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Computerised selection of materials and reliability

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COMPUTERISED
SELECTION OF
MATERIALS
& RELIABILITY

NABIL I. MIKHAIL

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ABSTRACT

The objective of this thesis is to design a computer programme for the selection of materials and reliability.

The selection of materials and calculation of reliability can be totally automated by means of computers. Failure investigation and analysis help in determining the type and cause of failure, therefore the selection of a reliability equation that suits that type of failure will become easier and more accurate. The data collected from tests, simulation and service conditions concerning failures are statistically treated using several distribution methods to yield the necessary terms of reliability. The selection computer programme aided by a reliability subroutine will compute for reliability using the required equation of a specified distribution to feed back into the computer with a reliability requirement. For non sufficient data from tests and simulations a second subroutine computes for the reliability using the method of property grouping.

Cost is usually an important requirement. A cost subroutine stems from the selection programme. The function of cost subroutine is to compute for the cost data given under two main categories, variable costs plus fixed costs. The subroutine is so designed to accept any items under the sub categories. A cost requirement results from computations

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and enter the main selection programme along with the other requirements.

The selection programme in conjunction with a mini data bank that contains the properties and composition of materials will carry out the selection process according to the specification of functional requirements assigned by the designer. To perform the selection process two methods are used. The weighting factor method and the limits on properties method. Both methods start by assigning a relative emphasis coefficient for every requirement or in other word every property of the material needed for the specific application. The relative emphasis coefficient shows the degree of importance of each requirement. Assigning the relative emphasis coefficient is carried out manually as it depends on the experience of the selection engineer and might differ for another. Using mathematical relations for each method will lead to a figure of merit by which the computer will sort the candidate materials according to their suitability for the required product.

Since the values of the candidate material are of different units which might cause errors in computations a subroutine is designed for grading those properties values. The grading or scaling system is from 1 to 100. Therefore all property values will be unitless.

For testing the programme, examples from industry were computed and the optimum material for each product were selected. The results were accurate and coincide with what are actually widely used in industry.

The advantages of computerised selection of materials and reliability are the saving of time and money wasted in manual calculations, accuracy and flexibility in selecting alternative materials that can compensate between functional requirements and cost.

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INTRODUCTION

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The fields of materials engineering and selection, computer sciences and systems analysis, are very recent and play an important role in all areas of production. The knowledge, use, properties etc., of the different materials available for use in all fields of engineering are essential for all engineers.

The selection among alternative materials arose during the Second World War, when reserves of strategic materials were directed to the armaments industries. As a result of this government decision, many manufactures, especially in the United States, were obliged to use alternative materials for their products, which later proved in many cases to be better and less costly.

Space technology is considered as the launching ground for the majority of the new innovations in the fields of Computer Sciences, materials selection and reliability. This is particularly true in the selection of new materials for space application and conditions, which necessitates their fast development and evolution.

Objective

The objective of this thesis is to establish, test and propose a general Computer Programme for materials selection and reliability that covers the possible requirements of any product.

The initial interset of the writer in this new area of Materials Engineering and materials selection stems from his work situation in the Armed Forces, during his undergraduate and graduate studies. The topic of research became more interesting when the idea of computerised selection of materials began to formulate in the mind of the writer, to study, examine and experiment with the possibility of using the extensive capabilities of the computer. This would facilitate the tedious and long manual calculations involved in the computations of all the available and conflicting requirements such as the physical, chemical, and mechanical properties of the different materials and their alternative uses for safer and more sound production.

Importance

The concern of the Egyptian Government in general, and the Armed Forces in particular, in the establishment and expansion of the armament industry in Egypt, made the study of Materials Engineering an advantage. It can aid in the material selection process for the manufacture of military production at higher efficiency and at lower cost. It can also help improve on the materials already in use that have proved to be unsatisfactory under difficult service conditions.

Furthermore, the importance of research in the expansion of the use of the computer in areas beyond the conventional are of vital importance.

Methodology

The thesis is divided into two main parts. The first part is mainly based on the library survey and analysis of the literature on material selection problems of reliability failure etc. The second part is the application of a general computer programme for selection of materials. The Systems Analysis Skills are used for the analysis, testing and formulation of this programme.

A Mini Data Bank was established whose contents are the composition and properties of several materials, the selection of which was based on the information needed for the specific application of the examples from industry that need to be tested for the programme. This Mini Data Bank is a small scale model of the actual Data Bank.

CHAPTER I

FAILURE OF ENGINEERING COMPONENTS IN SERVICE

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FAILURE OF ENGINEERING COMPONENTS IN SERVICE

Introduction

A system, a subsystem or a component is considered to have failed if one of the following three conditions occurred:

1- Stop operating

2- Unable to perform its function satisfactorily

3- Unreliable or unsafe due to severe deterioration

The causes of failure are numerous, and they are found in every step in the history of a product, from design stage through materials selection, fabrication and processing, materials imperfection, testing, storage, service conditions, maintenance, overloading, chemical damage in service ... etc., and ending at unpredicted time during the performance life of the product.

In the following pages, reviewing the types, investigation and analysis of failure will help understand how to obtain important requirements such as reliability and safety factor which are deeply involved in the design and selection process.

1. Failure Investigation and Analysis

During the design stage, and when the prototype is under investigation, several tests and simulations under service condition yield a lot of information about the product which are very important in correcting the performance, shape, size, processing methods, reliability .. etc. It is not necessary to correct all the above criteria, the change may be in one or more that are related in some properties or affecting each other if a decision of change or correction has to be taken.

During the life of the product, investigations and analysis of failures and their causes should be carried out continuously, so that preventive and corrective actions may be taken to avoid mal-design, processing drawbacks and service environment effects.

Receiving the information about failure, the materials engineer has to draw his own procedure for the failure analysis. The procedure shown in the flow chart Fig. 1.2, (See page 32) is a successful way for reaching a solution and reliable results quickly and safely using the principles of system analysis. Types of failures, identification and protective measures will be treated thoroughly according to the proposed method of analysis. In case of stuborn complex failure, which is rarely met in industry, the use of further complicated analysis such as the tree theory, decision tables, path sets .. etc. is recommended.

In this thesis, failure and reliability analysis are considered as common-mode or common-cause and basic event coming from system components and system environment. For each common cause, we have to identify the basic events affected.

The materials engineer has to define the failure problem, its dimensions, effects on the product, the risk on human life or property.

The data included in Fig. (1.2) related to failure investigation and analysis can be stored in a data bank and using a suitable failure investigation programme, (not the concern of this thesis), entering the failure examination results, the computer is capable of identifying the type of failure and selecting the preventive and or protective actions. Therefore, the reliability equation which suits the detected type of failure is used. It is clear from the above passage that failure investigation and analysis is a vital part in the selection process.

2. Proposed Failure Analysis Method

The flow chart Fig. (1.2) proposes an active and quick method that aids the analyst in determining the type of failure under investigation. The information about the product are usually received as feed back from service supported by samples from the failed product. The data and the samples are treated as mentioned in Fig. (1.2). The final decision concerning the prevention of the failures is thus passed to the reliability engineer to compute the reliability of the reformed product. The reliability engineer sends his computation results as requirements to the materials engineer who is aided by a computer to carry out the selection process.

A) <u>Surface Damage</u>

The task of the failure analyst as mentioned previously, is to define the problem precisely to be able to draw his investigation plan. Analysing the data concerning loading conditions, rate of crack growth in case of cracks. Macroscopic and microscopic appearances, aided by photographs of the specimens. The result of the analysis will point out the type of failure. The best and quickest method for identifying the type of failure from the available data is by "If Statements" as shown in the flow chart of (Fig. 1.2). Therefore, if the analysis results show a surface damage, it is either corrosion or wear. (Metals Handbook: 1975, Vol. 10, pp. 168-204).

i- <u>Corrosion</u>

The definition of corrosion is "the unintended destructive chemical or electro-chemical reaction of a material with its environment." (Ibid, pp. 205).

Corrosion may lead to service failure or it might help in causing failure by other mechanisms.

According to the definition, the failure analyst has to determine the factors that influence corrosion failures as follows:

1. To find out whether the corrosion was the cause of, or contributed in some way to a failure.

2. To identify the type of corrosion, its rate and the extend of its progression, which is usually governed by :
   - nature
   - composition
   - uniformity and nonuniformity of the environment and the metal surface that is in contact with that environment.
3. To investigate other factors that have major effects on corrosion process such as :
   - temperature and temperature gradient at the metal-environment interface.
   - the presence of creveces in the metal part.
   - relative motion between the environment and the metal part.
   - the presence of dissimilar metals in an electrically conductive environment.

The knowledge of processing and fabrication, and fabrication history will be very helpful if not necessary for the analyst, for their influence on corrosion process. Among the processing and fabrication items are the following :

1. Surface grinding
2. Heat treatment
3. Welding
4. Cold working
5. Forming

6. Drilling
7. Shearing .. etc.

(Metals Handbook: 1975, Vol. 10, pp. 257-280, 916-939, 983-1052).

The above data will enable the failure analyst to decide upon the corrective measures and to pass his recommendations to the designer to redesign the product if necessary. Among the practical and economical measures for corrosion failure prevention, that a failure analyst's report may include are the following :

1. The use of polymeric, resinous or inorganic paints, electrolytic and chemical coatings and surface treatments.
2. Change in material
3. Change in heat treatment or product form
4. Change in product design to avoid corrosion initiators such as crevecies, grooves .. etc., dissimilar metals in contact etc.
5. Changing the lubricants to inert types
6. Use of galvanic protection
7. Use of metallic coatings
8. Use of inhibitors

ii- Wear

If the surface damage was not caused by corrosion, wear will be under investigation.

Wear is another cause of failure. It occurs in components that move or slide, relative to each other. Wear occurs when fragments of the material separate under high stresses between the two moving surfaces leading to change in the dimensions of the components. The increase in the tolerance along with the surface roughness induced by the separated fragments would lead to misallignments or severe vibration which may lead to total damage of the component (Petty: 1970, pp. 191, 192).

Wear is of the following five widely accepted types :

- Adhesive wear such as scoring, galling, seizing and scuffing which occur when two metallic surfaces slide against each other under pressure.
- Abrasive wear, when fragments of one surface of the material separates due to contact and acts as abrasive between the two surfaces.
- Errosive wear, or errosion-corrosion, which occurs when a metal surface moves against a corrosive fluid.
- Corrosive wear, is a type of abrasive wear when chemical or electro-chemical reaction with the environment contributes to the wear rate.

- Surface fatigue wear, which is a special type of surface damage in which fragments of the rubbing surfaces separate under cyclic contact loading causing pitting or spalling. (Metals Handbook: 1975, Vol. 10, pp. 134-136. 138 & 146).

Among the measures to be taken to reduce wear are the following:

- Surface hardening (steels), which increases the hardness of the sliding surfaces, therefore, decreasing wear without affecting the component ductility.
- The use of lubricants.
- The selection of wear and friction resistant materials.

B) Distortion

When there is no sign of surface damage, and if the component is deformed and is no longer capable of performing its intended job, is unable to support its assigned load, and hinders the performance of other functioning components, the analyst is simply faced with a case of distortion failure (Van Vlak: 1971, pp. 208-215).

The distortion failure is not necessarily leading to fracture, it is usually of two types, size distortion such as buckling shrinkage, and shape distortion such as warping.

The analyst in studying the failure must go beyond the evident distortion to the cause which lead to this failure. Many times the cause of distortion failure is due to the malfunctioning of a related component that affects the failed component, or to the conditions under which the component performs, i.e. oiling, cooling etc.

The special types of elastic distortion are :

i- Elastic deflection or buckling. This type usually occurs when the component is made of a low modulus instead of a high modulus material, it will deflect under the assigned load and the component will hinder the function of the part in its path. Changing the modulus of elasticity will be the solution for this type of distortion. Temperature can also lead to elastic distortion. The change in temperature changes the modulus of elasticity of the material leading to distortion failure. Controlling the service temperature will maintain the modulus of elasticity of the material within the designed value (Metals Handbook: Vol. 10, 1975, pp. 125-133).

ii- Ratcheting: If the failed component found to be stressed by steady state loading, and the examination proved that a cyclic varying strain is super imposed on the component in a direction different from the direction of principal stress, the distortion is by ratcheting. The oscillating load as well as cyclic change in temperature strains the material beyond the yield point, plastic strain accumulates leading to the deformation of the materials dimensions. Ratcheting may lead to ductile fracture or failure by low cycle fatigue.

iii- Inelastic cyclic buckling: Occurs when the component is subjected to alternating stresses whose magnitude lies between the proportional limit and the yield strength, especially in columns made from materials that show cyclic strain softening behaviour. Controlling the modulus of elasticity along with sound selection of materials will prevent the inelastic cyclic buckling.

C) Yielding

The excessive plastic deformation or yielding can be seen by the naked eye. Permanent change of shape is obvious. It usually occurs because the elastic limit of the material is exceeded. Controlling the yielding strength along with a suitable empirical failure criterion, using one of the two accepted theories for predicting yielding in ductile materials will help prevent yielding (Maximum Shear Stress Theory, Distortion Energy Theory) (Dieter: 1961, pp. 58-62 and Metals Handbook: Vol. 10, 1975, p. 133).

D) Fracture

The component under examination, is sometimes found to be broken into two or more parts. The failure in this case is said to be by fracture under the action of stress. There are different types of fracture depending on the material, type of loading, rate of loading, state of stress and temperature. The failure analyst is faced now with the problem of identifying the type of fracture, the cause and the preventive measures. Following the analytical procedure shown in the flow chart Fig. (1.2), will facilitate the analysis. The familiar types of fractures that are usually encountered in industry are : (ASME: 1980, p. 6).

i- Brittle fractures

ii- Ductile fractures

iii- Fatigue fractures

iv- Combined effect stress/corrosion fractures

i- The brittle fracture: is identified microscopically from specimens by the very little or no plasticity on the fracture surface. Fragile materials always fail by brittle fracture. However, materials with high toughness might fail by brittle fracture because of the geometry of the component, such as thickness, presence of cracks or other severe strsss raisers (knotches) (Dieter: 1961, pp. 200-204).

The brittle tensile fractures usually have a bright, granular appearance with little or no necking when produced under plain strain conditions. The fracture surface is almost featureless and perpendicular to the direction of loading. Cheveron marks may be found on the surface of the fracture pointing towards the origin of the crack. Microscopic examination will reveal transgranular or intergranular facets. The transgranular facets are produced by microvoid coalescence, cleavage or combination of microvoid, coalescence and cleavage or by fatigue. The intergranular fracture is a result of grain boundary separation with or without microvoid coalescence,

Under certain conditions of low temperatures, high strain rate, thick sections or sharp notches, a transition from ductile to brittle fracture occurs in ductile materials, which could confuse the analyst if he is not aware of the previously mentioned conditions.

To avoid brittle fracture, the following measures are useful :

- Redesign the product
- Apply surface treatment
- Avoid imperfection in the as received material
- Avoid irregularities during processing, fabrication and heat treatment
- Check the fracture toughness

ii- Ductile fracture: is identified by the appearance of the surface of the fracture which exhibits the tearing of the metal along with appreciable plastic deformation. Ductile fracture in most materials have a grey fibrous appearance and it is of two types :

- Shear face tensile fracture which is produced under plain stress conditions in sections or near the surface. Microscopic examination shows elongated dimples that are produced by tensile shearing and the dimples long axes in the direction of the shear face, while in the mating face the axes are in the opposite direction of the force.

It is necessary for the failure analyst to detect the fracture origins and causes. Visual as well as optical examination usually reveal lines on the fracture surface called radial marks which are produced from the intersection of fractures propagating at different levels. Tracing these lines to the point of convergence reveals the fracture start point or the fracture initiation site. The initiation site is always followed by cheverson marks, also pointing to the fracture initiating site. The radial marks indicate unstable crack growth, and the crack front propagates with a high velocity. The crack initiation is always slow and stable as noticed from concentric rings around the initiation site which act as crack arrest lines.

The measures necessary to avoid ductile fractures are the following :

- Check the chemical composition of the material
- Check the micro structure
- Check the dimensions of the failed part

- Check the design for stress raisers (notches) and redesign if necessary.
- Check the direction of loading
- Check the strain rate
- check the chemical environment

(Van Vlack: 1971, pp. 445-447).

iii- Fatigue fractures:

Many of the machine parts such as axles, shafts, crank-shafts, connecting rods, springs, pinion teeth ... etc., are subjected to varying stresses. It includes the variation in the intensity of the same type of stress as well as different types of stresses (i.e. change of stress from tensile to compressive and vice versa). The varying stress may be broadly classified into the following four types, Fig. (1.1) (Metals Handbook: 1975, Vol. 10, pp. 96).

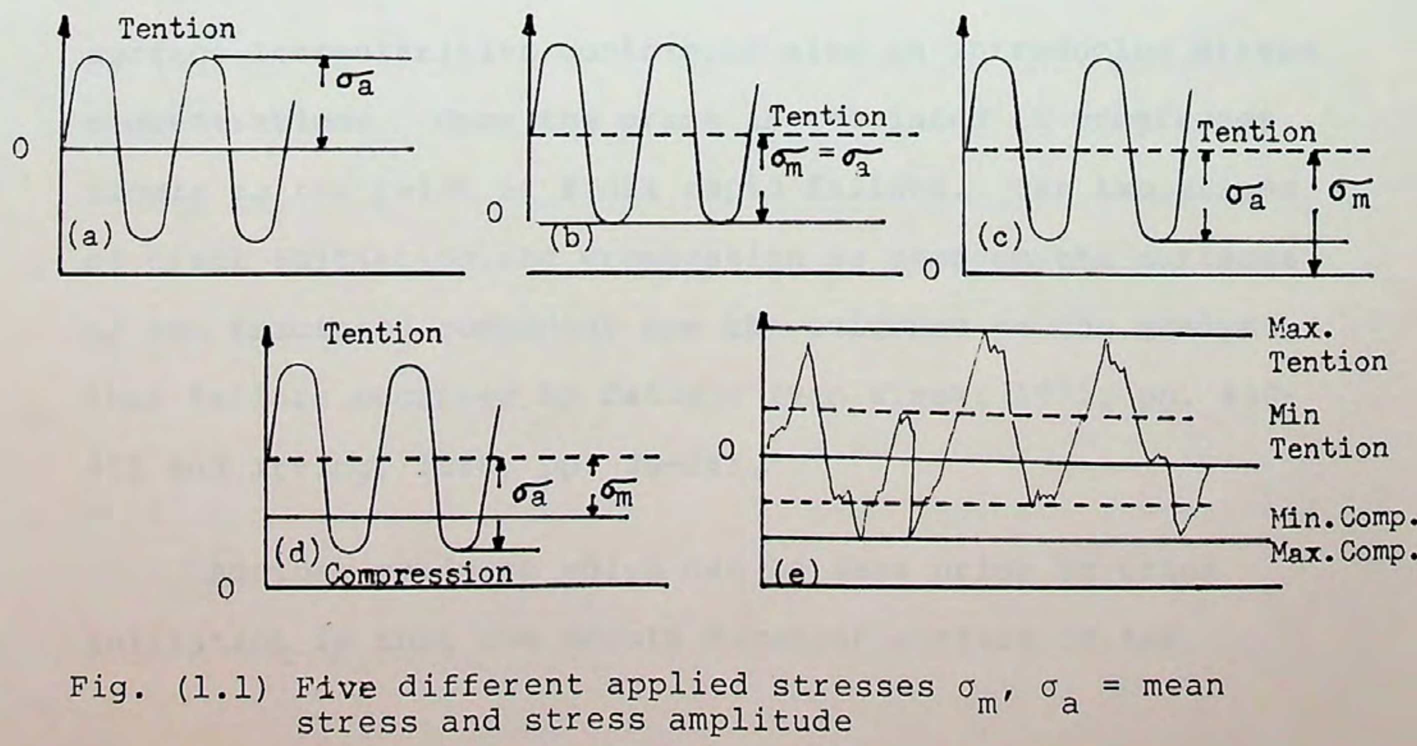


Fig. (1.1) Five different applied stresses σ_m, σ_a = mean stress and stress amplitude

- The stress varying between the limits of equal value but of opposite sign (a)
- The stress varying between two limits of unequal values but of opposite sign (d)
- The stress varying between zero and a definite value (b)
- The stress varying between two limits of unequal values, but of opposite sign (c)
- Randomly fluctuating stresses (e)

The above cycling stresses give rise to failure by fracture. This type of failure facing the analyst is fatigue failure. It is common that fatigue cracks usually start at the surface, though in some cases they may be initiated within a material, particularly at high stress levels. The reason for fatigue cracks to start at the surface is that bending or torsion in the component will subject the outer structure of the material to the highest stresses. The surface irregularities contribute also in introducing stress concentrations. Once the crack is initiated it progresses slowly to the point of final rapid failure. The two stages of crack initiation and propagation as seen on the surfaces of the fractured component are the evidence to the analyst that failure occurred by fatigue (Van Vlack: 1971, pp. 450-451 and Irving, 1980, pp. 36-38).

Another evidence which can be seen prior to crack initiation is that the smooth exterior surface of the component will often reveal extrusions and intrusions which arise from irreversible slip during the reverse of cyclic stress.

Setting the fatigue failure measures necessitates that the analyst should identify the causes of failure by investigating the following items :

1. <u>Effect of type of loading and part shape</u>

The fatigue crack initiation and propagation usually reveal the type of loading which caused it. Therefore, if the component was a beam of a uniform cross section that was subjected to fluctuating stresses and the crack initiated at any point along the beam, the type of loading is a unidirectional bending. In unidirectional bending, the bending moment is uniform along the length of the beam. The same thing happens in cant-lever mounting where the crack initiates and propagates in the beam near the fixed end.

In alternating bending, fatigue cracks initiate on both sides of the beam. In machine shafts subjected to fluctuating loads, the cracks usually initiate at any point or points at the circumference of the shaft indicating that fatigue occurred by rotational bending.

In shafts, if two sets of fatigue cracks perpendicular to each other were detected the loading type is alternating-reversed-tortional.

In flat components such as sheets or plates, the flat face or shear face fracture indicates that the loading was biaxial tension (Metals Handbook: Vol. 10, 1975, pp. 95-125).

2. Effect of over stress and stress concentration

The over stress is the amount by which the nominal stress exceeds the fatigue strength of the material. Exceeding the nominal stress subjects the components to crack initiation and the fast failure fracture is increased in size. Overstressing the component with higher amounts pronouncly reduces fatigue life and relatively the number of load cycles that the component can withstand before failure, and low cycle fatigue fractures are produced.

Stress raisers such as, notches, keyways, oil holes, grooves, steps, bolt holes, shoulders, threads, fillets .. etc., introduce stress concentration at their roots giving rise to stress gradient starting from the root and upwards to the middle of the stress raiser and a state of triaxial stress is created. In case of notches the failure analyst has to examine the fatigue notch factor which is expressed as the fatigue limit of unnotched component. The stress concentration initiates multiple cracks characterised by beach marks that are concave towards the crack initiation point. The beach mark surrounds the final fracture zone in case of rotational loading (Dieter: 1961, pp. 310-311).

Notches, as points of stress concentration, contribute to fatigue failures. The sensitivity of notch equation (1.1) is applied whenever the presence of points of stress concentrations constitute a major factor for brittle fracture by fatigue.

$$q = \frac{K_f - 1}{K_t - 1} \qquad (1.1)$$

where:

q = notch sensitivity

K_f = the ratio of the fatigue strength for unnotched specimen to the fatigue strength of the notched

K_t = stress concentration factor that represents the severity of the notch

$$K_t = \frac{\text{Max. local stress at notch}}{\text{Average stress}}$$

As (q) approaches zero the material becomes notch insensitive while as (q) approach unity the material is notch sensitive. In case of stress concentration, reducing the tensile strength reduces the notch sensitivity. Changing the design by changing the size or the shape of the component will reduce the notch sensitivity (Metals Handbook: 1975, Vol. 10, pp. 64, 96, 101-104 and 107).

3. Effect of frequency of loading

The frequency of loading is very difficult to detect from the appearance of the fractured specimen. However, examination with light microscope may reveal brittle appearance with a plate like structure. Beach marks are not necessarily present as it depends on the crack growth steadiness and occurrence of load variations.

4. Effect of design

Fatigue failure may result from mal design of a component. Investigating the design would reveal the mechanical and structural drawbacks. The soundness of material selection may sacrifice the fatigue resistance unintentially for other important requirements. Therefore, selection of material for any product performance must compensate between all requirements.

5. Effect of material conditions on fatigue strength

The fatigue crack is usually propagated by the localised plastic deformation. Therefore, the microstructure of the material from which the component under study is made plays a great role in the process of crack propagation. The microstructure can determine the transition from ductile to brittle fracture process. The grain size reduction increases fatigue life for many materials under low cycle strain. However, fatigue-life in materials that are subjected to high cyclic strain is not affected by grain size. It is rather critical in some alloys to reduce the grain size as it affects tremendously the other properties. (Brostow: 1979: pp. 323-328).

The chemical composition of the material (alloying) has a pronounced effect on the fatigue strength that is proportional to the effect on tensile strength.

Solid solution has a strengthening effect specially in aluminum alloys which proved to have higher fatigue strength (Brostow: 1979, pp. 197-199).

Fatigue strength can also be affected by second phases. Initiation and propagation of cracks can be accelerated or inhibited by the lattice strain created by the shape, size and distribution of the second phase. The nature of bond between the second phase and the matrix has also a pronounced influence on the mechanism of crack initiation and propagation (Guy: 1976, pp. 368-370).

6. <u>Effect of discontinuities on fatigue strength</u>

If the component under study were processed by thermal-mechanical method such as hammering or drawing etc., the possibility that these processes produce surface discontinuities is a usual matter. Laps, seams or foreign materials embeded into the metal surface due to rolling or forging produce notches which act as stress raisers, therefore, affecting the fatigue strength.

Burning the metal before forging, greatly affects the grain boundry near the surface by cracks, voids and intergranular oxidation which act as crack initiators, and reduces the fatigue strength leading to failure by fatigue fracture as in forged steels.

7. Effect of heat treatment on fatigue strength

Improper heat treatment of a product component can result in a very short fatigue life of that component. Improper heat treatment is caused by the lack of control over the temperature, incorrect rates of heat application or heat removal, contamination of the component metal by the furnace atmosphere and malpreparation of the component before heat treatment. Heat treatment is usually applied to increase the fatigue resistance of the material by increasing the hardness of the surface layer to resist cracks. Increasing the fatigue resistance by carburizing, nitriding or carbonitriding, is a very sensitive process which, if not carried out properly, undesirable structural discontinuities such as carbide networks, excessive nitriding, carbon or nitrogen gradient are formed (Keyser: 1980, pp. 67, 201-215).

8. Effect of manufacturing process on fatigue strength

The failure analyst can gather useful data from studying the manufacturing processes by which the component was produced. Machining, grinding, straightening, drilling, welding, plating, cleaning and even indentification marking can cause defects that lead to fatigue failures. These processes may produce surface irregularities, residual stresses as in straightening by heating in presses and pitting the surface due to cleaning by chemical and so forth. (Metals Handbook: Vol. 10, 1975, pp. 100-120).

a) Thermal fatigue

Data from service conditions would point out that the component under examination was separating under elevated temperatures. Therefore, the failure analyst will investigate whether the failure was by thermal fatigue or by creep followed by stress rupture (Guy: 1976, pp. 369-370).

The thermal fatigue occurs due to temperature cycling which means temperature change along with mechanical constraint which opposes the expansion and contraction of the material giving rise to thermal stress. The material would fail by fracture with a brittle appearance in case of low ductility (Brostow: 1979, pp. 328-329).

The thermal fatigue failure is identified by :

- Many crack initiation sites that gather randomly to form the main crack in a river pattern form

- Transverse fractures
- The crack is filled with the material oxide
- The fracture is transgranular
- The fracture surfaces are rough and more fibrous with shear lips at 45^{o} angles at the final area of fracture.

b) Creep

Creep and stress rupture is the mechanical failure of crystaline materials at high temperatures (Van Vlack: 1971, p. 453). Failure by creep and stress rupture occurs when the component is subjected to high temperature and high static tensile load, during service for a long time. Therefore, creep is a time dependent plastic strain. The creep is identified similar to thermal fatigue except for the fracture which is intergranular that is caused by stress rupture.

Applying corrosion factors to design, type of loading, magnitude and methods of load application, processing methods, environment along with the sound selection of material that can withstand the high temperature and high static tensile loading would be the appropriate measures for creep and stress rupture prevention. The most important source of information for such a type of failure is test and simulation which provides the necessary data for reliability calculations and therefore, the prediction of component service life.

E) Stress-Corrosion Fatigue

One of the most common failures in industry with mechanical-environmental nature is the stress-corrosion combined effect cracking. The simultaneous dual action of tensile stress and a corrosive environment lead to this type of failure. The tensile stress which contributes to this failure is far below the yield strength of the material. The conjoint stress-corrosion failure occurs much faster than the failure caused by the sole effect of either stress or corrosion or both added together. On the macroscopic scale, the surface of the component may exhibit faint signs of corrosion while fine cracks are penetrating deep into the component. Hydrogen, liquid and metal embrittlements are processes that also lead to this type of failure (Keyser: 1980, pp. 144-147).

The stress-corrosion cracks can be identified by the extensive branching that propagate in a direction perpendicular to the stresses contributed in their formation. The fracture may be intergranular or transgranular depending on the material-environment combination. The macroscopic examination reveals a brittle appearance of the fracture surfaces, flat and grain facets as the fracture changes planes during propagation. Regions of crack initiation can be easily observed on the surfaces of the fracture. The macrosopic examination also shows herring bone marks and lips which are evidence of ductilities at the final fracture area.

The microscopic examination is quite critical and could be misleading if a tight correlation between macroscopic features of crack surfaces were not done. The crack initiation sites and the directions of crack propagation must be studied throughly for identification of stress-corrosion failure.

The measures that are taken to prevent stress-corrosion failure lies in controlling both the stresses and the environment. The stress can be controlled by the sound design of the product, the suitable composition, the fine grain structure and the controlled grain orientation of the material to be perpendicular to crack propagation, thus blocking the propagation process. (Dieter: 1961, pp. 336-341, and Van Vlack, 1971, pp. 453-456).

Controlling the environment is carried out by controlling the following :

a. Service environment, which refers to all kinds of fluids, steam and chemicals used in the manufacturing process. These fluids and chemicals should be inspected and analysed regularly to prevent their corrosive effect on the machine components, especially the pH values. Usually stress-corrosion cracks start from the metal residues left by fabrication processes on the surface of the metal such as welding, flux and cleaning solutions etc. This type of residues leads to failure by stress-corrosion fatigue either during the production phase or in service time. Adjusting the composition of the chemicals, along with the addition of reducing agents, such as, hydrogen and sodium sulphate reduces the amount of oxygen in fluids, therefore, decelerating the corrosion. Using organic and polymeric coatings and paints isolate the components from the corrosive media and reduce the corrosion effect. The analyses of the chemicals used in manufacturing processes will help reveal the causes and mechanisms of stress-corrosion and decide on the protective method to be used.

b. Atmospheric environment contains many damaging chemical substances such as gases and fumes. Marine atmosphere is highly corrosive because it is loaded with salt, iodine and chlorine ions. According to the nature of the atmosphere, the protective measures are taken, isolating the product from the atmosphere by coating, painting, or plating will help fight the corrosive atmosphere (Metals Handbook: Vol. 10, 1975, p. 211).

3. Factor of safety

Studying a system from the design stage up to the actual operation of that system needs calculation and analysis. Almost all the mathematical calculations, and the mechanical, physical and chemical analyses are built on some predictions and usually are treated with a considerable amount of approximation. Therefore, a need for a factor of safety to compensate for the above reasons is essential. The factor of safety will secure a reliable safe planned life for the system. During the design stage, the designer should utilise the factor of safety with proper values in his calculations to secure the product against rapid failure.

To be within the safe margin, the working stress σ_w, which is assigned to the system or component of a system, should be less than the yield strength of ductile materials. For brittle materials the σ_w should be less than the ultimate tensile strength (UTS). Under cyclic loading, as in the case of fatigue, the endurance limit is useful in predicting the damaging stress.

Values of working stresses for brittle and ductile materials under static loading as well as endurance limit for cyclic loading (Dieter: 1961, pp. 12-13, and Khurmi: 1973, p. 617), are established by many agencies such as the American Society of Mechanical Engineers (ASME).

Relations to be used :

$$\sigma_w = \frac{\sigma_o}{\Phi_o} \quad \text{or} \quad \sigma_w = \frac{\sigma_u}{\Phi_u} \qquad (1.2)$$

where:

σ_w = working stress

σ_o = yiel; strength

σ_u = tensile strength

Φ_o = factor of safety for yield strength

Φ_u = factor of safety for tensile strength

For fatigue, it is well known that for identical components, each component has its own fatigue limit, even if they are identical. Above this fatigue limit (stress) the component will fail. It is rather difficult to determine the fatigue limit, and the majority of the available data are concerned with the nominal stress required to produce a factor in a given number of cycles (SN Curves). These data are obtained from endurance tests. The endurance ratio is normally used to obtain an approximate fatigue strength.

