43 | 7.76 | 295.26 |
| brace | 0.00 | 0.00 | 0.00 | 0.00 |
| bracket | 9.00 | 1.43 | 0.30 | 11.29 |
| brass | 1.00 | 0.16 | 0.01 | 0.19 |
| cable | 18.00 | 2.87 | 1.33 | 50.60 |
| carburetto | 1.00 | 0.16 | 0.02 | 0.72 |
| cargo | 1.00 | 0.16 | 0.01 | 0.37 |
| casing | 17.00 | 2.71 | 0.77 | 29.14 |
| casting | 3.00 | 0.48 | 0.06 | 2.28 |
| catch | 2.00 | 0.32 | 0.08 | 3.04 |
| cavity | 8.00 | 1.27 | 9.54 | 362.82 |
| chain | 7.00 | 1.11 | 0.47 | 17.72 |
| channel | 2.00 | 0.32 | 0.04 | 1.52 |
| chromate | 1.00 | 0.16 | 0.12 | 4.61 |
| clearance | 26.00 | 4.14 | 1.01 | 38.46 |
| clip | 5.00 | 0.80 | 0.20 | 7.74 |
| clog | 4.00 | 0.64 | 1.04 | 39.53 |
| clutch | 15.00 | 2.39 | 0.93 | 35.27 |
| connect | 11.00 | 1.75 | 0.17 | 6.35 |
| conrod | 5.00 | 0.80 | 0.20 | 7.55 |
| contain | 0.00 | 0.00 | 0.00 | 0.00 |
| control | 27.00 | 4.30 | 2.42 | 91.91 |
| corner | 2.00 | 0.32 | 0.11 | 4.17 |
| coupling | 14.00 | 2.23 | 0.47 | 17.93 |

Table 5.5 Features ordered alphabeticaly

1
18- 3-1988
00:32:39

**Table 5.6**
**Features ordered by occurrence rate**

| Feature | Occur. rate | Prob of occur in reports | Cum.% occur all equipmnts | Equiv. occur rate/10^6 hrs |
|---|---|---|---|---|
| transmissi | 47.00 | 7.48 | 2.09 | 79.45 |
| instructio | 47.00 | 7.48 | 3.27 | 124.43 |
| locking | 39.00 | 6.21 | 1.38 | 52.33 |
| pump | 39.00 | 6.21 | 1.20 | 45.79 |
| assembly | 39.00 | 6.21 | 1.76 | 66.81 |
| tank | 38.00 | 6.05 | 1.39 | 52.85 |
| engine | 37.00 | 5.89 | 3.46 | 131.49 |
| dimension | 37.00 | 5.89 | 2.46 | 93.56 |
| seal | 36.00 | 5.73 | 1.84 | 69.90 |
| aluminium | 35.00 | 5.57 | 11.35 | 431.84 |
| shaft | 34.00 | 5.41 | 3.58 | 136.07 |
| bearing | 33.00 | 5.25 | 2.40 | 91.33 |
| nut | 32.00 | 5.10 | 11.93 | 454.05 |
| hinge | 30.00 | 4.78 | 36.36 | 1383.67 |
| fuel | 27.00 | 4.30 | 1.08 | 40.95 |
| control | 27.00 | 4.30 | 2.42 | 91.91 |
| clearance | 26.00 | 4.14 | 1.01 | 38.46 |
| fasten(er) | 22.00 | 3.50 | 32.63 | 1241.48 |
| tow | 20.00 | 3.18 | 0.57 | 21.57 |
| mount | 20.00 | 3.18 | 2.00 | 76.25 |
| valve | 19.00 | 3.03 | 1.57 | 59.74 |
| storage | 19.00 | 3.03 | 1.13 | 43.07 |
| cable | 18.00 | 2.87 | 1.33 | 50.60 |
| bolt | 17.00 | 2.71 | 2.91 | 110.61 |
| handle | 17.00 | 2.71 | 1.81 | 68.77 |
| casing | 17.00 | 2.71 | 0.77 | 29.14 |
| marine | 16.00 | 2.55 | 3.84 | 146.20 |
| frame | 16.00 | 2.55 | 0.74 | 28.04 |
| clutch | 15.00 | 2.39 | 0.93 | 35.27 |
| adhesive | 14.00 | 2.23 | 1.25 | 47.68 |
| coupling | 14.00 | 2.23 | 0.47 | 17.93 |
| guard | 14.00 | 2.23 | 0.90 | 34.22 |
| screw | 14.00 | 2.23 | 0.62 | 23.55 |
| rubber | 13.00 | 2.07 | 1.59 | 60.65 |
| roller | 12.00 | 1.91 | 4.53 | 172.52 |
| paint | 11.00 | 1.75 | 8.81 | 335.16 |
| electric | 11.00 | 1.75 | 1.69 | 64.19 |
| bend | 11.00 | 1.75 | 0.62 | 23.47 |
| connect | 11.00 | 1.75 | 0.17 | 6.35 |
| maintenanc | 11.00 | 1.75 | 0.53 | 20.18 |
| cover | 11.00 | 1.75 | 1.62 | 61.73 |
| plate | 11.00 | 1.75 | 1.34 | 51.03 |
| plating | 11.00 | 1.75 | 2.66 | 101.33 |
| pulley | 10.00 | 1.59 | 0.24 | 9.31 |

Table 5.6 Features ordered by occurrence rate

18- 3-1988
00:32:39

**Table 5.7**
**Ordered by cumulative occurrence**

| Feature | Occur. rate | Prob of occur in reports | Cum.% occur all equipmnts | Equiv. occur rate/10^6 hrs |
|---|---|---|---|---|
| hinge | 30.00 | 4.78 | 36.36 | 1383.67 |
| fasten(er) | 22.00 | 3.50 | 32.63 | 1241.48 |
| vibration | 99.00 | 15.76 | 32.37 | 1231.68 |
| nut | 32.00 | 5.10 | 11.93 | 454.05 |
| aluminium | 35.00 | 5.57 | 11.35 | 431.84 |
| cavity | 8.00 | 1.27 | 9.54 | 362.82 |
| paint | 11.00 | 1.75 | 8.81 | 335.16 |
| deck | 8.00 | 1.27 | 7.98 | 303.54 |
| washer | 8.00 | 1.27 | 7.97 | 303.14 |
| box | 9.00 | 1.43 | 7.76 | 295.26 |
| retainer | 10.00 | 1.59 | 4.55 | 173.01 |
| roller | 12.00 | 1.91 | 4.53 | 172.52 |
| treatment | 1.00 | 0.16 | 4.46 | 169.70 |
| weld | 64.00 | 10.19 | 4.14 | 157.41 |
| marine | 16.00 | 2.55 | 3.84 | 146.20 |
| shaft | 34.00 | 5.41 | 3.58 | 136.07 |
| water | 27.00 | 4.30 | 3.54 | 134.70 |
| engine | 37.00 | 5.89 | 3.46 | 131.49 |
| instructio | 47.00 | 7.48 | 3.27 | 124.43 |
| bolt | 17.00 | 2.71 | 2.91 | 110.61 |
| plating | 11.00 | 1.75 | 2.66 | 101.33 |
| dimension | 37.00 | 5.89 | 2.46 | 93.56 |
| control | 27.00 | 4.30 | 2.42 | 91.91 |
| bearing | 33.00 | 5.25 | 2.40 | 91.33 |
| transmissi | 47.00 | 7.48 | 2.09 | 79.45 |
| mount | 20.00 | 3.18 | 2.00 | 76.25 |
| seal | 36.00 | 5.73 | 1.84 | 69.90 |
| handle | 17.00 | 2.71 | 1.81 | 68.77 |
| assembly | 39.00 | 6.21 | 1.76 | 66.81 |
| electric | 11.00 | 1.75 | 1.69 | 64.19 |
| cover | 11.00 | 1.75 | 1.62 | 61.73 |
| rubber | 13.00 | 2.07 | 1.59 | 60.65 |
| valve | 19.00 | 3.03 | 1.57 | 59.74 |
| safety | 8.00 | 1.27 | 1.56 | 59.36 |
| exhaust | 7.00 | 1.11 | 1.44 | 54.77 |
| tank | 38.00 | 6.05 | 1.39 | 52.85 |
| locking | 39.00 | 6.21 | 1.38 | 52.33 |
| plate | 11.00 | 1.75 | 1.34 | 51.03 |
| cable | 18.00 | 2.87 | 1.33 | 50.60 |
| adhesive | 14.00 | 2.23 | 1.25 | 47.68 |
| pump | 39.00 | 6.21 | 1.20 | 45.79 |
| storage | 19.00 | 3.03 | 1.13 | 43.07 |
| mast | 7.00 | 1.11 | 1.12 | 42.67 |
| Bowden | 7.00 | 1.11 | 1.09 | 41.37 |

Table 5.7 Features ordered by cumulative occurrence

APPENDIX A

# USE OF WORDS IN LANGUAGE

## A.1. INTRODUCTION

As stated in chapter 2, an aim of the study was to produce a mathematical model of the keyword indexing system. Such a model was needed as a benchmark against which to compare the real system generated. An obvious starting point is the use of words and word structures in natural language. Words and word structures are used to convey ideas. They must convey the general theme, giving adequate cover to place the idea in context, yet they should be sufficiently precise to give specific detail of the required subject or idea. In indexing and allied subjects these concepts are contained in the indexing topics of 'Recall' for adequate cover, and 'Precision' for specific detail. This appendix details some of the aspects of the use of natural language.

## A.2. THE USE OF WORDS IN LANGUAGE

Words are used in language to communicate ideas. concepts, feelings, actions etc. They may be used individually in combinations, and in specific order. By altering the combinations or order, the entire meaning may be changed. In any language there is an essential core of words' the content words, which are used as a basic framework on which to build. These basic words fall into two main groups.

1. Verbs - which describe events, states of affairs, intentions, and attitudes.
2. Nouns - which describe entities.

Both groups may be amended by additives i.e. adverbs and adjectives and are thus modified to fit together. A variety of modifiers such as particles, prepositions and other determiners having syntactic or grammatical function but little or no independant meaning are used with the content words. They act as modifiers to qualify the given situation and give it its precise meaning. For example:

Some Bolts - 10 Bolts - 10 Steel Bolts, shows an example of increasing precision of meaning. But '10 Steel Bolts' and '10 half inch Bolts' are both subgroups of '10 Bolts' with similar precision but different meaning. The word groups may overlap e.g. 'half inch steel bolts' but this is not implicit in the groups. It is this use of modifiers which makes up a large proportion of any language.

Words can have two different types of meaning:
  Grammatical - by virtue of position and context;
  Lexical - meaning in its own right.

In engineering, the meaning of words tends to be highly grammatical and is very dependant on context. This problem of Lexical/grammatical meaning is one of semantics, and becomes a matter of recalling a huge number of acquired associations. These associations, though not quite idioms, are discrete items of linguistic information. The problem is to cover and identify all these discrete linguistic events.

It has been reasonably well proved by several groups that the problem of multiple meaning is indeed rather minor if the subject matter is narrow enough, the text is not too large, and providing one is charitable in interpreting the output.

With any given dictionary/thesaurus, it may be assumed that for certain words the choice among the various equivalents listed doesn't really matter, and therefore should be excluded from a multiple meaning analysis at the beginning. For other words the choice matters in some contexts but not for all cases. With some words a choice is always necessary.

Less evident but more interesting is the fact that for some words in certain contexts several equivalent words are clearly better than any one alone, since the reader is given the opportunity to interpolate a meaning which may not exist in any one word or phrase.

## A.3. WORD STRUCTURES

Nouns can be divided into a hierarchical structure and the usual way is

Human
→ Animate
→ Countable
→ Concrete
→ Abstract

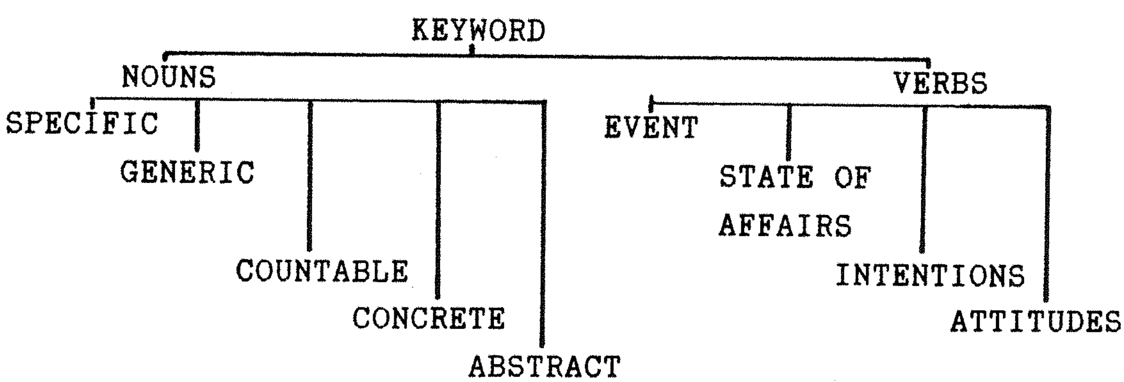
For the purpose of this work the following is suggested:

| Noun Group | Example |
|---|---|
| Specific item/type | Individual item/Equipment |
| Generic type | Family of Equipment |
| Countable | Standard item |
| Concrete | Material |
| Abstract | Measurable Value or Property |

Verbs can be divided into:

Events
→ States of Affairs
→ Intentions
→ Attitudes

From the foregoing it is apparent that any set of keywords used will have the following structure:




If this Structure is now used when counting a keyword index for a set of failure records, the following form emerges:-

- Nouns
  - Specific — Item of Equipment
  - Generic — Equipment type
  - Countable — Geometric form
  - Concrete — Material
  - Abstract — Environment Temperature, Pressure, Energy (measurable values)

- Verbs
  - Events
    - Failure mode [instantaneous type]
    - Operation or Maintenance
    - Design Function which failed
  - State of Affairs
    - Imposed Environment,
    - Failure mode [time dependant]
    - Process
  - Intentions
    - Test or inspection procedures
    - modifications, Instructions
  - Attitude
    - Repair and disposal policy,
    - general concepts and philosophy

The result of this when translated into an indexing format is the form shown in figure A.1.

A.4. WORD GROUPS AND USE IN TEXT

It can be shown that with unrestricted permutations and combinations the maximum number of combinations possible with a given body of n different words taken k at a time is:

$$N = \frac{n!}{k!(n-k)!} \qquad (1)$$

where n = total number of different words in the sample

k = number of words in any one group, i.e. groups of words taken k at a time.

Thus for all sizes of word group, i.e. for all k for k = 1 to k = n the total number of combinations possible are:

$$C(tot) = \sum_{K=1}^{n} \left( \frac{n!}{k!(n-k)!} \right) \quad (2)$$

If this case of unrestricted combinations were allowed for all words then they would all have an equal use potential, and hence equal precision. This would be the case where the meaning of each word was dependant on its lexical meaning and its position. This is somewhat akin to the elements of the pictographs used in oriental languages.

By restricting the allowable combinations and permutations the precision of a word can be enhanced. In the extreme case it can be made to have only one specific meaning, and use in only one precise context. The precision in meaning of a word is determined by those restrictions which may be arbitrary or follow grammatical structural laws. The final effect is the same, control of the precision of meaning. From the previous argument it can be seen, that in general, the less a word is used the more precise is its meaning, i.e.

$$f(t) \propto p \quad (3)$$

where p = precision of meaning

t = mean time between occurrence in text.

If some standard written text is examined and the occurrence of the individual words counted then the frequency of use of individual words can be plotted against the cumulative occurrence of all words. An example is shown in Figure A.1. taken from a random sample of text. [a.2]

From the graph it is apparent that:

$$U(t) \propto e^{-dt} \quad (4)$$

It is apparent on detailed analysis that the most frequently used words are the various modifiers described earlier. It can also be seen that the content words follow the distribution for occurrence and precision given in equations (4) and (3).

## A.5. KEYWORD INDEX STRUCTURES

It follows that in any keyword index of a random set of reports, the expected distribution of the keywords would also follow these two rules. Ideally with a keyword index it should be possible to locate a precise report and also locate associated groups and subgroups held within the data bank. For the index to be truly relevant it is usually necessary to use several keywords to adequately index an individual report, i.e. the combination of words qualifies the identification and improves precision. With an indexing system using many different words the number of different word combinations possible for indexing becomes very large.

Consider a system with a set of n different keywords x1,x2,x3,......xn .

For n different words taken all at once there are n! distinct permutations possible.

For n different words taken k at a time the number of permutations is:

$$^{n}P_{k} = \frac{n!}{(n-k)!} \qquad (5)$$

and for n different words the total number of permutations is:

$$\sum_{k=1}^{n} \left\{ {}^{n}P_{k} \right\} = \sum_{k=1}^{n} \frac{n!}{(n-k)!} \qquad (6)$$

Now if x1 occurs a times, x2 occurs b times, x3 occurs c times etc. in a given indexing system then the number of all different n-tuples is:

$$P_{x(a,b,c.....)} = \frac{n!}{a!b!c!....} \qquad (7)$$

For n elements the number of combinations taken k at a time is:

$$C^n_k = \frac{n!}{k!(n-k)!} \qquad (8)$$

or from (5)

$$C^n_k = \frac{P^n_k}{k!} \qquad (9)$$

Substituting (7) for $P^n_k$

$$C^n_{k(a,b,c,...)} = \frac{n!}{k!(n-k)!a!b!c!...} \qquad (10)$$

where $C^n_{k(a,b,c...)}$ is the maximum number of different combinations in the set of words comprising the keyword system, k is the restrictor, a,b,c... etc. are constants for the set of keywords. If there are several duplications of individual words then this must also act as a further restrictor to Equation 1.

Therefore total restrictions imposed will be the reduced value of the optimum condition given in (1) substituted for n! in Equation (9). This will then give the maximum value possible for the reduced set of permutations given the above limitations.

Now total number of permutations from n words with x1 occurring a times, x2 occurring b times, x3 occurring c times etc.

$$p(total) = \sum_{k=1}^{n} \frac{n!}{(a!b!c!...n!)} \frac{1}{(n-k)!} \qquad (11)$$

$$= \frac{n!}{(a!b!c!...n!)} \sum_{k=1}^{n} \frac{1}{(n-k)!} \qquad (12)$$

Using Stirlings formula for large values of n the approximation [A.3]

$$n! \simeq \left(\frac{n}{e}\right)^{n} \sqrt{2\pi n} \qquad (13)$$

Using this to evaluate (11) term by term

Let $\frac{n!}{a!b!c! \ldots n!} = \psi$

$$\psi \simeq \left(\frac{n}{e}\right)^{n} \cdot \sqrt{2\pi n} \cdot \left(\frac{e}{a}\right)^{a} \cdot \frac{1}{\sqrt{2\pi a}} \cdot \left(\frac{e}{b}\right)^{b} \cdot \frac{1}{\sqrt{2\pi b}} \cdots \left(\frac{e}{n}\right)^{n} \cdot \frac{1}{\sqrt{2\pi n}} \cdots (14)$$

Let $\frac{1}{(n-k)!} = \rho$

and the $\frac{1}{(n-k)!}$ term becomes

$$\rho_K = \frac{1}{(n-k)!} \simeq \left(\frac{e}{n-k}\right)^{(n-k)} \cdot \frac{1}{\sqrt{2\pi(n-k)}} \quad ---- (15)$$

Then substituting (14) and (15) in (12)

$$P(\text{total}) = \psi \cdot \sum_{k=1}^{n} \left\{ \frac{e}{(n-k)} \right\}^{(n-k)} \cdot \frac{1}{\sqrt{2\Pi(n-k)}} \qquad (16)$$

$$= \psi \cdot \sum_{k=1}^{n} \rho_k \qquad (17)$$

For any bank of words or data file in word form the $\psi$ term can be taken as the maximum possible number of permutations with the particular set of data. It is a constant and can be evaluated.

e.g. for n = 4000, $n! \simeq 30 \times 10^{12700}$

The $\rho$ term in the equation is the variable term. However if the case shown in (16) is taken and k is not restricted in any way i.e. if k varies from b to n then

$$\sum_{k=1}^{n} p_k = \frac{1}{(n-1)!} + \frac{1}{(n-2)!} + \ldots\ldots \frac{1}{0!}$$

In the limit when n is large this will tend towards e (within 0.1% of e) and for $n \geq 6$ can be taken as e. Thus the maximum number of permutations for a data set is

$$P(\max) = \psi \cdot e$$

When there are no duplicated values this maximum becomes

$$n!e \tag{20}$$

If the maximum value of k is limited. for example by grammatical laws, by sentence or phrase length, or by a limit to the number of terms in a search procedure, then the $p$ term becomes very small and acts as a restrictor on the large $\psi$ term. In addition, if only combinations are used, that is the word string is not structured in any way, then the number of indexing combinations possible will be further limited by the k! term in the denominator.

With a restricted vocabulary of say 500 words and a maximum number permitted of 10 then the total number of combinations possible is:

$$C^{n}_{10} = \sum_{k=1}^{10} \frac{n!}{k!(n-k)!} \tag{21}$$

where n is the number of words in the document/report store. For n = 4000 Say

$$C^{n}_{10} = \sum_{k=1}^{10} \frac{4000!}{k!(4000-k)!} \tag{22}$$

If this is then restricted by the frequency of use criteria i.e. the < 'x1' occurring a times etc.> (see Equation 10) then a binomial type solution applies (fixed quantity, integer jumps in values etc).

Using an exponential distribution for the frequency of occurrence of words (see Equation 4), the values of the a,b,c,... terms can be found. Thus for a keyword index of a store of data/reports the $\theta$ term gives the degree of precision of the words used. The $\lambda t$ term gives the measure of relevance of the word groups to the individual reports.

It is thus possible to index a large number of documents using a small number of words, and Table 1 shows the number of features required to index a sample of records. However the object is to transmit information, not just index the reports.

It can be seen that a small increase in the number of keywords used to index a report will give a large increase in both the quantity and precision of information transmitted. Let us take an example of a particular subject.

If we use as a sample a block of 1000 reports the object is twofold.

1. To index the reports.
2. To transmit information.

It can be shown that to index these 1000 reports it is only necessary to use seven different keywords i.e. 7! = 5040. The choice of seven different keywords to cover a complete subject is unrealistic. However it may well be possible to cover certain subject fields with very few terms. For example if item geometry is to be used as an index subject it would only require a few terms to cover a large part of the subject field. Mathematics does just that, and any geometry can be described in terms of distance from the x,y, and z axes, angles of rotation about these axes, and such terms as Surface or Solid. At a more realistic level such terms as sphere, cylinder, cone, cube, prism, triangle. square, circle, ellipse are more meaningful to the average user. It is therefore more convenient to use the properties of natural language just described. That is the use of exponentially decaying occurrance of words to enhance their importance or precision of meaning, coupled with their use in a combinational way to give both the precision and the recall required.

## A.6. SUMMARY OF THE USE OF KEYWORDS IN INDEXING

If a series of reports are individually indexed by groups of keywords then the thesaurus of keywords generated would be expected to contain the nine main types of keywords specified in paragraph A.3 plus a miscellaneous group.

Precision of indexing can be achieved by two means:

(a) The use of very specific terms,

(b) The use of combinations of less precise terms.

A statistical analysis of a keyword index will show which are the most commonly occurring words and word groups, and therefore the most closely related keywords. It should also give an indication of the precision of the words.

The probability of a report being indexed by a number of indexing terms is given by the product of their individual probabilities of occurrence in the index. It follows that by combining several quite general terms, all related to the individual failure report, the probability of other reports being indexed with this exact combination is low. The introduction of a high precision term in the indexing group implies the probability of similarly indexed reports existing in the group/file will rapidly diminish to zero. Conversely a search strategy for recall of reports should be arranged such that initial enquiries always contain general low precision terms. In the first instance, any high precision terms should only be used with a search logic that does not exclude records which are not indexed with this term, i.e. an 'OR' logic search. The search can then be refined by use of the more precise terms for final selection of the information required.

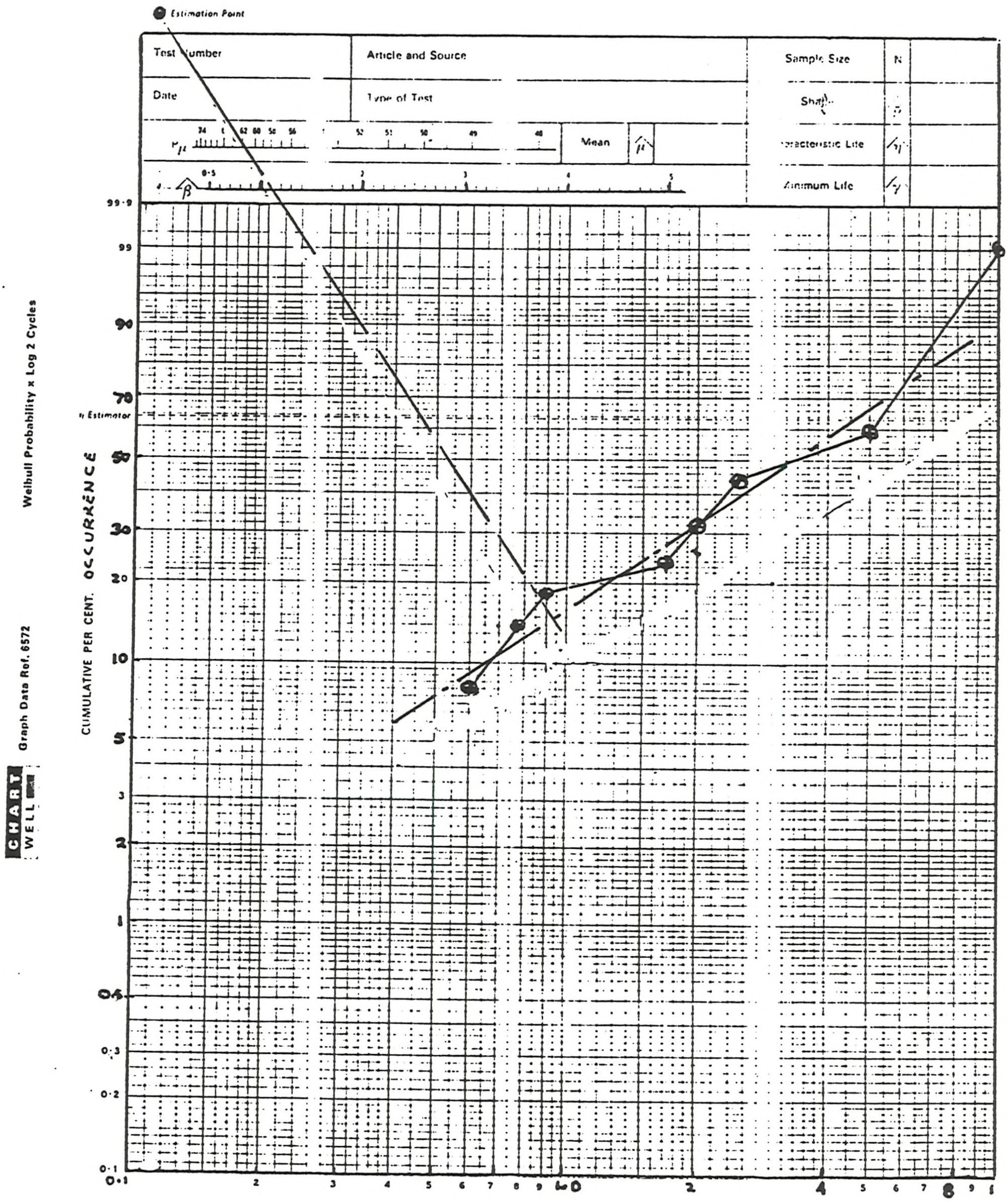



FIGURE A.1 KEYWORD OCCURRENCE IN TEXT

## Appendix B

### Search Probabilities, Precision and Recall

1. When searching record databases, the precision of the search is a measure of the accuracy of the retrieval process. The recall is a measure of the extent of the total number of valid records recovered.

Fundamental to the operation of the system is the existence of a set of data. The basic data will either be in existence in the system (E1) or it will not(E0).

Records that are retrieved are either valid or invalid, i.e. the data is either 'true'(probability T) or 'false'(probability F), and these are presumed to be independent. The user will generally only be able to judge their validity after reading the reports. It follows that the sum of nT, the probability of no true record being present, and T is unity, i.e.:

$$T + nT = 1$$

similarly

$$F + nF = 1$$

From an information theory viewpoint, it is of interest to know what is the likelyhood of the information being true, and of use to the user.

There are only four fundamental data sets possible. They are:

1. True and False data, TF
2. True data but no False data TnF
3. False data but no True data nTF
4. No True or False data nTnF

Though there are only these four sets, the various probabilities of their occurrence depend on the probability of detecting the data (dt and df respectively) and the probability that, having detected it, the data is correctly classified as true or false (Ct and Cf respectively).

As a result there are up to 16 combinations possible, these are listed in table 1, including case 16, the trivial case of no data in the system. These combinations can be grouped into 3 possible results from the search:

| | | |
|---|---|---|
| 1. | Nothing found | D0 |
| 2. | Records found, assumed valid | D1 |
| 3. | Records found, assumed invalid | D2 |

These outcomes can be rearranged to give the following joint probabilities:

| | | |
|---|---|---|
| p(E1,D0) | = 9+12 | nill found |
| p(E1,D1) | = 1+2+4+5+8+10 | some T & F, class. valid |
| p(E1,D2) | = 3+6+7+11 | some T & F, class. invalid |
| p(E0,D0) | = 15+16 | nill found |
| p(E0,D1) | = 14 | F found, class. valid |
| p(E0,D2) | = 13 | F found, class. invalid |

## Appendix C

## The textual aspect of information retrieval

### C.1 DESCRIPTIVE FEATURES - LOGICAL CREATION

There are some terms which if used would present very little difficulty in interpretation e.g cylinder, cube, aluminium, gold. However, other terms may well either confuse or raise further questions for clarification. For example the actuator for an aircraft control surface, this may be electrical or hydraulic in operation or purely mechanical. It is therefore of crucial importance that any set of features are carefully checked to ensure that such anomolies can be dealt with, either by further definition or by the operation of the information system. Even so, it may eventually come down to relying on the users basic engineering knowledge and common sense. When indexing a report using a feature indexing technique such as PITFA, the indexing terms can be selected in either a "Top Down" or "Bottom Up" way, or both if sufficient terms are used. Principally one should aim at the user, therefore cause and consequence will both be relevant as enquiries will be interested in what failed, why it failed, and any effects of the failure Looking at the casual aspects first, and using Kipling (Ref ) as a well known design guide, the enquirer is interested in what failed, why it failed, when did it fail, where, how and who was involved. This would give a minimum 6 terms, though for completeness it is likely to be more. Taken in turn.

### C.2 WHAT FAILED

The user will be concerned with the details of the item, this is most likely to involve some form of descriptive label of the parent equipment, (e.g. a bridge or a boat) to set the failures in context , plus more specific detail of the actual element which has failed. This detail may involve more than one term to give a complete description, however, it may also have implicit aspects in the description used which are peculiar to that equipment. This is particularly so if the information system is peculiar to one organisation where such details would be generally known. For example with a system at the RETS/MVEE

Establishment, giving details of an equipment name will quite often imply the material used and may give other details such as manufacturing processes, storage environment and even general use patterns Therefore the indexer should be aware of the end user, and the system manager should be aware of any caveats in use which should be brought to the notice of a casual or foreign (i.e. external) user. When detailing what failed, it is not sufficient to give a bland generic term which will not assist the enquirer to pin point the item. Hence 'weld" on its own would not be sufficient in view of the vast plethora of different features involved in describing welds, their application, and modes of use.

### C.3. WHY it Failed - THE CAUSE

This may well be one of the most difficult questions to answer when cataloging/indexing a report. Quite often a failure may be recorded as a "Random Event", particularly when there is no apparent cause. If there is a design problem then it may be that several similar incidents are needed before a pattern appears which gives a firm indication of a specific or a generic problem. (An example is given in later chapters) MGB LN problem. In each of these reports there may be different apparent causes, only when taken as a whole does it become clear that there is a common thread to all the related failures.

When the indexer is identifying the features related to the failures cause,a good starting point is to examine what phase in the design/creation/use process the failure was related to.

There is one specific break point which can clearly be seen in this process, namely the appearance of a completed product. Hence the main division is between:

1. Pre creation

and -

2. Post creation of the product

The Pre creation phase can be broken down into several sub-sets. i.e.

a. Concept
b. Design
c. Manufacture

and the post creation phase can also be broken down into further sub sets viz;

d. Delivery
e. Storage
f. Use

Taken in order:-

**a. CONCEPT**

The history of engineering must be littered with cases where the basic concept/design philosophy is at fault. Most will have been strangled at birth however typical of incorrect materials (for example samples in this area are use of Fracture sensitive materials in the wrong way/application, e.g. the Tay Bridge disaster Carbon fibre fan blades on the RB211) or use of incorrect materials (e.g. hydrogen in airships) or use of simple flapping wings in early attempts ornithopters. A well known example is the absence of wind resonance effects in the design of the bridge with the spectacular results which are retained on film for all to see. Failures under this heading will therefore be restricted to cases where the basic design concept is flawed. The change in design concept from 'Safe Life' to 'Fail Safe' in civil aircraft design has been a notable conceptual change in this respect.

**b. DESIGN**

Conversely failures under this heading will be restricted to case where the designer has failed to implement a known technique/process algorithm correctly. A typical example, (again with bridging) is the extrapolation of the box girder concept beyond its original limits in large bridge structures created in the latter half of this century (e.g.Sydney Harbour Bridge, Severn Bridge). This group of failures will also encompass cases where the designer has made mistakes in the design calculations. A well publicised case was the blade thickness error in the QE2 turbine blades. As were the Comet aircraft disasters in the 1950's. Within this group will be failures which occur during the transcription of the designers original concept into a full production design by the main D.O.team (See MGB example). There must be many cases where a particular design technique is known but a designer has not used it from ignorance of the technique. This will be particularly relevant to some of the more exotic techniques which the average designer may never use or need to use under normal circumstances. In this area one would expect to find problems related to some of the more exotic field stress analysis techniques such as fracture mechanics or the use of such reliability techniques as fault, hazard and event tree analysis. Also included will be those cases where a deliberate design decision has been made to work to very tight limits and these have then proved inadequate. This is particularly in the defence industry with its drive for ultimate in performance and apparent in mass production industries where the gains from large production runs make the gamble clearly worthwhile to the manufacturer. Whether the subsequent impact on the company's reputation from a failure warrants the risk is a straight commercial decision and has not been addressed in this study, though one only has to look at the public's conception of of the Comet and DC10 aircraft, Leyland's problems with transmission couplings, even in food, with people's suspicion of cheap olive oil and certain wines.

c. **MANUFACTURE**

Many failures occur due to the actual item not being manufactured as the designer intended. In many cases this is due to simple human error, i.e. quality drop off, items are omitted, dimensions incorrectly measured, treatment times may vary. The list is endless. Other causes are unrealistic manufacturing requirements by the designer, policy decisions by management, deliberate use or supply of inferior quality materials, or unusual environmental aspects. Again, the list is many and varied in its form.

Many of the so-called 'Infant Mortality' or 'burn in' failures are due to manufacturing 'drop off', in some instances this is accepted and the total creative process takes account of it with such techniques as proof stress, voltage overload checks, electronic components 'burn in', and pre delivery operational cycling of complete equipment.

Within the Post Creation Stage:

**d DELIVERY**

Them stresses imposed on a product during delivery may be severe. Rail transport can give severe shocks during shunting and loading; road transport, particularly when used over un-metalled roads, can also subject a project to severe pounding, dust, and vibration. Air transport can produce extremes of pressure and temperature; carriage by sea will bring in the associated wet corrosive atmosphere. The environmental factors used in reliability calculations (ref MIL 217, DX99 etc) give a clear indication of the problem, and designers should be aware of it and take the necessary precautions to counter it.

**e. STORAGE**

This can be one of the most benign environments and yet there are a surprising number of failures attributed to storage. If the environment is hostile or the materials used have not been adequately selected for the chosen environment, or the product has not been designed for long term storage, then the probability of failure may be high. This area is principally one of materials compatibility, though incorrect or inadequate maintenance routines during storage are also a major area of concern. Typical examples encountered are long term storage effects on plastics and rubbers, e.g. diaphragms and seals, degradation of electrolytic capacitors, rubber seals bonding in hydraulic rams, long term corrosion due to electolytic cell action of coolant, lubricant or even grease. Climatic changes can cause problems which many designers can overlook e.g. the effects of rainwater freezing or the high temperature effects of solar radiation in hot climates. Within this stage are the effects of biological action such as mould and fungal growth, bacterial contamination, and even the effects of animals such as rodents and insects such as termites.

**f. USE**

The probability of a failure occurring due to misuse by the operator is well known. The Navy ask for products to be 'sailor proof', the Army 'soldier proof',the Airforce 'airman proof', Civil engineers 'Paddy proof. Whichever organisation the end user is in, the effect is the same. Operators will misuse, abuse, or in some way overload or operate the equipment in a way that the designer never intended. Whether it is through ignorance, deliberate or otherwise is not relevant, it happens and the information from the subsequent failures is of use to the designer. It gives an awareness of the likely misuses which may occur to the proposed design and enables him to introduce countermeasures or design to cope with these operational aberations.

**C.4 WHEN.**

The third of 6 main questions raised by Kipling, involves detail of when the incident occurred in the life of the product. Was it old or new; did it happen during operation, if so then when in the operation, if so then when in the operating cycle? For example was it an old item that failed under a suddenly applied local condition after a long period of continuous operation. A point which is often missed but which is very relevant to the 'when' question concerns so called 'consumables'. Some items, though complex, are regarded as throw away items on failure. This is particularly so in the automotive industry where the economics of scale make them more expensive to repair than to replace. This work s well until a case arises in which the replacement rate is excessive Such cases are often difficult to track at the user end of the life cycle. They are more readily seen at the supply end due to abnormally high demands for replacements. This latter point is true for high turnover in Unit by Exchange (UxE) systems where a rapid use of stock items with the subsequent high numbers for repair is seen in the supply loop. This highlights that failure data and information should be fed back from all areas, not just the end user.

## C.5 WHERE

Is predominantly related to the environment associated with the failure. It may be the local natural environment, it may also include artificially imposed aspects such as the high temperatures associated with an engine exhaust. For example, a number of turbine bearing failures have occurred in power stations due to the metal bearing material undergoing crystalline growth due to the high operating temperatures. A point to note is that the environmental aspects may also have been covered under the ´Why it failed" question. Similarly the question "Where on the equipment did it fail´ should also be covered under the ´What failed´ question.

## C.6 HOW did it fail - THE CONSEQUENCE

This is probably only secondary in importance to the ´Why´ question. Predominantly a question related to failure mode, however, for completeness this should also include the effects of the failure as they give a pointer to previously unanswered questions and will be of use as a design tool in FMEA. In order to determine how an item failed one has to define the function that was being performed, and then to determine the method of presentation. Catastrophic failures are more readily seen, investigated and understood. Intermittent failures are more insidious. They are often difficult to localize and rectify, and one is always left with a measure of uncertainty that the solution is both correct and adequate to prevent a recurrence. Failures of degradation are a further complication in that they may be either a degradation of performance below the maximum value specified or of a kind, e.g. wear, that if left may well result in a catastrophic failure. How often has one heard of a car engine ´knocking´ or seen one smoking badly and known that if left to continue the result will probably be a catastrophic failure in the engine. Similarly with a dripping tap, if the washer is replaced early enough then the tap works correctly; if left to drip then the seat becomes damaged and a simple washer replacement will not cure the problem. This latter problem highlights the difficulty in determining what is a degraded failure and what is a catastrophic failure. At what stage in the damage to seat and washer would the leaking tap become a catastrophic failure? Opinions may differ. A further complication which is of great interest to the designer is whether a failure of one item will indicate that the whole batch will fail. Such a characteristic is very important in application of safety factors, depth of analysis during designs, manufacturing tolerances and test/trials regimes. Clearly such a "failure characteristic"is a desirable output of any design fault feedback system. When defining the function that is being performed a casual use may put "lifting" for a crane hook, or "driving vehicle" for an automotive engine. It is clear that a more formal and ordered structure is (or should be) used. Fig shows the breakdown of such a formal structure.

## C.7 MODES OF FAILURE

Generally in the literature one finds that the 'how' of failure is variously described as the failure mode, or effect, or mechanism, or even classification (for example see BS4778). The failure mode is then described as 'the effect by which the failure is observed'. This is considered to be too loose a description and for the purpose of this study the following definition of failure mode will be used:

The mode of failure is the primitive measure by which the function has been judged to have failed. It will be one of three different types namely:

MODE I (M1) Failure to produce an action or reaction. It is a failure which has occurred over a short time interval and after which the equipment is incapable of providing the specified function even at a greatly reduced performance level.

MODE II (M2) Degredation Failure i.e. failure to maintain the specified action or reaction. It is a failure which may have occurred over a considerable period of time and one in which the design function may still be performed by the equipment but at a reduced level of performance.

MODE III (M3) Failure to control an action or reaction.

The further descriptor used is the EFFECT of the failure. This is the visible evidence resulting from the failure mode and is the group of terms most engineers and designers will recognise, e.g. fatigue, fracture, crack, seize, shear, tear, buckle etc. These terms are more general and indicate considerable background information to an aware person. They will often be linked to specific failure mechanisms e.g. fatigue with cyclic loading, seizure with inadequate lubrication between moving surfaces, and hence to the reason why the failure has occured. However, the mechanism of failure may not supply all of the detail required to understand why the failure occurred. For example fatigue failure will be due to a cyclic loading mechanism but this loading may be by physical loading (e.g. bridges), or by thermal cycling (e.g. gas appliance flame sensors), or even pressure cycling (e.g. pressure vessels, submarines). Similarly failures in the moving surface failure group such as seize and jam would both involve friction. However in the case of seize it would be associated with a welding bonding mechanism whereas a failure caused by jamming is a combination of friction and a jamming couple in the resolution of the forces involved. In some instances the mechanism may be obscure or it may be that more than one mechanism has caused the observed effect. For example corrosion may be caused by the external environment e.g. salt water, acid etc., however it could in some circumstances be due to the material itself, e.g. the tendency of some aluminium/magnesium/zinc alloys to exfoliation corrosion. No doubt the true basic mechanism in each case is related, perhaps chemical energy producing inter molecular stresses and lots of dislocations zapping their way between grain boundaries, but the average designer has to take a more pragmatic view of the situation. What is required is an awareness that a specific material may need special treatment in its manufacture and use, particularly if it is to be used in an environment which peculiarly hostile to it.

From the above dissertation it is clear that an information system based on failure reports should have a well structured indexing mechanism. for each report this index should ideally contain a number of specific elements of data. This may not be possible in every case and so the system should be tolerant of missing data.

Table C.1 summarizes the situation laid out in the above discussion. there is one point where there would seem to be a duplication of effort. This is with the 'cause' of failure and the last part of the consequence 'mechanism of failure'. However, take the case of a cantilever beam structure failing by buckling. The mechanism involved is the classic Euler buckling mechanism but the reason for the buckling may be because the beam was overloaded beyond the design limits, or the design calculation was incorrect, or these was an additional factor involved that the designer did not take account of in the design calculations, e.g. unusual sidewind loading on an external structure, tidal current on a marine structure, or perhaps thermal distortion due to solar radiation, such that the structure moves outside the design calculations and hence buckles under load.

When representing this information to the designer it can be fed back in a variety of ways. It can be displayed as sets of listings of the relevant reports with their individual set of indexing terms. It can be fed back as a list of terms requested with their historical failure event details such as failure modes or failure effects listed. Details of environmental aspects can be presented as can operation and use aspects. The list is multi faceted and will clearly expand as users become familiar with the system and grow in confidence with the output from it. Details of output variations and examples are given in later chapters and in the figures associated with the cases described.

| FAIL 1 (FEATURE ANALYSIS INDEX LIST) | | | | | |
|---|---|---|---|---|---|
| RETS REPORT NUMBER | | | | | |
| EQUIPMENT NAME AND TYPE | | | | | |

| DESIGN FUNCTION | | | | | FEATURES |
|---|---|---|---|---|---|
| FUNCTION WHICH FAILED | QUANTITY | PERFORMANCE | TRANSMIT | FORCE | |
| | | | | MOTION | |
| | | | | ENERGY | |
| | | | STORE | ENERGY | |
| | | | | MATERIAL | |
| | QUALITY | ACCURACY / STABILITY | CONTAIN | ENERGY | |
| | | | | MOTION | |
| | | | | MATERIAL | |
| | | | CONTROL | POWER | |
| | | | | VELOCITY | |
| | | | | POSITION | |

| FEATURE GROUP | | | | FEATURES |
|---|---|---|---|---|
| CAUSE | USE | ENVIRONMENT | NATURAL | |
| | | | IMPOSED | |
| | | RESULT OF OPERATION OR MAINTENANCE | | |
| | DELIVERY | | TRANSPORT | |
| | | | STORAGE | |
| | MANUFACTURE | | TEST AND INSPECTION | |
| | | | PROCESS AND PROCEEDURE | |
| | DESIGN | | MEASURED VALUE (SCALE) | |
| | | | GEOMETRIC FORM | |
| | | | MATERIAL | |
| | CONCEPT / PHILOSOPHY | | | |

| CONSEQUENCE (FAILURE MODE OR EVENT ETC.) | MODE | |
|---|---|---|

PREPARED BY :
DATE :

TABLE C.1 FEATURE ANALYSIS INDEX LIST

## APPENDIX D

## FAILURE ASPECTS

### D.1. INTRODUCTION

To paraphrase a well known saying 'Failure, like beauty, is in the eye of the beholder." People's attitude to failure will vary depending on their role. They may be users, producers, or simply detached observers. One group may be interested in the cause of failure, another in the effects of failure.

### D.2. DEFINITION OF FAILURE

Failure is generally defined as 'The termination of the ability of an item to perform a required function' [4.7].

A failure is not necessarily permanent, it may be a transient condition, or repairable, or correctable by an operator. It is a failure irrespective of its impact on the mission.

A failure is critical if it prevents successful completion of a specified mission. Except for the simplest of devices, critical failures are a subset of total Failures and can be identified by fault analysis.

Failure of a specific component or design element may be critical in one application and trivial in another. For example failure of a single bolt on a vehicle braking system has been known to cause a fatal accident. Failure of a similar bolt in a redundant configuration in a structure could well be considered irrelevant.

Any design can be considered as a 'Collage' of components, units and subassemblies. Most of these will be standard form with known characteristics. The components, units etc. which make up a system can usually fail in several different ways. Each of these modes of failure will effect the overall system operation and these effects may be similar or diverse. The individual failure mechanisms are variations of different physical, chemical or dynamic changes caused by either design, manufacture, supply, or use.

Failure itself can be sudden, gradual, partial, total, permanent or intermittent. Its effect on the operation of the system can be catastrophic, inconvenient, or trivial.

It is thus important for engineers and designers to know how items can fail and why. With an awareness of the various failure modes and mechanisms of the particular elements used in a design, a designer can make allowances to compensate for or alleviate these effects.

Knowledge of failure modes and mechanisms is acquired through experience, either of a personal nature or learning of others personal experience. The experience of a designer, engineer or analyst, is a personal variable. To ensure an individual carrying out a failure analysis task has an adequate knowledge of failures, use must be made of the largest corporate body of failure experience possible. A good source is the collected file of failure and defect reports, e.g. 'First Fit' and 'In Service' defect reports.

## D.2 CLASSIFICATION

Failures can be classified by cause, to show the reasons for their occurrence; by effect, to show the various consequences, modes and mechanisms of failure; and by occurrence rate, to show how the risk of failure varies with such factors as time, stress, and environment.

### CAUSE

To classify a failure by cause it must be placed into one of three groups, failure due to;

(i) Creation (Design or manufacture).
(ii) Supply (Storage or delivery).
(iii) Use (Operation or environment).

Within these main groups will be sub-groups, and these have been expanded in Figure D.1 into a tree structure to illustrate the situation more clearly. A full description of the reasoning has been given in Appendix C.

**EFFECT**

In addition to the three failure mode groups defined in appendic C, the effects of failure can be gathered into a number of groups of which the four main groups are:

| | | |
|---|---|---|
| (i) | Mechanical/Structural based failure. | (A) |
| (ii) | Material based failure. | (B) |
| (iii) | Dynamic/Stability based failure. | (C) |
| (iv) | Human/ergomic based failure. | (D) |

Of these:

(i) Will be predominantly material, geometry, stress oriented e.g. fractures, distortion, open and short circuits.

(ii) Will cover all aspects of material property failures, chemical, physical, electrical/magnetic, and in particular, material compatibility within these fields.

(iii) Will include dynamic aspects such as accuracy, control, stability, resonance etc.

(iv) Is complex but must cover human physical limitations, human fallibility, errors, omissions, in both manufacture, training, and operation.

These failure effects (modes and mechanisms) have been arranged as a 'tree' in Figure D.2. As can be seen, this feature tree is an expansion of the subset 'Function' in Figure D.1.

**OCCURRENCE RATE**

In addition to the above groupings failure can be categorised by the item life profile, as manifest in the failure rate/life distribution function, into three main types of failure profile.

These are:

(i) Failure rate decreasing with time, more commonly known as 'Infant Mortality' or 'Burn-in'.

(ii) Failure rate constant, or 'Random' Failure (sometimes known as 'Useful-life').

(iii) Failure rate increasing with time or 'Wear-out' failure.

Traditionally these three profiles (Figure D.3) are merged to give the familiar 'Bathtub' curve (Figure D.4)

**INFANT MORTALITY**

Taking these three periods in turn, the first, infant mortality, initially has a high failure rate. This rapidly decreases to a stable value as all the weak and faulty items are eliminated. These failures are due to such things as manufacturing errors, damage incurred during transport, storage, and installation. In addition some early life failures are caused by installation errors, operator errors, misuse of equipment due to lack of training or experience.

Typical of infant mortality failures are:

(1) Assembly errors: Items missing or incorrectly positioned, incorrect assembly sequence, wrong items used.

(2) Connection errors: Poor quality joints - welds, soldered joints, loose bolts and fasteners, poor seals, poor bonds, damaged connectors, overstressed bolts.

(3) Cleanliness errors: Dirt or oil contamination, surface contamination, chemical contamination or chemical impurities, dirty castings, poor cleaning before/between surface processing (plating, etching, anodizing, bonding, diffusing, etc.). Oxidation or corrosion through contamination.

(4) Fabrication errors: Incorrect machining, cracks, voids, delamination, incorrect materials, distortion, poor quality materials.

**RANDOM FAILURES**

The second period, that of constant failure rate, or Random Failure, is the traditional domain of the Reliability specialist It can be modelled easily by the exponential failure distribution and, if the design and manufacture has been carried out correctly, this is a valid analysis. In addition, if an equipment is being repaired and returned to service, then the failure rate will tend to become random irrespective of the failure rates profiles of the individual elements within the equipment. Failures in this period tend to be stress related. Failures are also assumed to occur when the imposed stress exceeds the strength of the item. This simple relationship is not always sufficient, in some cases the time/energy integral becomes the dominant factor. Typical examples are the fracture time-energy relationship (D.3) used in brittle fractures and fatigue cracking/ failure, and the time-power integral relationship (D.3) used for estimating solid state electronic component failures (I.C's, transistors, diodes). Assuming a stress/strength relationship holds, then Figure D.5 gives the situation as normally presented. The effects of loading roughness (D.4) and quality are clearly seen. Figure D.5d would seem to give a good prospect of success with a well defined and relatively smooth load combined with a high quality component typical of high reliability components (i.e. a very narrow distribution of strength around the mean value). However, a small mistake in the design calculations or a drop in manufacturing quality could lead to a disastrous situation with a very high probability of failure. In the overlap region shown in the different figures the probability of failure is not simply obtained by the multiplication formula.

Hence:

$$P \neq P_o * P_s$$

The situation is that of conditional probability; the probability of stress occurring in an item of strength S where:

$$O_i \geq S_i$$

and with a failure resulting if the stress-time integral is sufficient to cause a failure. This problem can be modelled more explicitly using a 3-dimensional model. The effects are more clearly seen in Figure D.6 and show that the relationship is that of a cusp catastrophe.

As the quality level in components rises, there is also a corresponding rise in the susceptibility to imperfections. Hence the problems noted above for high reliability components.

In view of the above comments it is apparent that the stress ratio of load:strength is the biggest single factor influencing random failures. Careful stressing and derating will have the greatest influence on this group of failures.

**WEAR-OUT FAILURES**

This group of failures covers all time dependent failure modes. Time dependent failures fall into two principle groups:

(1) Mechanical Time Dependent Failures - Frictional wear, fatigue, leakage, plastic shrinkage/ cracking and cranying, delamination, insulation breakdown or leakage, water absorption, thermal ageing.

(2) Material Time Dependent Failures - Corrosion, exhaustion of sacrificial anodes, chemical degradation, decomposition, rotting, chemical diffusion, ion migration, oxidation, grain/crystal growth, bacterial and organic growth, environmental contamination, metal migration (in IC´s), material phase changes (at high temperature) radiation damage.

Typical items exhibiting wear-out failure would be:

(a) Those items which move relative to their surroundings e.g. Bearings, seals, guides, wipers, missing blades, switches, gears, transmission belts and chains.

(b) Those items subject to chemical affects over time, e.g. sacrificial anodes, protective plating, fabrics in corrosive/severe environment, ICs at high temperature, some plastics in moist atmospheres, organic material oxidation and ageing (rubber/plastics).

(c) Those items subject to cyclical load conditions either from mechanical or thermal stresses.

**D.3 EFFECTS OF MAINTENANCE**

A problem peculiar to maintained items is that of maintenance induced failure. It has been found that some complex equipments have a failure pdf of hyper-exponential form. On analysis it is apparent that a large number of the failures occur within a short time of a maintenance/repair action.

These failures are due to:

(a) Human fallibility in the form of errors, mistakes and omissions, and difficulties in matching the actual repair to the required repair.

(b) Disturbance of the 'Status Quo' as evidenced by disturbance to seals, introduction of dirt and foreign bodies, loosening of dirt in piped systems, disturbance of electrical connectors, movement of trimmers and adjusters etc.

In this situation many of the failures are unnecessary and could be avoided. The failure rate will be much higher than usual or than expected.

To avoid this situation requires attention to the maintenance aspects in design and in the training of operators and maintainers.

**D.4 FAILURE CHARACTERISTICS (see also Chapter 4)**

Failure itself can be a deterministic event i.e a failure has/has not occurred. However the probability of a failure occurring is a stochastic function dependant on several variables. These variables can be grouped under environmental characteristics and design characteristics. The former will include the environment imposed as a result of the duty demanded, and the external environment of the items surroundings. The latter will cover the various characteristics of the design element such as the material, its geometry, the various processes of manufacture, and the functions the item has to perform. Many of these parameters are stochastic variables and when combined will result in a multi-valued distribution for the probability of failure.

In any design certain features will dominate the failure pattern Each design feature will have a dominant failure characteristic, for example a plain bearing will have a 'wear out' characteristic, and electric connector may have a 'burn in' characteristic. The failure characteristics of these dominant features will determine the failure characteristics of the design and hence the failure curve for the design. This failure characteristic is normally plotted as a two dimensional figure and is called the 'hazard rate' or instantaneous failure rate, or force of mortality. In reality the figure is a three dimensional model, the third axis being a duty function. However the characteristics are more readily seen when plotted on a Survival curve.

Figure D.7 shows a typical infant mortality or 'burn in' curve. Figure D.7(a) shows how the curve may change with increasing duty and give a stable characteristic. The designer can use his trials results with some confidence to predict failure rates and safety levels.

Figure D.4(b) shows a similar curve, but in this case as the duty function approaches the maximum value then there is a rapid change in the failure characteristic. This can be linked to the Zener effect in semiconductors. Thus were a designer to operate close to this maximum value, a small variation in manufacturing quality or a design mis-calculation could have disastrous results. If such a mistake occurs there could be a total failure of the whole batch. Another classic case is the S-N curve for fatigue in materials. This is shown in Figure D.8(a).[D.1].

Figure D.8(b) shows the curve with the hazard rate function included. In the figure shown the region from S to S is a contentious region. It has been postulated [D.2] that in this region there is a discontinuity in the S-N curve. What is certain is that the hazard rate curve does not conform to a normal distribution in this area.

If one accepts the case of a failure occurring because the design parameters have quite clearly been exceeded, then the remaining failures will be covered by the situation where the failure should not have occurred but did occur. In general this will be a combination of the probabilities of failure due to these various parameters.

With the case of two possible states, i.e. failure/survival, coexisting at the same stress level then this can be described by catastrophe theory. Which particular catastrophe model is relevant to any particular failure situation is a matter for conjecture. However it can be shown that the first four catastrophe models described by Thom [6.7], can be combined to give a close approximation to an exponential model. The combination is particularly accurate over the domain $-1<x<0$ such that

$$\sum_{i=1}^{4} Gi\ (x,u,v,w,t) \simeq e^{x} - 1 \qquad (1)$$

for set values of u,v,w,t, (u=4, v=15, w=41, t=60). The error being typically less than 1% .

Now from reliability theory [4.8],

$$R(t) = 1 - F(t) = e^{-\lambda t} \quad \text{for the random failure case}$$

Hence

$$-F(t) = e^{-\lambda t} - 1 \qquad (2)$$

Clearly there would seem to be some relationship between (1) and (2), though this may well be fortuitous i.e.

$$F(x) \quad \sum_{i=1}^{4} Gi(\lambda x) \qquad (3)$$

for the set values of u,v,w,t.v

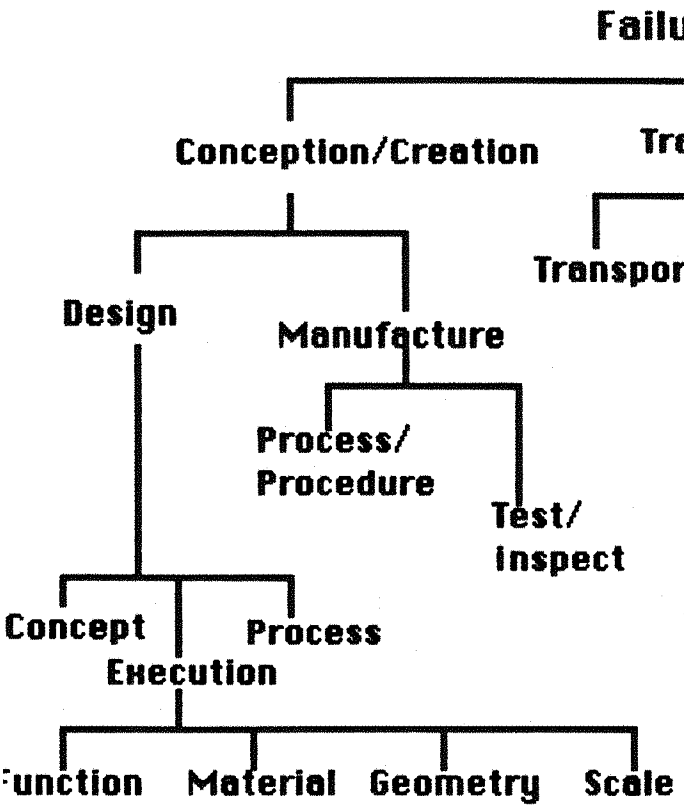



Figure D.1 Failure Cause Feature Tree

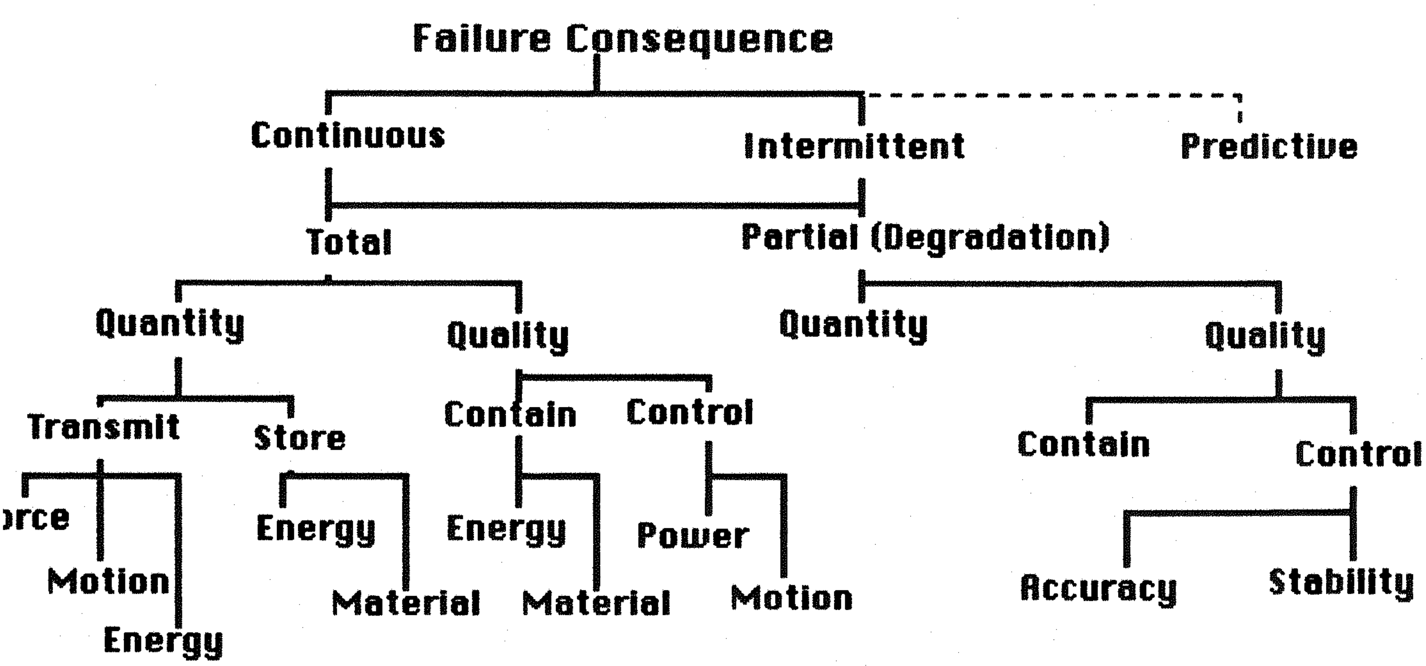



Figure D.2 Failure Consequence Feature Tree

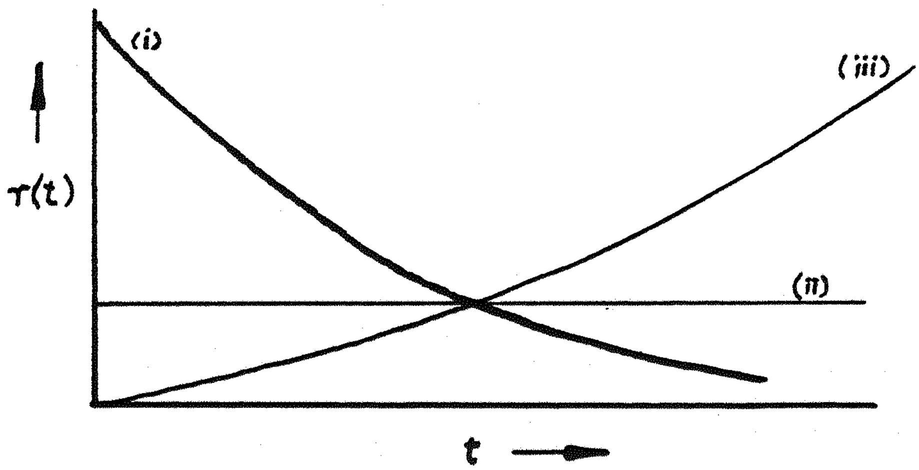



FIG. D3 FAILURE RATE PROFILES

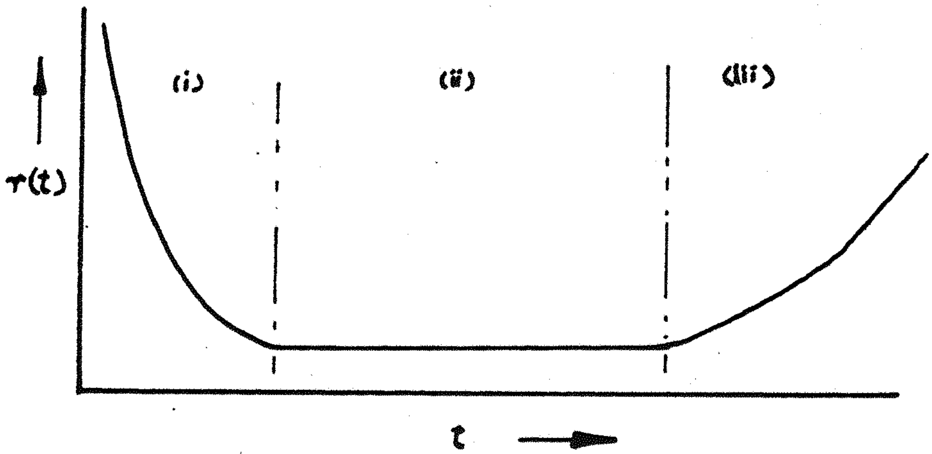



FIG. D4 'BATHTUB' CURVE

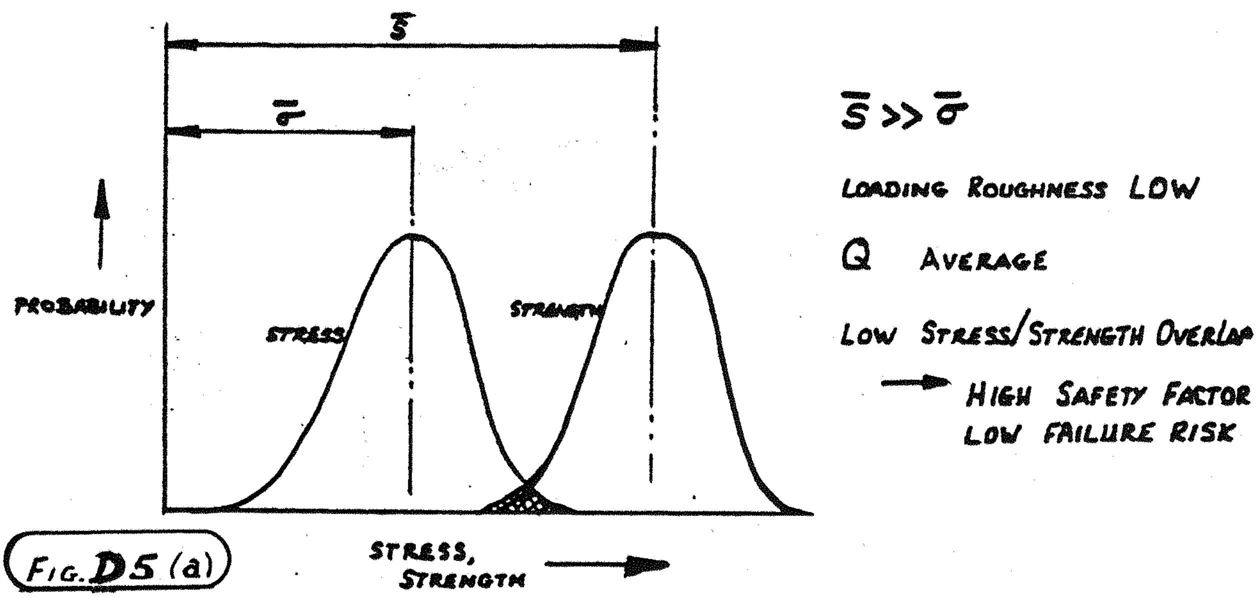
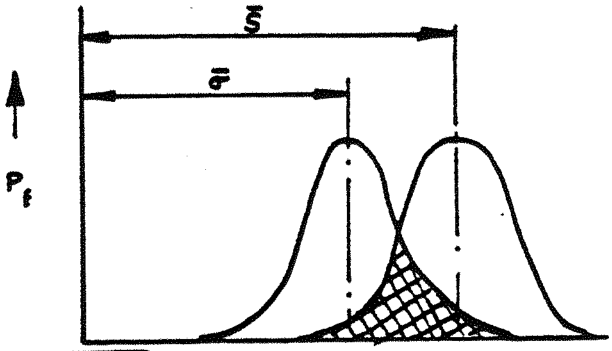



FIG. D5 (a)

FIG D5 — STRESS/STRENGTH LOADING ROUGHNESS CURVES FOR DIFFERENT PRODUCT QUALITY PROFILES




$\bar{S} > \bar{\sigma}$

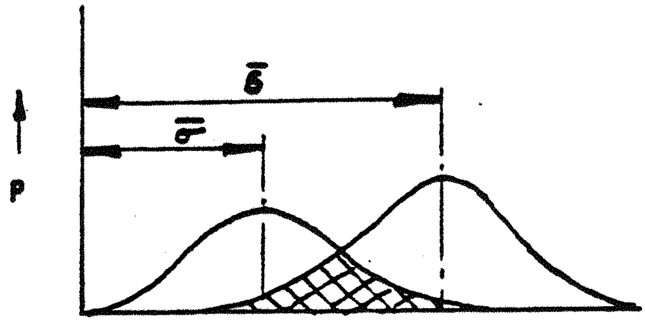
LOADING ROUGHNESS HIGH

Q AVERAGE

LARGE $P_s/P_\sigma$ OVERLAP

⇨ LOW SAFETY FACTOR
HIGH FAILURE RISK

FIG D.5(b) $S, \sigma$ →




$\bar{S} >> \bar{\sigma}$

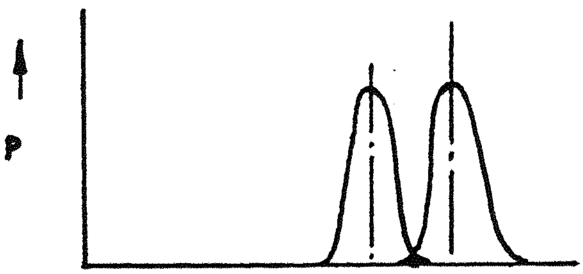
L.R. HIGH

Q LOW

LARGE $P_s/P_\sigma$ OVERLAP

⇨ HIGH S.F.
HIGH F.R.

FIG D.5(c) $S, \sigma$ →




$\bar{S} > \bar{\sigma}$

L.R. LOW

Q HIGH

SMALL $P_s/P_\sigma$ OVERLAP

⇨ LOW S.F.
LOW F.R.