Flow Chart

Of A Proposed Method For Failure Analysis

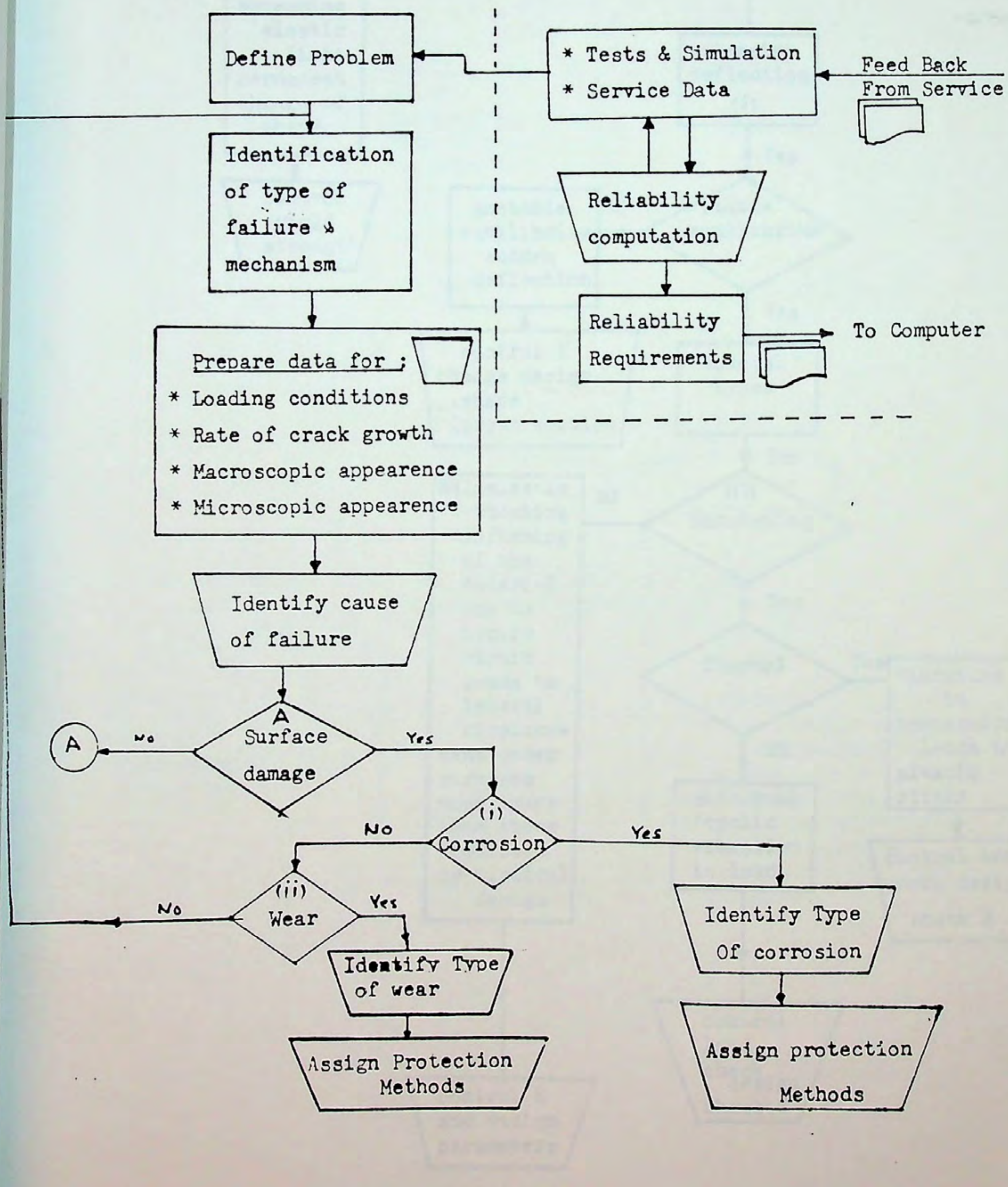
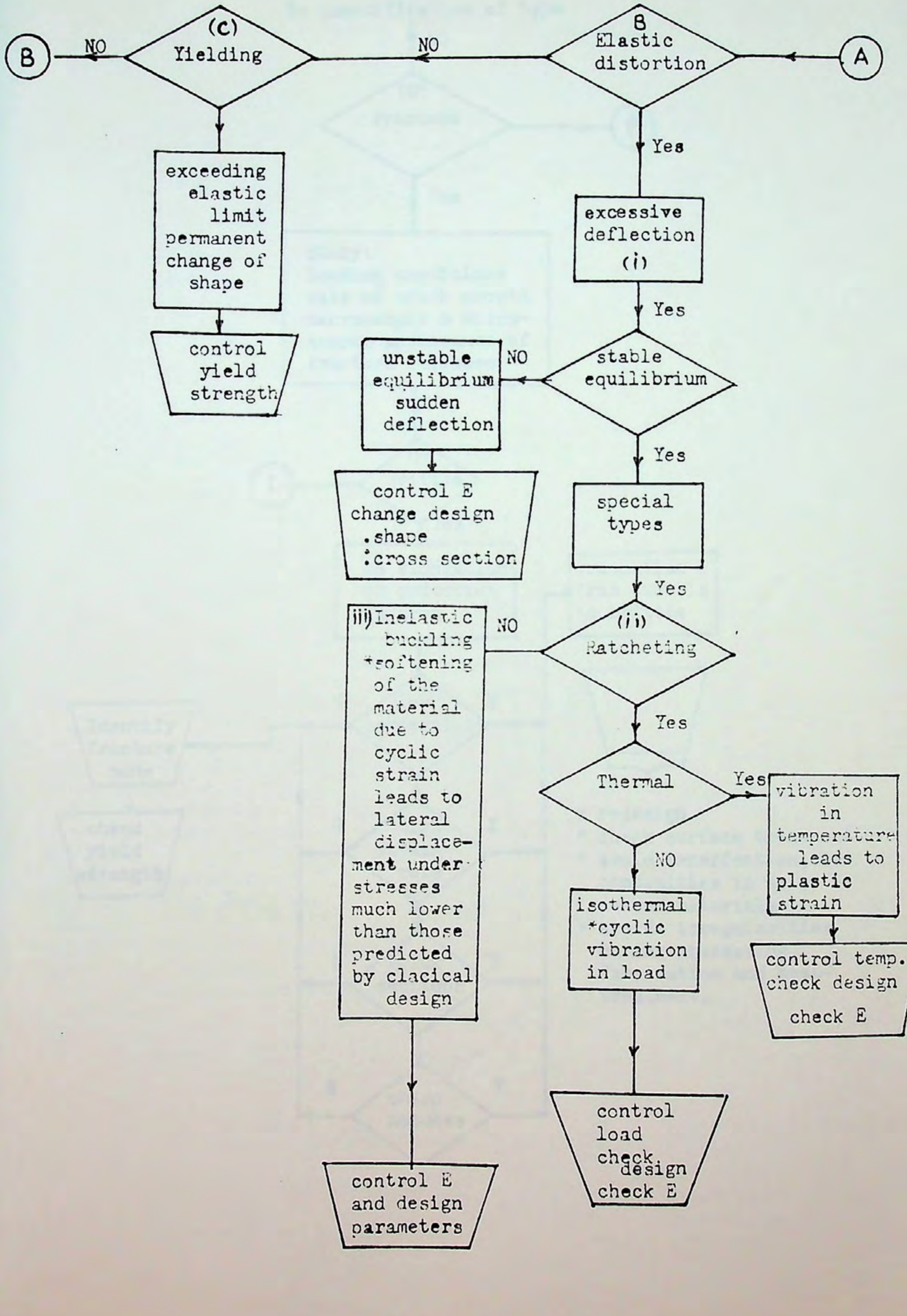
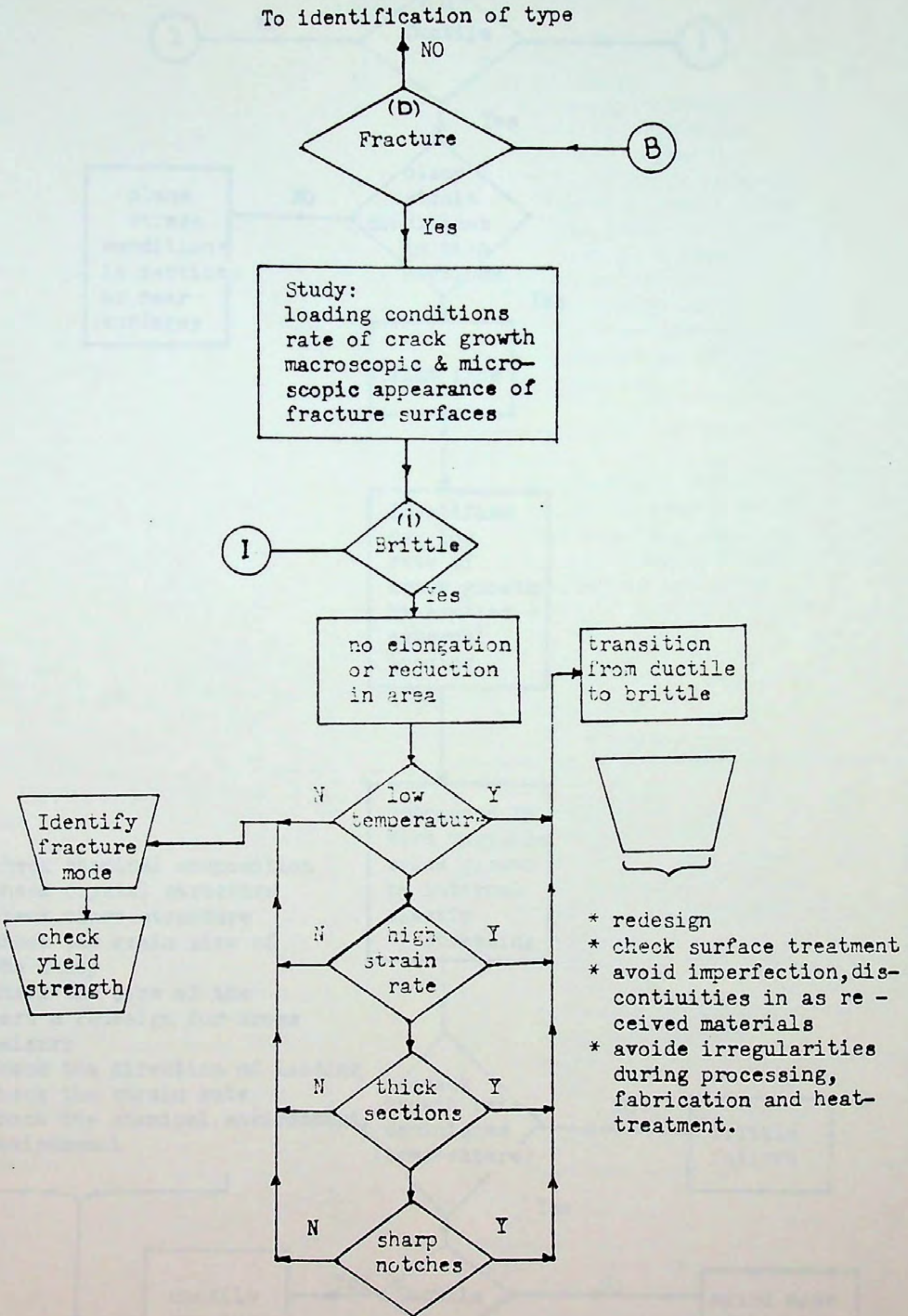
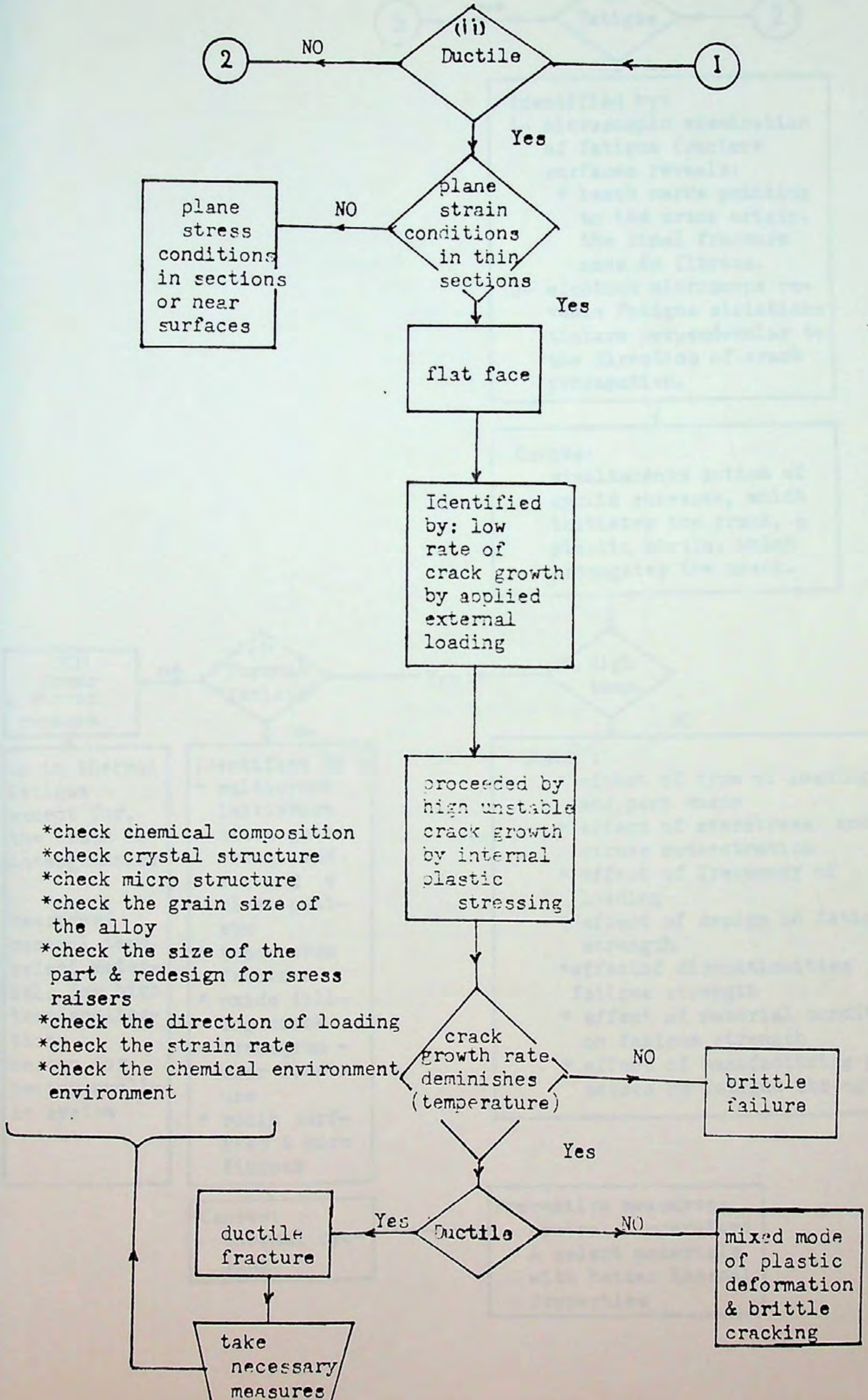
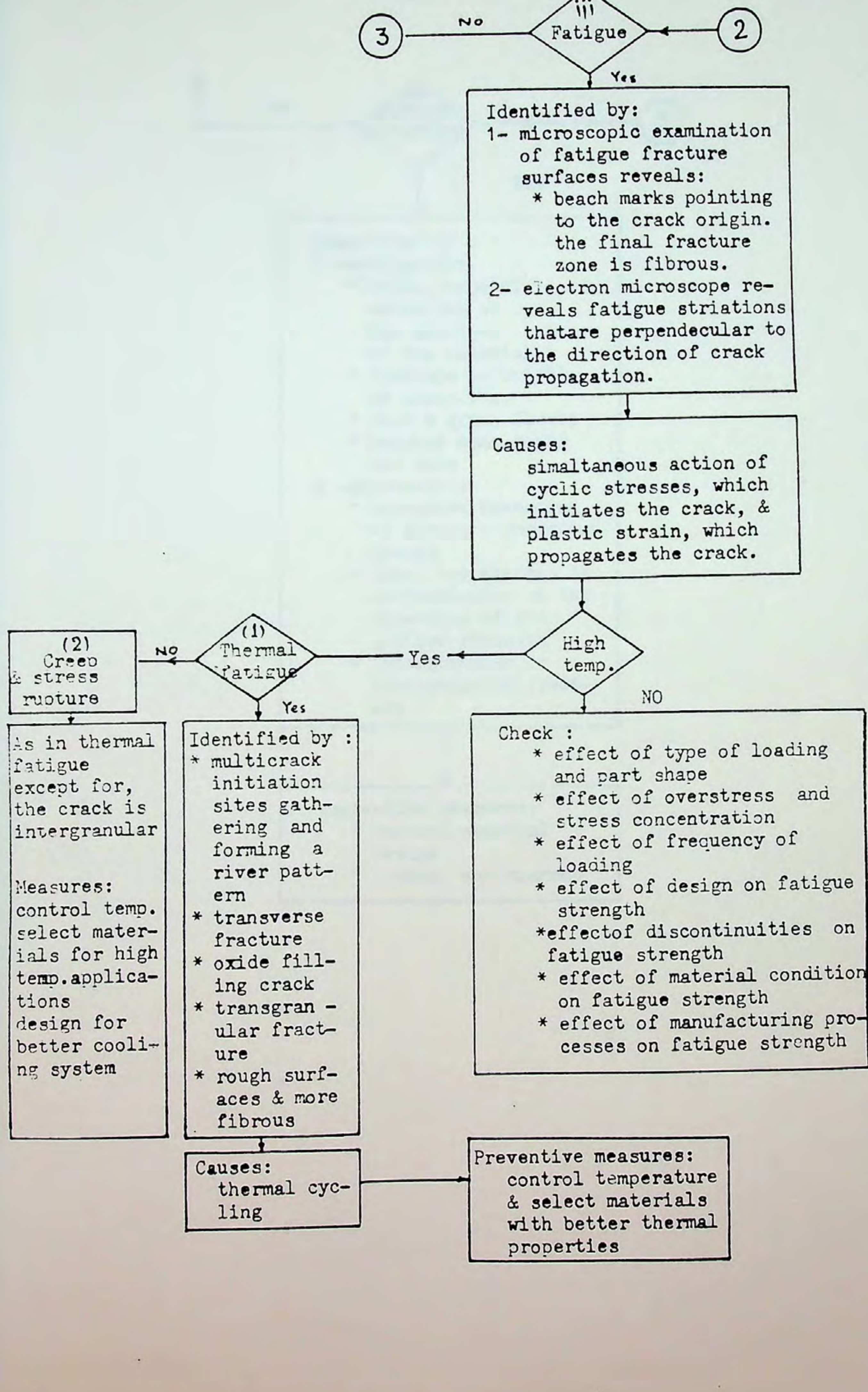


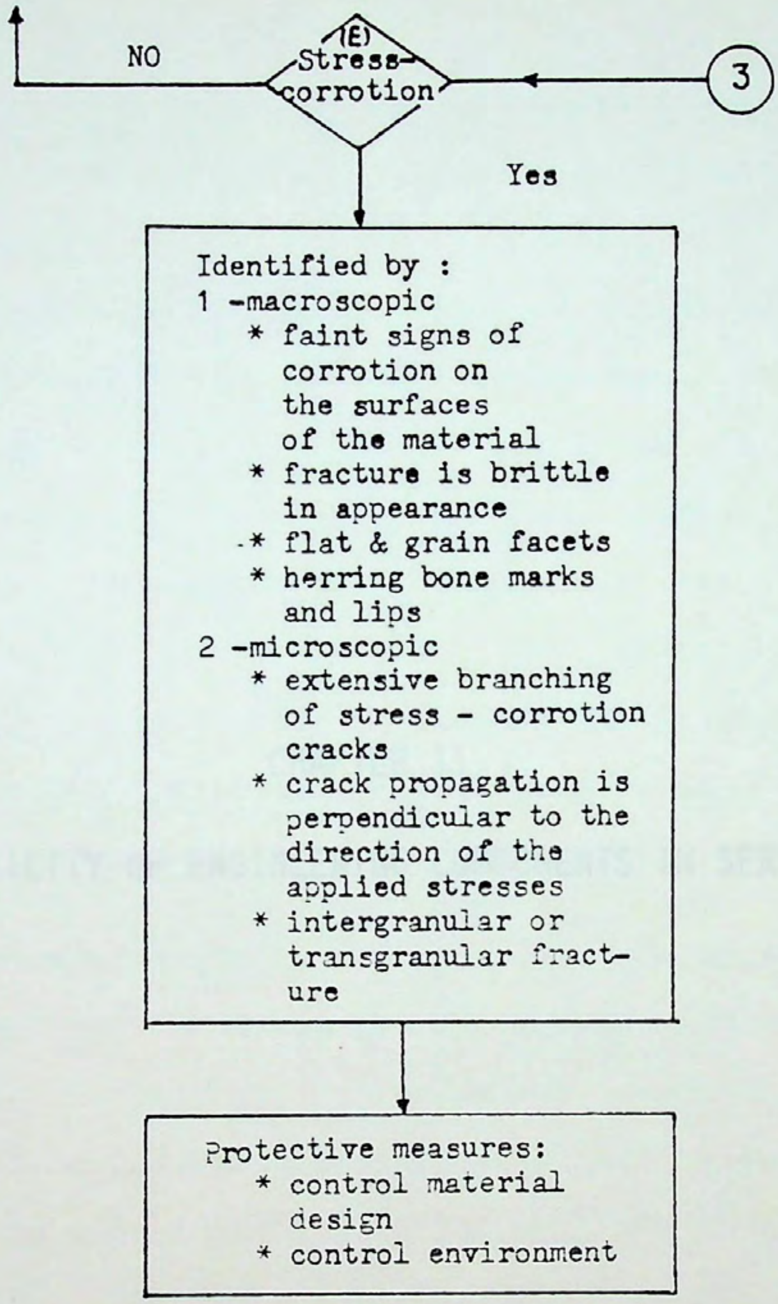
fig (1.2)


B
NO
(c)
Yielding
NO
B
Elastic
distortion
A
exceeding
elastic
limit
permanent
change of
shape
Yes
control
yield
strength
excessive
deflection
(i)
Yes
unstable
equilibrium
sudden
deflection
NO
stable
equilibrium
Yes
control E
change design
.shape
:cross section
special
types
Yes
iii) Inelastic
buckling
*softening
of the
material
due to
cyclic
strain
leads to
lateral
displace-
ment under
stresses
much lower
than those
predicted
by clacical
design
NO
(ii)
Ratcheting
Yes
Thermal
Yes
vibration
in
temperature
leads to
plastic
strain
NO
isothermal
*cyclic
vibration
in load
control temp.
check design
check E
control
load
check design
check E
control E
and design
parameters


To identification of type
NO
(D)
Fracture
B
Yes
Study:
loading conditions
rate of crack growth
macroscopic & microscopic appearance of fracture surfaces
(i)
Brittle
I
Yes
no elongation or reduction in area
transition from ductile to brittle
N
low temperature
Y
Identify fracture mode
check yield strength
N
high strain rate
Y
N
thick sections
Y
N
sharp notches
Y
* redesign
* check surface treatment
* avoid imperfection, discontiuities in as received materials
* avoide irregularities during processing, fabrication and heat-treatment.


(ii)
Ductile
2
NO
I
Yes
plane strain conditions in thin sections
NO
plane stress conditions in sections or near surfaces
Yes
flat face
Identified by: low rate of crack growth by applied external loading
proceeded by high unstable crack growth by internal plastic stressing
*check chemical composition
*check crystal structure
*check micro structure
*check the grain size of the alloy
*check the size of the part & redesign for sress raisers
*check the direction of loading
*check the strain rate
*check the chemical environment environment
crack growth rate deminishes (temperature)
NO
brittle failure
Yes
Ductile
Yes
ductile fracture
NO
mixed mode of plastic deformation & brittle cracking
take necessary measures


3
No
iii
Fatigue
2
Yes
Identified by:
1- microscopic examination of fatigue fracture surfaces reveals:
* beach marks pointing to the crack origin. the final fracture zone is fibrous.
2- electron microscope reveals fatigue striations thatare perpendecular to the direction of crack propagation.
Causes:
simaltaneous action of cyclic stresses, which initiates the crack, & plastic strain, which propagates the crack.
High temp.
Yes
(1)
Thermal fatigue
NO
(2)
Creep & stress rupture
NO
Check :
* effect of type of loading and part shape
* effect of overstress and stress concentration
* effect of frequency of loading
* effect of design on fatigue strength
*effectof discontinuities on fatigue strength
* effect of material condition on fatigue strength
* effect of manufacturing processes on fatigue strength
Yes
Identified by :
* multicrack initiation sites gathering and forming a river pattern
* transverse fracture
* oxide filling crack
* transgranular fracture
* rough surfaces & more fibrous
As in thermal fatigue except for, the crack is intergranular
Measures:
control temp.
select materials for high temp.applications
design for better cooling system
Causes:
thermal cycling
Preventive measures:
control temperature & select materials with better thermal properties


NO
(E)
Stress-
corrotion
3
Yes
Identified by :
1 -macroscopic
* faint signs of corrotion on the surfaces of the material
* fracture is brittle in appearance
* flat & grain facets
* herring bone marks and lips
2 -microscopic
* extensive branching of stress - corrotion cracks
* crack propagation is perpendicular to the direction of the applied stresses
* intergranular or transgranular fract-ure
Protective measures:
* control material design
* control environment

CHAPTER II

RELIABILITY OF ENGINEERING COMPONENTS IN SERVICE

CHAPTER II

RELIABILITY OF ENGINEERING COMPONENTS IN SERVICE

Introduction

The field of reliability engineering is extremely extended, covering many areas of technology. The growth of knowledge in reliability engineering and its application helped in ensuring the success of a vast number of projects and designs. In dealing with complex projects, an engineer faces a great difficulty in gathering information needed for reliability application as the topics are scattered in so many papers and specialized books rather than a specific number of references.

A quick review of the fundamental concepts in reliability engineering is necessary to help understand the methods used in this thesis to achieve a sound reliability term in the computerized process selection of materials which is the concern of this work.

1. Reliability Evaluation Techniques

There are many techniques to evaluate reliability such as, binomial, Marcov Processes (state space approach), dicomposition, minimal cut set, network reduction and delta star techniques. Some of these techniques are oriented to specific applications such as power reliability, electronic circuits, and computer hardware failure, the others, are very useful in determining reliability of product either in the design stage or during service. These techniques are highly dependent on the available data of the product under study. In case of inavailability of data, tests, simulations and information from the product service life are vital for the reliability computations, which will be discussed in the following passage. (Billinton: 1983, pp. 36, 70, 206-252 & 288 ; Dhillon: 1981, p. 153, and Kurtz: 1984, pp. 2.125-2.154).

2. Reliability and Failure

Reliability and failure are closely related, this made many research workers devote a vast number of their researches to study failure and predicting service life, which in turn is the input source of data to the computations of reliability. Since a general equation that describes failure as a whole is not available, each type of failure is treated separately to correlate it to mechanical, physical and chemical properties, and constructing an imperical relation depending on tests and simulations. The present numerous failure computations are not suitable for computer application except as subroutines that depend in its construction on the type or types of failure at hand, either in the design stage, during processing, or operating life of the product (Dhillon: 1981, p. 3).

In our case, and for computer application, the failure problem is treated analytically to help the engineer arrive at a decision that defines the failure understudy.

Once the type of failure, causes, frequency of occurrence are well defined, the preventive measures are set, then the reliability of the product will be computed using the suitable relation.

The data obtained from tests and simulations will be treated according to statistical methods to yield the necessary terms for the construction of suitable reliability relations that can deal with various types of failure.

3. Complex System Analysis

In a complex system which contains many components that function together, a tool to evaluate the design in the early stage or when the product is under development from the reliability aspect, is vitally needed. This tool must realise a routine upward procedure that begins from the detailed level, and by evaluating each component performing in the system individually, the whole system is evaluated and the weak points of the system design are identified. The most suitable tool for the complex system is the Failure Mode and Effect Analysis (FMEA) to achieve the required reliability. This procedure starts with assigning reliability targets for subsystems. Once the subsystem reliability is achieved, the overall goal will be fulfilled. The process for setting reliability goals is known as reliability apportionment, and it is usually carried before the key design or product decision for development are made. Fig. (2.1) shows the FMEA flowchart*.

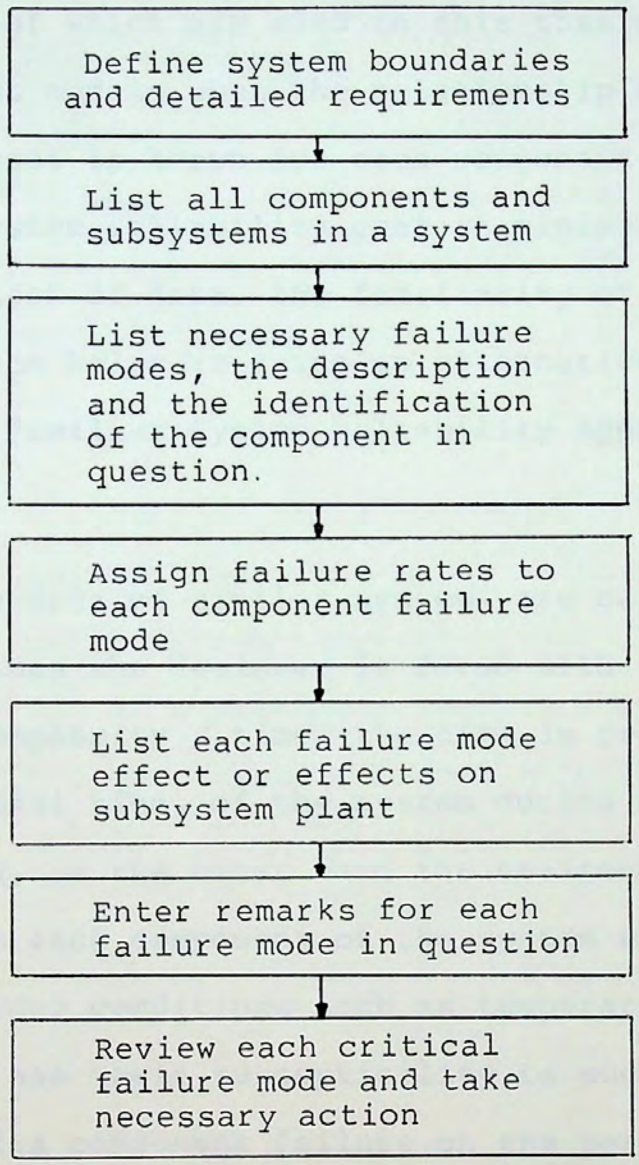


Fig. (2.1) Failure Mode and Effects Analysis (FMEA) Flow Chart.

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* Modified from Engineering Reliability New Techniques and applications, B.S. Dhillon and Chanan Singh, John Wiley and Sons, New York, 1981, p. 44.

Several techniques for reliability apportionment can be applied according to their suitability to the system under study some of which are used in this thesis such as reliability / cost models when the relationship between reliability and cost is known for each component of the system to meet system reliability goal at minimum cost. In case of cost lack of data, the familiarity of the designer with similar system helps in using an alternative technique which is Similar Familiar System Reliability Apportionment Approach.

The failure data of similar systems are collected and utilised. Sometimes the designer is faced with the fact that, in the case of complexity / time, the time is related to the relative operational time, of the system during the total functional period, on the other hand the environmental factor and its effect on each component of the system when they operate in different conditions such as temperature, humidity, vibration media, and their susceptibility to such conditions, and the effect of a component failure on the performance of the whole system which is known as the subsystem failure criticality. The above factors lead the designer to use the factors of influence method which is used here in the performance analysis stage of the product under process selection. Using one method alone is a point of weakness, thus, the creation and utilisation of combined methods, where each method suits a specific condition is more powerful in achieving better and more accurate results.

4. Mechanical Distribution Methods

The use of relative frequency interpretation of probability provides the link between the mathematical concept of probability and the imperical results of the component or system behaviour in the continuous tests and simulation procedure.

The relative frequency interpretation of probability is the use of the data collected from the experimental methods before and after product operation and calculation of the probablity (P) of a particular event, e.g. failure occurring in a period of time in a number of experiments, using a simple relation:

$$P = \lim_{n \to \infty} \left(\frac{f}{n}\right) \qquad (2.1)$$

where,

n = number of times the experiment is repeated

f = number of occurrences of the event

(Green and Bourne: 1972, p. 26, and Kurtz: 1984, pp. 2.73-2.87).

5. Probability Distributions

By gathering the data from experiments, tests, and simulations, and applying probability relations to obtain a value, would simplify the problem, instead a whole range of values of probability and frequency of occurence of an event will result. In probability applications, it is essential that the occurence of the event and consequently the values that result occur randomly in time or space or both. The event being measured (failure rate of a component, mechanical strength etc.) is thus a random variable. This variable can be considered discrete and random since the possibilities of occurence are just two, either to occur or not to occur (Billinton: 1983, pp. 25-29).

The data obtained from simulations and tests are analysed by using probability density function and probability distribution function. The probability density function f(t), can be deduced from the data after rearranging them and plotting the frequency of occurence of the events vs. time or number of experiments (App.1 Fig.1), dividing the frequency of occurence by the number of experiments or by the time of experiment, the summation of the probabilities obtained must equal unity.

The probability distribution function is another method of presenting the same values or results. This is done by arranging the random values obtained in ascending or discending order. By cumulative manner, the probabilities of occurence are built from the first value to last value until all values are cumulated. The final value of probability must equal unity (See Appendix 1) (Gross: 1975, p. 4).

6. Selection of Materials and Reliability Requirements

The design engineer may assign, before hand, a required reliability value for his product along with the other performance requirements. In this case, the material selection process has to determine the material that can fulfill all the requirements. Sometimes, this is not the case where the requirements are conflicting. The reliability might be sacrificed for another preferred requirement. Therefore, reliability computations must be a continuous process, from the design stage to the final product operation. The material of the product may be changed, if it is proved that it is responsible for failure during processing or operation.

The Flow Chart Fig. (2.2), explains the process of reliability determination from the design to operating stages for a new system/component as follows :

A. Design stage:

i- The product has to be defined thoroughly by studying :

- The nature, function and purpose of the product
- The design and design alternatives and variables
- The material properties and specifications
- The processing method or methods and their effect on the product
- The conditions under which the product will perform in operating life
- The hazards that might occur to human life or production system due to failures

ii- A reliability specifications preliminary study is carried out supported by the results from item i.

iii- The results of the reliability study will allocate the reliability requirements.

iv- A decision for the design is reached. The prototype is tested for failure modes and the observations and results are subjected to effect and reliability analysis.

v- The design is finally revised and corrected for the final shape.

B. Processing stage and operating life

Data received from processing stage, operating life, and service conditions may necessitate a new reliability requirement. Therefore, the reliability specification Step ii must be reconsidered and corrected. The reconsideration of reliability due to the new failure and reliability analysis will affect the allocation of reliability targets. The development of the product design has to take place to fulfil the new reliability boundaries which are obtained from the feed back failure and reliability analysis. The new design is revised, if any drawbacks are discovered the process is repeated until the final shape is achieved (Green and Bourne: 1972, pp. 527-553).

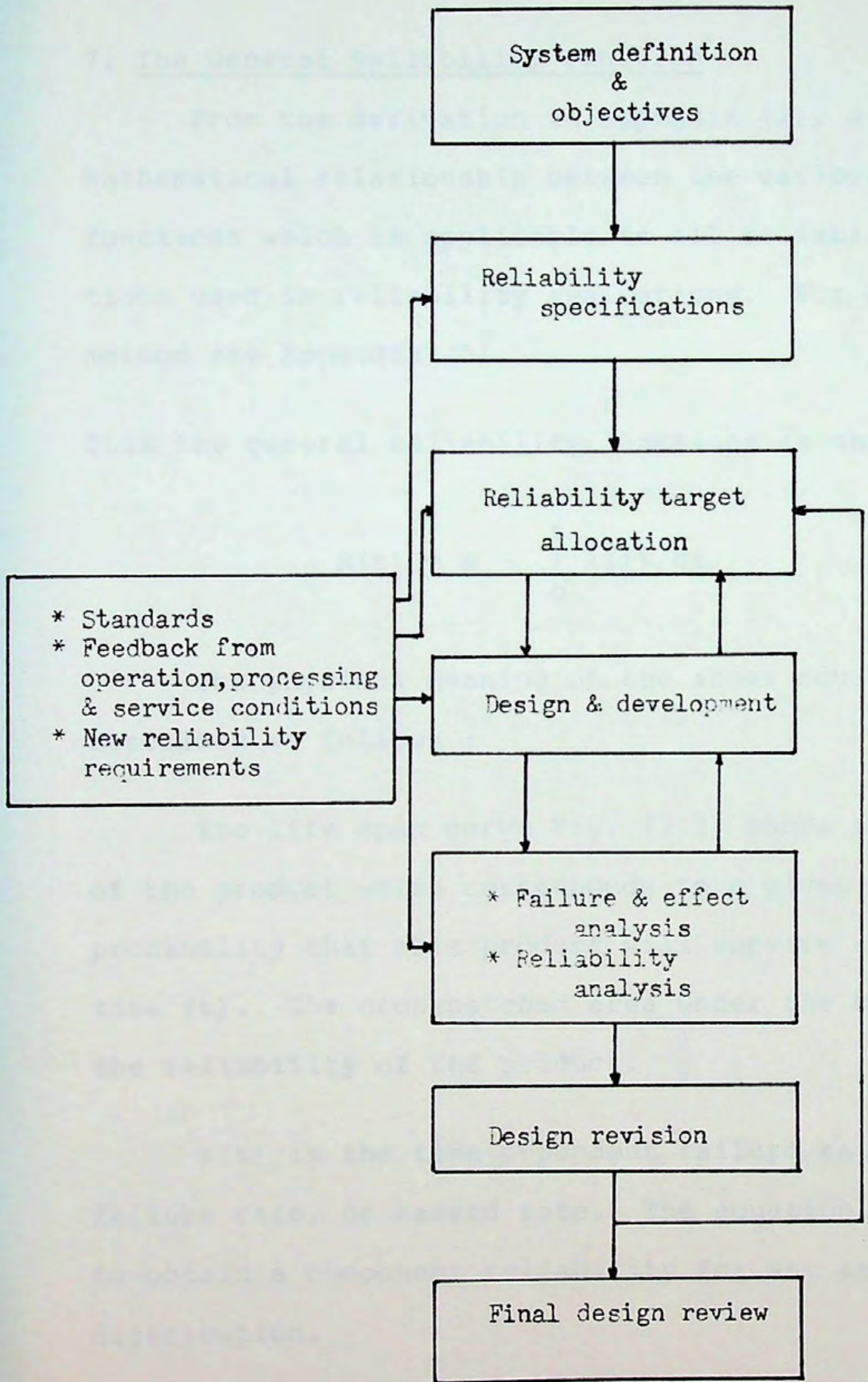

Fig. (2.2) Reliability of product from design to operating stages.

7. The General Reliability Function

From the derivation in Appendix (2), a general mathematical relationship between the various reliability functions which is applicable to all reliability distributions used in reliability evaluations. For distribution method see Appendix (5).

Thus the general reliability functions is then :

$$R(t) = e - \int_{o}^{t} \lambda(t)\, dt \qquad (2.2)$$

The physical meaning of the above equation can be described as follows :

The life span curve Fig. (2.3) shows that the probability of the product which corresponds to a given time (t) is the probability that this product will survive and operate after time (t). The crosshatched area under the curve represents the reliability of the product.

$\lambda(t)$ is the time dependent failure rate or instantaneous failure rate, or hazard rate. The equation (2.2) can be used to obtain a component reliability for any known failure time distribution.

The above equation is widely used in mechanical failures. It is used in calculating the reliability of a product whose failure rate increases exponentially with increasing operating time as in wear and corrosion.

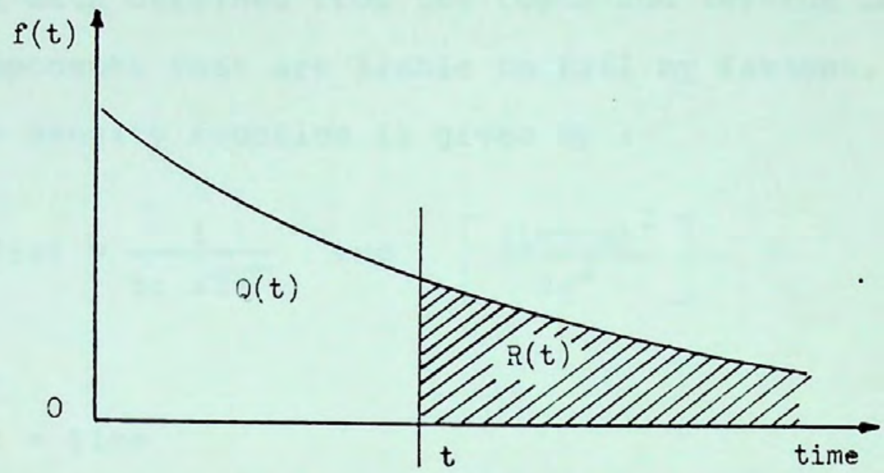

Fig. (2.3) Hypothetical failure density function. Q(t), probability of failure in time t, R(t), probability of surviving beyond time t.

Stresses and load capacities which might lead to failure, the most suitable reliability equation is that obtained from treating the random variable data according to the Normal Distribution Method (Appendix 3). The equation is :

$$F\ (Z) = \frac{1}{\sqrt{2\pi}}\ \exp\left[-\ \frac{Z^2}{2}\right] \qquad (2.3)$$

The above equation (2.3) is valid for use with failure caused by yielding. The normal density function of this equation is symmetrical about the average mean value of the random variable.

All the probabilities of failure lie under the normal density function curve. The derivation of the equation and the Normal Distribution Method are described in Appendix (3).

The Log-Normal Distribution is a very effective method for the data obtained from the tests and service concerning the components that are liable to fail by fatigue. The failure density function is given by :

$$F(t) = \frac{1}{t\sigma\sqrt{2\pi}} \quad \exp\left[\frac{(\ln t-\mu)^2}{2\sigma^2}\right] \qquad (2.4)$$

where:

t = time

σ = standard deviation or shape parameter

μ = mean value or scale parameter

Since fatigue failure occurs by the application of fluctuating load, therefore, the frequency of the fluctuating load is time dependent and time (t) is normally distributed with the scale parameter or mean value (μ), and the shape parameter or standard deviation (σ). For further details refer to Appendix (4).

CHAPTER III

SELECTION METHODS

CHAPTER III

SELECTION METHODS

Introduction

In the process of selection among alternatives, the materials engineer is faced with two types of environments: the technical and the economic. His knowledge of technical and physical laws determine his success in using the technical environment to manufacture products or services. On the other hand, the materials engineer must be well aware of the fact that the value of his products and services depends on their utility which is measured in economic terms. The different materials and structures at the disposal of the engineer have varying characteristics exhibiting excellent properties, sometimes having little economic value and thus, not explored so far industrially. Therefore, the decision taken by the engineer when selecting new materials or procedures must be based on the technical and physical requirements as well as evaluated in terms of cost and merit. Economic feasibility is important in the selection process (Farag: 1979, p. 148).

1. The digital Logic Approach Method

This method is useful in determining the relative importance of performance of requirements, (Weighting factor Method).

In the process of solving selection problems, the materials engineer is usually confronted with a complex combination of requirements. To evaluate the importance of each requirement versus the other requirements, which is carried out one at a time, is by giving a numerical decision 1 for importance, and zero decision for less importance. Therefore, if there are (n) number of requirements, the number of possible decisions will be :

$N = n(n-1)/2$. The number of positive decisions in each requirement is then summed up and divided by the (N) the total number of possible decisions to give the emphasis coefficient (α) for this requirement. The summation of all the emphasis coefficients of all requirements should equal unity (See Table 3.1).

Table 3.1

Relative Importance Form

Requirements	Possible Decisions										Positive Decisions	Relative Coefficient
	1	2	3	4	5	6	7	8	9	10		
Req. 1	1	1	0	1							3	= 0.3
Req. 2	0				1	0	1				2	= 0.2
Req. 3		0			0			1	0		1	= 0.1
Req. 4			1			1		0		0	2	= 0.2
Req. 5				0			0		1	1	2	= 0.2
Total number of positive decisions											= 10	= 1.0

For the candidate materials properties, the evaluation of the values for each requirement is carried out by comparing each value with the other relatively by dividing the value under comparison by the summation of this value and the value compared with. This method will give a more accurate performance ratio between the two values. The result of this evaluation method will be a number of ratios called (β) factors for each requirement. Therefore, if there are (m) number of requirements, there will be (n) number of lists of (β). Multiplying the Betas of each requirement by the (α) of this requirement produced by the digital logic approach, thus, a figure of merit (γ) will result for each requirement (property) of the candidate materials. After summing the gamas (Σγ) for all requirements of each candidate material, the material with the highest (Σγ) will be the optimum material for the selection process. This process can be introduced by a percentage figure of merit γ_r relative by following the relation :

$$\frac{(\gamma) \text{ of the candidate material X 100}}{\text{Maximum } (\gamma) \text{ in the list}}$$

$$\text{or} \quad \gamma_r = \frac{\gamma_i \text{ X } 100}{\gamma_i \text{ Max}} \qquad (3.1)$$

(Farag: 1979, p. 161, and Crum: 1971 pp. 92-94).

2. Limit on Properties Method for Evaluation

This method assigns specific conditions for material requirements. These conditions depend on the required application. Therefore, the requirements are classified into 3 groups, the upper limit properties, lower limit properties and target values. The upper limit is assigned to the properties required to be not lower than a certain high value, therefore, an upper limit under which the property is no more preferred, is assigned. On the other hand, for the lower limit values, the property should in no way exceed it. Moreover, for the properties that must have a specific value, a target value may be specified.

The selection process using this method starts by assigning a weighting factor (α) by the forced decision, or digital logic approach, for each material property. Y_{l1}, Y_{l2}, Y_{l3} .... Y_{ln} denote the lower limits for properties, 1, 2, 3, ... n, where Y_{u1}, Y_{u2}, Y_{u3} ..... Y_{un}, represent upper limit for properties 1, 2, 3, ... n and Y_{t1}, Y_{t2}, Y_{t3} ..... Y_{tn}, are the target values assigned for properties 1, 2, 3, ... n. For candidate materials properties, the corresponding notations for a material (j) are : X_{l1j}, X_{l2j}, X_{l3j}, ... X_{lnj}; X_{u1j}, X_{u2j}, X_{u3j}, ... X_{unj}; and X_{t1j}, X_{t2j}, X_{t3j}, ... X_{tnj}. As mentioned before, for the lower limits if, $\frac{Y_l}{X_l}$ is less than or equal to unity, the material is accepted. For upper limits, if $\frac{X_u}{Y_u} \leqslant$ unity, the material is accepted. In case of target value properties $|(X_t/Y_t) - 1|$ must be within the specified limit to accept the material.

The materials that are accepted are graded by a figure of merit (δ), which can be obtained as follows :

$$\delta = \sum_{i=1}^{nl} \alpha_{li} \frac{Y_{li}}{X_{li}} + \sum_{i=1}^{nu} \alpha_{ui} \frac{X_{ui}}{Y_{ui}} + \sum_{i=1}^{nt} \alpha_{ti} \left| \frac{X_{ti}}{Y_{ti}} - 1 \right| \qquad (3.2)$$

where :

nl = number of lower limit properties

nu = number of upper limit properties

nt = number of target values

The above equation (3.2) sums the lower limit, upper limit and target values multiplied by their specified alphas (α). The calculation will result in a figure of merit (δ) for each candidate material. The optimum material will be the one that has the lowest value of (δ). (Farag: 1979, pp. 160-162).

CHAPTER IV

PROGRAMME MATHEMATICS AND COMPUTATION

CAHPTER IV

PROGRAMME MATHEMATICS AND COMPUTATION

Introduction

The data is received from the designer and the reliability engineer as detailed requirements and specification that explains the required product performance. For computer application a special form must be designed to facilitate the flow of data between the designer, reliability engineer and the materials engineer who carries out the selection process. The data received by the materials engineer usually states the desired function and the performance as well as the environmental conditions in which the product will serve. If there are specific conditions that affect product performance due to the effect of the job supposed to be done by it, they must be stated.

1. Performance Requirements

The materials performance requirements data usually cover the following areas :

a- Functional requirements

b- Processability requirements

c- Cost

d- Reliability

e- Resistance to environmental service condition

First step : The material engineer's task is to analyse the data received and correlate it to mechanical, physical and chemical properties. In this step, experience, and simulation tests help in evaluating the properties that cannot be measured directly. The system analysis in this step must be carried out manually to yield the necessary data for the computer processing step to facilitate the selection process. The requirements can be grouped as: obdurate requirements that cannot be ignored or substituted by alternative solutions; and flexible requirements that can be compromised. The above requirements classification are product dependent and the classification depends on the material application, thus, this step is usually difficult if not impossible to computerise.

The second step : to start calculation of the selection process by choosing one of the several methods of evaluation. The weighting factor method is used in this thesis, as discussed in Chapter III.

To calculate the (α) emphasis coefficient (Section 1, Chapter III), the digital logic approach is used. Each requirement is compared with the others manually, as this depends on the experience of the selection engineer. The values of emphasis coefficient (α) for the requirements are stored in the computer to be used in following steps. In case of more than one service condition, the emphasis coefficient (α) is determined for each requirement under every condition, and is given a suffix denoting the number of the condition ($\alpha_{1,2,...n}$).

The third step: all the data concerning the candidate materials for the specific application under selection is called from the mini data bank by the programme. The properties values of the candidate materials are listed in a matrix form Fig. (4.1) as requirements vs. solutions. The requirements in the matrix are those values that were given the emphasis coefficients in the second step. The solutions are the properties values of the candidate materials.

$$
\begin{array}{cc}
 & \begin{array}{cccc} R_1 & R_2 & R_3 \;\ldots & R_n \end{array} \\
RS = \begin{array}{c} S_1 \\ S_2 \\ S_3 \\ S_k \end{array} & \left[\begin{array}{cccc} RS(1,1) & RS(1,2) & RS(1,3) & RS(1,n) \\ RS(2,1) & RS(2,2) & RS(2,3) & RS(2,n) \\ RS(3,1) & RS(3,2) & RS(3,3) & RS(3,n) \\ RS(,1) & RS(k,2) & RS(k,3) & RS(k,n) \end{array} \right]
\end{array}
$$

Fig. (4.1) Matrix solving for the properties values of the candidate materials

where :

n = number of requirements

R = Requirement

S = Solution

k = Number of solutions

and each element in this matrix is $RS(\ i\ ,\ j)$

where $i = 1 \rightarrow n$, $j = 1 \rightarrow k$

Since the properties of the candidate materials are of different units that would lead to incorrect results when compared to the requirements, a need for scaling system to change them into unitless values that would overcome the previous drawback. The scaling is carried out by giving a grade of 100, or one for the higher, lower or target values in each material property. (The target value is added in the selection process as a modification to the weighting factor method). As an example of this, the cost is always needed low, therefore the lowest value is considered the most convenient in the selection process and is given a grade of 100 and the lowest value is given one. On the other hand, some of the mechanical properties are needed with high values, thus, a grade of 100 while the lowest is given one. The rest of the values are scaled proportionally using equations No. (4.1), (4.2) & (4.3). In case of target value, the nearest value in the candidate materials properties values is graded 100. The remaining values are graded according to their dispersion from the assigned target value. After scaling, the selection will be according to a unitless system of grading.

For high values to equal 100 and low values to equal 1.

$$RS(i,j) = \left[RS(i,j) - \text{Min } RS(i,j) \times \frac{100-1}{\text{Max } RS(i,j) - \text{Min } RS(i,j)} \right] + 1 \qquad (4.1)$$

For low values to equal 100 : and high values to equal 1

$$\text{Scaled RS}(i,j) = \left[100 - \text{RS}(i,j) - \text{Min RS}(i,j) \times \frac{100-1}{\text{MaxRS}(i,j) - \text{MinRS}(i,j)}\right] \quad (4.2)$$

For target value :

Calculate for RS(i,j) = RS(i,j) - target value

where: RS(i,j) in absolute value of the difference between the property value and target value using equation (2) RS is scaled (4.3)

The meaning of equations (4.1 - 4.3) :

(4.1) The scaled value will equal the difference between the value under scaling and the maximum value in the list, multiplied by the difference between the maximum grade 100, and the minimum grade 1. The product will be the value of the difference between the minimum value which is scaled 1, and the value under scaling. If we add one to the difference, the result is the scaled value.

(4.2) For low values to equal 100, the same equation is applied, except that it is subtracted from 100, instead of adding 1. This will reverse the scale allowing the low values to take the higher grades.

(4.3) The target value is subtracted from the value under scaling regardless of the sign. The result will be treated by equation (4.2), the scaled value will then be obtained.

The scaled value here may be higher or lower than the target value, but still have a grade according to its nearness to the target value as the target value is considered of grade 100.

For reliability and cost, if received as ready calculated values, they are directly joined to the programme as requirements. In case the selection engineer has to carry out these calculations from the data given, the subroutines in the programme will carry it out as will be explained later in this chapter. For non available data on reliability and cost, a proposed method for their determination is recommended. The method is built on the basis of the tight relation between the sound selection of mechanical, physical and chemical properties of materials and their probability to fail during their service life. The method proposes an ideal material having values of some properties that realise the highest possible reliability. The selection programme will consider the values of the properties of the ideal material as a reference. The selection will be for the material whose property values are the nearest to the reference imaginary material.

The Fourth Step : The calculations of the solution emphasis coefficient (β) as described in section 1, Chapter III, (digital logic approach):

The calculations start by :

1. Comparing each property value for candidate materials one against the other. Therefore, a table of values referred to for solutions S, of each property (requirement R), are organised in matrix form (Fig. 4.2). If we have (M) number of requirements, where, m = 1,2,3,...m, the matrix which will carry out the comparison is: $SS_m(i,j)$, i = 1,2,3,...K, j = 1,2,3, ...K. The comparison will be calculated using a modified type of the digital logic approach method. Instead of using unity and zero for preference, the property value is divided by the summation of both the two values under comparison, e.g. value A compared with value B, therefore, the comparison solution for A will be $\frac{A}{A+B}$. This method gives more accurate results for the relation between the two values compared, and the matrix will be as follows :

$$SS_m = \begin{array}{c} \\ S_1 \\ S_2 \\ S_3 \\ \vdots \\ S_k \end{array} \begin{array}{c} \begin{array}{cccc} S_1 & S_2 & S_3 & \ldots\ldots S_k \end{array} \\ \begin{bmatrix} 0 & ss(1,2) & ss(1,3) & ss(1,k) \\ ss(2,1) & 0 & ss(2,3) & ss(2,k) \\ ss(3,1) & ss(3,2) & 0 & ss(3,k) \\ \vdots & & & \\ ss(k,1) & ss(k,2) & ss(k,3) & 0 \end{bmatrix} \end{array}$$

Fig. (4.2) Matrix solving for comparisons between solutions

The mathematical formula for the elements of the above matrix is :

$$SS(i,j) = \frac{RS(i,m)}{RS(i,m) + RS(j,m)} \qquad (4.4)$$

and, $SS(j,i) = 1 - SS(i,j)$,

$SS(i,j) = 0$ for $j = i$

The physical meaning of the above matrix is as follows : every single property value, S_1, S_2, S_3.....S_k, is compared with all the other values separately. Thus, each resulting comparison is considered as an element of the matrix i.e. SS(1,2) and SS(2,3), etc. Consequently, each row in the matrix is a comparison of one value against all other values. As seen from the above matrix, the diagonal is zero, as it represents the comparison between each value (solution) with itself, which is equal to zero. This matrix is repeated for every property (requirement).

2. From the previous matrix results, a new matrix (Fig. 4.3) is formed to solve for the solution emphasis coefficient (ß) as follows :

$$\beta_m = \begin{bmatrix} B(1,m) \\ B(2,m) \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ B(k,m) \end{bmatrix}$$

Fig. (4.3) Matrix solving for solution emphasis coefficient (ß) where $\beta(i,m) = \dfrac{\sum_{j=1}^{k} SS(i,j)}{k(k-1)/2}$

The matrix of Fig. (4.3) will give the β values for the solutions of requirement (m), meaning only one requirement.

The previous step is therefore repeated for every requirement 1,2,3,...n.

Now we have an emphasis coefficient for every value for all properties of the candidate materials. Since the relative emphasis coefficient (α) determines the importance of the requirements against each other. Therefore to get a figure of merit (γ) for each property value for a candidate material, the (α) of this requirement is multiplied by the (β) of this property. The summation of all the values of (γ) for a candidate material will give a total figure of merit for this material. The above procedure is calculated in one step using the following relation (4.6).

$$\gamma_i = \sum_{j=1}^{n} \alpha_j \beta(i,j) \qquad (4.6)$$

where: $i = 1 \rightarrow k$, $j = 1 \rightarrow n$

The material with the highest (γ) has the optimum possible requirements.

The computer, with a sorting programme, will order the materials according to their suitability to the required application. The sorting programme uses (γ_r) the relative figure of merit which is :

$$\gamma_r(i) = \frac{\gamma_i \text{ X } 100}{\gamma \text{ Max}} \qquad (4.7)$$

where : γ Max is the highest (γ) of the optimum material

In case of more than one service condition, which necessitates a change in the relative emphasis coefficients (α), another figure of merit (γ') will be calculated such that :

$$\gamma'_i = \sum_{j=1}^{n} \alpha_j \; \beta(i,j) \qquad (4.8)$$

2. Programme Description

The following computation steps describe the programme print out along with the programme system flow chart (4.1) and programme flow chart see Appendix (6).

Steps from counter:

From	To	
27	84	Read and write data called from data bank
86	94	Define the method used (weighting factor or limit on properties)
112	-	Decision needed for, application of cost, reliability, scaling and target values.
124	138	Scaling for target value in case of limit on properties method
148	175	Calculations of cost from subroutine (variable cost and fixed cost items)
183	226	Reliability calculations, 2 subroutines.
232	247	Scaling calculations of property values (subroutine)
248	320	Calculation of (α) emphasis coefficient after entering the preference ratios.
321	401	Calculations of (β) solution emphasis coefficient.
408	444	Calculation of (γ) and (γ_r).
455	553	Limit on properties method of selection.

Subroutine 1:

5	27	Cost subroutine

Subroutine 2:

3	15	Reliability by property grouping (maximum property value).

Subroutine 3:

3 15 Reliability by property grouping

(minimum property value).

Subroutine 4:

4 22 Scaling subroutine.

Subroutine 5:

2 18 Reliability calculations by distribution methods.

Programme - System Flow Chart

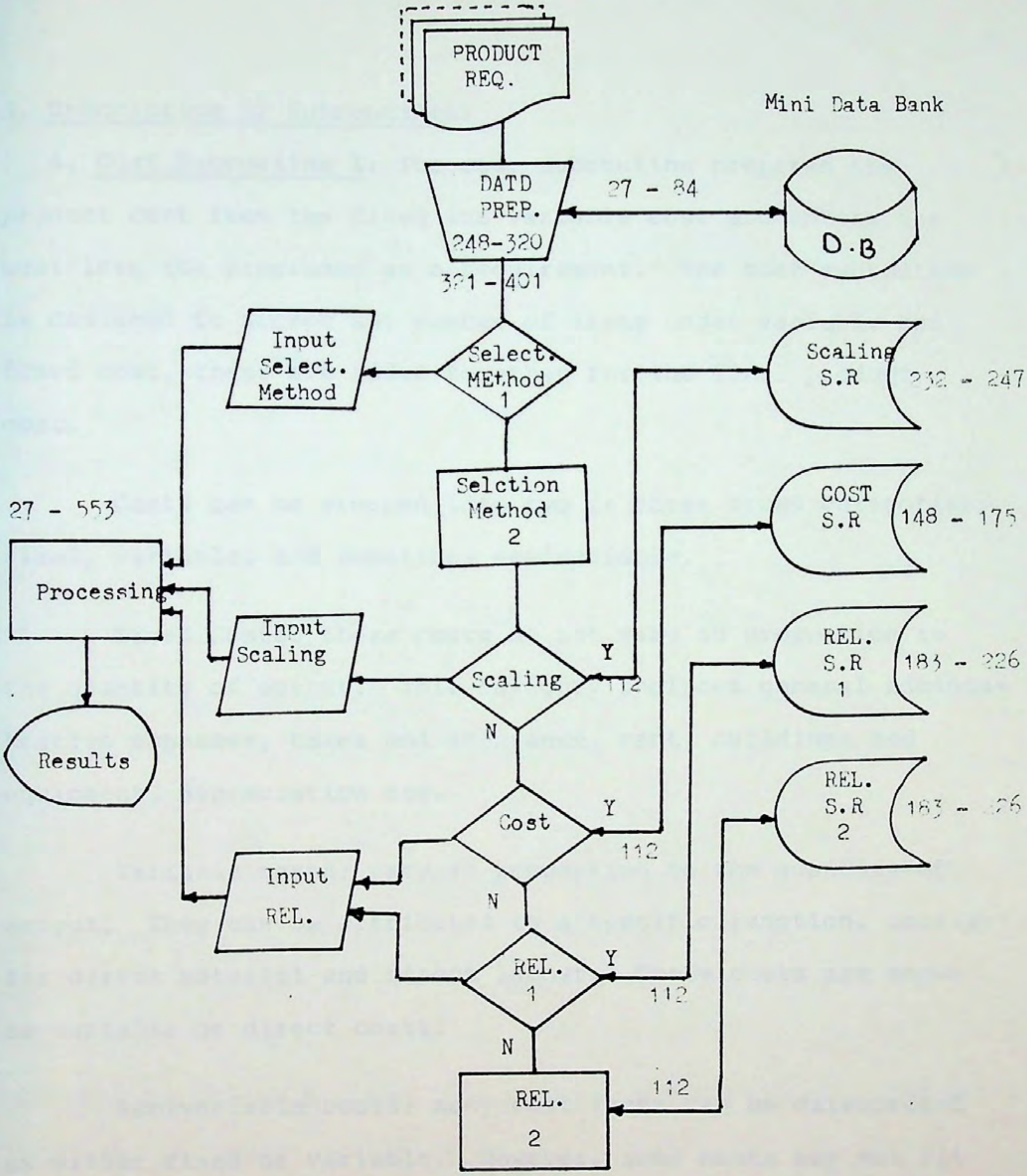

Fig. (4.1)

Programme system flow chart showing the flow of data from the different sources to the processing stage where results are printed.

3. Description of Subroutines:

A. Cost Subroutine 1: The cost subroutine prepares the product cost from the fixed and variable cost and enters the cost into the programme as a requirement. The cost subroutine is designed to accept any number of items under variable and fixed cost, these are added together for the final product cost.

Costs can be grouped into two or three broad categories: fixed, variable, and sometimes semivariable.

Fixed Costs: these costs do not vary in proportion to the quantity of output. This category includes general administrative expenses, taxes and insurance, rent, buildings and equipment, depreciation etc.

Variable costs: vary in proportion to the quantity of output. They can be attributed to a specific function, usually for direct material and direct labour. These costs are known as variable or direct costs.

Semivariable costs: many cost items can be categorised as either fixed or variable. However, some costs may not fit into either of these categories but assume some features of each. These costs are termed as semivariable, and are associated with a firms need to keep a portion of its physical facilities and personnel intact regardless of the level of production. This includes indirect labour, temporary personnel additional administrative expenses necessary to handle heavy work loads. (Farag: 1979, pp. 148-149, and Park: 1973, pp. 120-121).

B. Subroutines 2 and 3 on Reliability by Property Grouping : In case of insufficient data for reliability calculations, reliability is computed by determining the properties that have a pronounced effect on product resistance to failure. Entering the computer with the condition required for each property (high or low). The subroutines will group and scale all the assigned properties of all candidate materials giving 9 to the highest reliability and 1 to the lowest.

C. Scaling Subroutine 4: This performs the scaling described in section (1) Chapter (IV), using the 3 scaling equations (4.1 - 4.3).

D. Reliability Subroutine 5: In case of available data for reliability calculations, the values of random variables, μ and σ are intered into the computer. The subroutines will solve for reliability using the 3 relations in section (1), Chapter (III), (2.2 - 2.4) for normal, log-normal and exponential distributions according to the type of failure. The result is in the form of a reliability requirement and joins the other material requirements in the main selection programme.

CHAPTER V

INDUSTRIAL APPLICATIONS

CHAPTER V

INDUSTRIAL APPLICATIONS

In this chapter, the computerised selection of materials is applied to five examples from industry*. The choice of these examples are deliberately selected to cover different fields of application with different conditions for selection.

The examples are as follows :

1. Selection of material for lathe cutting tool
2. Selection of a material for gas turbine blade
3. Selection of a material for cryogenic vessel
4. Selection of a material for car paint
5. Selection of a material for electrical insulator

The data of the materials used in the five examples were previously stored in the mini data bank Appendix (8). Since there are no available data from service, therefore, tests and simulation to be fed to the computer for the calculation of reliability, the properties that increase the resistence of the component to failure will be grouped and graded as reliability index. Moreover, the subroutine in the selection programme is ready to receive the data and compute them whenever they are available. The cost subroutine can accept any data from various types of costs, compute them and give the final cost requirement. For simplicity, the cost was considered as the end cost of the product.

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* These examples are from: M. Farag: Materials and Process Selection in Engineering, Applied Science Publishers Ltd., Lond, 1979.

Example 1:

A- Selection of Material for Cutting Tools

The designer sends Form 1, stating the requirements needed for cutting tools to perform satisfactorily, these are :

- Functional requirements: tool life, maximum cutting speed, edge toughness, rigidity.
- Processability requirements: heat treatability, possibility of intricate shapes.
- Cost requirements: final tool costs.
- Reliability requirements: resistance to sudden failure and accidental braking.
- Service conditions requirements: resistance to vibrations, mechanical shocks, and thermal shocks.

The selection engineer then translates the performance requirements into the corresponding material properties on the right hand side of the form, deciding on the selection requirements that have the major importance in cutting tool materials such as :

- Room temperature hardness
- High temperature hardness
- Liability to fracture
- Cost

The allocation of weighting factors are then calculated manually in Form 2.

The emphasis coefficients (α) are fed into the computer along with the candidate materials data. The programme then executes the selection process as described previously.

The final results are consistent with those reached by manual calculations, and with what are actually used in industry.

The best material is M 10, followed by M 2, which are the most widely used types of high speed steels. In the second condition where high rates of metal removal is in process, alumina was leading the ceramics, followed by sintered carbides, group one and group eight.

Proposed Product Requirements

Form 1

Component No.: *001*

Component Name: *Cutting tool for lathe* Date:

To be filled by						To be filled by: *Selection Engineer*				
Requirements	Performance Req.	Req. values (if any)*				Material Req.	Selection Req.	Service Conditions	Corresponding property	Statu
		Value	t	u	L					
1- Functional	*- Tool life* *- Max. cutting speed* *- Edge toughness* *- Rigidity*					*Room temp. hardness* *High temp. hardness* *Toughness* *Young's Modulus*	*-R.T Hardness* *-H temp. "* *-Toughness* *-Liability to fracture* *-Cost*	*1-Workpiece has a rough surfaces hard inclusions* *2-High rate of metal removal*	*-Toughness* *-Hardness*	*(1)* *(1)*
2- Processability	*- Heat treatability* *- Possibility of intricate shapes*					*Hardenability* *Dimensional changes* *Formability* *grindability*				
3- Cost	*- Final tool cost*					*Material cost* *processing cost*				
6- Reliability	*- Resistance to sudden failure and accidental braking*					*Toughness* *Homoginity*				
7- Service Conditions	*- Vibrations* *- Mechanical shocks* *- Thermal shocks*					*Toughness, Y.m* *Toughness* *Thermal conductivity* *Ductility*				

* t = target value u = upper limit L = lower limit

Form 2

Component no. 001 Component name: Cutting tool for lathe Condition No. 1

Condition: Requirements	Number of decisions										positive decisions	Relative emphasis coefficient
	1	2	3	4	5	6	7	8	9	10		
Room temp	0.5	0	0	1							1.5	0.15
High temp.	0.5				0	1	1				2.5	0.25
Toughness		1			1			1	1		4	0.40
Liability to fracture			1			0		0		0	1.0	0.10
Cost				0			0		0	1	1.0	0.10

<u>Form 2</u>

Component no. 001   Component name: Cutting tool for lathe   Condition No. 2

Condition:

Requirements	Number of decisions 1	2	3	4	5	6	7	8	9	10	positive decisions	Relative emphasis coefficient
Room temp	0	0.5	1	1							2.5	0.25
High temp.	1				1	1	1				4.0	0.40
Toughness		0.5			0			1	0		1.5	0.15
Liability to fracture			0			0		0		1	1.0	0.10
Cost				0			0		1	0	1.0	0.10

Example 2

B- Selection of Material for Gas Turbine Blade (High temperature application)

Turbines are widely used in many fields, such as air craft jet engines, power stations, gas pumps and for propelling ships etc.

The compressor, compression chamber, shaft and turbine of the gas turbine are the major parts of the engine. The turbine may be designed to have many stages. Usually the first two are for high pressure and the rest are for low pressure. Since the engine converts the thermal energy of the combustion into mechanical energy, therefore, the turbine is the device which executes the conversion. During the conversion process, the turbine blades are subjected to very high temperatures which can exceed 1600K. The highest efficiency is reached when the temperature of the turbine material approaches gas temperature. Selection of material that can resist high temperatures, the design of better internal cooling system, the use of coatings to protect against corrosion and high temperatures will increase the efficiency of the turbine blade.

Serivce conditions

Turbine blades operate under severe conditions. The blades are always attacked by :

- Corrosion caused by the gases of combustion.
- Oxidation as excess O_2 and sulpher in combustion gases along with high temperatures are oxidizing media.
- Very high stresses that reach 100 - 160 MN/m^2.
- High temperatures that might exceed 1600K.
- Thermal shock and thermal fatigue due to the usual start and stop of the engine which cause strain in the blades.