FIG D.5(d) $S, \sigma$ —

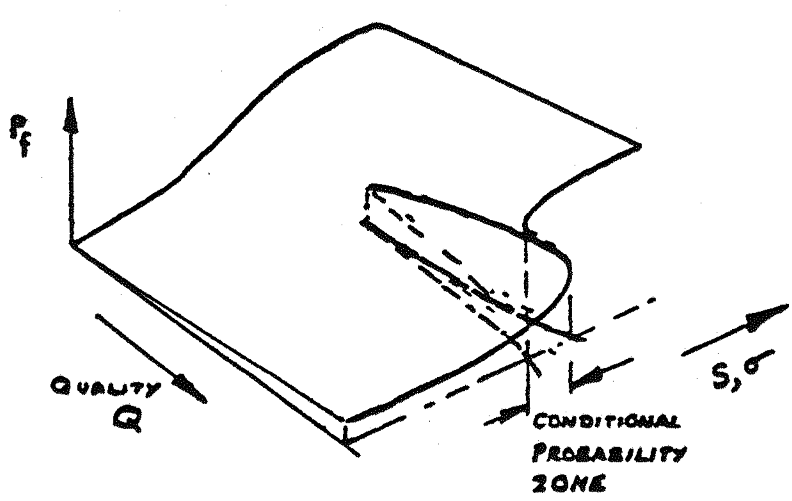



FIG D.6

STRESS/STRENGTH vs. QUALITY
FOR FIXED LOADING ROUGHNESS

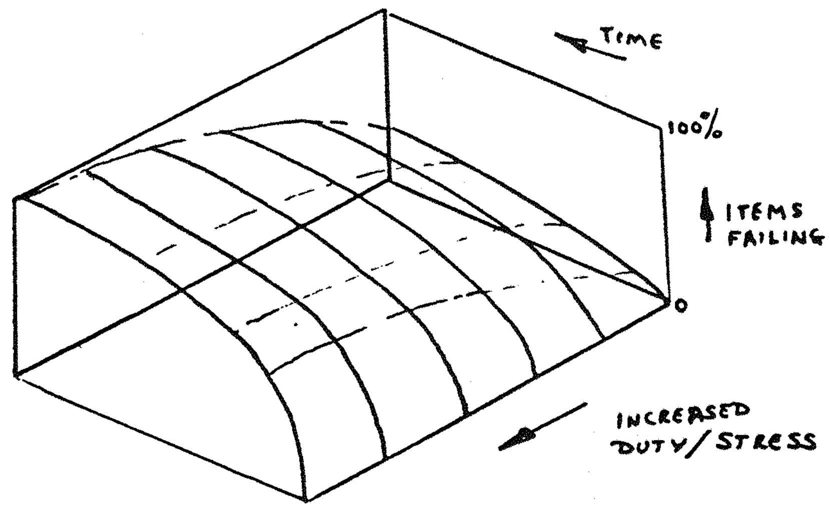



FIGURE D.7(a) INFANT MORTALITY
STABLE CHARACTERISTIC

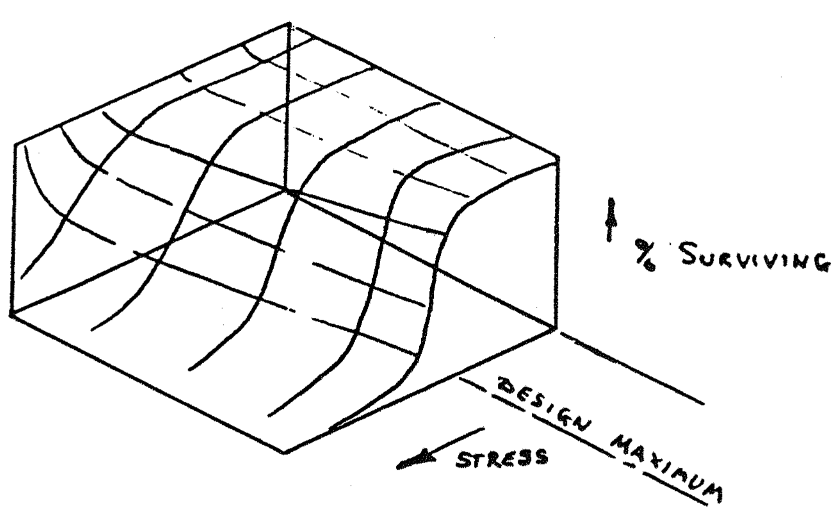



FIGURE D 7.(b) CATASTROPHIC CHARACTERISTIC

FIGURE D7 FAILURE CHARACTERISTICS

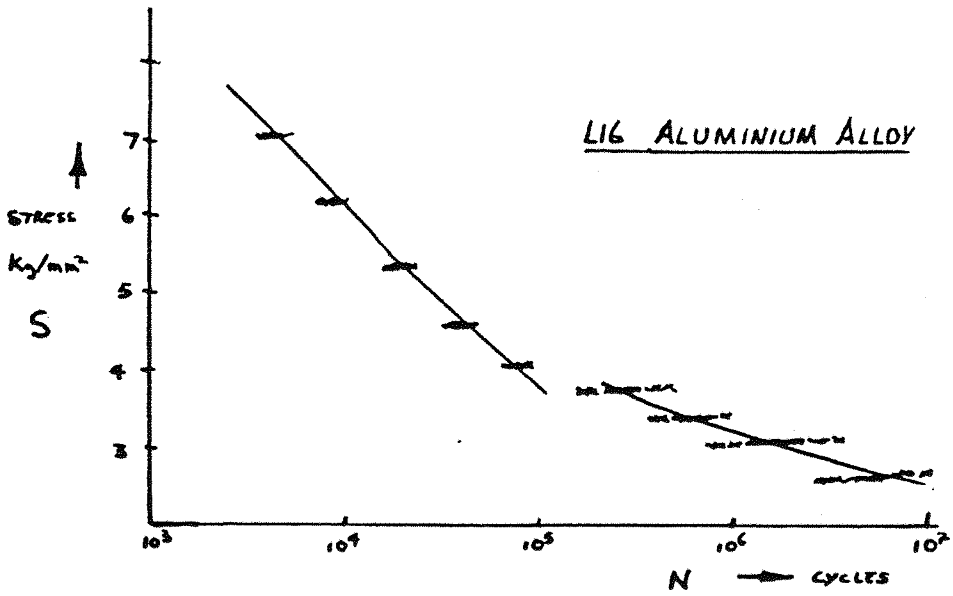



FIGURE D8(a) TYPICAL S/N CURVE

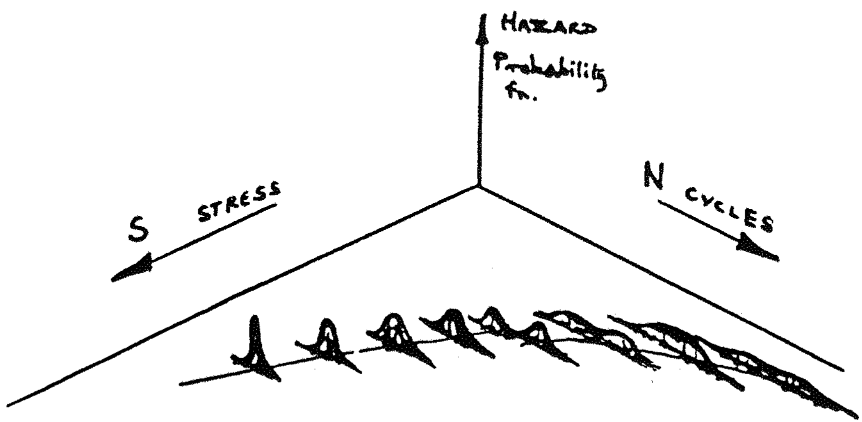



FIGURE D8(b) S/N CURVE HAZARD FUNCTION.

FIGURE D8 FAILURE ASPECTS RELATED TO FATIGUE

## APPENDIX E

## DICTIONARY OF TERMS USED IN THE THESAURUS

## LISTING OF FEATURE GROUPS AND FEATURE OCCURRENCE RATES IN THE INDEX

The following set of descriptors was created to index the set of failure records held by the Royal Engineers Technical Service. The data set covers records of problems and failures that have occurred in the experience of the Royal Engineers with their civil engineering equipment. The index created was created for the use of the engineers and designers working on this equipment and new design equipment at MVEE.

This appendix contains the set of descriptors in alpha-numeric order, details of the groups within which they are arranged, and their occurrence rates in the index. This has been expressed in terms of numbers of occurrences and occurrence rate per $10^6$ hours.

| Conversion number | FEATURE | Design: Concept/Philosophy | Design: Process | Design: Product: Function | Design: Product: Material | Design: Product: Geometry | Design: Product: Scale | Manufacture: Process/Procedure | Manufacture: Test and Inspection | Transition: Storage | Transition: Transport | Use: Operating Procedure | Use: Environment: Natural Environment | Use: Environment: Imposed Environment | FEATURE DEFINITION (where required) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | | | | | | | | | | | | | | Rubbing damage to surface: a roughening process. |
| 2 | ABRADE | | x | | | | | | | | | | | x | A roughening process: rubbing damage to a surface during use. |
| 3 | ACCEPT | x | | | | | x | | x | | | | | | The question of acceptibility has been raised. |
| 4 | ACCESS | x | | x | | x | | | | | | x | | | Access with respect to manufacture and use. |
| 5 | ACCESSORY | | | | | | | | | | | x | | | Item additional to main equipment to enhance performance or ability. |
| 6 | ADAPTOR | | | x | | x | x | | | | | x | | | Item permitting coupling of Geometric/Scale dissimilar but functionally similar units. |
| 7 | ADHES*-(BOND) | | x | x | x | | | x | | | | | | | Action of bonding or material used for bonding (an adhesive) or property of |
| 8 | ADJUST* | x | | | | x | ? | | | | | x | | | Ability/requirement to vary Geometry and other Scalar Values. |
| 9 | AGE | x | ? | | | | | | | | | | | x | A period of time as in process, or expected life. |
| 10 | AIR | | | | x | | | | | | | | | x | Process fluid: Environment. |
| 11 | ALIGNMENT | x | x | x | | x | | | | | | x | | | Concept process and function of relative position between geometric axes. |
| 12 | ALLEN | | | | | | | | | | | | | | Type of socket lead screw. |
| 13 | ALUMINIUM | | | | x | | | | | | | | | | The metal or any of its alloys. - Generic term for material family. |
| 14 | ANCHOR | | x | x | | ? | | | | | | x | | | Process or function of securing by detachable means. |
| 15 | ANGLE | | | | x | x | | | | | | | | | Geometry: or Material form. |
| 16 | ANITFREEZE | | | x | x | | | | | | | | | | Chemical used to prevent liquid freezing at low temperatures. |
| 17 | APB | | | | | | | | | | | | | | Air Portable Bridge. |
| 18 | ARMOUR | | | x | x | | | | | | | | | | Material giving protections against impact. |
| 19 | ARTICULATOR | | | ? | | x | | | | | | | | | Equipment name for unit which changes bridge geometry (usually an hydraulic jack) |
| 20 | ASPHALTMIXER | | | ? | | | | | | | | | | | Equipment type, name describing use. |
| 21 | ASSEMBL* | x | x | x | | x | | x | x | | | x | | | Procedure of grouping and connecting items and components to produce complete equipment |
| 22 | ASYMETR* | | | | | x | | | x | | | x | | | Geometric property of asymetry. |
| 23 | ATTACHMENT | | | x | | x | | | | | | x | | | Item additional to but fastened to main equipment to enhance performance or ability. |
| 24 | ATTITUDE | x | | | | x | | | x | | | x | | | Geometric function representing relative orientation. |
| 25 | AXLE | | | ? | | | | | | | | | | | Component name describing function. |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 26 | BACKPLATE | | | | | | | | | | | | | | Component specifically used for brake backplates. |
| 27 | BALL | | | | | x | ? | | | | | | | | Component with spherical form. |
| 28 | BAR | | | | x | x | | | | | | | | | Material supplied in solid section form. |
| 29 | BASE | | | ? | | x | | | | | | | | | Component with function of support and/or location. |
| 30 | BAYONET | | | ? | | x | | | | | | | | | Dismountable connector with male/female geometry. |
| 31 | BEAM | | | | | | ? | | | | | | | | Structural member loaded normal to its axis. |
| 32 | BEARING | | | x | | x | | | | | | | | | A structural member allowing relative movement between c. |
| 33 | BELT | | | | | x | | | | | | | | | 'V' belt or flat belt or toothed belt; a flexible member for transmitting a force. |
| 34 | BEND/DISTORT | | | x | | x | | x | x | | | | | | Failure mode resulting in a change in component shape. |
| 35 | BENDIX | | | | | x | | | | | | | | | Trade name for Helical shafts/Pinion engagement mechanism. |
| 36 | BEVEL | | | | | x | | | | | | | | | Geometric form oblique to principal axis or surface. |
| 37 | BITUMEN | | | | x | | | | | | | | | | Material family. |
| 38 | BLEED* | | x | x | | | | | | | | | | | Process of purging a system; function of removing unwanted fluid. |
| 39 | BOAT | | | | | | | | | | | | | | Waterborne crafts for conveying men/equipment. |
| 40 | BOLT | | x | | | ? | | | | | | | | | Screwed fastener of specific geometery: action of securing using bolts. |
| 41 | BOW | | | | | x | | | | | | | | | Bow of boat. |
| 42 | BOWDEN | | | ? | | x | | | | | | | | | Generic term for all forms of sheathed cable where reaction is provided by the sheath. |
| 43 | BP | | | ? | | x | | | | | | | | | Bottom Panel -component from M.G.B. |
| 44 | BRACE | | | x | | x | | x | | | | | | | Action of bracing or the actual component with this function. |
| 45 | BRACKET | | | | | x | | | | | | | | | Minor structure for attaching subassembly or component to main structure. |
| 46 | BRAKE/ING | | | x | | | | | | | | | | | Component for dissipating kinetic energy. |
| 47 | BRASS | | | | x | | | | | | | | | | |
| 48 | BRIGHT | | | | | | | | | | | | | | Shiny surface. |
| 49 | BSB | | | | | | | | | | | | | | Bank Seat Beam - M.G.B. component. |
| 50 | BUCKLE | | | x | | x | | | | | | | | | Failure mode : component used with flexible straps as a fastener. |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 51 | CABLE | | | | x | | | | | | | | | | Steel Cable used as a flexible tensile member. |
| 52 | CADMIUM | | | | x | | | | | | | | | | |
| 53 | CANVAS | | | | x | | | | | | | | | | |
| 54 | CAPACITY | x | | | | | x | | x | | | | | | Quantitative measure. |
| 55 | CARBURRETOR | | | | | | | | | | | | | | Components. |
| 56 | CARGO | | | | | | | | | | | x | | | |
| 57 | CASING | | | | | x | | | | | | | | | Outer shell of assembly - as in Engine - or Gearbox. |
| 58 | CASTING | | | | x | | | x | | | | | | | |
| 59 | CASTIRON | | | | x | | | | | | | | | | |
| 60 | CAVITY | | | | | x | | | | | | | | x | A hollow which is totally or partially enclosed. |
| 61 | CHAIN | | | | x | x | | | | | | | | | Renolds type or traditional link chain. |
| 62 | CHANNEL | | | | x | x | | | | | | | | | Material in specific cross section form. |
| 63 | CHROMATE | | | | x | | | | | | | | | | Chrome material in form for surface application. |
| 64 | CLAMP | | x | x | | x | | | | | | x | | | Action of or item for clamping. |
| 65 | CLEAN | | x | | | | | | | | | x | | x | Action of or requirement for cleaning or convene - dirty (as in hydraulics). |
| 66 | CLEARANCE | | | | | x | x | | x | | | x | | x | Geometric property,including all cases of fouling where clearance is inadequate. |
| 67 | CLIP | | | x | | x | | | | | | | | | Action and item. |
| 68 | CLOG | | | | | | | | | | | x | | x | Unintended obstruction of fluid flow. |
| 69 | CLUTCH | | | x | | | | | | | | | | | Component for transferring torque. |
| 70 | COIL | | | x | | | | | | | | | | | The action of coiling a cable on a drum; A coil of wire or rope. |
| 71 | COILING | | | ? | | | | | | | | | | | Failure mode with cable when cable takes uninteded coil form. |
| 72 | COMBUSTION | | | | | | | | | | | | | x | Oxidation process at elevated temperature. |
| 73 | COMPRESS | | | x | | x | | | x | | | | | x | To put a fluid or structural member under compression or machine with this function. |
| 74 | CONCRETEMIXER | | | | | | | | | | | | | | Generic term for equipment - Describes function of equipment. |
| 75 | CONCRETEPOKER | | | | | | | | | | | | | | Generic term for equipment - Describes function of equipment. |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 76 | CONDUIT | | | | | x | | | | | | | | | Tube for wires etc to passsalong/lie in - A duct. |
| 77 | CONNECT | | | x | | x | | x | | | | | | | Generic term for the action of connecting of any item with this function. |
| 78 | CONROD | | | x | | | | | | | | | | | |
| 79 | CONTAIN | | | x | | x | | x | ? | | | | | x | Function of containing of items with this function. |
| 80 | CONTROL | | | x | | | | x | x | | | x | | | Function of controlling of item with this function. |
| 81 | CORROSION | | | | | | | | x | x | x | x | | | Failure mode. |
| 82 | COUPLING | | | x | | x | | | | | | | | | Similar to connector but used when components to be connected act in Unison e.g. hydraulics |
| 83 | COVER | | | x | | x | | x | | | x | | | x | Action and item. |
| 84 | CRACK | | | | | x | | | x | x | x | x | | | Failure mode. |
| 85 | CRANE | | | | | | | | | | | | | | Generic term for lifting device which suspends load from above. |
| 86 | CRANK | | | ? | | x | | | | | | | | | Components for changing force into moment and vie versa. |
| 87 | CRUSH | | | x | | x | | x | x | x | x | x | | | Failure mode. |
| 88 | CRUSHER | | | | | | | | | | | | | | Generic term for Rock Crushers (Equipment type). |
| 89 | CYCLIC | | | ? | | ? | | | | | | | | x | |
| 90 | CYLINDER | | | | | x | | | | | | | | | Geometric form. |
| 91 | CYLINDERHEAD | | | | | | | | | | | | | | Component of reciprocating engine. |
| 92 | DAMAGE | | | | | | | | x | x | x | x | | | |
| 93 | DAMP | | | | | | | | | x | | x | x | | See Moisture? |
| 94 | DAMPING | x | x | x | | | x | | | | | x | | | Energy absorbing function of components/items with this function. |
| 95 | DANDO | | | | | | | | | | | | | | Manufacturers Name. |
| 96 | DECK | | | | | x | | | | | | | | | |
| 97 | DESERT | | | | | | | | | x | x | | x | | Arid environment with grit and solar radiation present. |
| 98 | DESIGN | | | | | | | | | | | | | | Used when failure is believed to be direct result of design error. |
| 99 | DIESEL | | | | | | | | | | | | | | Type of I/C engine : Type of fuel. |
| 100 | DIFFERENTIAL | | | ? | | | | | | | | | | | Transmission Component with function allowing different relative motion. |

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| 101 | DIMENSION | | | | | x | x | | x | | | | | | Any value describing size. |
| 102 | DIRECTION | x | | | | x | | | x | | x | x | | | Orientation with respect to a datum. |
| 103 | DISPOS* | | | x | | | | | | x | | x | | | Disposable or action of disposing. |
| 104 | DISTORT | | | | | x | | x | x | | x | x | | | Taking on an unintended shape. |
| 105 | DOOR | | | | | | | | | | | | | | Any form of access panel. |
| 106 | DRAWBAR | | | | | | | | | | | | | | The link used for towing. |
| 107 | DRIER | | | x | | | | | | | | | | | Dehumidifier or similar. |
| 108 | DRILL | | | x | | | | x | | | | | | | Action of drilling or Machine for drilling. |
| 109 | DRILLRIG | | | | | | | | | | | | | | Soil drill or similar. |
| 110 | DRUM | | | | | x | | | | | | | | | A hollow cylinder. |
| 111 | EARTH | | | x | | | | x | x | | | | x | | Action of making an electrical earth. |
| 112 | EDGE | | | | | x | | | | | | | | | Boundary of a surface. |
| 113 | ELECTRIC | | | | | | | | | | | | | x | Related to electricity - Generic function. |
| 114 | ENGINE | | | | | | | | | | | | | | Internal combustion engine. |
| 115 | EPOXY | | x | | x | | | | | | | | | | Epoxy resin. |
| 116 | EWBB | | | | | | | | | | | | | | Extra wide Bailey Bridge. |
| 117 | EXHAUST | | | x | | | | | | | | x | | x | System for removing gases. |
| 118 | EXPANSION | | | | | | x | x | x | | | x | | | |
| 119 | EXPENDABLE | x | | | | | | | | x | | x | | | Item which is not intended to be recoverable or repairable.. |
| 120 | EXTENSION | x | | x | | x | x | | x | | | x | | | Relating to change in Physical length. |
| 121 | EXTRUSION | | x | | x | x | | | | | | | | | Material in extruded form/Process of extrusion. |
| 122 | EYE | | | | | x | | | | | | | | | As in Eye bolt or Fabric/Rope eye. |
| 123 | FABRIC | | | | x | | | | | | | | | | Flexible woven material, may be (reinforced) rubber sheet. |
| 124 | FASTEN | | x | x | ? | | | | ? | | | | | | Related to action of fastening or to item fastener. |
| 125 | FATIGUE | | | | | | | | | | | x | | | Failure mode. |

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| 126 | FB | | | | | | | | | | | | x | | Foreign body - Debris - dirt etc. |
| 127 | FENDER | | | x | | | | | | | | | | | Flexible collison guard around Gunwhale of boat. |
| 128 | FERRULE | | | | | x | | | | | | | | | Tubular type fitting for use over end of item - e.g. cable, handle, cable sheath. |
| 129 | FILLET | | | | | x | | | | | | | | | Generally triangular shaped infill : A weld with a planar surface défect. |
| 130 | FILTER | | x | x | | | | | | | | x | | x | Item with function or action of separating out dissimilar fluids/Suspension/Materials. |
| 131 | FIRE | | | | | | | | | | | | x | | |
| 132 | FLAKING | | | | | | | | x | x | | x | | | Action of surface separating from main structure in flakes. |
| 133 | FLANGE | | | | | x | | x | | | | x | | | Action of producing a flange and the geometric feature of a projecting flat rim/collar |
| 134 | FLEXIBLE | x | | | x | | | | | | | x | | x | |
| 135 | FLIMSY | x | | | | | | | ? | | | | | | Inadequate rigidity. |
| 136 | FLOAT | | | x | | | | | | | | | | | A bouyant component. |
| 137 | FLYWHEEL | | | ? | | ? | | | | | | | | | Device for storing kinetic energy. |
| 138 | FORGING | | x | | ? | | | | | | | | | | Item produced by the forging process. |
| 139 | FRACTURE | | | | | | | | | | | | | | Failure mode. |
| 140 | FRAME | | | | | x | | | | | | | | | A Geometrically "rigid" structure. |
| 141 | FRICTION | x | | | | | | | | | | x | | x | |
| 142 | FUEL | | | | x | | | | | | | x | | x | |
| 143 | FULL | | | | | | | | | | | x | | | |
| 144 | GAS | | | | x | | | | | | | x | x | | |
| 145 | GAUGE | | | ? | | | x | | | | | x | | | The item of equipment/The action of gauging or measuring. |
| 146 | GEAR | | | | | | | | | | | | | | A toothed component for transmitting rotary motion. |
| 147 | GEARBOX | | | | | | | | | | | | | | Unit for transmitting rotary motion by use of gears. |
| 148 | GEARWHEEL | | | | | x | | | | | | | | | As for gear. |
| 149 | GENERATOR | | | | | | | | | | | | | | Electrical generator; also includes alternators. |
| 150 | GEOMETRY | | | | | x | | | x | | | | | | |

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| 151 | GIRDER | | | | x | x | | | | | | | | | Any fabricated Beam. |
| 152 | GLASS | | | | x | | | | | | | | | | |
| 153 | GRAVELWASHER | | | | | | | | | | | | | | Item of equipment. |
| 154 | GREASE | | | | x | | | | | x | | x | | x | Material and action of applying grease. |
| 155 | GRIND | | x | | | | | | | | | | | | The action of cutting or removing material by an abrasive process. |
| 156 | GRIP | | | x | | | | | | | x | x | | | A measure of ability to transmit a force by use of a clamping force perpendicular to the main force and the effects of friction between the clamped surfaces. |
| 157 | GRP | | | | x | | | | | | | | | | |
| 158 | GUARD | x | | x | | | | | | | x | x | | | Action of Guarding and items with that function. |
| 159 | GUIDE | x | x | x | | | | | | | | x | | | Positioning process and item with that function. |
| 160 | GUSSETPLATE | | | | | | x | | | | | | | | Stiffening plate generally triangular in shape. |
| 161 | HAMMER | | | ? | | | | | x | | | | | | Item of equipment (road hammer) and action of hammering. |
| 162 | HANDBOOK | | | | | | | | | | | x | | | Any document giving instructions for operating and/or servicing equipment. |
| 163 | HANDLE | x | | | | | | | | | | x | | x | Item and any function related to hand/manual operation. |
| 164 | HANDRAIL | | | ? | | | | | | | | | | | Any safety rail used for preventing accidental access or a rail used as a handhold to assist intentional access. |
| 165 | HARDBOARD | | | | x | | | | | | | | | | Any material resembling high quality paperboard. |
| 166 | HATCH | | | | | | | | | | | | | | Access opening in horizontal surface with a covering door or lid. |
| 167 | HEALTH | x | | | | | | | | | | x | | | Related to health of user. |
| 168 | HEAVYFERRY | | | | | | | | | | | | | | Equipment type. |
| 169 | HINGE | | | ? | | x | | | | | | | | | A mechanical joint allowing rotational movement of less than 360°. |
| 170 | HITEMP | x | | | | | x | | x | x | x | x | | x | Anything related to temperature - high; low; abnormal; or temperature dependant. |
| 171 | HOLE | | | | | x | | | | | | | | | |
| 172 | HOOK | | | x | | x | | | | | | | | | |
| 173 | HOPPER | | | | | x | | | | | | | | | A Container supplying particulate material by gravity. |
| 174 | HOSE | | | | | | | | | | | | | | Flexible hose for carrying fluids. |
| 175 | HOTTEAR | | | | | | | | | | | | | | Failure mode experienced during casting/welding. |

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| 176 | HOUSING | | | x | | | | | | | | | | | An enclosure with the function of protecting or locating. |
| 177 | HTS | | | | x | | | | | | | | | | High tensile steel. |
| 178 | HUB | | | x | | x | | | | | | | | | Central part of a wheel structure with function of load transmission between wheel and axle |
| 179 | HULL | | | x | | | | | | | | | | | The main bouyant structure of a boat or pontoon. |
| 180 | HYDRAULIC | | | | x | | | | | | | | | x | Related to hydraulic systems - Implies presence of hydraulic fluids. |
| 181 | IDENTIFICATION | x | | x | | | x | | x | x | x | x | | | Anything which contributes to the identification of a component. |
| 182 | IMPACT | | | | | | | | | | x | x | | x | Use shock. |
| 183 | INCORRECT | | | | | | | | x | | | x | | | |
| 184 | INFLATE | x | x | x | | | x | | | | ? | x | | x | Action of inflation; Ability to be inflated etc. as in inflatable boat. |
| 185 | INHIBIT | x | x | x | x | | | | | x | x | | | x | Action of inhibiting and material used for inhibiting. |
| 186 | INJECTOR | | | | | | | | | | | | | | Diesel injector. |
| 187 | INSERT | x | x | | | | | | | | | x | | | Action of inserting and item inserted. |
| 188 | INSPECT | x | x | | | | | | x | x | | ? | | | If inspection is required or defects found as a result of inspection. |
| 189 | INSTRUCTION | x | x | | | | | | | x | | x | | | If instruction is required or has been issued as a result of failure. |
| 190 | INTERNAL | | | | | x | | | | x | | | | x | Enclosed within a structure. |
| 191 | INTERRUPT | | x | | | x | x | | | | | x | | x | Any non continuous operation or process. Particularly used as a qualifier welding process. |
| 192 | JACK | | | x | | x | | | | | | x | | | Item of equipment and action of jacking. |
| 193 | JACKPOST | | | | | | | | | | | | | | Item of equipment. |
| 194 | JAM | | | x | | | | | | | x | x | | x | Action of jamming. |
| 195 | JAW | | | x | | x | | | | | | | | | One of a pair or group of joined items in which the parts to be joined have inter-linking members with two or more embracing similar members on the adjacent part. |
| 196 | JOINT | x | x | x | | x | | | | | | | | | Action of item with function. |
| 197 | JOURNAL | | | | | x | | | | | | | | | As in journal bearing. |
| 198 | KERB | | | | | | | | | | | | | | Guide or constraint for traffic. |

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| 199 | KEY | | | | | x | | x | | | | | | | As used in keyways. |
| 200 | KIT | | | | | | | | | | | | | | A group of components to be assembled. |
| 201 | LAMP | | | | | | | | | | | | | | Accessory on Vehicle - as in road use. |
| 202 | LASHING | x | | | | | | | | | x | | | | Securing technique using a flexible retainer. |
| 203 | LAUNCH | | x | x | | | | | | | | x | | | Action and any part or process related to launching. |
| 204 | LAUNCHINGNOSE | | x | | | | | | | | | | | | Item of equipment. |
| 205 | LEAK | | | | | | | | | x | | x | | | Use seal. |
| 206 | LEVEL | | x | x | | x | x | | | | | x | | | Action of levelling and also positional requirements to horizontal datum. |
| 207 | LEVER | | | x | | x | | ? | | | | | | | Action of levering of item. |
| 208 | LEVERAGE | | | | | x | ? | | | | | | | | Property of a lever. |
| 209 | LIFE | x | | | | | | | x | x | | x | | | As in expected life as opposed to 'Agl'; Preferred term. |
| 210 | LIFT | | x | x | | | x | | | | | x | | | Action of lifting: an elevating platform. |
| 211 | LIGHT | x | | | | | | | | | | | | | Item of equipment for illumination. |
| 212 | LIGHTTOWER | | | | | | | | | | | | | | Item of equipment. |
| 213 | LIGHTWEIGHT | | | | | | | | | | | | | | Designed and built to minimum weight constraints. |
| 214 | LIMITATION | x | | | | | ? | | x | | | x | | | When a limit has been defined or needs to be defined w.r.t. Operation/Manufacture. |
| 215 | LINER | | | | | x | | | | | | | | x | Item providing a separate inner surface to a cavity. |
| 216 | LINING | | x | x | | x | | | | | | | | x | Process of providing a separate liner surface to a cavity. |
| 217 | LINK | | ? | x | | x | | x | | | | x | | | Item used to join two units together. |
| 218 | LN | | | | | | | | | | | | | | Launching nose of a bridge. |
| 219 | LNLR | | | | | | | | | | | | | | Launching nose light rear (M.G.B. component) |
| 220 | LOAD | | x | | | | x | | | | x | x | | x | The load that is carried or action of Loading/Unloading. |
| 221 | LOCATION | | | x | | x | | x | x | | | x | | | Problems related to location of one unit with respect to another. |
| 222 | LOCK | | | x | | x | | | | | | | | | Item designed to prevent unintended release. |
| 223 | LOCKING | | x | | | x | | | | | x | x | | | Action of locking. |
| 224 | LOCTITE | | | | x | | | x | | | | | | | Proprietary brand of sealant/adhesive/cement. |

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| 225 | LUBRICATE | | | x | | | | x | | x | | x | | x | Anything related to lubrication. |
| 226 | LUB | | | | | x | | | | | | | | | Piece projecting from main structure (not including hinge jaws). |
| 227 | LUMINARY | | | | | | | | | | | | | | Visual marker for night use. |
| 228 | M2 | | | | | | | | | | | | | | Self propelled bridge equipment. |
| 229 | MAINTENANCE | x | | | | | | | | x | x | x | | | Action of maintenance and any problems arising as a result of maint. or lack of maint |
| 230 | MANUFACTURE | x | | | | | | | | | | | | | Problem due to manfacturing process or arising during manufacture. |
| 231 | MARINE | | | | | | | | | x | x | | x | | General marine environment. |
| 232 | MARKING | | x | | | | | | x | x | x | x | | | Marking for identification. |
| 233 | MAST | | | | | x | | | | | | | | | |
| 234 | MAT | | | | | x | | | | | | | | | Non reflective surface: Flexible support pad. |
| 235 | MATERIAL | | | | x | | | | | | | | | | |
| 236 | MEMBER | | | | | | | | | | | | | | Structural components. |
| 237 | MEMBRANE | | | | x | x | | | | | | | | | A thin sheet of material used for separation. |
| 238 | METAL | | | | x | | | | | | | | | | |
| 239 | METHOD | x | | | | | | | | | | x | | | Procedure or technique for carrying out an action. |
| 240 | MGB | | | | | | | | | | | | | | Medium Girder Bridge. |
| 241 | MICROSWITCH | | | | | | | | | | | | | | A switch operated by a small movement. |
| 242 | MIRROR | | | x | | x | | | | | | ? | | | A component with an optically shaped reflecting surface. |
| 243 | MISUSE | | | | | | | | | | | x | | x | Contravention of recommended procedures or unreasonable use. |
| 244 | MIXER | | | x | | | | | | | | | | | Item of equipment : Preferred terms are concretemixer or Aspheltmixer. |
| 245 | MODIFY | x | | | | | | x | | | | | | | Modification as a result of failures or causing failures. |
| 246 | MOISTURE | | | | | | | | | x | x | | x | | Problem related to small quantity of water within bounds of non gravitational bonding |
| 247 | MOMENT | | | | | x | x | | | | | | | | Mechanical moment - Duplicates 'leverage' |
| 248 | MOTOR | | | ? | | | | | | | | | | | Power source; hydraulic or electric or pneumatic. |
| 249 | MOUNT | | | x | | | | x | | | | | | | Item for mounting equipment or the action of mounting or problems w.r.t. mounting. |
| 250 | MUDGUARD | | | ? | | | | | | | | | | | Vehicle components designed to contain and protect against road water, mud, and grit thrown up during transit. |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 251 | JLTIFUEL | ? | | | x | | | | | | | | | | Type of engine |
| 252 | N8TANKBRIDGE | | | x | | | | | | | | | | | Self propelled bridge type |
| 253 | NEEDLE | | | | | x | | | | | | | | | A round section tapered rod. |
| 254 | NEW | | | | | | | | | | | | | | An unused component. |
| 255 | NIPPLE | | | x | | x | | | | | | | | | A hollow protruberance used as an access for transferring fluids or greases. |
| 257 | NITRILE | | | | x | | | | | | | | | | Nitrile Rubber. |
| 258 | NOISE | | | | | | x | | | | | x | x | ? | |
| 259 | NOTCH | | | | | x | | x | | | | | | | Geometric feature with sudden change of section. |
| 260 | NUT | | | | | x | | | | | | | | | Item with female helical thread form. |
| 261 | NYLON | | | | x | | | | | | | | | | Nylon material. |
| 262 | OBM | | | | | | | | | | | | | | Outboard Motor. |
| 263 | OBSTRUCTION | | | | | x | x | | | | | x | x | | |
| 264 | OPERATION | x | | | | | | | x | | | x | | | Problem caused by or occurring during operation. |
| 265 | OPERATOR | | | | | | | | | | | x | | | Problem caused by operators or affecting operators. |
| 266 | OVERLOAD | x | | | | | x | | x | | x | x | | x | An imposed stress in excess of the maximum design stress. |
| 267 | OZONE | | | | x | | | | | x | | | x | | Ozone. |
| 268 | PACKING | x | x | x | x | x | x | | | x | x | x | | | As used to adjust position; As used in packing for storage and transit. |
| 269 | PAD | | | | | | | | | | | | | | Load distribution member. |
| 270 | PAINT | | x | | x | | | | | x | | | | | Material and action of application. |
| 271 | PALLET | | | | | x | | | | | x | | | | Flat temporary based used for support in handling and transport of cargo. |
| 272 | PANEL | | | | | ? | | | | | | | | | Flat Panel in a structure - may be stiffened. |
| 273 | PAVER | | | | | | | | | | | | | | Equipment type. |
| 274 | PENETRATION | | | | | x | | | x | | | | | | Action of producing a hole by piercing action; or the hole produced. |
| 275 | PERSONNEL | | | | | | | | | | | x | | | |

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| 276 | PETROLEUM | | | | x | | | | | | | | | x | Material. |
| 277 | PHOENIX | | | | | | | | | | | | | | Specific Equipment. |
| 278 | PHOSPHATE | | x | | x | | | | | | | | | | Material and material surface treatment process. |
| 279 | PICKET | | | x | | x | | | | | | | | | Peg for securing to ground. |
| 280 | PIER | | | x | | x | | | | | | | | | Vertical member for supporting load platform used on bridges. |
| 281 | PILEDRIVER | | | | | | | | | | | | | | Equipment type. |
| 282 | PILLAR | | | x | | x | | | | | | | | | Use pier. |
| 283 | PIN | | | x | | x | | x | | | | | | | Cylindrical fastener and action of fitting pins. |
| 284 | PINION | | | | | x | | | | | | | | | Use gear wheel. |
| 285 | PISTON | | | | | x | | | | | | | | | Pipe. |
| 287 | PISTONROD | | | | | | | | | | | | | | |
| 288 | PIVOT | | | x | | x | | | | | | | | | |
| 289 | PLASTIC | | | | x | | | | | | | | | | Material. |
| 290 | PLATE | | | | x | x | | | | | | | | | Item manufactured from sheet material of uniform thickness. |
| 291 | PLATFORM | | | x | | x | | | | | | | | | Structure for operator to stand on. |
| 292 | PLATING | | x | | x | x | | | | | | | | | The process of electro plating and the plating created by this process. |
| 293 | PLUNGER | | | | | | | | | | | | | | Use piston. |
| 294 | PNEUMATIC | | | | x | | | | | | | | | | Related to pneumatic systems - compressed air systems. |
| 295 | PONTOON | | | x | | x | | | | | | | | | Stationary bouyant structure used as fixed load platform. |
| 296 | POROUS | | | x | x | x | x | | | | | | | | |
| 297 | POSITION | x | | x | x | x | | x | x | ? | | x | | | To position (the action); having the function of positioning; position w.r.t. somethin els |
| 298 | POWDER | | | | | x | x | | | | | | | | |
| 299 | POWER | | | | | | | | | | | | | | |
| 300 | POWERPACK | | | x | | | | | | | | | | | Complete I.C. engine unit supplying mechanical power. |

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| 301 | PRELOAD | x | | | | | x | x | x | | | x | | | Load exerted by equipment prior to application of operating stresses. |
| 302 | PREPARATION | | x | | | | | | | x | | x | | | Action to prepare for a following process e.g. Welding, printing assembly. |
| 303 | PRESSURE | | | | | | x | | | | | x | x | x | Related to a pressure difference e.g. air, hydraulics, ~ p ~ , Allow for vacuum? |
| 304 | PROCEDURE | x | | | | | | | | x | x | x | | | Related to the techniques, timing and sequence of an operation or process. |
| 305 | PRODUCTION | x | | ? | | | | | | | | | | | Failure arising from or corrected by the production process. |
| 306 | PROOFLOAD | x | | | | | x | | x | | | | | x | Specific test stress greater than maximum designed stress. |
| 307 | PROPELLOR | | | | | x | | | | | | | | | Water screw as used on boats, ships etc. |
| 308 | PROPULSION UNIT | | | x | | | | | | | | | | | As used in marine propulsion - e.g. outboard, outdrive unit. |
| 309 | PROTECTION | x | x | x | | | | | x | x | x | | | | From a damaging environment e.g. as given by paint, grease, plating; or electro |
| 310 | PROTRUSION | | | | | ? | | | | | x | | | | |
| 311 | PTO | | | | | | | | | | | | | | Power take off. |
| 312 | PULLEY | | | | | x | | | | | | | | | Rotary power transmission component changes linear drive from belt to rotary drive. |
| 313 | PUMP | | x | x | | | | | | | | | | | Action and item. |
| 314 | PUSHROD | | | | | ? | | | | | | | | | Rigid means of transferring end load. |
| 315 | PVC | | | | x | | | | | | | | | | Poly vinyl chloride. |
| 316 | RAIN | | | | | | | | | x | x | | x | | |
| 317 | RAM | | | x | | | | | | | | | | | Use piston. |
| 318 | RAMP | | | x | | | x | | | | | | | | An access slope : specific equipment used on military bridges. |
| 319 | RATCHET | | | x | | | x | | | | | | | | Item for and action of changing reciprocating motion into cyclic uni directional motio |
| 320 | RECLAIM | x | x | | | | | | | x | | x | | | Repair/Rebuild scrap item or extensively damaged item or written off item. |
| 321 | REINFORCE | x | x | x | | | x | x | | | | | | | Action or equipment with function of increasing load capacity. |
| 322 | RELIEF | | | x | | | | | | | | x | | | Pressure relief in hydraulics or Pneumatics. |
| 323 | REPAIR | x | x | | | | | | | | | x | | | To return to working condition. |
| 324 | REPLACE | x | | | | | | | | | | | | | To repair by replacing defective component with working components. |
| 325 | REQUIREMENT | x | | | | | | | x | x | | x | | | Special requirement raised w.r.t. manufacture or operation procedure etc. |

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| 326 | RETAINER | | | x | | | | | | | | x | | | Use fastener. |
| 327 | REVERSE | | ? | | | x | | | | | x | x | | | Operating function. |
| 328 | RING | | | | | x | | | | | | | | | In general a lifting ring or sealing ring; on anular items. |
| 329 | RISK | x | | | | | x | | x | x | x | x | | x | Incident in which probability of failure was assessed or noteable. |
| 330 | RIVET | | x | x | | x | | | | | | | | | Item and action of rivetting : a permanent fastening caused by deformation. |
| 331 | ROADROLLER | | | | | | | | | | | | | | Item of equipment. |
| 332 | ROLLER | | | ? | | x | | | | | | | | | Cylindrical geometry item. |
| 333 | ROLLERBEAM | | | | | | | | | | | | | | Item of equipment in bridge erection. |
| 334 | ROPE | | | | x | x | | | | | | | | | Flexible tensile member of generally circular section, standard material stock. |
| 335 | ROTARY | | | | | x | | | | | | | | | Item with complete rotational movement about at least one axis. |
| 336 | ROTTING | | | | | | | | x | x | | | x | x | Time and environment based failure mode due to chemical degradation. |
| 337 | RRR | | | | | | | | | | | | | | Rapid runway repair equipment. |
| 338 | RUBBER | | | | x | | | | | | | | | | Generic term for material family. |
| 339 | RUBBING | | | ? | | x | | | x | | x | | | ? | Action of two surfaces in contact and with relative tangential movement. |
| 340 | RUNNER | | | x | | | | | | | | | | | Item for load carrying and guidance in one dimension (implies rollers are in use). |
| 341 | RUPTURE | | | | | | | | x | | | x | | | Time independant failure mode. |
| 342 | SAFETY | x | | | | | x | | x | | x | x | | | Related to personal safety. |
| 343 | SALT | | | | x | | | | | x | | | x | | Common salt : Saline solution or atmosphere. |
| 3444 | SAND | | | | x | | | | | x | | | x | | Fine stone and grit particles in large quantity. |
| 345 | SAW | | | | | x | | x | | | | x | | | Equipment for and action of cutting. |
| 346 | SCREEN | | | x | | x | | | | | | | | | Item for differential filtration of stone, gravel, rock. |
| 347 | SCREW | | x | x | | x | | | | | | | | | Helical screw threads - as in~fastener, or jack. |
| 348 | SEAL | | x | x | | x | | | x | x | | x | | x | Items and action of sealing and its inverse i.e. leaks. |
| 349 | SEAM | | | x | | x | | | | | | | | | Joint in sheet material - e.g. Bonded seam in fabric: Stitched ~; weld ~ |
| 350 | SEAT | | | x | | x | | | | | | | | | Item on which person or equipment is seated. |

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| 351 | SECURITY | x | | | | | x | | x | x | x | x | | x | Related to the loosening or failure of a joint or bond or individual fastener. |
| 352 | SEIZE | | | | | | | | x | | | x | | | Prevention of relative movement due to local welding or bonding of surfaces. |
| 353 | SELECT | | | x | | | | | | | | x | | | Related to a selection mechanisms or process. |
| 354 | SEVERED | | | | | | | | x | | | x | | | A result of cutting action : A failure mode. |
| 355 | SHACKLE | | | x | | x | | | | | | x | | | Action of fastening loosely together: A removeable chain link or fastener. |
| 356 | SHAFT | | | | | x | | | | | | | | | Load transmission member. |
| 357 | SHEAR | | | x | | | | x | x | | | xx | | | Shear- failure mode. |
| 358 | SHEARPIN | | | x | | x | | | | | | | | | Load limiting device which shears on overload. |
| 359 | | | | | | | | | | | | | | | |
| 360 | SHEATH | x | x | x | | x | | | | | | | | x | As in sheathed cable - Associated term Bouden cable. |
| 361 | SHEAVE | | | ? | | x | | | | | | | | | Pulley used in lifting block. |
| 362 | SHEET | | | | x | | | | | | | | | | Flat material as in plate and panel - no stiffeners. |
| 363 | SHOCK | x | | | | | x | | x | | x | x | | x | Suddenly applied load. |
| 364 | SHOE | | | x | | x | | | | | | | | | Carrier for a wearing surface - replaceable wear item (e.g. brakesshoe or shot pickin |
| 365 | SLIDERAIL | | | x | | x | | | | | | | | | Similar to 'runner' (but implies sliding action in use). |
| 366 | SLIDE | x | | x | | x | | x | | | x | x | | x | Action of sliding. |
| 367 | SLING | x | | | | x | | x | | x | x | x | | x | Flexible lifting strap : action of securing by slings for lifting. |
| 368 | SOCKET | | | | | x | | | | | | | | | Female part of fitted or screw assy;- Scoket screw; pipe socket; or socket spanner. |
| 369 | SOILLAB | | | | | | | | | | | | | | Portable/mobile cabin or workshop fitted out as a soil test laboratory. |
| 370 | SOLDER | x | x | | x | | | | | | | | | | Material and bonding technique using solder. |
| 371 | SOUND | | | | | | x | | | | | | x | | Mechanical/physical vibration in audible spectrum- use noise. |
| 372 | SPARE | x | | | | | | | | | | x | | | Item held in reserve for repair or maintenance. |
| 373 | SPLITPIN | | | | | x | | | | | | | | | Semi permanent thread locking or sleeve retaining pin split along axis. |
| 374 | SPONSON | | | | | | | | | | | | | | Side projecting assembly to improve bouyancy/stability of boat or pontoon. |
| 375 | SPOOLING | | | x | | x | | | | | | x | | | Action of winding a cable on a drum (also problems of incorrect spooling. |

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| 376 | SPRAY | x | x | x | | | | | | x | | | x | | Liquid in small drops projected against equipment. |
| 377 | SPRING | | | x | | | | | | | | | | | A device for storing energy by elastic deflection. |
| 378 | SPROCKET | | | | | x | | | | | | | | | Toothed wheel for chain drive. |
| 379 | STABILITY | x | | | | | x | | | x | x | x | | x | Ability to return to state of equilibrium, also the inverse - instability. |
| 380 | STACK | x | x | x | | x | | | | x | x | x | | | To pile up : ability to be piled in an ordered stack. |
| 381 | START | x | x | x | | | | | x | | | x | | | |
| 382 | STAY | | | x | | x | | x | | | | | | | A support - see brace, reinforce. Use brace. |
| 383 | STEEL | | | | x | | | | | | | | | | Any ferrous metal alloy. |
| 384 | STEERING | | | x | | x | | | | | x | x | | | Action of or equipment for alteration of the direction of motion of a vehicle or vessel |
| 385 | STEP | | | | | x | | | | | | | | | As in stairs or ladder - a foot tread. |
| 386 | STIFFENER | | | | | x | | | | | | | | | Additional member attached to sheet or plate to restrain movement normal to plane of surface. |
| 387 | STONE | | | | x | | | | | | | | x | | Small rocks etc. |
| 388 | STOP | | | x | | x | | | x | | | x | | | The action of stopping or a mechanical stop to limit movement. |
| 389 | STORAGE | x | | x | | | | | x | x | | x | | x | Related to storage of equipment etc. |
| 390 | STOWAGE | x | | x | | | | | x | x | | x | | x | Related to storing a named item in a specific position. |
| 391 | STRAP | | | | | x | | | | | | | | | Flat band - usually flexible as in canvas straps but may be rigid as in butt straps. |
| 392 | STRENGTH | | | x | | | x | | x | | | | | | |
| 393 | STRESS | x | | | | | x | | x | | | | | x | |
| 394 | STRIP | | | | | x | | | | | | | | | To accidentaly remove screw thread or gear teeth: to remove surface coatings: a thin band of material (in latter form use strap). |
| 395 | STRUCTURE | | | | | x | | | | | | | | | |
| 396 | STRUT | | | x | | x | | | | | | | | | Compression member. |
| 397 | STUD | | | | | x | | | | | | | | | Fastener which sticks out from main surface (welded stud or screwed stud). |
| 398 | SUBFRAME | | | | | x | | | | | | | | | |
| 399 | SUPPLY | | | x | | | | | | | x | x | | | |
| 400 | SUPPORT | | | x | | x | | | | | x | x | | | |

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| 401 | SURFACE | | | | | x | | | | | | | | | Related to Surface treatment : Surface coating : Surface finish. |
| 402 | SUSPENSION | | | x | | x | | | | | x | x | | | Related to suspension of vehicles and trailers etc. |
| 403 | SWEEPER | | | | | | | | | | | | | | Equipment for sweeping roads. |
| 404 | SWITCH | | | x | | | | | | | | | | | Electrical switch. |
| 405 | SWIVEL | x | | x | | | | | | | | | | | A joint allowing rotation on more than one axis. |
| 406 | SWR | | | | x | | | | | | | | | | Steel Wire Rope. |
| 407 | TAMPER | | | | | | | | | | | | | | Equipment type. |
| 408 | TANK | | | | | x | | | | | | | | | Container for fluid. |
| 409 | TARSPREADER | | | | | | | | | | | | | | Equipment type. |
| 410 | TEAK | | | | x | | | | | | | | | | A specific type of wood. |
| 411 | TEAR | | x | | | x | | | x | | | x | | | Failure mode. |
| 412 | TEE | | | | | x | | | | | | | | | Having a 'T' shaped geometric form : A form of pipe joint : an extended metal section. |
| 413 | TEETH | | | | | x | | | | | | | | | Gear teeth. |
| 414 | TENSION | | | | | | x | | | | | x | | x | Preloading in a belt or chain transmission. |
| 415 | TENSIONER | | | x | | | | | | | | | | | A chain, rope or belt tensioner. |
| 416 | TERYLENE | | | | x | | | | | | | | | | Material type. |
| 417 | TEST | x | x | x | x | | | | x | | | | | | Related to material, equipment or operation testing or results from tests. |
| 418 | TESTUNIT | | | x | | | | | x | | | | | | Equipment for carrying out test. |
| 419 | THEFT | | | | | | | | | x | x | | | | Related to items susceptible to theft. |
| 420 | THIMBLE | | | ? | | x | | | | | | | | | Short tube fitted on rope or wire to prevent chaffing : Tube used in coupling or joint. |
| 421 | THREAD | | | | x | x | x | x | | | | | | | Action of threading and material - \|Scalar Probelm with rope etc\| : Material filament. |
| 422 | THRUST | x | | x | | | | | | | | | | x | To apply a propulsive force. |
| 423 | TOE | | | | | x | | | | | | | | | Extreme end of bridge. |
| 424 | TOOL | | | | | | | | | | | | | | |
| 425 | TORQUE | | | | | | x | | | | | | | x | Related to torque. |
| 426 | TORSION | | | | | | | | | | | | | x | Action of applying torque. |

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| 427 | TOW | | x | | | | | | | | x | x | | x | Action of towing : any item related to towing e.g. Tow Bar : Towing Eye etc. |
| 428 | TOWEDFLEXIBLEBARGE | | | | | | | | | | | | | | Equipment type. |
| 429 | TP | | | | | | | | | | | | | | Top panel - Component part of a medium girder bridge. |
| 430 | TRACK | | | | | x | | | | | | | | | Path :- as in bearing track : Geometry of vehicle. |
| 431 | TRACKWAY | | | | | x | | | | | | | | | Equipment type. |
| 432 | TRACTION | | | | | | x | | | | | x | | x | Related to tractive effort or force transmission tangential to a surface. |
| 433 | TRAILER | | | | | x | | | | | x | | | | Related to a towed vehicle. |
| 434 | TRANSIT | | x | x | | | | | | | x | | | x | Related to incident occurring during transit. |
| 435 | TRANSMISSION | ? | | x | | | | | | | | ? | | | Mechanical transmission of Power i.e. gearboxes, shafts, axles etc. |
| 436 | TRAPPED | | | | | | | | | | | x | | x | Unintended restraint. |
| 437 | TREAD | | | | | x | | | | | | | | | Related to roadwheel tread on tyres. |
| 438 | TREATMENT | x | x | ? | | | | | | | | | | | Process function e.g. heat treatment : Anodizing : Phosphate treatment. |
| 439 | TRUCK | | | | | ? | | | | | x | | | | A self propelled wheeled transport vehicle. |
| 440 | TUBE | | | | | x | | | | | | | | | Annular material form. |
| 441 | TUBULAR | | | | | x | | | | | | | | | In tube form - use tube. |
| 442 | TUNER | | | x | | | | | | | | | | | Electrical equipment used for adjusting equipment characteristics. |
| 443 | TURNTABLE | | | x | | x | | | | | | | | | Horizontal platform rotatable about central vertical axis. |
| 444 | TYRE | | | | | x | | | | | | | | | Removeable running surface to a wheel. |
| 445 | VACUUM | | | | | x | | | | | | | x | | A pressure lower than ambient pressure : - use Pressure. |
| 446 | VALVE | | | x | | | | | | | | | | | Component used in piped systems for controlling fluid flow. |
| 447 | VALVEROCKER | | | | | | | | | | | | | | Component. |
| 448 | VEHICLE | ? | | ? | | x | | | | | x | ? | | | Generic term for self propelled transport equipment. |
| 449 | VENTILATE | | x | | | x | | | | x | x | x | | x | Action of equipment for aspirating a cavity : also used for lack of ventilation. |
| 450 | VIBRATION | | | | | | x | | | | x | | x | x | A cyclical motion of limited amplitude. |
| 451 | VISIBILITY | x | | x | | x | | | | | | x | | x | Related to the field of vision i.e. scalar measurements of solid angle subtended by field of view. |

| Conversion number | FEATURE | Design: Concept/Philosophy | Design: Process | Design – Product: Function | Design – Product: Material | Design – Product: Geometry | Design – Product: Scale | Manufacture: Process/Procedure | Manufacture: Test and Inspection | Transition: Storage | Transition: Transport | Use – Environment: Operating Procedure | Use – Environment: Natural Environment | Use – Environment: Imposed Environment | FEATURE DEFINITION (where required) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 452 | VULNERABLE | | | | | | | | x | | | | | x | |
| 453 | WASHER | | | x | | x | | | | | | | | | Annular item(usually flat), improves security , used to distribute load under nut and also for sealing. |
| 454 | WATER | | | | x | | | | | x | x | | x | | Material : Marine environment : Excess moisture such as rain. |
| 455 | WEAK | | | | | | x | | | | | | | x | A Structure incapable of withstanding a large overload. |
| 456 | WEAR | | | | | x | x | | | | | x | x | x | Failure mode : Removal of material by abrasive action. |
| 457 | WEATHER | | | | | | | | | x | x | | x | | Related to the natural weather -environment. |
| 458 | WEB | | | | | x | | | | | | | | | Thin flat part connecting larger parts for stiffening. See also stiffener, Brace, Stay. |
| 459 | WEDGE | x | | x | | x | | | | | | | | | Very acute angle triangular prism : Action of forcing a wedge between two surfaces to exert a force at right angles to and greater than the applied force. |
| 460 | WELD | x | x | | x | | | | | | | | | | Related to welds, or the welding process. |
| 461 | WHEEL | | | x | x | ? | | | | | | | | | Rotary load transfer member on axle/bearings. |
| 462 | WICKING | | | | | | | | | | | | | | Failure mode in nonporous membrane structure. |
| 463 | WINCH | | x | | | | | | | | | x | | | Related to winches or the action of winching. |
| 464 | WIND | | | | | | x | | | | x | | x | | As in weather - air movement : for"wind and drum" use coiling mech. |
| 465 | WIRE | | | | x | x | | | | | | | | | Electrical conducting wire : metal wire for load transmission (preferred term S.W.R. for latter application). |
| 466 | WIRING | | | | | x | | | | | | | | | Electrical wiring only. |
| 467 | WOOD | | | | x | | | | | | | | | | Material. |
| 468 | WORKBOAT | | | | | | | | | | | | | | Equipment type. |
| 469 | ZINC | | | | x | | | | | | | | | | Metal. |

| Feature | Occur. | Prob of occ. | Cum% occur | Equiv occur |
|---|---|---|---|---|
| brass | 1.00 | 0.16 | 0.01 | 0.19 |
| bright | 1.00 | 0.16 | 0.02 | 0.74 |
| MGB-BSB | 7.00 | 1.11 | 4.66 | 177.29 |
| buckle | 6.00 | 0.96 | 3.54 | 134.64 |
| cable | 18.00 | 2.87 | 1.33 | 50.60 |
| cadmium | 6.00 | 0.96 | 1.84 | 70.01 |
| canvas | 3.00 | 0.48 | 0.16 | 6.26 |
| capacity | 1.00 | 0.16 | 0.10 | 3.81 |
| carburetto | 1.00 | 0.16 | 0.02 | 0.72 |
| cargo | 1.00 | 0.16 | 0.01 | 0.37 |
| casing | 17.00 | 2.71 | 0.77 | 29.14 |
| castiron | 2.00 | 0.32 | 0.11 | 4.17 |
| casting | 3.00 | 0.48 | 0.06 | 2.28 |
| catch | 2.00 | 0.32 | 0.08 | 3.04 |
| cavity | 8.00 | 1.27 | 9.54 | 362.82 |
| chain | 7.00 | 1.11 | 0.47 | 17.72 |
| channel | 2.00 | 0.32 | 0.04 | 1.52 |
| chromate | 1.00 | 0.16 | 0.12 | 4.61 |
| clamp | 8.00 | 1.27 | 0.51 | 19.35 |
| clean | 2.00 | 0.32 | 0.12 | 4.54 |
| clearance | 26.00 | 4.14 | 1.01 | 38.46 |
| clip | 5.00 | 0.80 | 0.20 | 7.74 |
| clog | 4.00 | 0.64 | 1.04 | 39.53 |
| clutch | 15.00 | 2.39 | 0.93 | 35.27 |
| coil | 0.00 | 0.00 | 0.00 | 0.00 |
| coiling | 2.00 | 0.32 | 0.20 | 7.61 |
| collapse | 4.00 | 0.64 | 0.07 | 2.61 |
| combustion | 0.00 | 0.00 | 0.00 | 0.00 |
| compress | 5.00 | 0.80 | 0.26 | 9.93 |
| concretemi | 6.00 | 0.96 | 0.25 | 9.61 |
| concretevi | 4.00 | 0.64 | 0.33 | 12.68 |
| conduit | 1.00 | 0.16 | 0.10 | 3.81 |
| connect | 11.00 | 1.75 | 0.17 | 6.35 |
| conretepok | 3.00 | 0.48 | 0.04 | 1.56 |
| conrod | 5.00 | 0.80 | 0.20 | 7.55 |
| contain | 0.00 | 0.00 | 0.00 | 0.00 |
| control | 27.00 | 4.30 | 2.42 | 91.91 |
| cord | 1.00 | 0.16 | 0.01 | 0.38 |
| corner | 2.00 | 0.32 | 0.11 | 4.17 |
| corrosion | 50.00 | 7.96 | 18.21 | 692.96 |
| counterbal | 1.00 | 0.16 | 0.02 | 0.86 |
| coupling | 14.00 | 2.23 | 0.47 | 17.93 |
| cover | 11.00 | 1.75 | 1.62 | 61.73 |
| crack | 80.00 | 12.74 | 4.60 | 175.09 |
| crane | 6.00 | 0.96 | 0.22 | 8.30 |
| crank | 4.00 | 0.64 | 0.09 | 3.33 |
| cross | 0.00 | 0.00 | 0.00 | 0.00 |
| crush | 4.00 | 0.64 | 0.11 | 4.17 |
| crusher | 12.00 | 1.91 | 1.64 | 62.30 |
| cyclic | 0.00 | 0.00 | 0.00 | 0.00 |
| cylinder | 8.00 | 1.27 | 0.18 | 6.89 |
| cylinderhe | 4.00 | 0.64 | 0.04 | 1.52 |
| damage | 6.00 | 0.96 | 0.69 | 26.11 |
| damp | 0.00 | 0.00 | 0.00 | 0.00 |
| damping | 0.00 | 0.00 | 0.00 | 0.00 |
| DANDO | 15.00 | 2.39 | 0.34 | 12.97 |
| deck | 8.00 | 1.27 | 7.98 | 303.54 |
| deflector | 1.00 | 0.16 | 0.10 | 3.81 |
| desert | 8.00 | 1.27 | 0.37 | 14.24 |
| design | 10.00 |  | 0.71 | 27.02 |
| diesel | 2.00 | 0.32 | 0.26 | 9.86 |

| Feature | Occur. | Prob of occ. | Cum% occur | Equiv occur |
|---|---|---|---|---|
| differenti | 5.00 | 0.80 | 0.35 | 13.29 |
| dimension | 37.00 | 5.89 | 2.46 | 93.56 |
| direction | 2.00 | 0.32 | 0.02 | 0.83 |
| discharge | 1.00 | 0.16 | 0.01 | 0.55 |
| disintegra | 2.00 | 0.32 | 0.54 | 20.65 |
| dispose | 1.00 | 0.16 | 0.25 | 9.51 |
| distort | 17.00 | 2.71 | 0.54 | 20.65 |
| door | 5.00 | 0.80 | 0.25 | 9.35 |
| drain | 2.00 | 0.32 | 0.05 | 1.99 |
| drawbar | 0.00 | 0.00 | 0.00 | 0.00 |
| drier | 2.00 | 0.32 | 0.07 | 2.63 |
| drill | 2.00 | 0.32 | 0.05 | 1.95 |
| drillrig | 42.00 | 6.69 | 1.38 | 52.32 |
| drop | 2.00 | 0.32 | 0.02 | 0.74 |
| drum | 5.00 | 0.80 | 0.34 | 12.99 |
| earth | 2.00 | 0.32 | 0.20 | 7.61 |
| edge | 3.00 | 0.48 | 0.37 | 14.06 |
| electric | 11.00 | 1.75 | 1.69 | 64.19 |
| electric-c | 1.00 | 0.16 | 1.00 | 38.05 |
| ELSAN-SEAT | 1.00 | 0.16 | 0.01 | 0.37 |
| engine | 37.00 | 5.89 | 3.46 | 131.49 |
| epoxy | 5.00 | 0.80 | 0.05 | 1.79 |
| equipment | 1.00 | 0.16 | 0.10 | 3.81 |
| erection | 2.00 | 0.32 | 0.15 | 5.71 |
| EVOSTIC | 1.00 | 0.16 | 0.01 | 0.37 |
| EWBB | 1.00 | 0.16 | 0.02 | 0.86 |
| exhaust | 7.00 | 1.11 | 1.44 | 54.77 |
| expansion | 1.00 | 0.16 | 0.03 | 1.19 |
| expendable | 2.00 | 0.32 | 0.13 | 5.07 |
| extension | 4.00 | 0.64 | 0.18 | 6.94 |
| extrusion | 1.00 | 0.16 | 0.01 | 0.37 |
| eye | 9.00 | 1.43 | 0.29 | 11.05 |
| fabric | 30.00 | 4.78 | 1.71 | 65.03 |
| fasten(er) | 22.00 | 3.50 | 32.63 | 1241.48 |
| fatigue | 2.00 | 0.32 | 0.10 | 3.83 |
| FB(foreign | 4.00 | 0.64 | 0.48 | 18.07 |
| fender | 1.00 | 0.16 | 0.00 | 0.07 |
| ferrule | 2.00 | 0.32 | 1.03 | 39.32 |
| filler | 1.00 | 0.16 | 0.14 | 5.33 |
| fillet | 7.00 | 1.11 | 0.50 | 18.89 |
| filter | 10.00 | 1.59 | 0.07 | 2.55 |
| fire | 1.00 | 0.16 | 0.10 | 3.81 |
| flange | 6.00 | 0.96 | 0.19 | 7.18 |
| flaking | 3.00 | 0.48 | 1.21 | 45.92 |
| flexible | 5.00 | 0.80 | 0.14 | 5.43 |
| flimsy | 3.00 | 0.48 | 2.55 | 97.08 |
| float | 2.00 | 0.32 | 0.49 | 18.56 |
| flowmeter* | 2.00 | 0.32 | 0.05 | 1.90 |
| fluid | 1.00 | 0.16 | 0.10 | 3.81 |
| flywheel | 1.00 | 0.16 | 0.01 | 0.36 |
| forging | 2.00 | 0.32 | 0.04 | 1.52 |
| fracture | 71.00 | 11.31 | 4.74 | 180.22 |
| frame | 16.00 | 2.55 | 0.74 | 28.04 |
| friction | 2.00 | 0.32 | 0.10 | 3.81 |
| fuel | 27.00 | 4.30 | 1.08 | 40.95 |
| full | 2.00 | 0.32 | 0.13 | 4.99 |
| gas | 0.00 | 0.00 | 0.00 | 0.00 |
| gauge | 2.00 | 0.32 | 0.22 | 8.47 |
| gear | 40.00 | 6.37 | 1.37 | 52.31 |
| gearbox | 16.00 | 2.55 | 0.71 | 27.05 |
| gearwheel | 0.00 | 0.00 | 0.00 | 0.00 |

| Feature | Occur. | Prob of occ. | Cum% occur | Equiv occur |
|---|---|---|---|---|
| GEMINI | 1.00 | 0.16 | 0.78 | 29.73 |
| generator | 5.00 | 0.80 | 0.24 | 9.23 |
| geometry | 1.00 | 0.16 | 0.02 | 0.86 |
| GERMAN | 5.00 | 0.80 | 0.03 | 0.95 |
| girder | 2.00 | 0.32 | 0.04 | 1.52 |
| glass | 2.00 | 0.32 | 0.12 | 4.54 |
| GRAVELWASH | 3.00 | 0.48 | 0.21 | 8.13 |
| grease | 3.00 | 0.48 | 0.06 | 2.17 |
| grind | 1.00 | 0.16 | 0.02 | 0.86 |
| grip | 2.00 | 0.32 | 0.04 | 1.57 |
| groove | 2.00 | 0.32 | 0.05 | 1.90 |
| GRP | 1.00 | 0.16 | 0.00 | 0.07 |
| guard | 14.00 | 2.23 | 0.90 | 34.22 |
| guide | 3.00 | 0.48 | 0.01 | 0.19 |
| GUSSETPLAT | 4.00 | 0.64 | 0.05 | 1.73 |
| hammer | 8.00 | 1.27 | 0.16 | 6.18 |
| handbook | 0.00 | 0.00 | 0.00 | 0.00 |
| handle | 17.00 | 2.71 | 1.81 | 68.77 |
| handrail | 1.00 | 0.16 | 0.02 | 0.86 |
| hardboard | 1.00 | 0.16 | 0.00 | 0.08 |
| hatch | 3.00 | 0.48 | 0.12 | 4.54 |
| head | 1.00 | 0.16 | 1.00 | 38.05 |
| health | 1.00 | 0.16 | 0.20 | 7.61 |
| heat | 2.00 | 0.32 | 0.55 | 20.92 |
| heater | 1.00 | 0.16 | 0.02 | 0.76 |
| HEAVYFERRY | 4.00 | 0.64 | 0.29 | 10.99 |
| helicopter | 0.00 | 0.00 | 0.00 | 0.00 |
| hightemper | 13.00 | 2.07 | 1.26 | 48.10 |
| hinge | 30.00 | 4.78 | 36.36 | 1383.67 |
| hole | 18.00 | 2.87 | 0.57 | 21.74 |
| hook | 5.00 | 0.80 | 1.07 | 40.62 |
| hopper | 2.00 | 0.32 | 0.11 | 4.17 |
| hose | 4.00 | 0.64 | 0.07 | 2.71 |
| hot-tear | 2.00 | 0.32 | 0.05 | 1.91 |
| housing | 9.00 | 1.43 | 0.20 | 7.68 |
| HT30WP-ste | 1.00 | 0.16 | 0.00 | 0.08 |
| HTS-steel | 2.00 | 0.32 | 0.05 | 1.95 |
| hub | 2.00 | 0.32 | 0.04 | 1.52 |
| hull | 2.00 | 0.32 | 0.02 | 0.73 |
| hydraulic | 39.00 | 6.21 | 2.89 | 110.02 |
| ice | 1.00 | 0.16 | 0.03 | 1.19 |
| identifica | 2.00 | 0.32 | 0.38 | 14.46 |
| pier | 2.00 | 0.32 | 0.03 | 1.13 |
| impact | 6.00 | 0.96 | 1.30 | 49.64 |
| incorrect | 0.00 | 0.00 | 0.00 | 0.00 |
| inflate | 6.00 | 0.96 | 0.41 | 15.45 |
| inhibit | 5.00 | 0.80 | 0.03 | 0.99 |
| INJECTOR | 1.00 | 0.16 | 0.01 | 0.37 |
| inlet | 0.00 | 0.00 | 0.00 | 0.00 |
| insert | 1.00 | 0.16 | 0.20 | 7.61 |
| inspect | 10.00 | 1.59 | 0.39 | 14.87 |
| instructio | 47.00 | 7.48 | 3.27 | 124.43 |
| internal | 1.00 | 0.16 | 1.00 | 38.05 |
| interrupt | 2.00 | 0.32 | 0.01 | 0.44 |
| jack | 17.00 | 2.71 | 1.07 | 40.53 |
| MGB-JACKPO | 1.00 | 0.16 | 0.02 | 0.76 |
| jam | 4.00 | 0.64 | 1.07 | 40.77 |
| jaw | 10.00 | 1.59 | 5.88 | 223.59 |
| joint | 2.00 | 0.32 | 0.02 | 0.63 |
| journal | 7.00 | 1.11 | 0.19 | 7.24 |
| kerb | 1.00 | 0.16 | 0.06 | 2.28 |

| Feature | Occur. | Prob of occ. | Cum% occur | Equiv occur |
|---|---|---|---|---|
| key | 1.00 | 0.16 | 0.06 | 2.38 |
| kit | 1.00 | 0.16 | 0.02 | 0.86 |
| lamp | 1.00 | 0.16 | 0.02 | 0.86 |
| lashing | 12.00 | 1.91 | 0.93 | 35.38 |
| launch | 2.00 | 0.32 | 0.03 | 1.13 |
| MGB-LAUNIN | 0.00 | 0.00 | 0.00 | 0.00 |
| law | 5.00 | 0.80 | 0.03 | 0.95 |
| leak | 1.00 | 0.16 | 0.02 | 0.74 |
| level | 4.00 | 0.64 | 0.20 | 7.44 |
| lever | 0.00 | 0.00 | 0.00 | 0.00 |
| leverage | 6.00 | 0.96 | 0.42 | 16.11 |
| life | 3.00 | 0.48 | 1.06 | 40.43 |
| LIFEJACKET | | ?n? | | ?n? |
| lift | 10.00 | 1.59 | 0.39 | 14.67 |
| light | 5.00 | 0.80 | 0.03 | 0.95 |
| LIGHT-TOWE | 12.00 | 1.91 | 1.64 | 62.25 |
| lightweigh | 2.00 | 0.32 | 0.04 | 1.40 |
| limitation | 8.00 | 1.27 | 0.16 | 6.11 |
| liner | 1.00 | 0.16 | 0.20 | 7.61 |
| lining | 0.00 | 0.00 | 0.00 | 0.00 |
| link | 10.00 | 1.59 | 0.40 | 15.20 |
| MGB-LN | 6.00 | 0.96 | 0.15 | 5.81 |
| MGB-LNLR | 5.00 | 0.80 | 0.09 | 3.41 |
| load | 5.00 | 0.80 | 0.59 | 22.37 |
| location | 23.00 | 3.66 | 1.88 | 71.45 |
| lock | 1.00 | 0.16 | 0.10 | 3.81 |
| locking | 39.00 | 6.21 | 1.38 | 52.33 |
| LOCTITE | 5.00 | 0.80 | 0.21 | 8.08 |
| lubricate | 40.00 | 6.37 | 2.40 | 91.43 |
| lug | 10.00 | 1.59 | 0.98 | 37.45 |
| LUMINARY | 1.00 | 0.16 | 0.01 | 0.36 |
| M2-bridge | 182.00 | 28.98 | 12.08 | 459.55 |
| magnetic | 0.00 | 0.00 | 0.00 | 0.00 |
| maintenanc | 11.00 | 1.75 | 0.53 | 20.18 |
| manual | 1.00 | 0.16 | 0.00 | 0.14 |
| manufactur | 25.00 | 3.98 | 1.30 | 49.63 |
| marine | 16.00 | 2.55 | 3.84 | 146.20 |
| marking | 2.00 | 0.32 | 0.04 | 1.63 |
| mast | 7.00 | 1.11 | 1.12 | 42.67 |
| mat | 1.00 | 0.16 | 0.02 | 0.74 |
| material | 5.00 | 0.80 | 0.47 | 17.80 |
| microswitc | 1.00 | 0.16 | 0.03 | 1.15 |
| member | 1.00 | 0.16 | 0.01 | 0.37 |
| membrane | 2.00 | 0.32 | 0.22 | 8.24 |
| metal | 4.00 | 0.64 | 0.07 | 2.59 |
| method | 1.00 | 0.16 | 0.03 | 1.19 |
| MGB | 94.00 | 14.97 | 22.39 | 852.09 |
| mirror | 1.00 | 0.16 | 0.02 | 0.74 |
| missing | 1.00 | 0.16 | 0.10 | 3.81 |
| misuse | 6.00 | 0.96 | 0.26 | 10.08 |
| mixer | 2.00 | 0.32 | 0.04 | 1.56 |
| modify | 8.00 | 1.27 | 0.17 | 6.30 |
| moisture | 1.00 | 0.16 | 0.00 | 0.08 |
| moment | 1.00 | 0.16 | 0.01 | 0.28 |
| motor | 3.00 | 0.48 | 0.07 | 2.83 |
| mount | 20.00 | 3.18 | 2.00 | 76.25 |
| mudguard | 1.00 | 0.16 | 0.01 | 0.19 |
| MULTIFUEL | 4.00 | 0.64 | 0.05 | 1.85 |
| N8TANKBRID | 36.00 | 5.73 | 7.33 | 278.98 |
| needle | 3.00 | 0.48 | 0.10 | 3.81 |
| new | 9.00 | 1.43 | 0.34 | 12.82 |