Data Preparation

Data were prepared following the same procedure in examples 1 and 2 for the relative emphasis coefficients and form 1 was filled and the computer run was executed. The results were very satisfactory and coincide with what is actually widely used in industry. The material preference was as follows :

Material	Preference
Udimet 700	The optimum solution
Nimonic 115	The second or alternative material
MAR-M 246	The third
713C	The fourth

Udimet 700 proved to be the best material for gas turbine blades.

Proposed Product Requirements

Form 1

Component No.: *002* | Component Name: *Turbine blade* | Date:

To be filled by *Designer*						To be filled by: *Selection Engineer*				
Requirements	Performance Req.	Req. values (if any)* Value	t	u	L	Material Req.	Selection Req.	Service Conditions	Corresponding property	Statu
1- Functional	*.Blade Life .Light weight .Rigidity .High Temp. Performance*					*.Specific gravity .% elongation & rupture .High temp. strength .High temp. fatigue*	*1-Specific strength 2-Specific rupture strength 3-Oxidation resistance 4-High temp. fatigue resistance 5- Cost*	*. High temp. . Vibrations . Thermal shocks . High cyclic stresses . Corrosion & oxidation environment*	*.High temp. strength .High temp. fatigue .High temp. fatigue resistance .Rupture strength . Coating*	*High High High High -*
2- Processability	*.Possibility of internal channels .Machinability .Extrusionability .Formability .Castability*					*.Forging .Extrusion .Precision casting .Directional solidification*				
3- Cost	*Final blade cost + surface coating*					*.Material cost +Processing cost*				
4- Reliability	*.Sudden failure .blade rubbing*					*.Homogenity of structure .Stresses*				
5- Service conditions	*.Resistance to - High temp. - Vibrations - Thermal shocks - High cyclic stresses - Corrosion - Oxidation*	*<1600 K*				*.High temp. strength . " " rupture " . High temp. fatigue . High temp. strength . Corrosion resistance . Oxidation resistance*				

* t = target value u = upper limit L = lower limit

Form 2

omponent No. 002   Component name: Gas turbine blade   Condition No. 1

Requirements	Number of possible decisions										positive decisions	Relative emphasis coefficient
	1	2	3	4	5	6	7	8	9	10		
Specific strength	0.5	0.5	0.5	0.5							2.0	0.20
Specific rupture strength	0.5				0.7	0.5	1				2.7	0.27
Oxidation resistance		0.5			0.3			0	0.9		1.7	0.17
Thermal fatigue resistance			0.5			0.5		1		0.3	2.3	0.23
Cost				0.5			0		0.1	0.3	0.9	0.09

Example 3

C- Selection of Materials for Low Temperature Applications

Low temperature in a broad sense could mean refrigeration and cryogenic. The range of temperature for each one of them is not yet clearly defined. Cryogenic temperature can be considered below 123K or - 150°. Material selection for low temperature application, especially cryogenic components, is a very difficult process. A large number of conflicting conditions and requirements must be taken into consideration. Usually, the solution of selection is arrived at by a great deal of compromises between requirements.

The cryogene equipment failure may lead to extensive hazards. The properties of component materials may be greatly affected by the cryogenic fluids or liquid gases that are often manipulated by the system. The leakage of the cryogenic fluids due to system failure is very harmful if not fatal to human lives. Therefore, utmost care must be taken to perfect the design along with high safety specifications.

It should always be kept in mind that cryogenic fluids exhibit an increase in pressure when the temperature increases, therefore, pressure release values must be fixed to the containers.

If the internal stresses are increased during the cooling process due to thermal gradients, the room temperature strength is more suitable for design than low temperature strength.

The vessel for storing or transporting cryogenic fluids in the present example is of the insulated type. The selection will be for a material suitable for cryogenic fluids with a temperature of 77K. A light weight portable vessel is required. The material selected must be tough in order to avoid accidental breakage during transportation.

The emphasis coefficient was determined as previously described using the digital logic approach. The values entered the computer as follows :

Requirement	Weighting factor
1. Toughess	0.22
2. Room temperature yield strength	0.15
3. Room temperature Young's Modulus	0.11
4. Specific gravity	0.11
5. Thermal expansion coefficient	0.11
6. Thermal conductivity	0.11
7. Specific heat	0.08
8. Cost	0.11

Candidate materials are graded by the selection programme and the results are given as :

Material	Preference
1. 301 (full hard) stainless steel	1
2. 310 (75% cold worked) stainless steel	2
3. Inconel X-750 super alloy	3
4. Inconel 718 super alloy	4

Stainless steel 301 full hard steel is the optimum solution for manufacturing a cryogenic vessel.

Proposed Product Requirements

Form 1

Component No.: *003* | Component Name: *Cryogin Vessel* | Date:

To be filled by *Design*						To be filled by:				
Requirements	Performance Req.	Req. values (if any)* Value	t	u	L	Material Req.	Selection Req.	Service Conditions	Corresponding property	Status
1- Function	*- Light weight* *- Rigidity*					*Specific gravity* *Toughness*	*1-Toughness* *2-R.T yield strength* *3-R.T Y.M.* *4-Specific gravity* *5-Thermal expansion coefficient* *6-Thermal conductivity* *7-Specific heat* *8-Cost*	*- Vessel is subjected to shocks*	*-Low temp. toughness index* $= TI = \frac{UTS+Y}{2}^{**} \times \varepsilon$	*High*
2- Processability	*- Possibility of manufacturing from welded sheets*					*- Bending* *- Weldability* *- Machinability*				
3- Cost	*- Cost of finished product*					*- Material cost* *+ processing cost*				
4- Reliability	*- Resistance to shocks and accidental braking*					*- Toughness* *- Structure and hemogenity*				
5- Service conditions	*- Low temperature* *- Thermal gradient* *- Mechanical shocks*	*77K* *RT→77K*				*- Low temp. ductility* *- Coefficient of expansion* *- Thermal conductivity* *- Toughness*				

* t = target value   u = upper limit   L = lower limit

** *UTS = Ultimate tensile strength*   *Y = Yield at 77K*
ε = elongation at 77K

Example 4

D- Selection of Materials for Protective Coating

Protective coatings are widely used either to provide the product with an environment resistant layer to protect it against corrosion and deterioration, or to give it an attractive appearance. Coatings vary according to the techniques used. Additive coatings are paints, lacquers, varnishes and plating. Anodizing, sheradizing and diffusion coatings are applied either by thermal, electrochemical or mechanical methods and are called conversion finishes.

The most important requirement in coating materials is strong adhesion to the surface of the product. Therefore, cleaning surfaces before applying the coating layer is a must. Many chemical, water base solvents, acids, even ultrasonic vibrations are used to clean the surfaces. For drying the coatings, controlled temperature and humidity are sufficient.

Form 1 shows the requirements for an organic coating for motor car bodies. Weighting factors are calculated by the computer step 284, after entering the relative importance values of the requirement which is carried out manually. The weighting factors are as follows :

Requirements	Weighting factor
1. Cost	0.10
2. Abrasion resistance	0.10
3. Flexibility	0.07
4. Adhesion	0.20
5. Resistance to atmosphere (salt spray)	0.15
6. Exterior durability	0.20
7. Colour retention	0.15
8. Resistance to chemicals	0.03
9. Maximum service temperature	0.00

A modification was made in the present example to test for the flexibility of the programme. Instead of entering the candidate materials properties values, a grade was given to each property value according to its suitability for the application. The grades were calculated with a separate operation on the computer (on-line storage) and stored in the Mini Data Bank (Appendix 8).

The grades were as follows :

Property grade	Property suitability for application
3	Excellent
2	Very good - Good - Fair
1	Fair
0	Poor

The optimum material was found to be acrylic which possess the optimum property values with a reasonable cost (very good, grade 2) followed by urethane and neoprane as second choice, PVF and PV2 are the third choice.

Proposed Product Requirements

Form 1

Component No.: *004* Component Name: *Motor car organic paint* Date: /12/85

To be filled by *Designer*						To be filled by: *Selection Engineer*				
Requirements	Performance Req.	Req. values (if any)* Value	t	u	L	Material Req.	Selection Req.	Service Conditions	Corresponding property	Status
1- Functional	*1-Protection against corrosion and oxidation, abrasive and wear* *2- Electrical and thermal insulation* *3- Surface appearance*					*1- Abrasion resistance* *2- Flexibility* *3- Adhesion* *4- External durability* *5- Colour retention* *6- Resistance to atmosphere* *7- Resistance to chemicals* *8- Maximum service temperature* *9- Cost*		*- High temp.* *- Corrosive atmosphere* *- Strong light (sun)* *- Corrosive chemicals* *- Subject to scraches & rubbing*	*- Resistance to service temp.* *- Resistance to atmos-phere* *- Colour retention* *- Resistance to chemicals (salt) (and general)*	*High* *High* *High* *High*
2- Processab-ility	*4- Adhesion* *- Spraying* *- Dipping*									
3- Cost	*Final cost of finished specific product*									
4- Reliability	*- Possibility of mechanical damage* *- Blistering* *- Softening, dis-couling*									
5- Service conditions	*- Salty atmosphere* *- Chemical "* *- High surface temperature*									

* t = target value u = upper limit L = lower limit

Example 5

E- Selection of Materials for Electrical Insulation

Electrical insulation necessitates a very high resistance to flow of electric current. There are various types of materials that can be used as insulators. The best suitable material is that which exhibits good thermal, mechanical and chemical properties.

The functions of the insulators are numerous, and depend on the requirements. The present example represents the selection of materials suitable for the following applications :

1- Airospace system, which necessitates that the insulator will endure the severe service conditions of high temperature caused by the aircraft engine.
2- Computer cables, where the conducting material is flexible flat aluminum cable.

For airospace system conditions, the operating temperature expected is 450 K. The insulating material should withstand mechanical stresses not less than 42 MN/m^2. Light weight is needed with a maximum allowable specific gravity of 3. Thermal expansion coefficient is a target value of 2.3×10^{-5}. The requirements of the designer for dielectric constant is less than 10 at 60 Hz, minimum dielectric strength 6 volts/mil, minimum volume resistance 10^{12} ohm/cm and dissipation factor 0.1 max. at 60 Hz.

For computer cable application, flexibility is important as the cable might be folded through an angle of 180^{o}. Service temperature will not exceed 350K. The lowest cost is required. Dielectric strength should be greater than 100 and volume resistivity greater than 10^{12}. The dielectric constant should be less than 3.5, and the dissipation factor should be less than 0.01 to avoid excessive heating when cables come close to each other. Light weight is a requirement therefore the specific gravity of the insulator should be less than 2.5. Thermal coefficient of expansion has a target value of 2.3×10^{-5} K. Elongation percent should be greater than 50% for the material to endure bending of the cable. According to the above received data form 1 was filled.

The selection will be from organic bulk insulating materials, which are polymeric in nature.

The limit on properties method will be used to select the best four materials suitable for the above applications under the two mentioned conditions.

The requirements were classified as follows :

1- Dielectric constant: upper limit for high voltage application and lower limit for capacitors.

2- Dielectric strength: low limit property.

3- Resistivity - lower limit property.

4- Dissipation factor - upper limit property.

5- Maximum operating temperature - lower limit property.

6- Tensile strength - lower limit property.

7- Elongation percent - lower limit property.

8- Impact resistance - lower limit property

9- Thermal expansion - target value property.

10- Specific gravity - upper limit property

11- Cost - upper limit property.

The weighting factors for electrical material properties were calculated for the two service conditions following the same procedure in example 1, 2. The weighting were as follows :

Property	Airospace condition 1	Computer, condition 2
- Dielectric constant	0.12	0.08
- Dielectric strength	0.15	0.13
- Volume resistivity	0.15	0.13
- Dissipation factor	0.10	0.10
- Maximum operating temp.	0.16	0.07
- Tensile strength	0.08	0.07
- Elongation percent	-	0.11
- Specific gravity	0.16	0.10
- Thermal expansion coefficient	0.08	0.08
- Cost	-	0.13

Form 1 was filled, a form for each service condition. The selection programme resulted in the following :

Materials which did not meet the requirements were rejected by the selection programme.

For airospace cable insulator the material which came first was fused silica, the second polysulphone followed by melamine and procelain. The fused silica is difficult to process therefore polysulphone is the alternative optimum solution.

For computer flat cable insulator, polyphenylene oxide came first followed by polypropylene, polysulphone and ETFE. The materials which were rejected do not fulfillthe flexibility or maximum service temperature requirements for computer cable application.

The optimum materials in both cases satisfied the design requirements with the minimum possible cost.

Proposed Product Requirements

Form 1

Component No.: 005 Component Name: Insulating material Date:

To be filled by Designer						To be filled by: Selection Engineer				
Requirements	Performance Req.	Req. values (if any)* Value	t	u	L	Material Req.	Selection Req.	Service Conditions [1]	Corresponding property	Status
1 - Functional	*insulation properties *heat resistance *flexibility *light weight	10 at 60 Hz min. 6V/mil 10^{12} ohm/cm max. .1at60Hz max450k 42 MN/m^2 – 3 2.[illegible] X 10^{-5}	 ✓	✓ ✓ ✓	 ✓ ✓ ✓ ✓	dielectric loss resistivity flashover creepage distance tracking tensile strength specific gravity	dielectric const. ,, ,,strength volume resistivity dissipation factor max. operating temp. tensile strength elongation % specific gravity thermal expantion coefficient cost	* high temp. * high stress	*max. operating temp. *tensile strength	high high
2 - Processability	*ability of shaping in the required form	–								
3 - Cost	* final cost	–				reasonable cost				
4 - Reliability	* sudden failure by: - flashover - tracking - shrinkage - heat shocks - embrittlement - gas evolution					acuired by sound processing	–			
5 - Service cond.	- high temp. - high stresses					–	as above	–	as above	

* t = target value u = upper limit L = lower limit

Proposed Product Requirements

Form 1

Component No.: 005

Component Name: Computer Cable Insulation mat. Date:

To be filled by Designer						To be filled by: Selection Engineer				
Requirements	Performance Req.	Req. values (if any)* Value	t	u	L	Material Req.	Selection Req.	Service Conditions 2	Corresponding property	Status
1- Functional	*insulation properties	3.5			✓	dielectric loss	dielectric const.	*high stress	*tensile	high
	* flexibility	100			✓	resistivity	,, ,, strength	*sever bend-	strength	
	* light weight	10^{12}			✓	flashover	volume resist.	ing	*expantion coef.	high
	* resists severe	0.01		✓		creepage distance	dissipation	*Space	*dielectric	high
	bending					tracking	factor	limitation	strength, vol.	
		max. 350K			✓	tensile strength	max. operating		resistivity	high
						specific gravity	temp.			
		-					tensile strength			
		50%			✓		elongation			
2- Processability	* Ability of shaping	less than 2.5			✓		specific grav.			
	in the required	2.3 $\times 10^{-5}$ K	✓				thermal expan-tion coefficient			
	form									
		lowest		✓			cost			
3- Cost	final cost									
4- Reliability	* failure by sever bending * embrittlement * shrinkage * cracks									
5- Service cond.	* severe bending * closely stacked					low dissipation factor	dissipation factor			
						high tensile strength	tensile strength	-	-	

* t = target value u = upper limit L = lower limit

CHAPTER VI

CONCLUSION AND RECOMMENDATIONS

CHAPTER VI

CONCLUSION AND RECOMMENDATIONS

The material available on materials selection and reliability is very limited. This is possibly due to the newness of the field. On the other hand, the literature on computer use for selection of materials is oriented towards specific products, such as, components of nuclear reactors, space systems and their components, electronic components etc.

Inspite of the drawbacks faced in the limited number of references and research material available on the subject, it can be concluded that the use of the computer and general computer programme in the analysis and selection of materials as tested on the four examples from industry proved to be successful and advantageous.

The use of manual calculations, extremely small differences between material property values could not be detected. However, the computerised programme differentiated between the smallest fraction of material property values. Thus, the devised computer programme results, using the double precision method - 8 decimals - were extremely accurate, in comparison with the conventional methods.

The accuracy of utilising the computer screen auditing, facilitates the continuous checking of the results and the convenience to enter or delate any requirement not planned before.

In cases of numerous and conflicting requirements, manual calculations are tedious, time and cost consuming, and often result in inaccuracies that do not present the actual preference order of the candiate materials. The computerised programme deals with the computations with speed, efficiency, lower cost etc., especially when faced with time limitations.

Computerisation in industry has many advantages. It is advisable to make full use of the capabilities and efficiencies of the computer. This of course relies basically on good systems analysis and programme design, without which the machine is ineffective and inefficient.

Computerised selection and reliability process requires software support, such as, mathematics packages to deal with reliability data distributions. Failure analysis can also be converted to computer software packages. Failure examination results can be entered into the computer, which in turn will designate the failure type as well as the preventive and protective solutions.

The establishment of a Data Bank containing classified data related to material composition, properties, processing, cost etc., is essential. This is costly in the short run, but in the long run it can prove to be vital, especially, when a country like Egypt is in the process of expanding its industrial base. The availability of such information is not only time saving but also necessary to facilitate accurate decision making. The know how in selection of materials is expensive, and in many cases not available. Industries consider this type of information as industrial classified data especially for strategic production.

It is recommended that further research should be directed towards the selection of materials for a complete system instead of for individual components using the multi-programming techniques and treating reliability for all the components as a whole. Moreover, the maintenance should be included in the programme as a result of failure analysis, which can predict the preventive measures, therefore, preventive and protective maintenance.

The need for new selection methods based on new mathematical approaches such as the weighting factor method and limit on properties method still depend on human skills and experience. The determination of the emphasis coefficient, which may differ from one selection engineer to another, have their effects on the results.

A similar programme can be devised to control the composition of alloys according to their required properties.

A programme for processing techniques and costs is vital. Processing costs in many cases are higher than the cost of the material itself. The computer programme can compute numerous processing methods/costs and give the ideal and least expensive machines involved in the processing of the product, on the basis of time required for each component of the product.

In conclusion it is recommended that further research is encouraged and directed towards the full utilisation of computer capabilities in the areas of material selection, failure problems, processing and all other aspects of industrial applications that can prove to be time and cost saving, as well as, result in greater efficiency and accuracy.

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BIBLIOGRAPHY

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APPENDICES

APPENDIX (1)

Probability Distrubution Curves

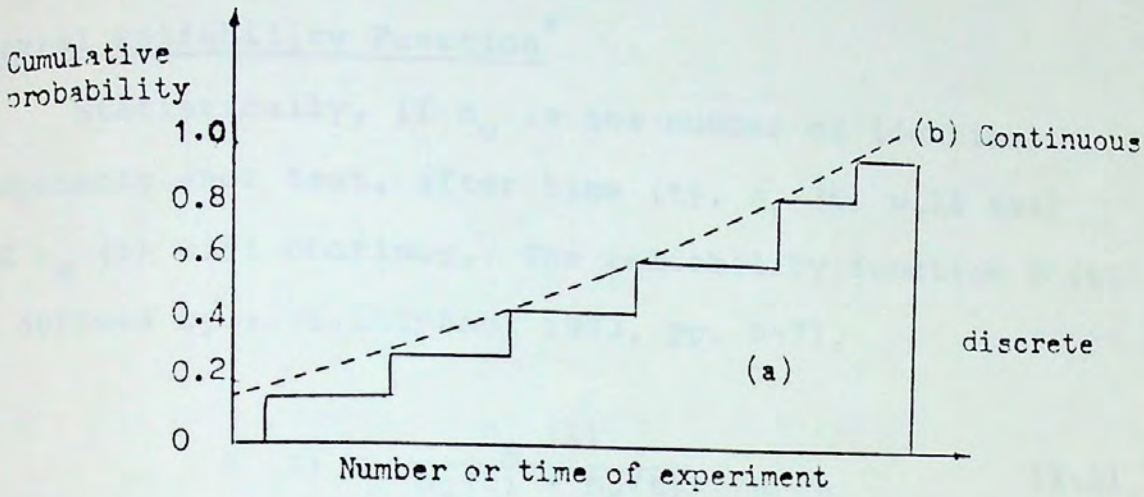

fig. (1)
a) Cumulative probabilities of random variable
b) Continuous probabilities of random variable

The previously mentioned type of distribution (Section 5, Chapter 2) is used only with discrete random variable events. For continuous random variables the probability function is a continuous curve that begins from zero distribution and ends at unity and the steps in the discrete random variable plot disappears (Fig. 1). The probability density function f(t) can be deduced simply by differentiating the probability distribution function F(X) of a continuous random variable (Kurtz: 1984, pp. 2-77 to 2-123).

APPENDIX (2)

General Reliability Function*

Statistically, if n_o is the number of identical components uner test, after time (t), n_f (t) will fail and n_s (t) will continue. The reliability function R (t) is defined by : (Billinton: 1983, pp. 6-7).

$$R(t) = \frac{n_s(t)}{n_s(t) + n_f(t)} \quad (2.1)$$

Since

$$n_s(t) + n_f(t) = n_o$$

The equation becomes

$$R(t) = \frac{n_s(t)}{n_o} \quad (2.2)$$

Since

$$R(t) + f(t) = 1 \quad (2.3)$$

Where f (t) is the failure probability at time (t)

$$f(t) = 1 - \frac{n_s(t)}{n_o}$$

$$f(t) = 1 - \left(\frac{n_o - n_{f(t)}}{n_o}\right) = \frac{n_f(t)}{n_o} \quad (2.4)$$

* Data obtained from product service life, tests and simulations.

using this relation in (2.3) we get :

$$R(t) = 1 - f(t) = 1 - \frac{n_f(t)}{n_o} \qquad (2.5)$$

deriving (2.4) w.r.t. time

$$\frac{dR(t)}{dt} = \frac{1}{n_o} \quad \frac{dn_f(t)}{dt} \qquad (2.6)$$

as dt approaches zero (2,4) is the instantaneous failure density function f(t), that is : (Green and Bourne: 1972, pp. 65-72, and Billinton: 1983, pp. 124-130).

$$\frac{1}{n_o} \quad \frac{dn_f(t)}{dt} \rightarrow f(t)$$

Therefore, expression (2.5) becomes

$$\frac{dR(t)}{dt} = - f(t) \qquad (2.7)$$

by using relation (2.2) the other form of (2.6) may be written as :

$$\frac{dn_f(t)}{dt} = - n_o \quad \frac{dR(t)}{dt} \quad \frac{dn_s(t)}{dt} \qquad (2.8)$$

<u>Instantaneous failure or Hazard rate $\lambda(t)$</u>

The hazard rate is the measure of the rate at which the failures occur, and is dependent on the number of failures in a specified interval of time, and the number of components under test.

Dividing both sides of equation (2.7) by $n_s(t)$ we get :

$$\frac{1}{n_s(t)} \quad \frac{dn_f(t)}{dt} = -\frac{n_o dR(t)}{n_s(t)dt} \qquad (2.9)$$

which is equal to the hazard rate $\lambda(t)$

Substituting (2.2) and (2.6) into (2.8). The hazard rate will be :

$$\lambda(t) = -\frac{1}{R(t)} \frac{dR(t)}{dt} = \frac{f(t)}{R(t)} \qquad (2.10)$$

Rewriting the above equation to get the reliability function on one side and the hazard rate on the other side, the expression becomes : (Kurtz: 1984, pp. 2.257-2.262).

$$-\frac{dR(t)}{R(t)} = \lambda(t)\ dt \qquad (2.11)$$

Integrating both sides over time 0 to t we get :

$$\int_o^t \lambda(t)\ dt = -\int_1^{R(t)} \frac{1}{R(t)}\ dR(t)$$

at t = o, R(t) = 1 it becomes :

$$Ln\ R(t) = -\int_o^t \lambda(t)\ dt \qquad (2.12)$$

APPENDIX (3)

The Normal Distribution Method

The normal distribution is the most widely used method, especially in reliability applications, sometimes referred to as Gausian Distribution.

One of the significant features of normal distribution is that the probability density function curve is symmetrical about the mean value (μ) and the dispersion about the mean value (μ) is evaluated by the standard deviation (σ). Therefore, the shape and the position of the density function f(t) can be determined by the mean value (μ) and the standard deviation (σ) only. (Dhillon: 1981, pp. 13, 151).

The probability density function f(t) of normal distribution, and indicating that for a continuous distribution the probability density function is :

$$\int_{-\infty}^{t} f(t)\,dt = 1$$

therefore :

$$f(t) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{t} \exp\left[-\frac{(t-\mu)^2}{2\sigma^2}\right] dt = 1 \qquad (1)$$

this means that the area under the curve between $-\infty$ and ∞ must include all the possible values of the random variable t on the x axis, and consequently equals unity. Due to the difficulty of solving the above integral, substitution of the entity $\frac{t - \mu}{\sigma}$ to be equal to a new random variable (z) considering the mean value (μ) to be zero and the standard deviation (σ) equals unity to create a standard curve. The new relation therefore becomes:

$$f(z) = \frac{1}{\sqrt{2\pi}} \exp \left[- \frac{z^2}{2} \right] \qquad (2)$$

The area under the curve of density function can be easily obtained for any values of (μ) and (σ) from constructed tables calculated for a large range of possible limits using the computer. These tables are stored in the mini data bank whose contents are shown in Appencix (8). Figure (1) shows a standard normal density function curve, and the standard deviation (σ) obtained from tables around the mean value (μ). The total area under the curve within the limits of $\pm$ 3σ is equal to 0.9972 which is close to unity, and

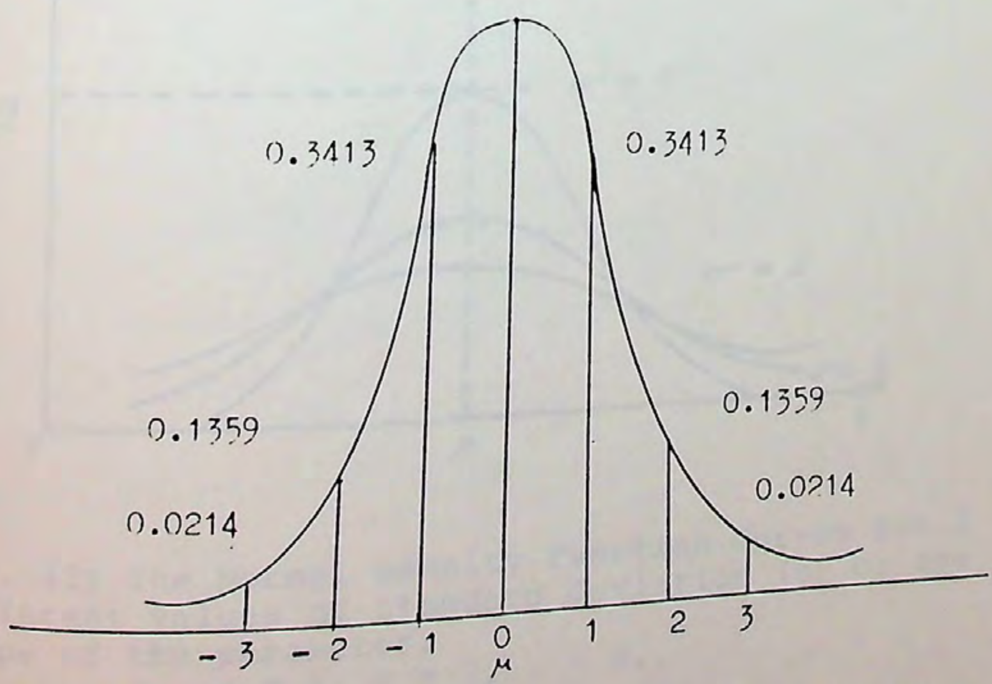

Fig. (1) Standard Normal Density Curve
The dispersion of the random variable values around the mean value (μ) between $\pm$ 1-3 (σ) characteristic of normal distribution.

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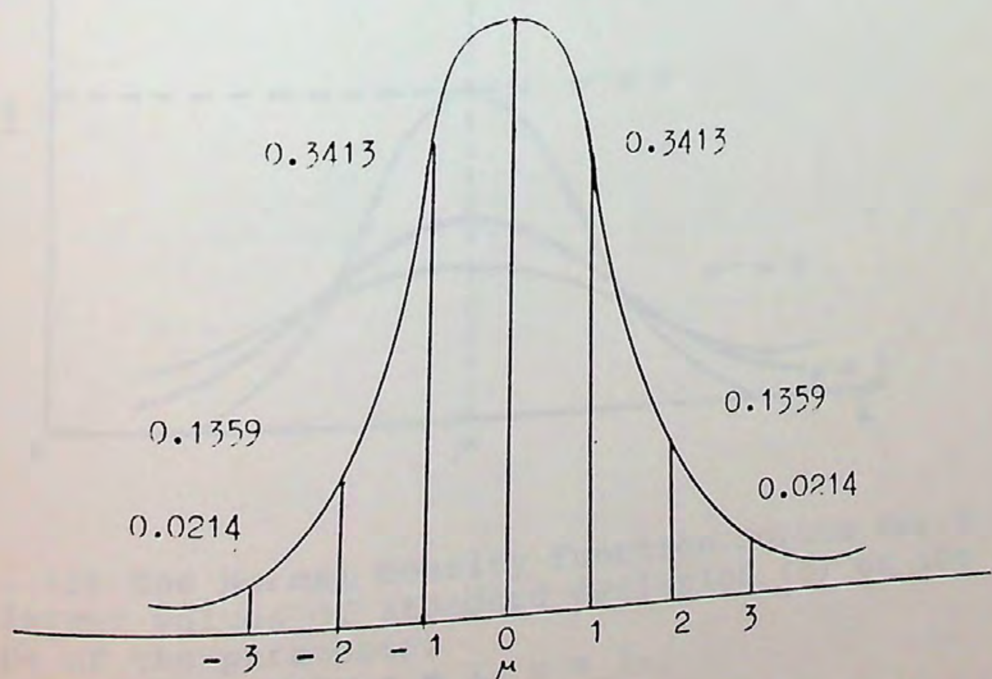


Fig. (1) Standard Normal Density Curve
The dispersion of the random variable values around the mean value (μ) between $\pm$ 1-3 (σ) characteristic of normal distribution.

therefore the probability that the random variable is outside the limits of the curve is very small and could be ignored. For this reason the standard deviation of $\pm$ 3 is usually used as limits with normal distribution and is considered as a confidence limit.

Figure (2) shows the normal density function curves for a given (μ) and 3 values of (σ), notice the dispersion about the mean (μ) and the shape of the curve for different values of (σ). Since (μ) determines the location of the curve on the (x) axis it is called the scale parameter, while (σ) determines the shape of the curve, therefore it is defined as the shape parameter (Billinton: 1983, p. 144).

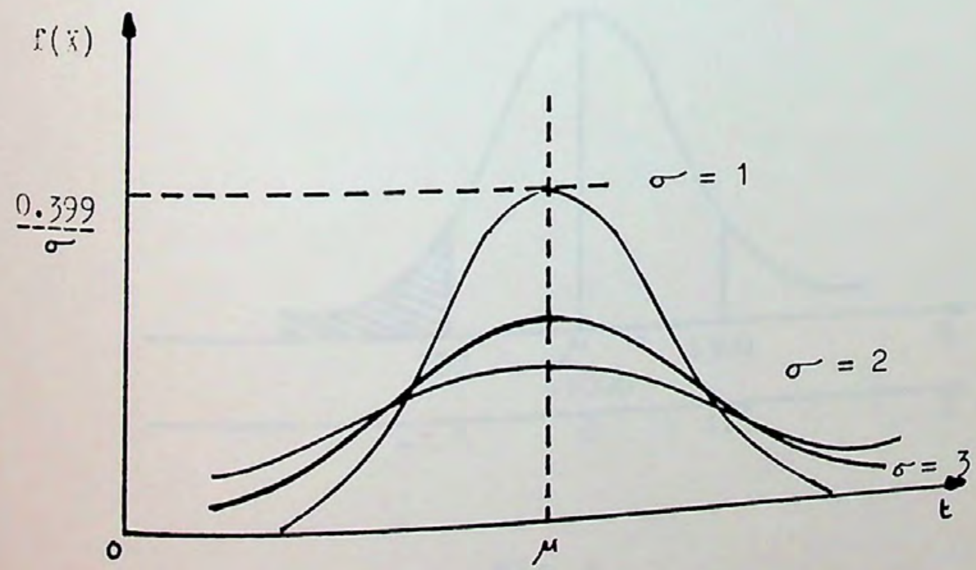


Fig. (2) The Normal Density Function Curves for 3 different values of standard deviation (σ) or the shape of the parameter.
$\sigma = 1$, $\sigma = 2$, $\sigma = 3$.

APPENDIX (3) cont.

Example on the Evaluation of Probabilities By the Normal Distribution

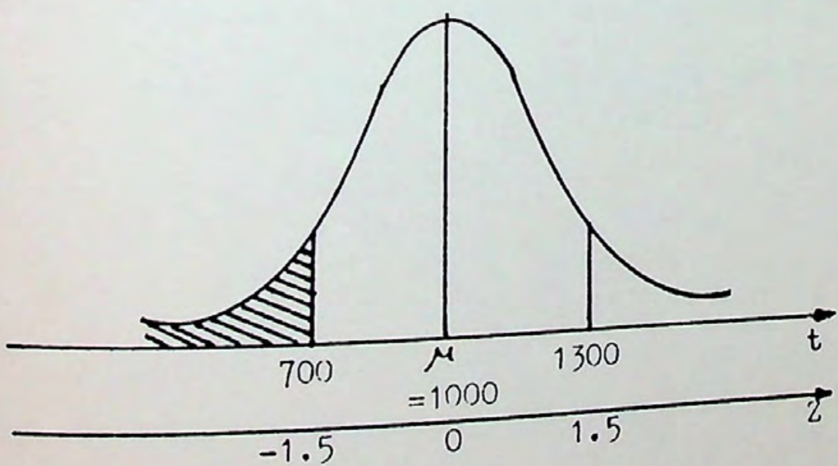
Assume that there are 2000 electric fuses in a power station control panel, which have an average life of 1000 burning hours, with a standard deviation (σ) of 200 hours. How many fuses are expected to burn in the first 700 burning hours.

Solution

From the probability density function curve, and where:

$(\mu) = 1000$ and $(\sigma) = 200$

the cross hatched area represents the required probability.



applying equation $Z = \frac{x - \mu}{\sigma}$

$$\therefore \quad Z = \frac{700-1000}{200} = 1.5$$

From the tables stored in the mini data bank (Appendix 8), the area is :

$$= 0.5 - 0.4332 = 0.0668$$

applying the polynomial approximation (Sympson's rule) for Z > 0, therefore, the required area

$$Q(Z) = Y\,|b_1t + b_2t^2 + b_3t^3 + b_bt^4 + b_5t^5| + e(Z)$$

$$Q(1.5) = 0.0668$$

therefore $Q(-1.5) = 0.0668$

and the expected number of failures = 2000 X 0.0668 = 133.6

= 134 fuses.

APPENDIX (4)

Mean Value of Statistical Data (μ)

After compiling the data from tests and simulation, it is necessary to analyse the data. The value of the variable that can be considered as representative of the whole set of values is referred to as the average value. The mean is the most frequently used average. Assume that the set of data consists of values $V_1, V_2, V_3, \ldots V_n$ and $f_1, f_2, f_3 \ldots f_k$ are the frequencies of occurrence of these values. Therefore, the mean will be :

$$\mu = \frac{f_1V_1 + f_2V_2 + f_3V_3 \ldots f_kV_n}{n}$$

where, n is the number of values.

Standard Deviation (σ)

The standard deviation is the widely used measure of dispersion. It represents the deviations of the individual events about the mean of these values and is given by :

$$\sigma = \frac{\sqrt{(V-\mu)}^2}{N}$$

where :

σ = standard deviation

V = values of the observations

N = total number of observations

μ = arithmatic mean

(Kurtz : 1984, p. 2.40)

APPENDIX (4) cont.

The Log Normal Distribution

The log normal distribution is a modified version of the normal distribution. Although it is not suited for predicting the life time of a product component, but it is useful in predicting the probability density function of the hazard rate and the reliability of components that are liable to fail by fatigue cracks. The log normal distribution, therefore, is best suited for component repair times and becomes an important distribution in the assessment of repairable systems. (Gross : 1975, p. 18)

The failure density function is therefore :

$$f(t) = \frac{1}{t\ \sigma\ \sqrt{2\ \pi}}\ \exp\ \left[\frac{(\ln t\ -\ \mu)^2}{2\ \sigma^2}\right] \qquad (1)$$

as seen from the equation, the difference between the normal and the log normal distribution lies in the random variable (t) which has a log normal distribution with the parameters μ and σ if ln(t) is normally distributed with parameters μ and σ. It should be emphasised that, even the values of μ and σ are the mean value and the standard deviation, respectively of ln(t) they are not μ and σ of (t). The above equation is simplified as in normal distribution by substituting lnt-μ/σ by z, and following the same procedure to reach the equation (2), Appendix (3). The expected value (E(t)) instead of mean value, and standard deviation of the log normal distribution are obtained by the following relations:

$$E(t) = \exp\left(\mu + \tfrac{1}{2}\sigma^2\right) \tag{2}$$

and the standard deviation = $\left[\exp(2\mu+2\sigma^2) - \exp(2\mu+\sigma^2)\right]^{\frac{1}{2}}$ (3)

It is clear from the previous equations that the mean value (μ) and standard deviation (σ) of the log normal distribution differ from those of the normal distribution as they have an exponential behaviour, Fig. (1), shows the shapes of the probability density function, the cumulative failure distribution and the hazard rate function of the log normal distribution (Billinton: 1983, pp. 163-164).

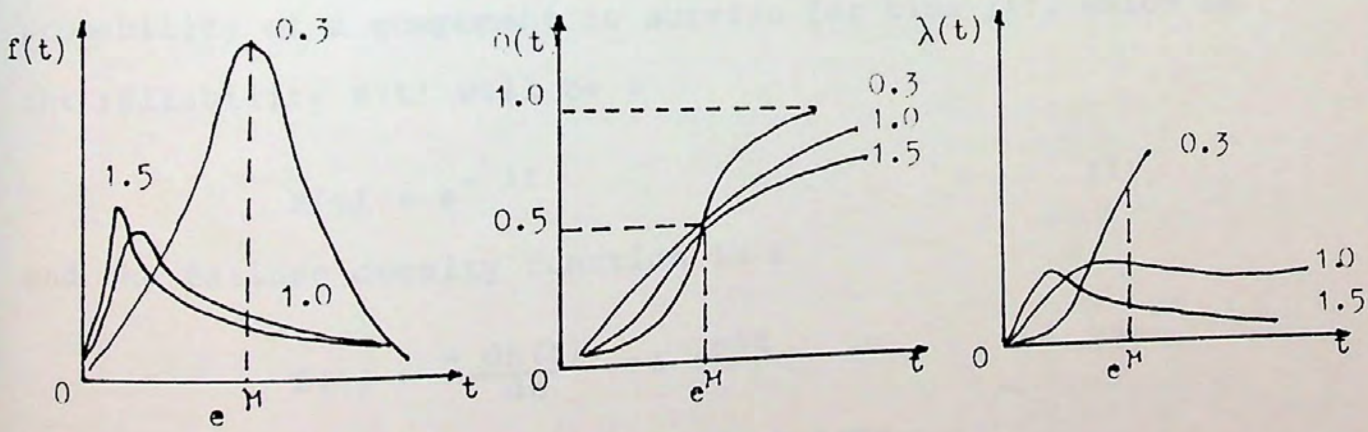


fig. 1

a) Probability density function f(t)

b) Cumulative failure distribution Q(t)

c) Failure or hazard rate λ(t)

APPENDIX (5)

Exponential Distribution

The exponential or the negative exponential distribution is the most widely used distribution in the reliability evaluation field. The most significant feature of this distribution is the constant failure rate (λ).

The exponential distribution can be safely considered as a special case of the Weibull and gamma distributions and the negative exponential distribution is a special case of the poisson distribution (Green and Bourne: 1972, p. 537).

The exponential distribution is valid only in evaluating the useful life or the operating period of a component. Therefore, if the hazard (failure) rate is constant, the probability of a component to survive for time (t), which is the reliability R(t) will be :

$$R(t) = e^{-\lambda t} \quad (1)$$

and the failure density function is :

$$f(t) = \frac{-\,dR(t)}{dt} = \lambda\, e^{-\lambda t} \quad (2)$$

where λ is the time dependent failure rate.

Figure (1) shows the exponential reliability functions. The cumulative failure distribution Q(t), is the area under the curve (a) from zero to t, while the reliability is the rest of the area after (t). Curve (b) is the failure density function in which the expected value of the continuous random variable = $1/\lambda$ similarly the standard deviation for the exponential distribution σ will also equal $1/\lambda$ as seen in curve (c), the constant failure rate which is the significant feature of the exponential distribution curve (d). (Kurtz: 1984, pp. 116-120, and Billinton: 1983, pp. 149-153).

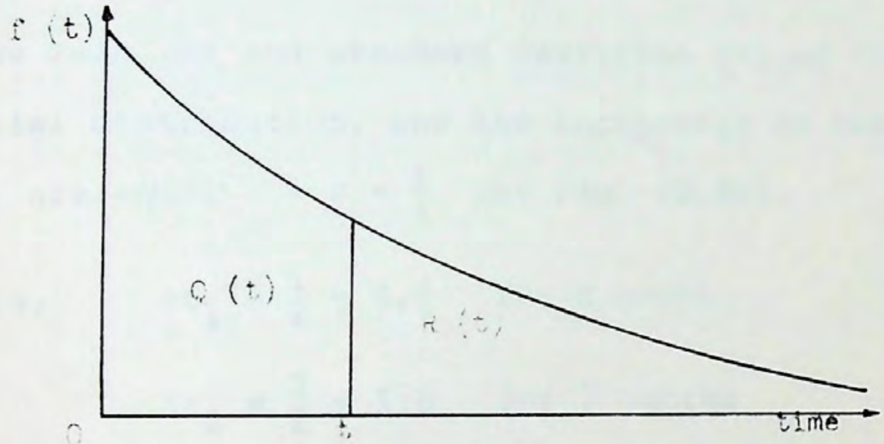
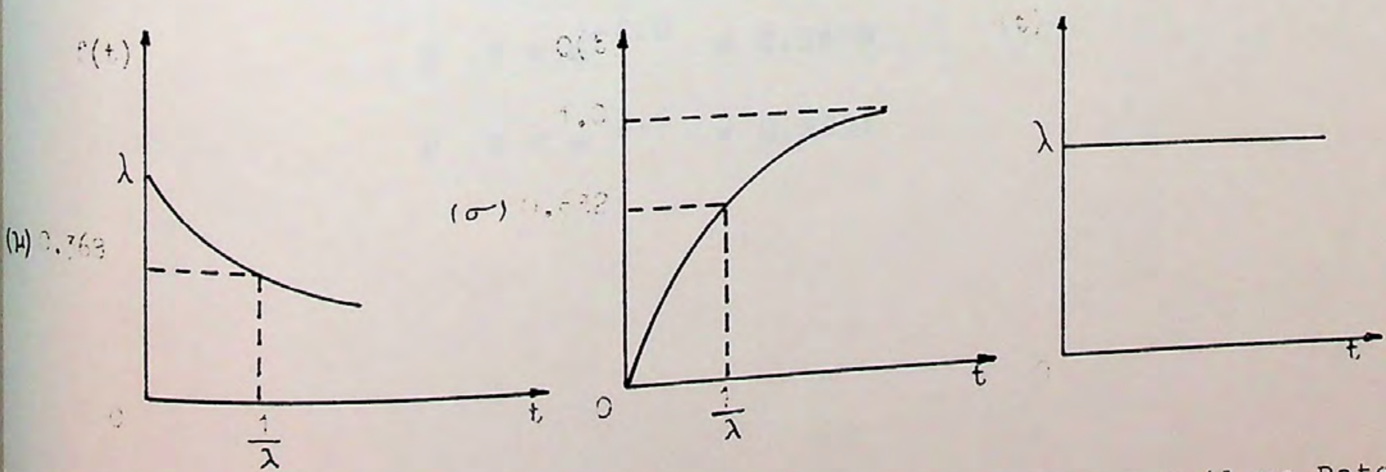


fig. 1

(a) The Exponential Nature of Reliability Function vs. Time of Exponential Distribution.
Area Q(t) is the cumulative Failure Distribution
Area R(t) is the Reliability of the Product from time (t)



(b) & (c) Mean value (μ) = the standard deviation (σ) = $1/\lambda$ (the Reciprocal of Fatigue Rate).

(d) Constant Failure Rate Characteristic of Exponential Distribution.

APPENDIX (5) cont.

Example on the Negative Exponential Distribution

Assume the mean life span of a machine component that operates continuously, is 2 months. The component has a negative exponential distribution. Find: the probability (p) that life span will exceed, 1 month, 2 months, 3 months.

Solution:

The mean (μ) and standard deviation (σ) of the negative exponential distribution, and the reciprocal of the failure rate ($\frac{1}{\lambda}$) are equal $= \sigma = \frac{1}{\lambda}$ see Fig. (2.8c).

Therefore, $\lambda t_1 = \frac{1}{2} = 0.5$ for 1 month

$\lambda t_2 = \frac{2}{2} = 1.0$ for 2 months

$\lambda t_3 = \frac{3}{2} = 1.5$ for 3 months

using equation (2) the probabilities are :

$$P\ 1 = e^{-0.5} = 0.6065$$

$$P\ 2 = e^{-1.0} = 0.3679$$

$$P\ 3 = e^{-1.5} = 0.2231$$

The previous study was built on the following assumptions:

1- The component operates continuously until it fails. The component life span is the period between start operating and failure.

2- The failure occurs instantaneously, and therefore the component life span has a specified value.

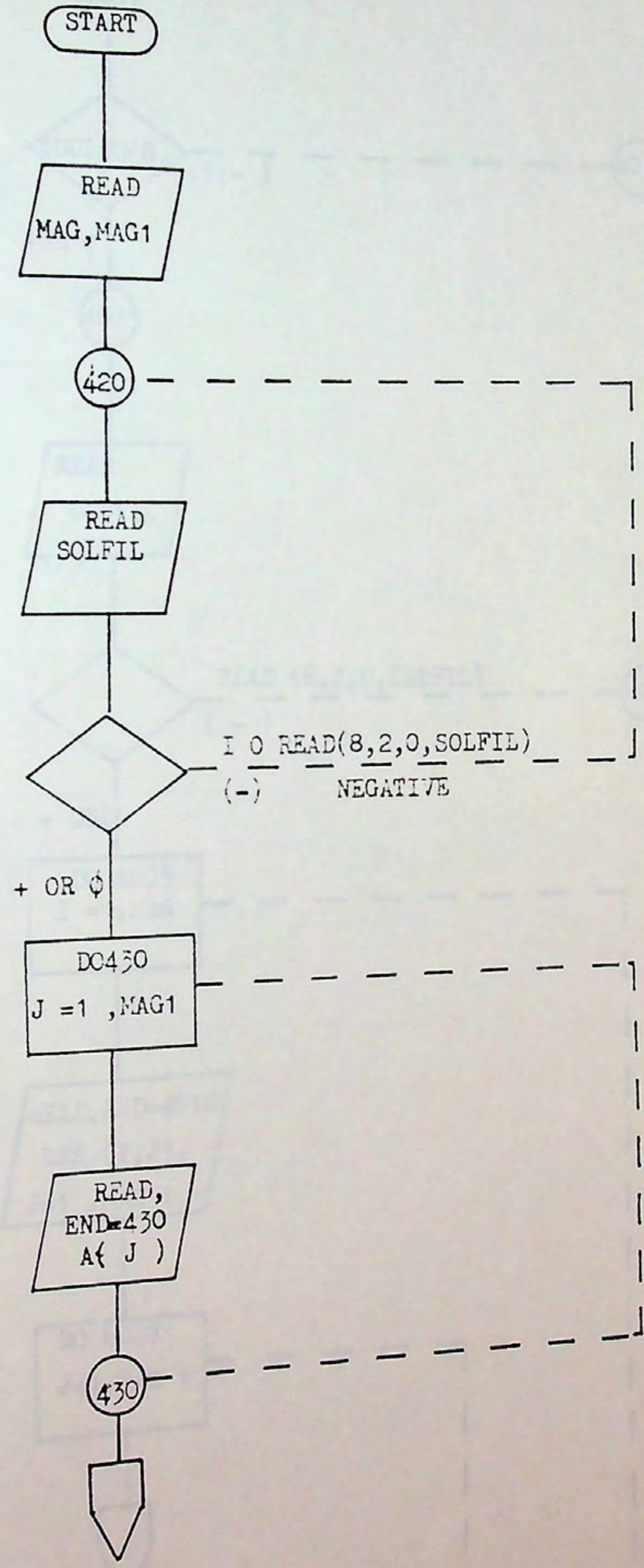
3- No defects are considered in the component, and it is expected to operate directly when activated.

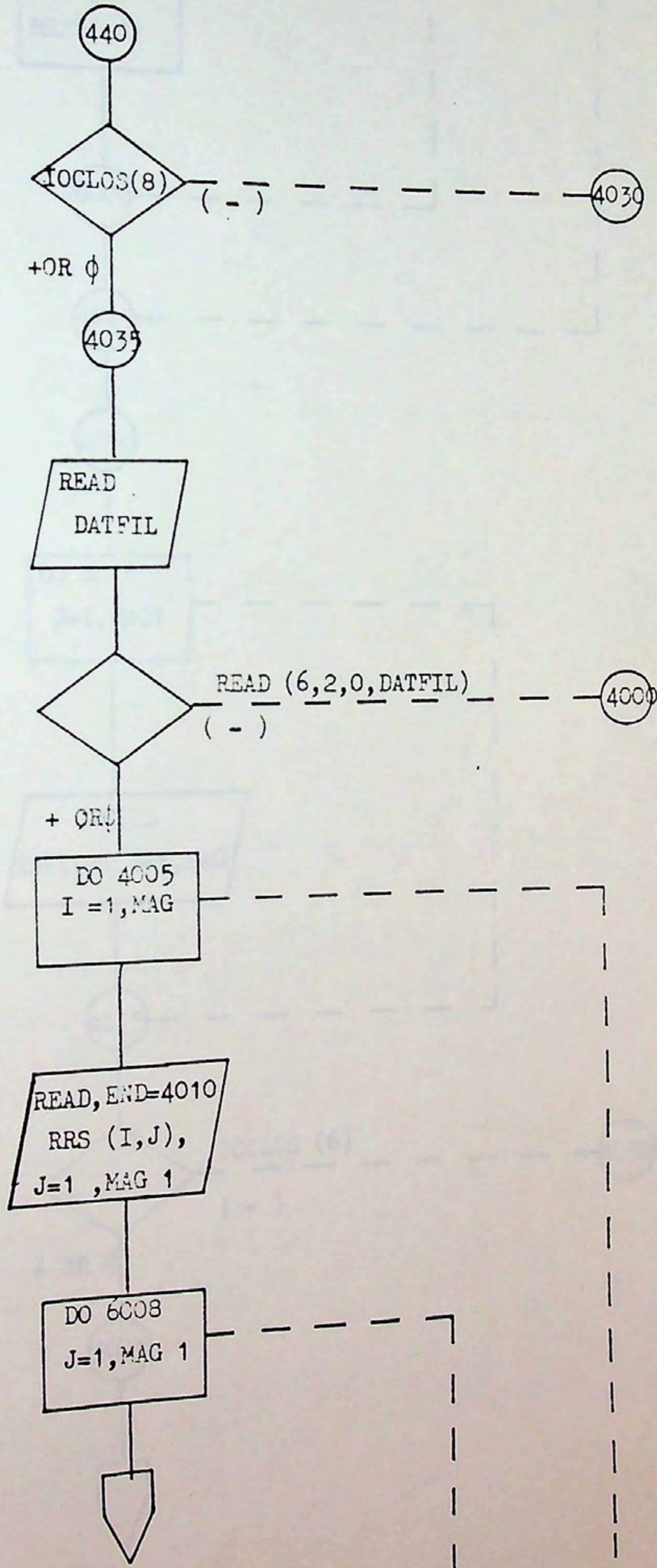
4- The life span of the component will never have a zero value however small this value is.

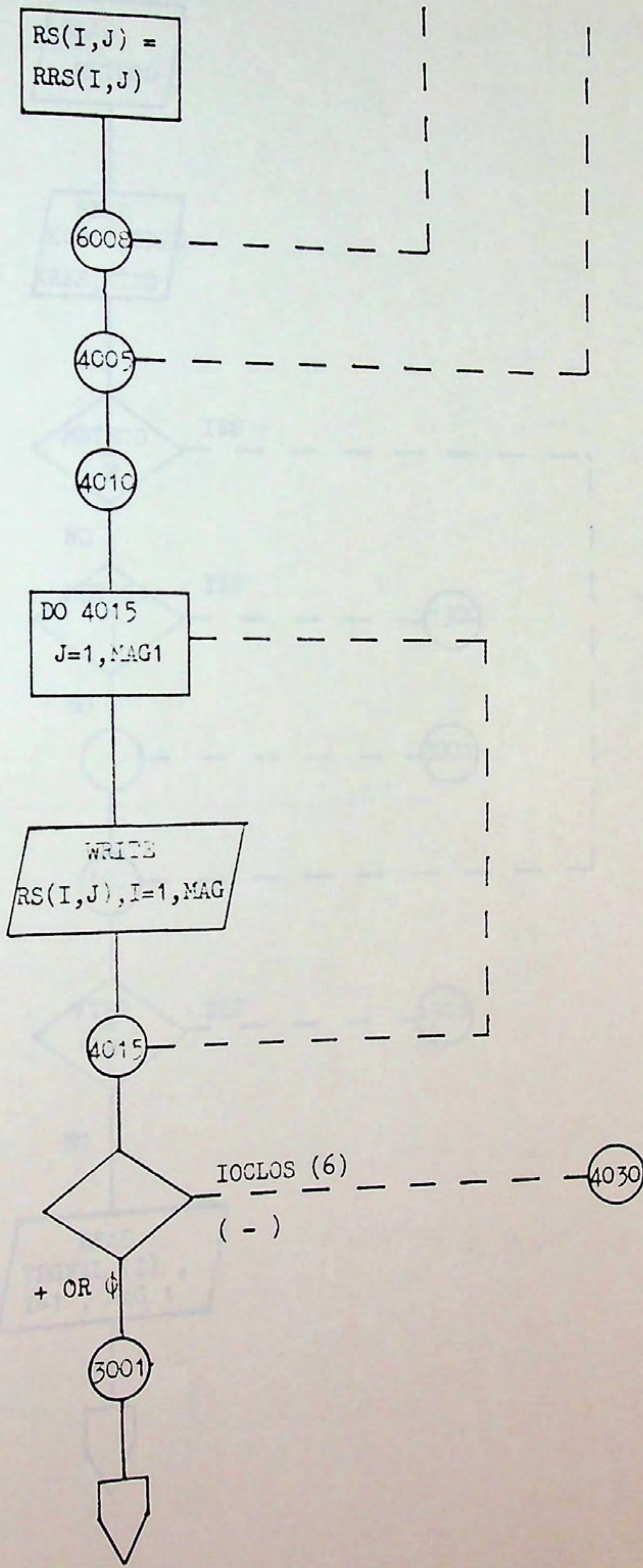
Experience proved that no two identical systems have the same life span even when they operate under the same conditions of load and temperature. The variations result from unavoidable differences in manufacture that are unpredictable. These differences affect the strength of the system/component. Consequently the life span of a system is continuous random variable, thus it cannot be predicted with accuracy, and it can be assigned a probability distribution on the bases of past results.

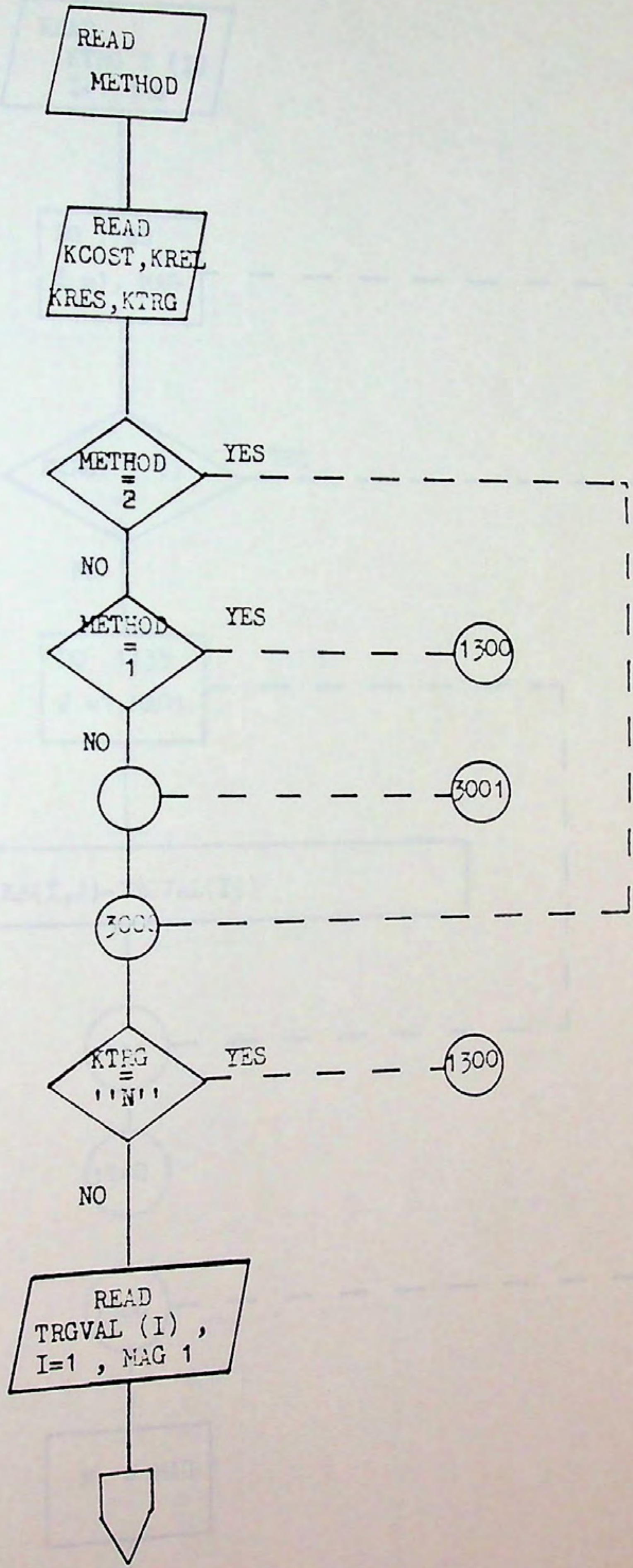
Appendix (6)

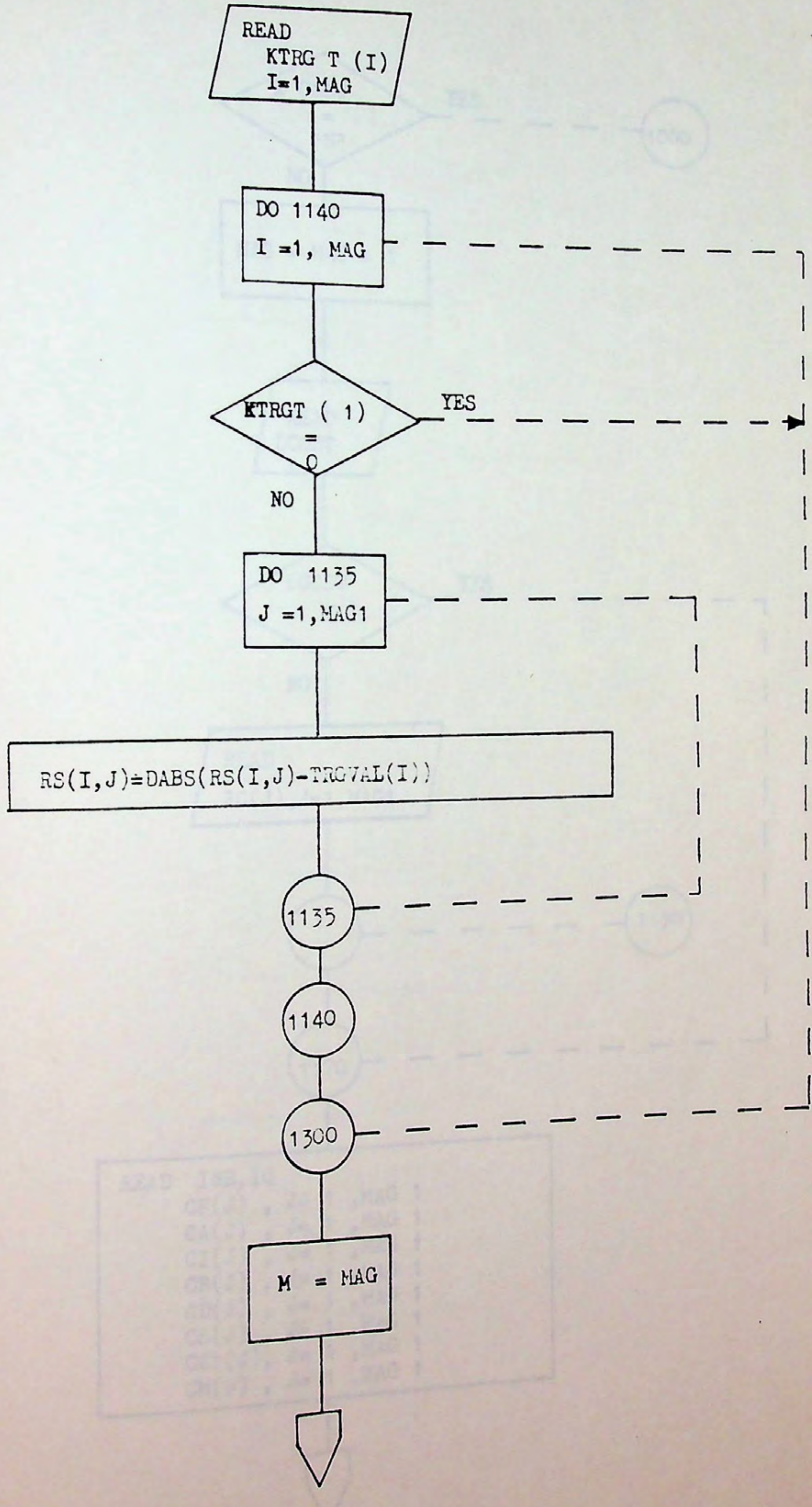
Programme Flow Chart.

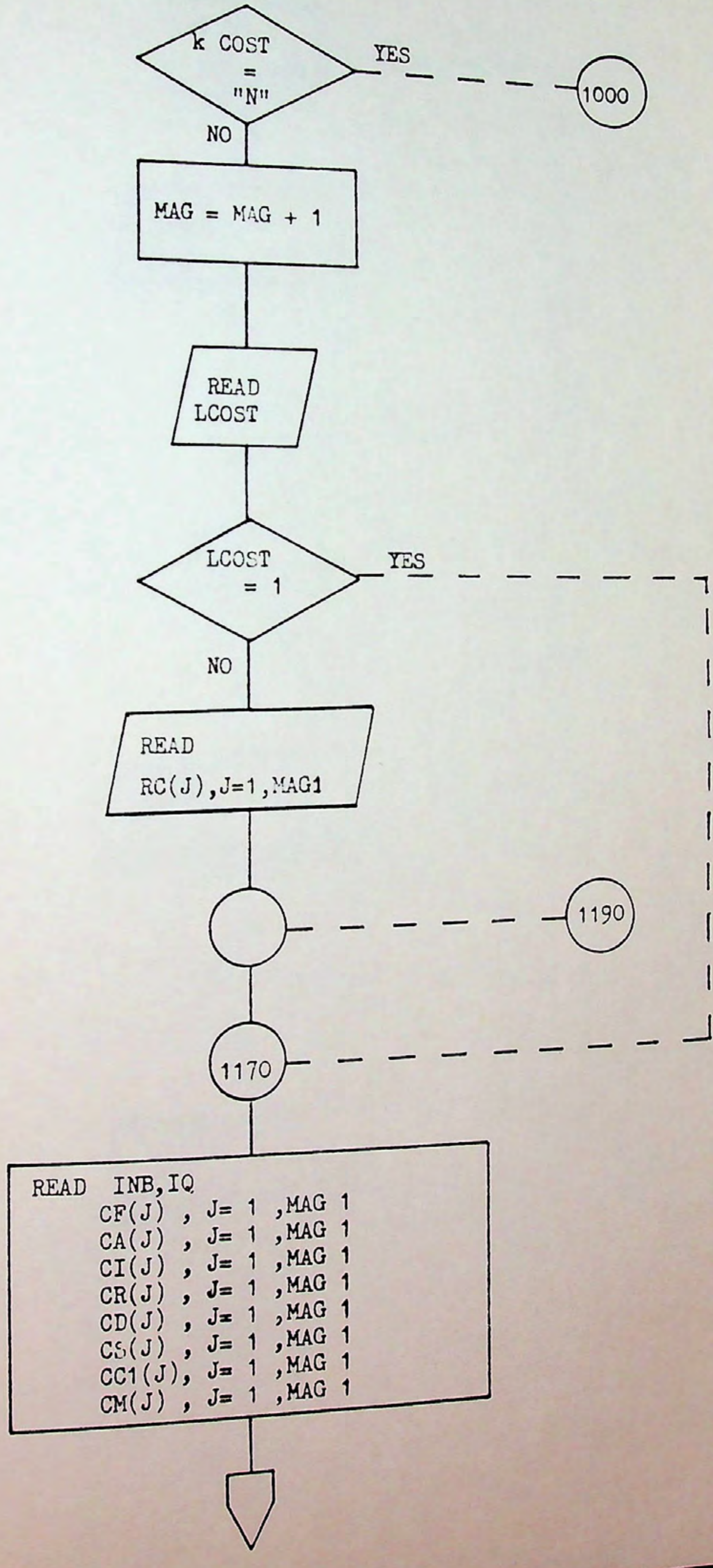



440
IOCLOS(8)
(-)
4030
+OR ϕ
4035
READ
DATFIL
READ (6,2,0,DATFIL)
(-)
4000
+ ORϕ
DO 4005
I =1,MAG
READ,END=4010
RRS (I,J),
J=1 ,MAG 1
DO 6008
J=1,MAG 1