| Feature | Occur. | Prob of occ. | Cum% occur | Equiv occur |
|---|---|---|---|---|
| nipple | 1.00 | 0.16 | 0.03 | 1.11 |
| nitrile | 1.00 | 0.16 | 0.01 | 0.24 |
| noise | 4.00 | 0.64 | 0.04 | 1.52 |
| notch | 2.00 | 0.32 | 0.04 | 1.52 |
| NUMBERPLAT | 5.00 | 0.80 | 0.03 | 0.95 |
| nut | 32.00 | 5.10 | 11.93 | 454.05 |
| nylon | 5.00 | 0.80 | 1.49 | 56.59 |
| OBM-outboa | 7.00 | 1.11 | 0.07 | 2.61 |
| obstuction | 3.00 | 0.48 | 0.83 | 31.45 |
| oil | 3.00 | 0.48 | 0.04 | 1.50 |
| operation | 71.00 | 11.31 | 5.89 | 224.15 |
| operator | 0.00 | 0.00 | 0.00 | 0.00 |
| overload | 17.00 | 2.71 | 0.66 | 25.21 |
| ozone | 1.00 | 0.16 | 0.01 | 0.24 |
| packing | 1.00 | 0.16 | 0.02 | 0.63 |
| pad | 4.00 | 0.64 | 1.19 | 45.37 |
| paint | 11.00 | 1.75 | 8.81 | 335.16 |
| pallet | 3.00 | 0.48 | 1.03 | 39.19 |
| panel | 5.00 | 0.80 | 0.07 | 2.50 |
| PAVER | 1.00 | 0.16 | 0.02 | 0.86 |
| penetratio | 2.00 | 0.32 | 0.04 | 1.56 |
| personnel | 0.00 | 0.00 | 0.00 | 0.00 |
| petroleum | 0.00 | 0.00 | 0.00 | 0.00 |
| PHOENIX | 1.00 | 0.16 | 0.10 | 3.81 |
| phosphate | 0.00 | 0.00 | 0.00 | 0.00 |
| picket | 2.00 | 0.32 | 1.01 | 38.24 |
| pier | 2.00 | 0.32 | 0.03 | 1.13 |
| PILEDRIVER | 1.00 | 0.16 | 0.02 | 0.86 |
| pillar | 1.00 | 0.16 | 0.03 | 1.19 |
| pin | 53.00 | 8.44 | 17.48 | 665.08 |
| pinion | 0.00 | 0.00 | 0.00 | 0.00 |
| pipe | 8.00 | 1.27 | 0.27 | 10.34 |
| piston | 7.00 | 1.11 | 0.20 | 7.69 |
| pistonrod | 0.00 | 0.00 | 0.00 | 0.00 |
| pivot | 2.00 | 0.32 | 0.26 | 9.98 |
| plastic | 4.00 | 0.64 | 0.07 | 2.59 |
| plate | 11.00 | 1.75 | 1.34 | 51.03 |
| platform | 0.00 | 0.00 | 0.00 | 0.00 |
| plating | 11.00 | 1.75 | 2.66 | 101.33 |
| plug | 1.00 | 0.16 | 0.09 | 3.26 |
| plunger | 1.00 | 0.16 | 0.07 | 2.59 |
| pneumatic | 1.00 | 0.16 | 0.02 | 0.72 |
| pontoon | 5.00 | 0.80 | 1.02 | 38.85 |
| porous | 1.00 | 0.16 | 0.50 | 19.03 |
| position | 14.00 | 2.23 | 0.64 | 24.31 |
| powder | 1.00 | 0.16 | 0.01 | 0.37 |
| power | 2.00 | 0.32 | 0.11 | 4.08 |
| POWERPACK | 0.00 | 0.00 | 0.00 | 0.00 |
| preload | 2.00 | 0.32 | 0.02 | 0.73 |
| preparatio | 1.00 | 0.16 | 0.01 | 0.37 |
| pressure | 6.00 | 0.96 | 0.11 | 4.26 |
| procedure | 6.00 | 0.96 | 3.25 | 123.59 |
| production | 6.00 | 0.96 | 5.27 | 200.56 |
| proofload | 1.00 | 0.16 | 0.25 | 9.51 |
| propellor | 4.00 | 0.64 | 0.08 | 3.13 |
| propulsion | 8.00 | 1.27 | 0.17 | 6.58 |
| protection | 8.00 | 1.27 | 4.23 | 160.95 |
| protrusion | 1.00 | 0.16 | 0.02 | 0.57 |
| PTO | 4.00 | 0.64 | 0.05 | 1.97 |
| pulley | 10.00 | 1.59 | 0.24 | 9.31 |
| pump | 39.00 | 6.21 | 1.20 | 45.79 |

| Feature | Occur. | Prob of occ. | Cum% occur | Equiv occur |
|---|---|---|---|---|
| pushrod | 1.00 | 0.16 | 0.10 | 3.81 |
| PVC | 2.00 | 0.32 | 0.02 | 0.61 |
| quadrant | 2.00 | 0.32 | 0.39 | 14.94 |
| rain | 0.00 | 0.00 | 0.00 | 0.00 |
| ram | 1.00 | 0.16 | 0.01 | 0.53 |
| ramp | 7.00 | 1.11 | 0.60 | 22.98 |
| ratchet | 4.00 | 0.64 | 3.74 | 142.27 |
| reclaim | 10.00 | 1.59 | 0.65 | 24.62 |
| reinforce | 1.00 | 0.16 | 0.10 | 3.81 |
| relief | 1.00 | 0.16 | 0.02 | 0.72 |
| remove | 3.00 | 0.48 | 0.07 | 2.55 |
| repair | 5.00 | 0.80 | 0.16 | 6.05 |
| replace | 3.00 | 0.48 | 1.04 | 39.57 |
| requiremen | 1.00 | 0.16 | 0.01 | 0.54 |
| retainer | 10.00 | 1.59 | 4.55 | 173.01 |
| reverse | 1.00 | 0.16 | 0.02 | 0.86 |
| ring | 2.00 | 0.32 | 0.05 | 1.91 |
| risk | 1.00 | 0.16 | 0.10 | 3.81 |
| rivet | 3.00 | 0.48 | 0.01 | 0.37 |
| ROADROLLER | 25.00 | 3.98 | 1.47 | 56.09 |
| roller | 12.00 | 1.91 | 4.53 | 172.52 |
| MGB-ROLLER | 1.00 | 0.16 | 0.02 | 0.76 |
| rope | 2.00 | 0.32 | 0.20 | 7.61 |
| rotary | 4.00 | 0.64 | 0.13 | 4.79 |
| rotting | 1.00 | 0.16 | 0.03 | 1.19 |
| RRR | 3.00 | 0.48 | 0.07 | 2.72 |
| rubber | 13.00 | 2.07 | 1.59 | 60.65 |
| rubbing | 0.00 | 0.00 | 0.00 | 0.00 |
| runner | 4.00 | 0.64 | 0.11 | 4.34 |
| rupture | 1.00 | 0.16 | 0.03 | 1.19 |
| safety | 8.00 | 1.27 | 1.56 | 59.36 |
| salt | 0.00 | 0.00 | 0.00 | 0.00 |
| sand | 3.00 | 0.48 | 0.06 | 2.47 |
| saw | 2.00 | 0.32 | 1.10 | 41.86 |
| screen | 0.00 | 0.00 | 0.00 | 0.00 |
| screw | 14.00 | 2.23 | 0.62 | 23.55 |
| seal | 36.00 | 5.73 | 1.84 | 69.90 |
| seam | 5.00 | 0.80 | 0.27 | 10.31 |
| seat | 5.00 | 0.80 | 0.07 | 2.64 |
| security | 1.00 | 0.16 | 0.02 | 0.86 |
| seize | 19.00 | 3.03 | 1.62 | 61.76 |
| select | 3.00 | 0.48 | 0.25 | 9.51 |
| severed | 1.00 | 0.16 | 0.03 | 1.14 |
| shackle | 3.00 | 0.48 | 0.24 | 9.13 |
| shaft | 34.00 | 5.41 | 3.58 | 136.07 |
| shear | 2.00 | 0.32 | 0.19 | 7.13 |
| shearpin | 7.00 | 1.11 | 0.08 | 3.03 |
| sheath | 0.00 | 0.00 | 0.00 | 0.00 |
| sheave | 0.00 | 0.00 | 0.00 | 0.00 |
| sheet | 0.00 | 0.00 | 0.00 | 0.00 |
| shock | 10.00 | 1.59 | 1.16 | 43.99 |
| shoe | 1.00 | 0.16 | 0.19 | 7.18 |
| SLIDERAIL | 0.00 | 0.00 | 0.00 | 0.00 |
| skin | 0.00 | 0.00 | 0.00 | 0.00 |
| slide | 4.00 | 0.64 | 0.60 | 22.79 |
| sling | 2.00 | 0.32 | 0.22 | 8.18 |
| socket | 1.00 | 0.16 | 0.10 | 3.81 |
| SOIL-LAB | 15.00 | 2.39 | 0.87 | 33.26 |
| solder | 0.00 | 0.00 | 0.00 | 0.00 |
| sound | 1.00 | 0.16 | 0.20 | 7.61 |
| spare | 4.00 | 0.64 | 0.38 | 14.46 |

| Feature | Occur. | Prob of occ. | Cum% occur | Equiv occur |
|---|---|---|---|---|
| speed | 2.00 | 0.32 | 0.05 | 1.89 |
| splitpin | 1.00 | 0.16 | 0.19 | 7.13 |
| SPONSON | 2.00 | 0.32 | 0.19 | 7.13 |
| spooling | 1.00 | 0.16 | 0.02 | 0.86 |
| spray | 2.00 | 0.32 | 0.20 | 7.61 |
| spring | 8.00 | 1.27 | 0.69 | 26.25 |
| sprocket | 6.00 | 0.96 | 0.82 | 31.28 |
| stability | 3.00 | 0.48 | 0.06 | 2.44 |
| stack | 0.00 | 0.00 | 0.00 | 0.00 |
| start | 4.00 | 0.64 | 0.43 | 16.25 |
| stay | 1.00 | 0.16 | 0.10 | 3.81 |
| steel | 37.00 | 5.89 | 12.40 | 471.82 |
| steering | 10.00 | 1.59 | 0.17 | 6.51 |
| step | 2.00 | 0.32 | 0.11 | 4.00 |
| stiffener | 1.00 | 0.16 | 0.14 | 5.33 |
| stone | 6.00 | 0.96 | 2.07 | 78.65 |
| stop | 2.00 | 0.32 | 0.09 | 3.41 |
| storage | 19.00 | 3.03 | 1.13 | 43.07 |
| stowage | 6.00 | 0.96 | 0.49 | 18.45 |
| strainer | 3.00 | 0.48 | 0.02 | 0.91 |
| strap | 6.00 | 0.96 | 4.06 | 154.60 |
| strength | 0.00 | 0.00 | 0.00 | 0.00 |
| stress | 6.00 | 0.96 | 0.11 | 4.11 |
| strip | 5.00 | 0.80 | 0.18 | 6.96 |
| structure | 4.00 | 0.64 | 0.32 | 12.18 |
| strut | 6.00 | 0.96 | 0.08 | 2.93 |
| stud | 2.00 | 0.32 | 0.11 | 4.17 |
| subframe | 4.00 | 0.64 | 0.10 | 3.73 |
| supply | 1.00 | 0.16 | 0.20 | 7.61 |
| support | 5.00 | 0.80 | 0.11 | 4.07 |
| surface | 19.00 | 3.03 | 0.77 | 29.45 |
| suspension | 4.00 | 0.64 | 0.05 | 1.71 |
| SWEEPER | 3.00 | 0.48 | 0.21 | 7.98 |
| switch | 4.00 | 0.64 | 0.15 | 5.56 |
| swivel | 1.00 | 0.16 | 0.01 | 0.19 |
| SWR | 5.00 | 0.80 | 0.76 | 29.07 |
| tamper**** | 3.00 | 0.48 | 0.03 | 0.96 |
| tank | 38.00 | 6.05 | 1.39 | 52.85 |
| TARSPREADE | 11.00 | 1.75 | 1.10 | 41.86 |
| teak | 0.00 | 0.00 | 0.00 | 0.00 |
| tear | 6.00 | 0.96 | 1.29 | 49.05 |
| tee | 1.00 | 0.16 | 0.10 | 3.81 |
| teeth | 3.00 | 0.48 | 0.08 | 3.02 |
| tension | 7.00 | 1.11 | 0.52 | 19.86 |
| tensioner | 3.00 | 0.48 | 0.42 | 15.90 |
| terrain | 1.00 | 0.16 | 0.09 | 3.26 |
| terylene | 2.00 | 0.32 | 0.20 | 7.61 |
| test | 5.00 | 0.80 | 5.81 | 221.18 |
| testunit | 2.00 | 0.32 | 0.13 | 4.95 |
| theft | 1.00 | 0.16 | 0.02 | 0.72 |
| thimble | 2.00 | 0.32 | 0.03 | 1.26 |
| thread | 1.00 | 0.16 | 0.20 | 7.61 |
| thrust | 3.00 | 0.48 | 0.10 | 3.68 |
| toe | | ?n? | | ?n? |
| tool | 5.00 | 0.80 | 0.33 | 12.63 |
| torque | 2.00 | 0.32 | 0.03 | 1.22 |
| torsion | 1.00 | 0.16 | 0.01 | 0.37 |
| tow | 20.00 | 3.18 | 0.57 | 21.57 |
| TOWEDFLEXI | 1.00 | 0.16 | 0.08 | 3.17 |
| MGB-TP | 16.00 | 2.55 | 5.96 | 226.78 |
| track | 1.00 | 0.16 | 0.16 | 5.94 |

| Feature | Occur. | Prob of occ. | Cum% occur | Equiv occur |
|---|---|---|---|---|
| TRACKLAYER | 4.00 | 0.64 | 0.35 | 13.28 |
| TRACKWAY | 6.00 | 0.96 | 0.06 | 2.36 |
| traction | 2.00 | 0.32 | 0.03 | 1.22 |
| traffic | 5.00 | 0.80 | 0.03 | 0.95 |
| trailer | 45.00 | 7.17 | 4.01 | 152.66 |
| transit | 3.00 | 0.48 | 0.18 | 6.96 |
| transmissi | 47.00 | 7.48 | 2.09 | 79.45 |
| transom | 0.00 | 0.00 | 0.00 | 0.00 |
| trapped | 2.00 | 0.32 | 1.01 | 38.43 |
| tread | 1.00 | 0.16 | 0.03 | 1.14 |
| treatment | 1.00 | 0.16 | 4.46 | 169.70 |
| truck | 1.00 | 0.16 | 0.10 | 3.81 |
| tube | 6.00 | 0.96 | 0.12 | 4.53 |
| tubular | 1.00 | 0.16 | 0.03 | 1.18 |
| TUNER | 1.00 | 0.16 | 1.00 | 38.05 |
| turntable | 3.00 | 0.48 | 0.17 | 6.47 |
| tyre | 1.00 | 0.16 | 0.03 | 1.14 |
| vacuum | 1.00 | 0.16 | 0.00 | 0.08 |
| valve | 19.00 | 3.03 | 1.57 | 59.74 |
| valverocke | 0.00 | 0.00 | 0.00 | 0.00 |
| vehicle | 3.00 | 0.48 | 0.05 | 1.98 |
| ventilate | 1.00 | 0.16 | 0.01 | 0.37 |
| vibration | 99.00 | 15.76 | 32.37 | 1231.68 |
| visibility | 1.00 | 0.16 | 0.01 | 0.36 |
| VTOL | 3.00 | 0.48 | 1.02 | 38.81 |
| vulnerable | 1.00 | 0.16 | 0.01 | 0.19 |
| washer | 8.00 | 1.27 | 7.97 | 303.14 |
| water | 27.00 | 4.30 | 3.54 | 134.70 |
| weak | 0.00 | 0.00 | 0.00 | 0.00 |
| wear | 26.00 | 4.14 | 35.80 | 1362.19 |
| weather | 2.00 | 0.32 | 0.15 | 5.71 |
| web | 3.00 | 0.48 | 0.14 | 5.44 |
| wedge | 1.00 | 0.16 | 0.02 | 0.88 |
| weld | 64.00 | 10.19 | 4.14 | 157.41 |
| wheel | 9.00 | 1.43 | 0.25 | 9.63 |
| wicking | 7.00 | 1.11 | 0.03 | 1.26 |
| winch | 2.00 | 0.32 | 0.03 | 0.95 |
| wind | 1.00 | 0.16 | 0.10 | 3.81 |
| wire | 1.00 | 0.16 | 0.10 | 3.81 |
| wiring | 0.00 | 0.00 | 0.00 | 0.00 |
| wood | 4.00 | 0.64 | 0.25 | 9.32 |
| WORKBOAT | 5.00 | 0.80 | 1.05 | 39.95 |
| zinc | 1.00 | 0.16 | 0.00 | 0.08 |

# APPENDIX F

The RETS reports for the period 1973-1977 were feature analysed and coded on to the MVEE 1903 computer and the University DEC-PDP11 using a look up table to convert the keyword descriptors to numeric descriptors.

The following is a listing of the numeric data file that was used in the study. The final page of this appendix is a single page that has been converted into textual descriptors to show how the file would appear in text form.

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1197 APB,LUG,LASHING,ASSEMBLY,FRACTURE,SHOCK,LOAD,@
1198 APB,CANVAS,COVER,WEAR,MISUSE,EXPENDABLE,@
1199 SOILLAB,TRAILER,JACK,SCREW,ALIGNMENT,MOUNT,EQUIPMENT,@
1200 SOILLAB,TRAILER,PANEL,FRACTURE,SUBFRAME,SEAL,@
1201 MGB,BSB,CRACK,OVERLOAD,LUG,WELD,@
1202 ASPHALTMIXER,AXLE,BOLT,VIBRATION,TRAILER,@
1203 M2,TRANSMISSION,DIFFERENTIAL,CLUTCH,@
1204 M2,TRANSMISSION,KEY,SHAFT,ROTARY,ASSEMBLY,@
1205 APB,HYDRAULIC,BOLT,SHAFT,ARTICULATOR,@
1206 APB,CANVAS,COVER,WEAR,ROTTING,MISUSE,@
1207 APB,REPAIR,KIT,DIMENSION,DRILL,@
1208 DRILLRIG,LUBRICATE,PIN,SHAFT,SEIZE,@
1209 APB,HYDRAULIC,PIN,LUBRICATE,DESIGN,@
1210 M2,ENGINE,CONROD,ASSEMBLY,@
1211 SOILLAB,PANEL,DOOR,ALIGNMENT,@
1212 PUMP,LUBRICATE,VACUUM,MOISTURE,HARDBOARD,PAINT,@
1213 TANK,FABRIC,MEMBRANE,SEAM,FUEL,LINER,@
1214 TRACKLAYER,ENGINE,VIBRATION,CARBURRETOR,FRACTURE,GUARD,@
1215 ROADROLLER,VIBRATION,WEAR,ACCEPT,HAMMER,@
1216 MGB,MARKING,VEHICLE,POSITION,@
1217 MGB,BEARING,THRUST,LOCTITE,ASSEMBLY,@
1218 MGB,BEARING,JOURNAL,LOCTITE,ASSEMBLY,@
1219 MGB,ROLLER,NUT,RETAINER,@
1220 M2,CHAIN,HOOK,DIMENSION,@
1221 TANK,FABRIC,TEST,SAFETY,INSTRUCTION,@
1222 M2,CRANE,HINGE,NEW,CLEARANCE,@
1223 APB,WELD,FRACTURE,MANUFACTURE,METHOD,@
1224 APB,CORROSION,CAVITY,PAINT,FB,@
1225 CRUSHER,SAW,CLOG,STONE,OPERATION,DIMENSION,@
1226 TRAILER,REVERSE,STEERING,GEOMETRY,@
1227 GRAVELWASHER,ELECTRIC,START,EARTH,WIRE,SOCKET,@
1228 TRACKLAYER,VIBRATION,FRACTURE,OVERLOAD,WEP,REINFORCE,@
1229 TRACKLAYER,WEAR,HYDRAULIC,HOSE,ARMOUR,VIBRATION,@
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1231 TANK,STEEL,BP,DIMENSION,@
1232 N8TANKBRIDGE,HINGE,PIN,SURFACE,RECLAIM,DESERT,LUBRICATE,@
1233 M2,ENGINE,SEIZE,@
1234 N8TANKBRIDGE,SPRING,CLIP,FRACTURE,@
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1236 M2,WELD,FILLET,FRACTURE,BEARING,@
1237 ROADROLLER,AXLE,BEARING,SEAL,HUB,@
1238 N8TANKBRIDGE,CORROSION,JAW,INHIBIT,STORAGE,@
1239 APB,LASHING,JACK,SEIZE,DIMENSION,@
1240 MGB,STEEL,PIN,MATERIAL,@
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1243 MIXER,SUSPENSION,SPRING,TOW,DIMENSION,@
1244 M2,CORROSION,BRACKET,@
1245 DRILLRIG,HYDRAULIC,JAW,@
1246 ROADROLLER,VIBRATION,CASING,FRACTURE,STEERING,FILLET,@

## APPENDIX G

If one describes the probability of an item of feature failing as a multi-valued function related to stress, strength, time, environment, and other factors, then the Failure Characteristic can be described as a characteristic of the shape of the failure probability surface.

If the probability of failure surface is multi-valued at any point, i.e. it has a fold in the surface, then the item or feature in question is said to have a catastrophic failure characteristic.

If a design feature has a catastrophic failure characteristic then in the event of the design aspects being incorrect or marginal, and one unit of the design failing, then it can be expected that all the items produced will fail.

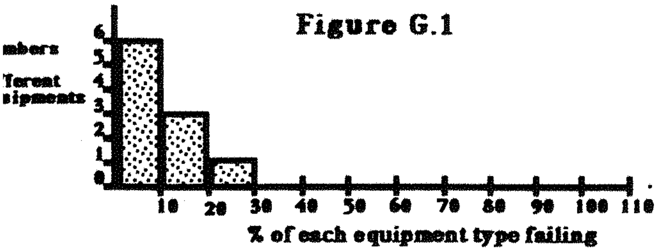
To check the failure characteristic one analyses all the failure records in the history file feature by feature and equipment by equipment. The failure characteristic is found by summing the percentage failing, for a specific equipment, of a specified feature or item for each record in which the feature occurs for a given time window (which must be chosen with care). If a feature has had 100% cumulative failures for a given equipment it is said to have a catastrophic failure characteristic. As the records are sent in by different users, is is not normally possible for any one user to see all the equipment failures. Hence there is some imprecision in the data.

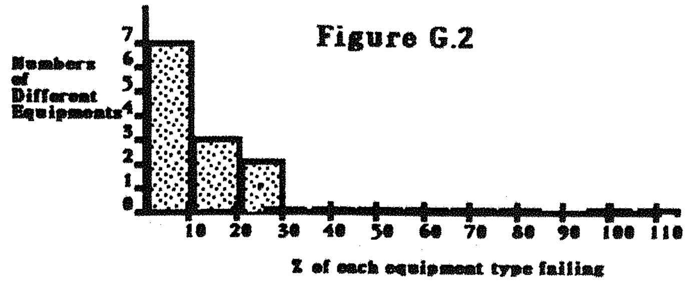
Figure G.1 shows a feature with a stable failure characteristic. As can be seen, within the given time interval, 6 equipments have had less than 10% failures, 3 equipments have had between 10% and 20% failures, and 1 equipment has had between 20% and 30% failures. Figure G.2 is similar.

Figure G.3 shows a feature with a catastrophic failure characteristic. In this case the failure rates for different equipments are similar to G.1 for the 0% to 30% range. However 2 equipments had failure percentages of 100% or greater. This is also seen in figure G.4 but in this case only one case of 100% failure has occurred. This is a case which should be looked at carefully and it would pay users to check on specific records and failure modes and effects.

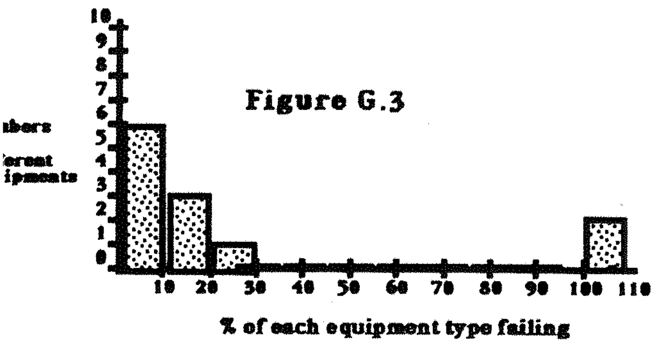
As specific examples, figure G.5 and G.6 show how the data can be grouped by a feature. G.5 shows a number of features related to surface protection or treatment. They all show a catastrophic failure characteristic. Plating, if it is inadequately specified or applied, will always fail. This can be seen in the automotive industry. Similarly with paint and case hardening. G.6 shows two stable features. Problems of alignment and clearance are generally due to manufacture, damage, or wear. Occasionally mistakes are made in the initial prototype stage when parts do not fit but this is not regarded as a normal use pattern and is hence disregarded.

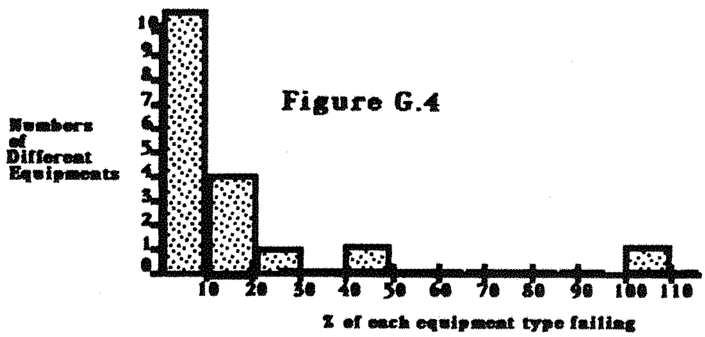
This appendix contains details of the failure characteristic analysis of the complete data set and they are in barchart form following figures G.1 to G.6. The shape of the graph/barchart is the important aspect, and for clarity the only textual detail in the charts is the feature keyword.




Examples of Stable Failure Characteristics




Examples of Catastrophic Failure Characteristics

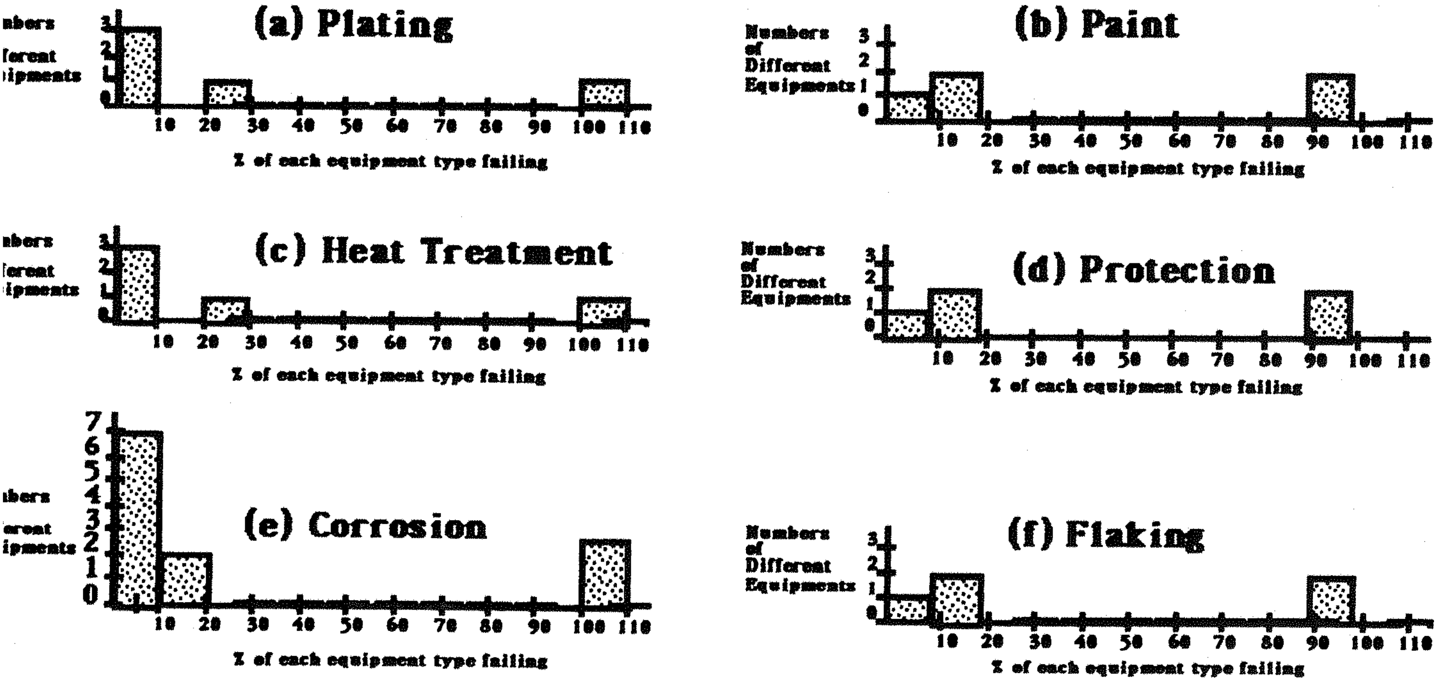



Figure G.5 Features relevant to Surface Protection or Treatment

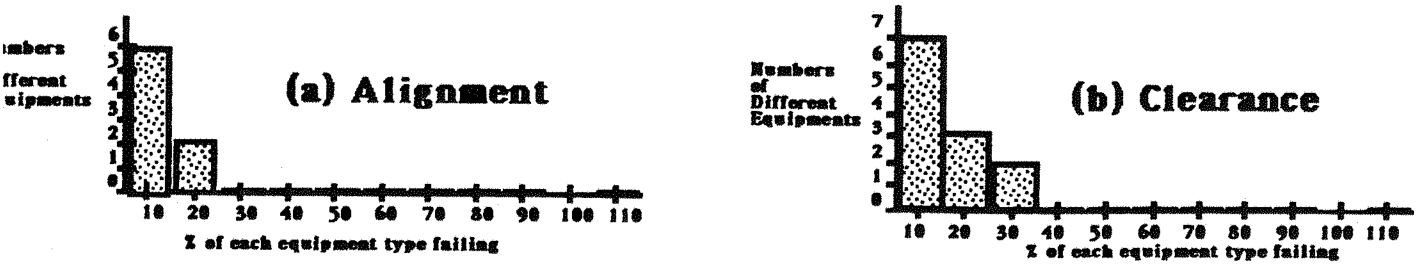
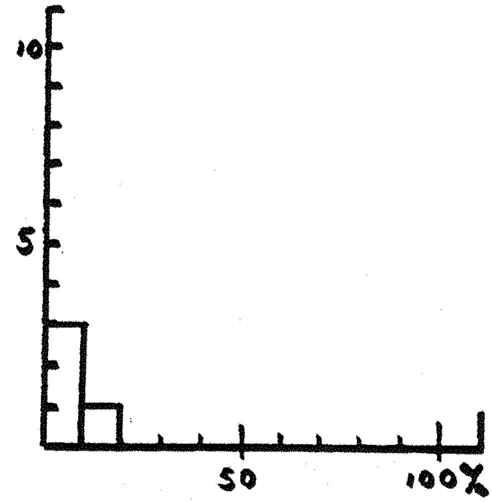



Figure G.6 Examples of Features with Stable Failure Characteristics



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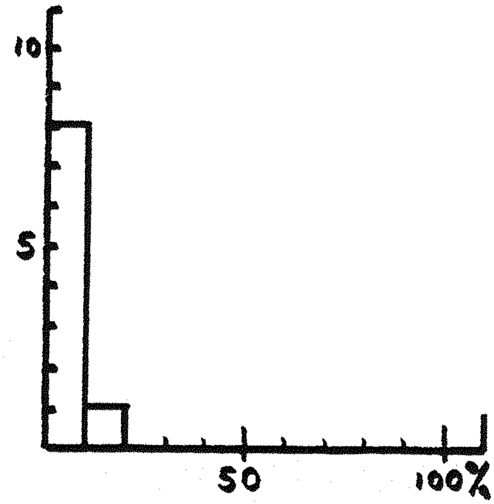
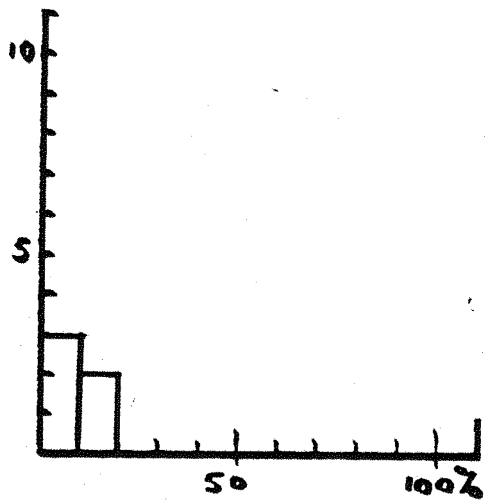
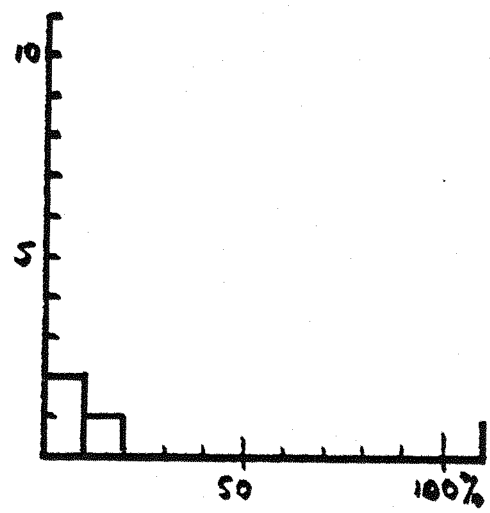


ACCESS



ACCESSORY



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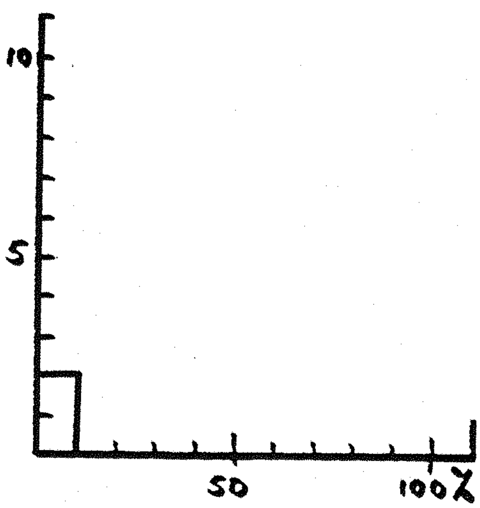
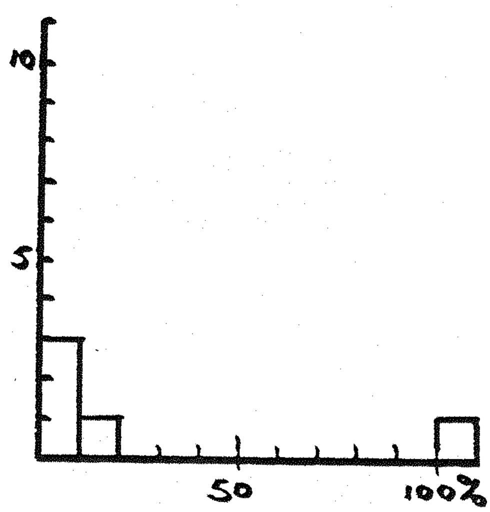
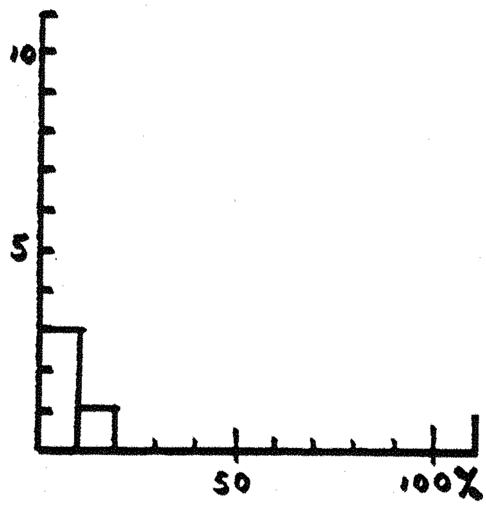


ADAPTOR



ADHESIVE



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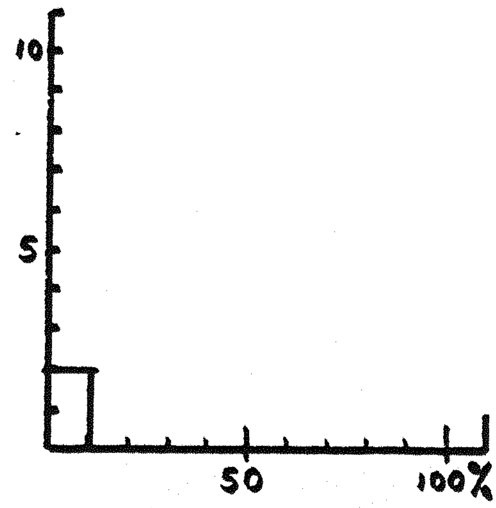

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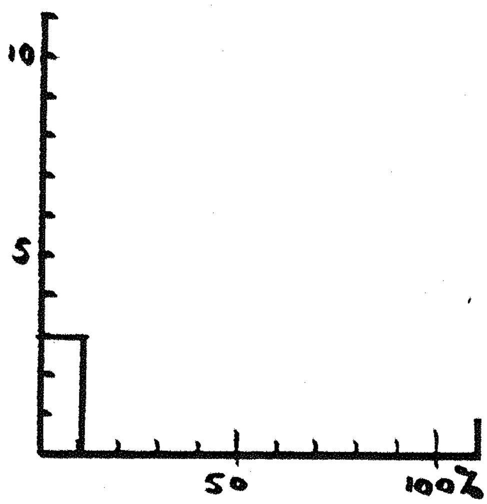

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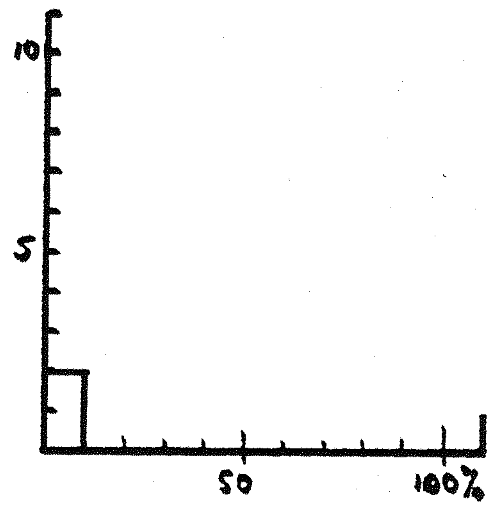
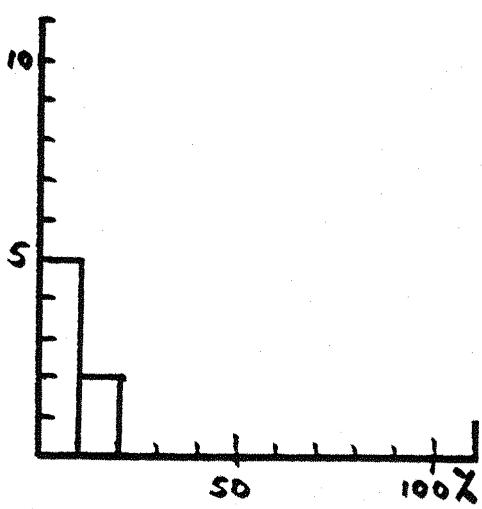


AIRCOOLED



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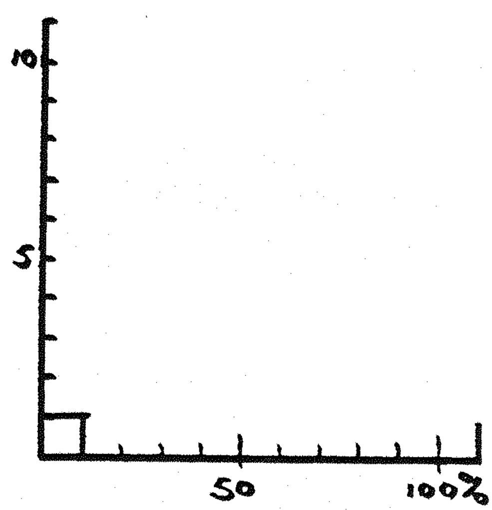

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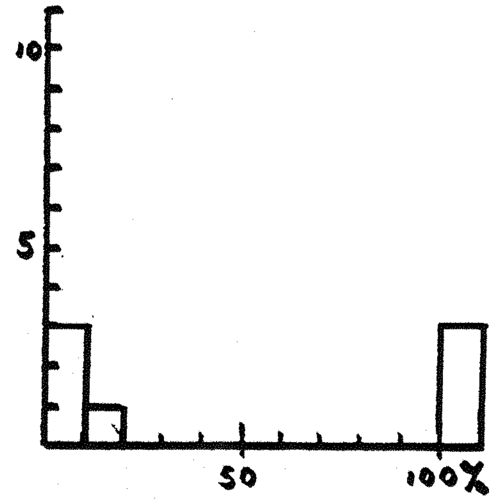


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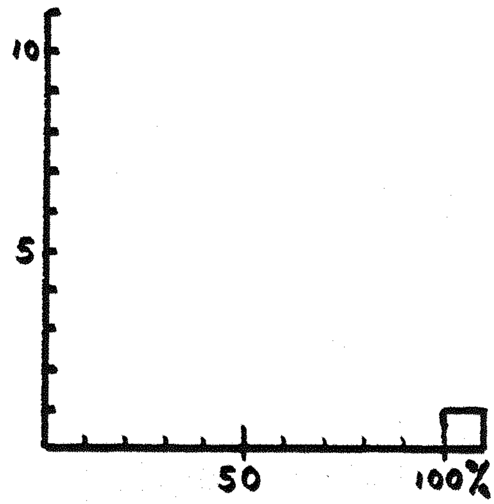
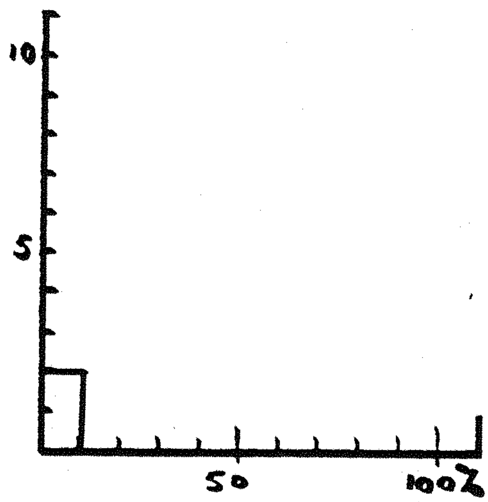



ANCHOR

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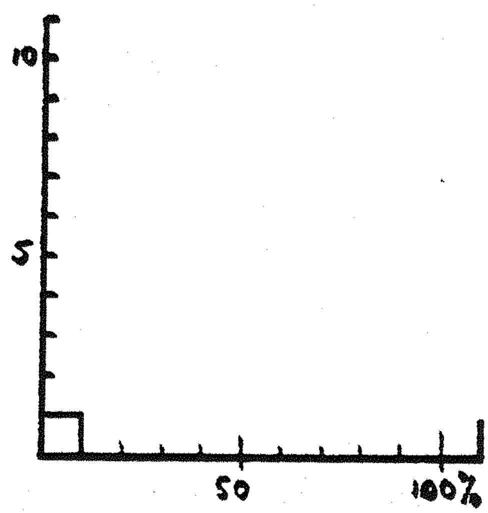


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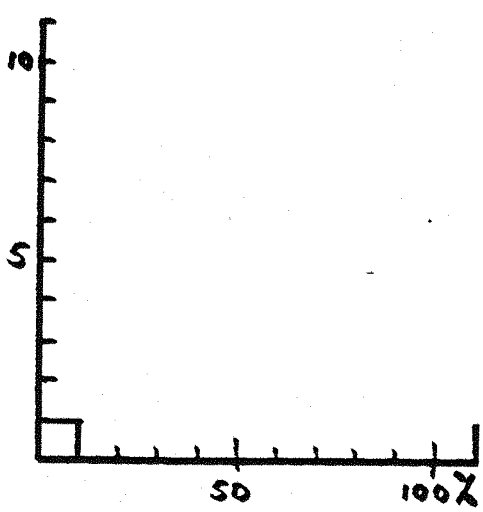


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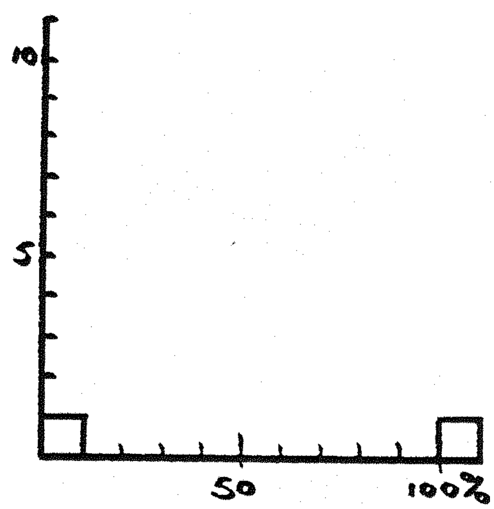


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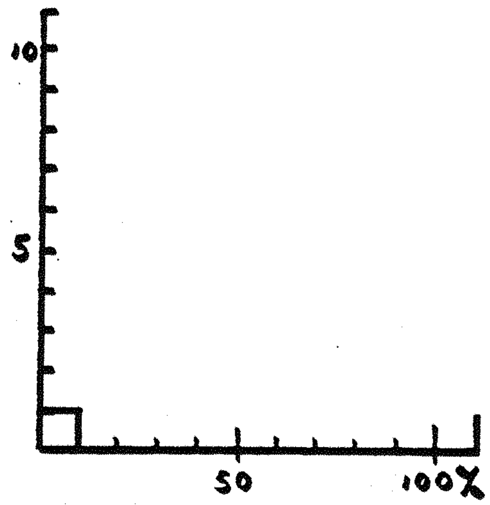


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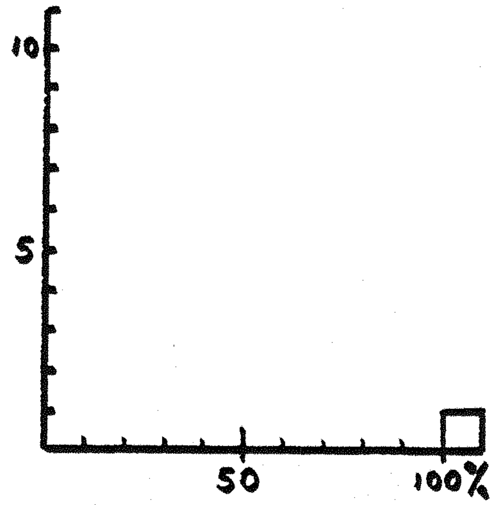


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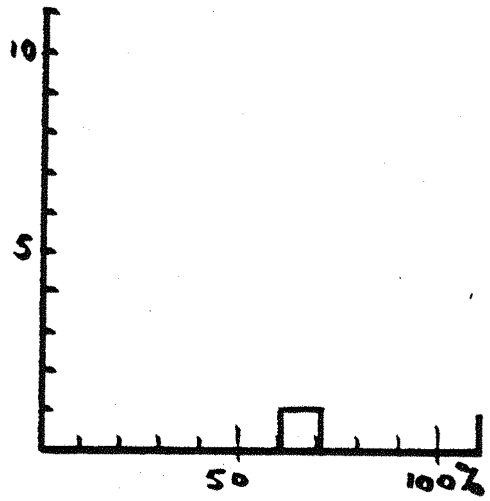


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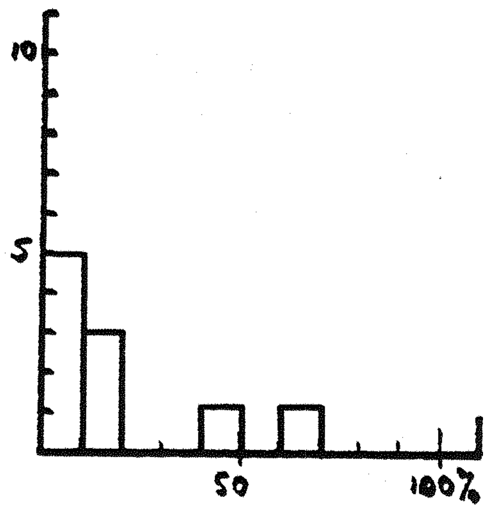


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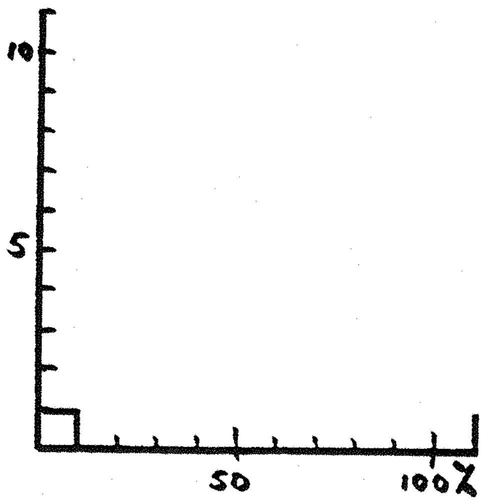


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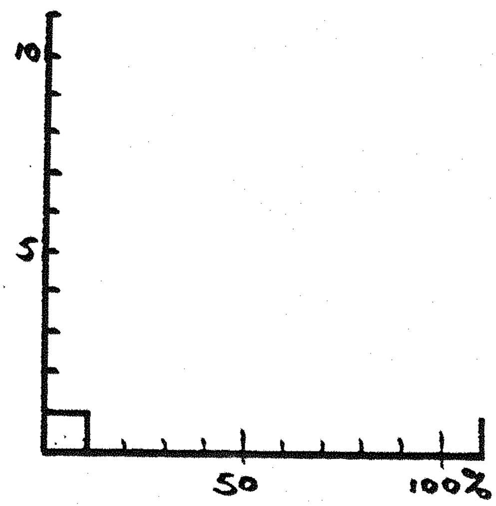


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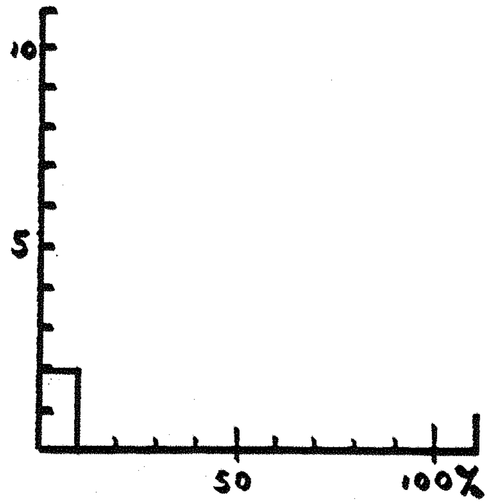


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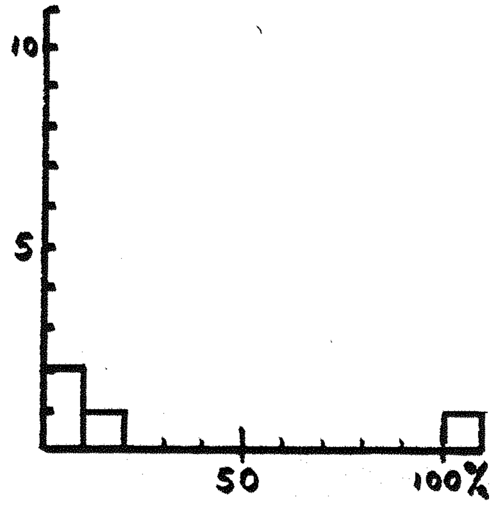


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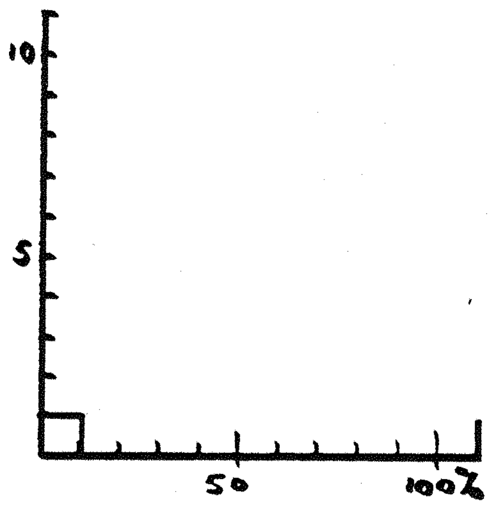


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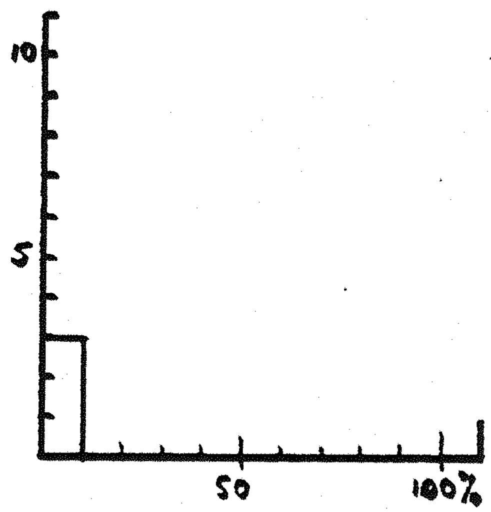


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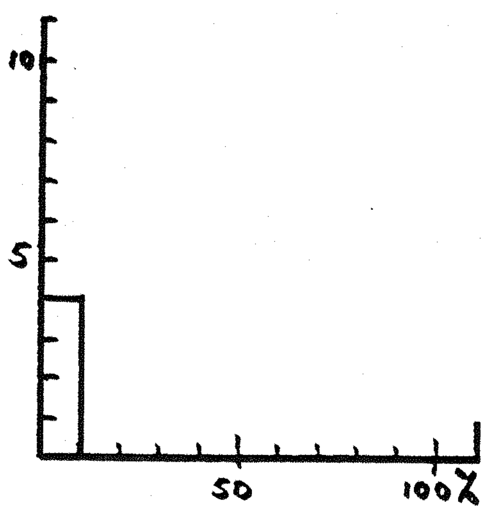


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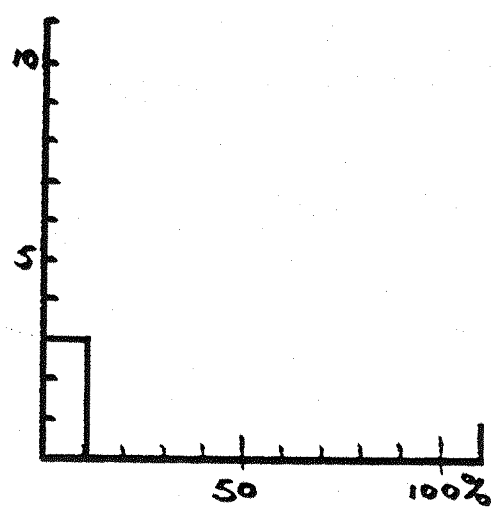


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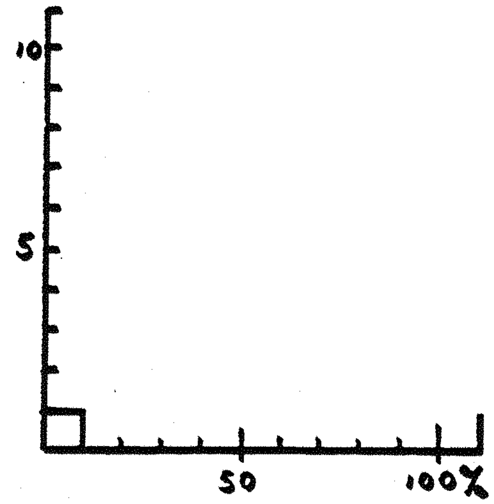


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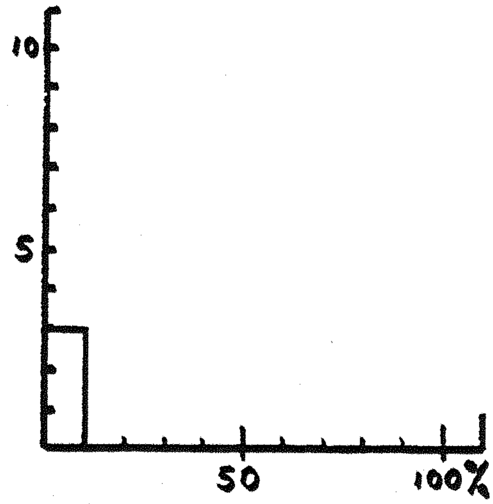


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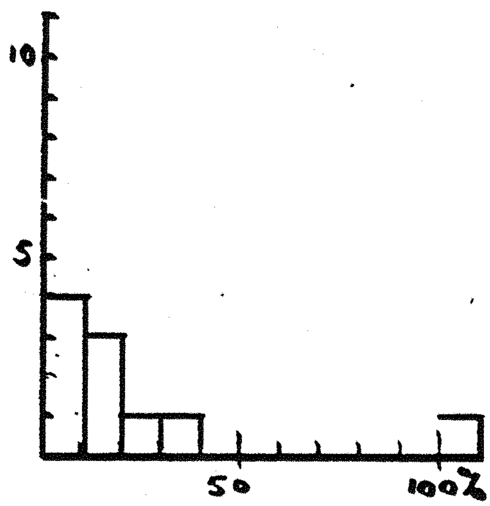


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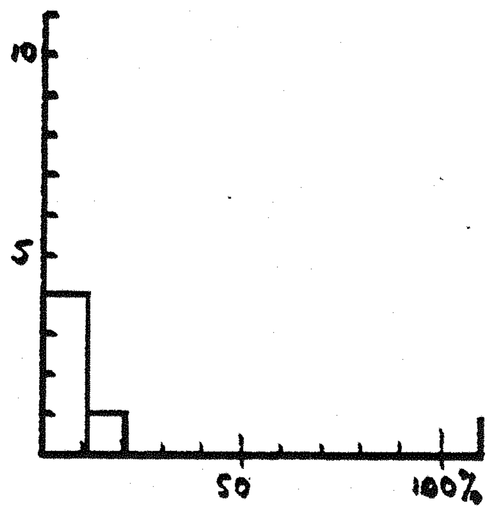


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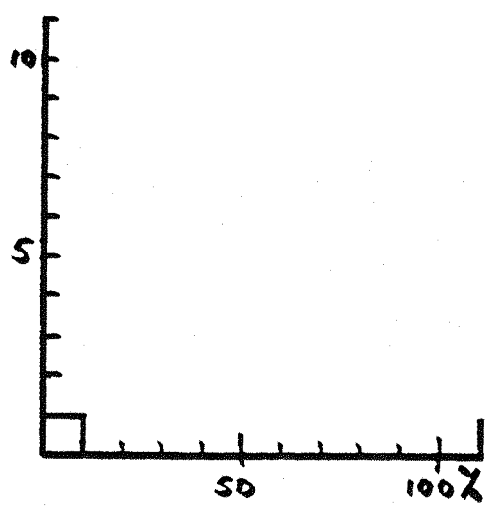


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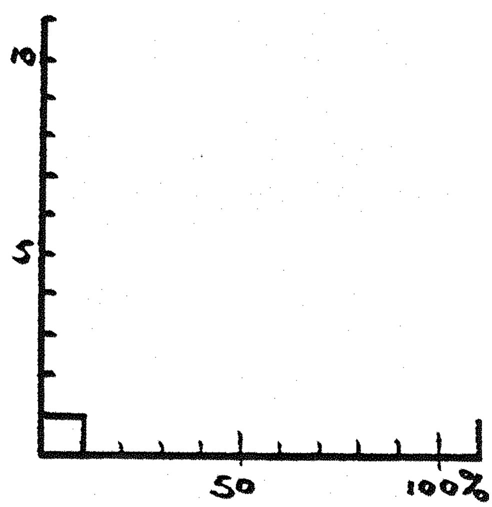


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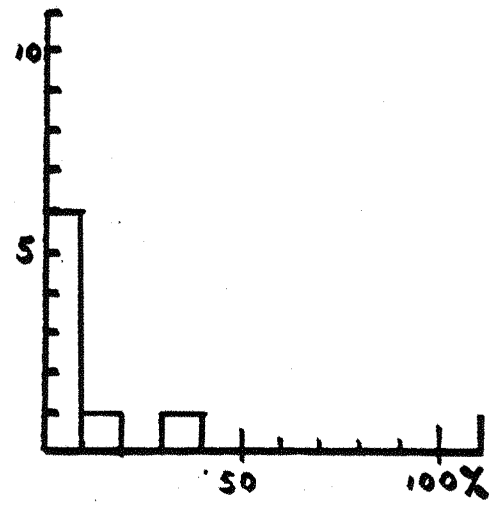


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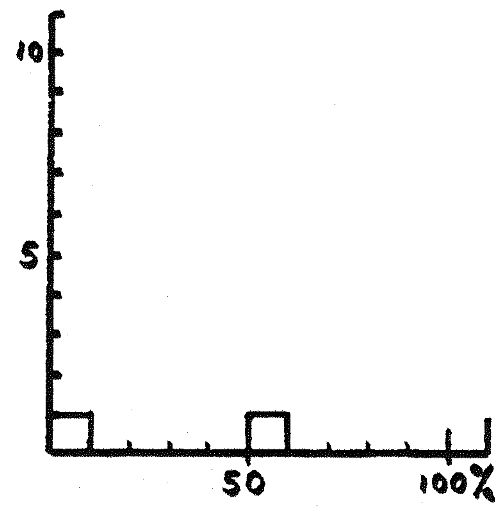


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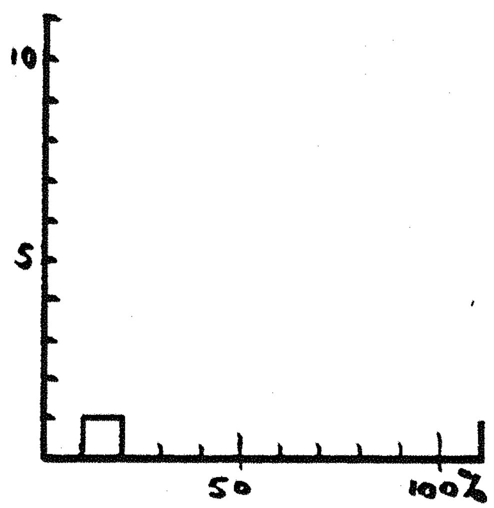


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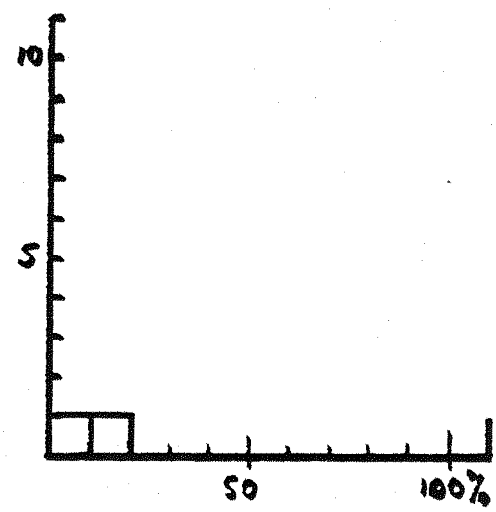


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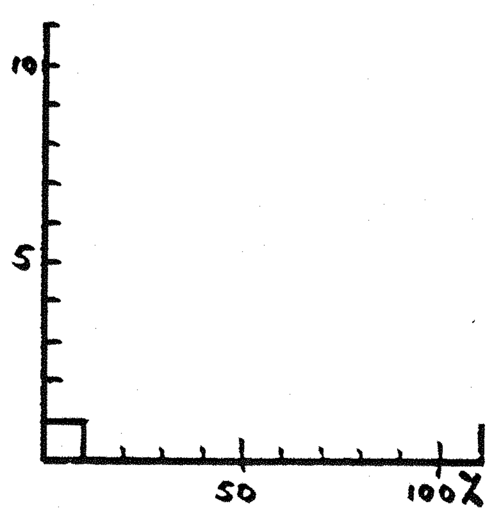


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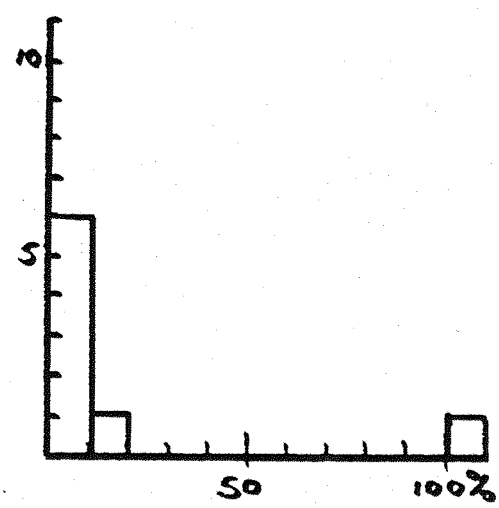


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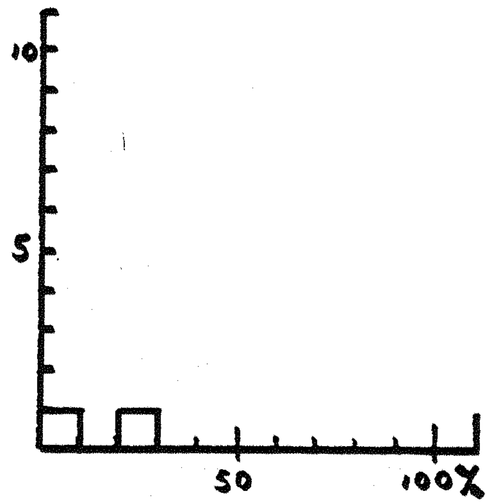


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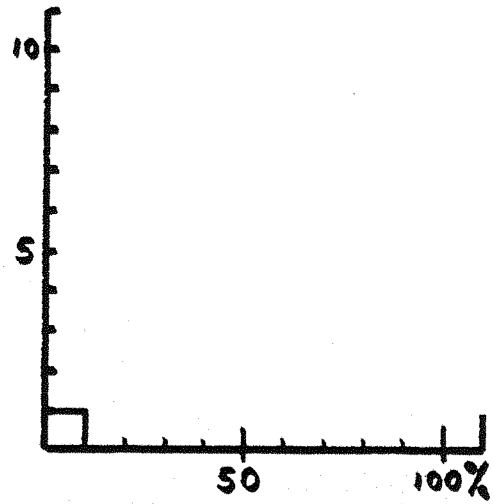


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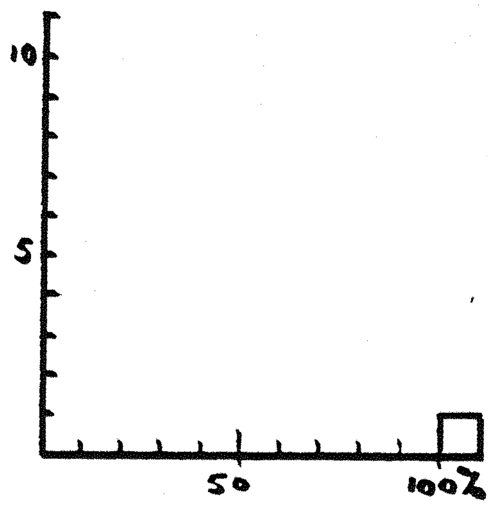


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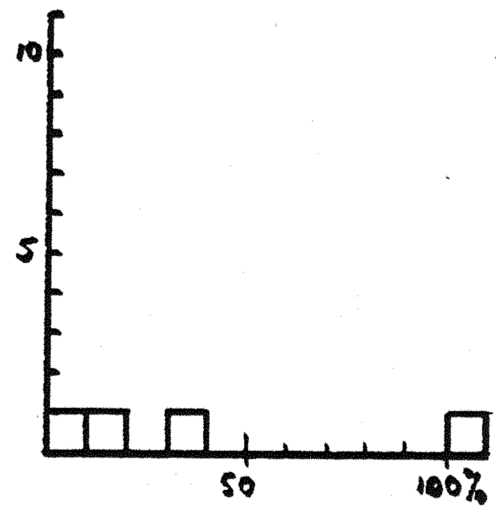


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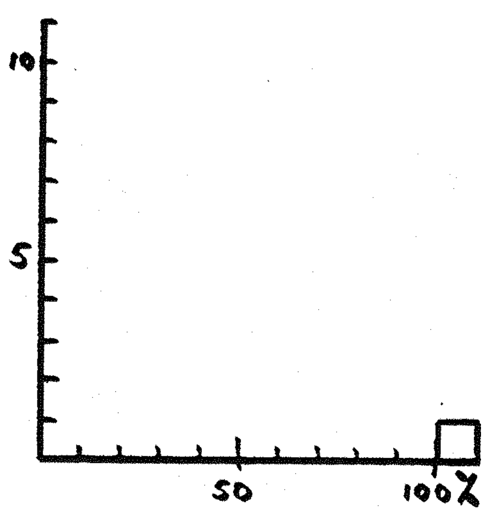


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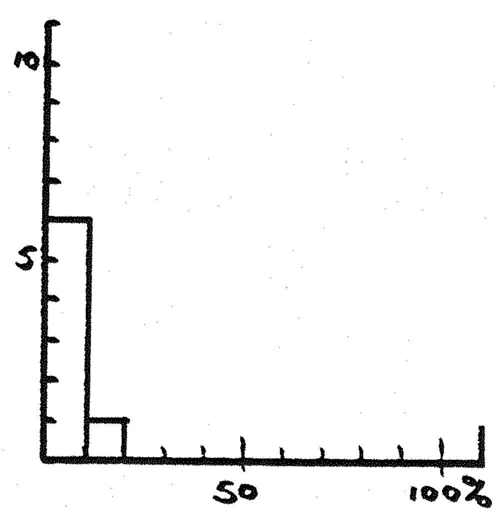


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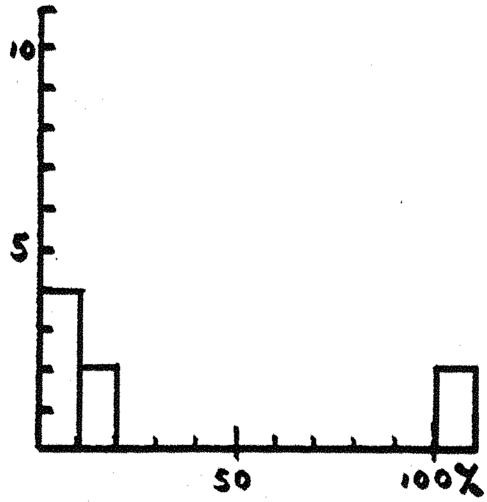


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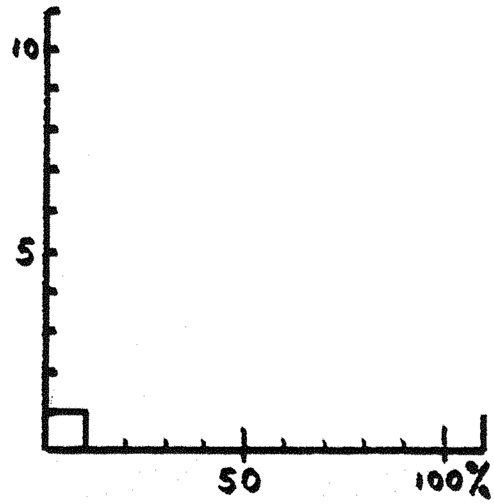


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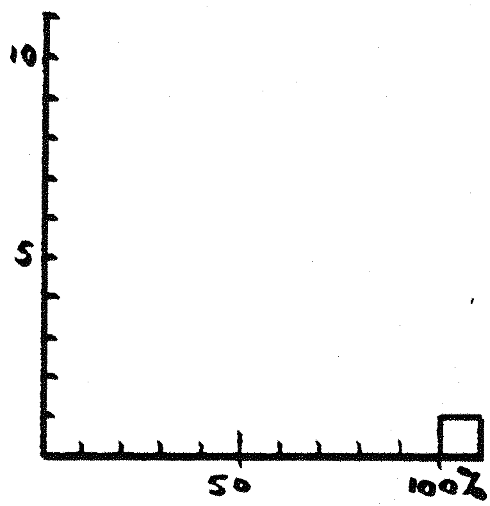


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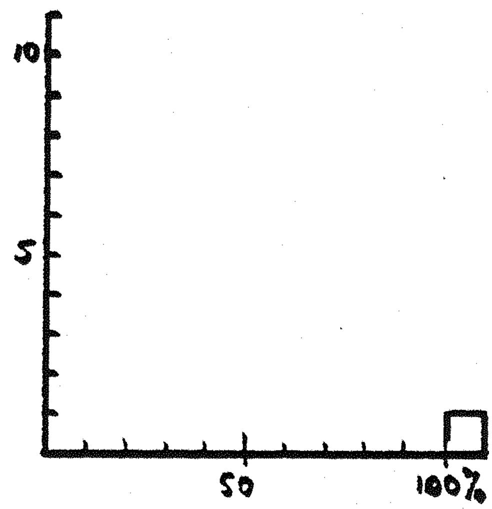


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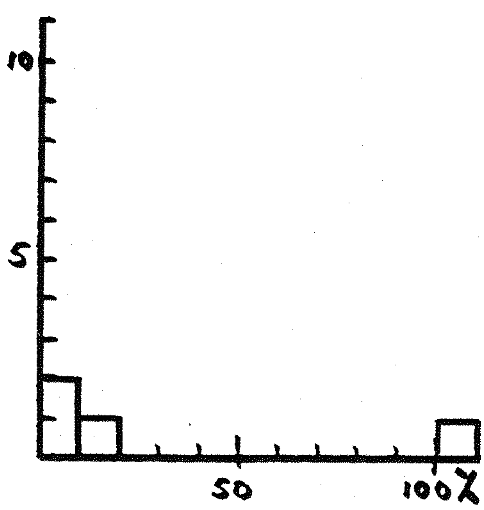


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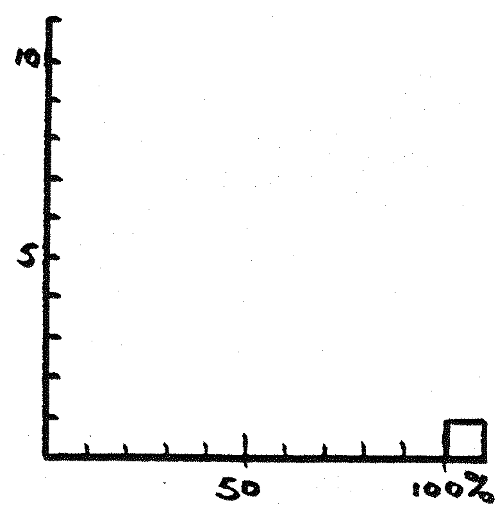


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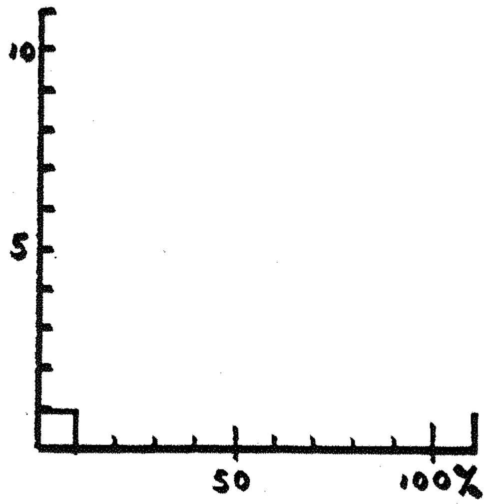


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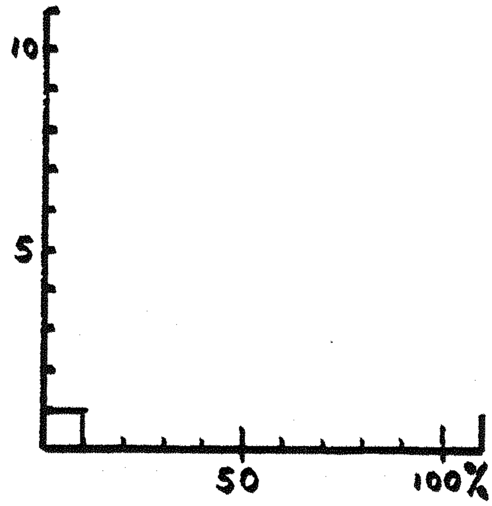


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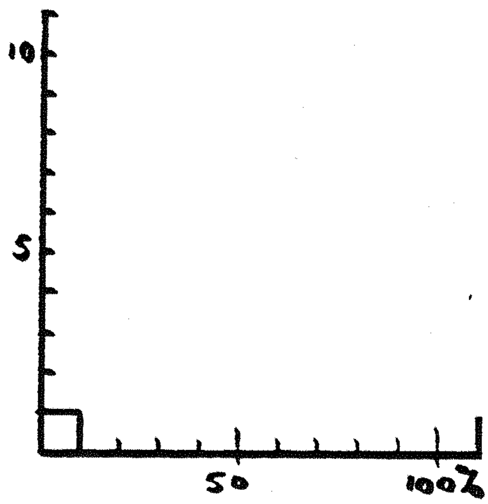


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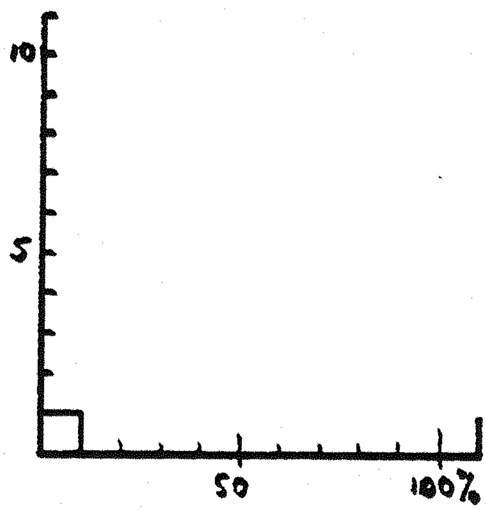


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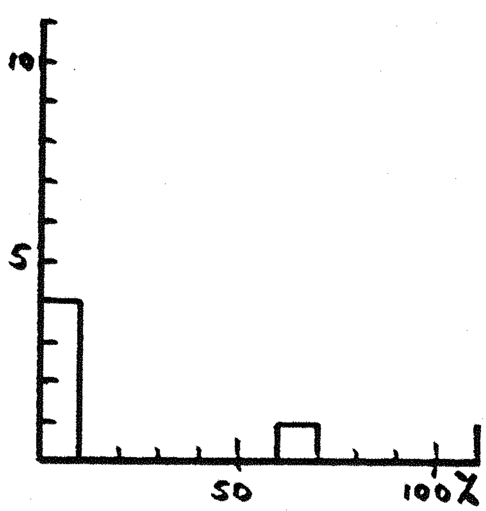


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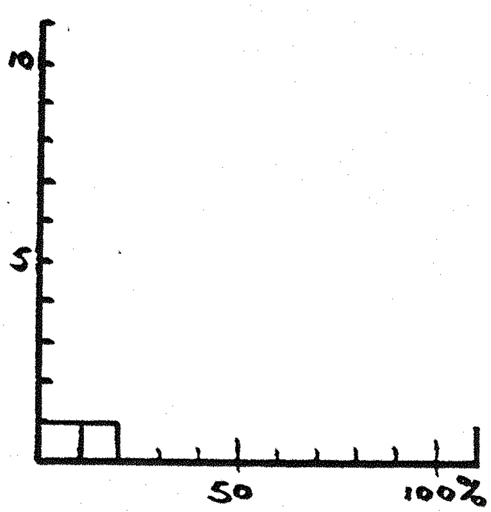


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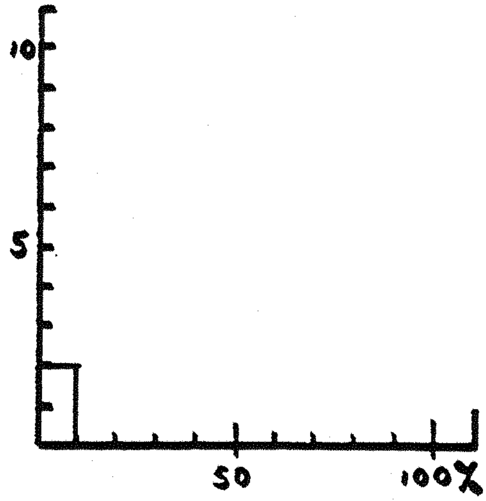


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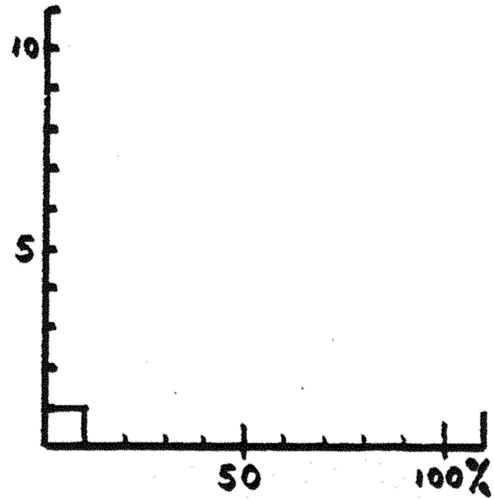


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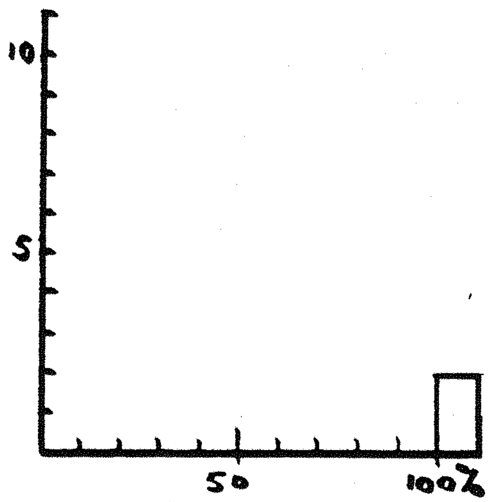


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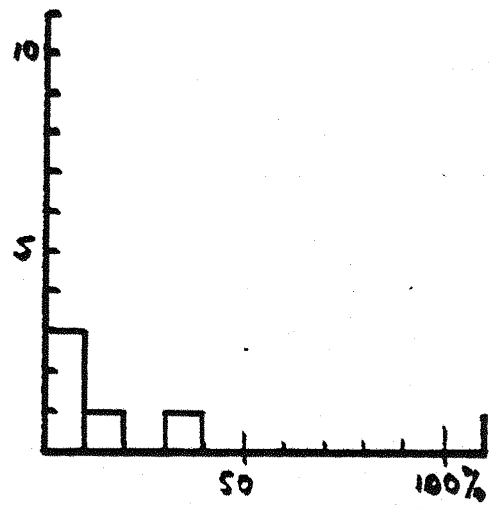


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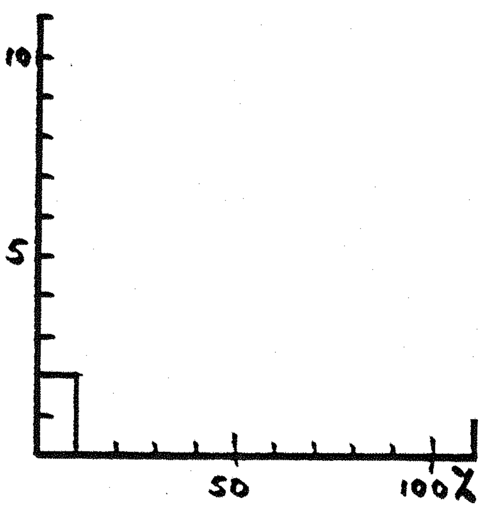


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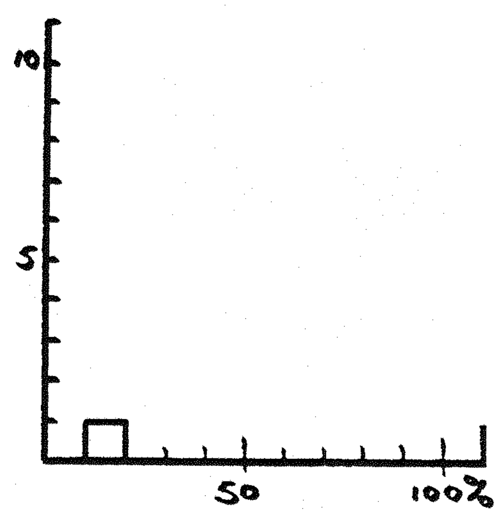


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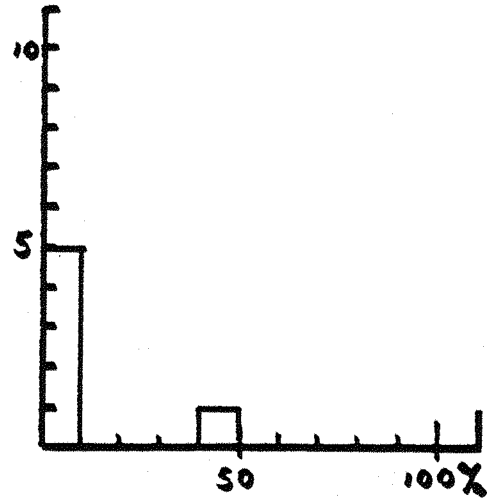


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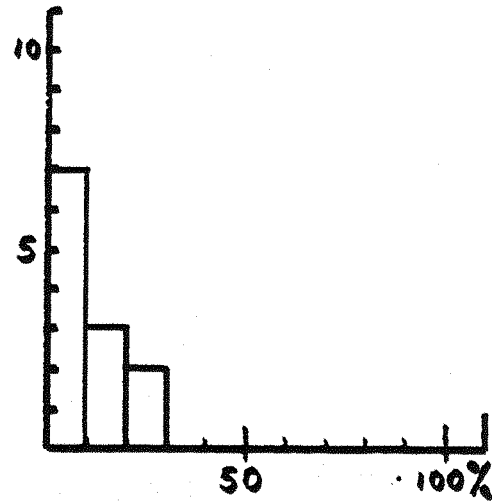


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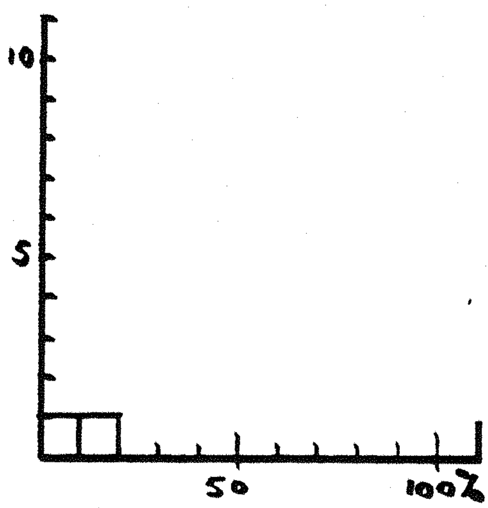


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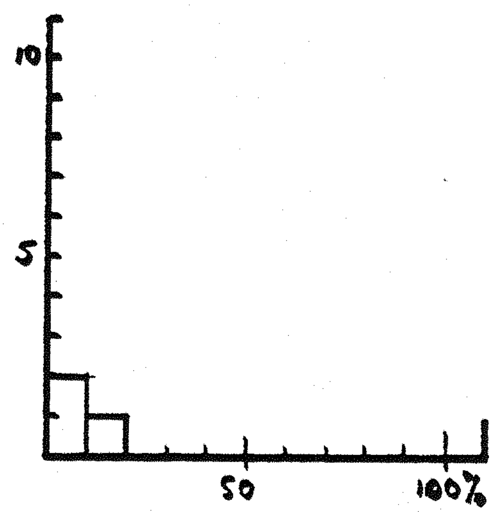


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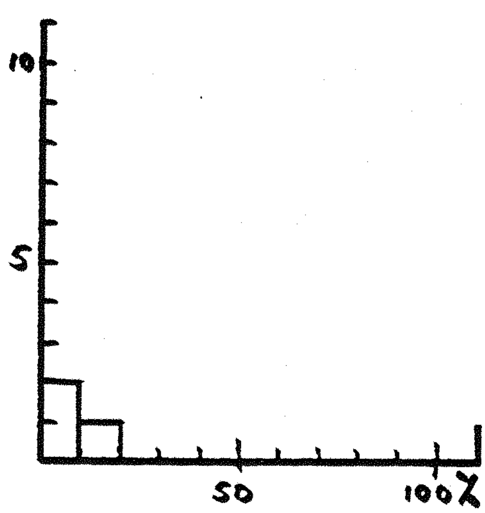


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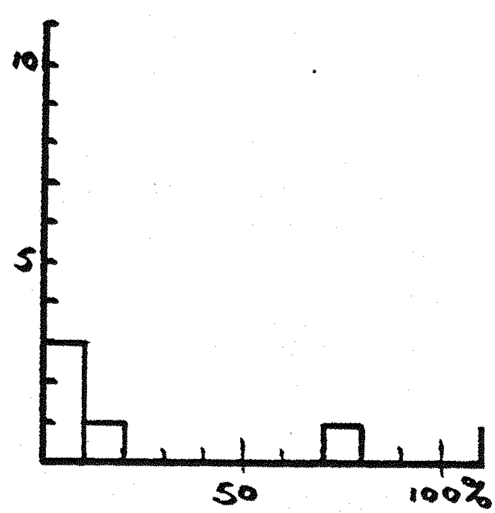


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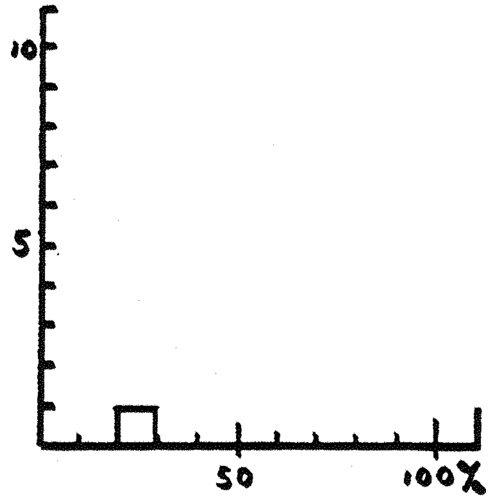


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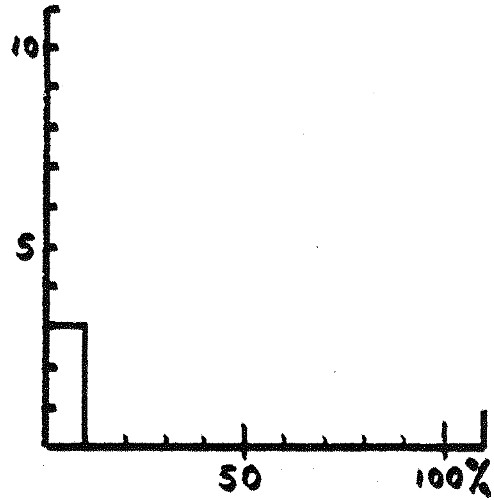


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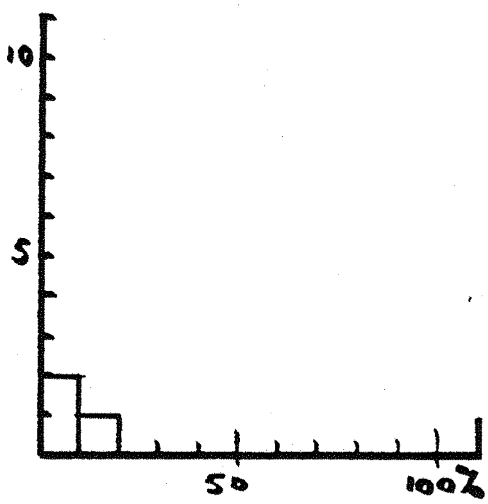


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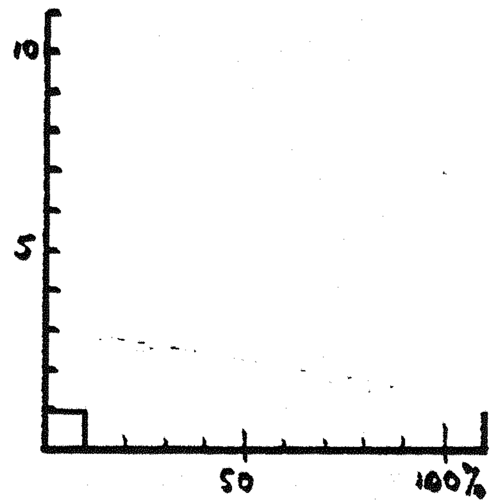


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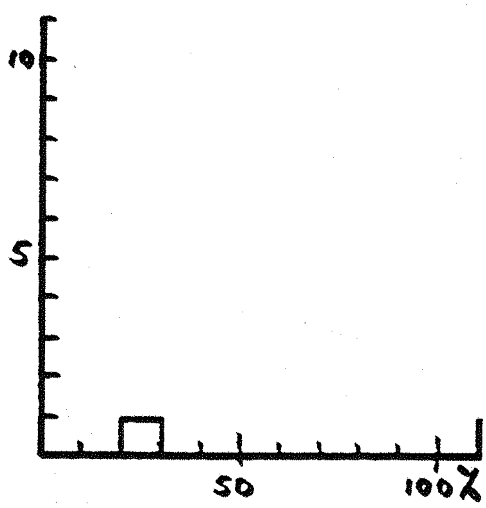


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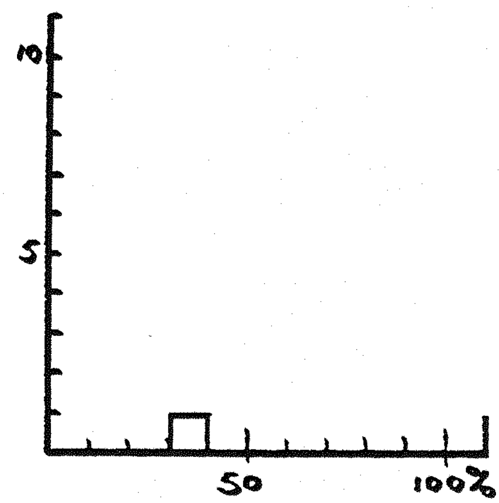


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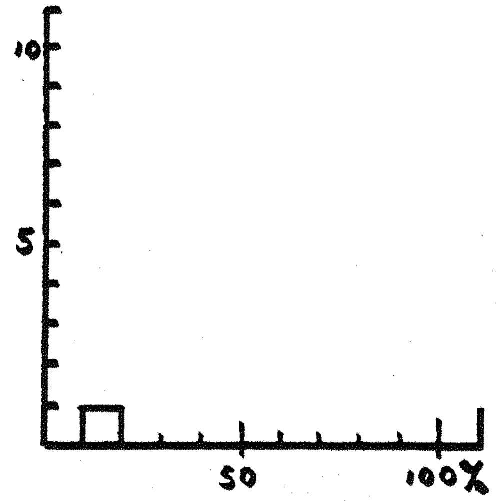

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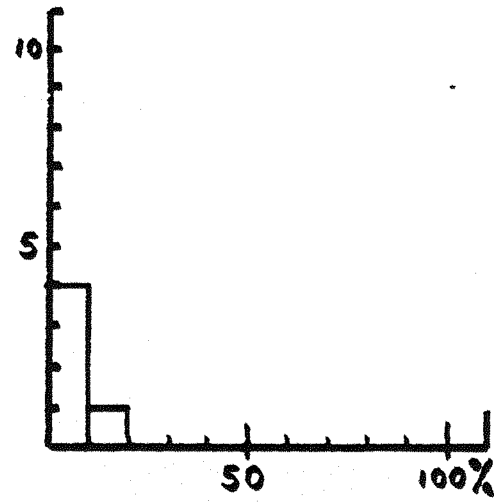

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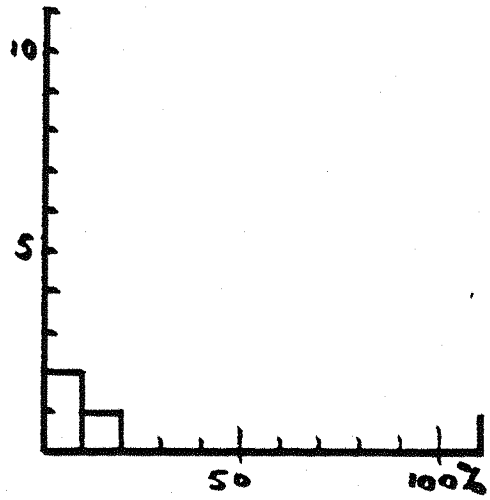

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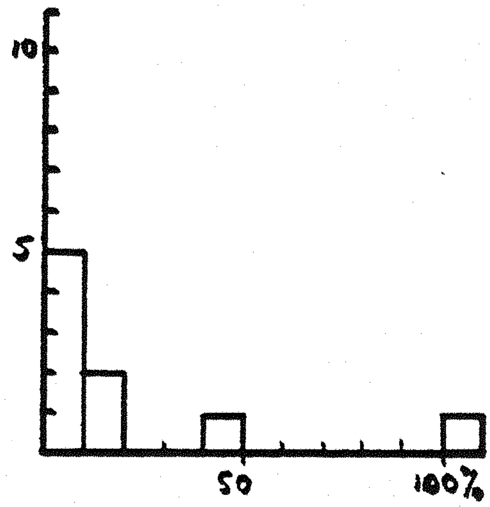

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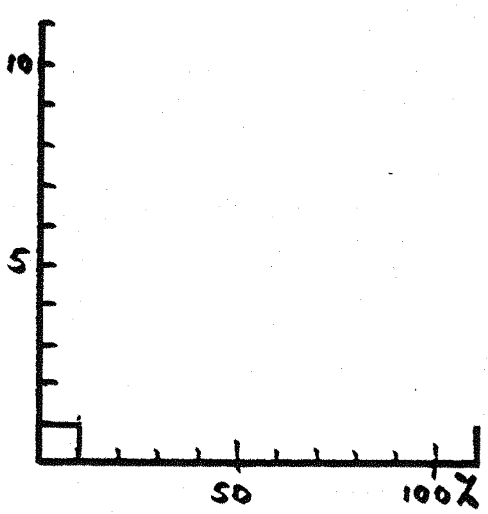

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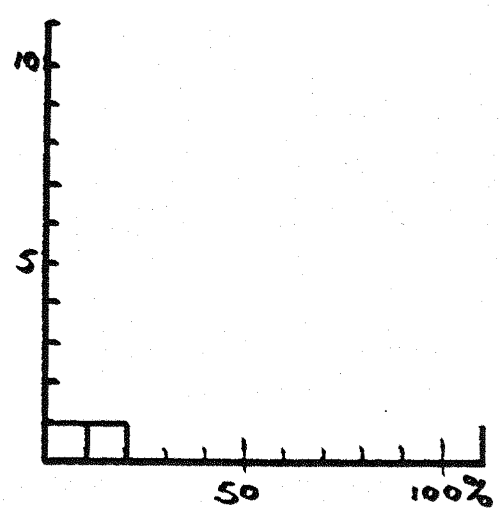

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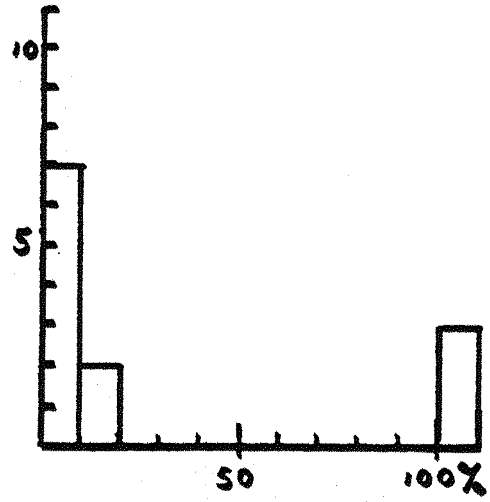


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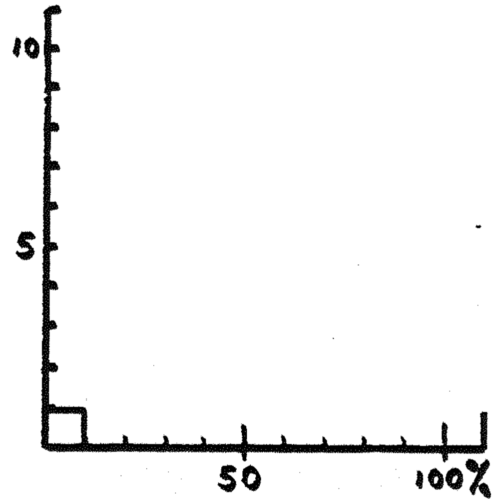


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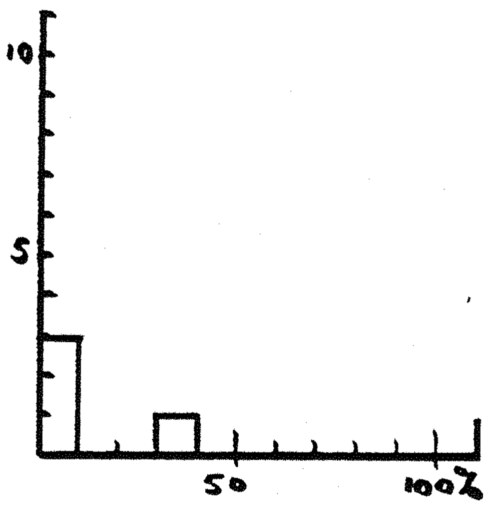


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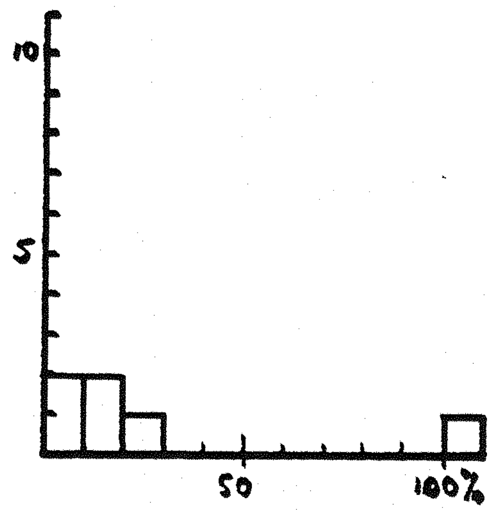


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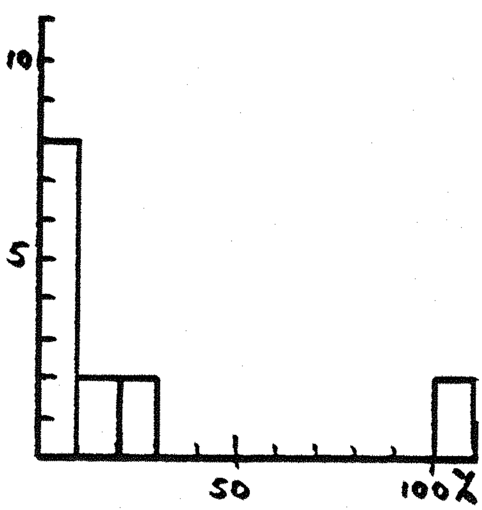


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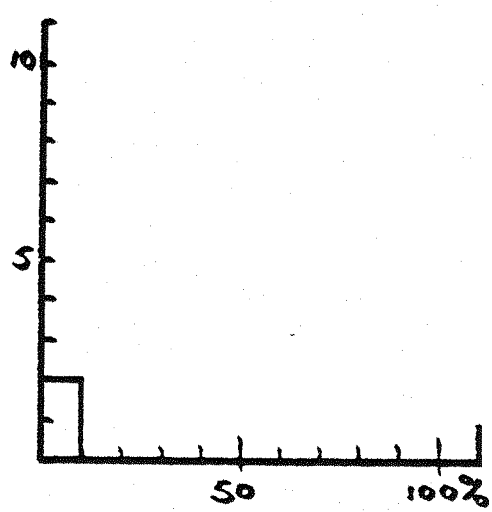


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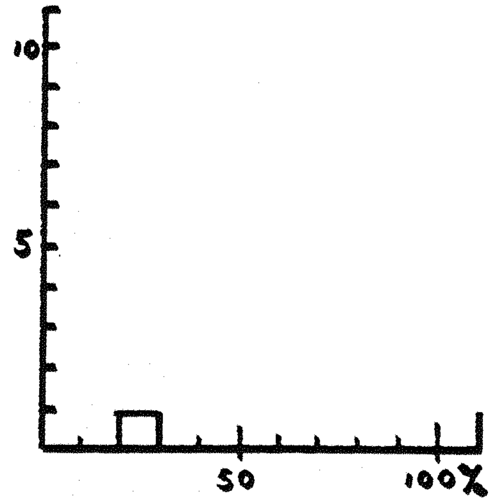


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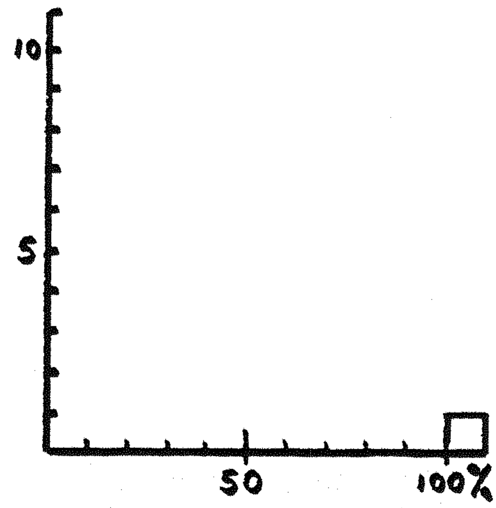


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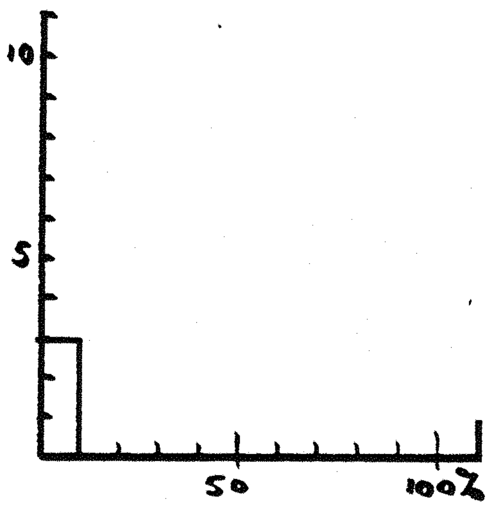


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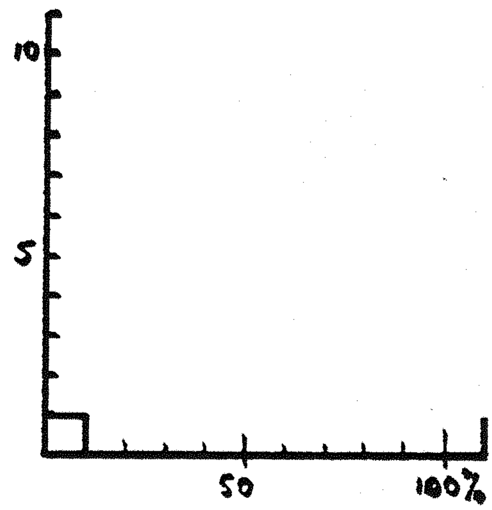


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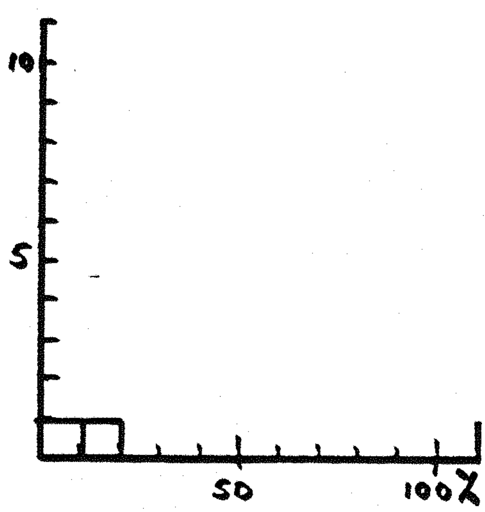


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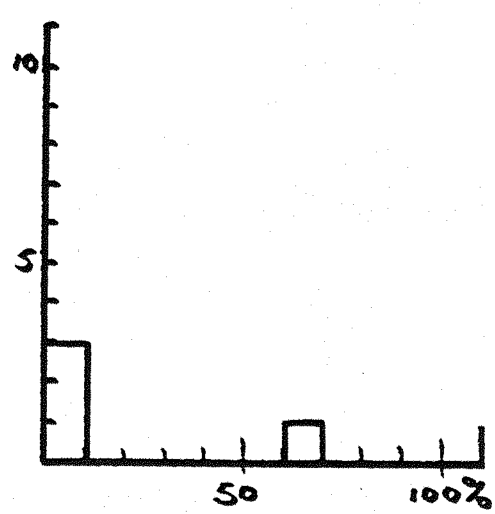


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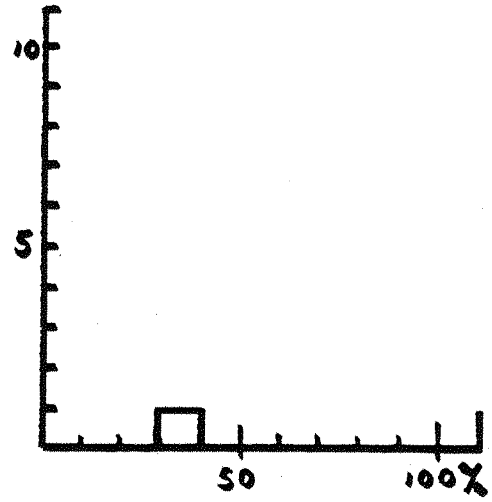


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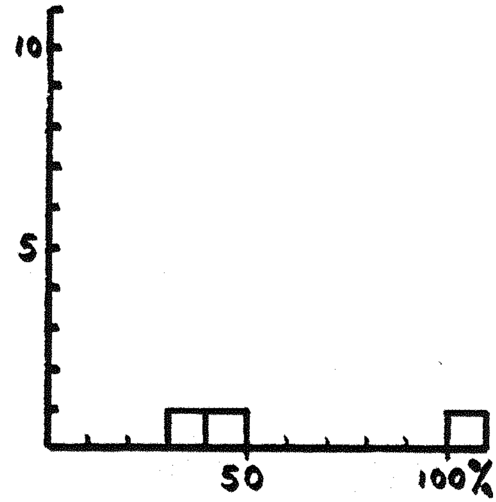


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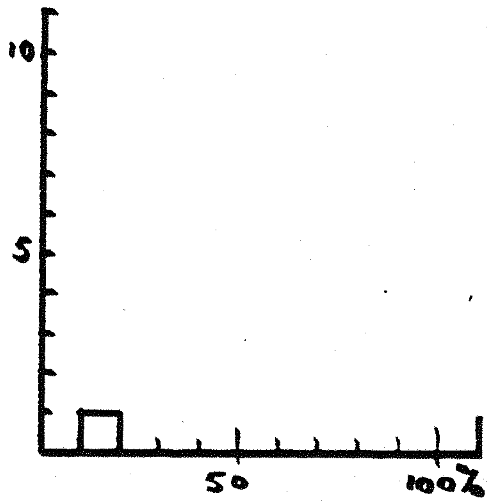


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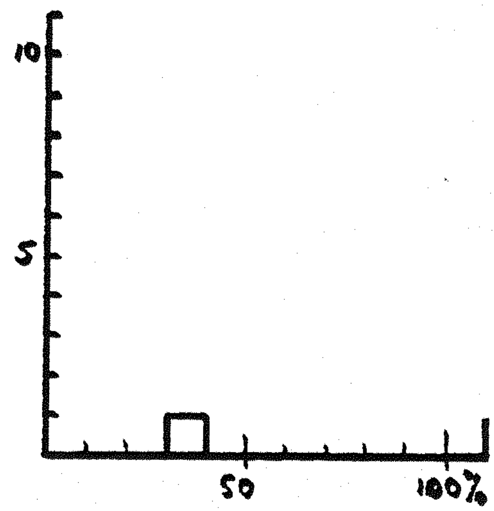


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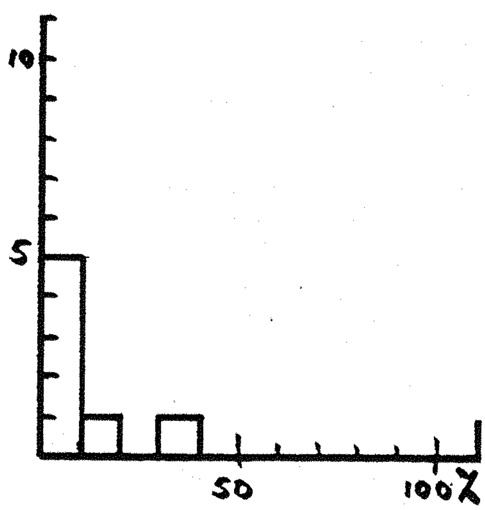


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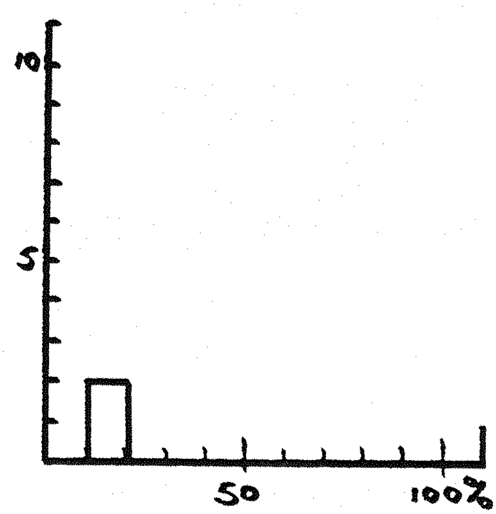


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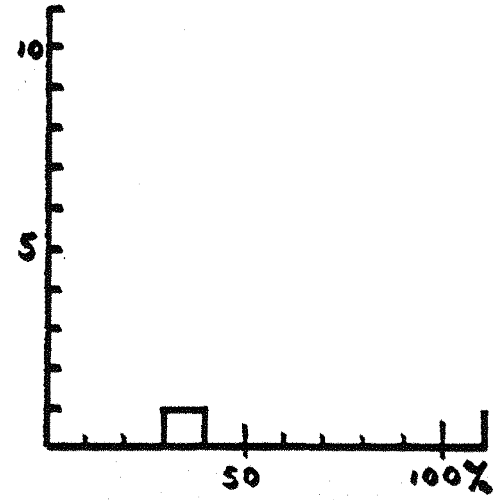


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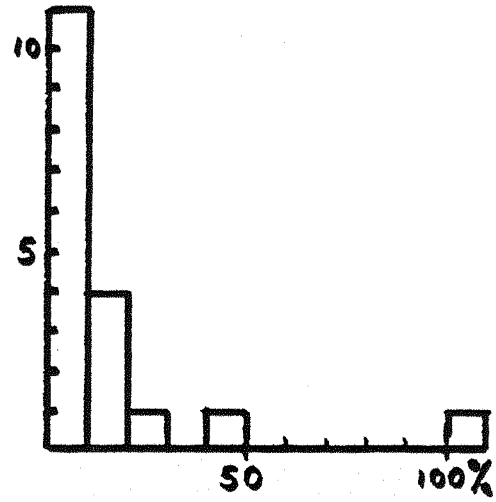


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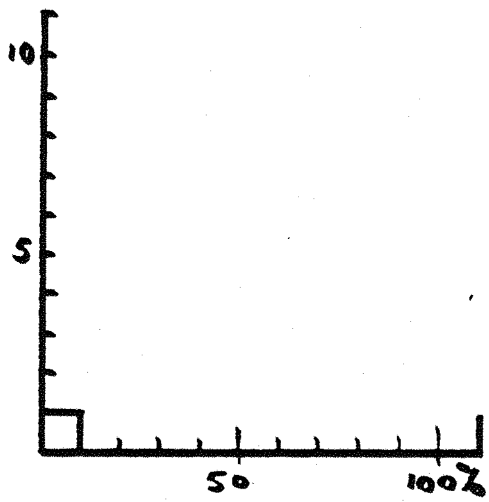


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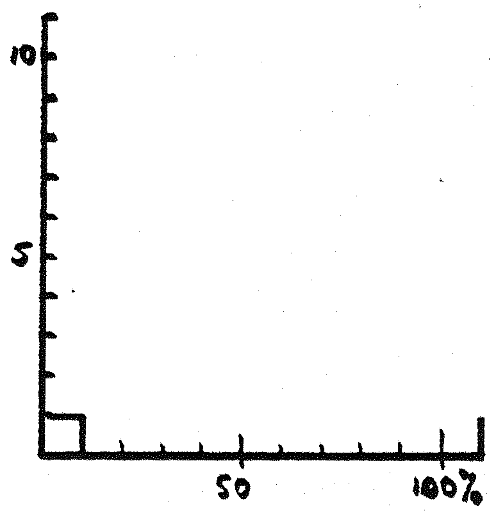


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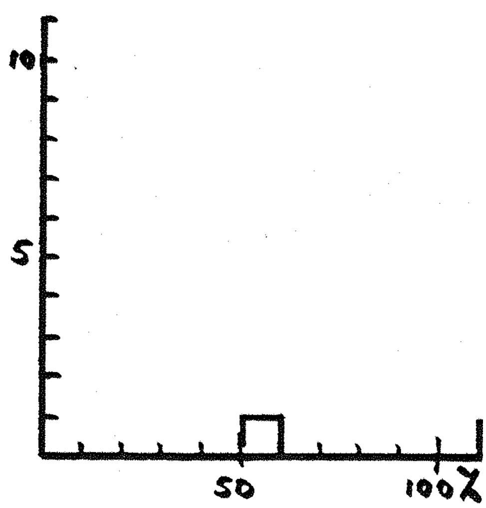


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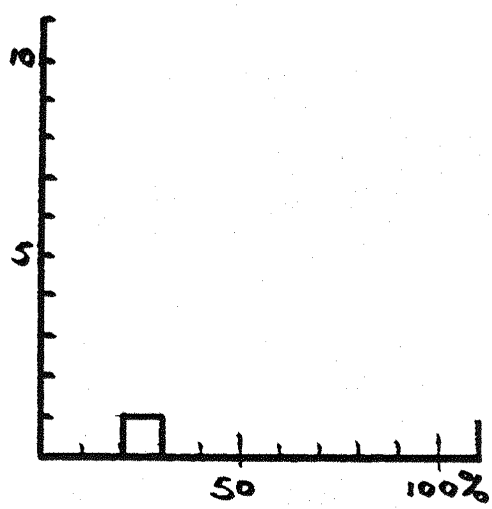


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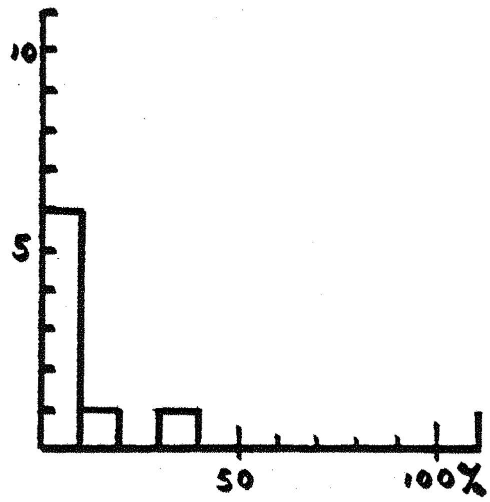


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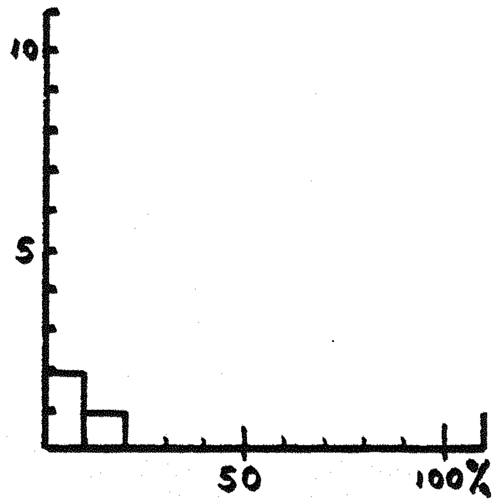


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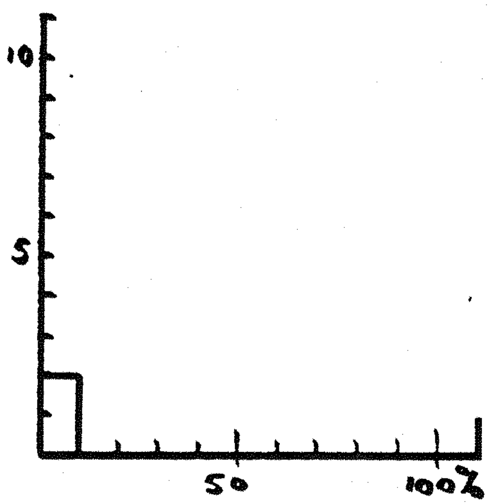


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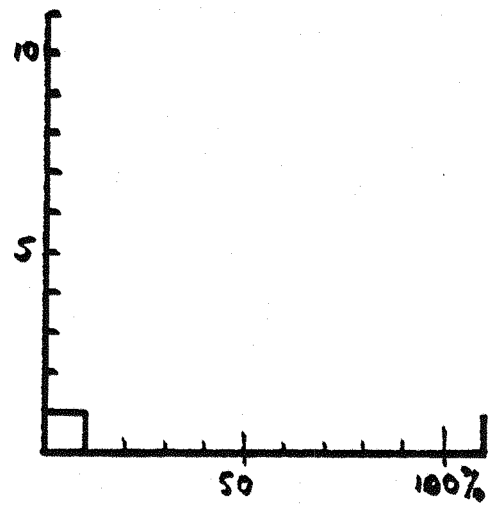


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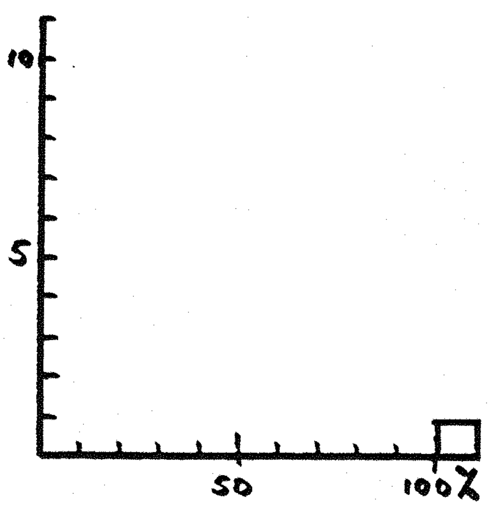


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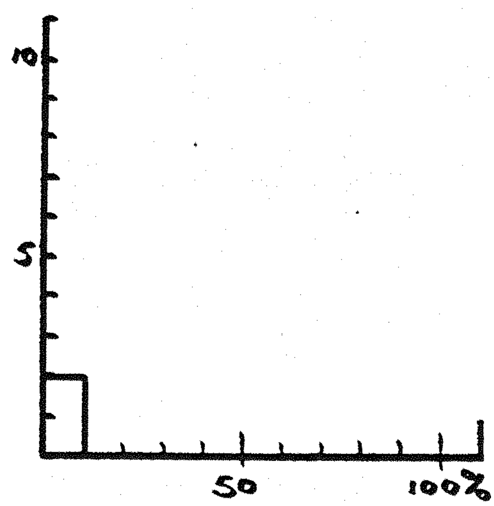


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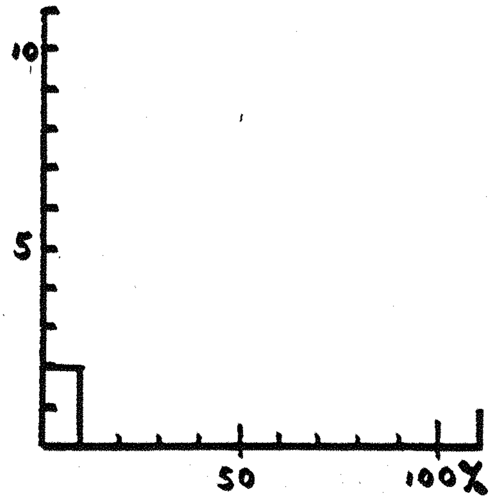

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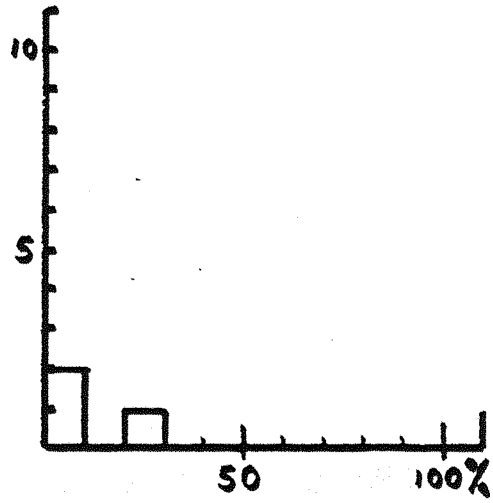

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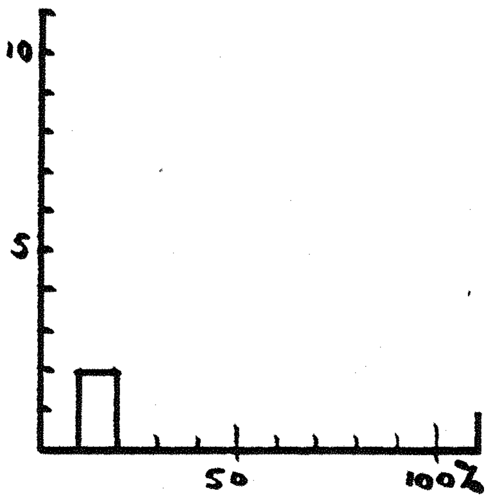

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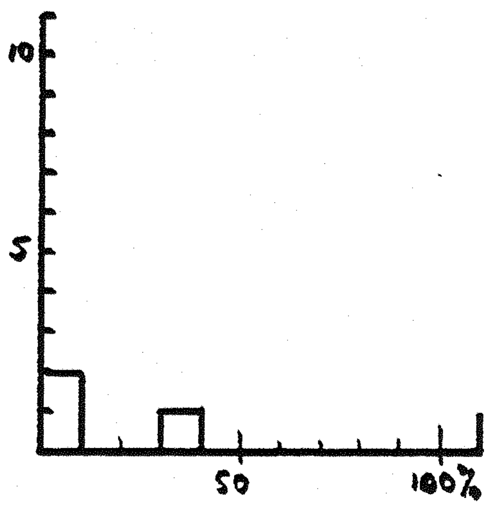

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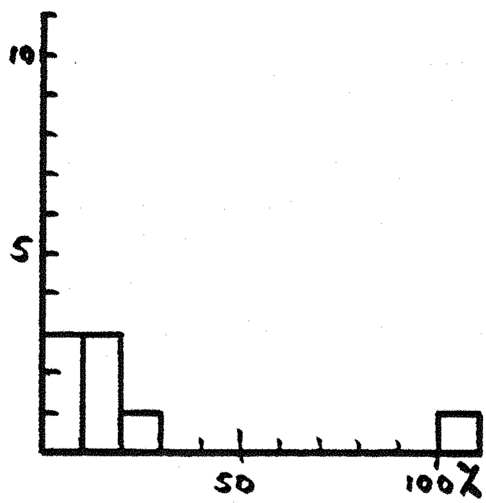

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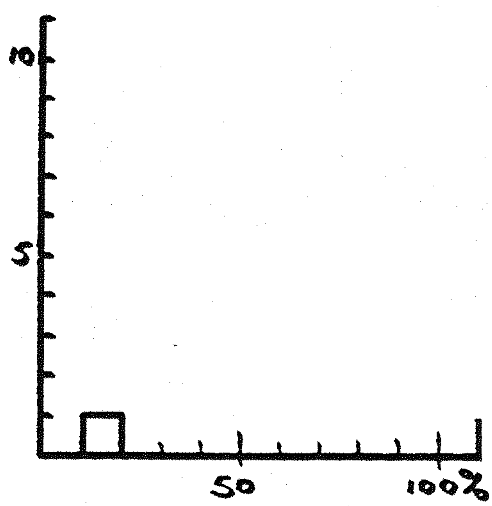

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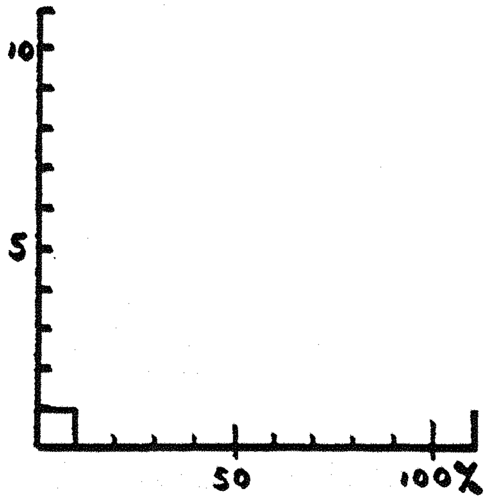


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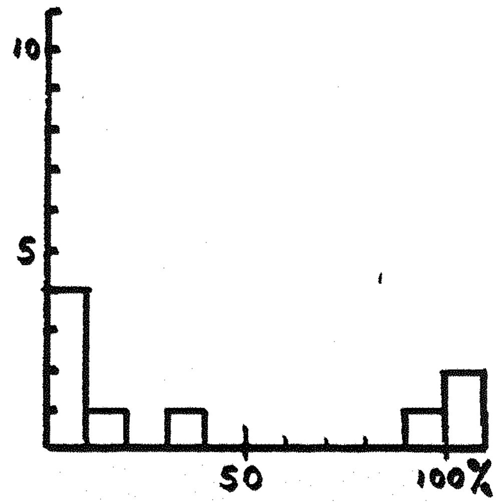


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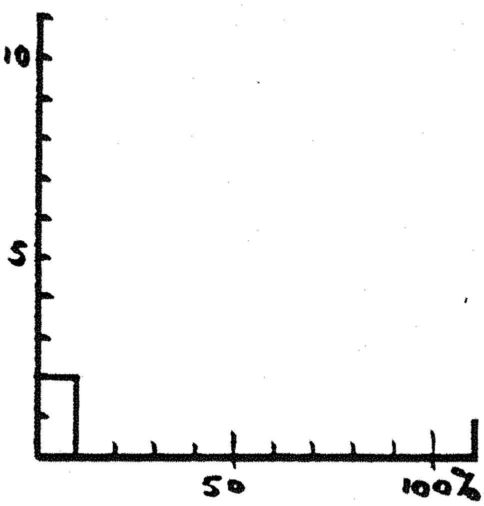


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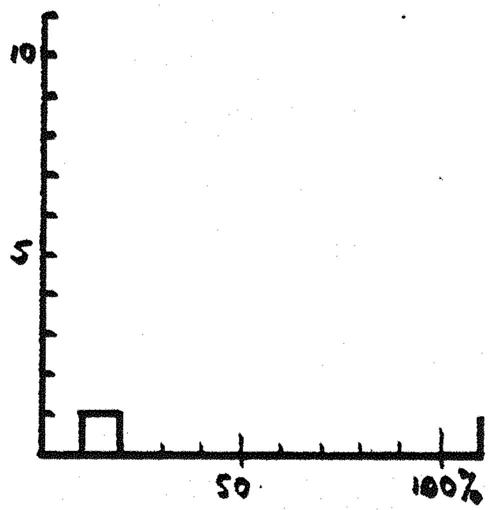


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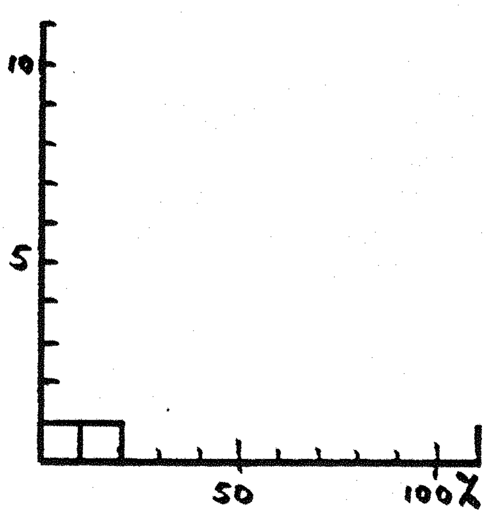


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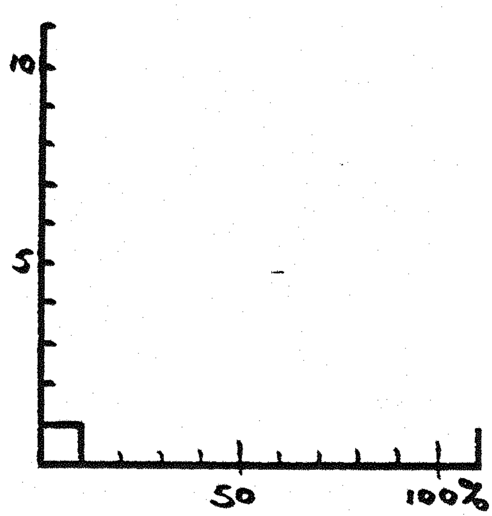


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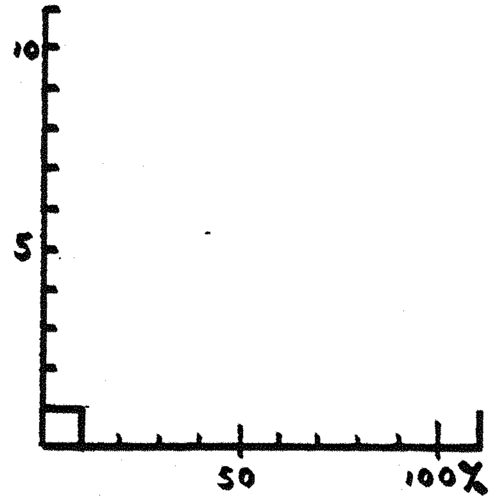


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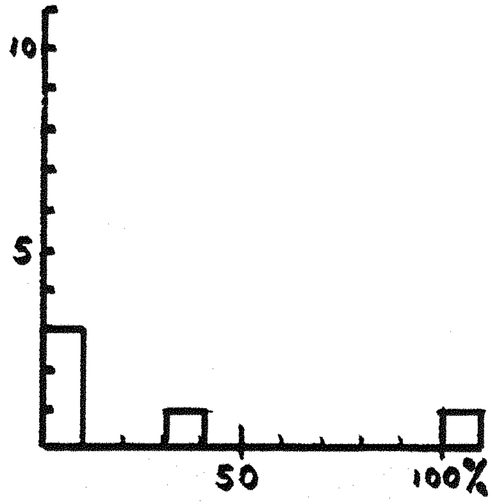


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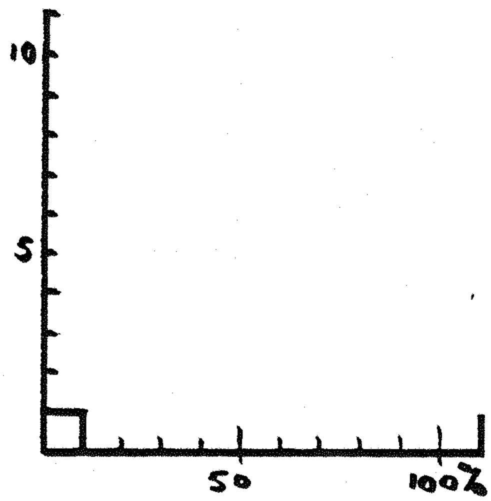


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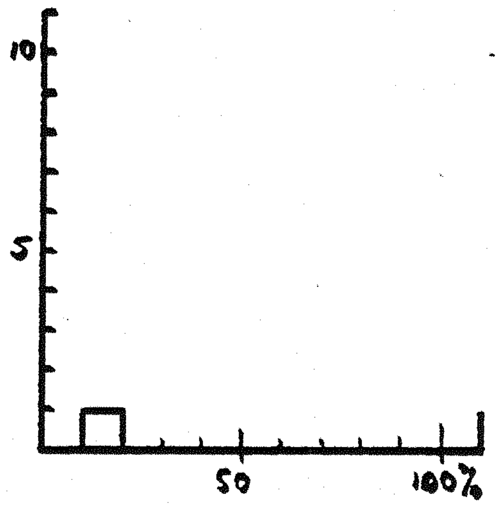


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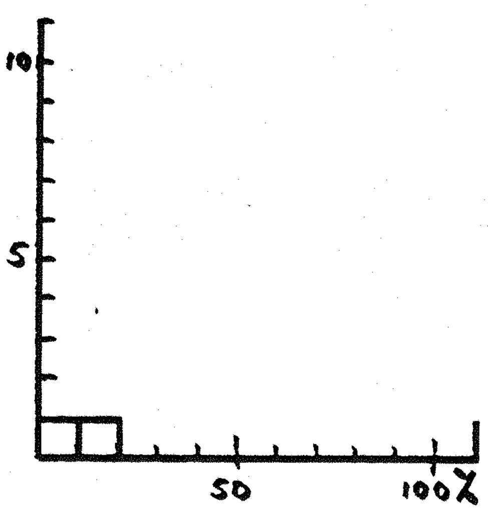


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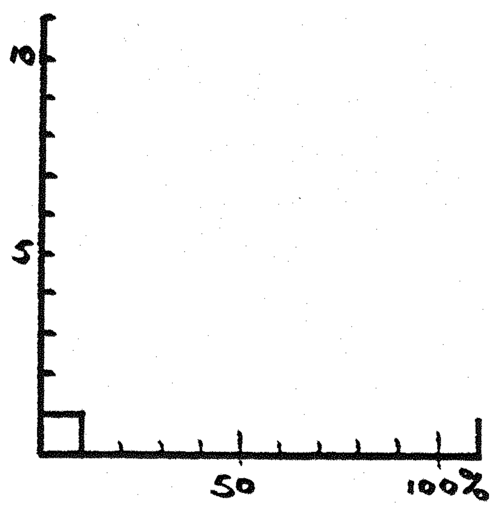


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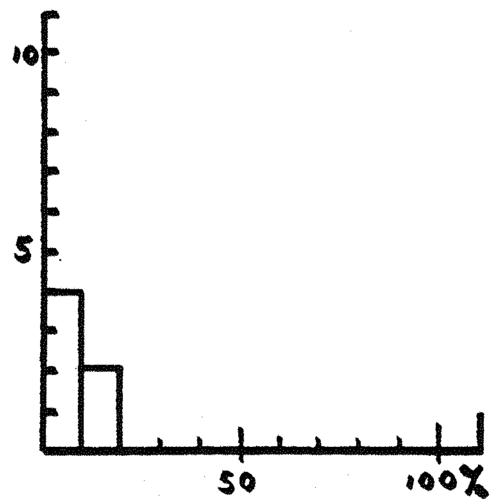

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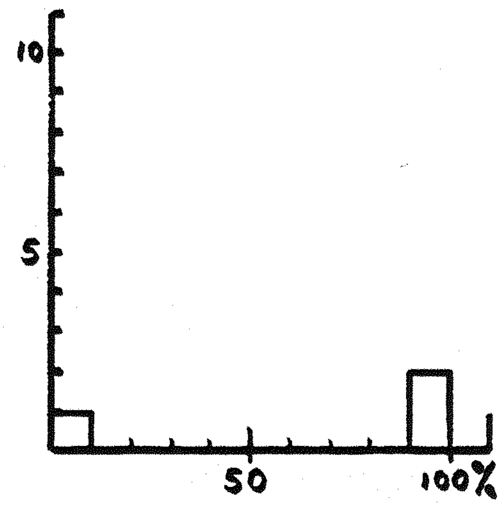

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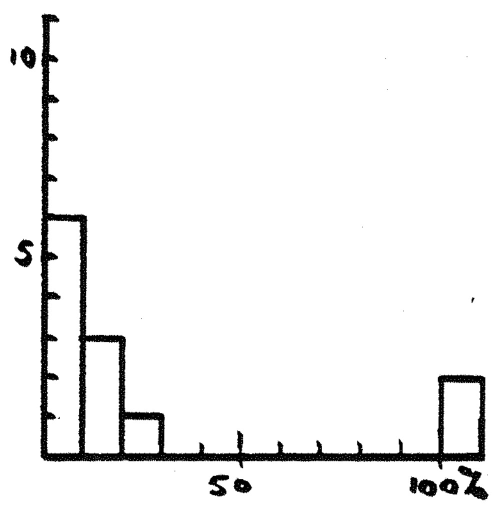

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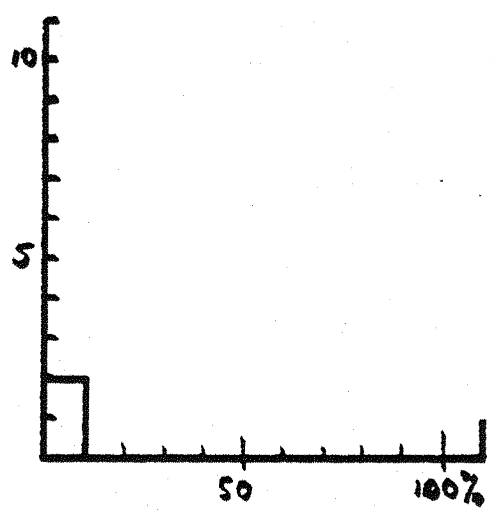

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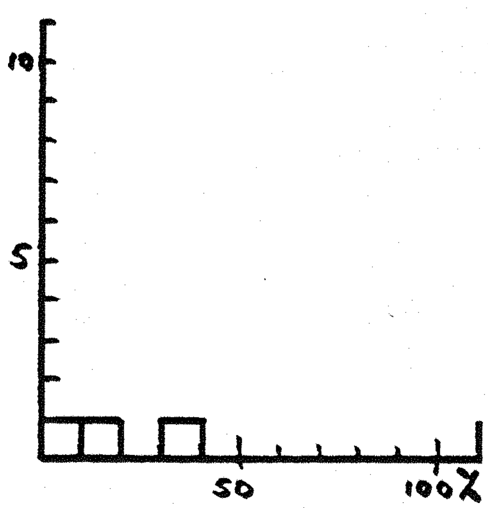

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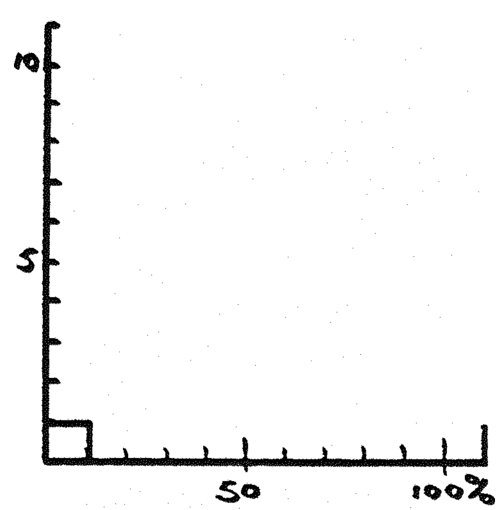