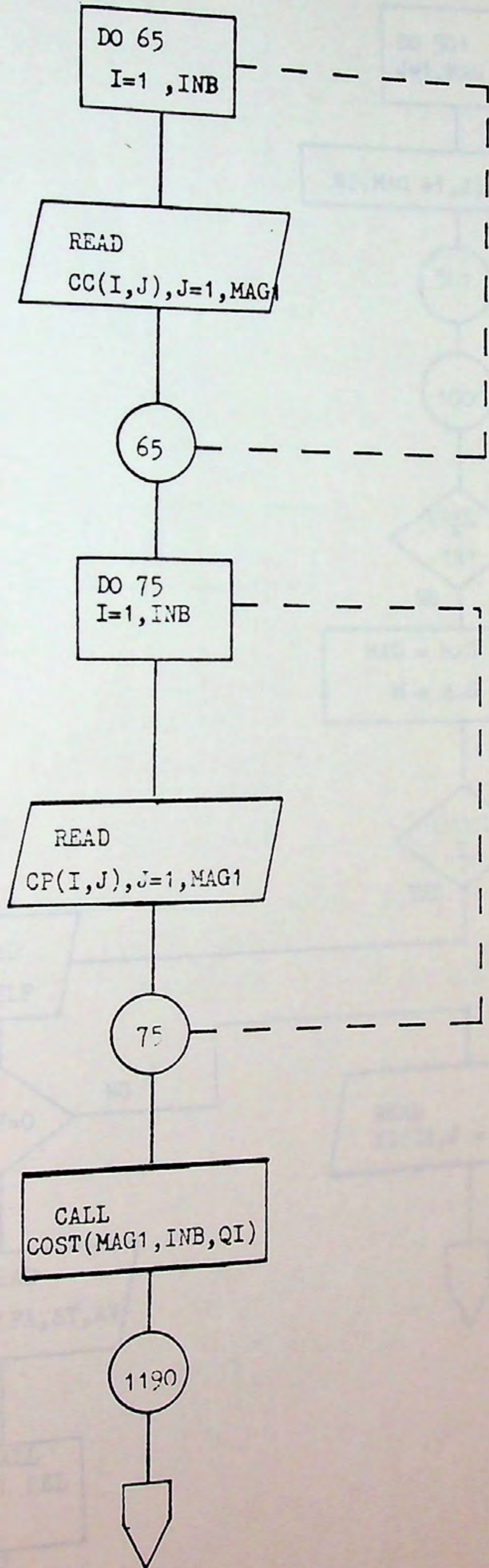

RS(I,J) =
RRS(I,J)
6008
4005
4010
DO 4015
J=1,MAG1
WRITE
RS(I,J),I=1,MAG
4015
IOCLOS (6)
(-)
4030
+ OR ¢
3001

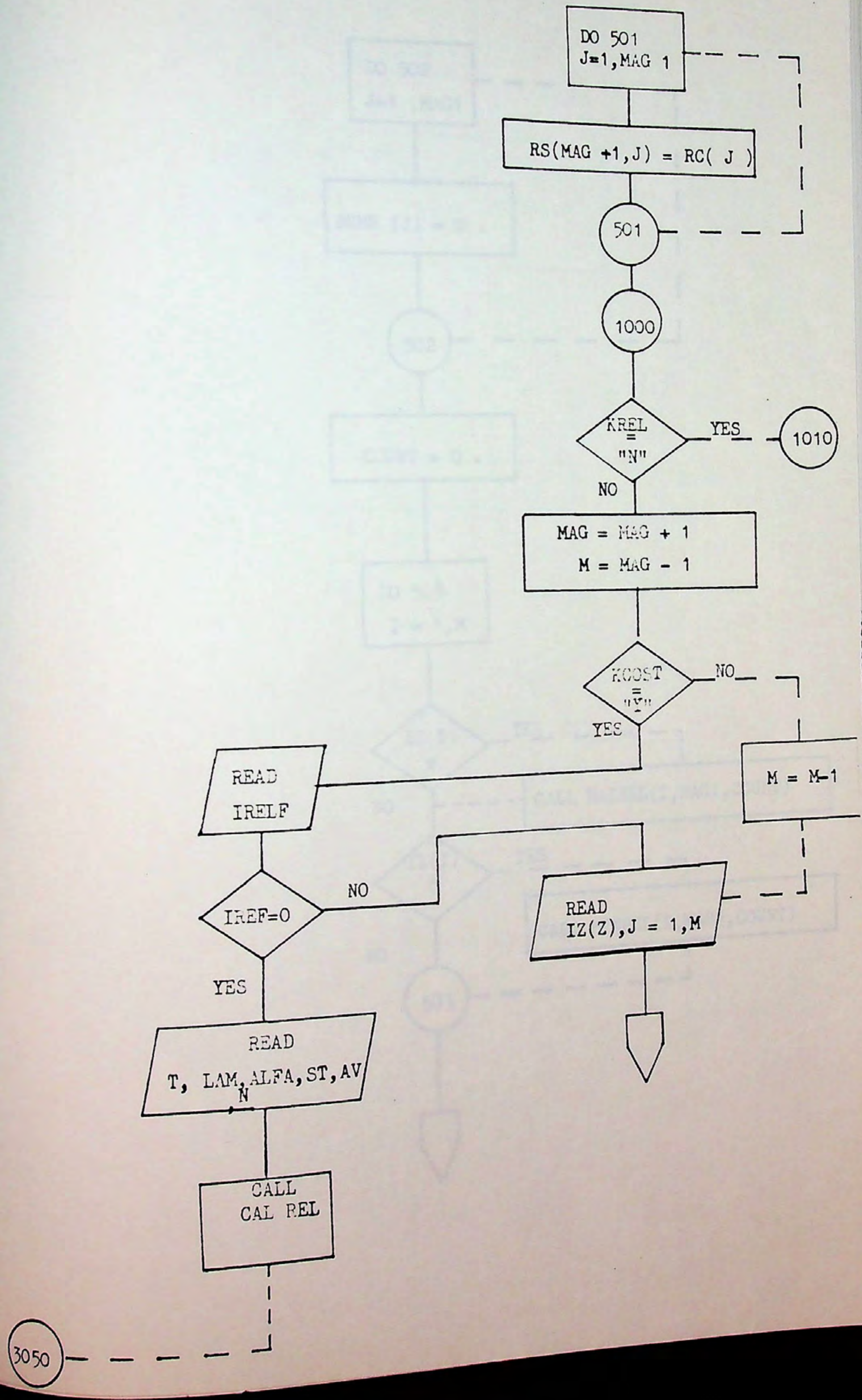

READ
METHOD
READ
KCOST,KREL
KRES,KTRG
METHOD
=
2
YES
NO
METHOD
=
1
YES
1300
NO
3001
3000
KTRG
=
''N''
YES
1300
NO
READ
TRGVAL (I) ,
I=1 , MAG 1

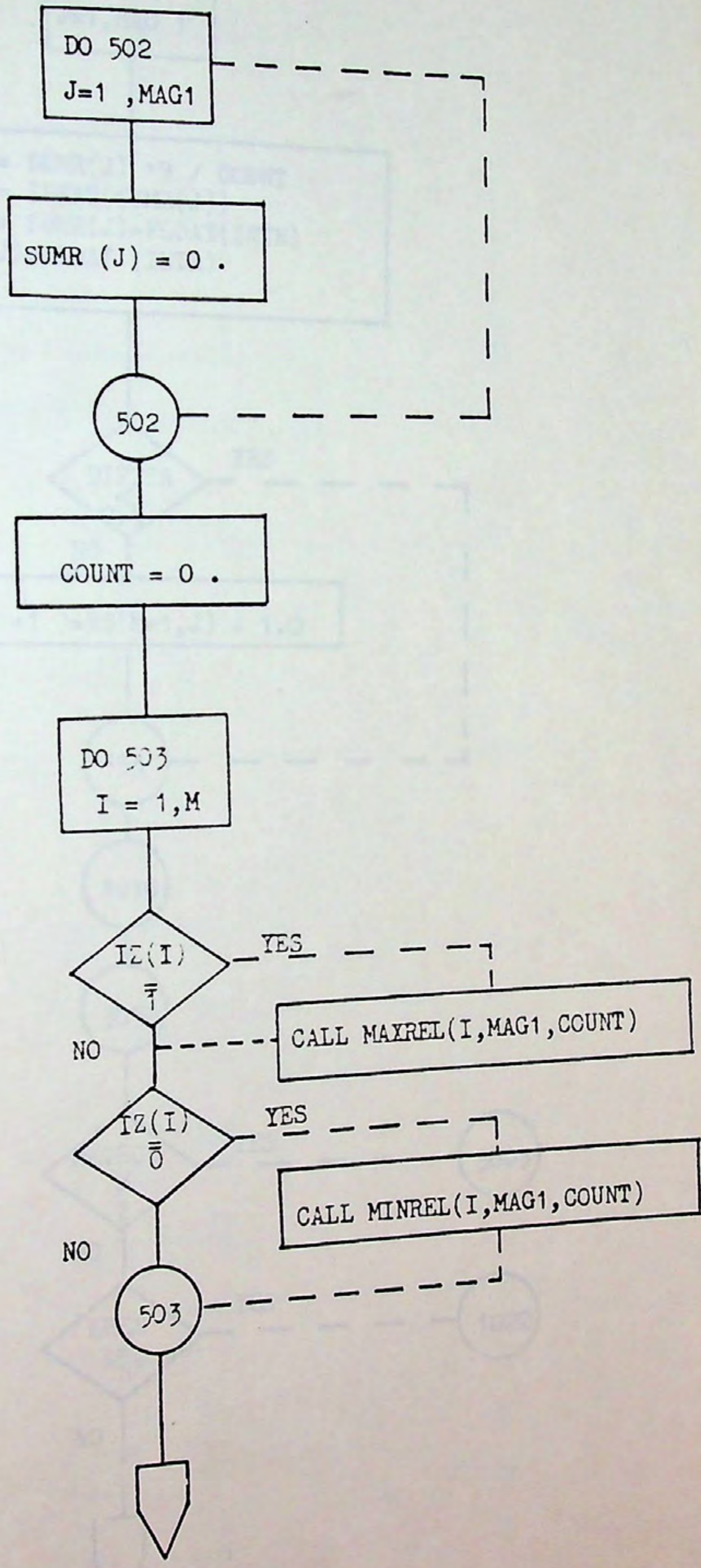

READ
KTRG T (I)
I=1,MAG
DO 1140
I =1, MAG
KTRGT (1)
=
0
YES
NO
DO 1135
J =1,MAG1
RS(I,J)=DABS(RS(I,J)-TRGVAL(I))
1135
1140
1300
M = MAG

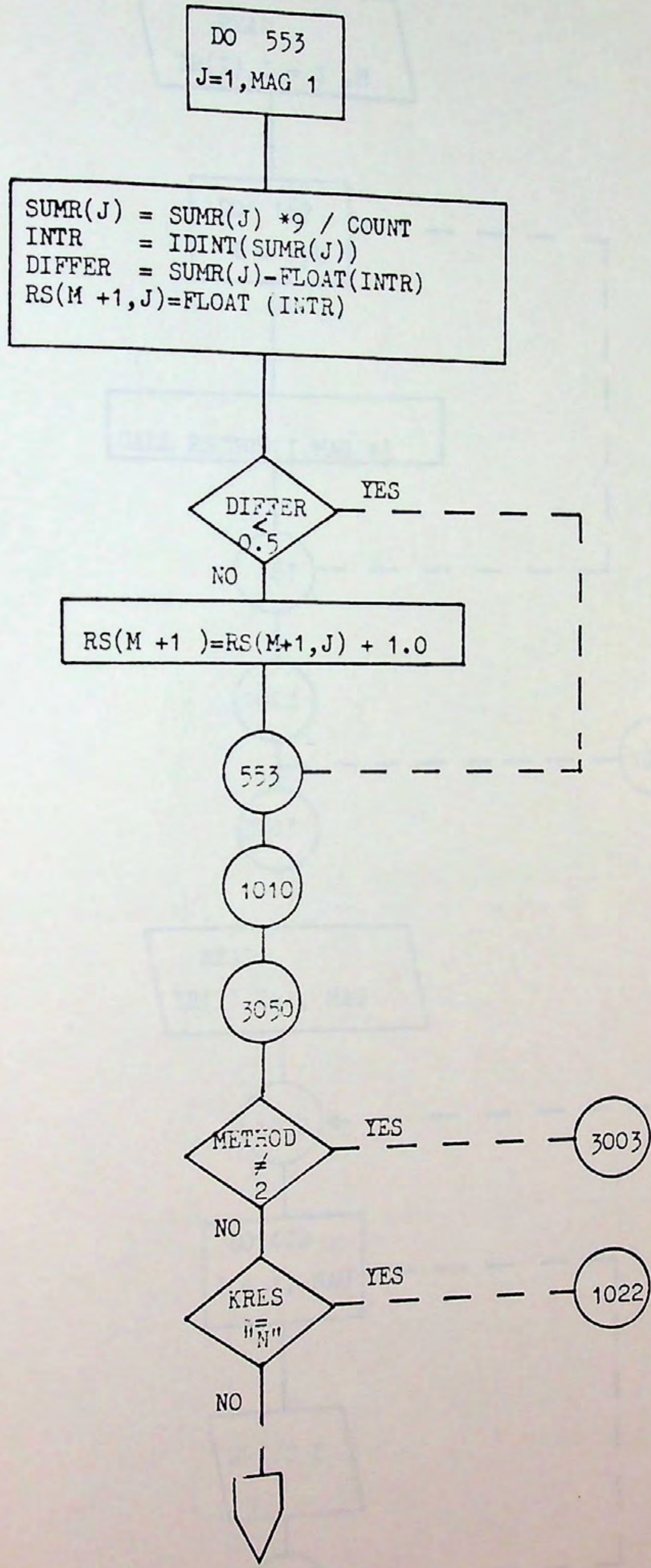


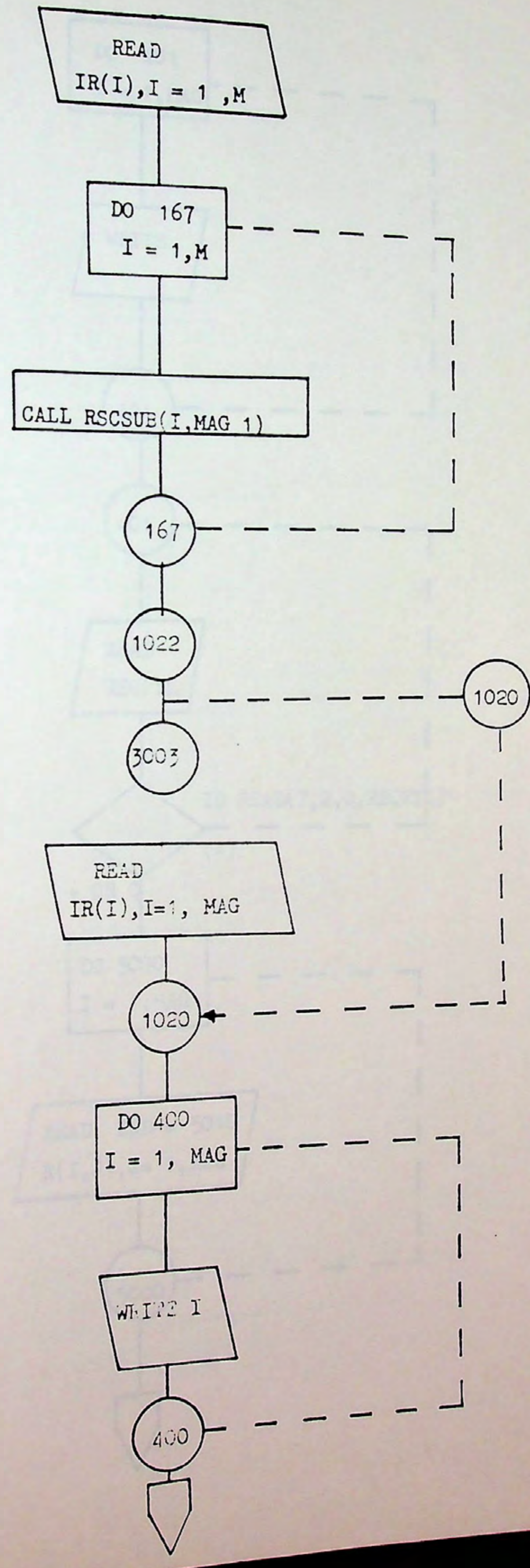
k COST = "N"
YES
1000
NO
MAG = MAG + 1
READ LCOST
LCOST = 1
YES
NO
READ
RC(J),J=1,MAG1
1190
1170
READ INB,IQ
CF(J) , J= 1 ,MAG 1
CA(J) , J= 1 ,MAG 1
CI(J) , J= 1 ,MAG 1
CR(J) , J= 1 ,MAG 1
CD(J) , J= 1 ,MAG 1
CS(J) , J= 1 ,MAG 1
CC1(J), J= 1 ,MAG 1
CM(J) , J= 1 ,MAG 1

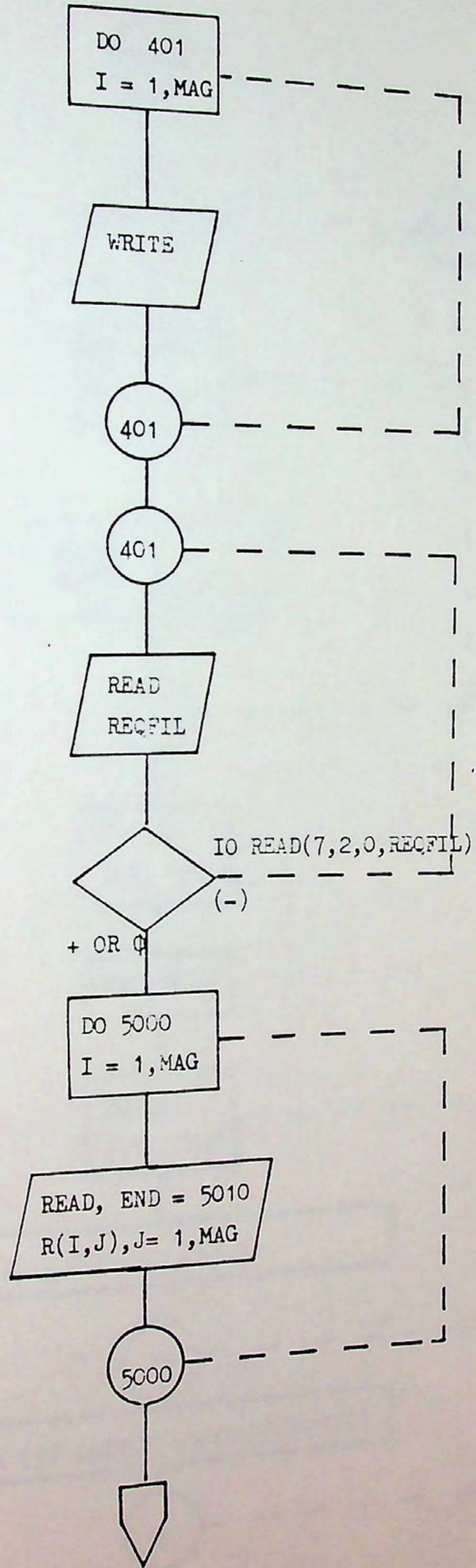

DO 65
I=1 ,INB
READ
CC(I,J),J=1,MAG1
65
DO 75
I=1,INB
READ
CP(I,J),J=1,MAG1
75
CALL
COST(MAG1,INB,QI)
1190

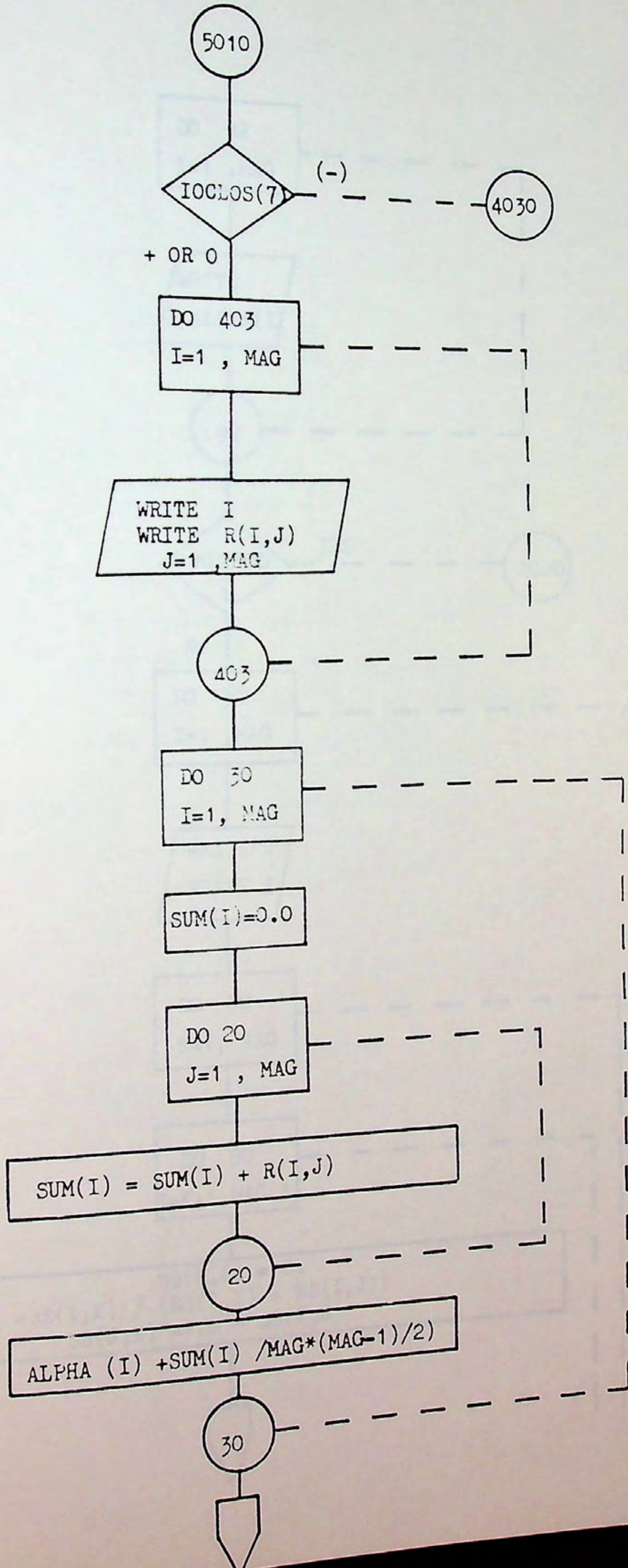

DO 501
J=1,MAG 1
RS(MAG +1,J) = RC(J)
501
1000
KREL = "N"
YES
1010
NO
MAG = MAG + 1
M = MAG - 1
KOOST = "Y"
NO
YES
M = M-1
READ IRELF
IREF=0
NO
READ IZ(Z),J = 1,M
YES
READ T, LAM,ALFA,ST,AV
CALL CAL REL
3050

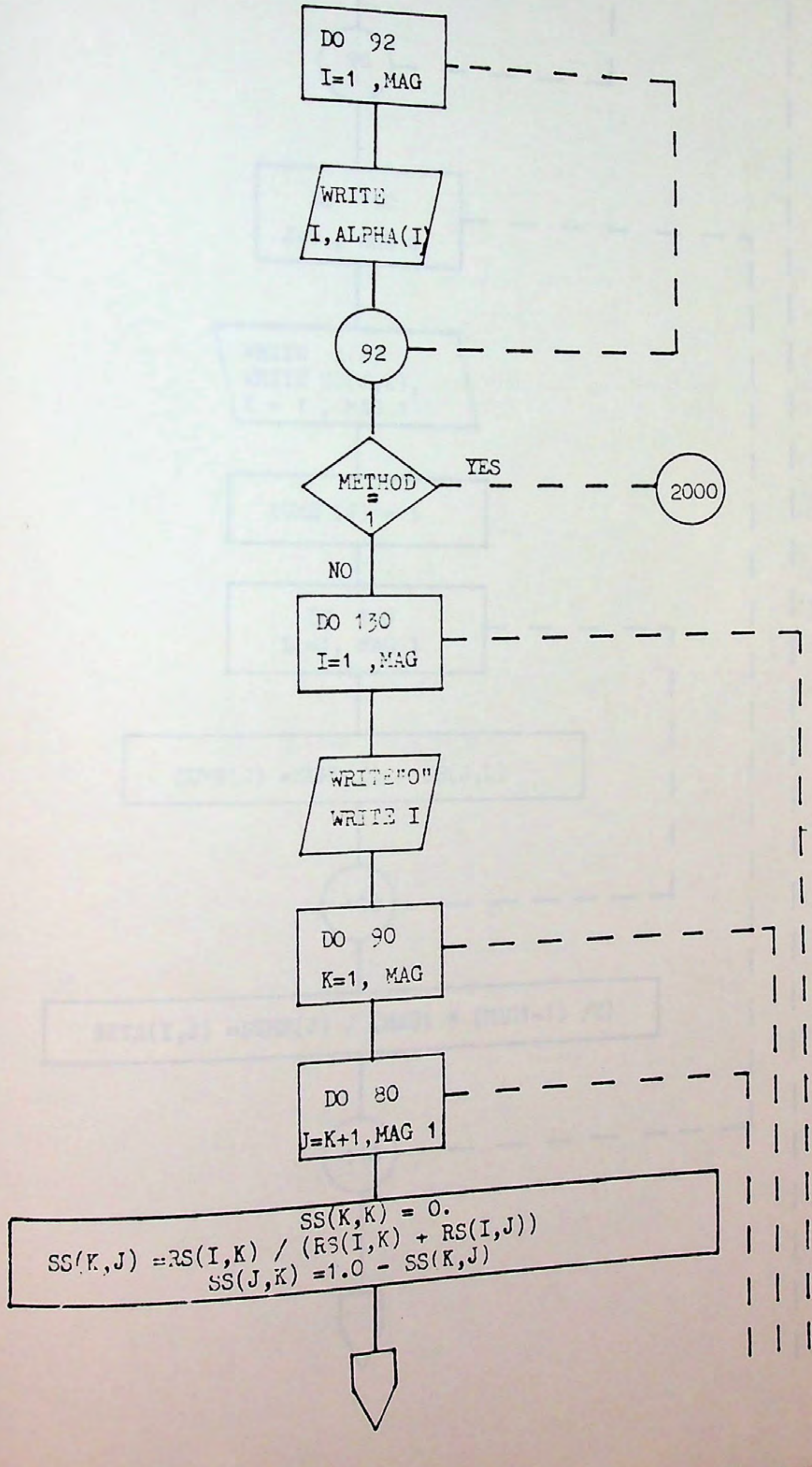

DO 502
J=1 ,MAG1
SUMR (J) = 0 .
502
COUNT = 0 .
DO 503
I = 1,M
IZ(I)
=
1
YES
CALL MAXREL(I,MAG1,COUNT)
NO
IZ(I)
=
0
YES
CALL MINREL(I,MAG1,COUNT)
NO
503

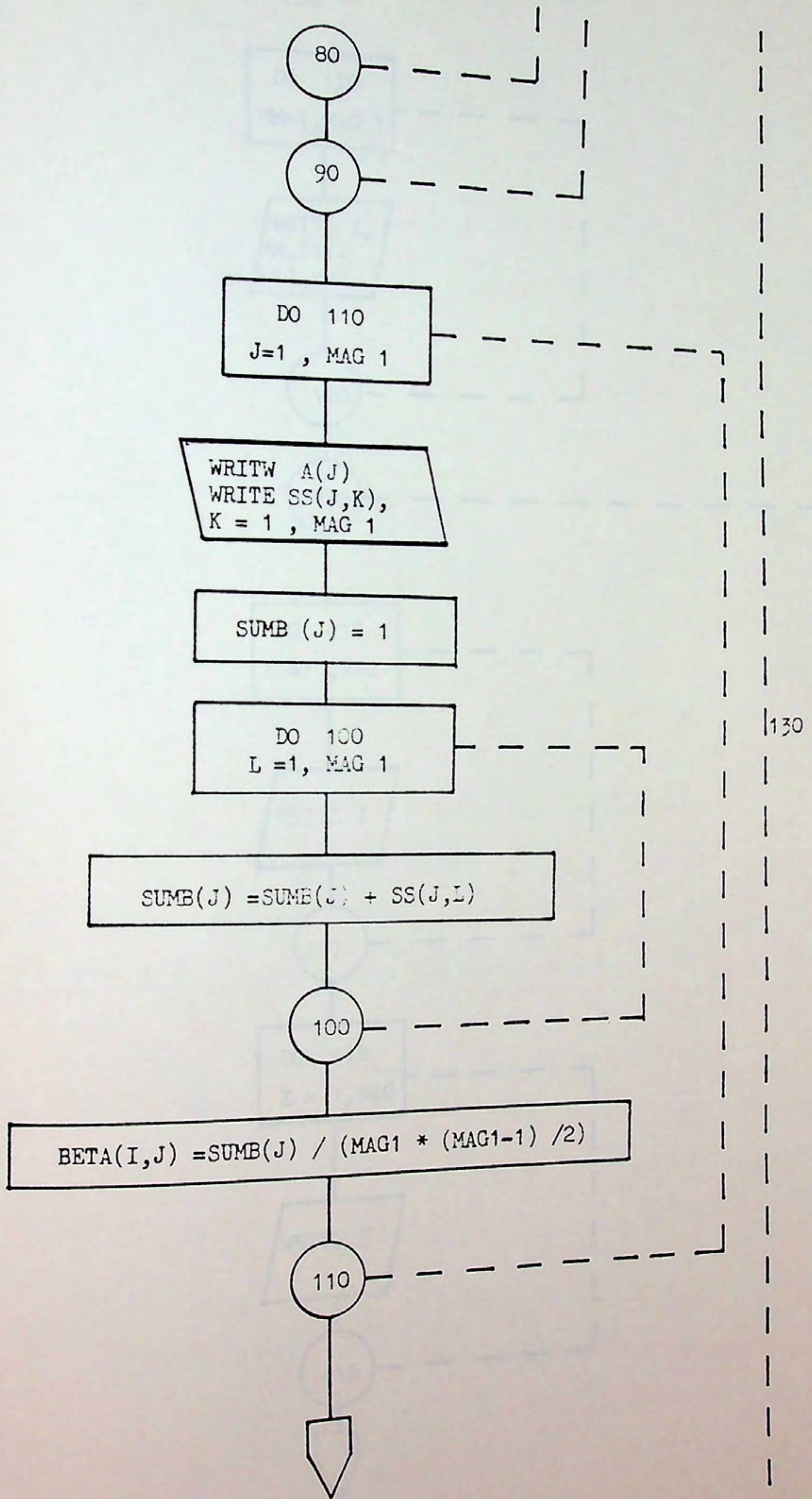

DO 553
J=1,MAG 1
SUMR(J) = SUMR(J) *9 / COUNT
INTR = IDINT(SUMR(J))
DIFFER = SUMR(J)-FLOAT(INTR)
RS(M +1,J)=FLOAT (INTR)
DIFFER < 0.5
YES
NO
RS(M +1)=RS(M+1,J) + 1.0
553
1010
3050
METHOD ≠ 2
YES
3003
NO
KRES = "N"
YES
1022
NO

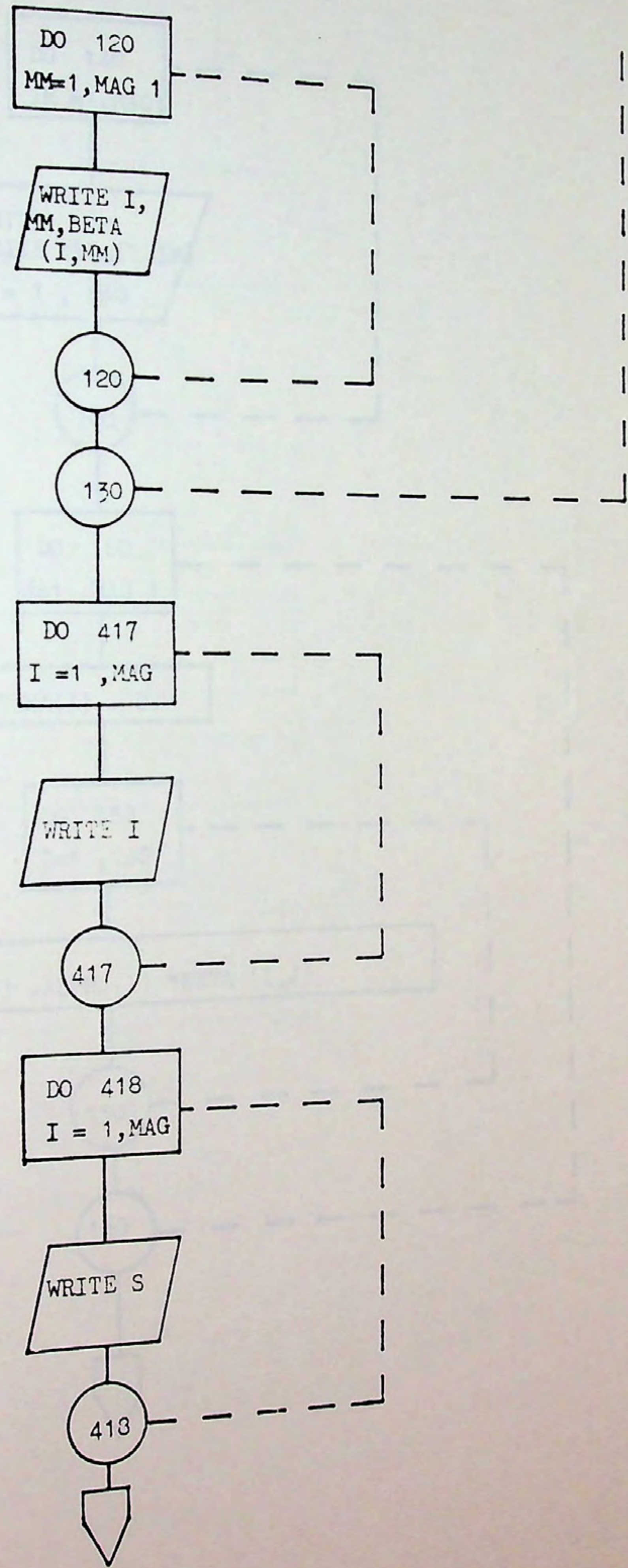

READ
IR(I),I = 1 ,M
DO 167
I = 1,M
CALL RSCSUB(I,MAG 1)
167
1022
1020
3003
READ
IR(I),I=1, MAG
1020
DO 400
I = 1, MAG
WRITE I
400

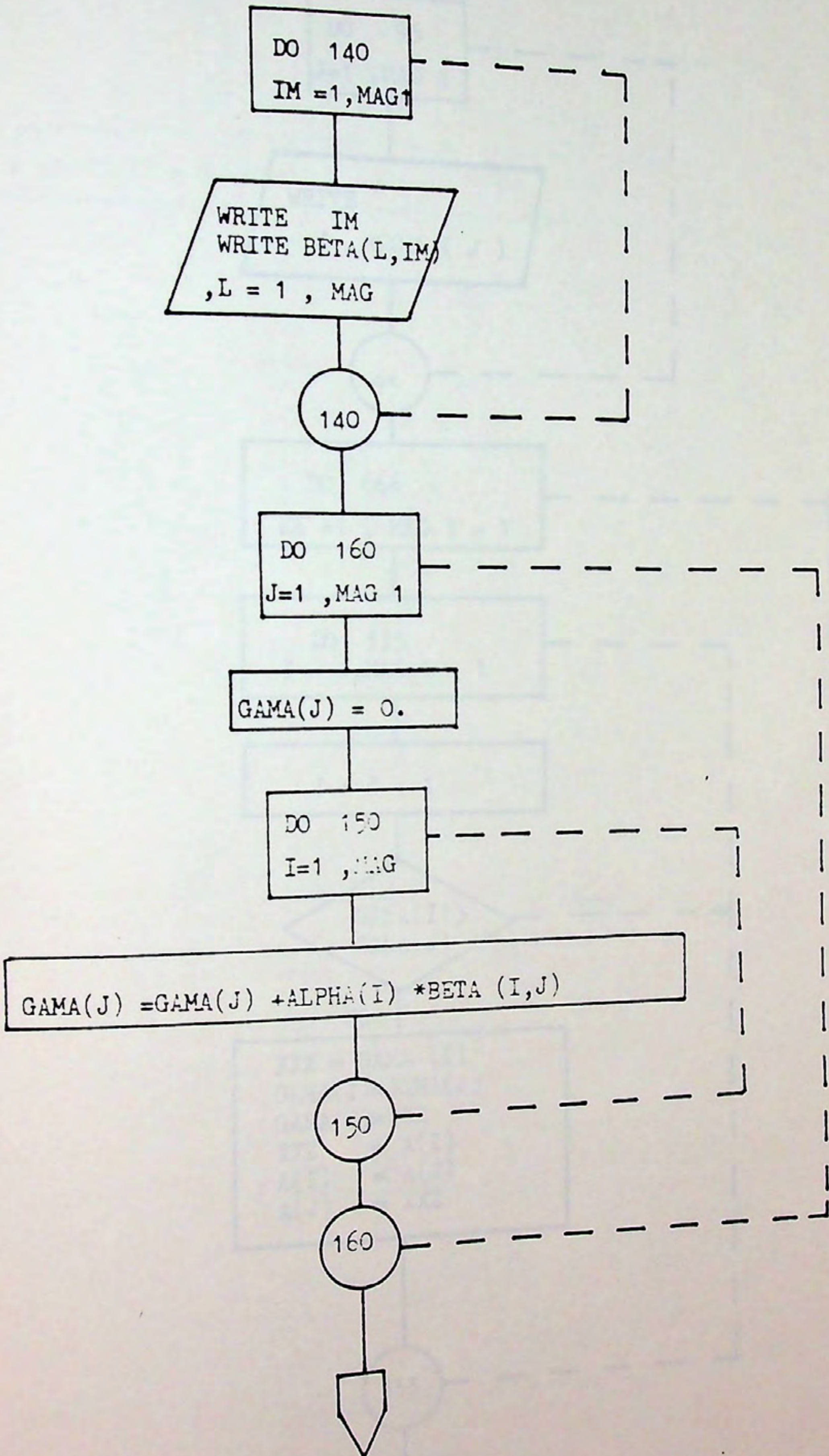

DO 401
I = 1,MAG
WRITE
401
401
READ
REQFIL
IO READ(7,2,0,REQFIL)
(-)
+ OR Ø
DO 5000
I = 1,MAG
READ, END = 5010
R(I,J),J= 1,MAG
5000