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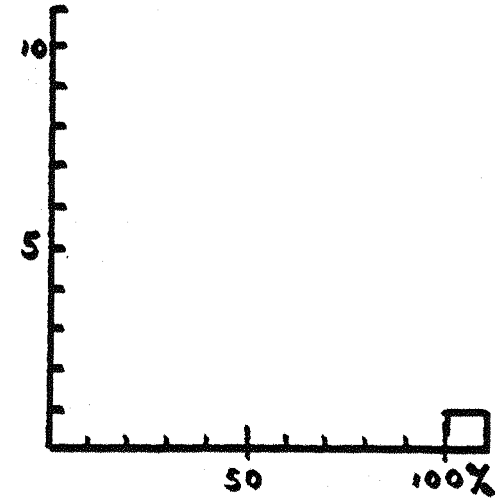


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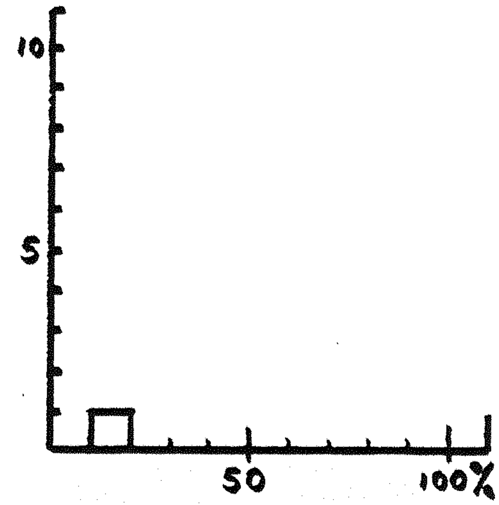


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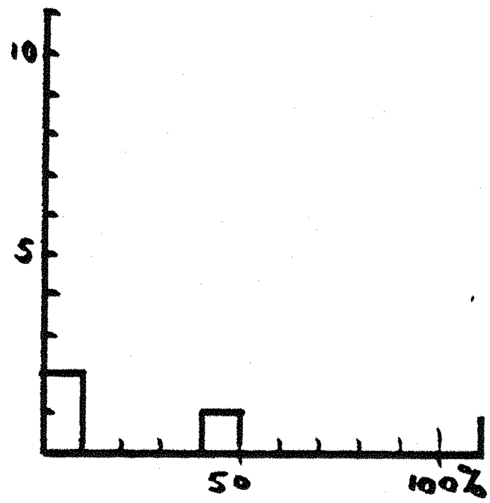


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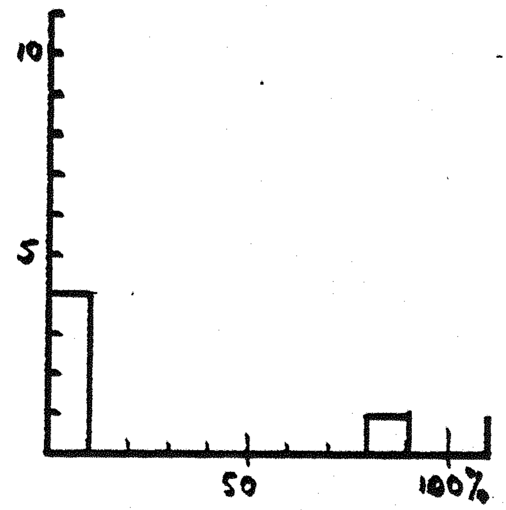


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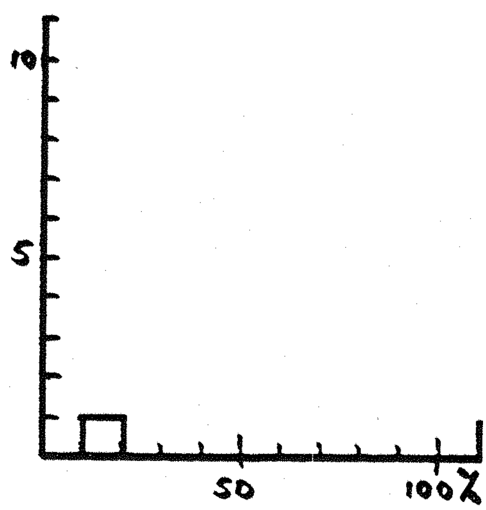


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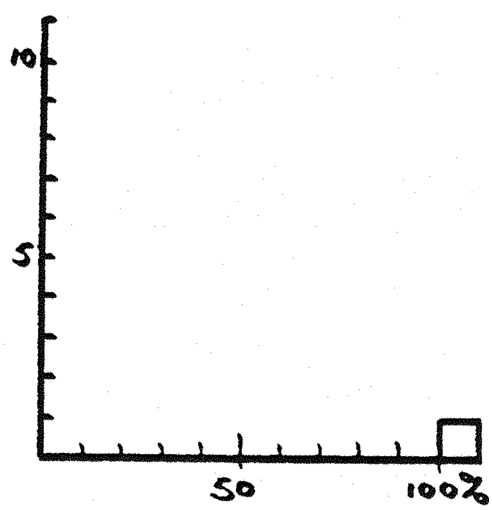


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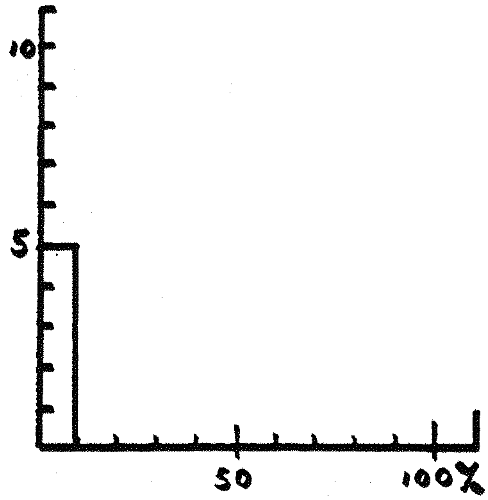


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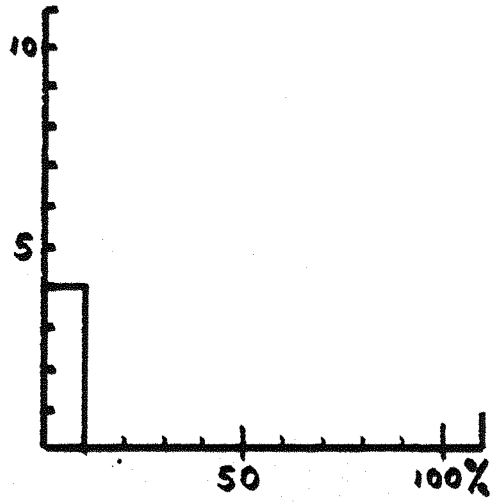


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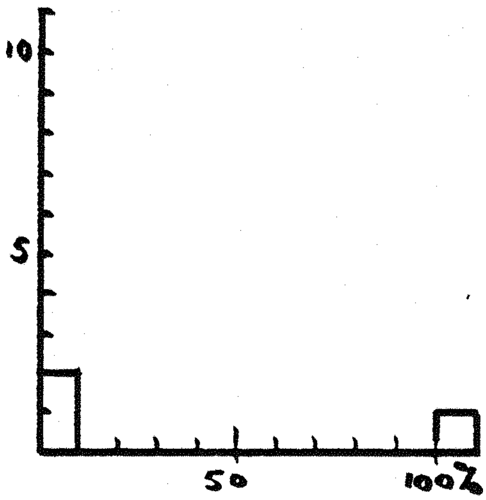


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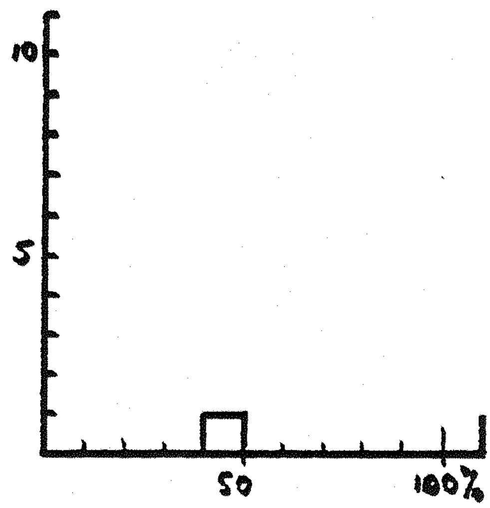


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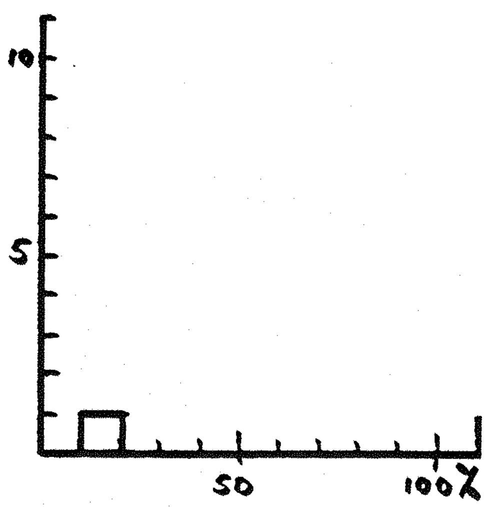


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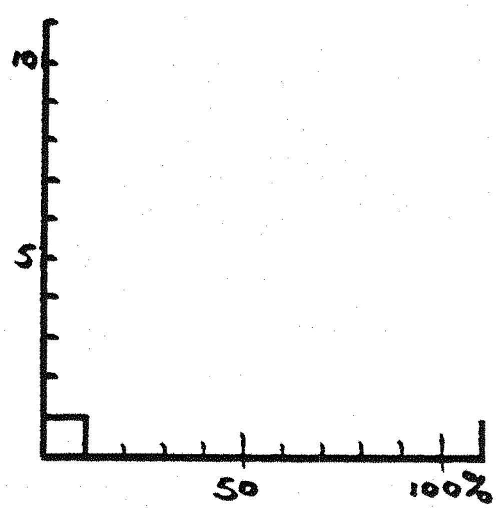


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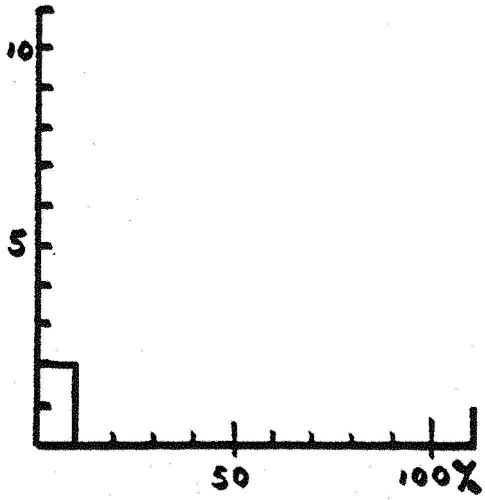


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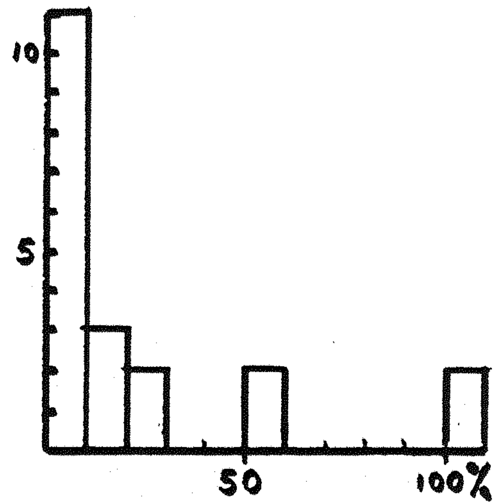


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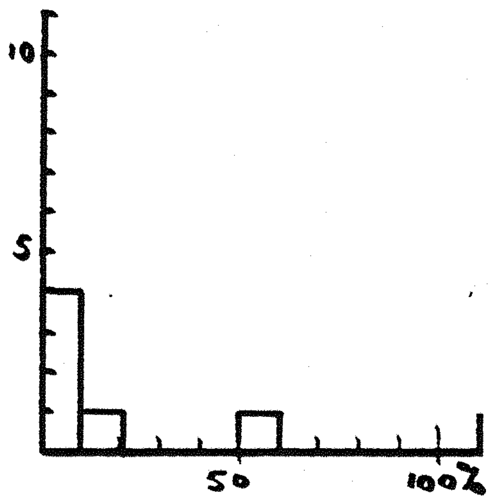


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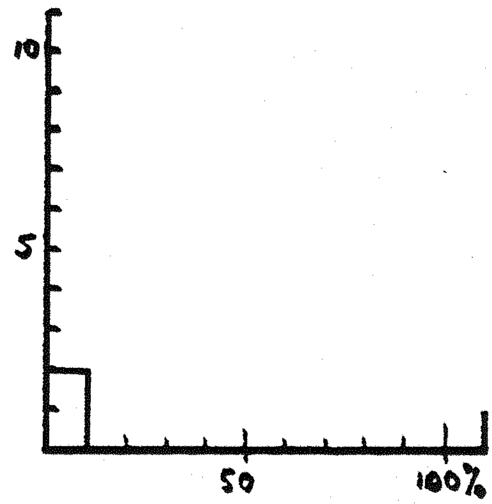


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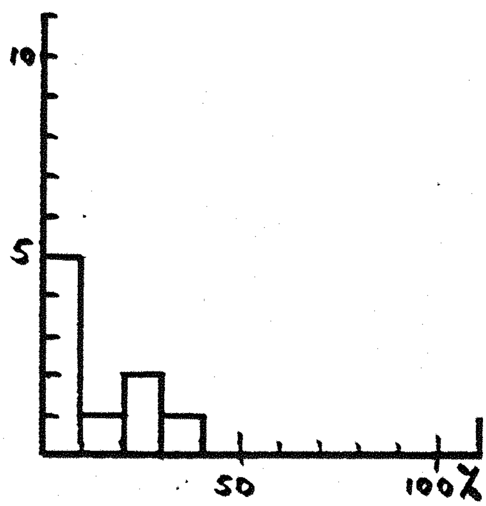


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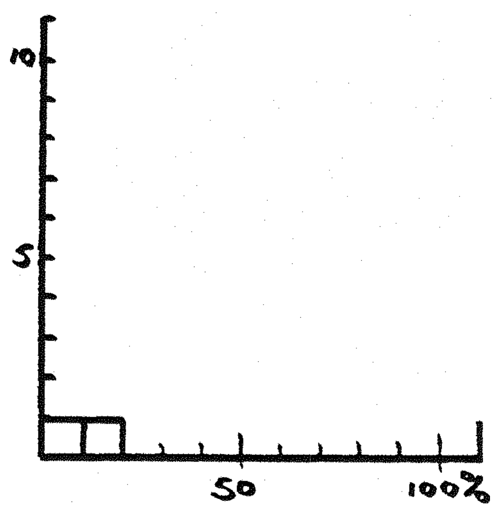


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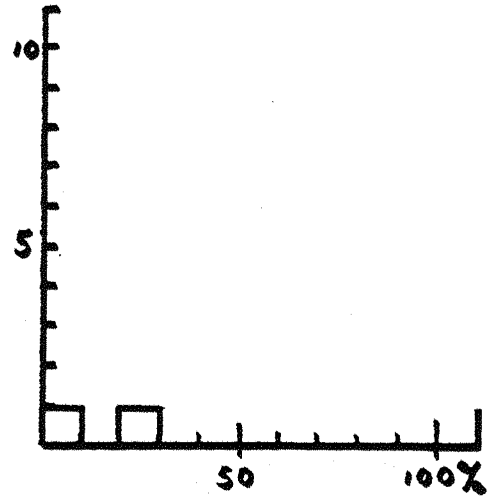


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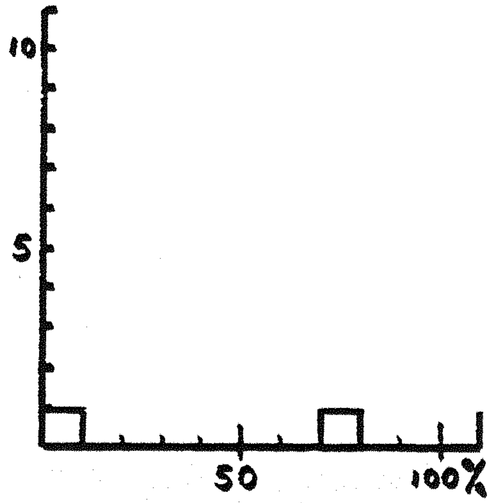


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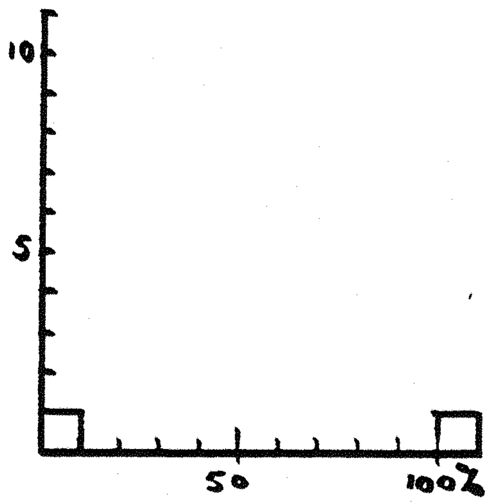


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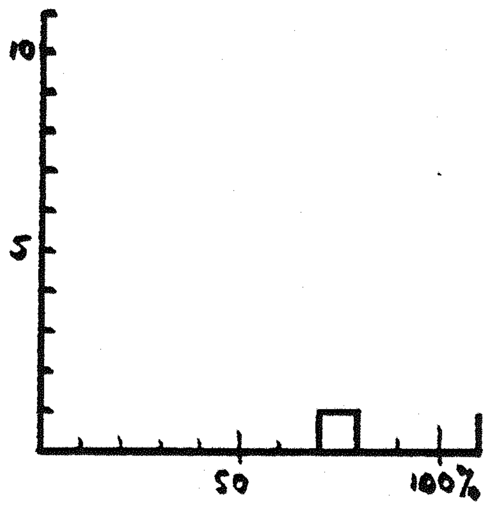


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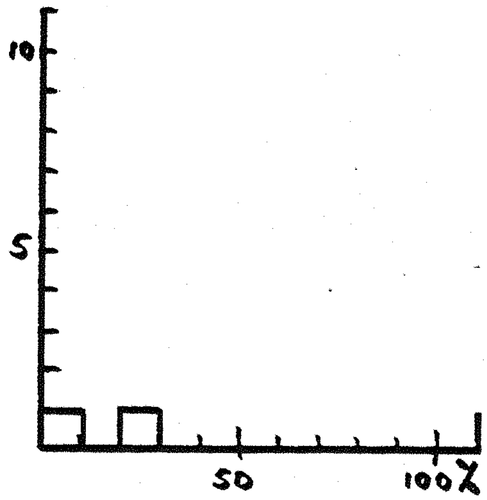


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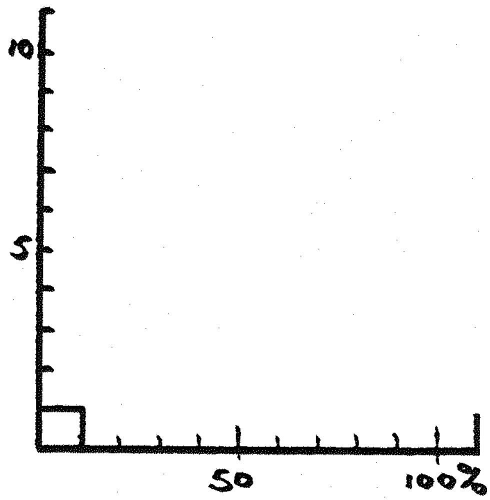


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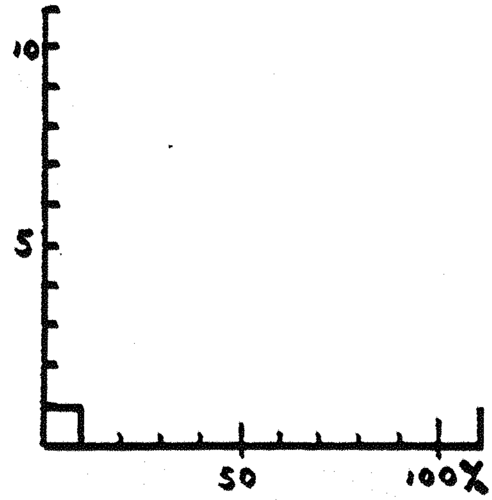

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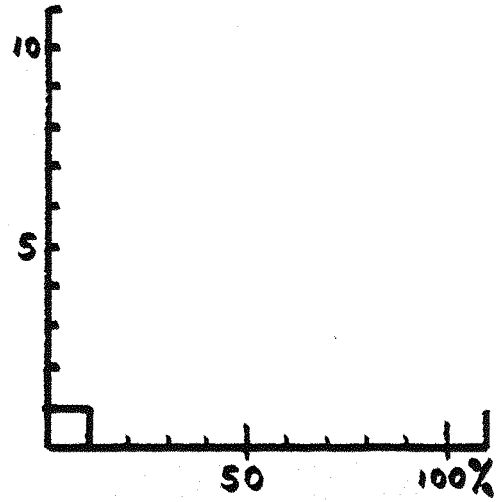

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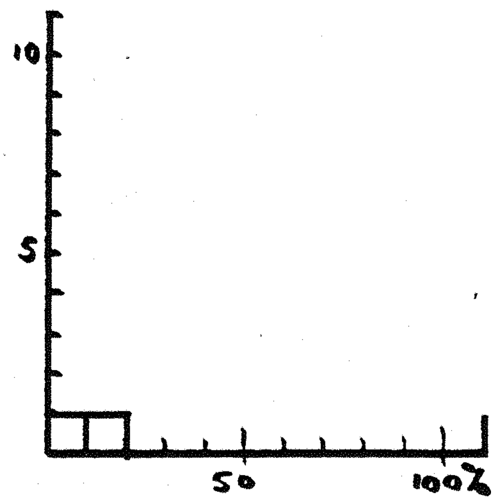

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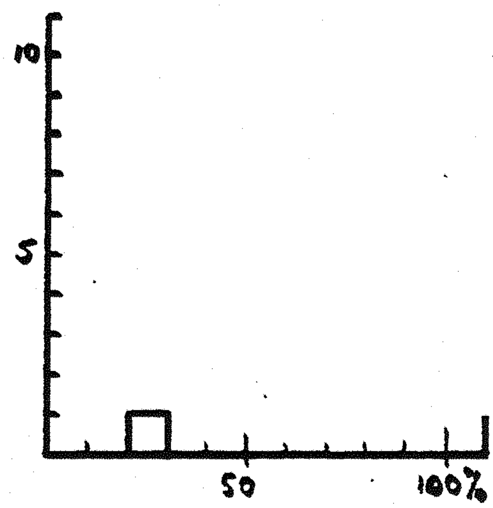

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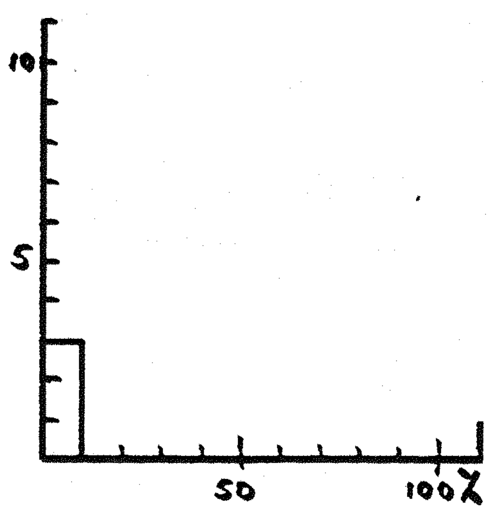

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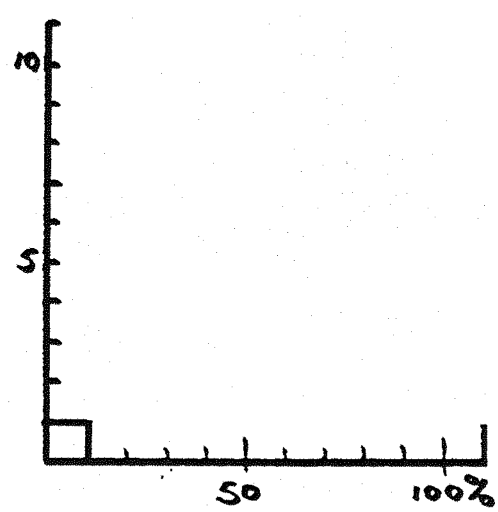

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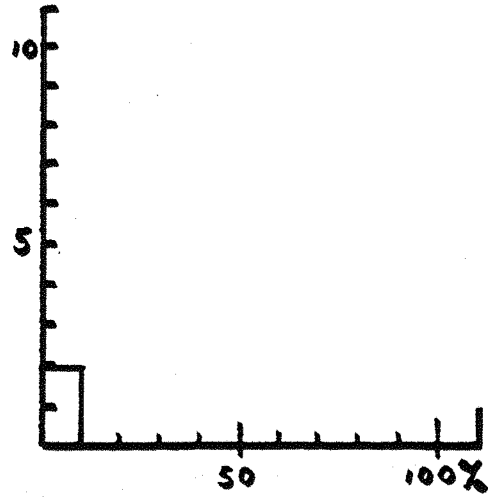


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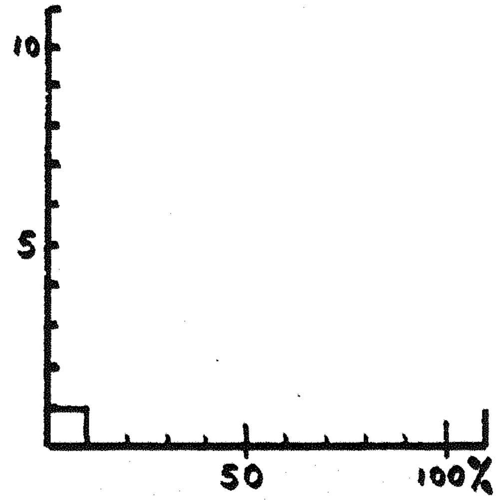


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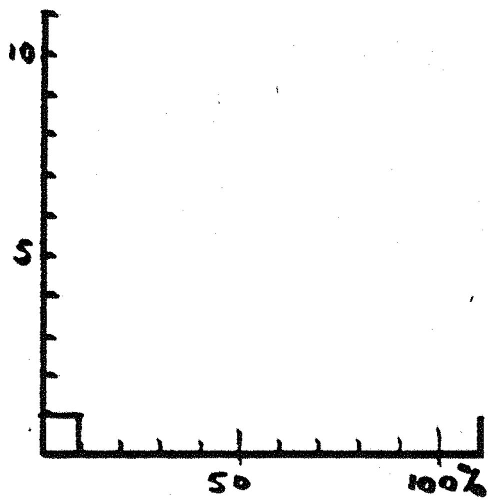


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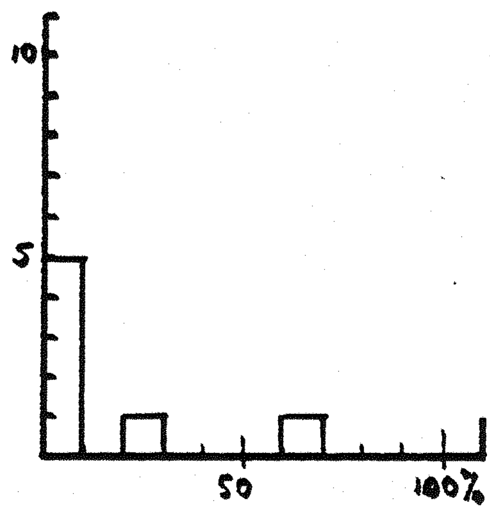


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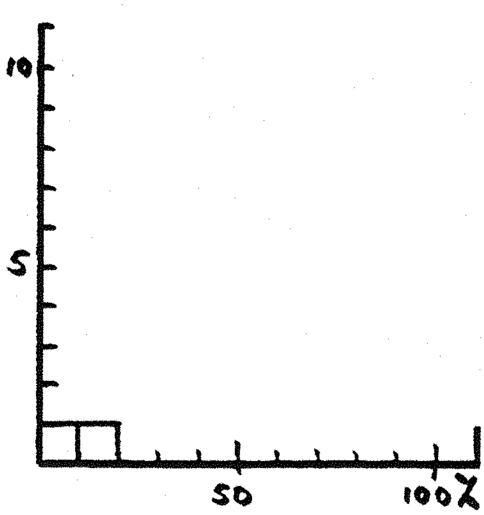


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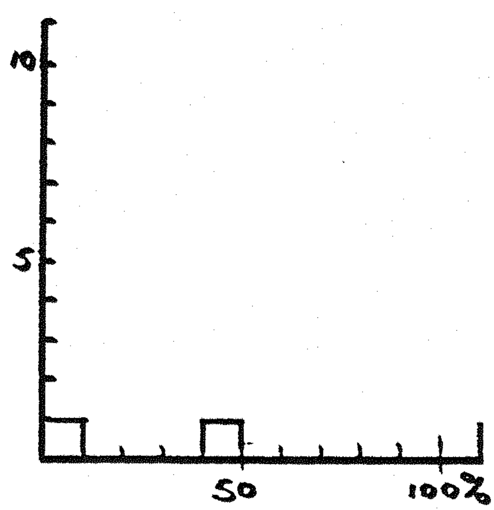


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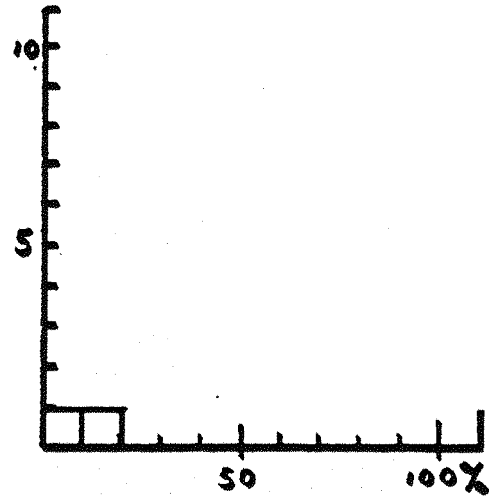

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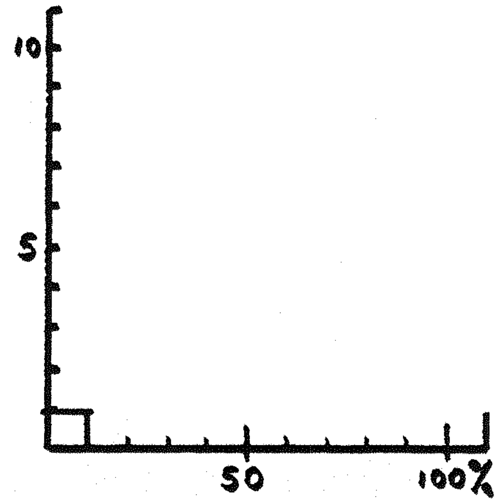

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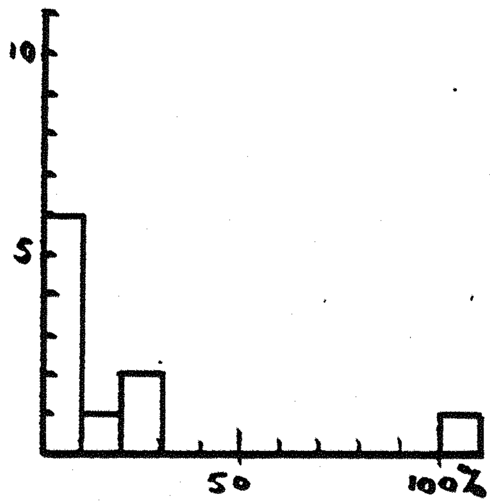

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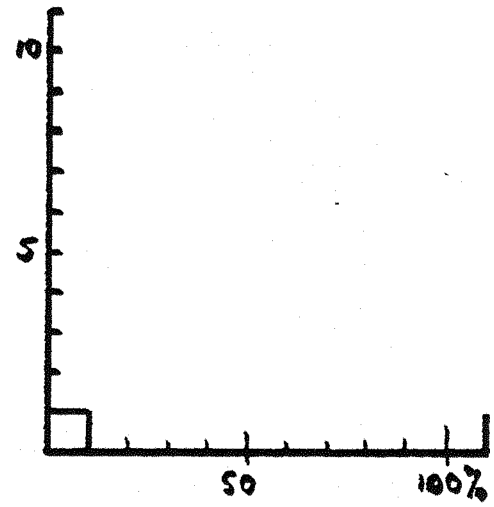

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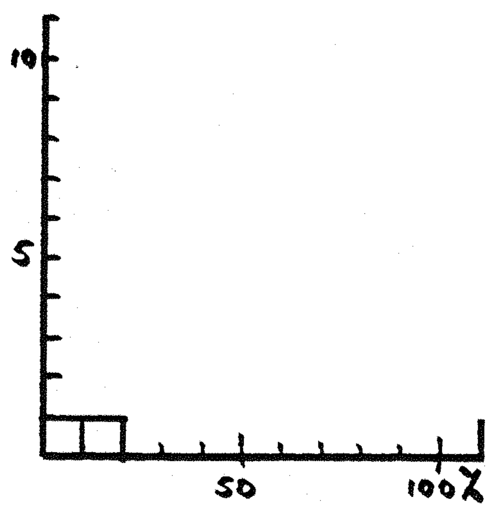

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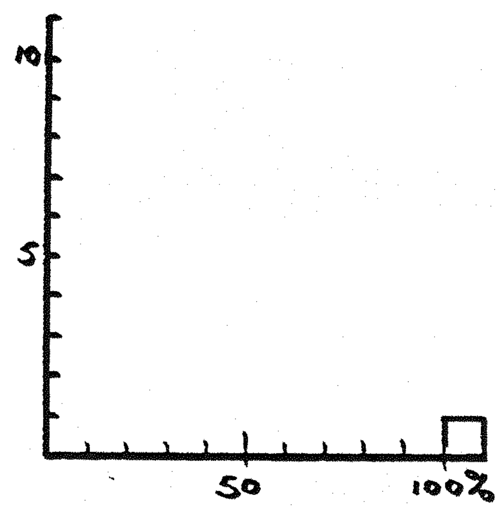

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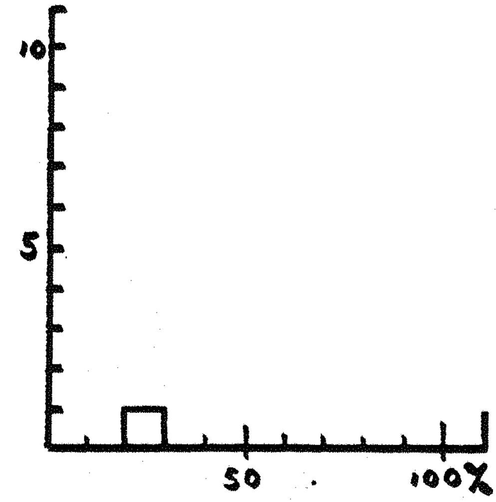


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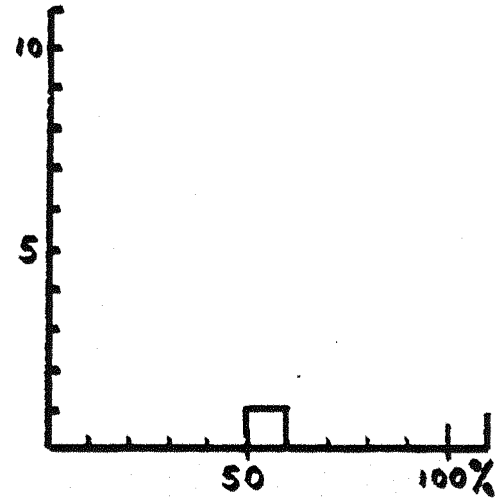


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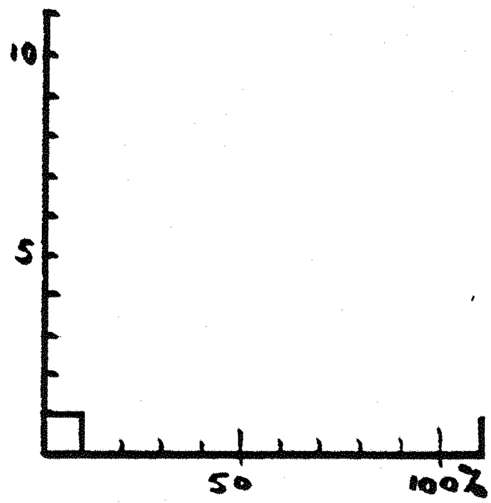


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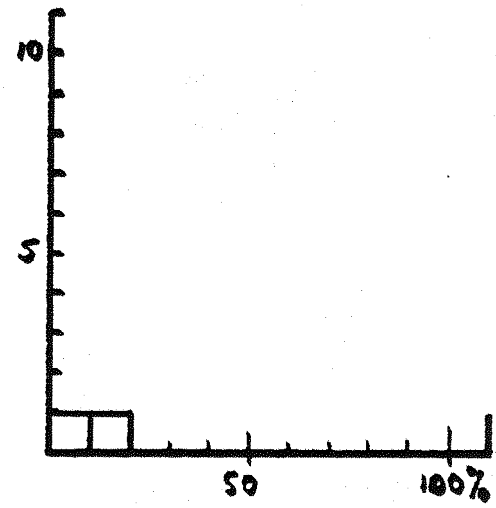


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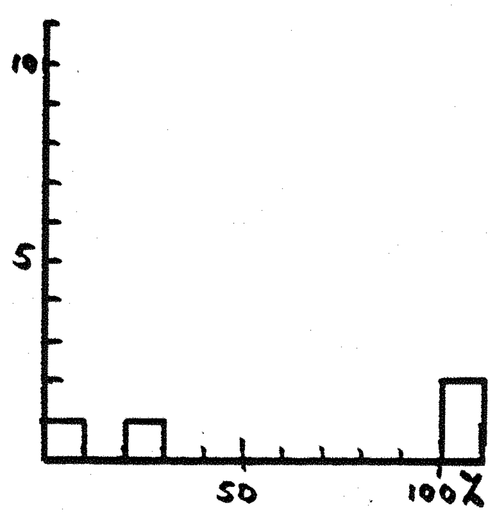


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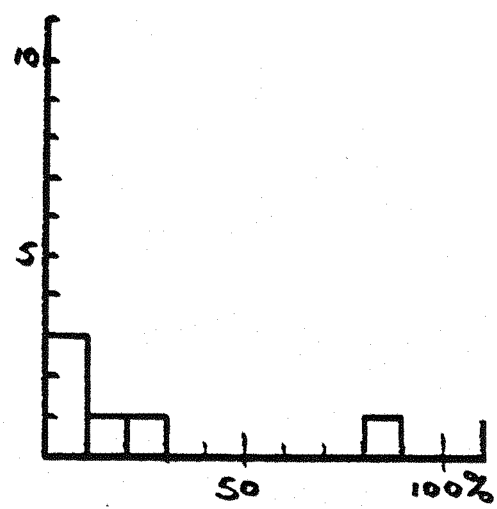


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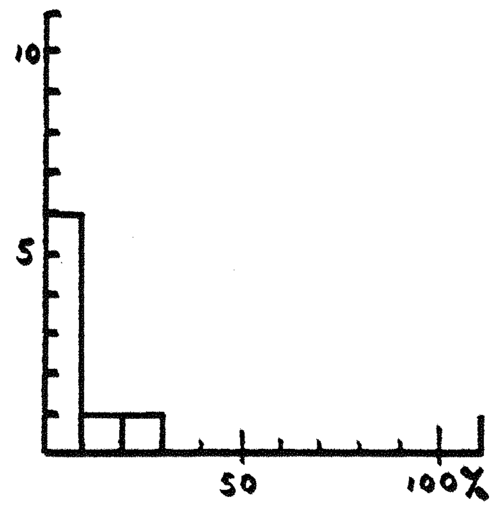

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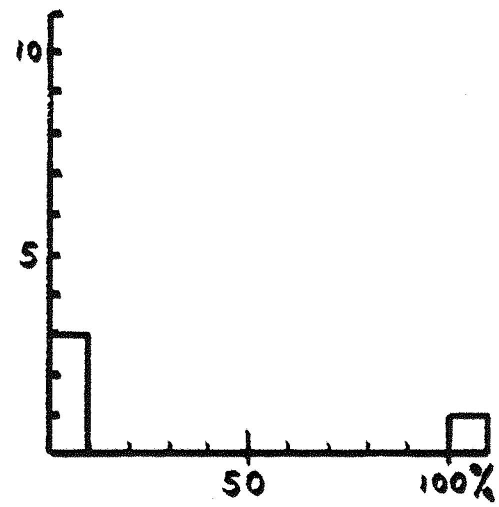

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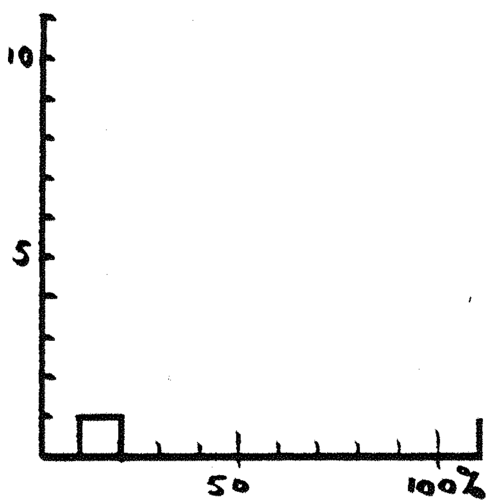

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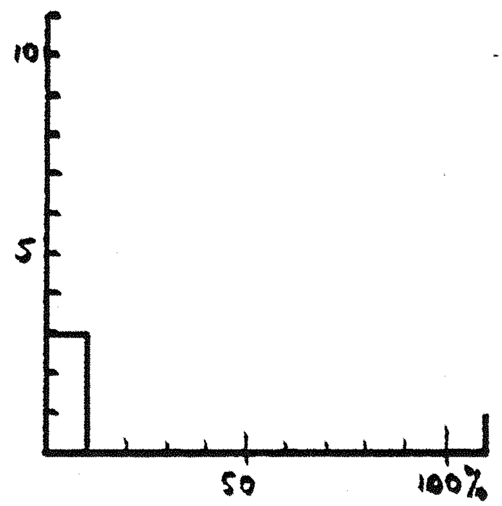

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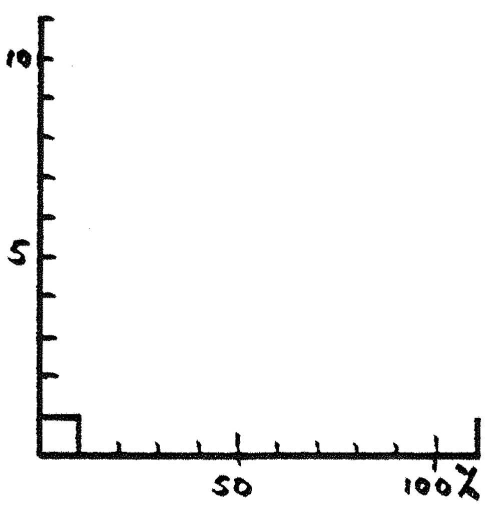

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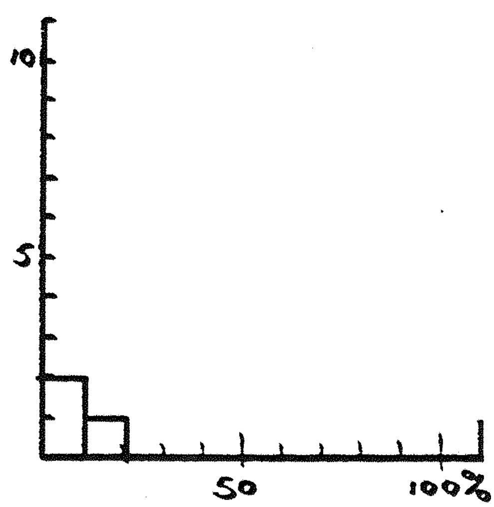

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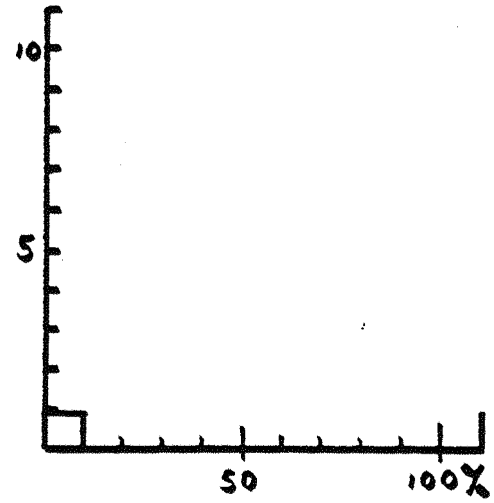


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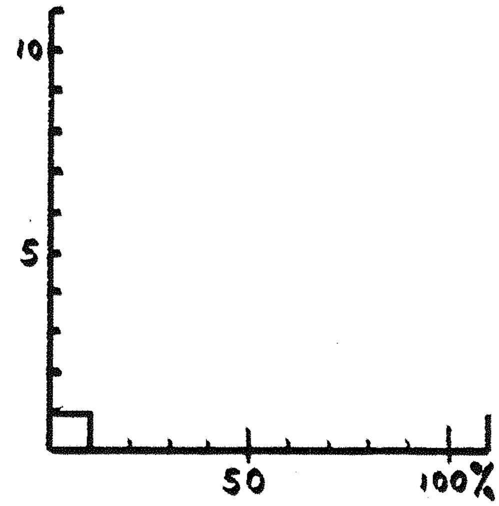


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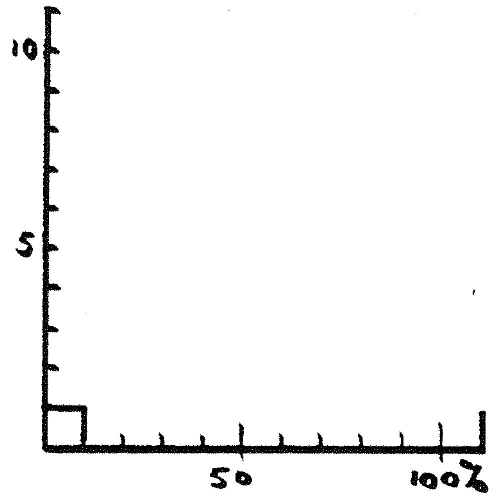


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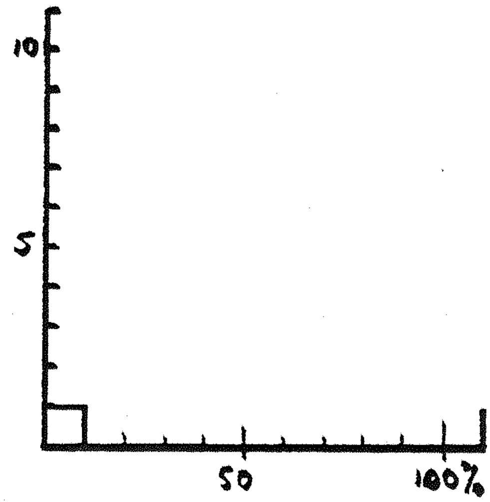


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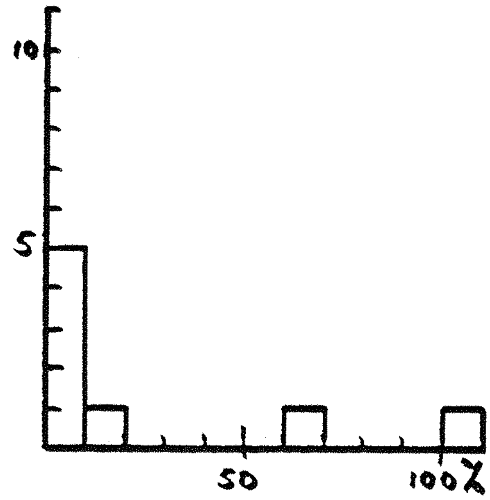


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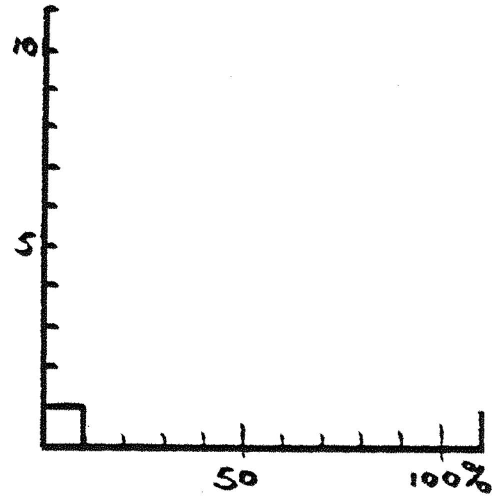


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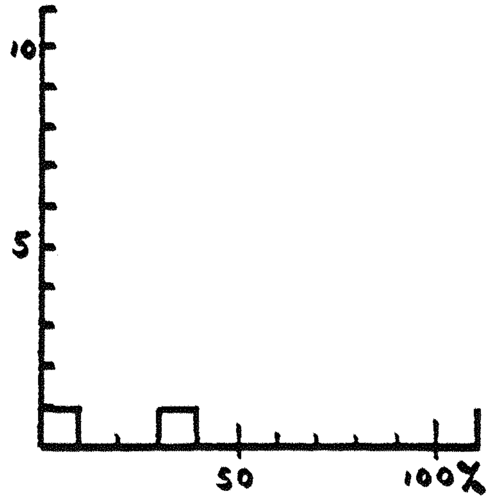


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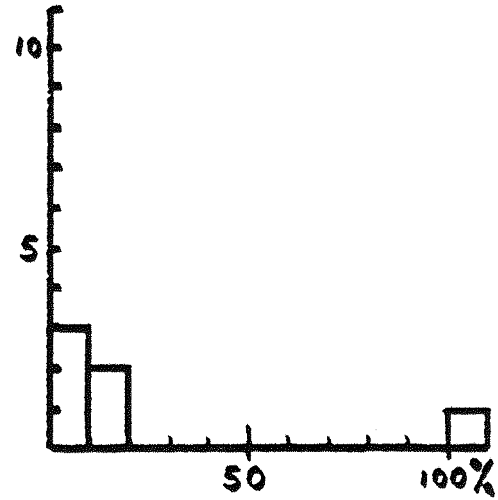


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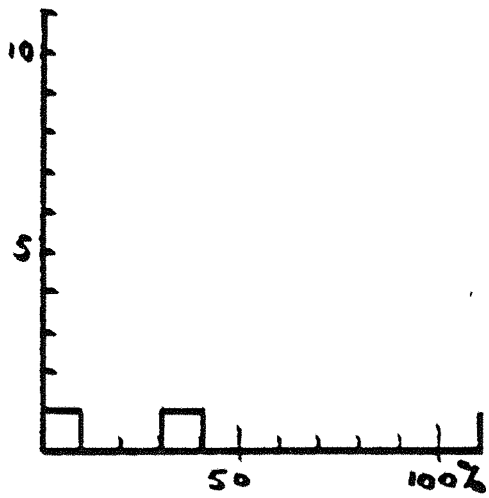


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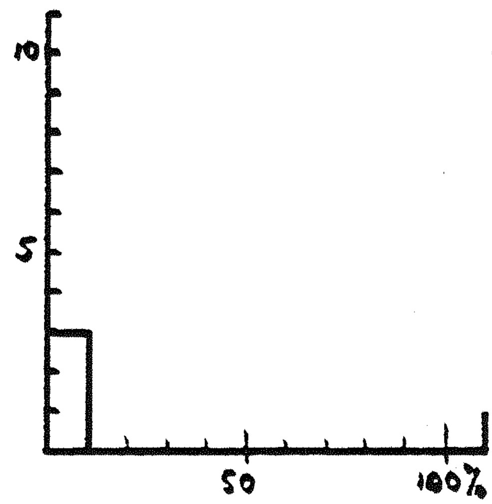


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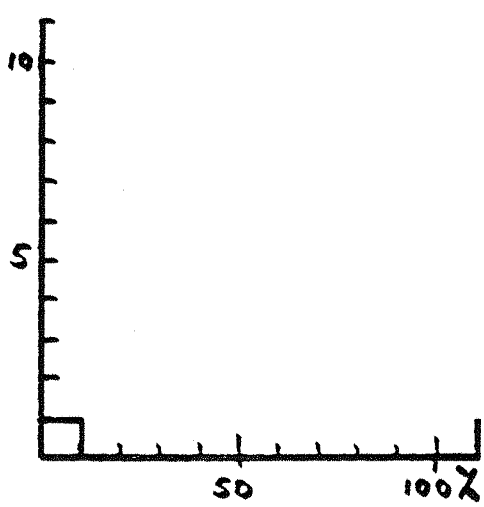


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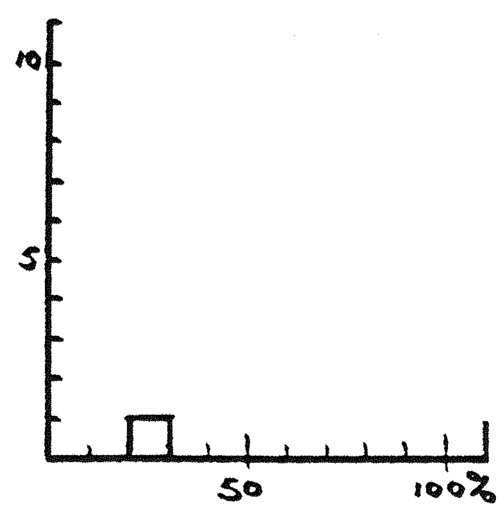


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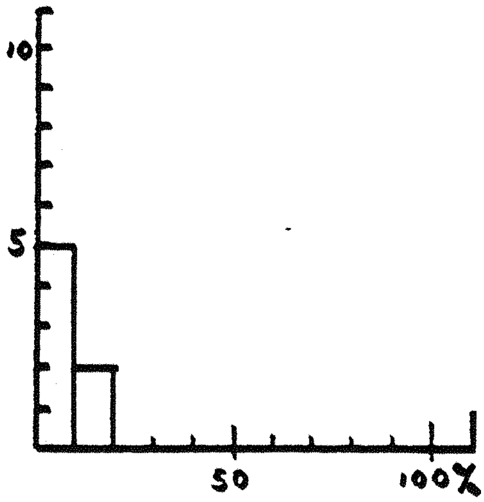


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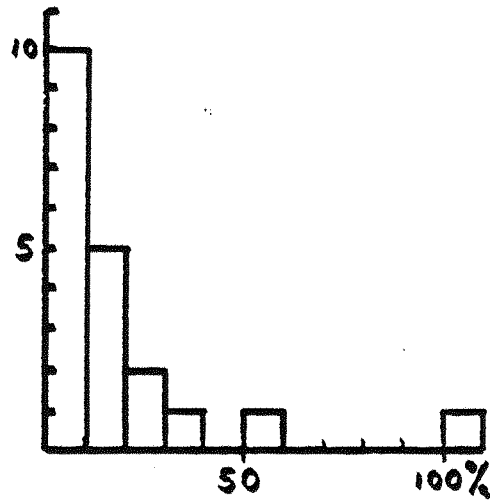


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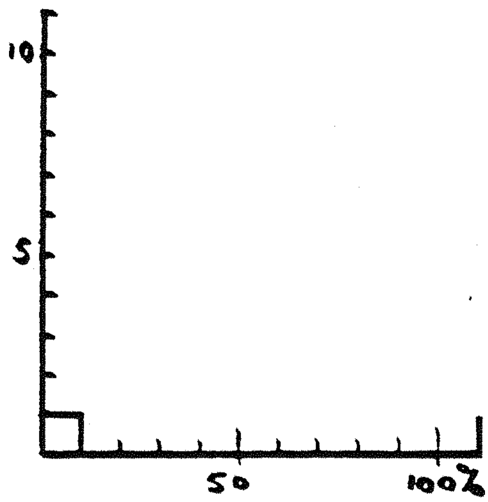


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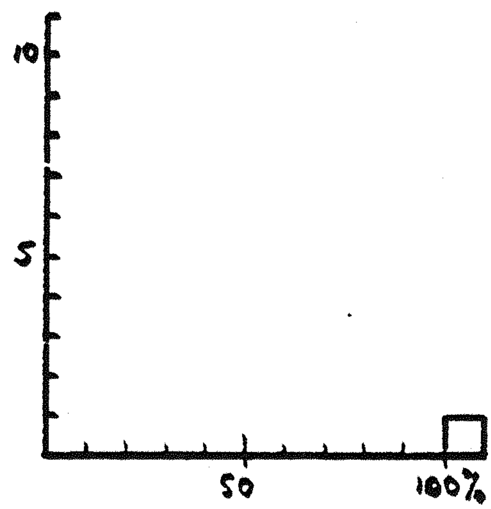


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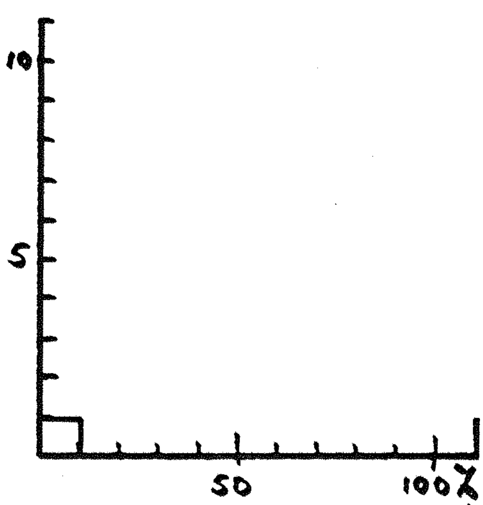


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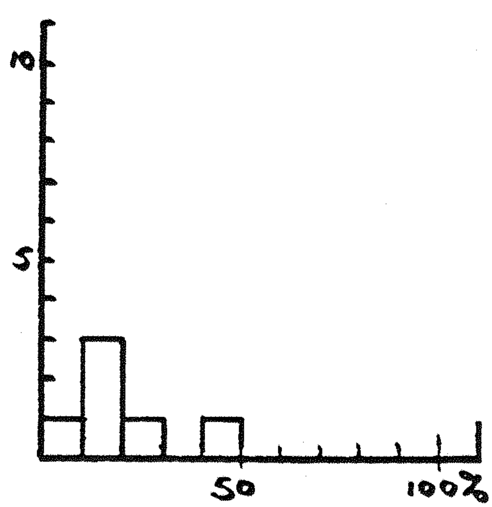


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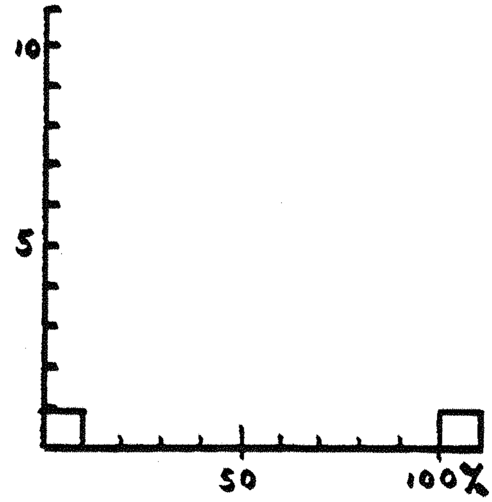


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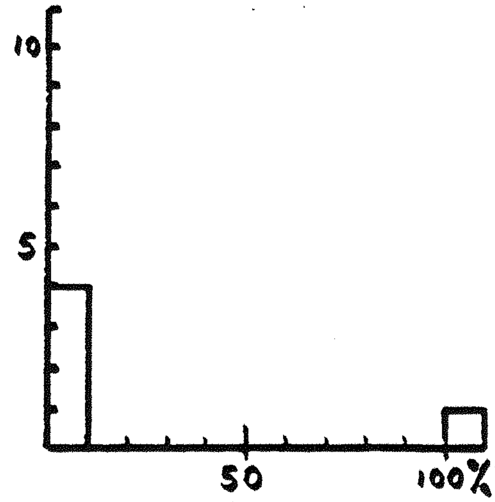


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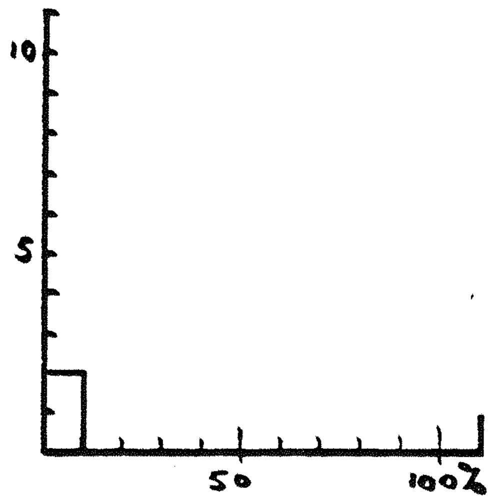


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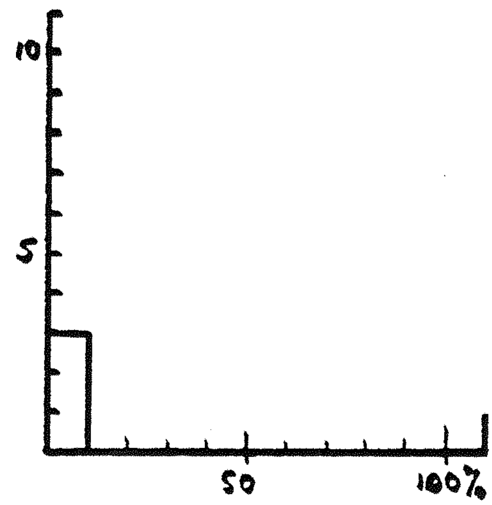


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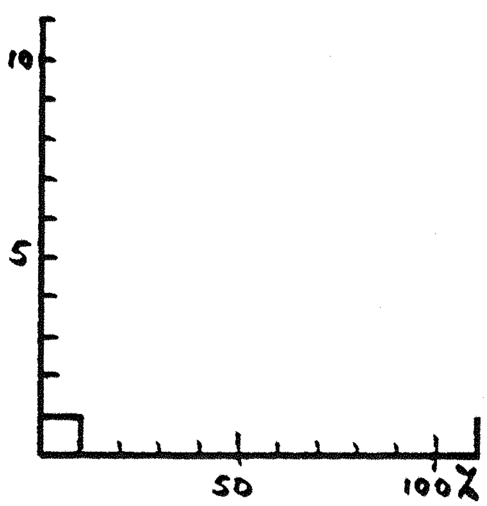


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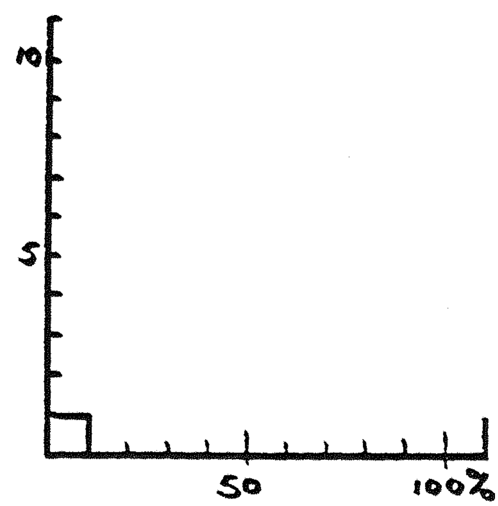


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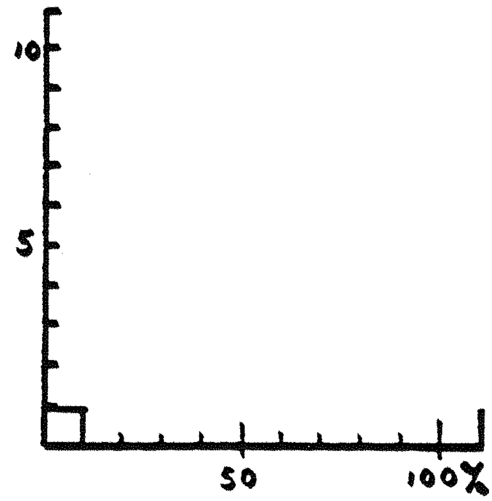


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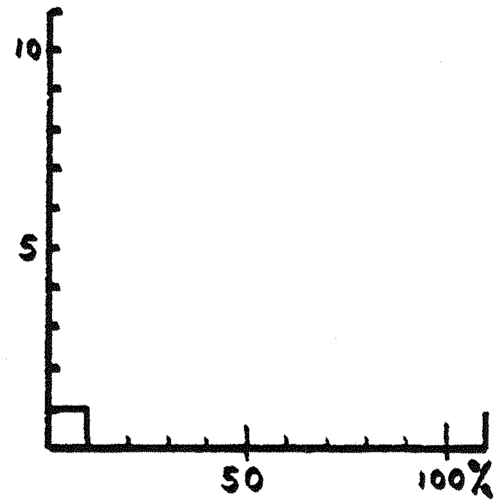


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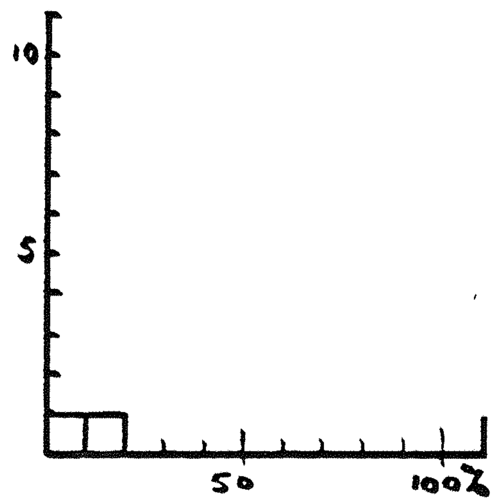


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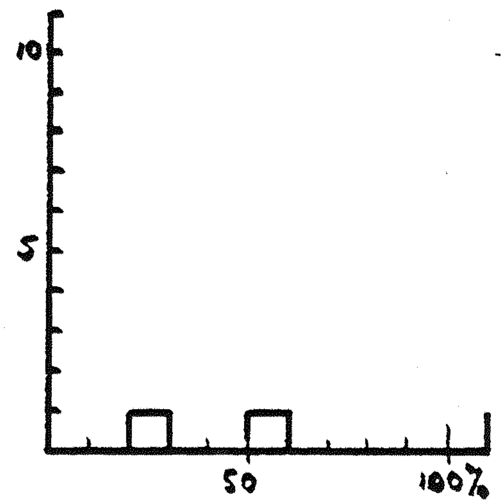


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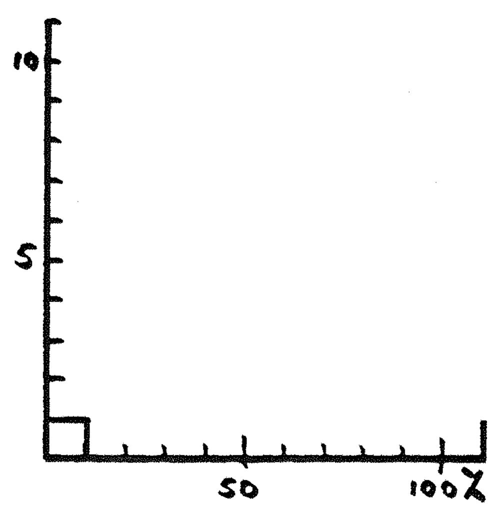


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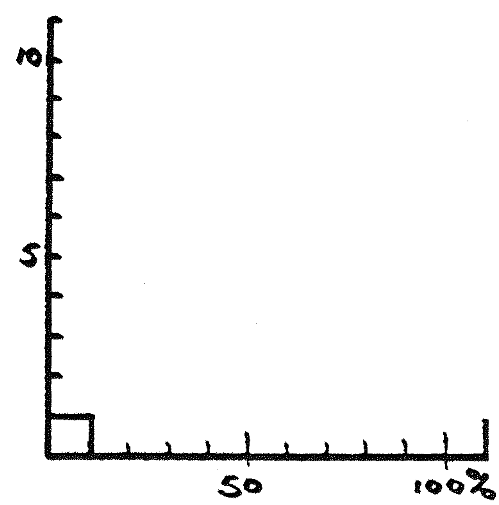


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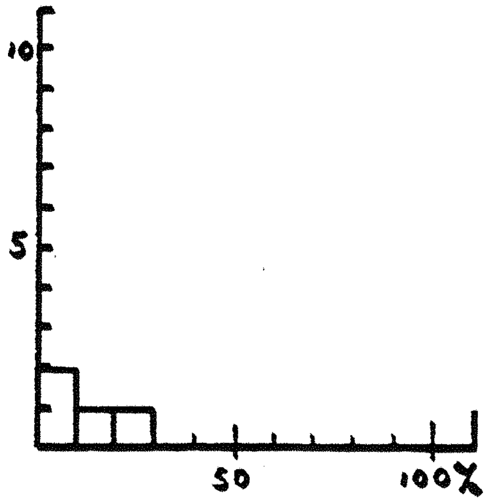


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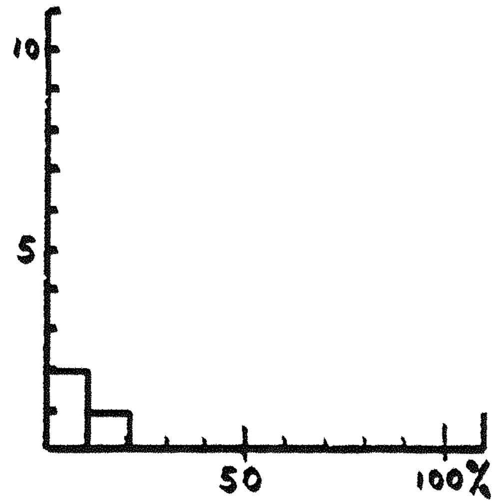


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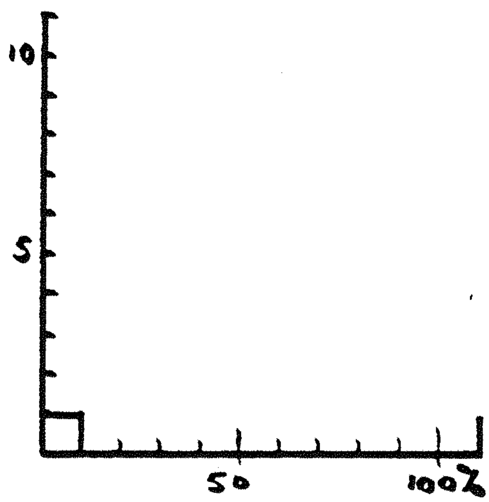


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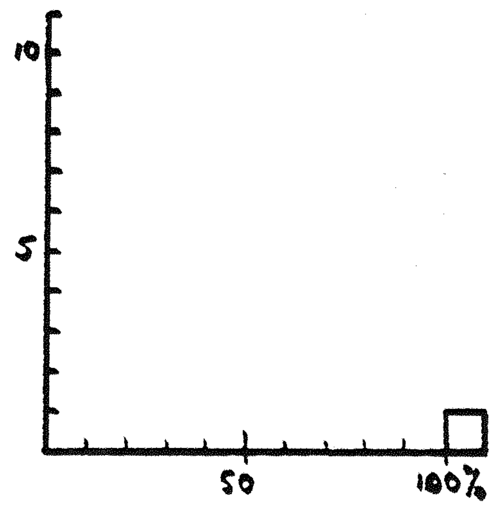


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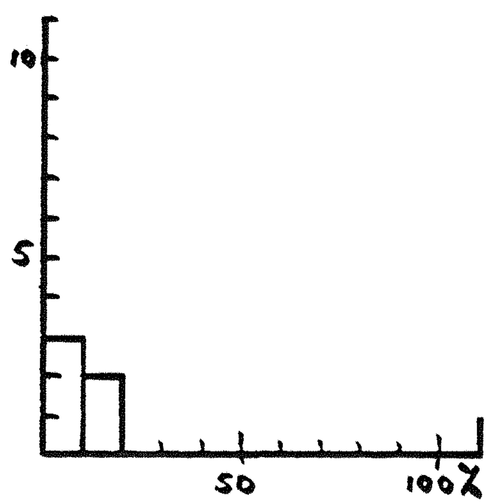