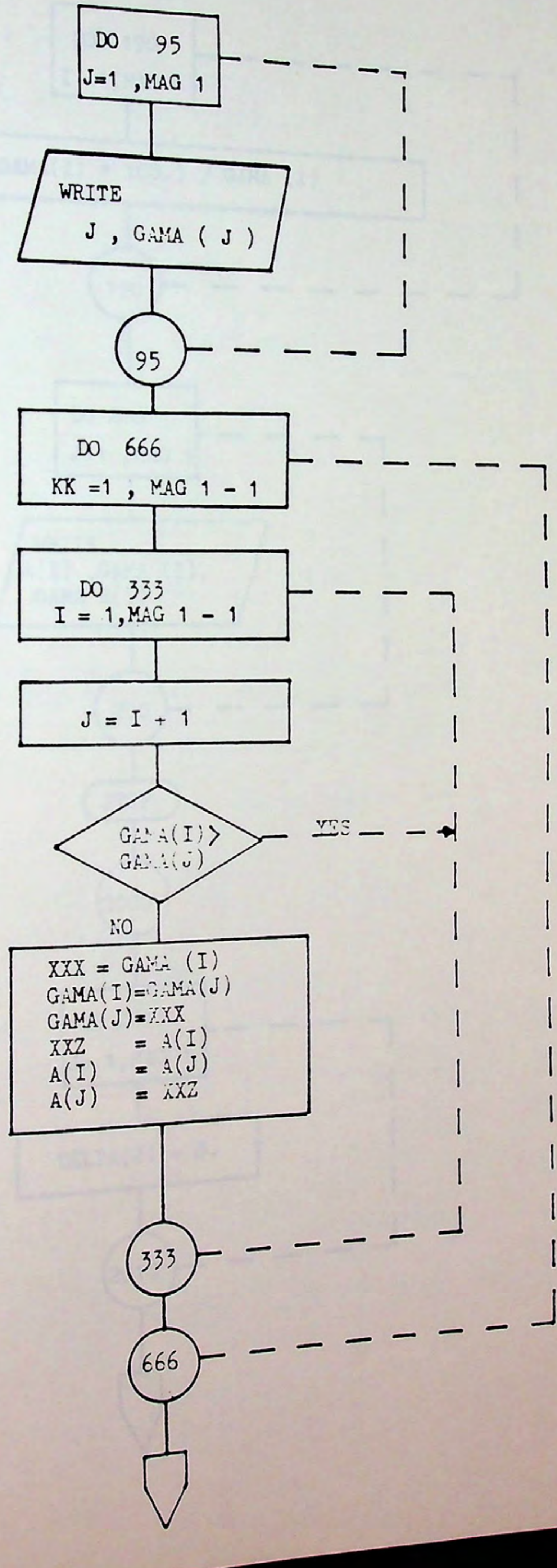

5010
IOCLOS(7)
(-)
4030
+ OR 0
DO 403
I=1 , MAG
WRITE I
WRITE R(I,J)
J=1 ,MAG
403
DO 30
I=1, MAG
SUM(I)=0.0
DO 20
J=1 , MAG
SUM(I) = SUM(I) + R(I,J)
20
ALPHA (I) +SUM(I) /MAG*(MAG-1)/2)
30

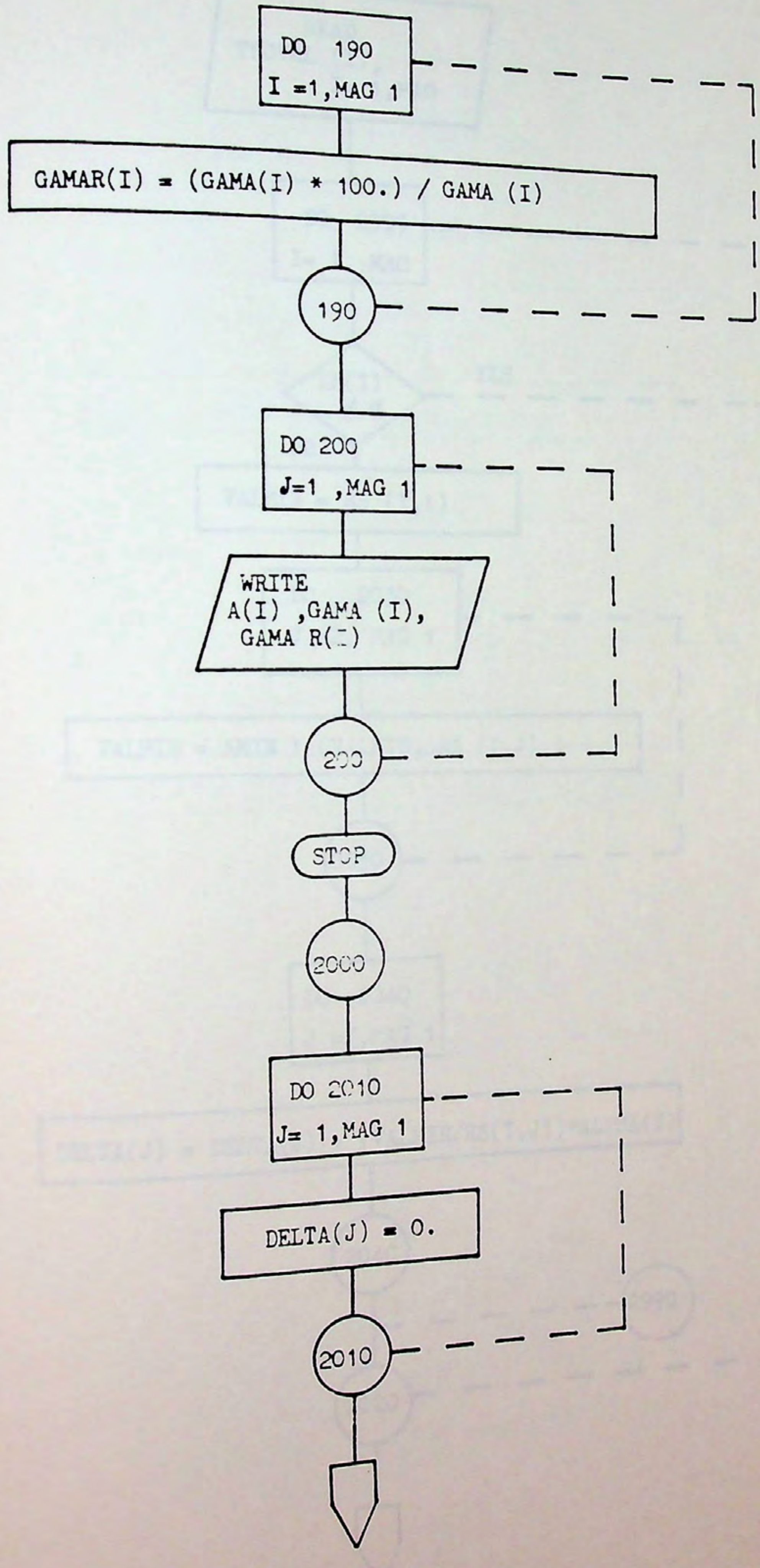

DO 92
I=1 ,MAG
WRITE
I,ALPHA(I)
92
METHOD = 1
YES
2000
NO
DO 130
I=1 ,MAG
WRITE"0"
WRITE I
DO 90
K=1, MAG
DO 80
J=K+1,MAG 1
SS(K,K) = 0.
SS(K,J) =RS(I,K) / (RS(I,K) + RS(I,J))
SS(J,K) =1.0 - SS(K,J)

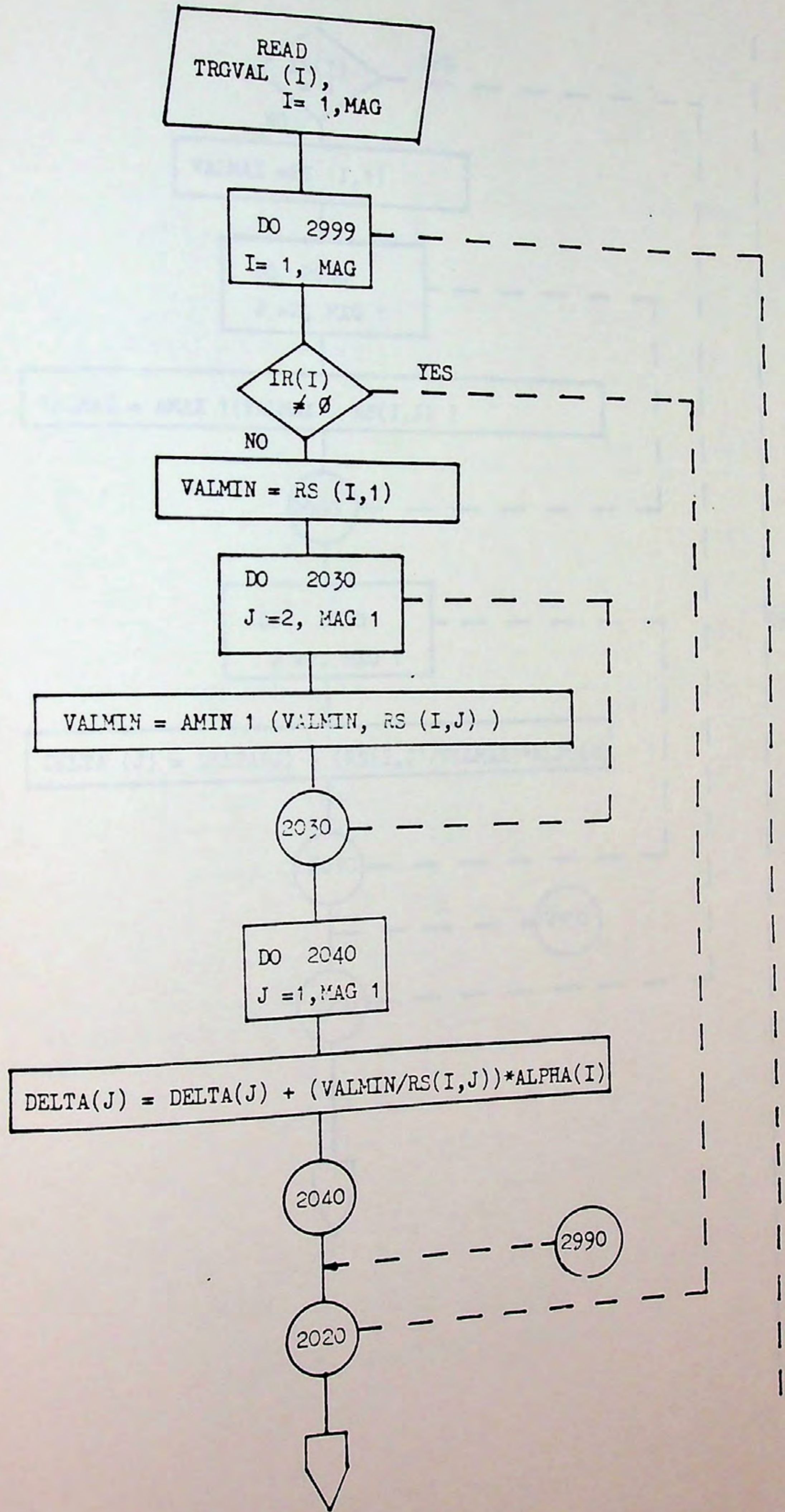

80
90
DO 110
J=1 , MAG 1
WRITW A(J)
WRITE SS(J,K),
K = 1 , MAG 1
SUMB (J) = 1
DO 100
L =1, MAG 1
SUMB(J) =SUMB(J) + SS(J,L)
100
BETA(I,J) =SUMB(J) / (MAG1 * (MAG1-1) /2)
110
130

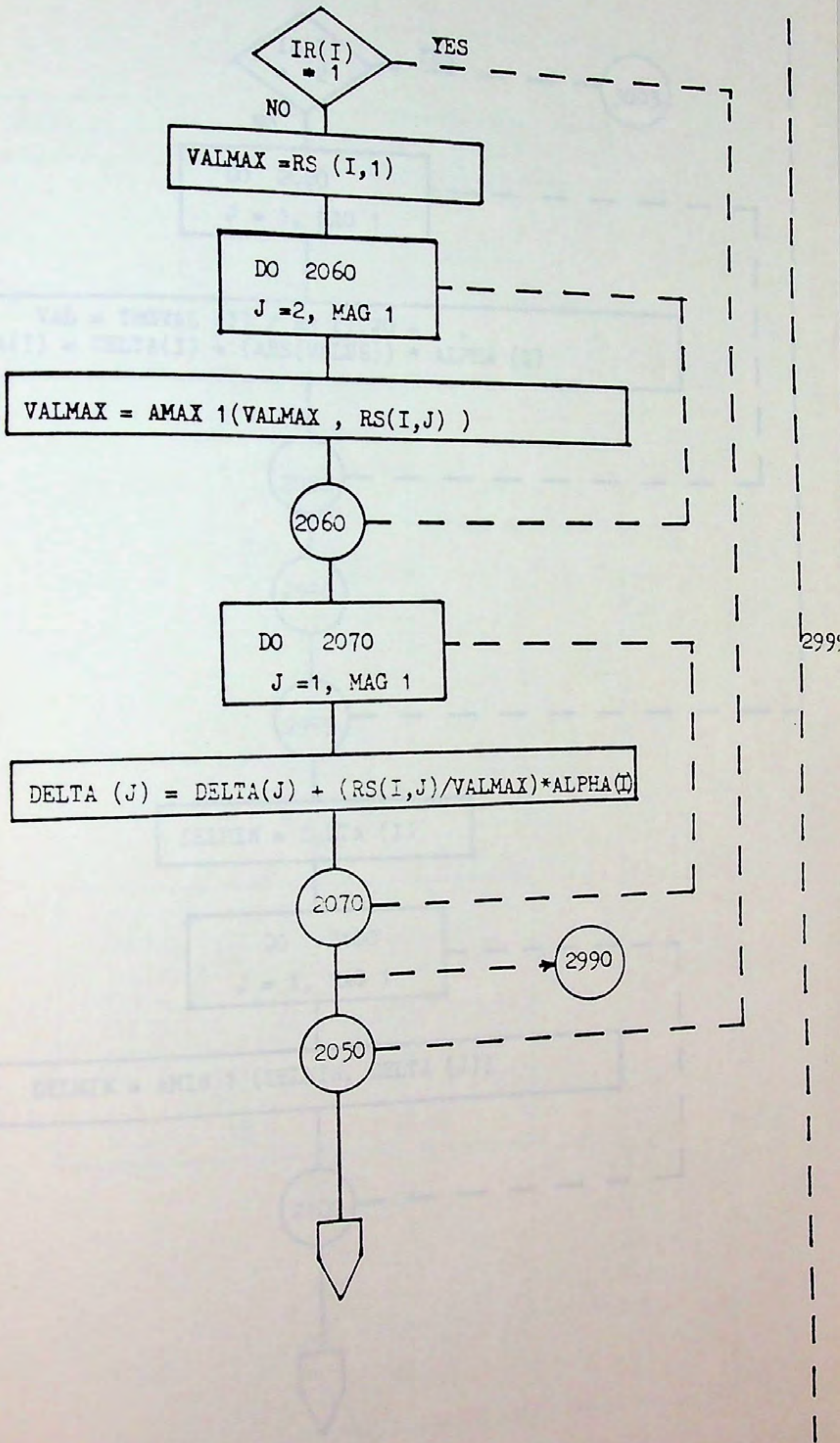

DO 120
MM=1,MAG 1
WRITE I,
MM,BETA
(I,MM)
120
130
DO 417
I =1 ,MAG
WRITE I
417
DO 418
I = 1,MAG
WRITE S
418

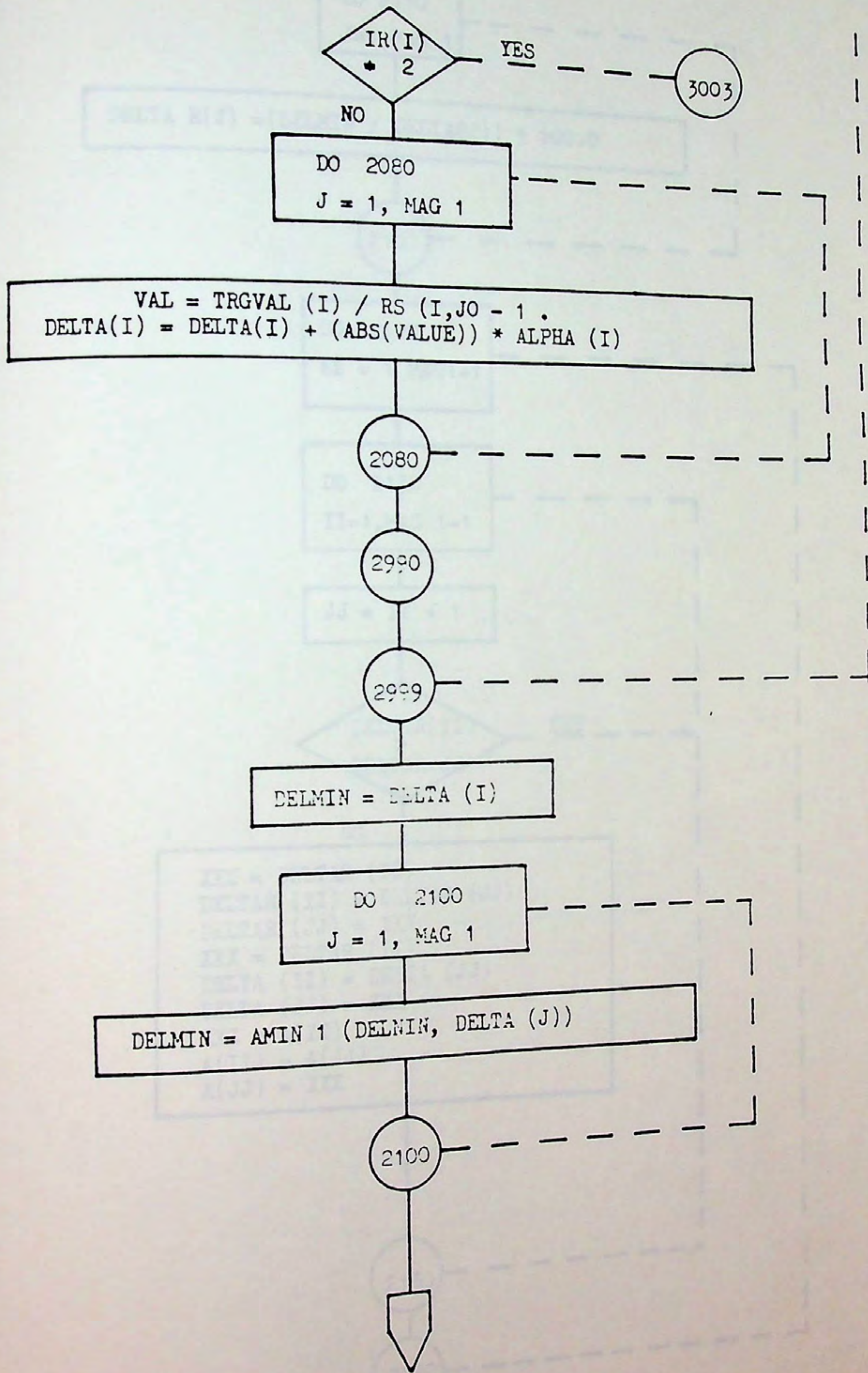

DO 140
IM =1,MAG1
WRITE IM
WRITE BETA(L,IM)
,L = 1 , MAG
140
DO 160
J=1 ,MAG 1
GAMA(J) = 0.
DO 150
I=1 ,MAG
GAMA(J) =GAMA(J) +ALPHA(I) *BETA (I,J)
150
160

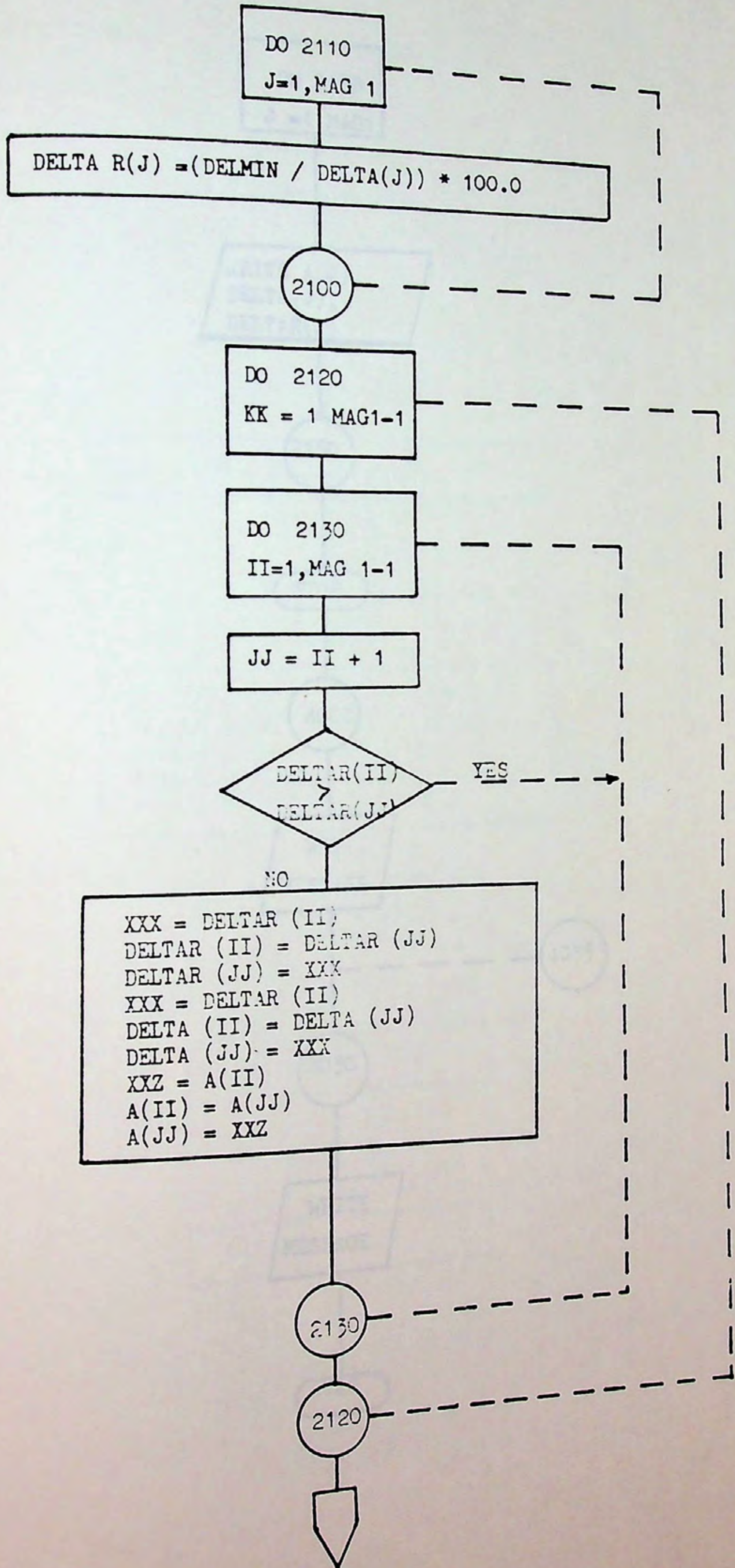

DO 95
J=1 ,MAG 1
WRITE
J , GAMA (J)
95
DO 666
KK =1 , MAG 1 - 1
DO 333
I = 1,MAG 1 - 1
J = I + 1
GAMA(I)>
GAMA(J)
YES
NO
XXX = GAMA (I)
GAMA(I)=GAMA(J)
GAMA(J)=XXX
XXZ = A(I)
A(I) = A(J)
A(J) = XXZ
333
666

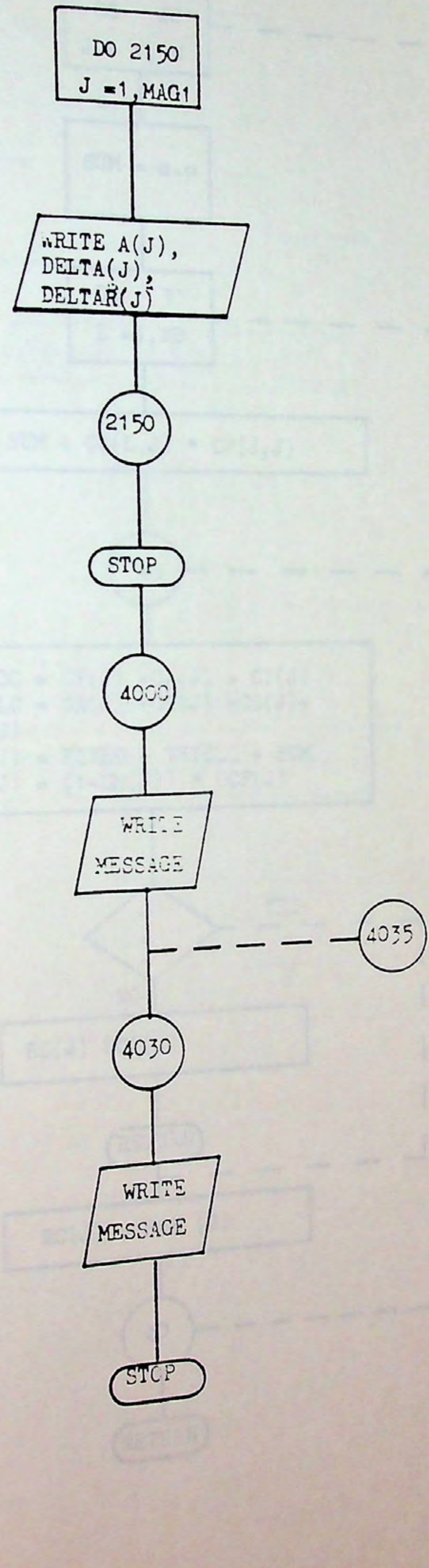

DO 190
I =1,MAG 1
GAMAR(I) = (GAMA(I) * 100.) / GAMA (I)
190
DO 200
J=1 ,MAG 1
WRITE
A(I) ,GAMA (I),
GAMA R(I)
200
STOP
2000
DO 2010
J= 1,MAG 1
DELTA(J) = 0.
2010


READ
TRGVAL (I),
I= 1,MAG
DO 2999
I= 1, MAG
IR(I)
≠ Ø
YES
NO
VALMIN = RS (I,1)
DO 2030
J =2, MAG 1
VALMIN = AMIN 1 (VALMIN, RS (I,J))
2030
DO 2040
J =1,MAG 1
DELTA(J) = DELTA(J) + (VALMIN/RS(I,J))*ALPHA(I)
2040
2990
2020


IR(I) = 1
YES
NO
VALMAX =RS (I,1)
DO 2060
J =2, MAG 1
VALMAX = AMAX 1(VALMAX , RS(I,J))
2060
DO 2070
J =1, MAG 1
DELTA (J) = DELTA(J) + (RS(I,J)/VALMAX)*ALPHA(I)
2070
2990
2050


IR(I)
≠ 2
YES
3003
NO
DO 2080
J = 1, MAG 1
VAL = TRGVAL (I) / RS (I,JO - 1 .
DELTA(I) = DELTA(I) + (ABS(VALUE)) * ALPHA (I)
2080
2990
2999
DELMIN = DELTA (I)
DO 2100
J = 1, MAG 1
DELMIN = AMIN 1 (DELMIN, DELTA (J))
2100

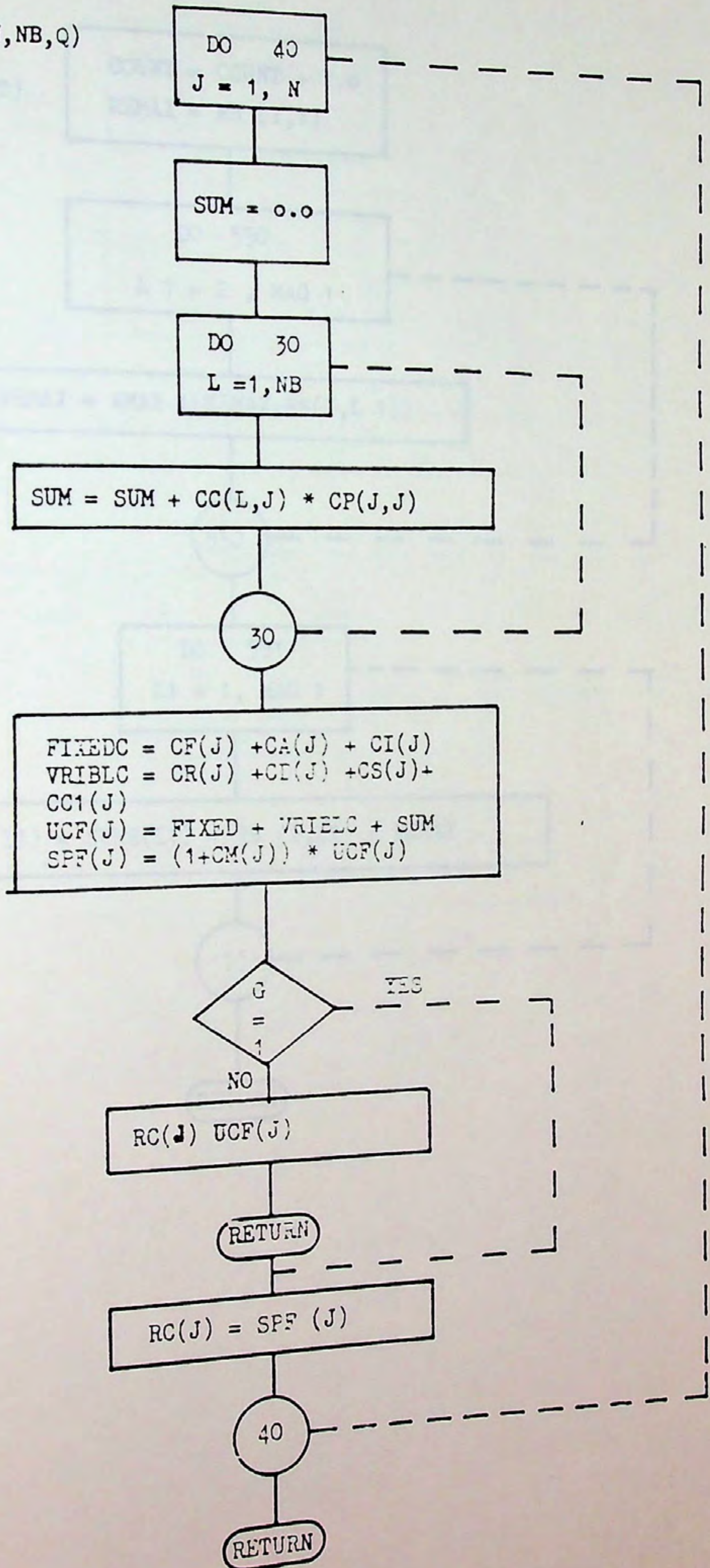

DO 2110
J=1,MAG 1
DELTA R(J) =(DELMIN / DELTA(J)) * 100.0
2100
DO 2120
KK = 1 MAG1-1
DO 2130
II=1,MAG 1-1
JJ = II + 1
DELTAR(II) > DELTAR(JJ)
YES
NO
XXX = DELTAR (II)
DELTAR (II) = DELTAR (JJ)
DELTAR (JJ) = XXX
XXX = DELTAR (II)
DELTA (II) = DELTA (JJ)
DELTA (JJ) = XXX
XXZ = A(II)
A(II) = A(JJ)
A(JJ) = XXZ
2130
2120