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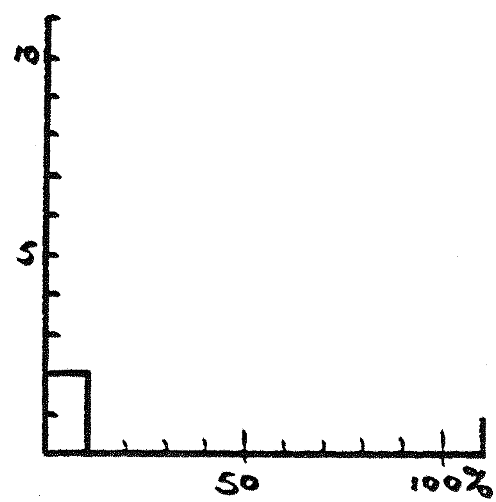


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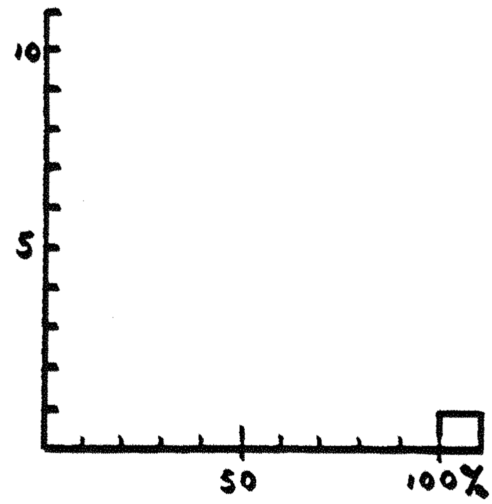


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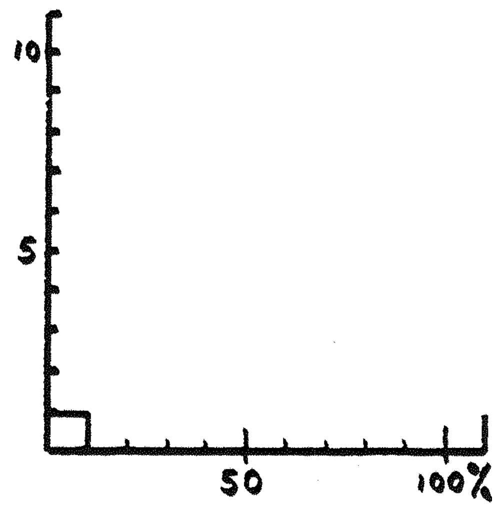


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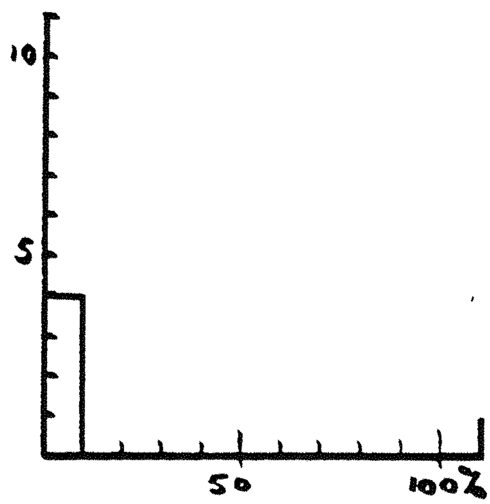


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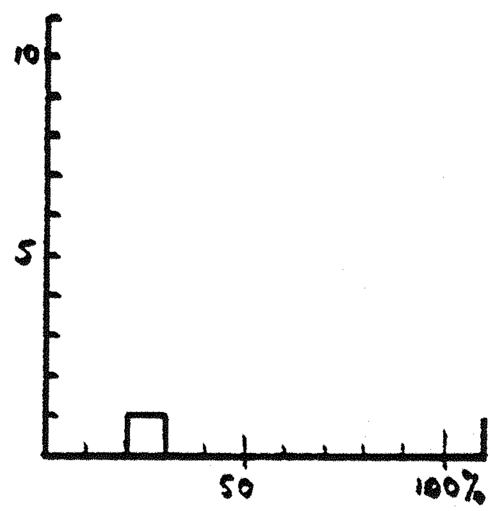


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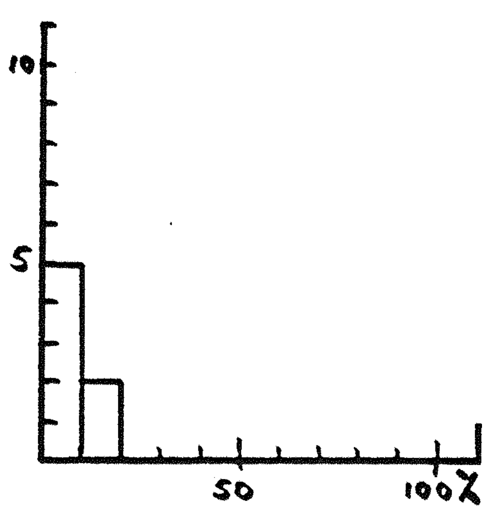


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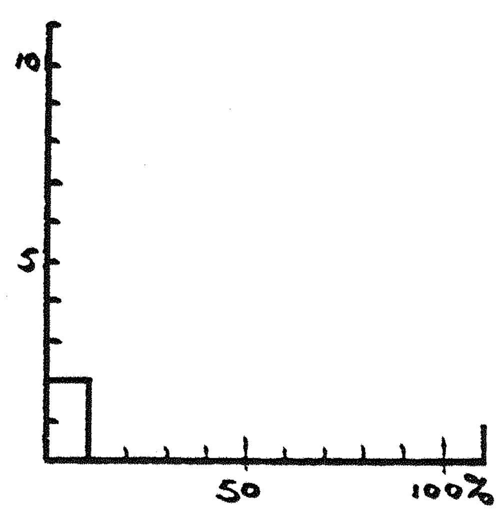


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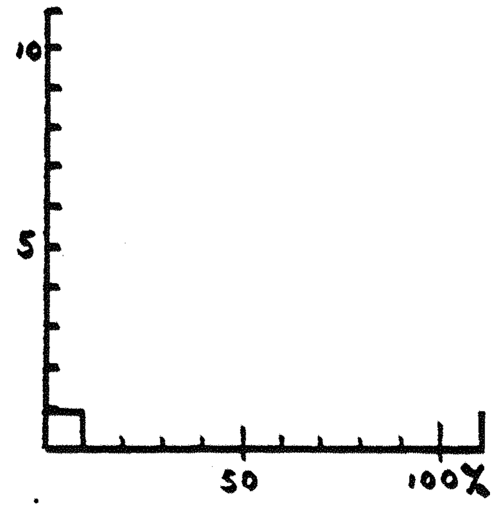


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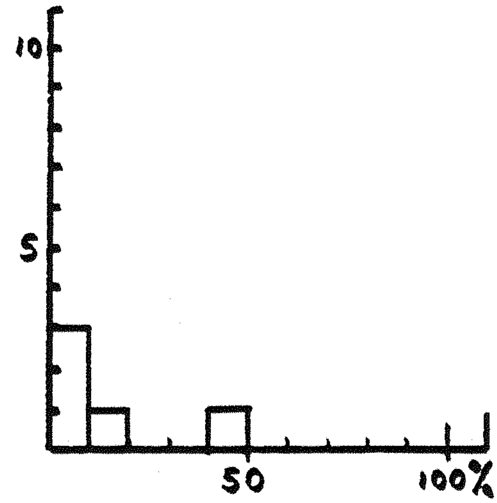


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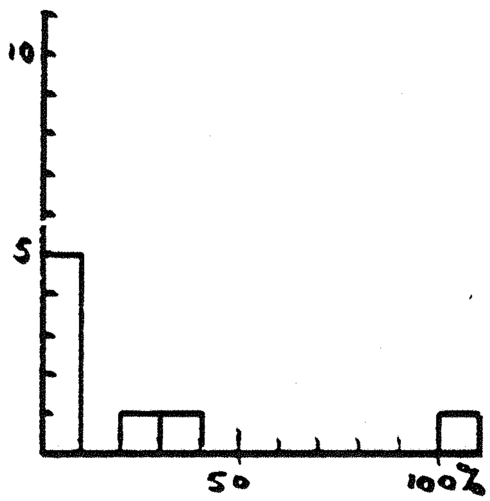


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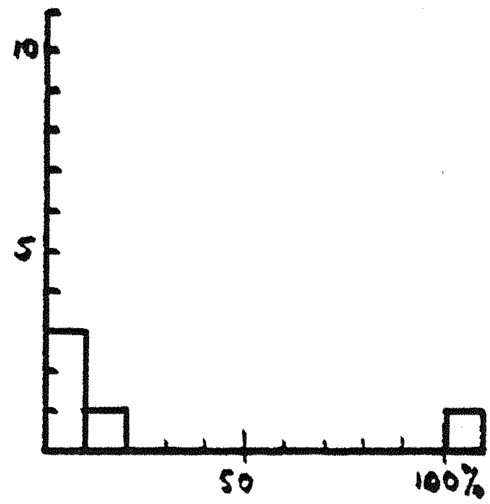


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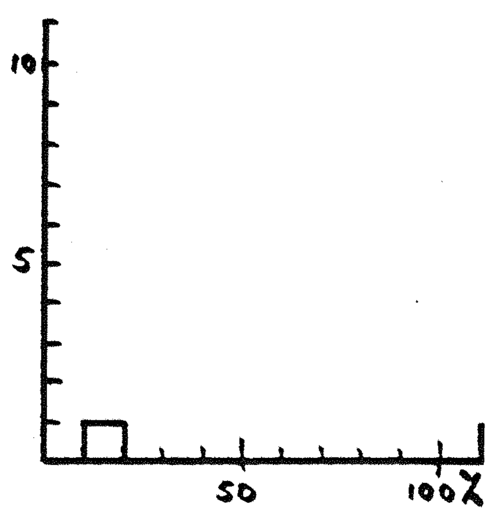


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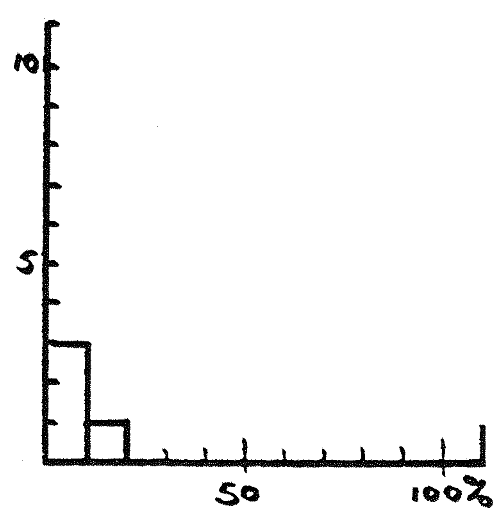


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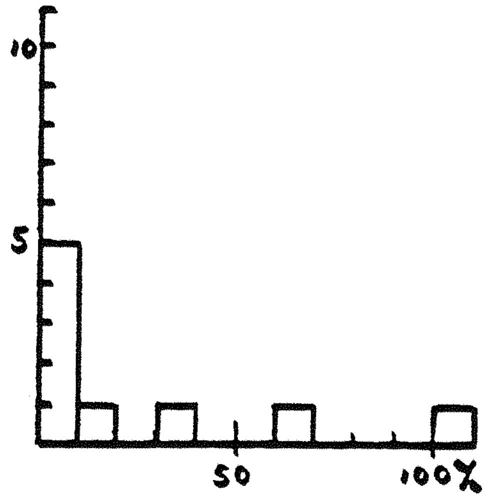

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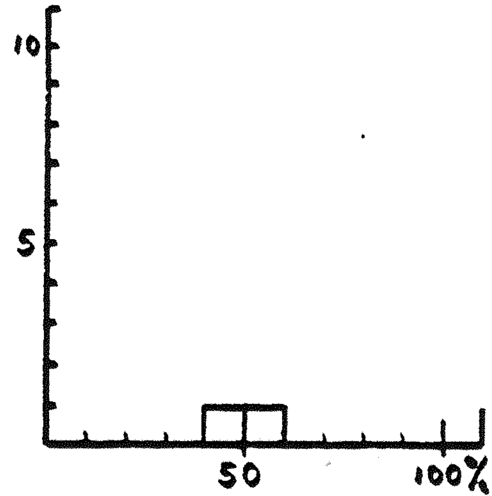

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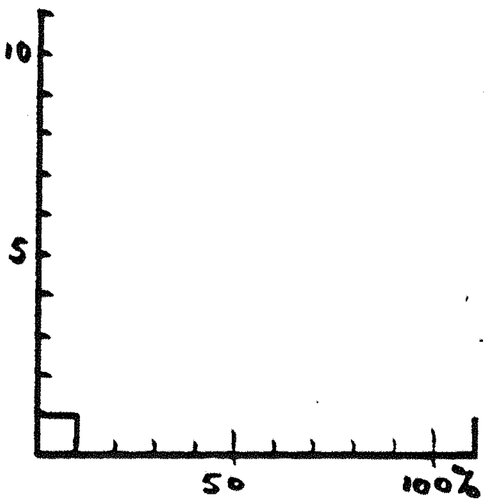

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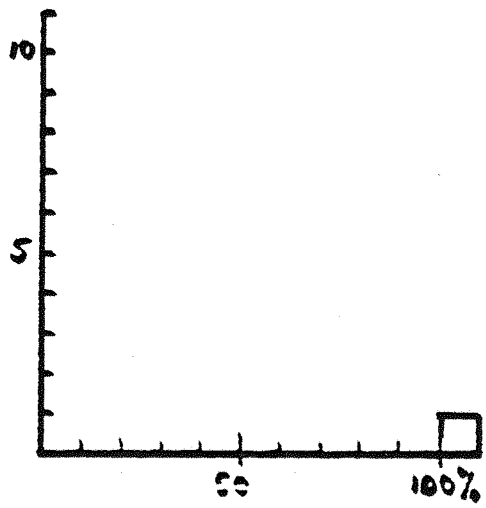

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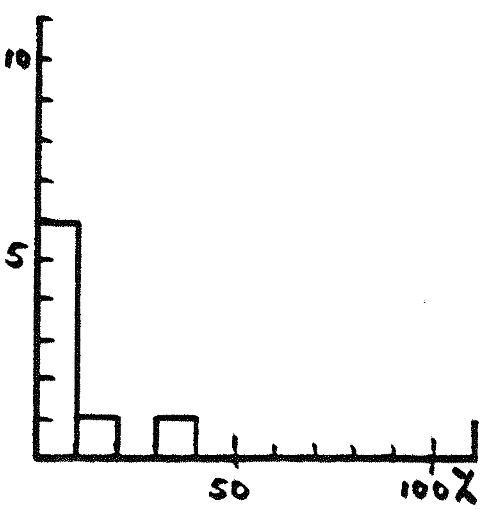

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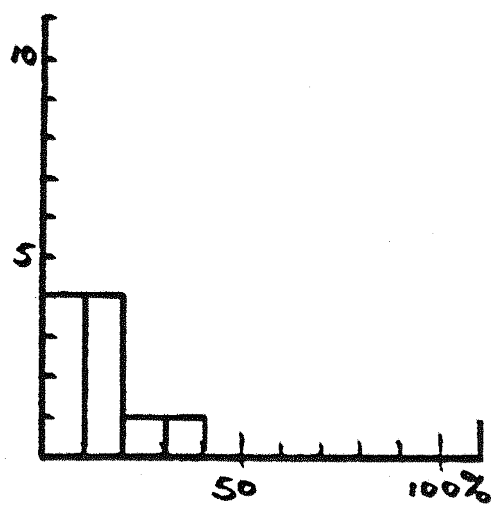

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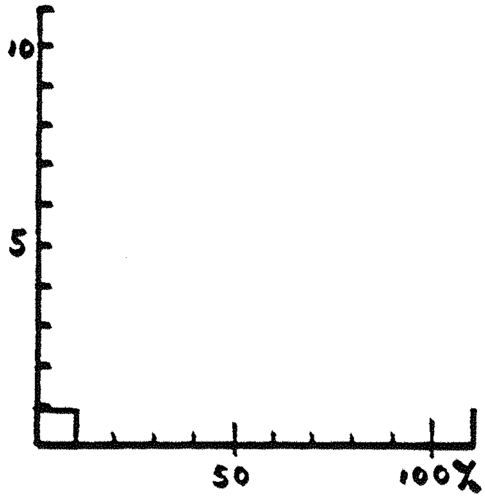


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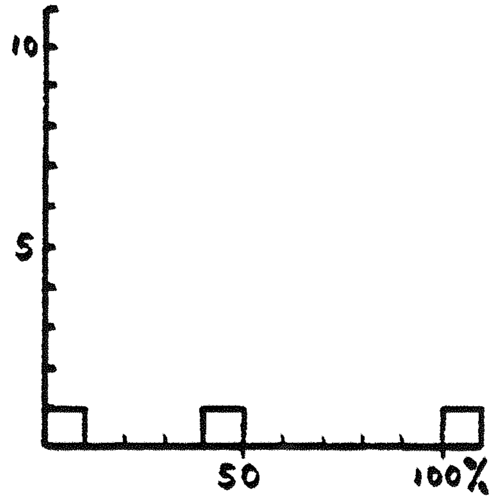


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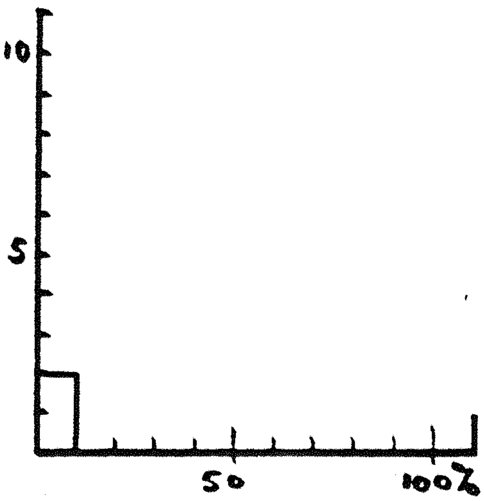


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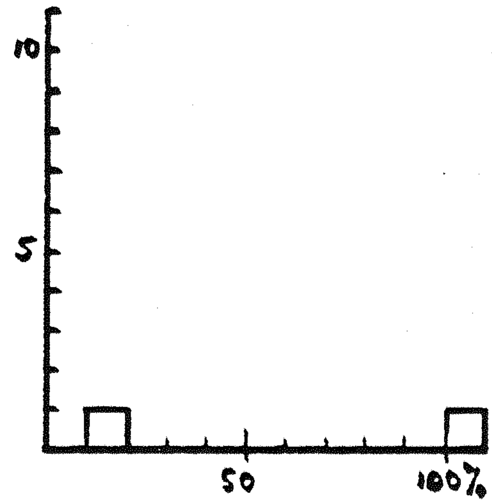


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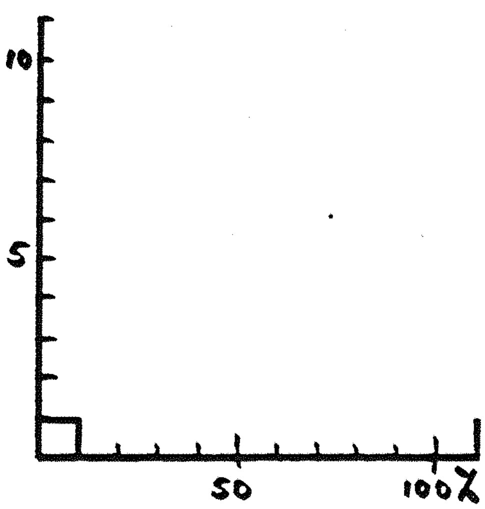


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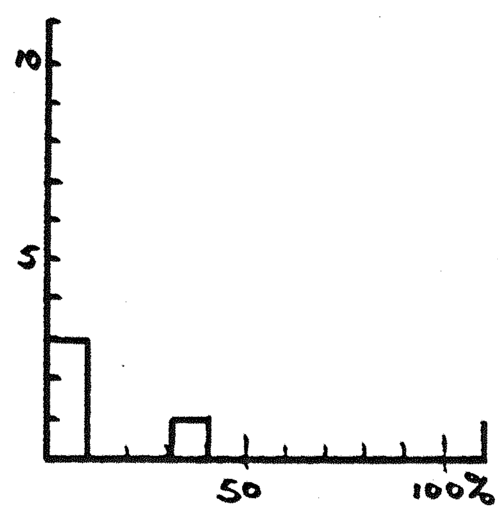


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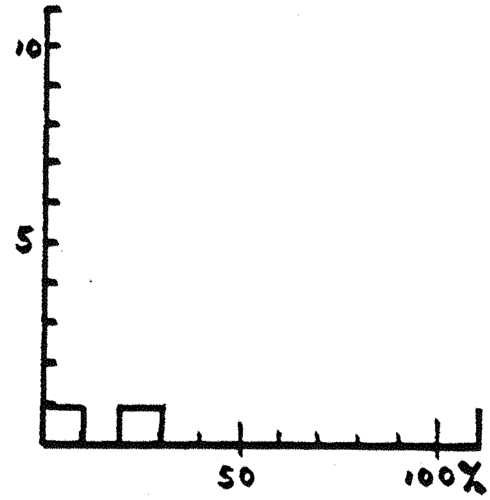


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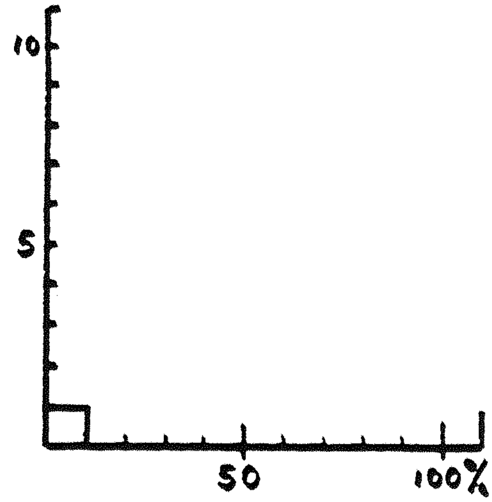


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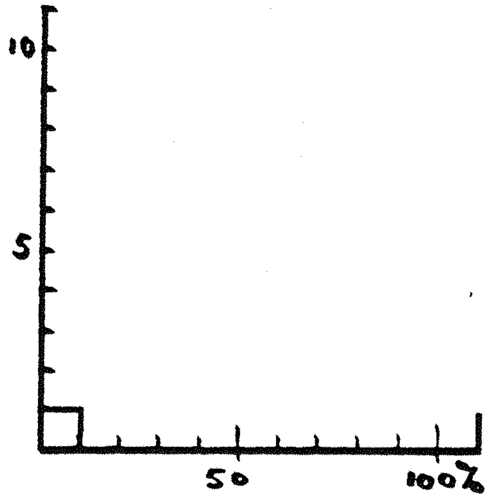


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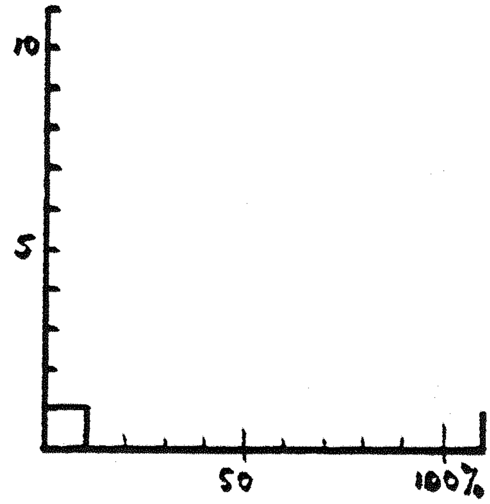


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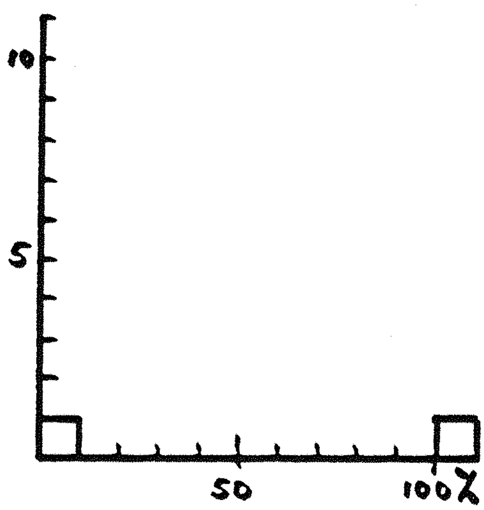


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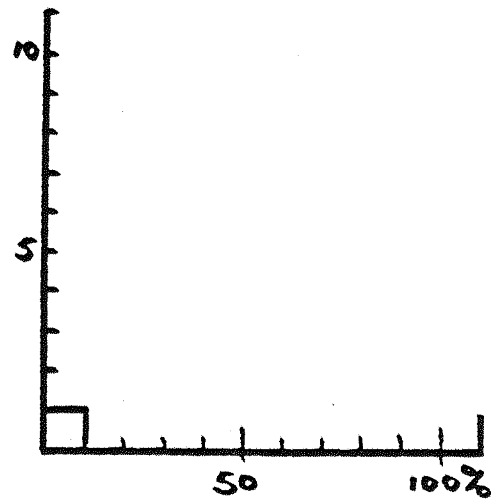


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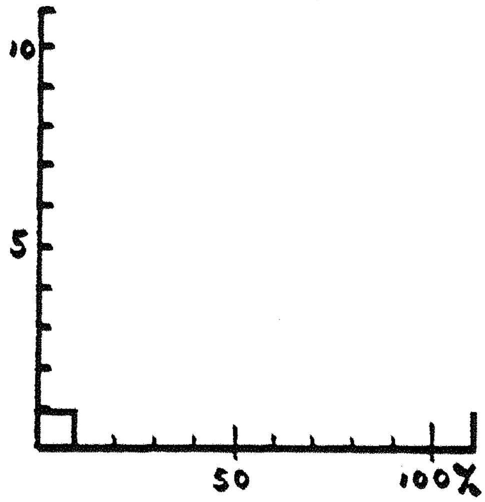

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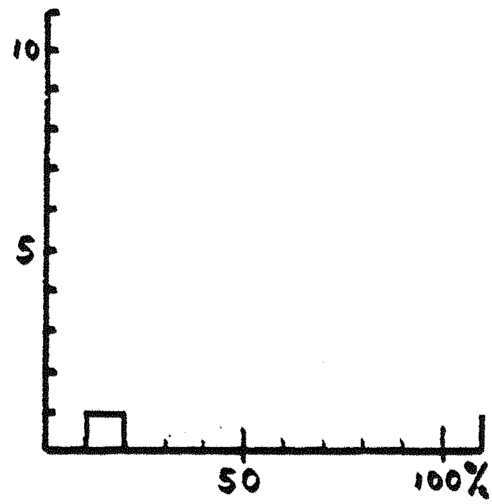

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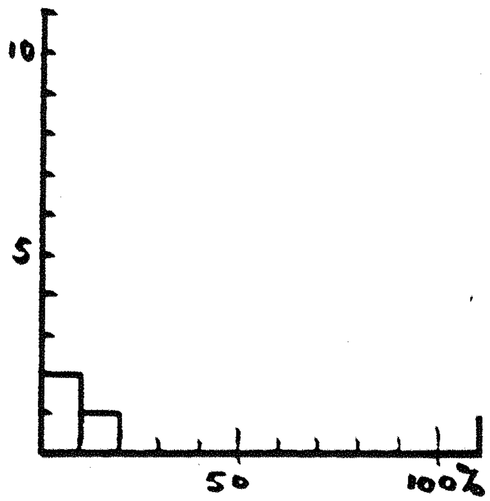

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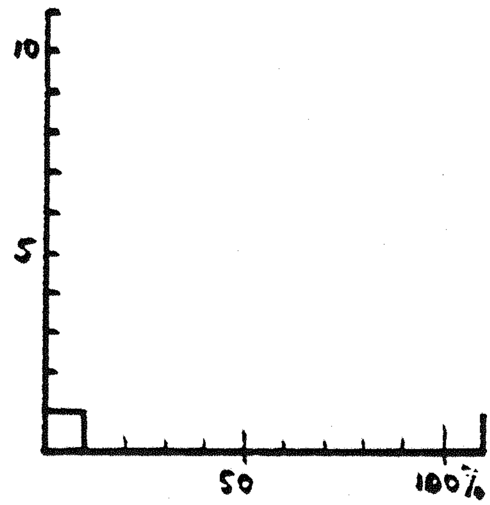

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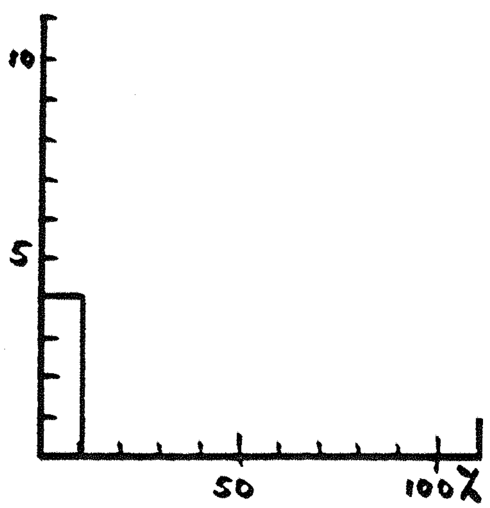

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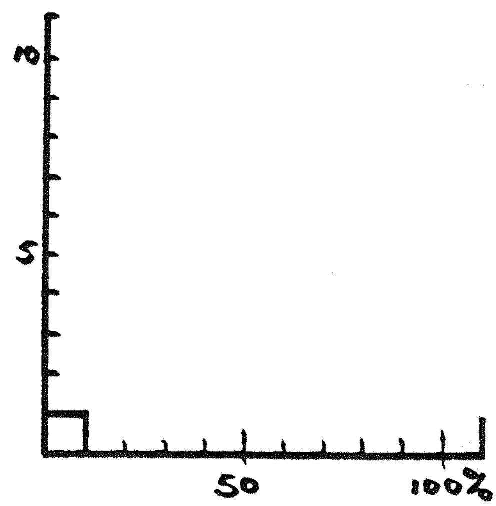

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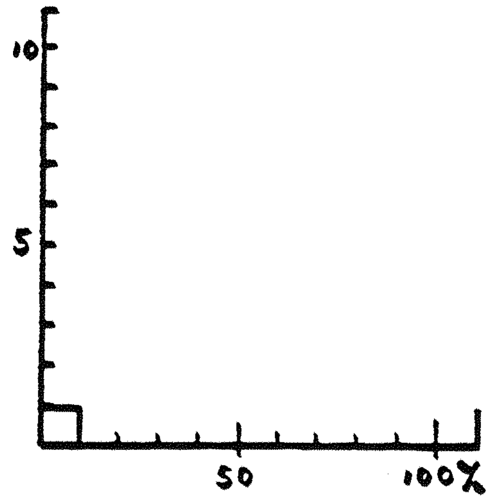


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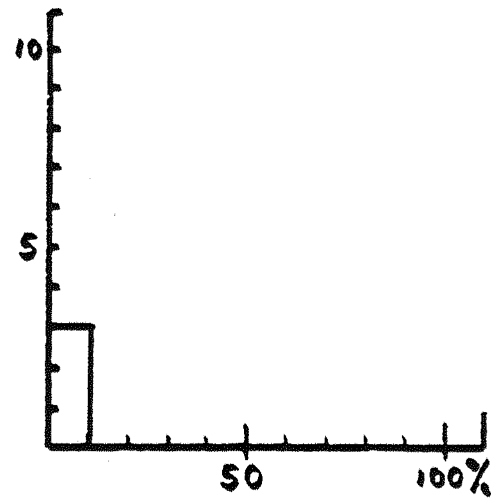


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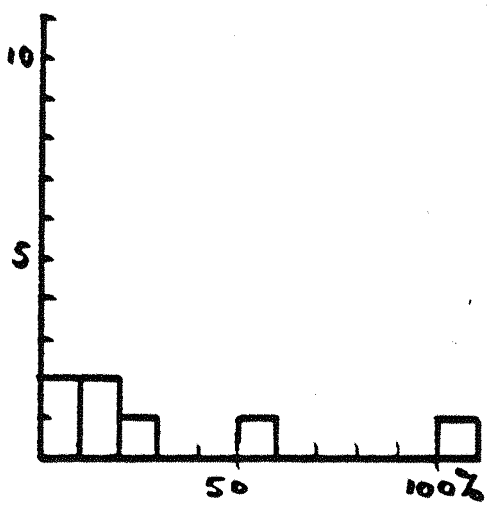


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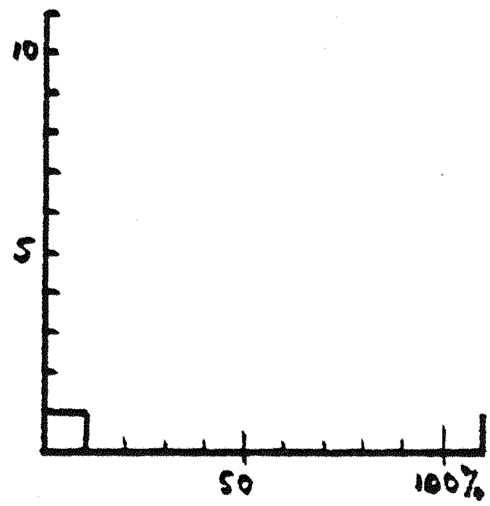


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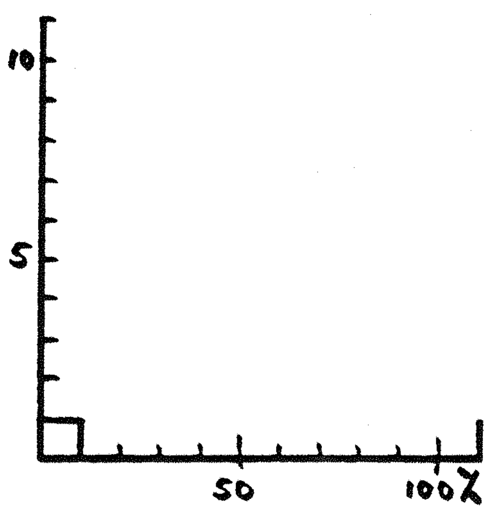


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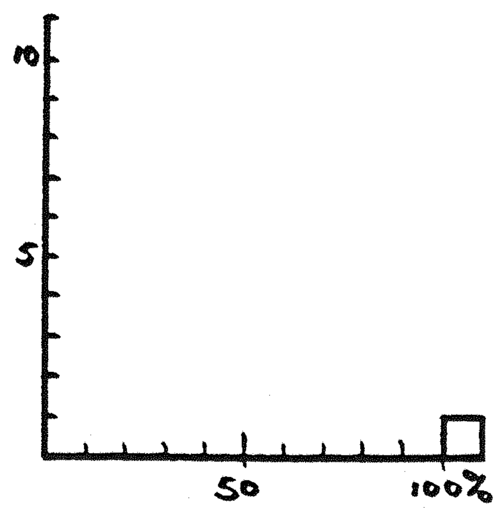


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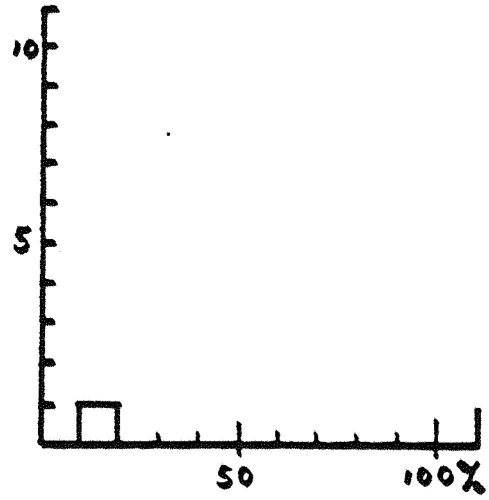


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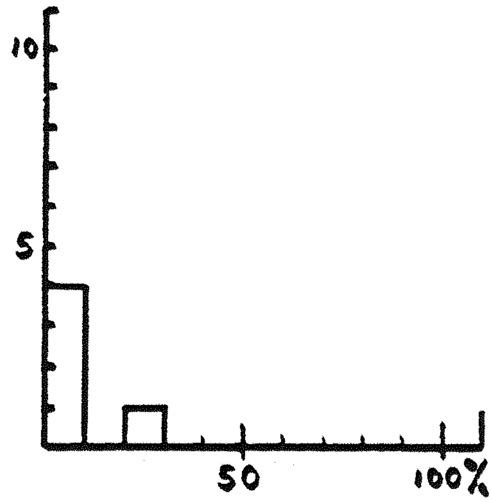


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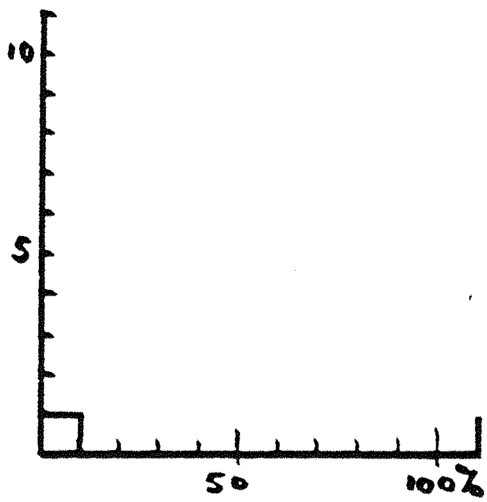


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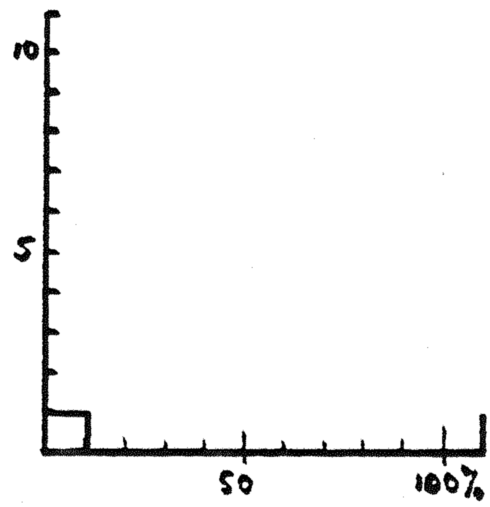


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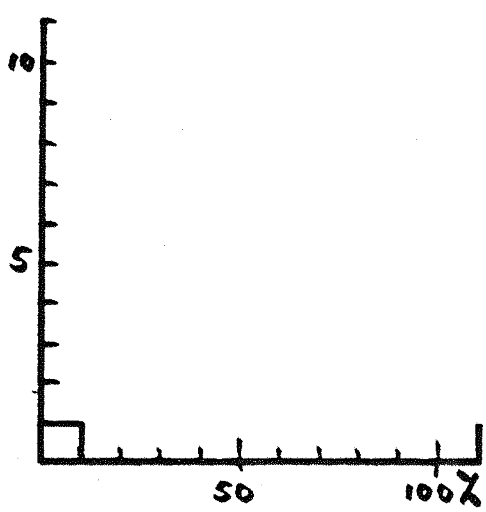


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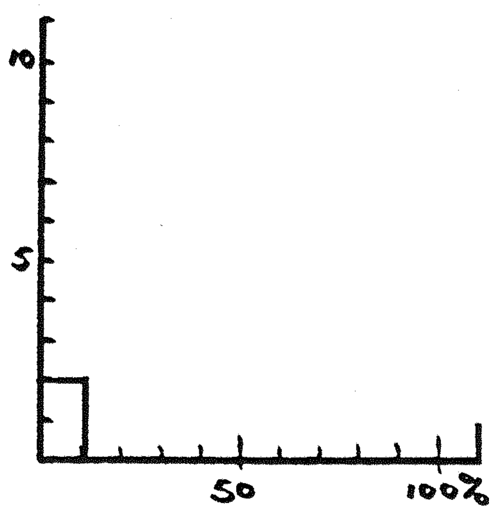


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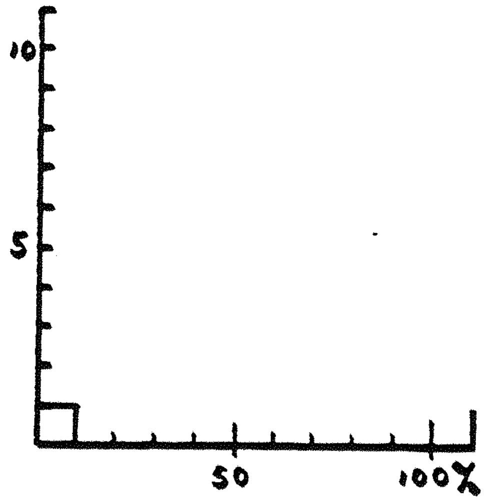

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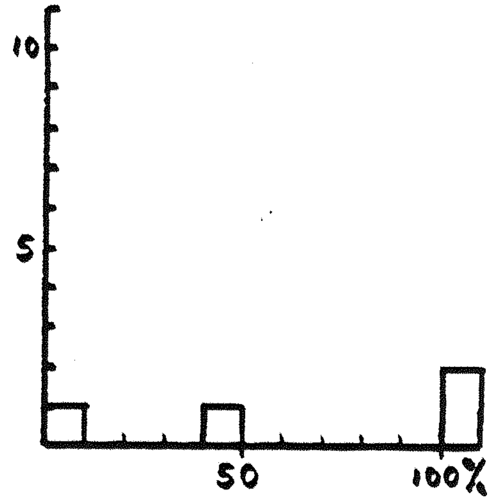

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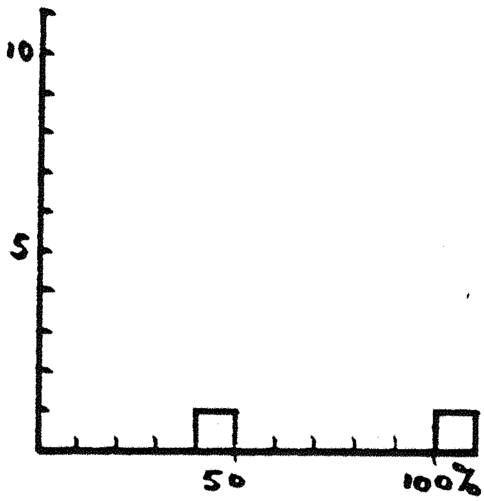

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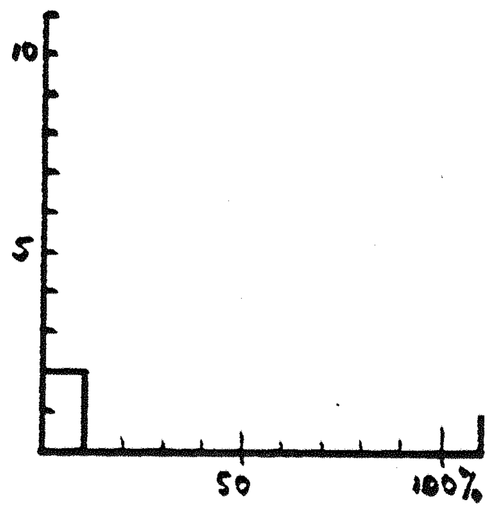

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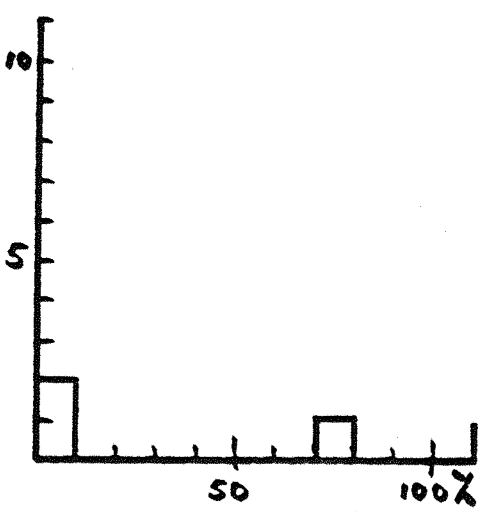

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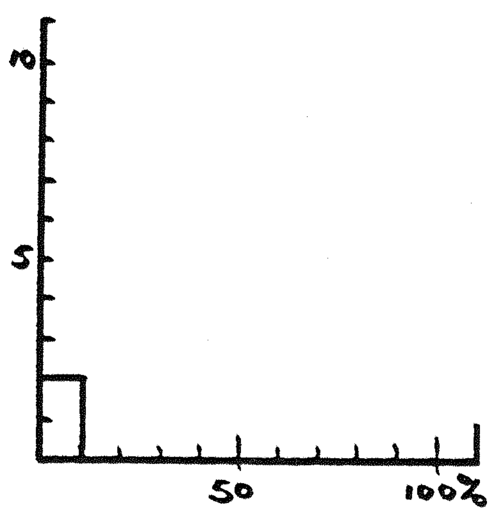

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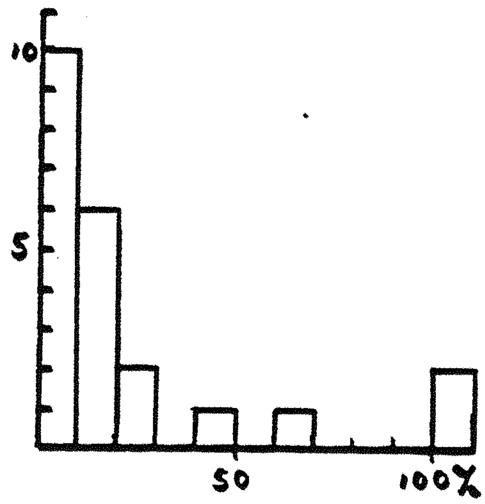


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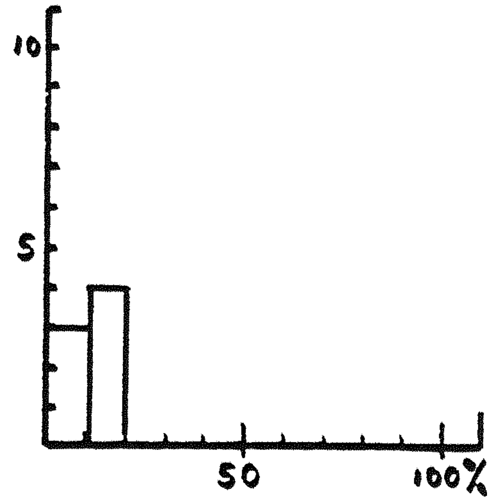


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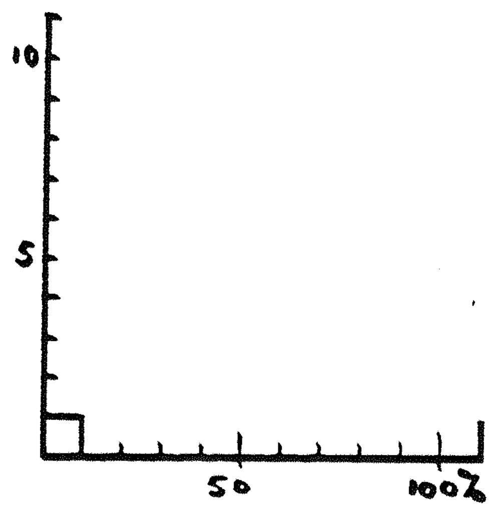


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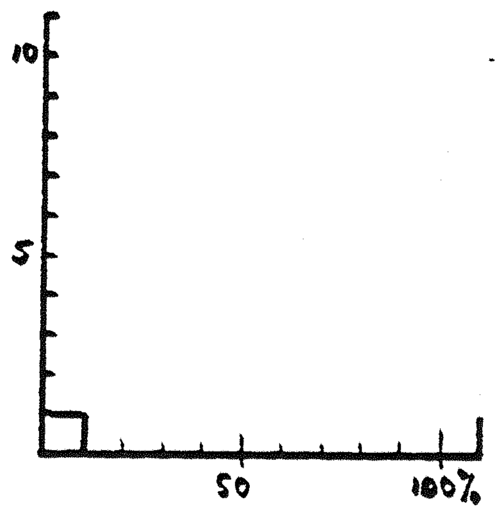


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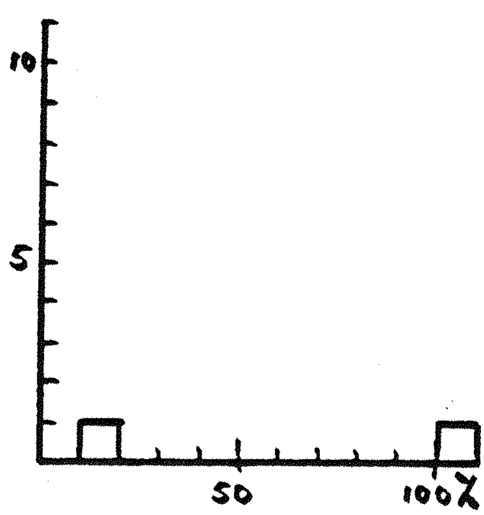


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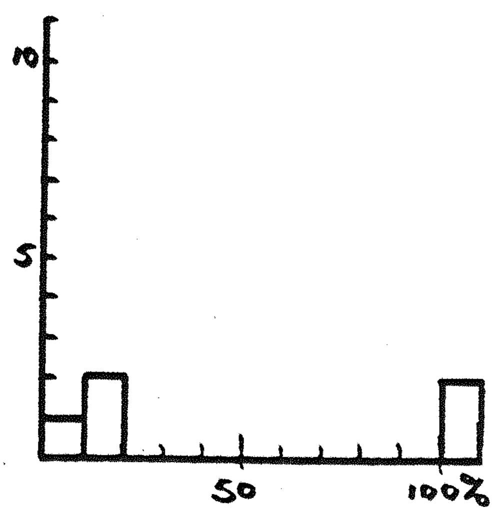


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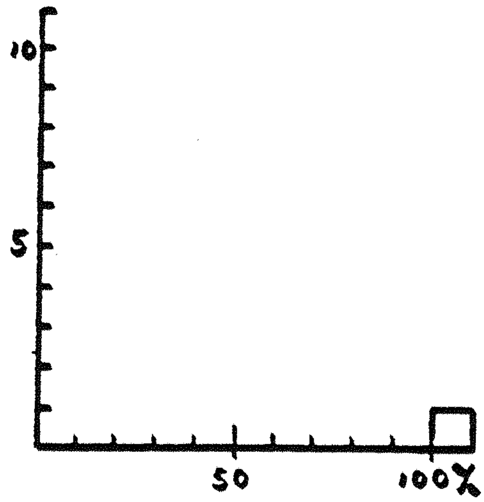


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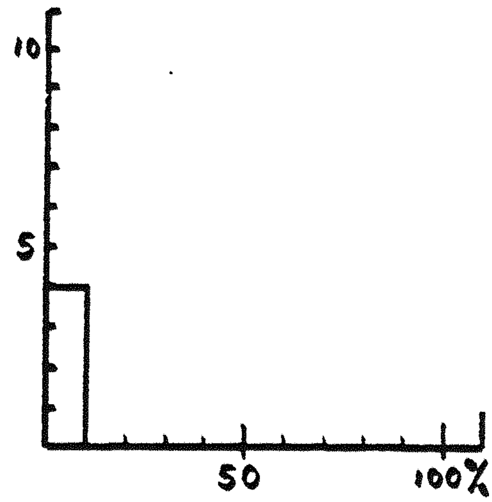


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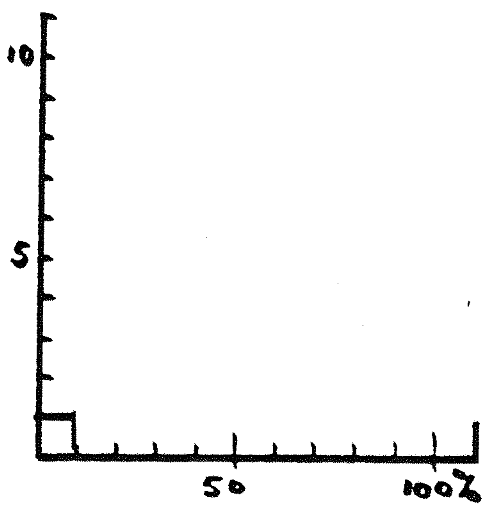


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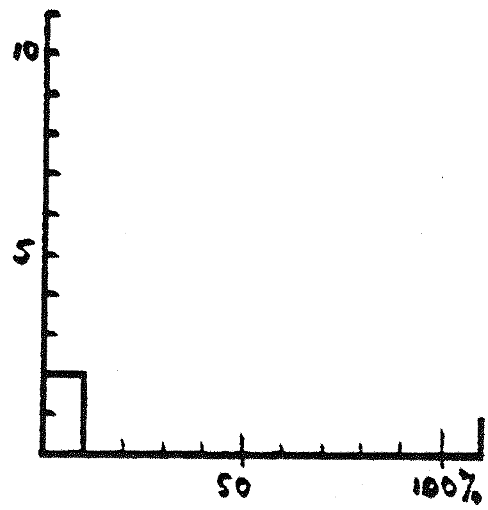


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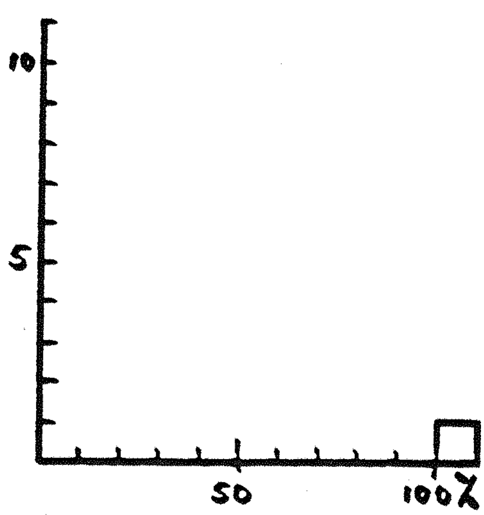


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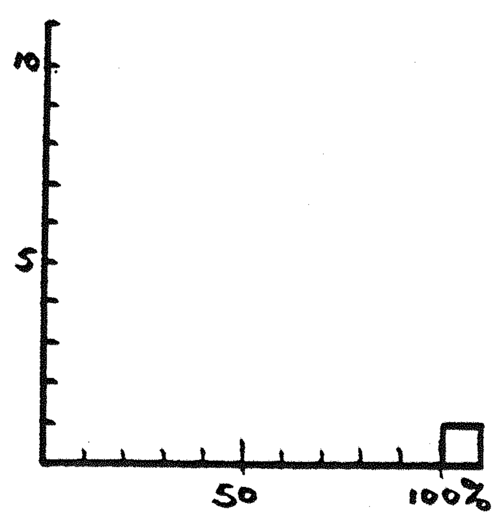


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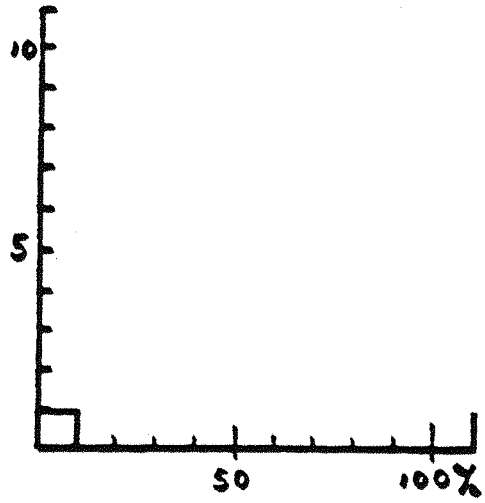


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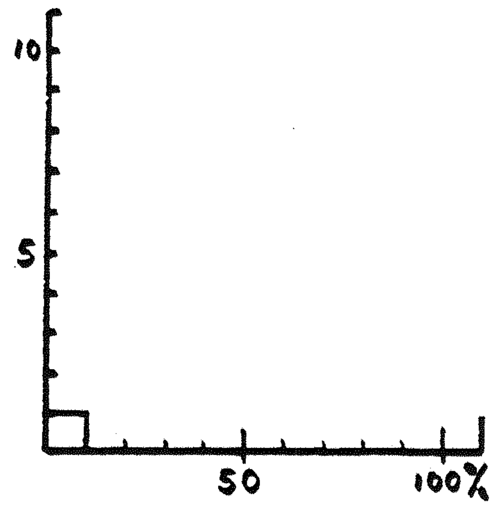


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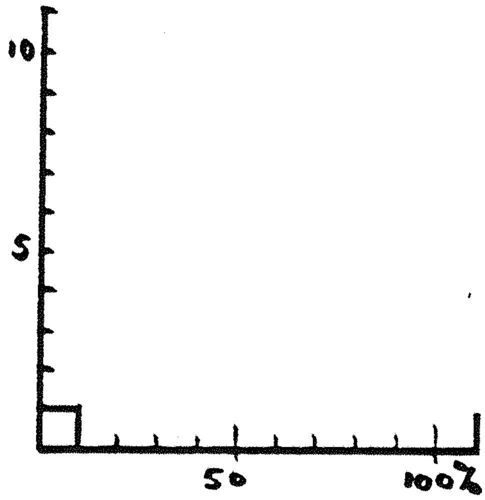


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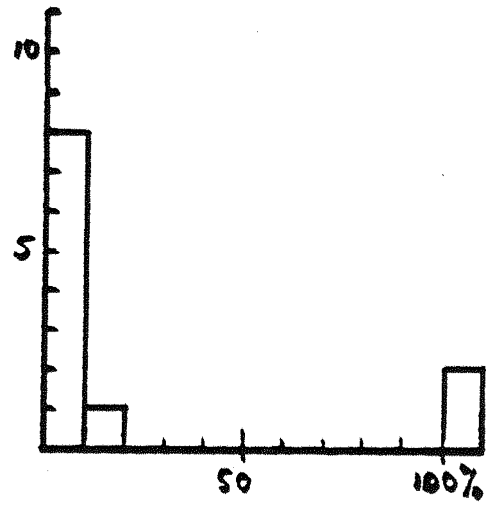


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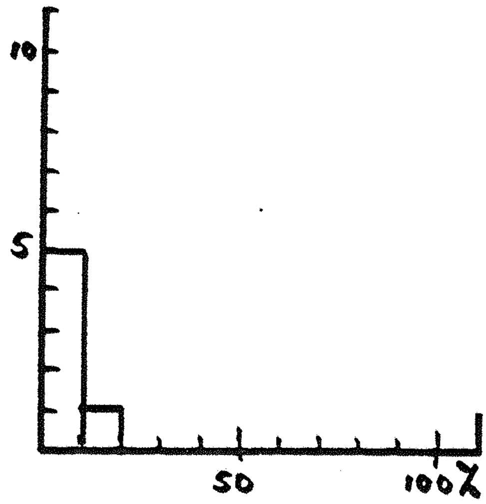


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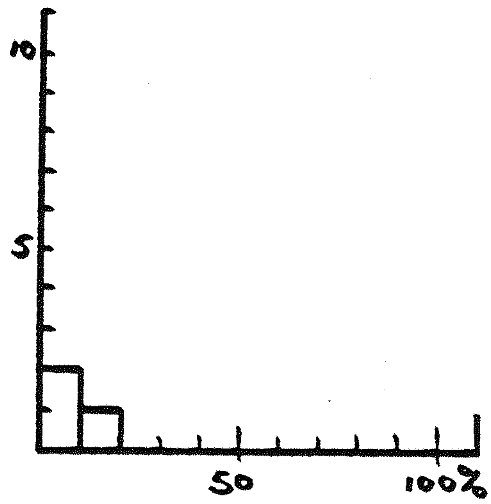


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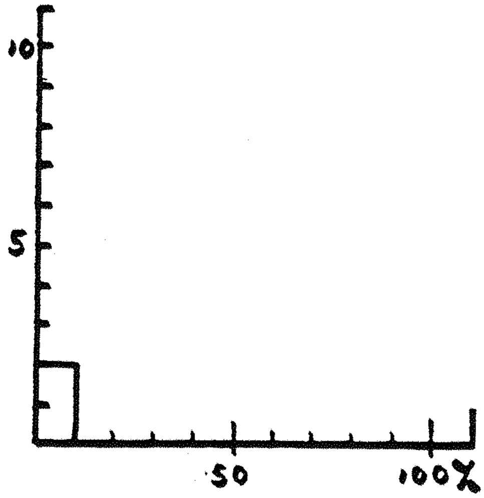


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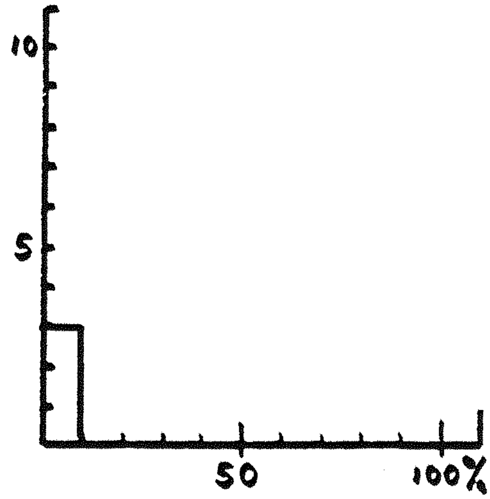


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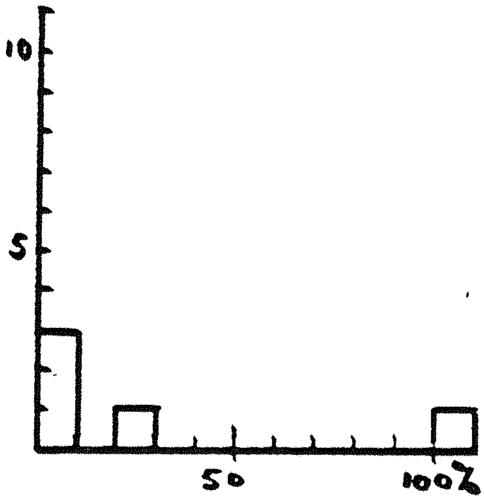


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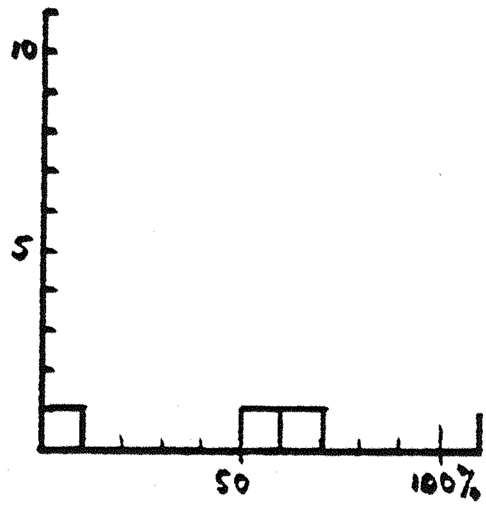


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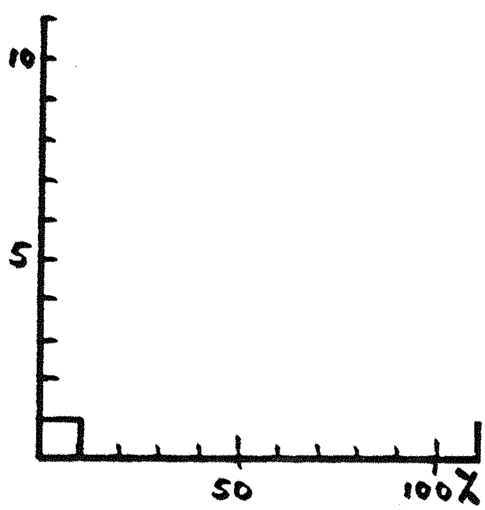


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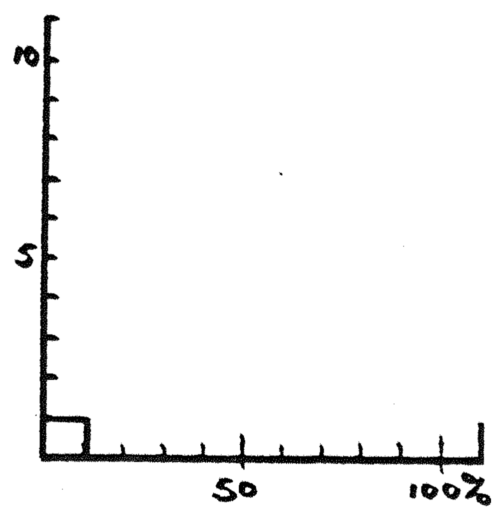


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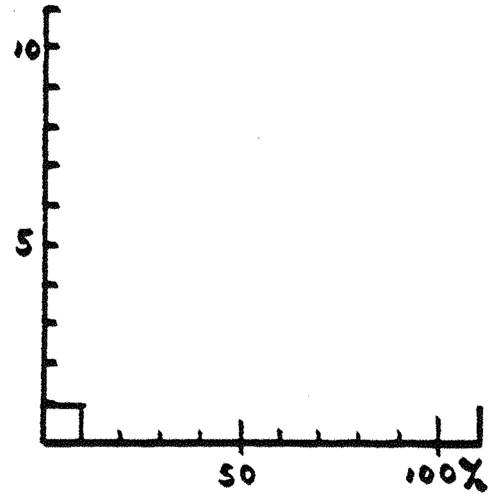


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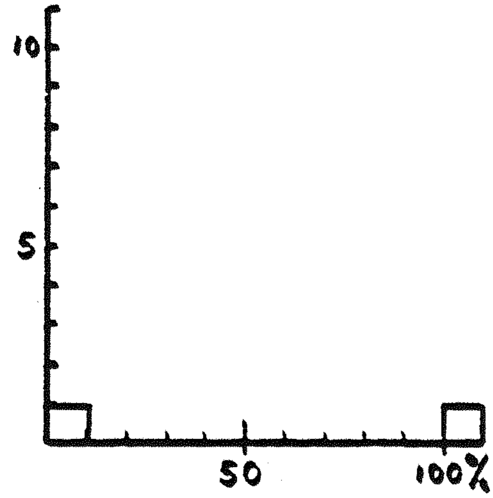


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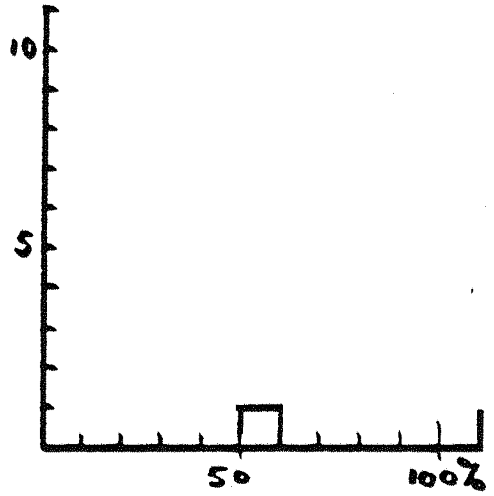


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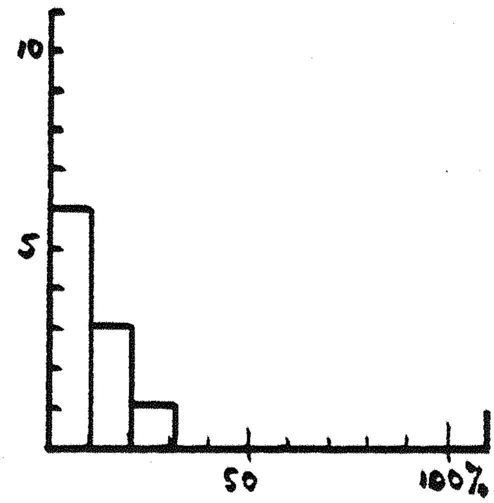


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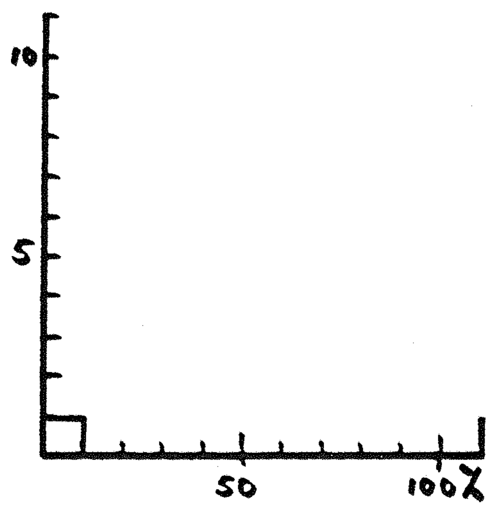


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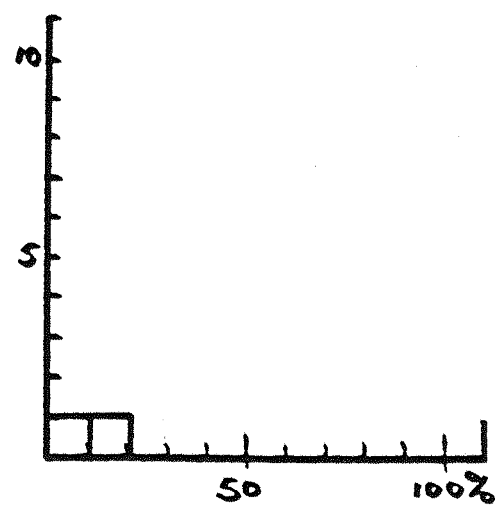


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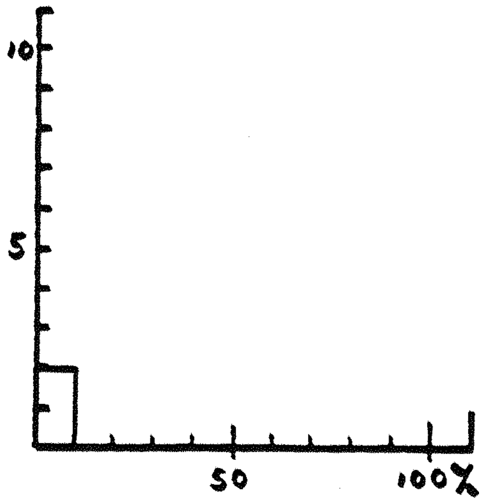


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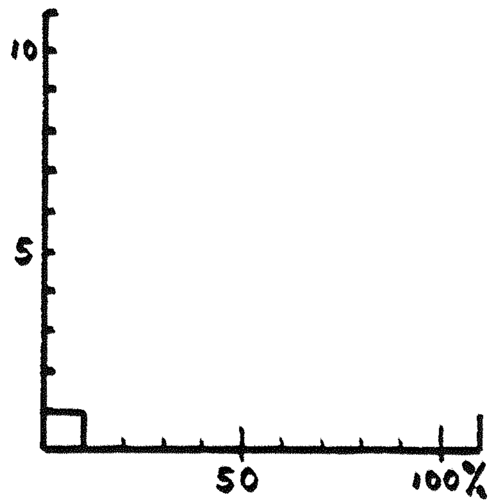


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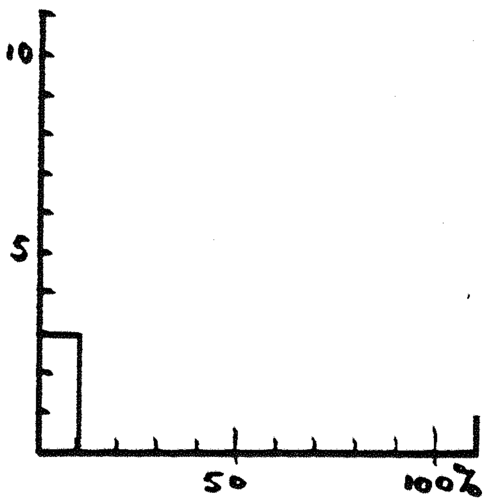


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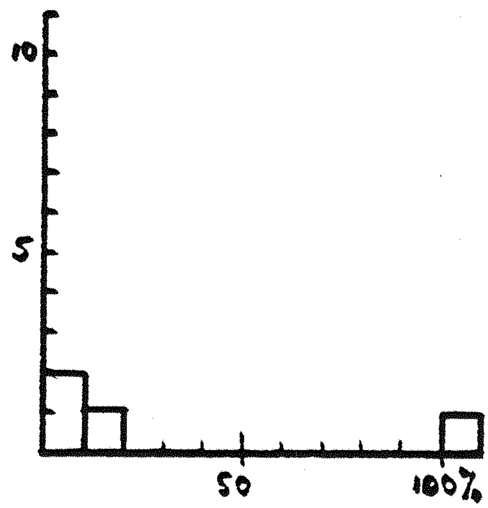


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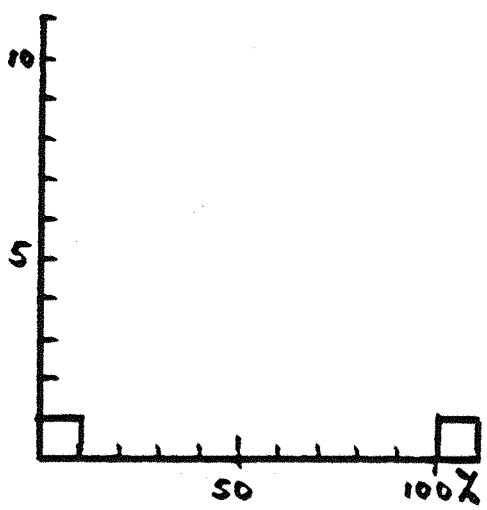


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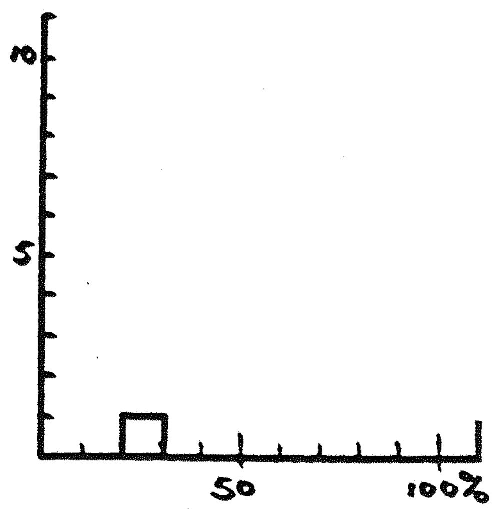


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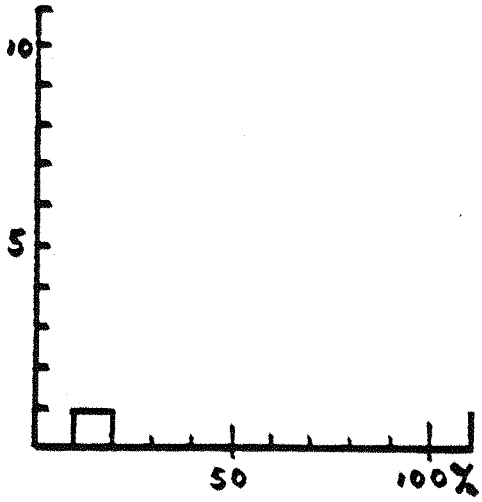


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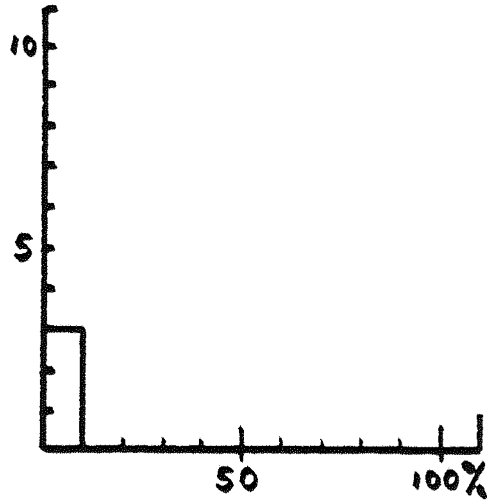


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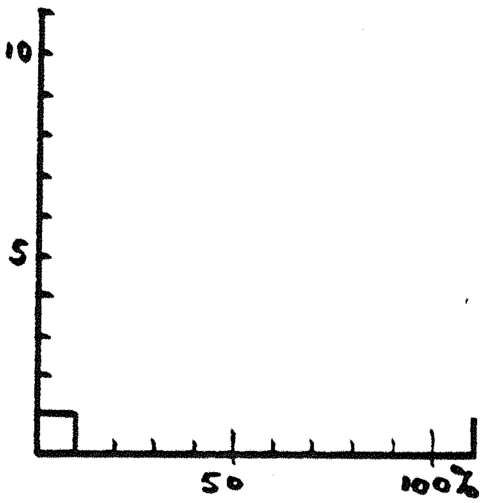


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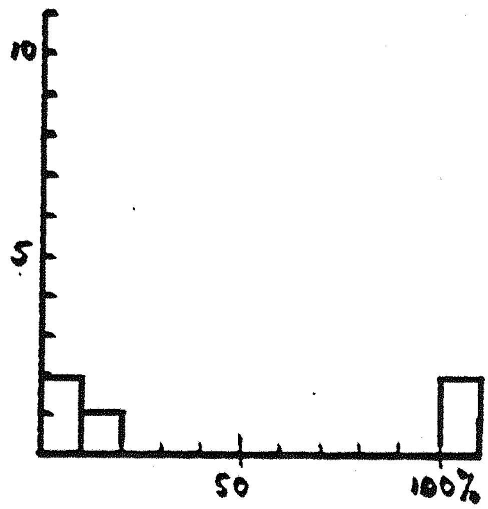


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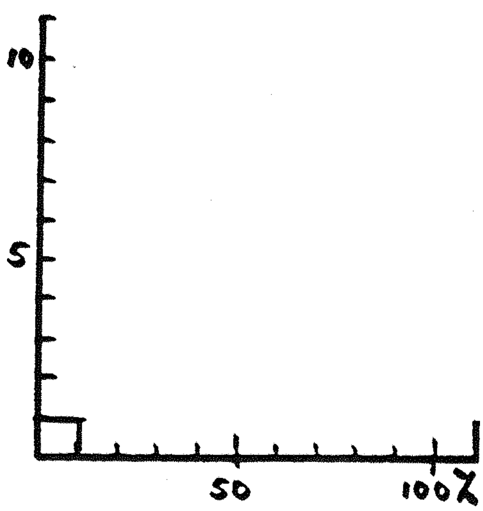


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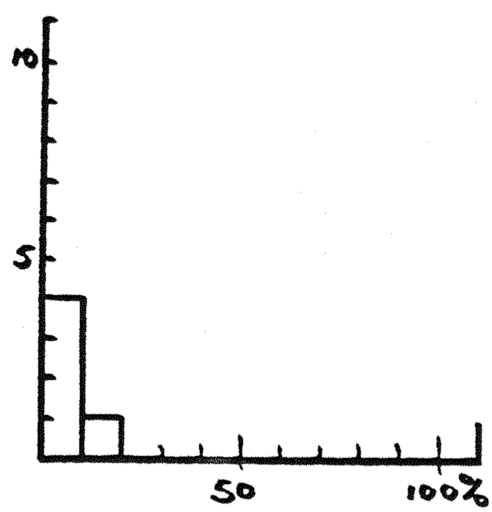


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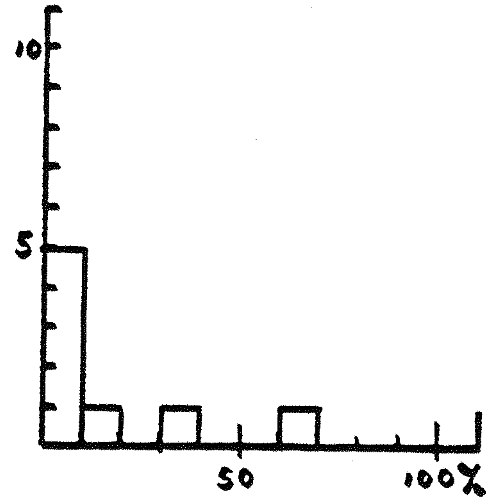


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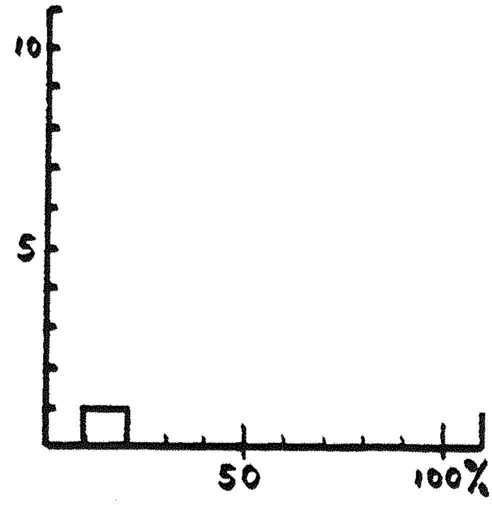


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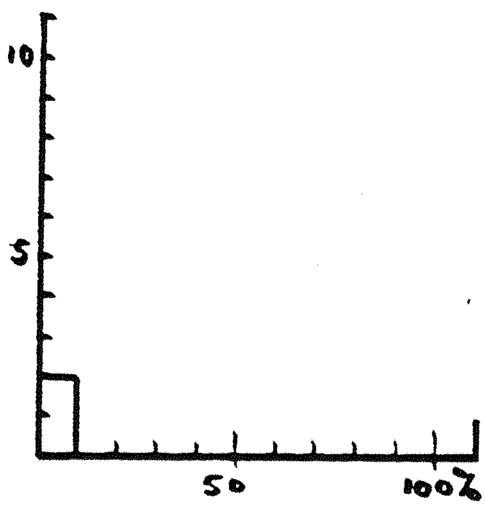


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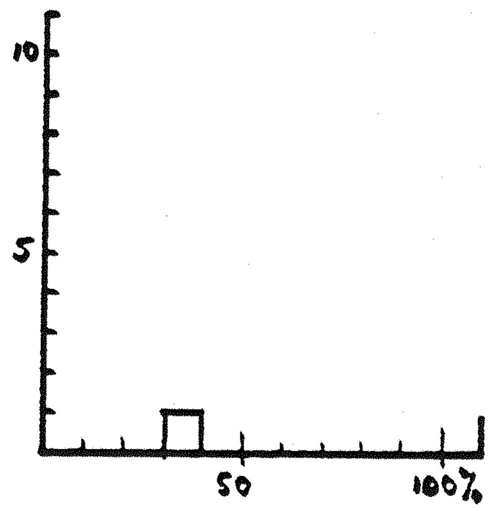


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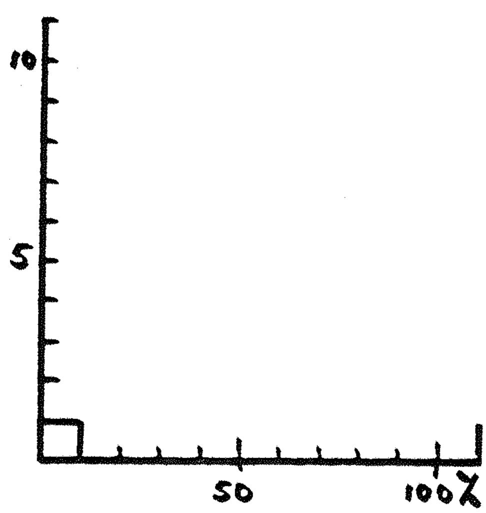


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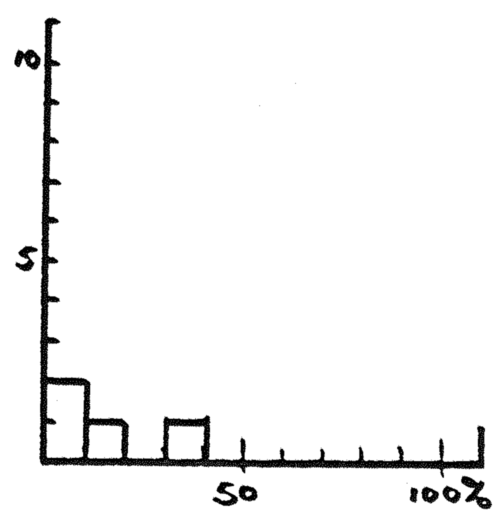


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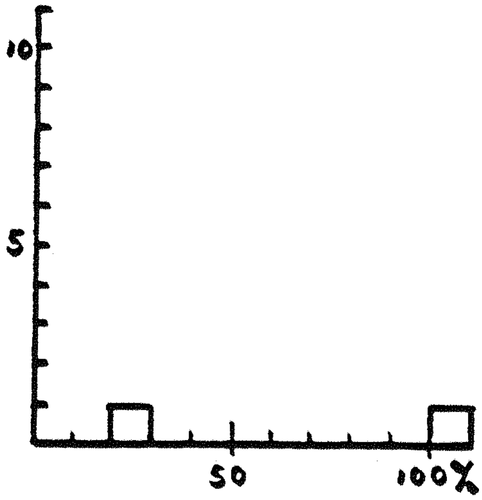


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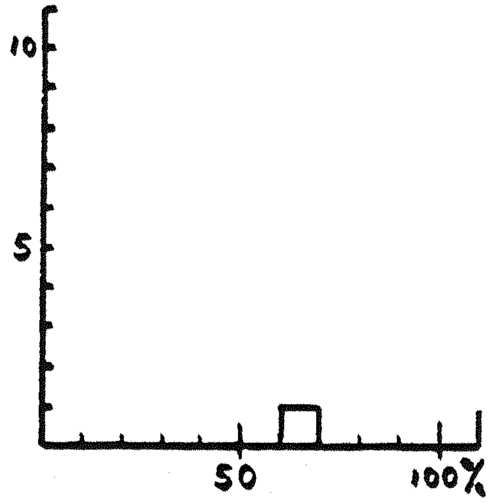


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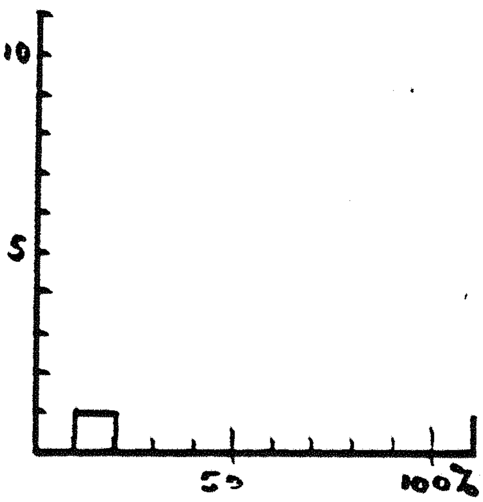


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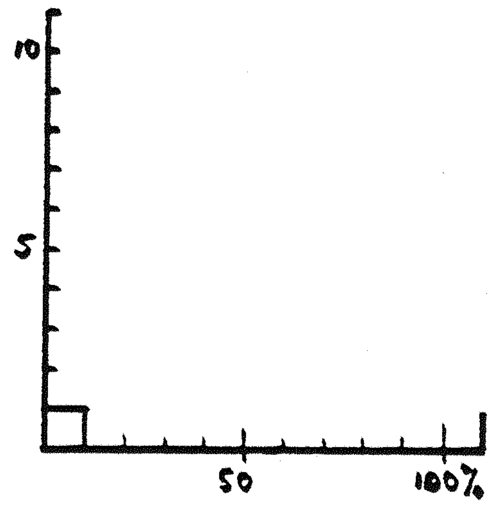


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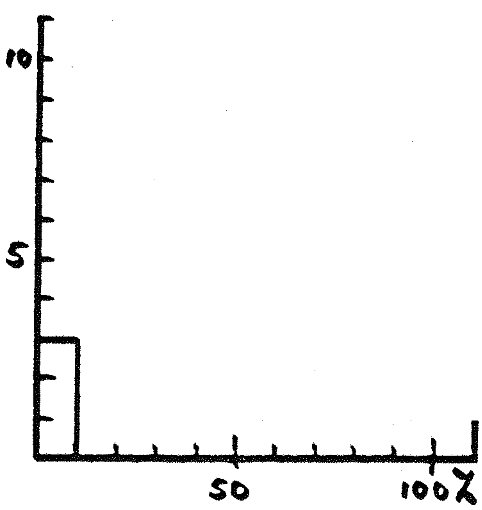


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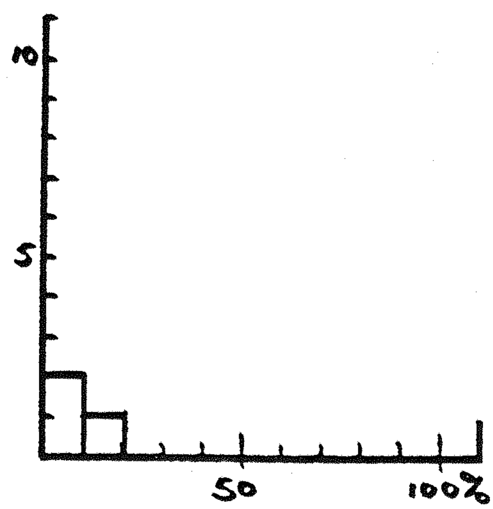


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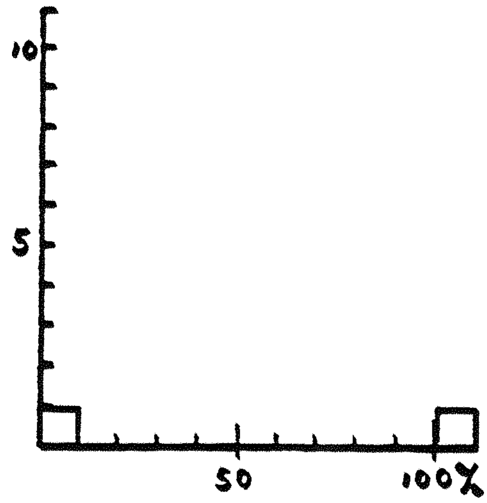

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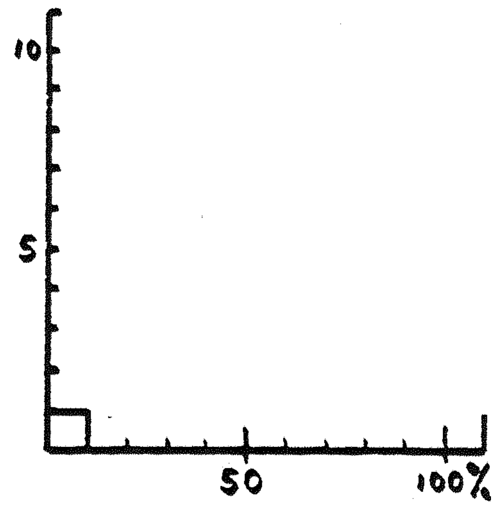

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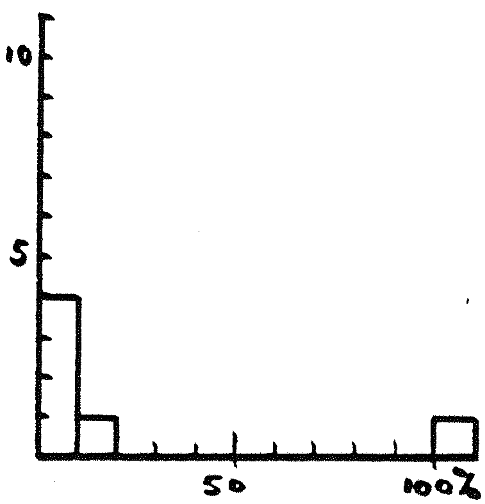

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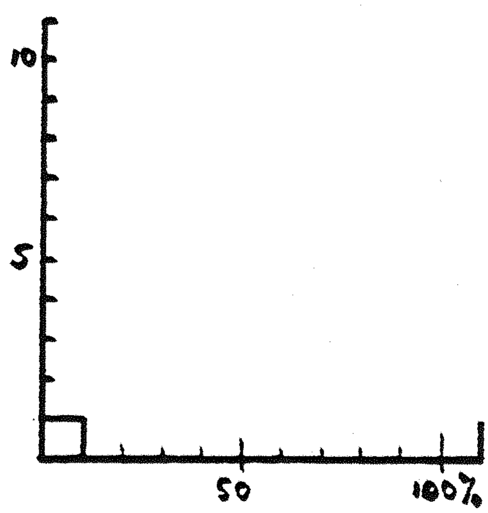

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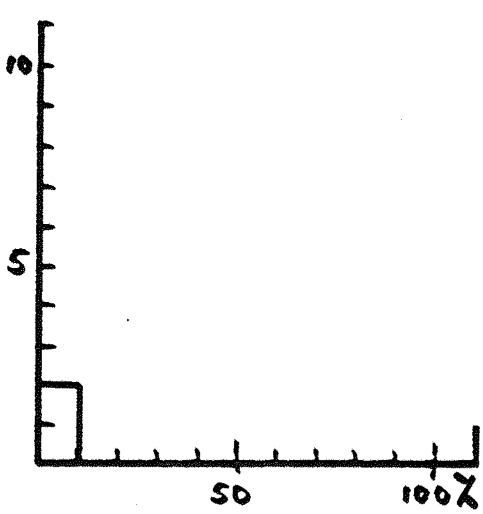

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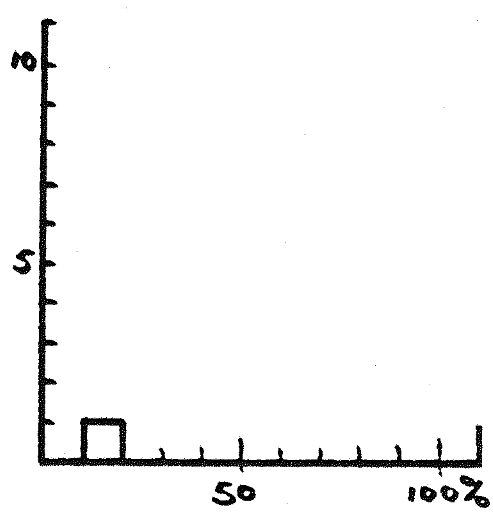

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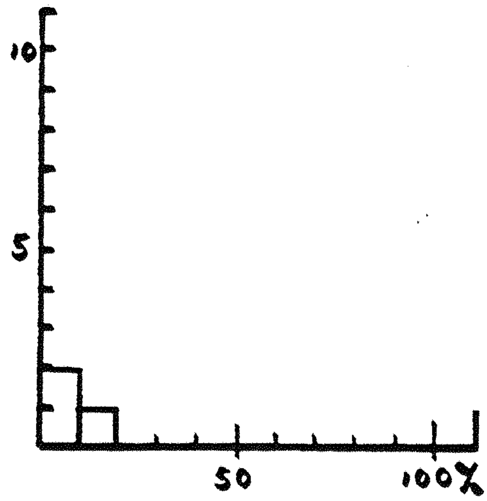


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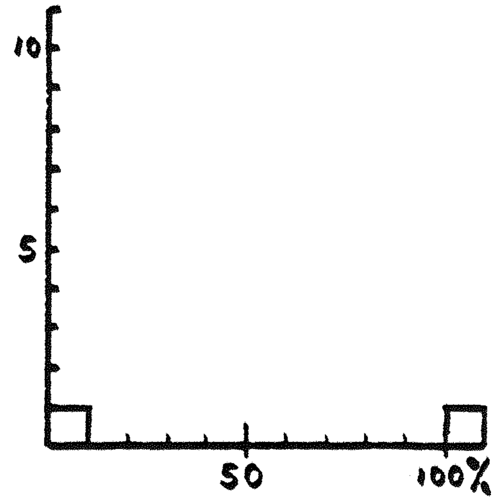


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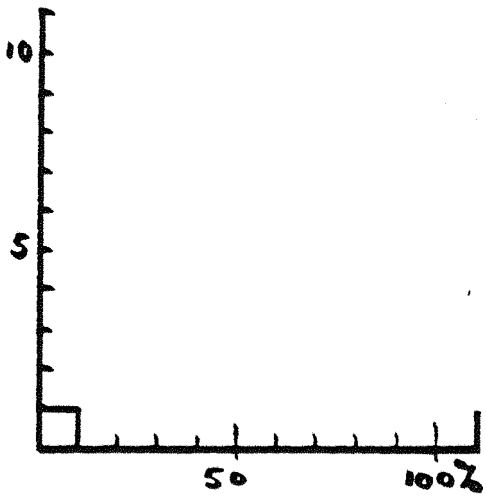


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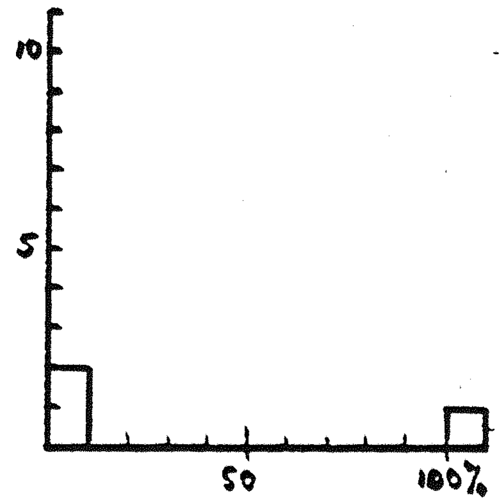


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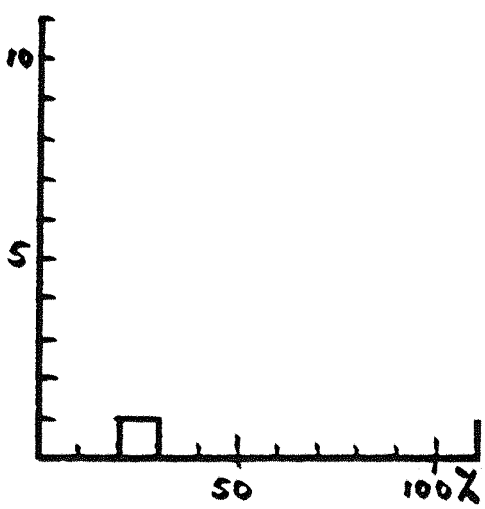


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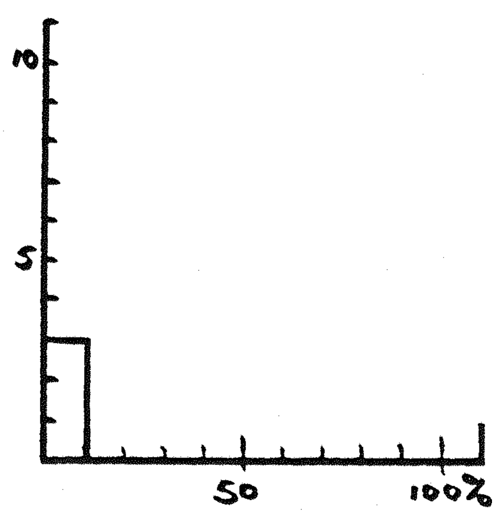


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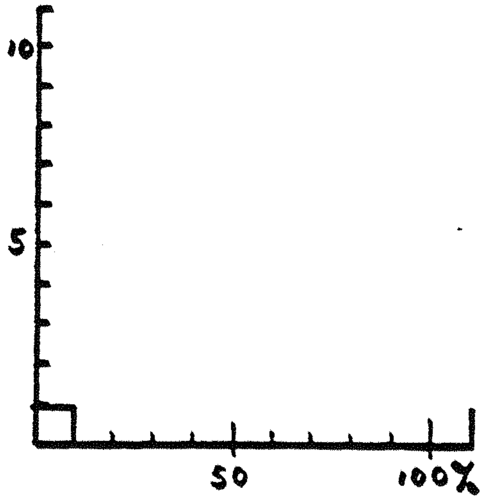


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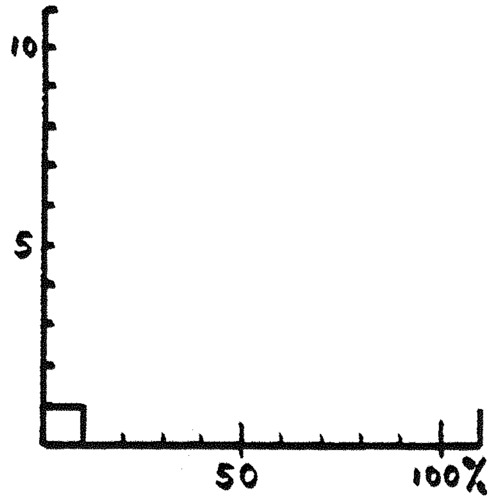


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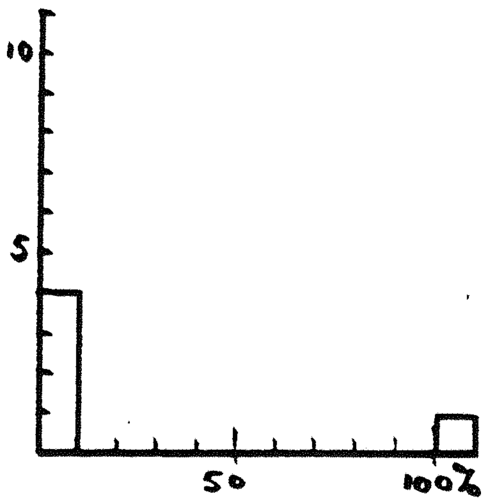


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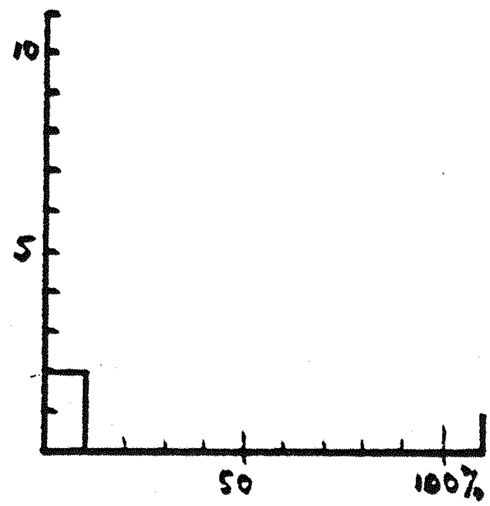


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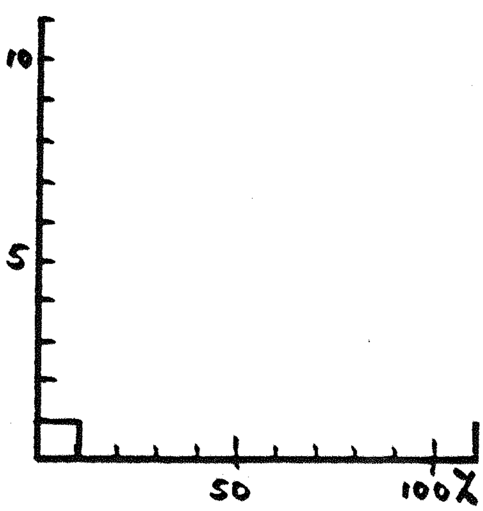


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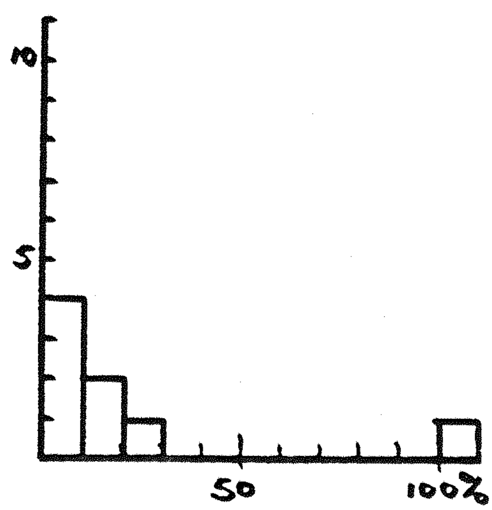


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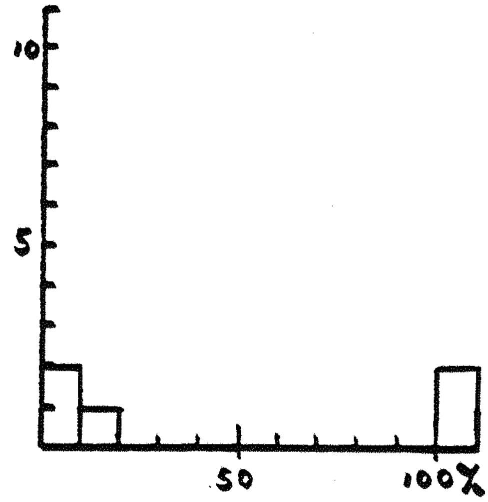


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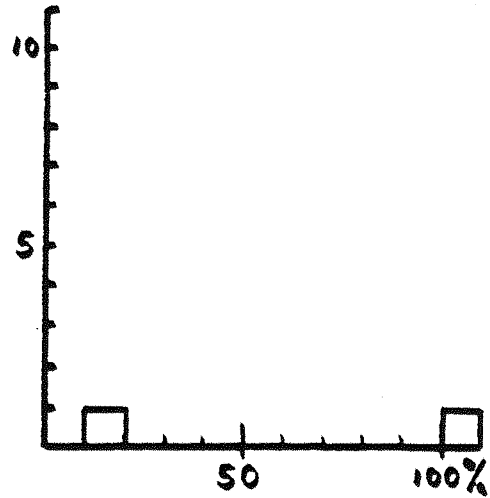


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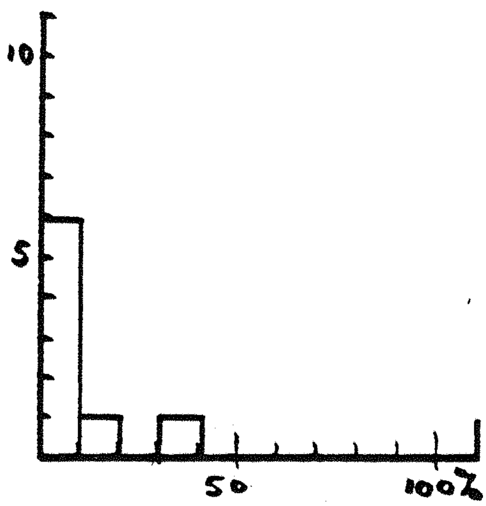


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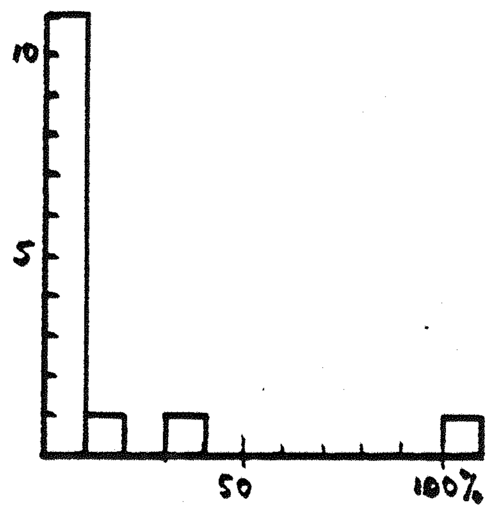


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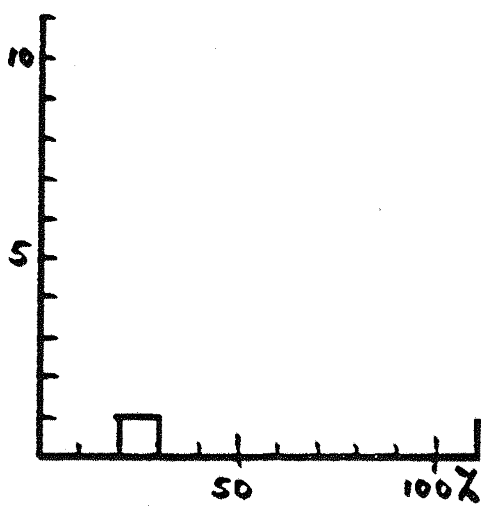


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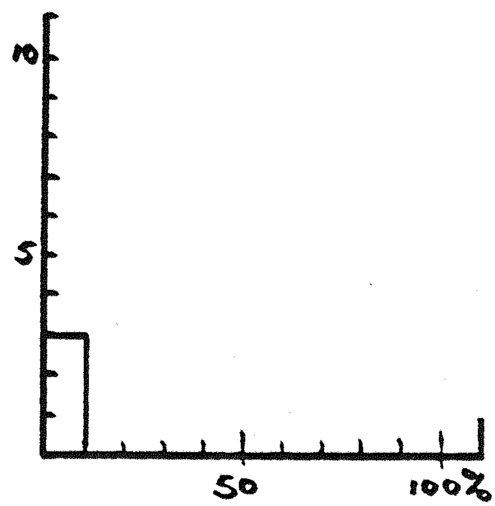


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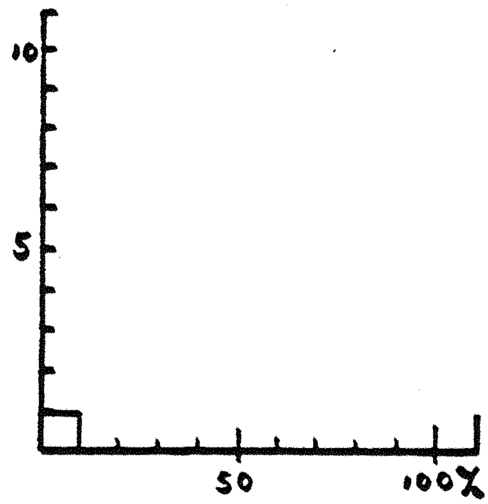

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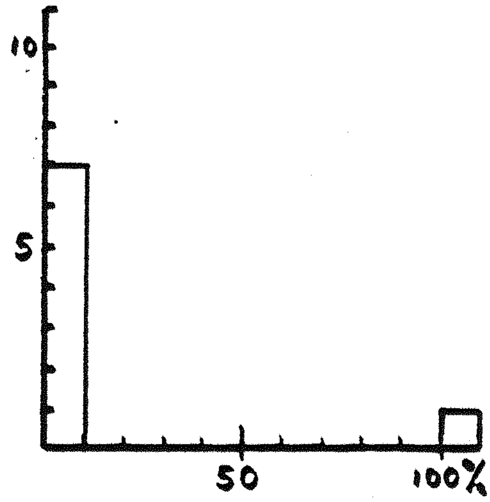

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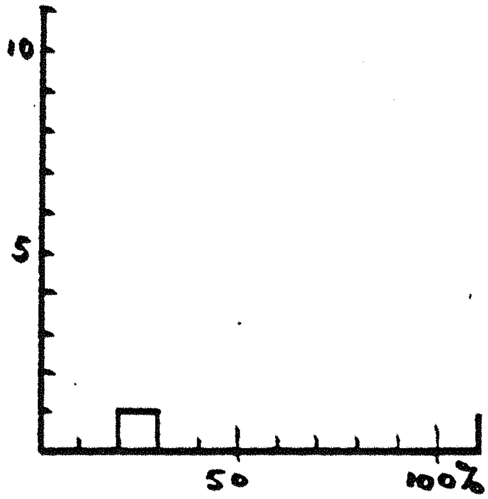

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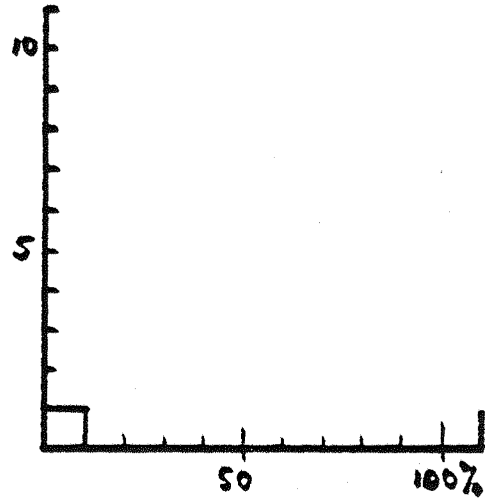

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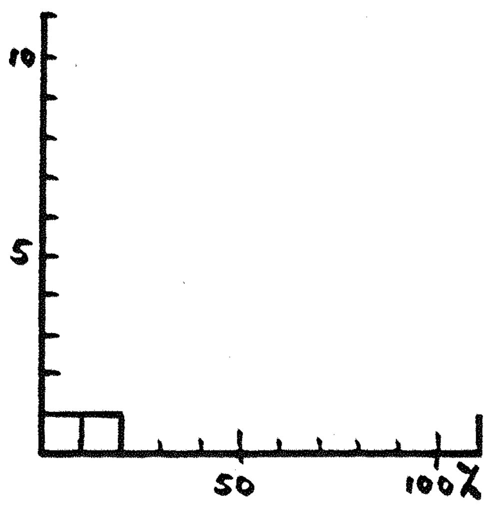

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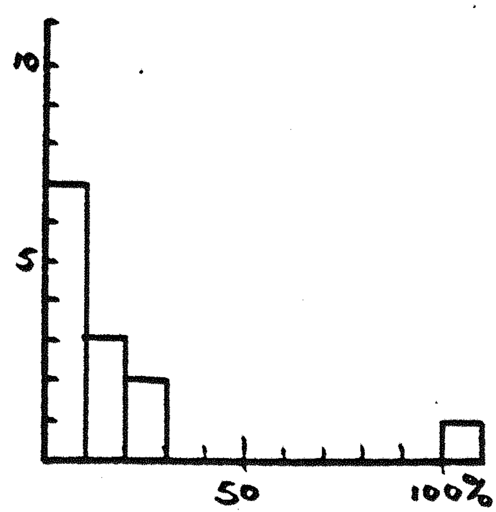

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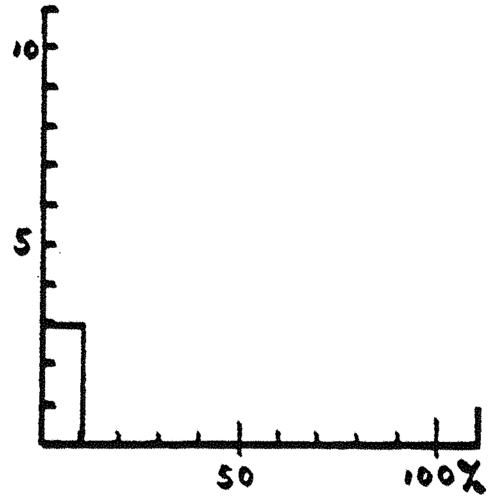


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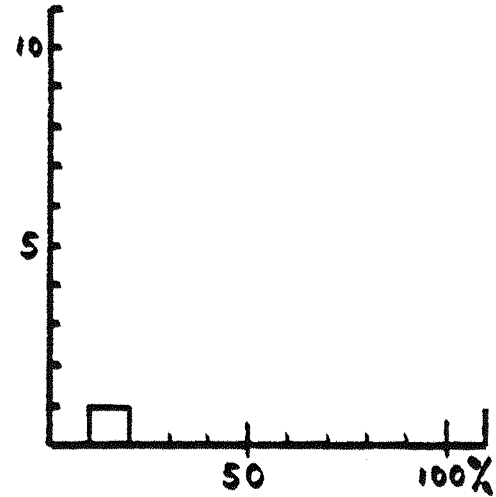


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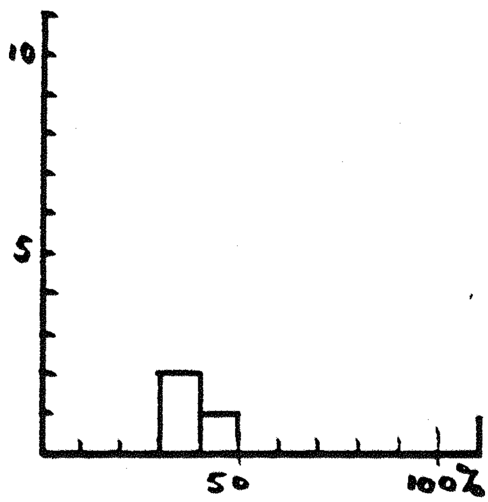


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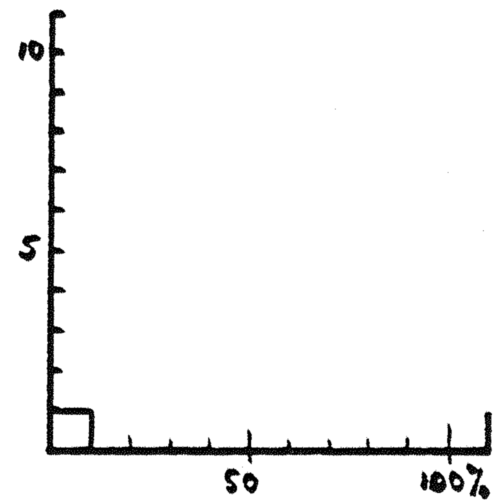


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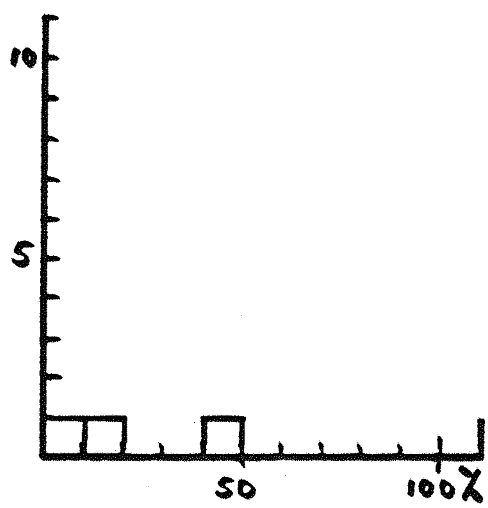


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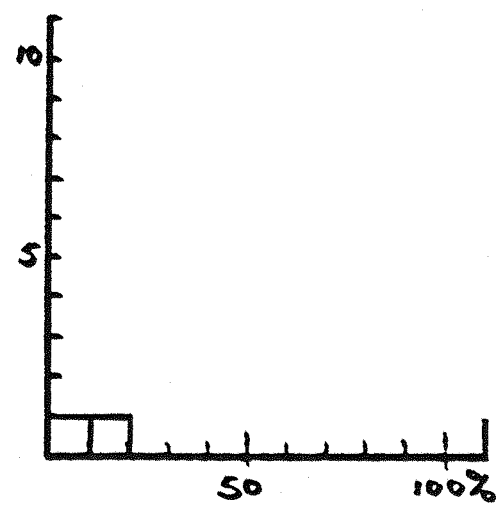


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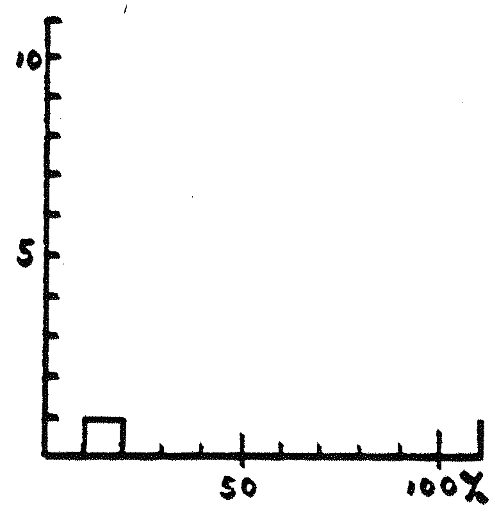


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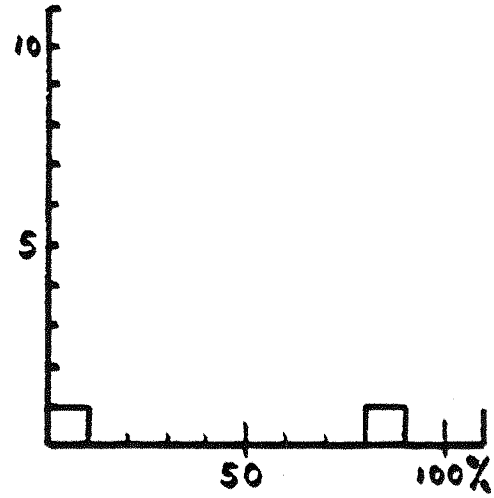


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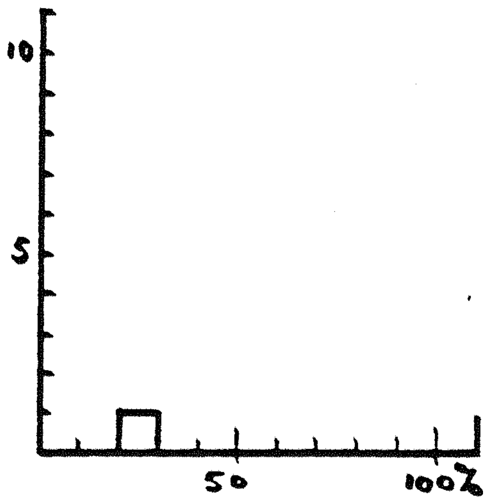


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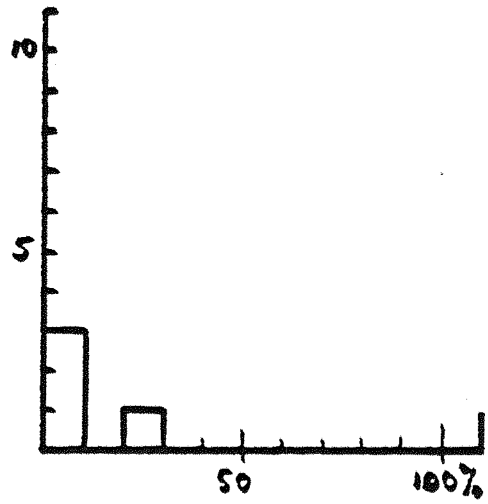


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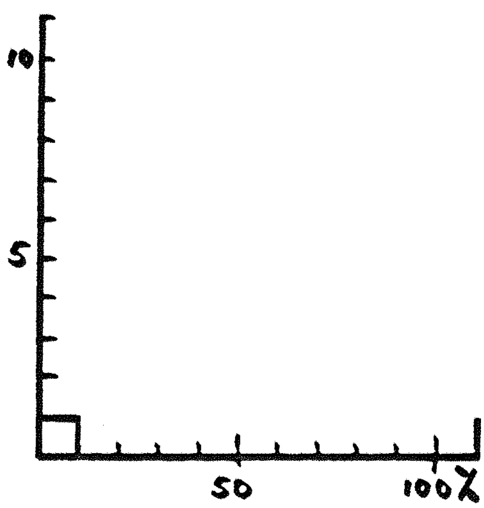


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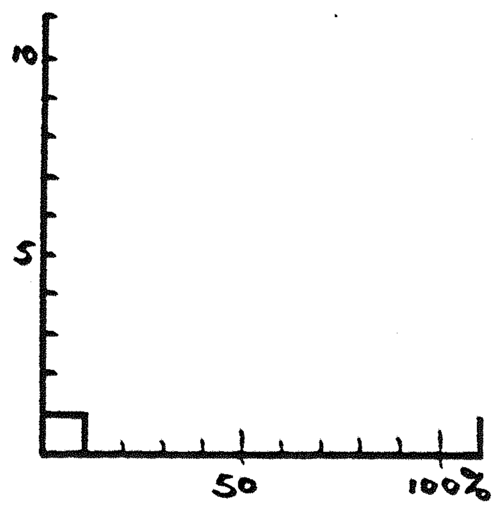


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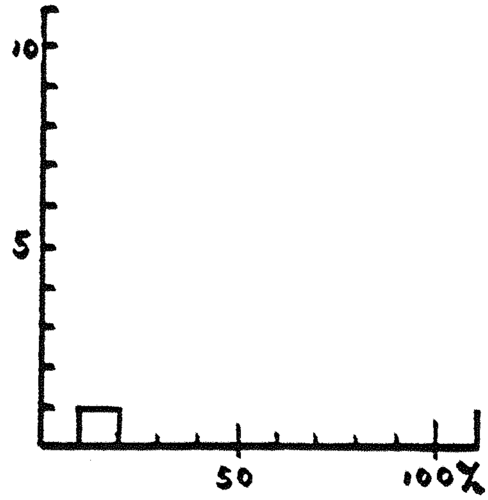


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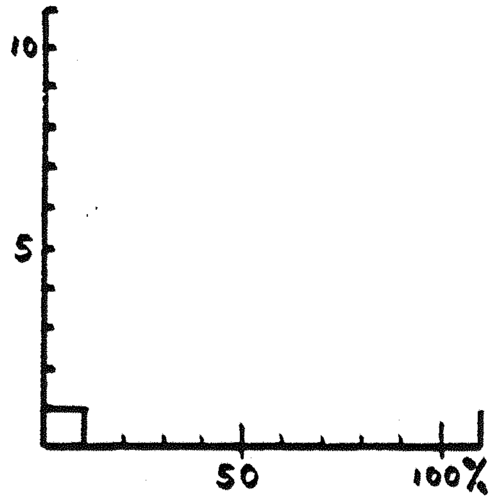


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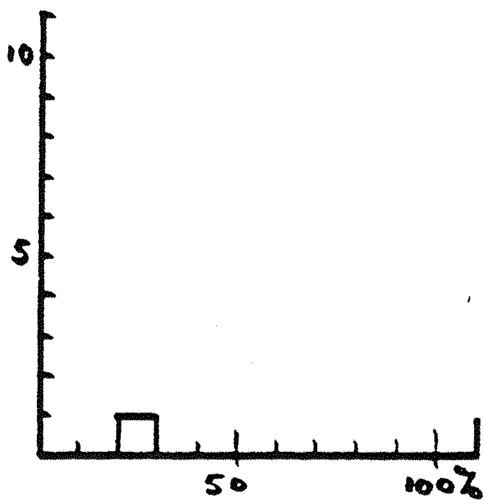


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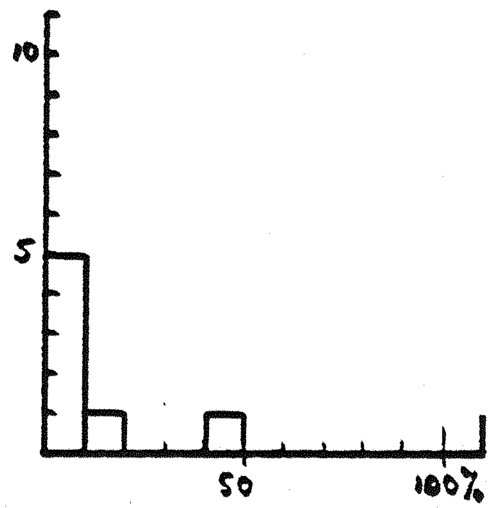


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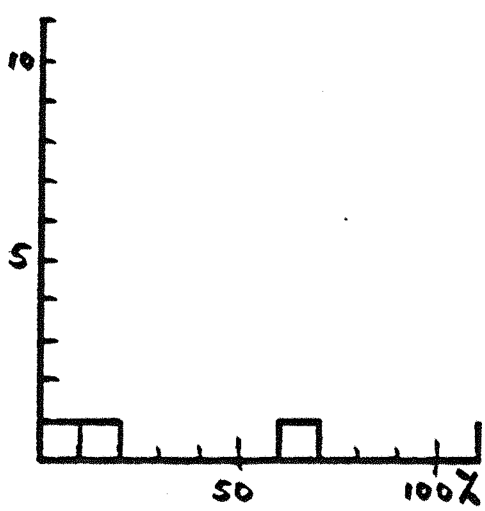


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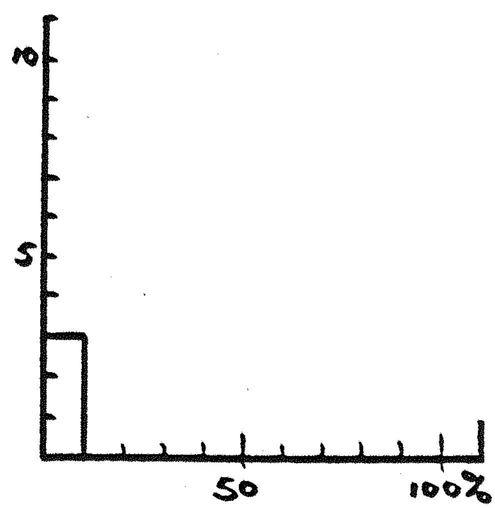


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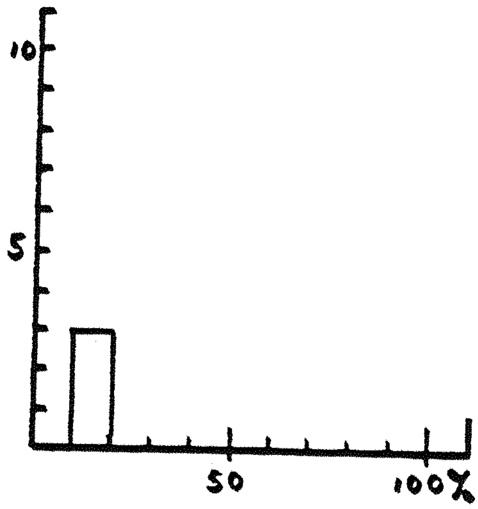


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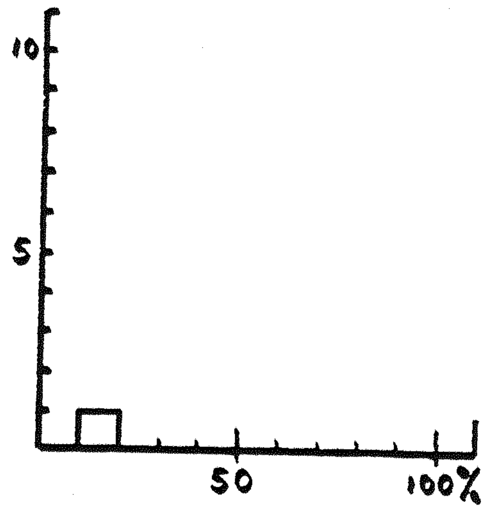


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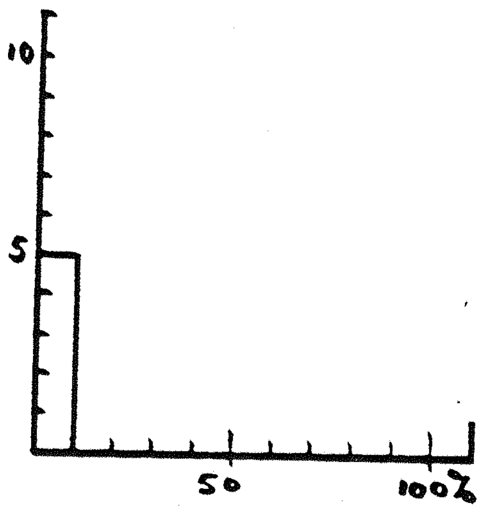


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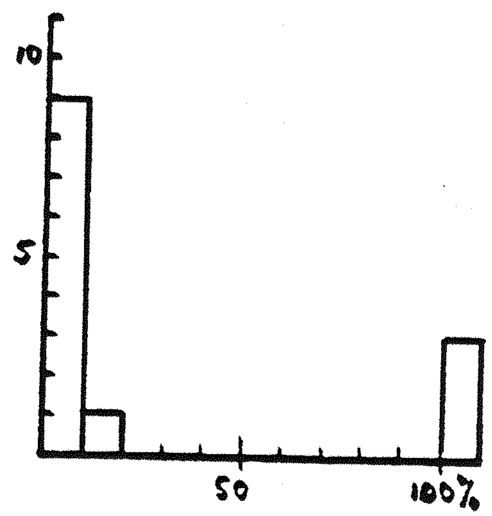


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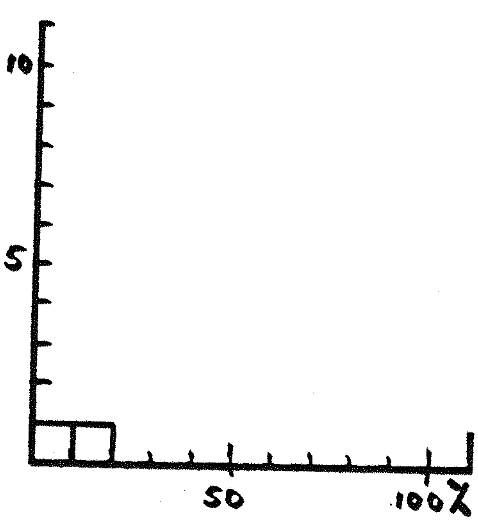


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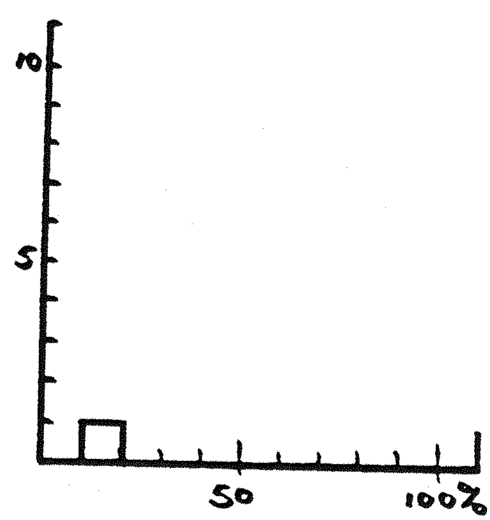


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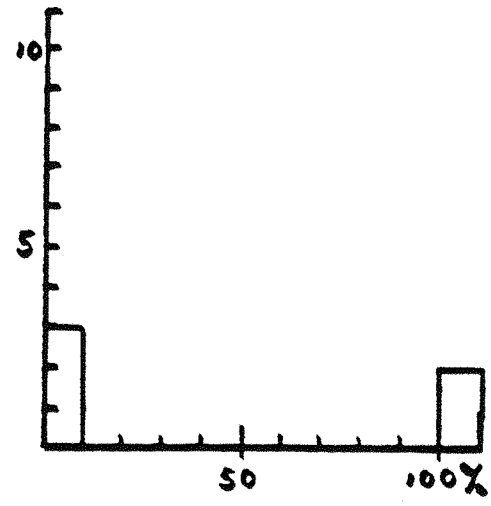


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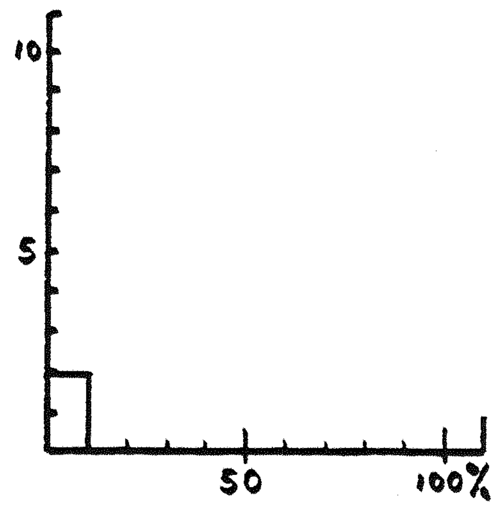


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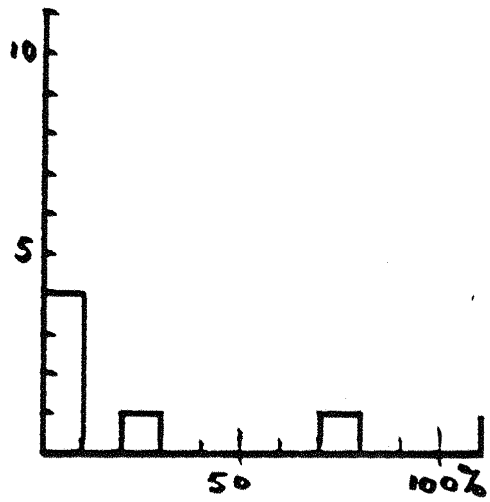


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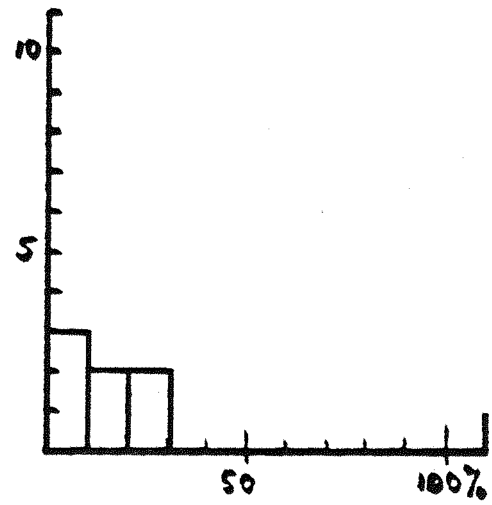


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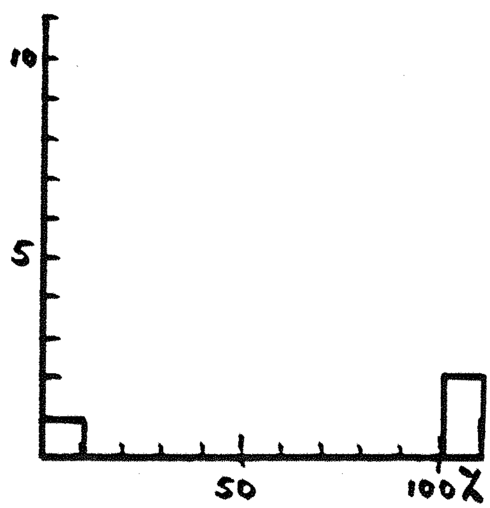


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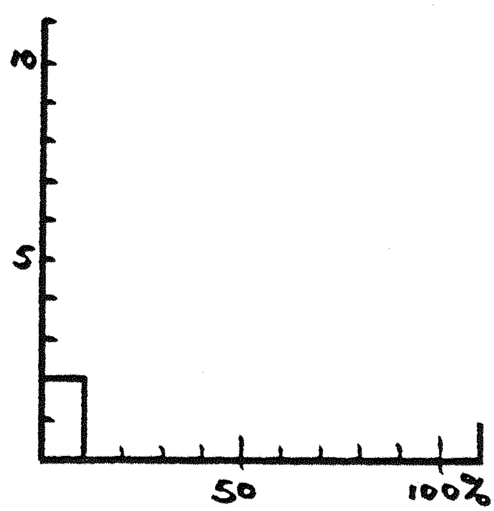


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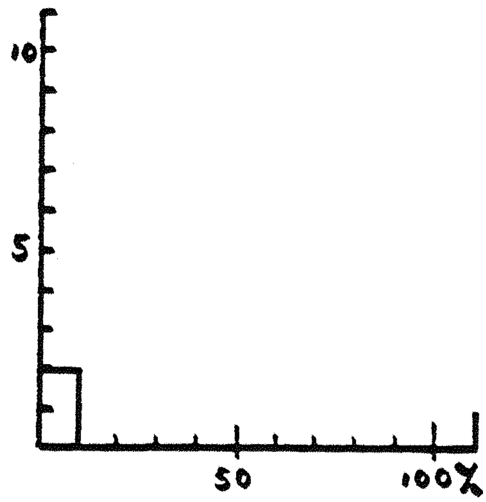

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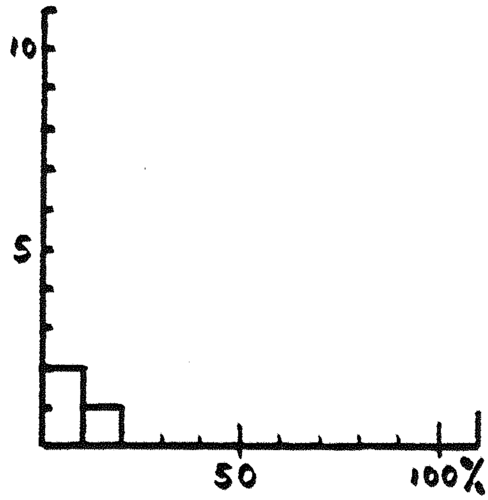

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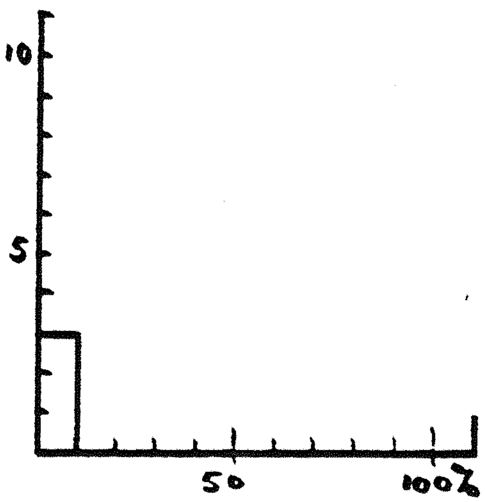

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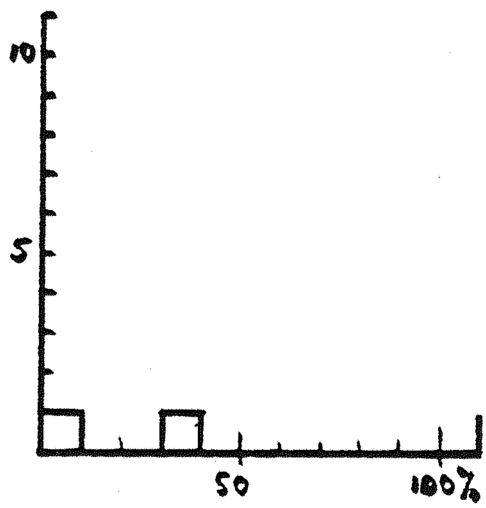

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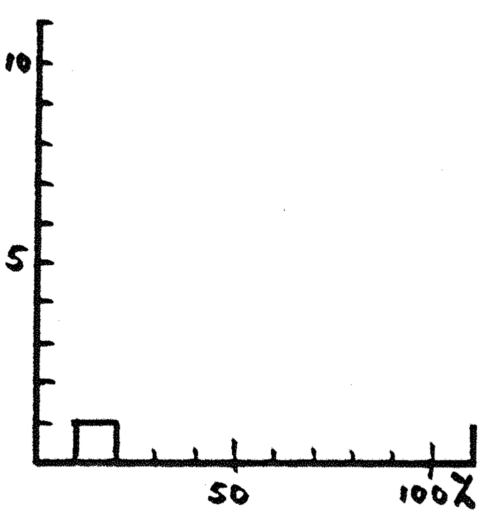

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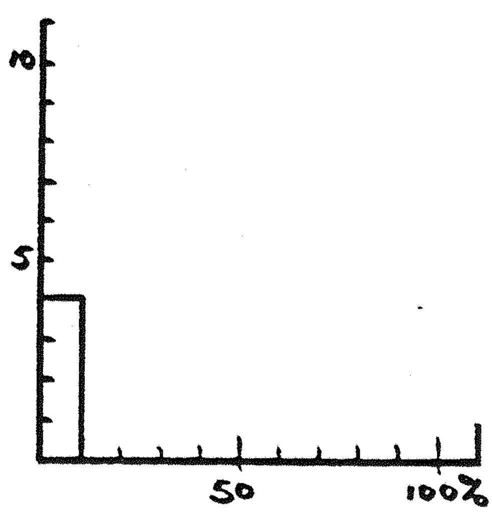

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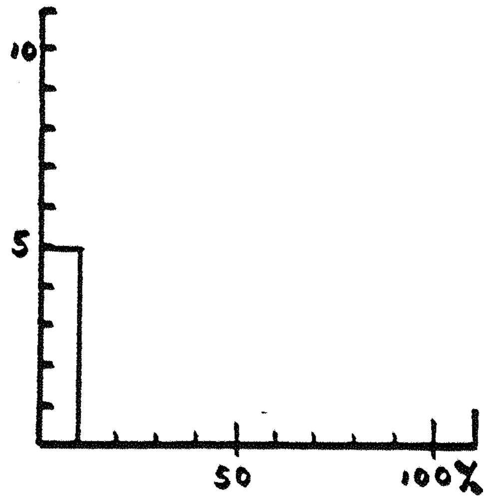


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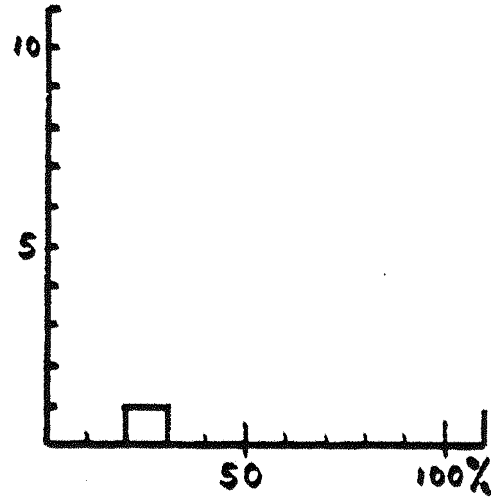


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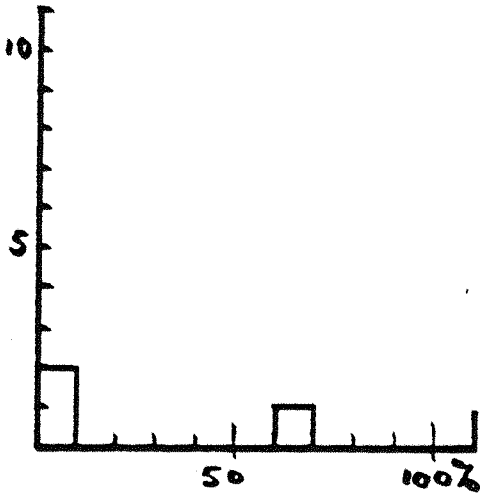


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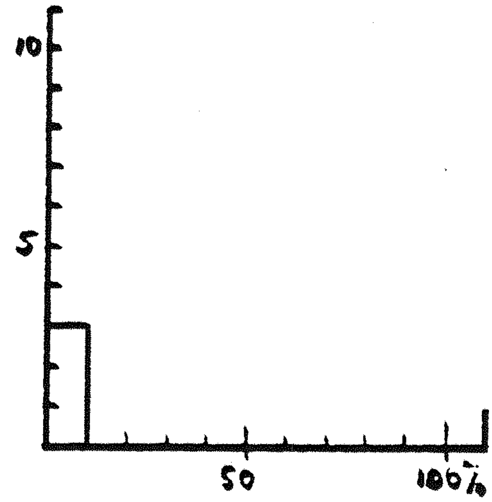


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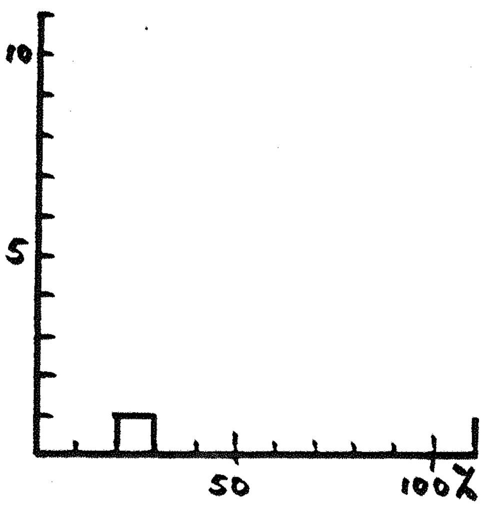


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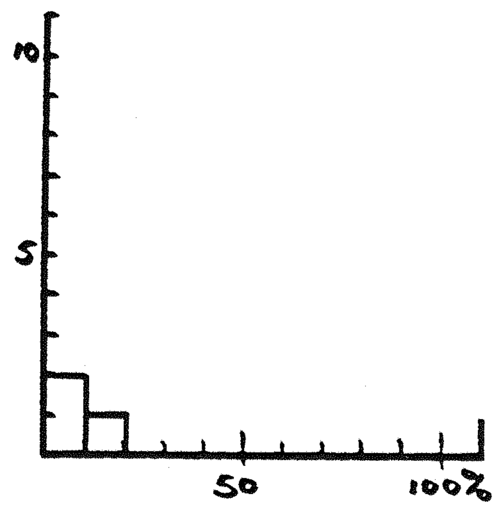


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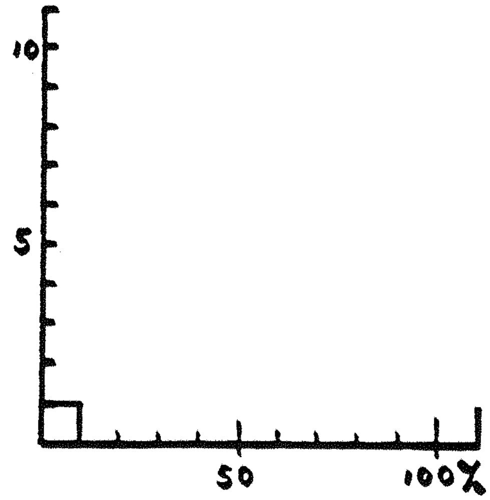


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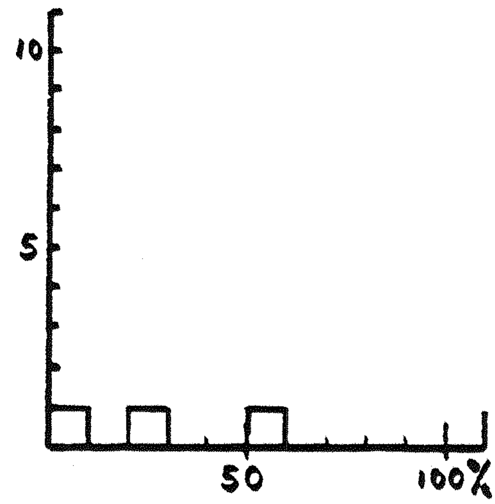


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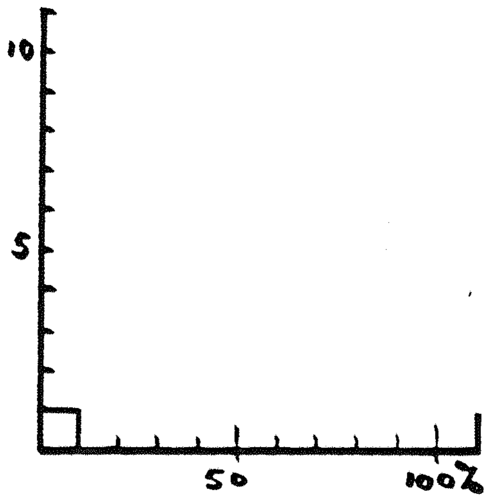


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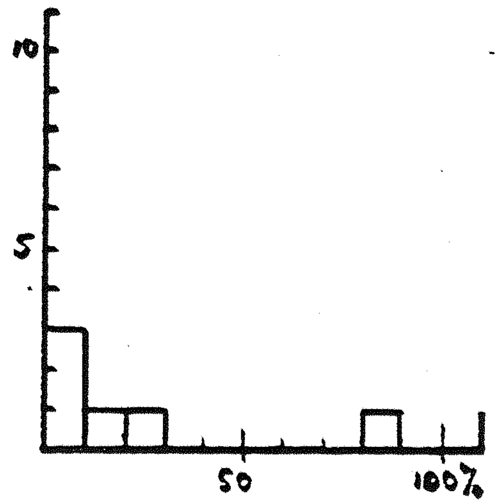


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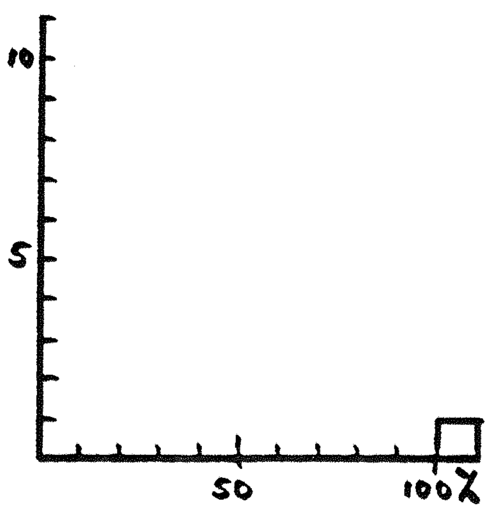


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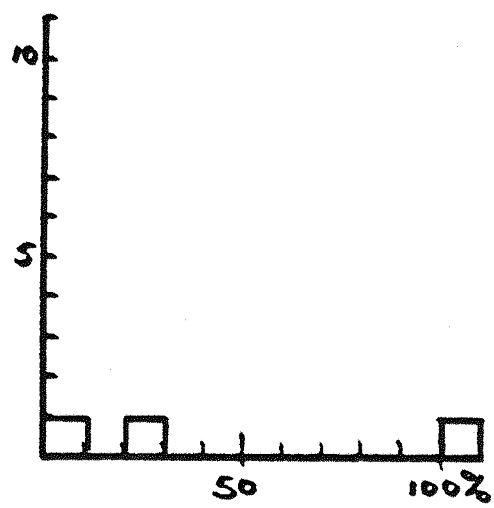


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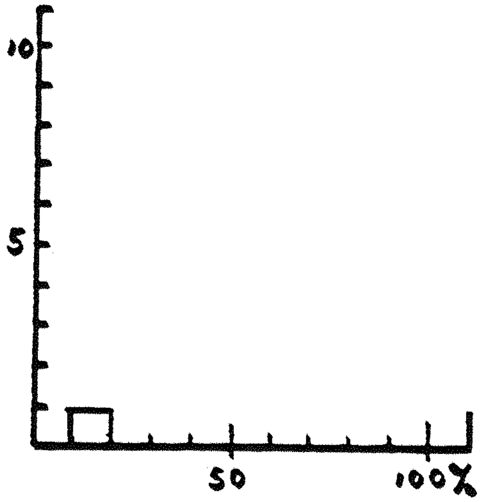


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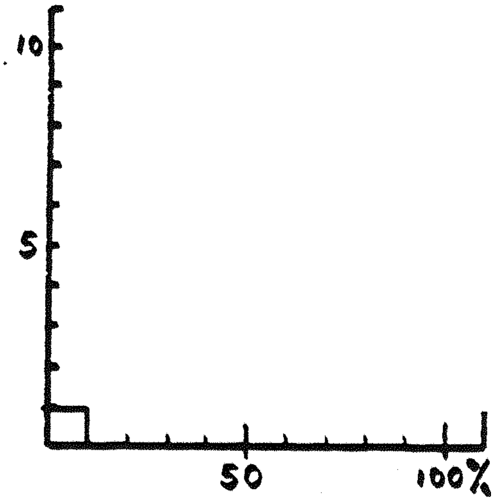


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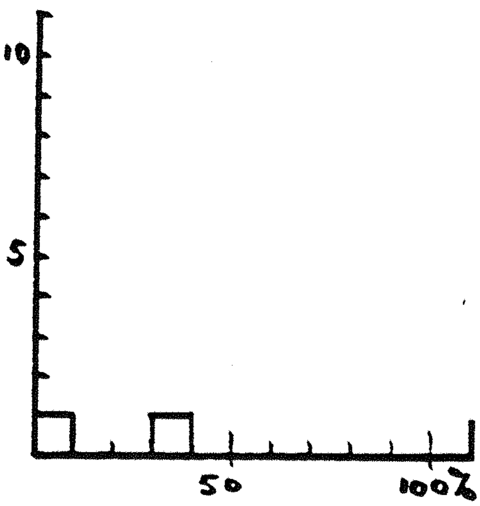


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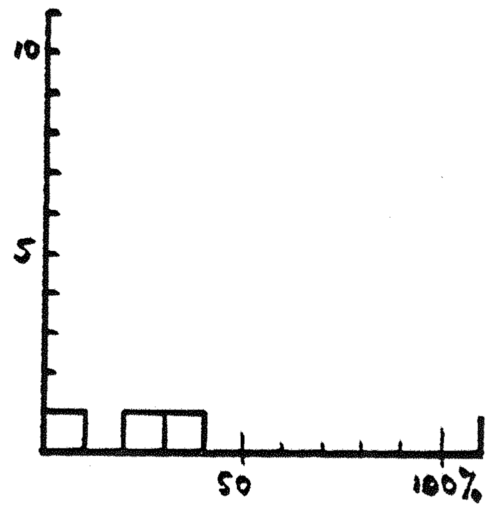


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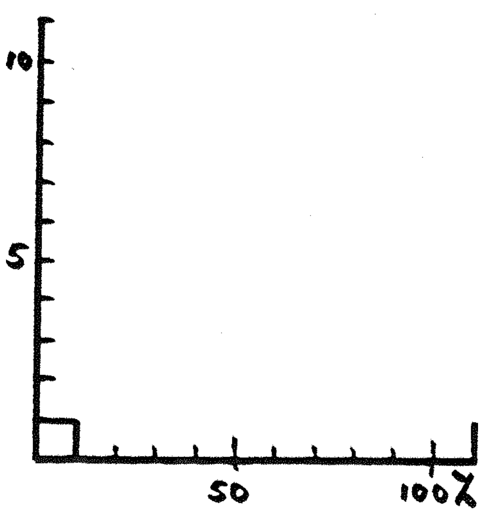


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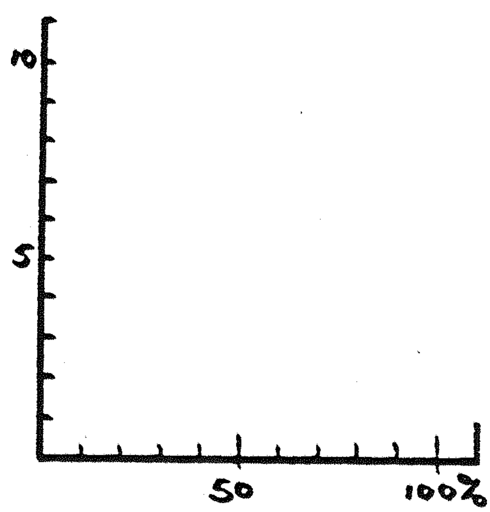

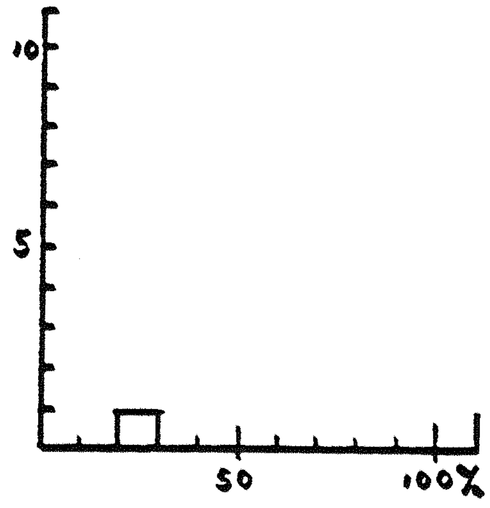

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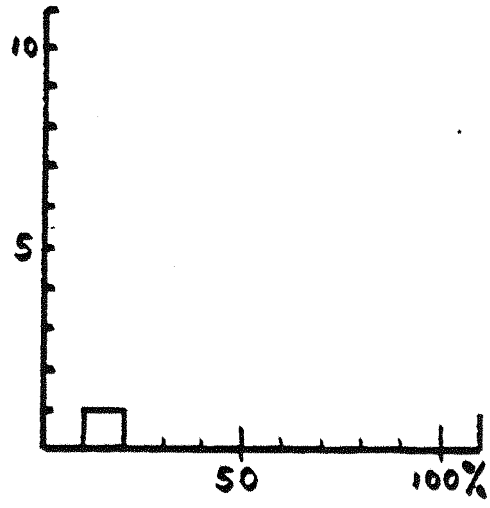

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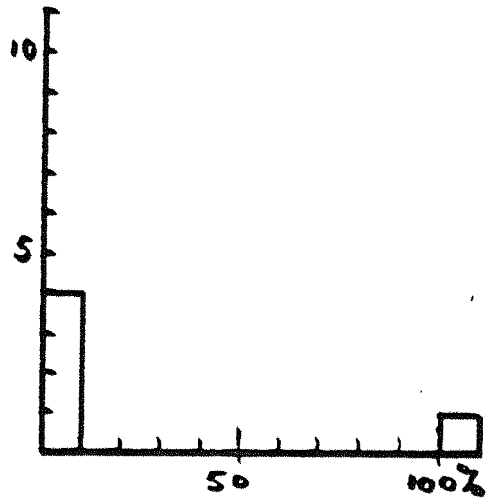

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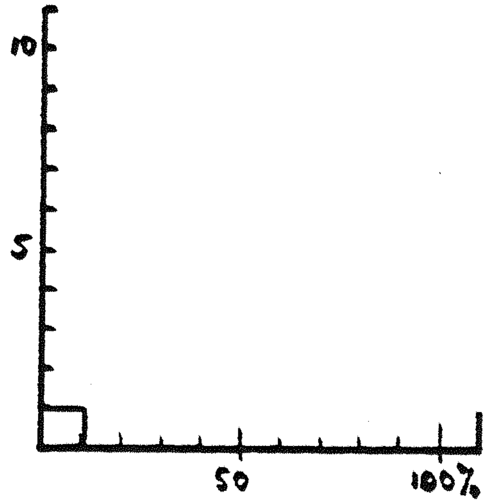

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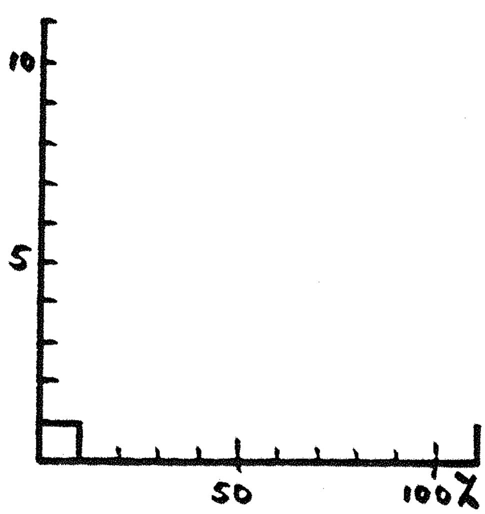

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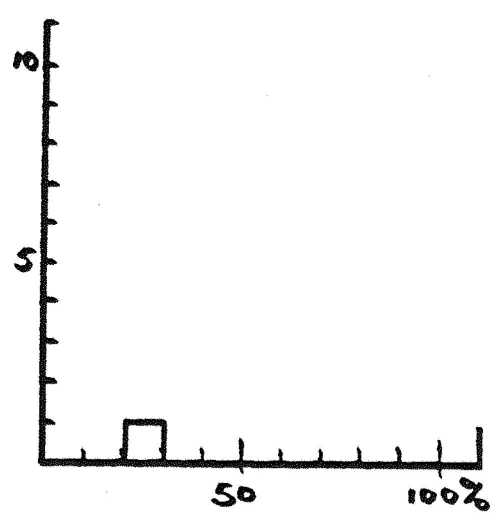

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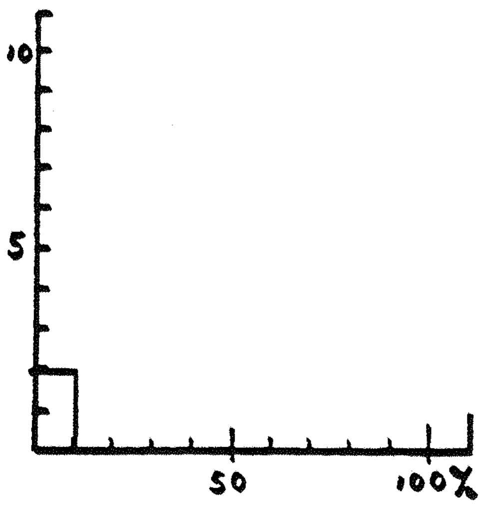


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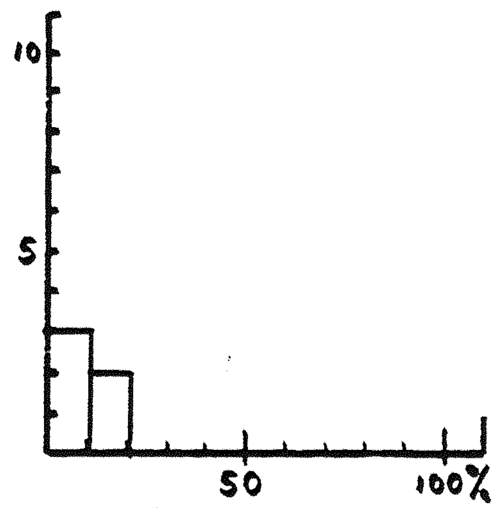


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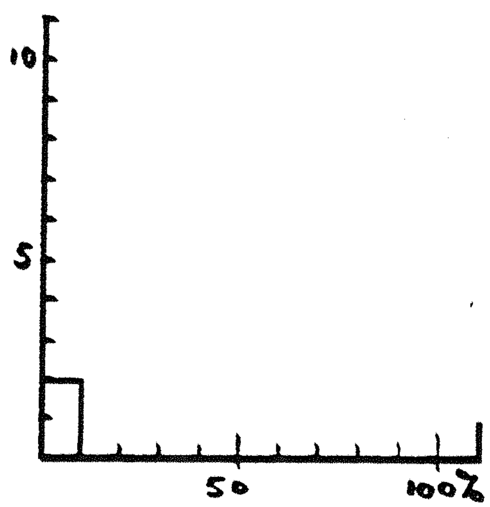


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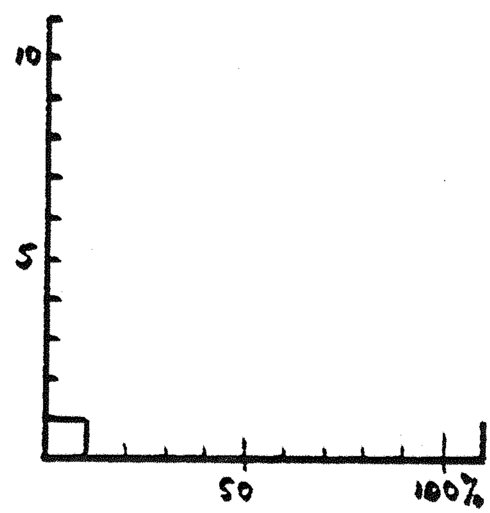


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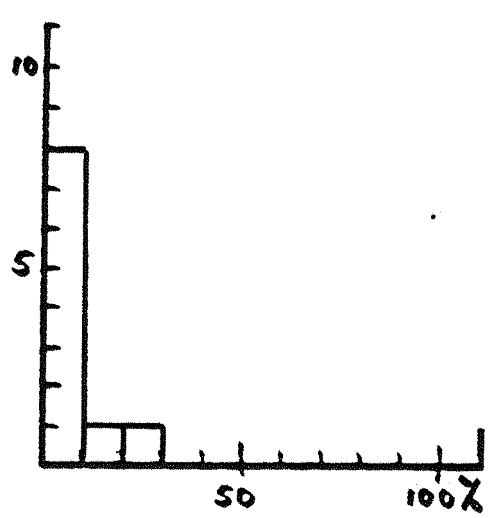


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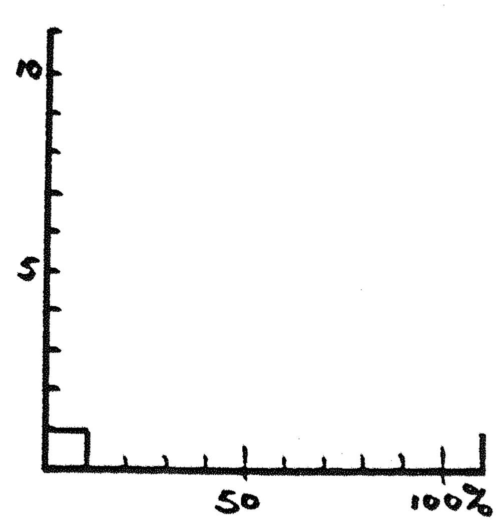
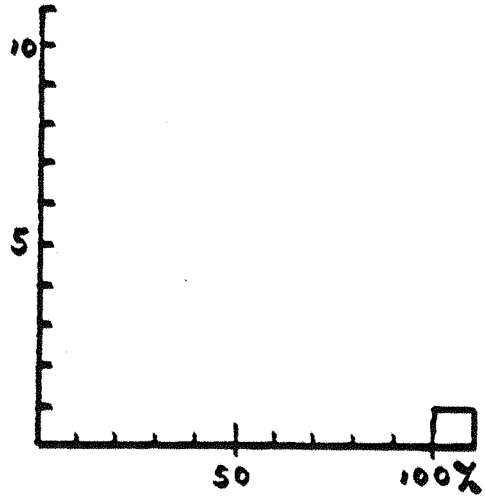
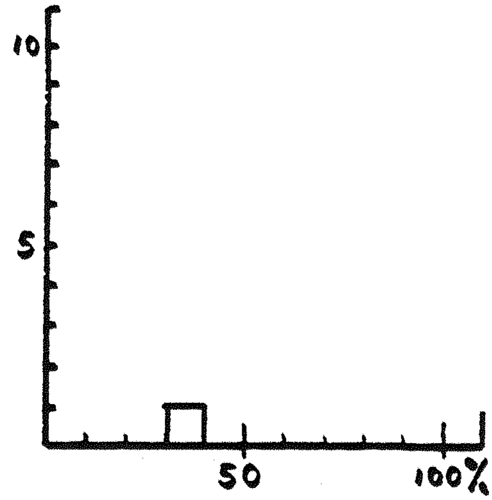


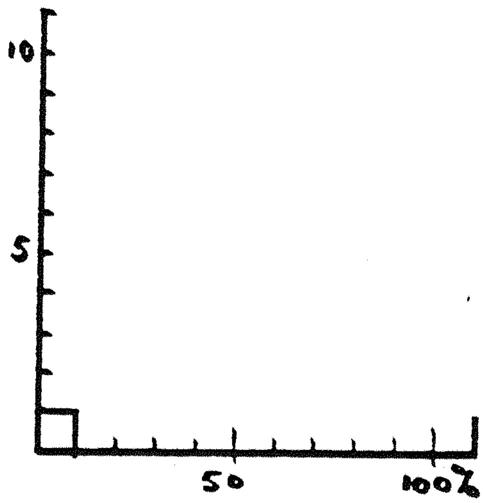

TOWED FLEXIBLE BAR




T.P.




TRACKLAYER

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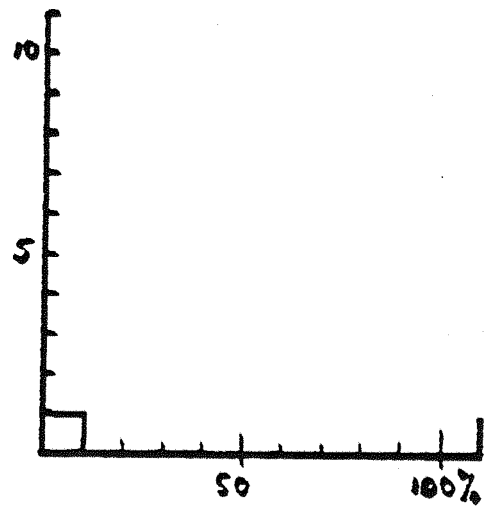


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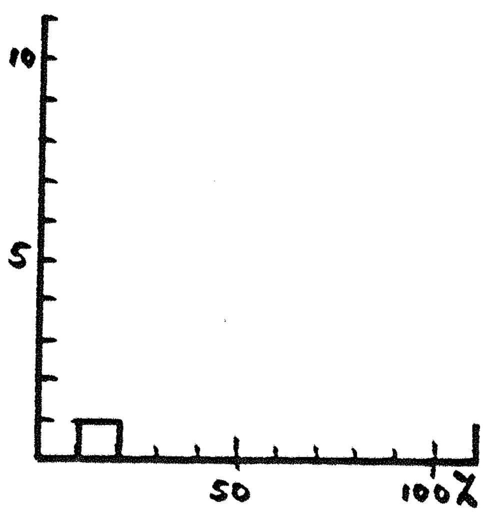
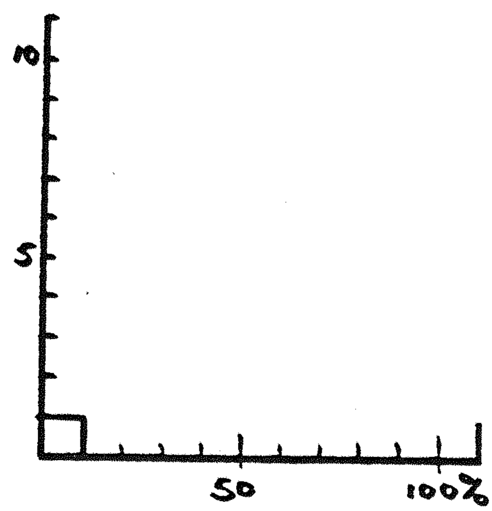



TRACK

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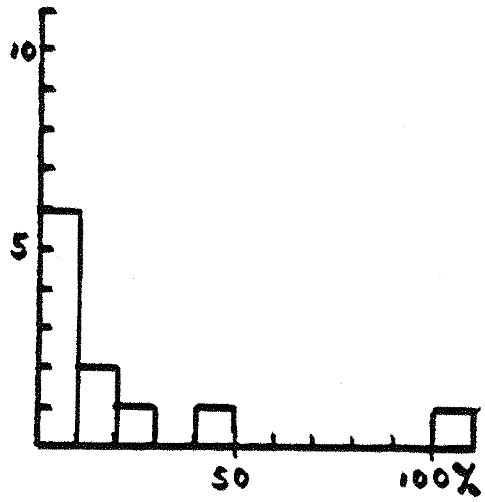


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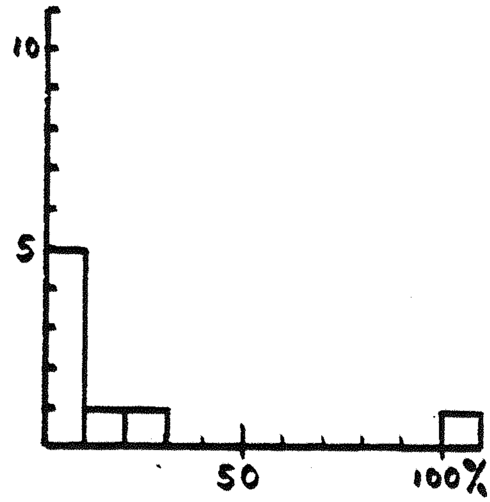


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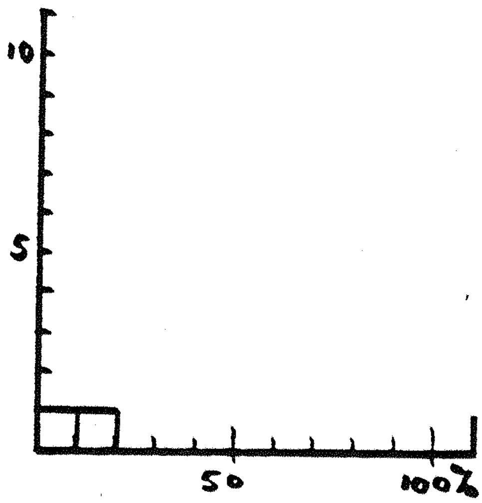


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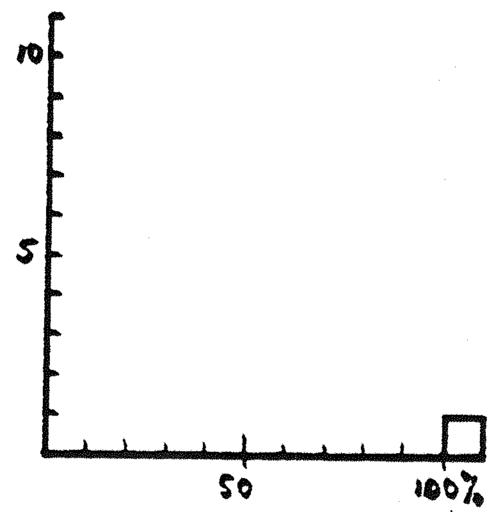


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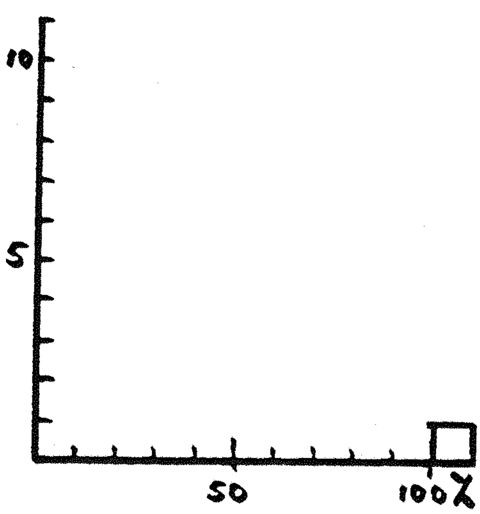


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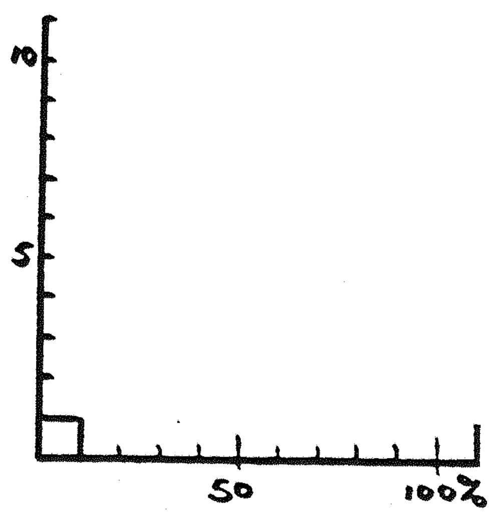


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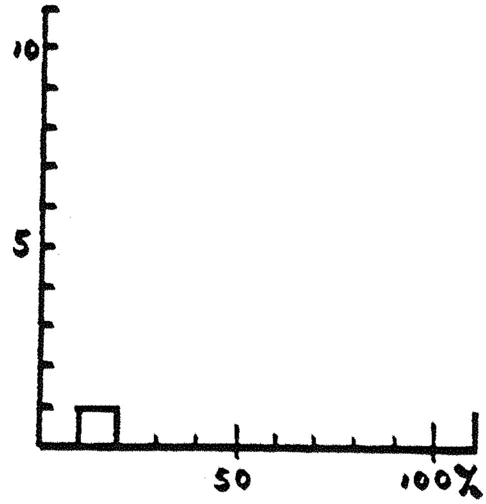


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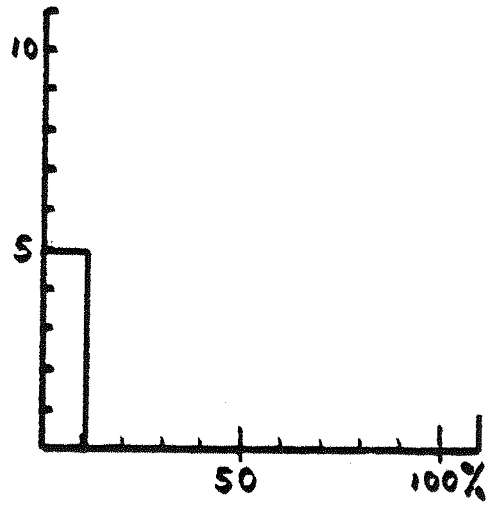


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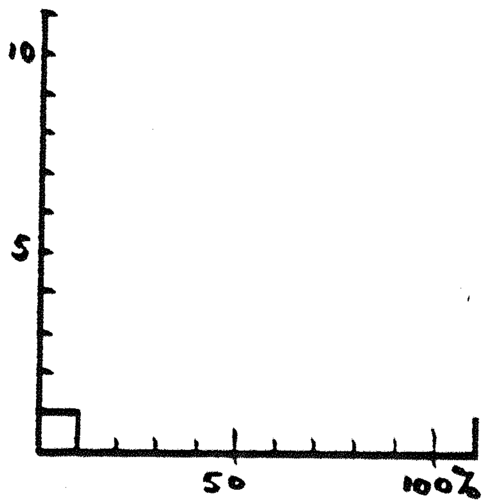


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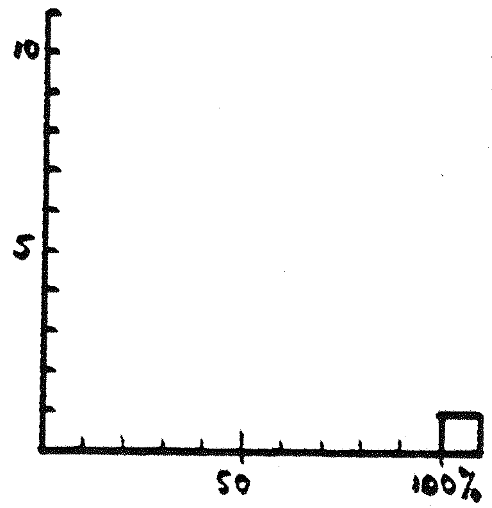
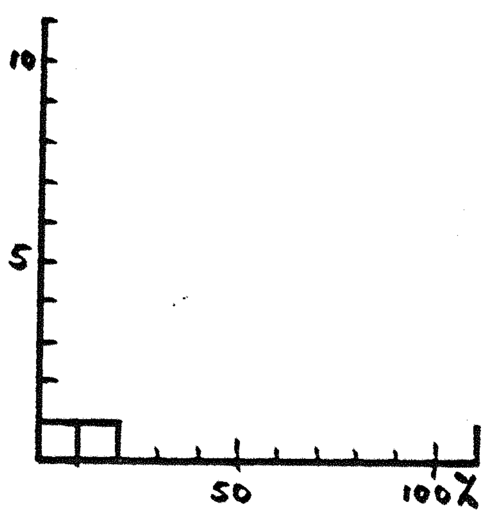



TUNER

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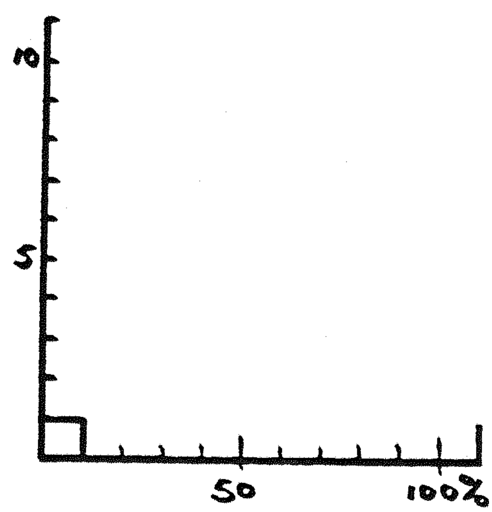


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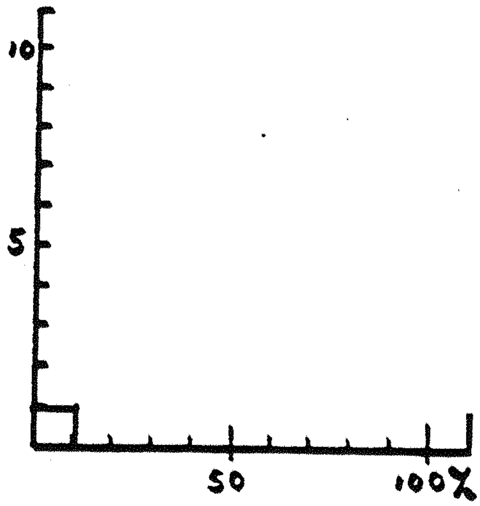

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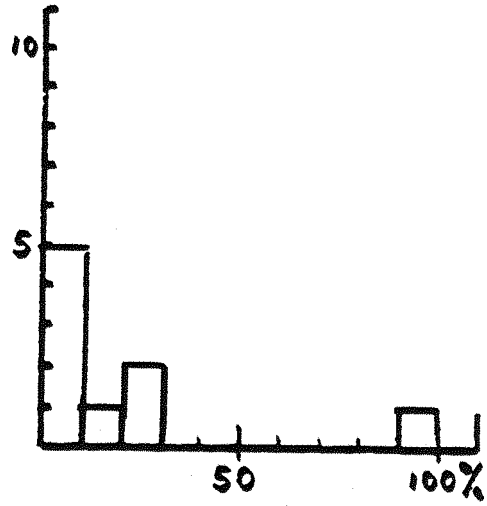

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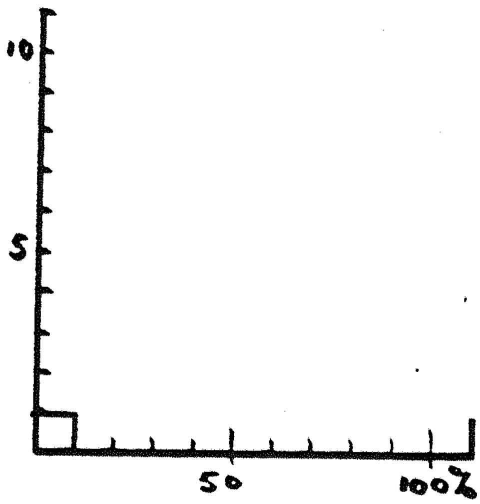

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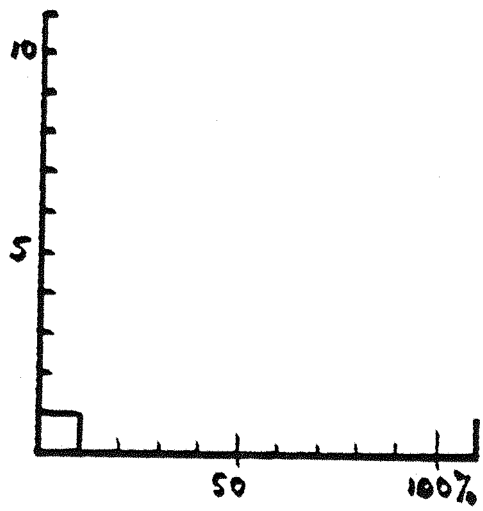
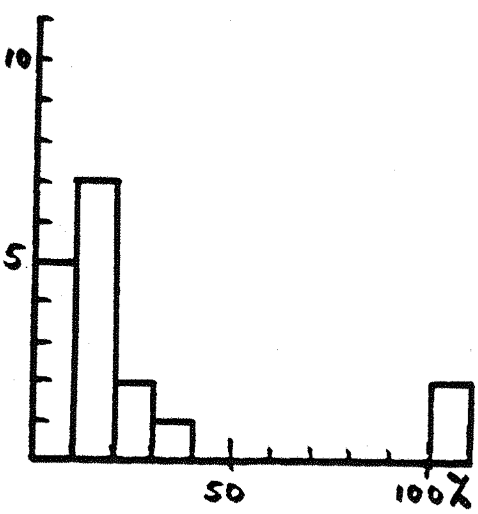


VENTILATE



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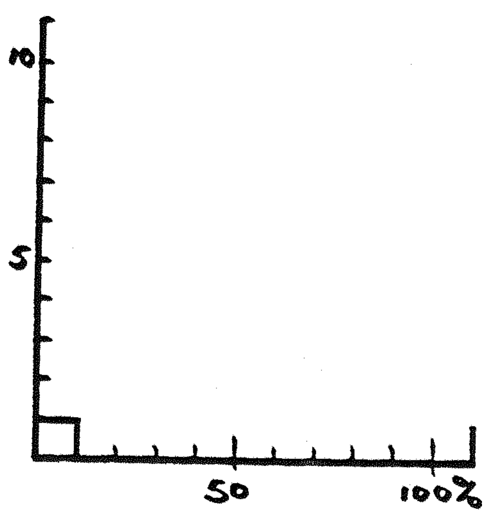

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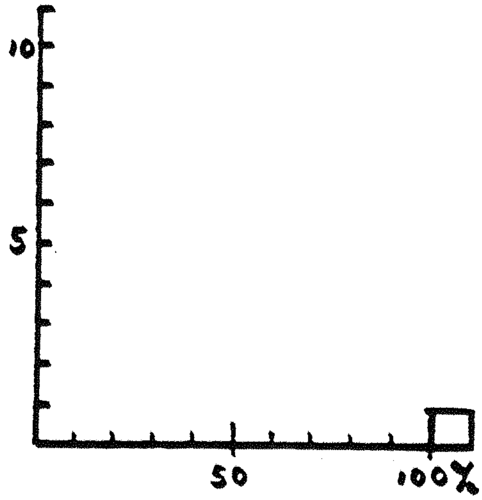
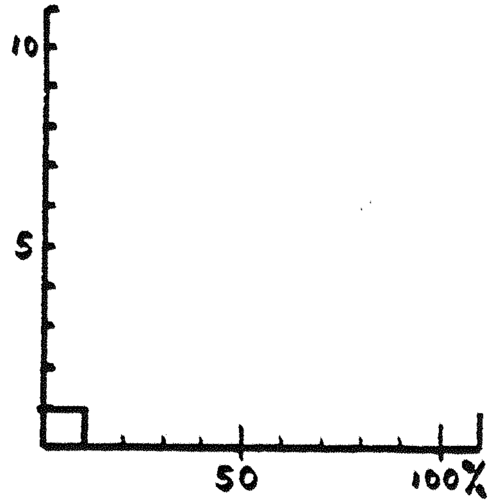



V.T.O.L.

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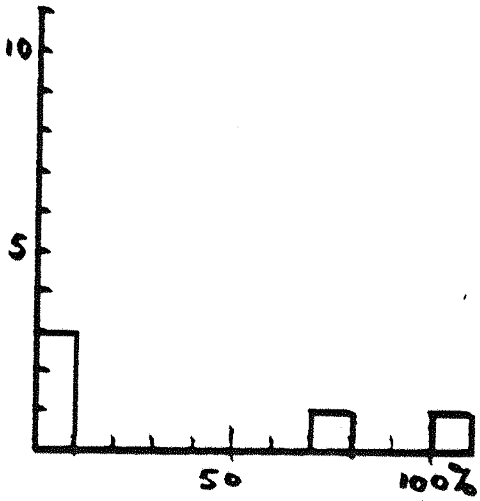


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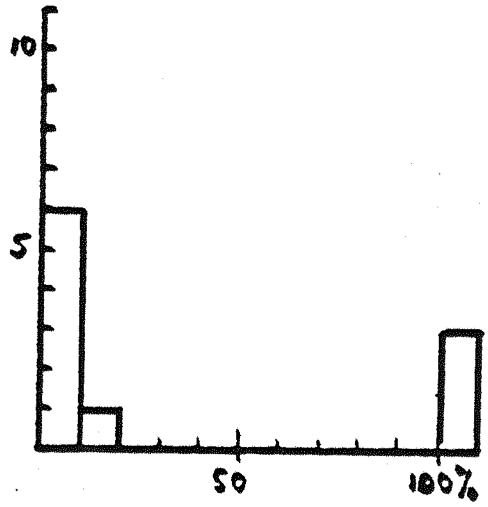


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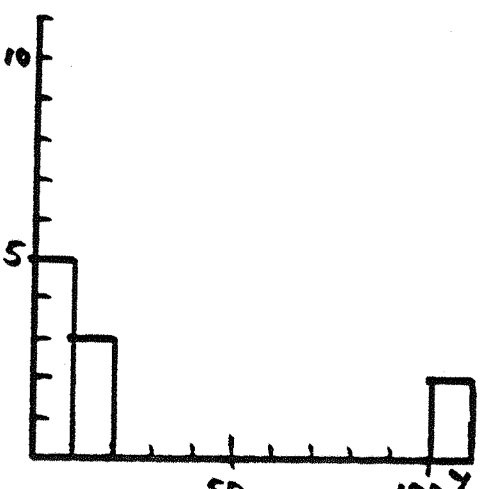


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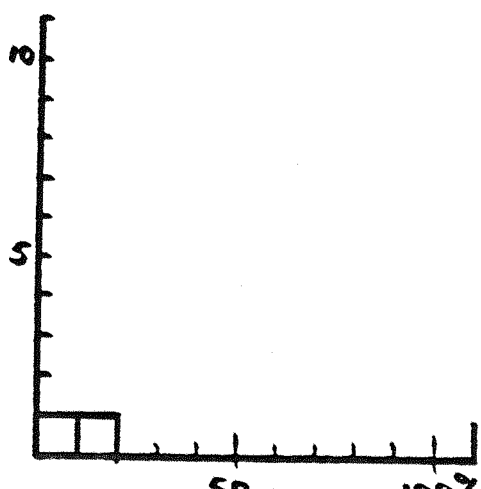


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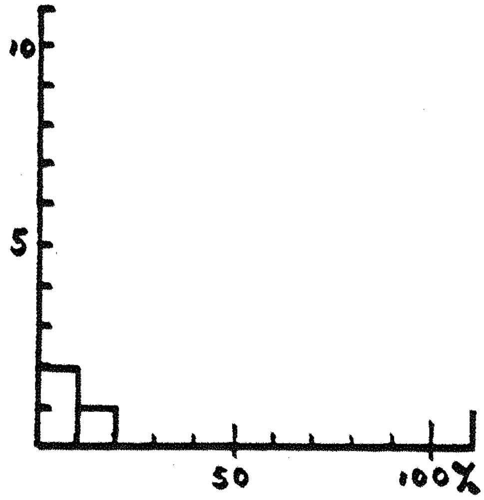


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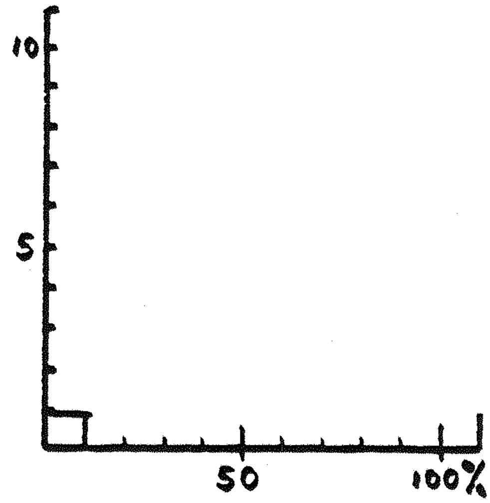


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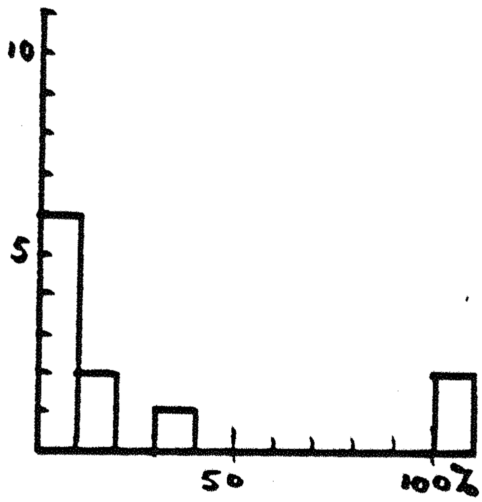


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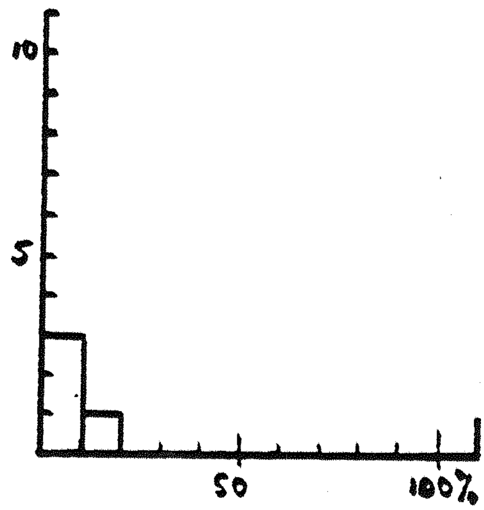


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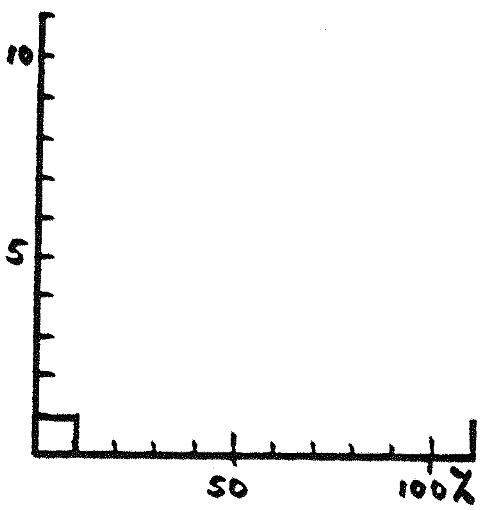


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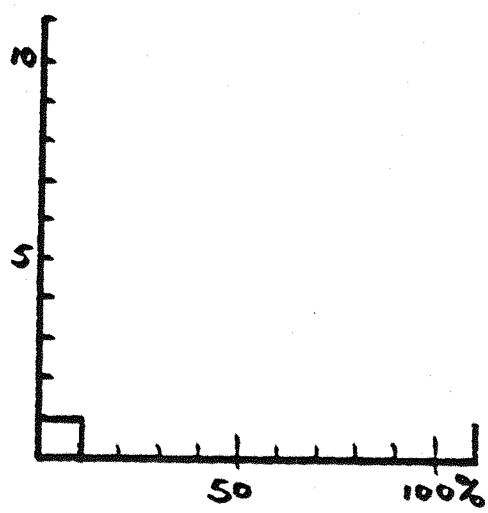
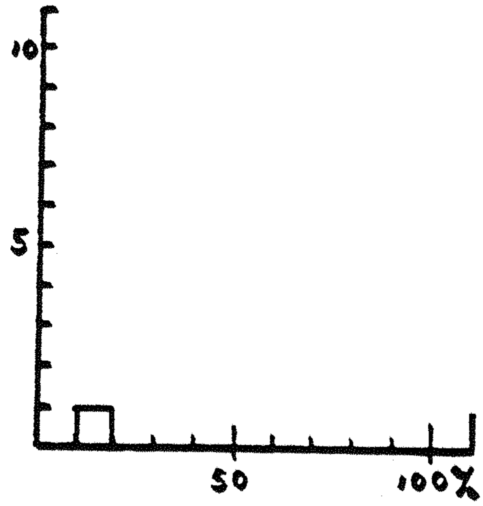
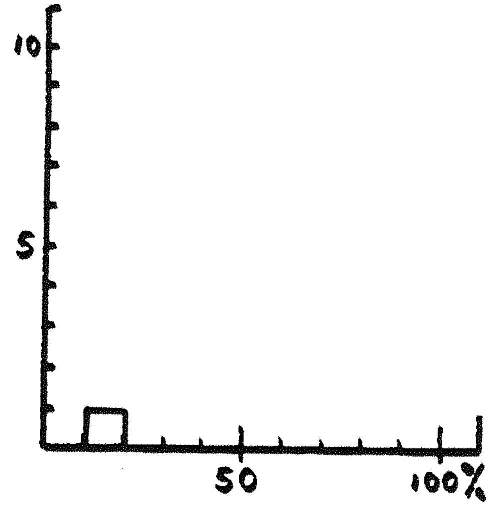



WINCH




WIND

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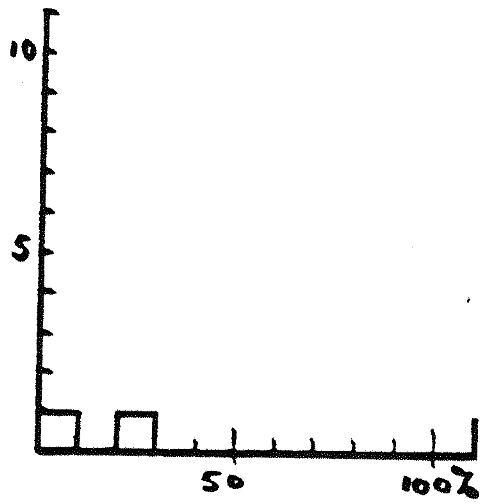


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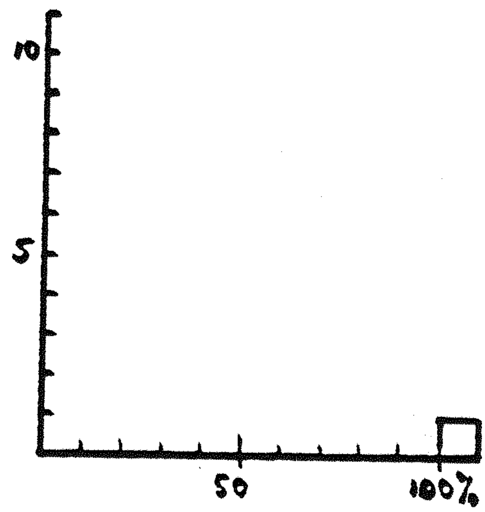
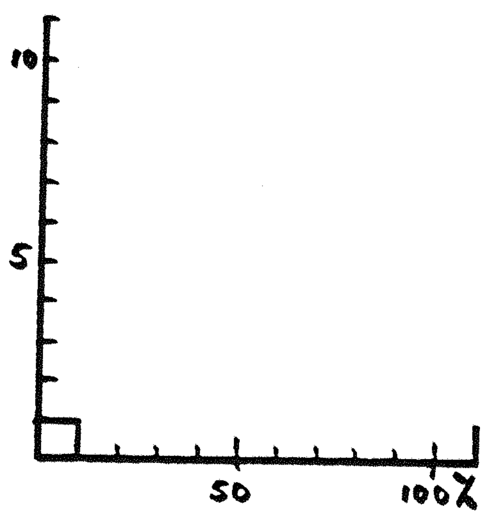



WORKBOAT

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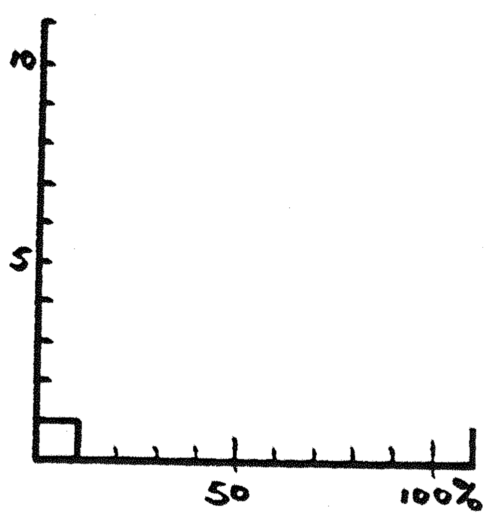
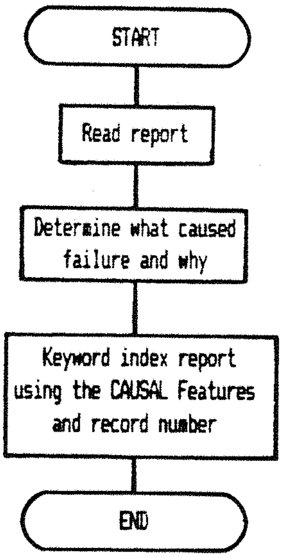



FLOWMETER

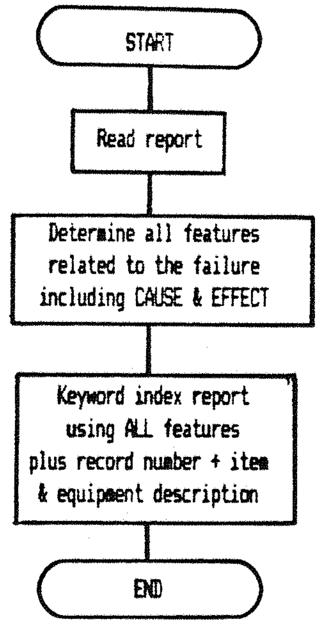
# APPENDIX H

This appendix contains flowcharts to describe the main analysis processes of this work.

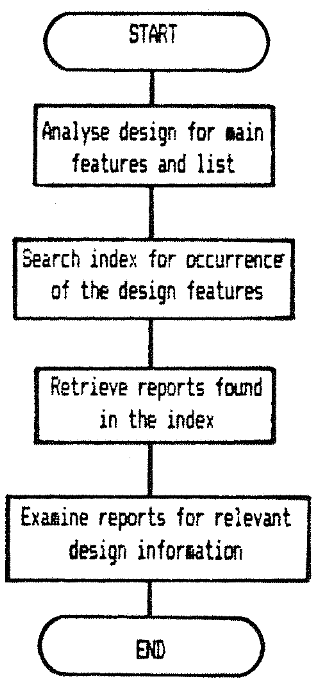
Details are given of the original PITFA process, and the revision to this process. In addition, details are given of the data analysis routines developed to use the data produced by the merging of the PITFA feature analysis index file and the numerical records of equipment held and failures experienced. The routines give occurrence of features in the files, and how significant these have been in the experience of the Royal Engineers. They also interactively produce a suggested Fault Tree using the past experience of the system for further Fault Tree Analysis by the normal processes.



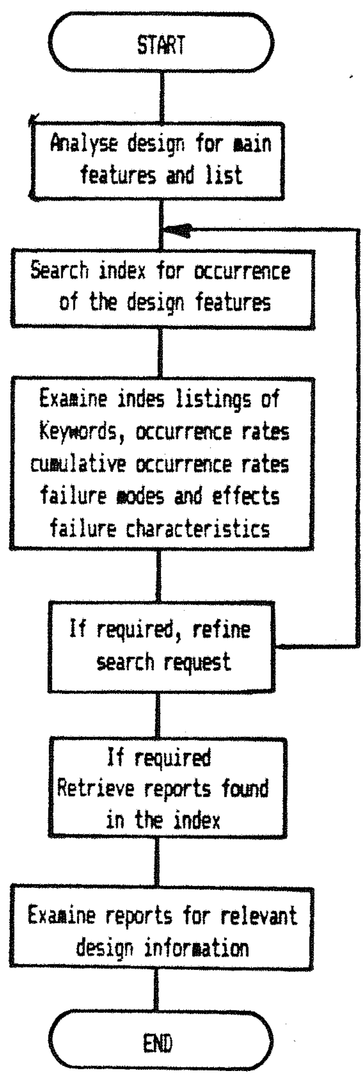

**Original PITFA index process**



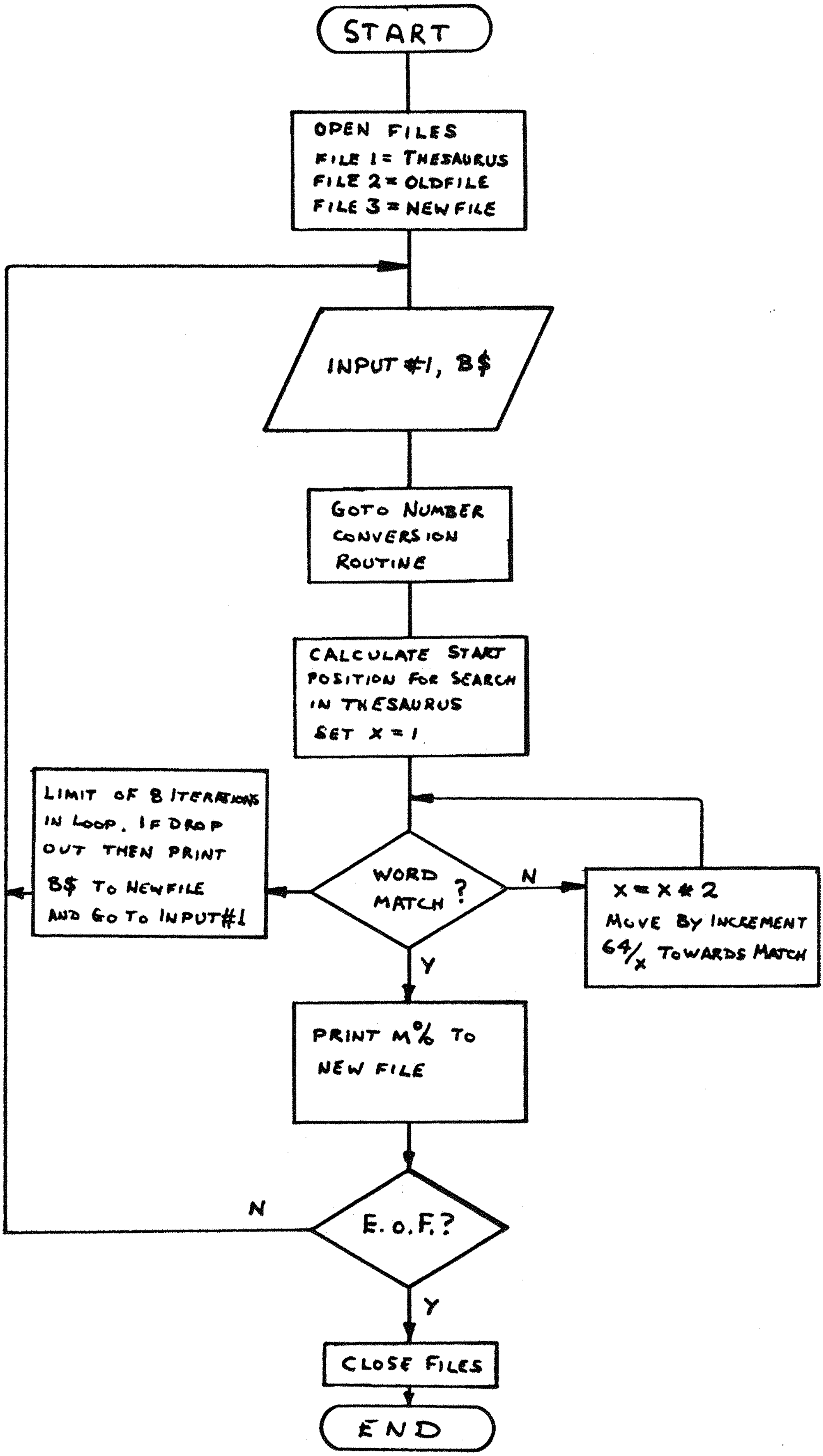

**Amended PITFA index process**



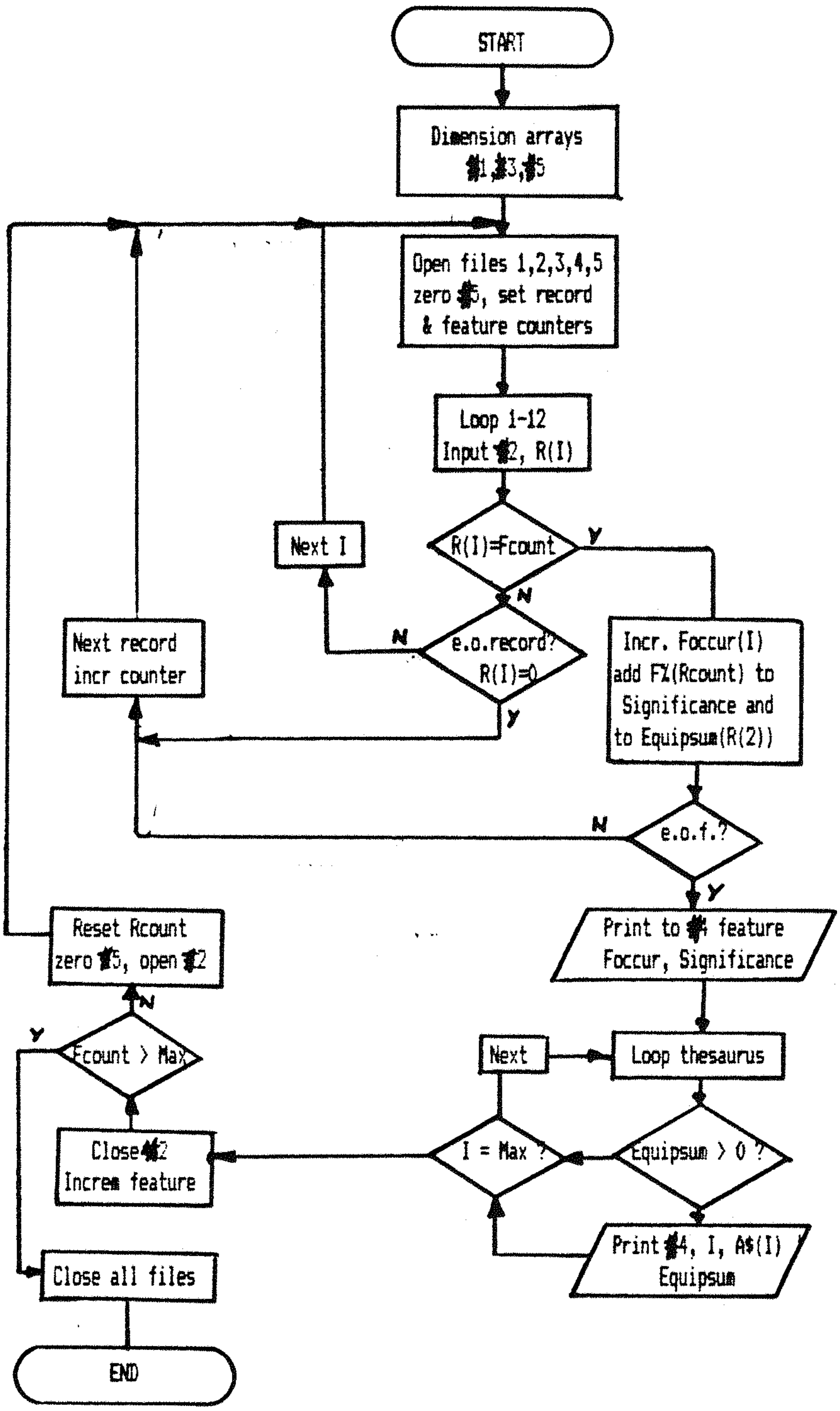

Initial PITFA retrieval process



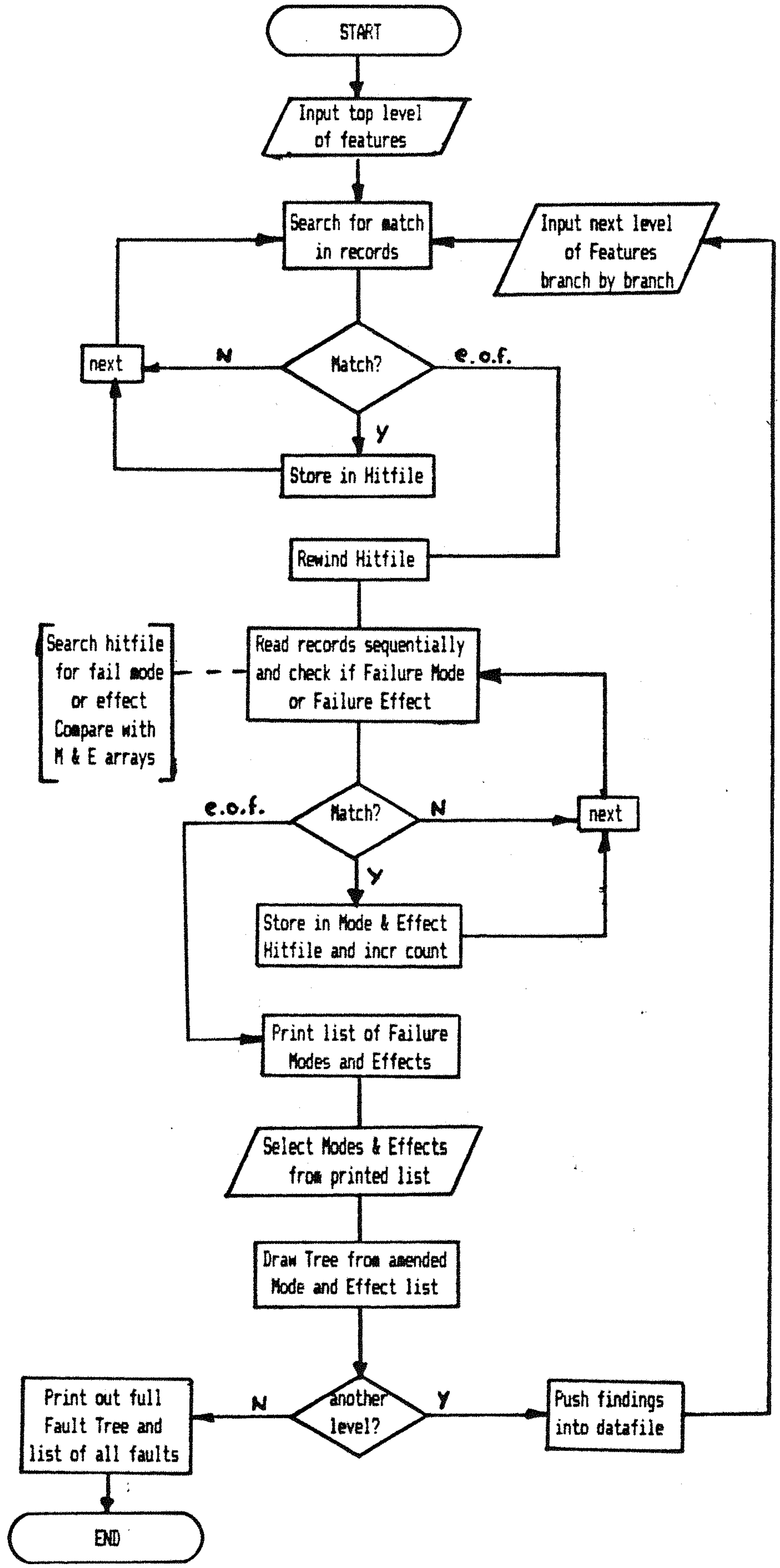

**Amended PITFA retrieval process**




WORDS TO NUMBERS CONVERSION




Flowchart for Occurrence, Significance, and
sum of % failures for each listed equipment
for each feature in the thesaurus




Fault Tree Creation Routine