DO 2150
J =1,MAG1
WRITE A(J),
DELTA(J),
DELTAR(J)
2150
STOP
4000
WRITE
MESSAGE
4035
4030
WRITE
MESSAGE
STOP

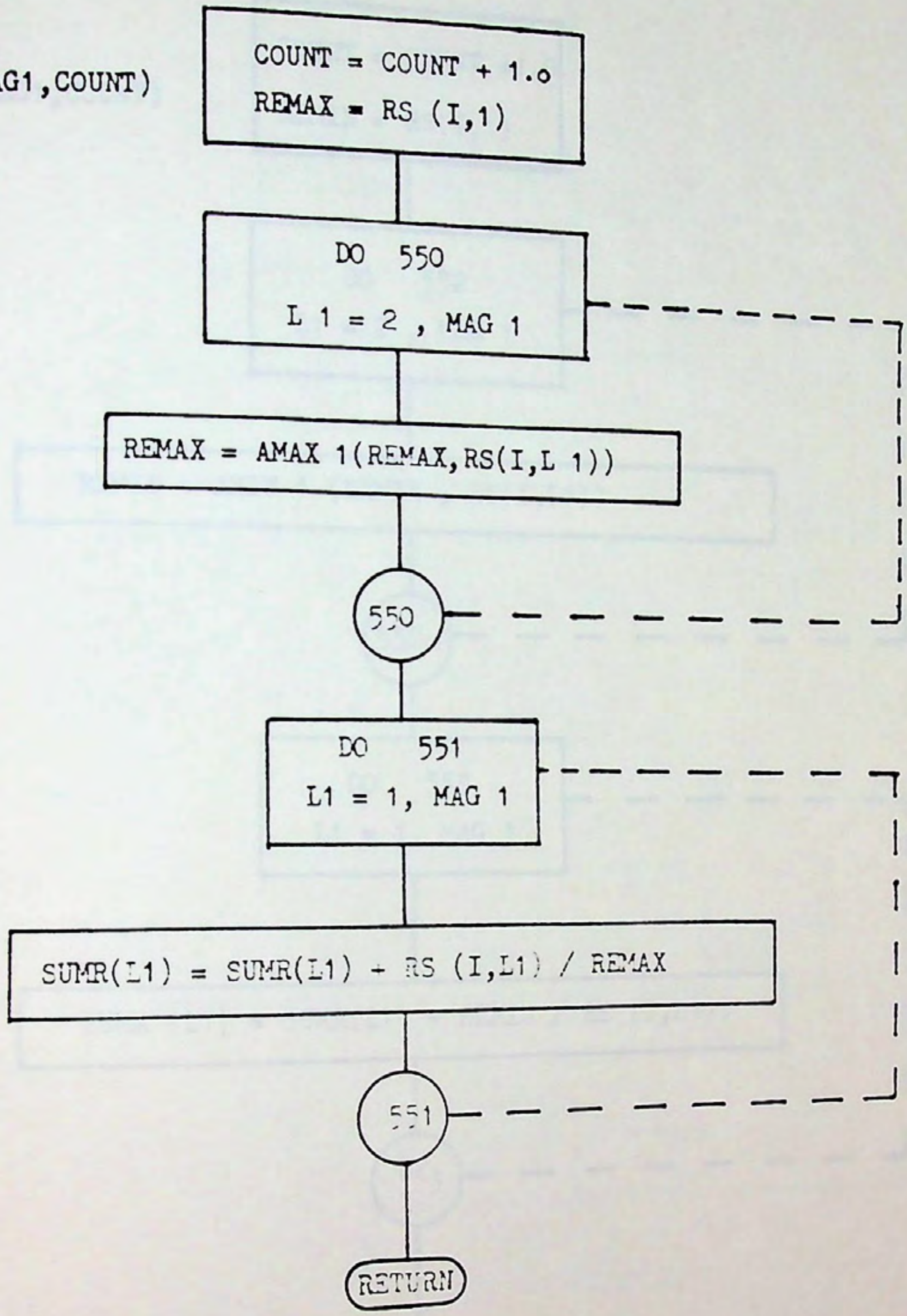
Appendix (7)

Subroutines Flow Charts

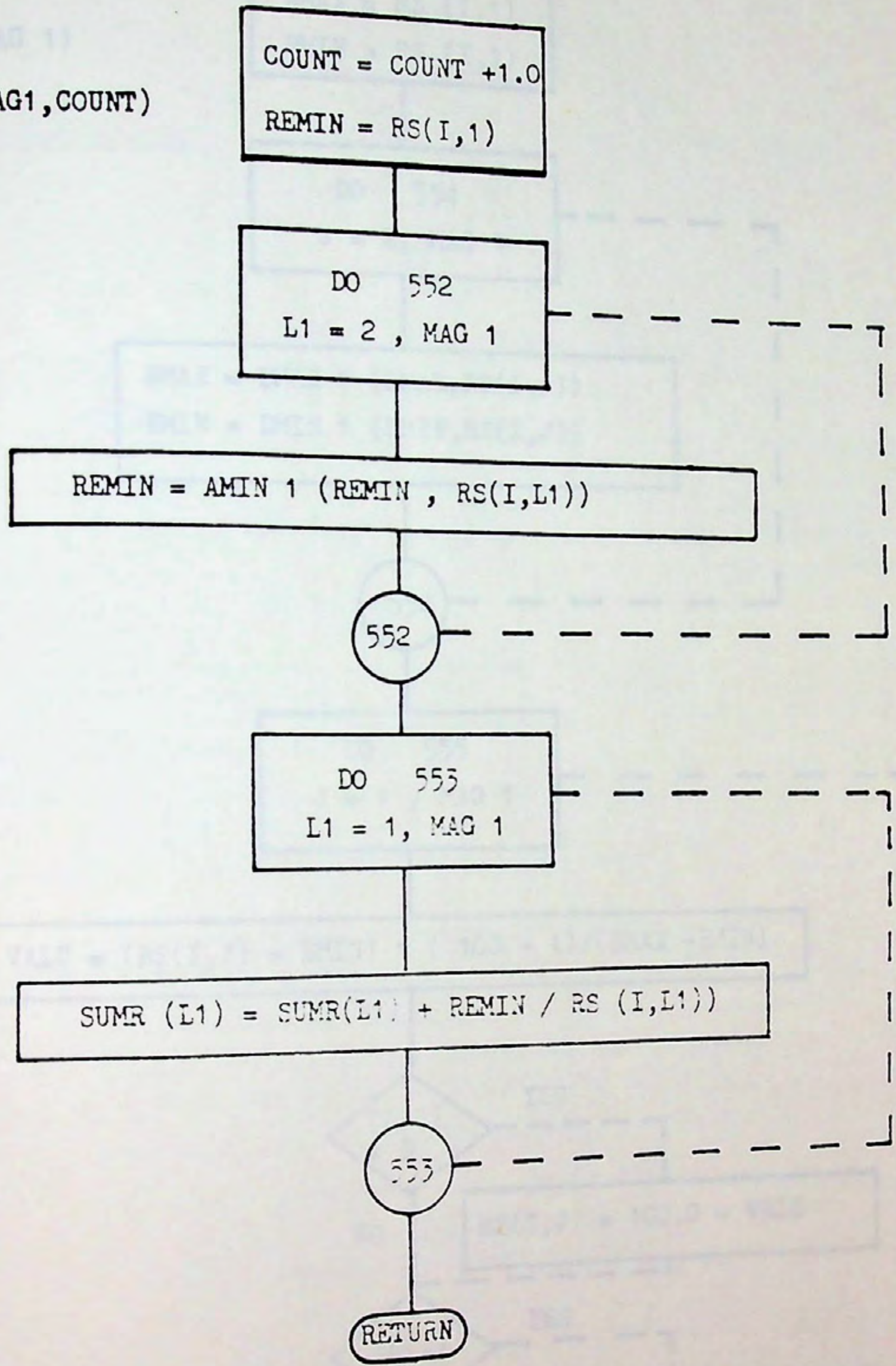
SUBROUTINE COST(N,NB,Q)

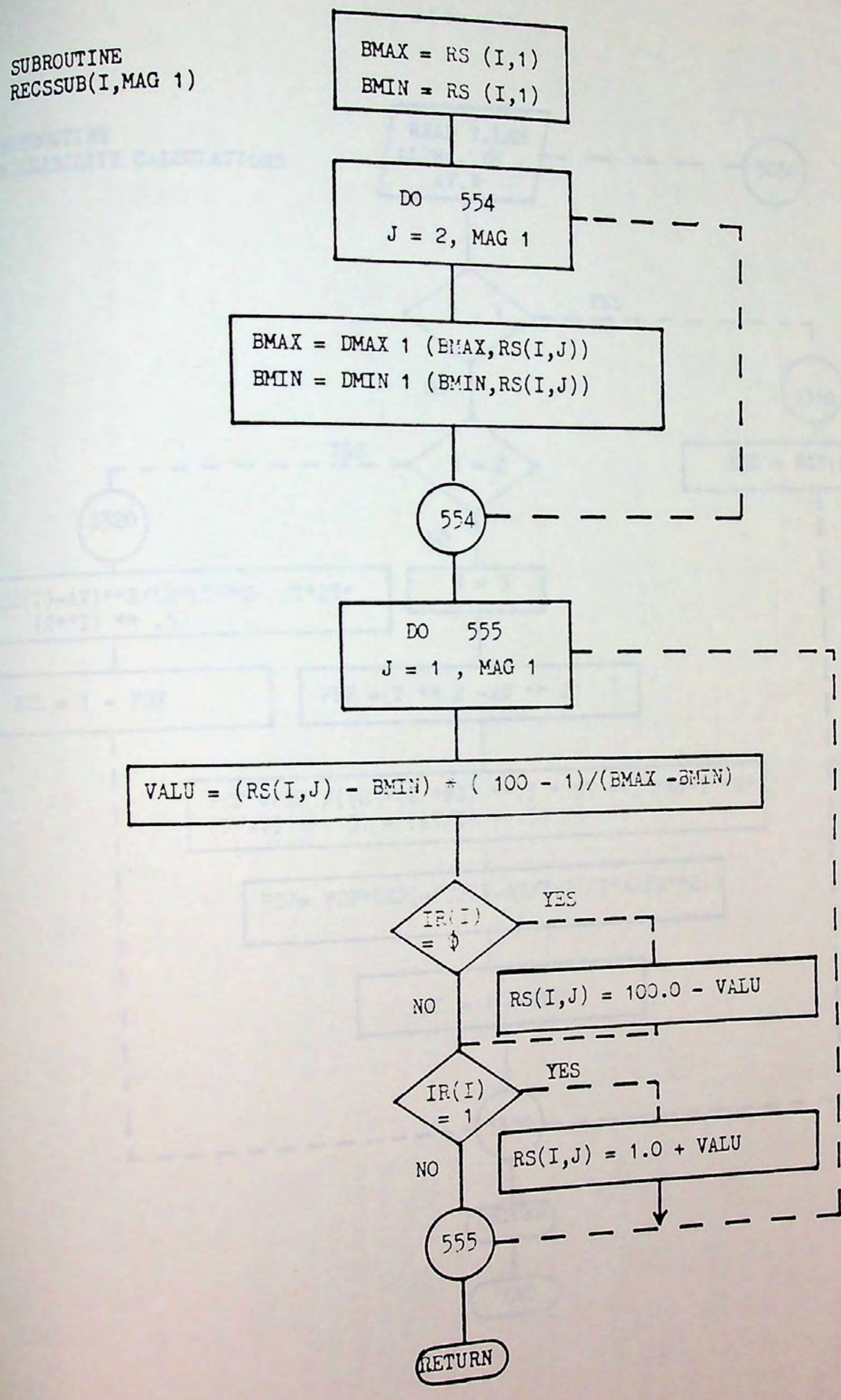


SUBROUTINE
MAXREL (I,MAG1,COUNT)

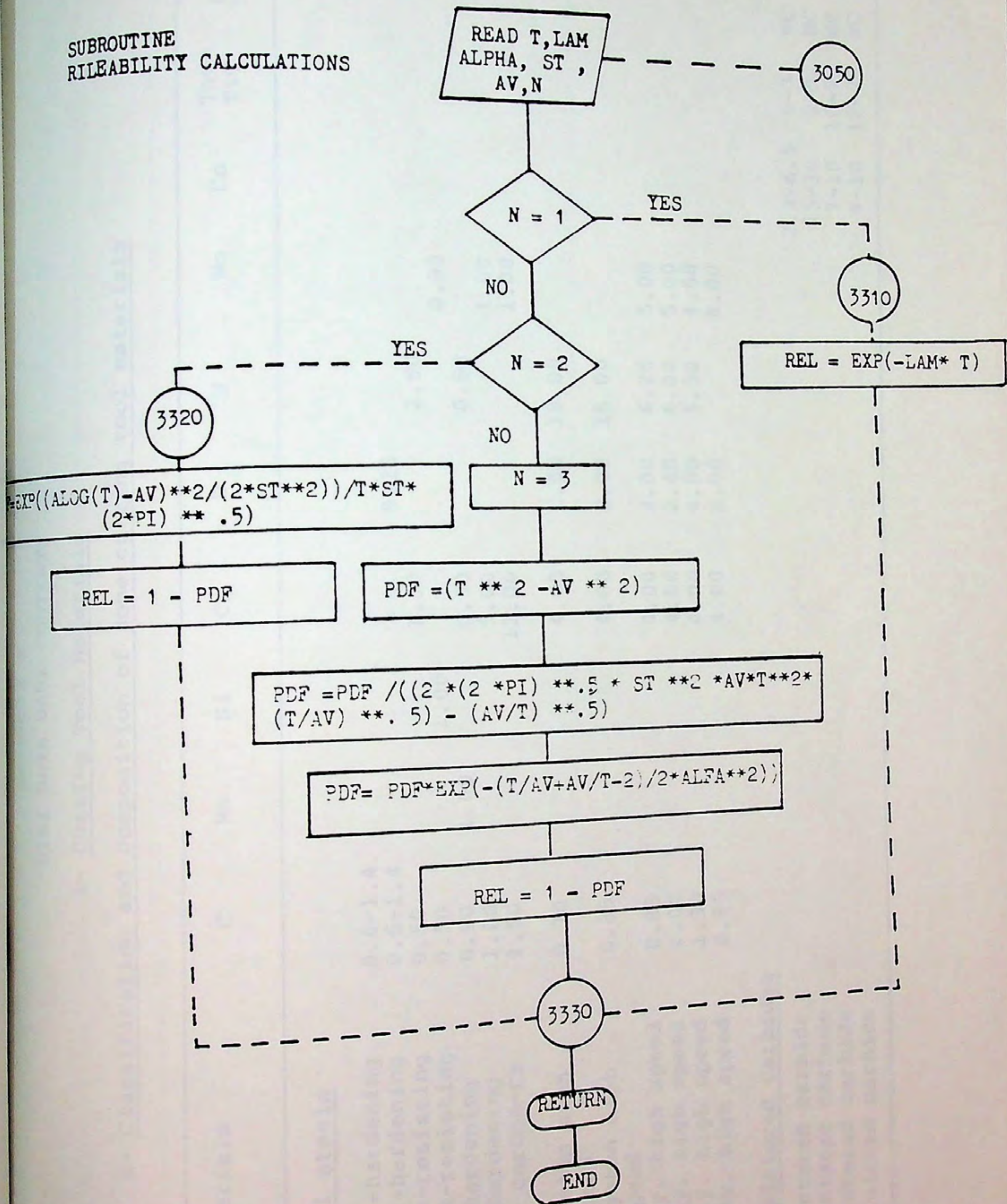


SUBROUTINE
MINRE (I,MAG1,COUNT)




SUBROUTINE
RECSSUB(I,MAG 1)
BMAX = RS (I,1)
BMIN = RS (I,1)
DO 554
J = 2, MAG 1
BMAX = DMAX 1 (BMAX,RS(I,J))
BMIN = DMIN 1 (BMIN,RS(I,J))
554
DO 555
J = 1 , MAG 1
VALU = (RS(I,J) - BMIN) * (100 - 1)/(BMAX -BMIN)
IR(I) = 0
YES
NO
RS(I,J) = 100.0 - VALU
IR(I) = 1
YES
NO
RS(I,J) = 1.0 + VALU
555
RETURN

SUBROUTINE
RILEABILITY CALCULATIONS



APPENDIX 8

MINI DATA BANK CONTENTS

1- Cutting Tool Materials

A- Classification and composition of some cutting tool materials

Grade	Materials	C	MN	Si	Cr	V	W	Mo	Co	TaC+ TiC	Other
	Tool steels										
W1	Water-hardening	0.6-1.4									
W2	Water-hardening	0.6-1.4				0.25					
S1	Shock-resisting	0.50			1.50		2.50				
S2	Shock-resisting	0.50		1.00				0.50			
O1	Oil-hardening	0.90	1.00		0.50		0.50				
A2	Air-hardening	1.00			5.00			1.00			
D2	High carbon-Cr	1.50			12.00			1.00			
T1	Tungsten high speed	0.70			4.00	1.00	18.00				
T2	Tungsten high speed	0.85			4.00	2.00	18.00				
M2	Moly. high speed	0.85			4.00	2.00	6.25	5.00			
M3	Moly. high speed	1.00			4.00	2.40	6.00	5.00			
M4	Moly. high speed	1.30			4.00	4.00	5.50	4.50			
M10	Moly. high speed	0.85			4.00	2.00		8.00			
	Sintered Carbides										
Gr.1	Sintered carbide								2.5-6.5	0-3	WC Rem.
Gr.3	Sintered carbide								15-30	0-5	WC Rem.
Gr.5	Sintered carbide								7-10	10-22	WC Rem.
Gr.8	Sintered carbide								8-10	12-20	WC Rem.

A - Cont.

Grade	Materials	C	Mn	Si	V	W	Mo	Co	TaC+ TiC	Other
	Co-Cr-W-Mo alloys									
18% W, 2.5%C	Cast alloy (hard)	2.5	1.0	1.00	30-32	17-18.5	0.80	Rem.		2.5-3.5 Ni
11% W, 2% C	Cast alloy (medium)	1.35-2.45	1.0	1.00	30.5-31	10-12		Rem.		3.00 Ni
4% W, 1% C	Cast alloy (soft)	0.6-1.6	1.0-2.0	1.5-2.0	30-31	4.50	1.5	Rem.		3.00 Ni
	Ceramic									
Ceramic	Aluminum									99.9% A_2O_3

B- Properties of cutting tool materials

Grade	R.T.H. Rc	Hardness at 830^{o}K Rc	Toughness Joule	Liability to fracture 1-9	Cost index
		Tool steels			
W1	63	10	68	8	100
W2	63	10	68	8	100
S1	60	20	95	9	100
S2	63	20	95	9	100
01	63	20	54	8	100
A2	63	30	48	7	100
D2	62	35	30	7	98
T1	66	52	61	8	84
T2	65	52	61	8	84
M2	65	52	68	9	88
M3	67	52	48	8	86
M4	67	52	48	8	86
M10	65	52	68	9	92
		Sintered carbides			
Group 1	76	69	0.97	3	29
Group 3	73	65	2.4	4	31
Group 5	73	65	0.8	2	36
Group 8	75	69	0.8	2	32
		Co-Cr-W-Mo alloys			
18% W, 2.5%C	62	52	3.4	3	61
11% W, 2% C	53	43	4.8	4	62
4% W, 1% C	41	32	12	5	63
		Ceramic			
Alumina	80	72	0.7	1	80

2 - Turbine Blade Materials

A- Chemical composition of some gas turbine blade materials

Nominal composition, weight %

	Ni	Cr	Co	Mo	W	Ta	Nb	Al	Ti	C	Zr	Fe	Others
Cast alloys													
713C	Bal	13		4			2	6	1	0.1			
M22	Bal	6		2	11	3		6		0.1			
MAR-M246	Bal	9	10	2.5	10.0			5.5	1.5	0.15	0.05		0.1Mn,0.05Si
MAR-M302		21.5	58.0		10.0	9.0				0.85	0.2		
MAR-M322		21.5	61.0		9.0	4.5			0.75	1.00	2.5		
MAR-M509	10	23.5	55		7.0	3.5			0.2	0.6	0.5		
NASA Co W Re		3	68		25				1.0	0.4	1.0		2.0Re
WI-52		21	63		11	2				0.45		2	0.25Mn,0.25Si
B1900	64	8.0	10	6.0		4.0		6.0	1.0	0.1	0.1		
Wrought alloys													
Nimonic 75	78.8	20.0							0.4	0.01			0.1Mn,0.7Si
Nimonic 80A	74.7	19.5	1.1					1.3	2.5	0.06			0.1Mn,0.7Si
Nimonic 90	57.4	19.5	18.0					1.4	2.4	0.07			0.5Mn,0.7Si
Nimonic 105	53.3	14.5	20.0	5.0				1.2	4.5	0.2			0.5Mn,0.7Si
Nimonic 115	57.3	15.0	15.0	3.5				5.0	4.0	0.15			
Rene 80	Bal	14	9.5	4.0	4.0			3.0	5.0	0.17	0.03		
Waspaloy A	58.3	19.5	13.5	4.3				1.4	3.0	0.07	0.09	2.0	0.5Mn,0.5Si
Udimet 700	53.4	15	18.5	5.2				4.3	3.5	0.08			
T-D Nickel	98.0												$2.0ThO_2$

B- <u>Properties of some gas turbine blade materials</u>

Materials	Specific gravity	UTS at 871°C MN/m²	Yield at 0.2% offset at 871°C MN/m²	Elongation % at 760°C	Rupture strength for 100 hr. life at 1000°C MN/m²	Oxidation resistance rating	Rel. cost on the job* of a blade	Relative thermal fatigue resistance	Specific UTS	Specific rupture strength
Cast alloys										
713C	7.91	725	497	6	147	60	55	21	91.7	18.6
M22	8.63	884	676	5	172.7	10	66	23	102.4	19.9
MAR-M246	8.44	862	690	5	189	35	51	24	102.1	22.4
MAR-M302	9.21	448	310	8	112	20	100	17	48.6	12.2
MAR-M322	8.91	552	345	6.5	140	40	78	15	62.0	15.7
MAR-M509	8.85	352	290	10	119	50	70	20	39.8	13.4
NASA Co WRe	9.59	496	350	2	126	10	58	5	51.7	13.1
WI-52	8.88	414	276	9	80.5	40	65	17	46.6	9.1
B1900	8.22	794	696	4	182	35	74	19	96.6	22.1
Wrought alloys										
Nimonic 75	8.37	145	110	70	9.42	100	65	53	17.3	1.1
Nimonic 80A	8.22	400	262	20	30	100	67	36	48.7	3.6
Nimonic 90	8.18	428	262	10	40	100	69	18	52.3	4.9
Nimonic 105	7.99	607	366	22	56.5	70	75	55	76.0	7.1
Nimonic 115	7.85	828	552	22	100.5	75	80	83	105.5	12.8
Rene 80	8.24	621	552	11	95	60	85	41	75.4	11.5
Waspaloy A	8.19	525	518	28	47.6	80	78	100	64.1	5.8
Udimet 700	7.91	690	635	20	119	75	79	88	87.2	15.0
TD Nickel	8.9	193	179	11	98	85	76	14	21.7	11.0

* Relative cost is calculated in relation to the cost of MAR-M302 which is taken as 100. The prices are based on 1977 prices in U.S.

3 - Low temperature application

COMPOSITION OF SOME ALLOYS USED IN LOW TEMPERATURE APPLICATIONS (%)

Material	*Al*	*Cu*	*Fe*	*Cr*	*Ni*	*Zn*	*Ti*	*Si*	*Mn*	*Mg*	*C*	*Others*
Aluminium alloys												
2014–T6	Rem.*	3·9–5·0	1·0 max	0·1 max		0·15 max		0·5–1·2	0·4–1·2	0·2–0·8		
5052–0	Rem.*	0·1 max	0·4 max	0·15–0·35				0·45 max	0·1 max	2·2–2·8		
5083–0	Rem.*	0·1 max	0·4 max	0·05–0·25			0·15 max	0·4 max	0·3–1·0	4–4·9		
5456–0	Rem.*	0·1 max		0·05–0·2			0·2 max	0·4 max	0·5–1·0	4·7–5·5		
7075–T6	Rem.*	1·2–2·0	0·7 max	0·18–0·4		5·1–6·1	0·2 max	0·2 max	0·3 max	2·1–2·9		
Stainless steels												
301 (full hard)			Rem.*	17	7							
304 (annealed)			Rem.*	19	10							
310–75% (cold worked)			Rem.*	25	20							
321 (annealed)			Rem.*	18	10		0·5					
410 (annealed)			Rem.*	12							0·05	0·3 N
Nitronic 33 60% (cold worked)				18	3·25				13			
Titanium alloys												
Ti–5Al–2·5Sn	4–6		0·5 max				Rem.*				0·1 max	2–3 Sn, 0·07 max N
Ti–6Al–4V	5·5–6·75		0·4 max				Rem.*				0·1 max	3·5–4·5 V, 0·07 max N
Superalloys												
Inconel X–750	0·7	0·2	7·0	15·5	Rem.*		2·5	0·25	0·5		0·04	1·0Nb
Inconel 718	0·5	0·2	18·5	19·0	Rem.*		0·9	0·2	0·2		0·04	3·0Mo, 5·0Nb
Copper alloys												
OFHC		99·95										0·07 max Pb
70Cu–30Zn		68·5–71·5	0·05 max			Rem.*						0·05 max Pb
70–30 Cupro-nickel (annealed)			0·4–0·7		29–33	1·0 max			1·0 max			

*Rem. = remainder.

4– RATING OF ORGANIC COATINGS

	Cost	Abrasion resistance	Flexibility	Adhesion	Resistance to atmosphere (salt spray)	Exterior durability	Colour retention	Resistance to chemicals (general)	Maximum service temperature rating
Alkyd	3	2	3	3	1	3	1	1	1
Amine-alkyd	3	3	2	3	1	3	1	1	2
Acrylic	2	2	3	2	3	3	3	1	1
Cellulose (Butyrate)	1	2	3	2	3	2	3	1	1
Epoxy	1	3	3	3	3	1	1	3	2
Epoxy ester	2	3	1	3	3	2	1	1	2
Fluorocarbon	0·5	1	1	2	3	3	1	3	2
Phenolic	2	3	1	3	3	3	0	2	2
Polyamide	2	3	1	2	1	0	2	1	2
Plastisol	3	3	3	2	3	2	1	3	1
Polyester (oil free)	2	2	2	3	3	2	2	1	1
Polyvinyl fluoride (PVF)	0·5	3	3	2	3	3	2	3	1
Polyvinylidene fluoride (PVF2)	0·5	3	3	2	3	3	2	3	1
Silicone	1	2	1	1	3	3	3	1	3
Silicone alkyd	1	2	1	2	2	3	2	2	3
Silicone polyester	1	2	2	2	3	3	2	2	3
Silicone acrylic	1	2	1	2	2	3	3	2	3
Vinyl	2	2	3	1	3	3	2	1	1
Vinyl alkyd	2	2	2	2	2	1	2	1	1
Polyvinyl chloride (PVC)	1	3	3	3	3	2	1	3	1
Neoprene (rubber)	3	3.	3	2	3	3	1	1	1
Urethane	0·5	3	3	3	3	3	1	1	2

5- Electrical Insulator

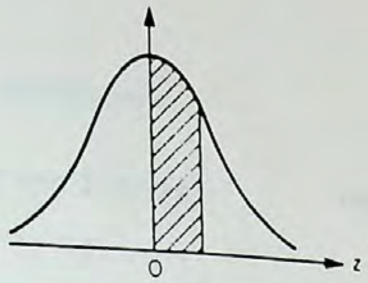
PROPERTIES OF SOME ELECTRICAL INSULATING MATERIALS

Material	*Dielectric constant (60 Hz)*	*Dielectric strength (volt/mil)*	*Volume resistivity (ohm/cm)*	*Dissipation factor (60 Hz)*	*Maximum operating temperature (K)*	*Tensile strength (MN/m^2)*	*Elongation (%)*	*Specific gravity*	*Thermal expansion coefficient m/m/K × 10^{-5}*	*Relative cost**
Organic materials										
Melamine	8·75	255	$1 \cdot 5 \times 10^{12}$	0·06	488	49	0·9	1·48	3·5	1·0
Urea	8·2	260	$10^{12 \cdot 5}$	0·04	408	55	1·0	1·5	5·2	1·2
Glass filled DAP	4·5	380	$10^{14 \cdot 5}$	0·03	423	62	10	1·75		2·3
PTFE	2·1	480	10^{18}	< 0·0002	394	24	300	2·17	9·5	8·8
CTFE	2·7	550	$1 \cdot 2 \times 10^{18}$	0·0012	388	49	200	1·8	14·4	16·8
ETFE	2·6	2000	10^{16}	0·0006	377	46	250	1·7	9	16·2
Polyphenylene oxide	2·6	525	10^{17}	0·0006	394	63	55	1·1	6·5	4·0
PVC	5	600	$10^{12 \cdot 5}$	0·12	347	17	250	1·35	13	1·1
Polysulphone	3·1	425	10^{14}	0·001	454	70	75	1·24	5·6	5·4
Polyethylene (low density)	2·25	750	$> 10^{16}$	0·0005	316	14	400	0·92	20	0·86
Polypropylene	2·2	550	$> 10^{16}$	0·0005	378	35	150	0·91	8·6	0·7
Inorganic materials										
Asbestos	6	6	2×10^{13}	0·1	588	1910		2·4	1	
Porcelain	6·8	150	5×10^{13}	0·014	643	42		2·5	0·6	
Alumina ($Al_2O_3 + SiO_2$)	9·0	350	10^{16}	0·001	1343	175		3·8	0·8	
Zircon ($ZrO_2 \cdot SiO_2$)	9·0	350	10^{15}	0·014	1143	91		3·6	0·5	
Boron nitride	4·2	1000	10^{14}	0·001	1073	25			0·43	
Fused silica	3·7	10	10^{13}	0·0002	1173	56		2·2	2·8	
Soda lime glass	7·5	0·4	10^{6}	0·04	523	14		2·5	45	
Muscovite mica	6·5	5000	10^{16}	0·0001	773	70		3·0	3200	

*Relative cost is cost relative to melamine which is considered as unity.

Appendix (8)
Mini ?ata Bank (cont.)

Reliability Data



Area under the Standard Normal Curve

Table presents value of area from $z = 0$ to indicated value of z.

z	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09
0.0	.00000	.00399	.00798	.01197	.01595	.01994	.02392	.02790	.03188	.03586
0.1	.03983	.04380	.04776	.05172	.05567	.05962	.06356	.06749	.07142	.07535
0.2	.07926	.08317	.08706	.09095	.09483	.09871	.10257	.10642	.11026	.11409
0.3	.11791	.12172	.12552	.12930	.13307	.13683	.14058	.14431	.14803	.15173
0.4	.15542	.15910	.16276	.16640	.17003	.17364	.17724	.18082	.18439	.18793
0.5	.19146	.19497	.19847	.20194	.20540	.20884	.21226	.21566	.21904	.22240
0.6	.22575	.22907	.23237	.23565	.23891	.24215	.24537	.24857	.25175	.25490
0.7	.25804	.26115	.26424	.26730	.27035	.27337	.27637	.27935	.28230	.28524
0.8	.28814	.29103	.29389	.29673	.29955	.30234	.30511	.30785	.31057	.31327
0.9	.31594	.31859	.32121	.32381	.32639	.32894	.33147	.33398	.33646	.33891
1.0	.34134	.34375	.34614	.34850	.35083	.35314	.35543	.35769	.35993	.36214
1.1	.36433	.36650	.36864	.37076	.37286	.37493	.37698	.37900	.38100	.38298
1.2	.38493	.38686	.38877	.39065	.39251	.39435	.39617	.39796	.39973	.40147
1.3	.40320	.40490	.40658	.40824	.40988	.41149	.41309	.41466	.41621	.41774
1.4	.41924	.42073	.42220	.42364	.42507	.42647	.42786	.42922	.43056	.43189
1.5	.43319	.43448	.43574	.43699	.43822	.43943	.44062	.44179	.44295	.44408
1.6	.44520	.44630	.44738	.44845	.44950	.45053	.45154	.45254	.45352	.45449
1.7	.45543	.45637	.45728	.45818	.45907	.45994	.46080	.46164	.46246	.46327
1.8	.46407	.46485	.46562	.46638	.46712	.46784	.46856	.46926	.46995	.47062
1.9	.47128	.47193	.47257	.47320	.47381	.47441	.47500	.47558	.47615	.47670
2.0	.47725	.47778	.47831	.47882	.47932	.47982	.48030	.48077	.48124	.48169
2.1	.48214	.48257	.48300	.48341	.48382	.48422	.48461	.48500	.48537	.48574
2.2	.48610	.48645	.48679	.48713	.48745	.48778	.48809	.48840	.48870	.48899
2.3	.48928	.48956	.48983	.49010	.49036	.49061	.49086	.49111	.49134	.49158
2.4	.49180	.49202	.49224	.49245	.49266	.49286	.49305	.49324	.49343	.49361
2.5	.49379	.49396	.49413	.49430	.49446	.49461	.49477	.49492	.49506	.49520
2.6	.49534	.49547	.49560	.49573	.49585	.49598	.49609	.49621	.49632	.49643
2.7	.49653	.49664	.49674	.49683	.49693	.49702	.49711	.49720	.49728	.49736
2.8	.49744	.49752	.49760	.49767	.49774	.49781	.49788	.49795	.49801	.49807
2.9	.49813	.49819	.49825	.49831	.49386	.49841	.49846	.49851	.49856	.49861
3.0	.49865	.49869	.49874	.49878	.49882	.49886	.49889	.49893	.49897	.49900
3.1	.49903	.49906	.49910	.49913	.49916	.49918	.49921	.49924	.49926	.49929
3.2	.49931	.49934	.49936	.49938	.49940	.49942	.49944	.49946	.49948	.49950
3.3	.49952	.49953	.49955	.49957	.49958	.49960	.49961	.49962	.49964	.49965
3.4	.49966	.49968	.49969	.49970	.49971	.49972	.49973	.49974	.49975	.49976
3.5	.49977	.49978	.49978	.49979	.49980	.49981	.49981	.49982	.49983	.49983
3.6	.49984	.49985	.49985	.49986	.49986	.49987	.49987	.49988	.49988	.49989
3.7	.49989	.49990	.49990	.49990	.49991	.49991	.49992	.49992	.49992	.49992
3.8	.49993	.49993	.49993	.49994	.49994	.49994	.49994	.49995	.49995	.49995
3.9	.49995	.49995	.49996	.49996	.49996	.49996	.49996	.49996	.49997	.49997
4.0	.49997									

Appendix 9

General Selection Computer Programme

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```
C     ****************************************************
C     ****************************************************
C     **                                                **
C     **             SELECTION OF MATERIALS             **
C     **                                                **
C     **    DATE  11/16/85          TIME  10:42:12.00   **
C     **                                                **
C     **             COMPUTER  NCR DM-V (PC)            **
C     **                                                **
C     ****************************************************
C     ****************************************************


      DIMENSION SS(30,30),SUMB(30),BETA(10,30),GAMA(30),A(30),R(10,10)
     1,SUM(10),ALPHA(10),GAMAR(30),IZ(10),TRGVAL(10),KTRGT(10),DELTA(30)
     1,DELTAR(30),RR(10,10),IRJCT(30)
      COMMON/COR/CF(30),CA(30),CI(30),CR(30),CD(30),CS(30),CC1(30)
      COMMON/COR1/CM(30),CC(30,30),CP(30,30)
      COMMON/OUT/RC(30)
      COMMON/REL/RS(10,30),SUMR(30)
      COMMON/RES/IR(10),RRS(10,30)
      REAL*8 SS,SUMB,BETA,GAMA,R,SUM,ALPHA,GAMAR,TRGVAL,RS,SUMR
      REAL*8 COUNT,DIFFER,XXX
      CHARACTER*15 DATFIL,REQFIL,SOLFIL
      CHARACTER*15 A
      CHARACTER*10 XXZ
      CHARACTER*1 KCOST,KREL,KRES,KTRG

C*****************************************************************
C*                    INITIALIZATION PHASE                       *
C*****************************************************************
C*  THE PROGRAM ACCEPTS THE NUMBER OF REQUIREMENTS USED IN THE   *
C*  VARIABLE "MAG" , AND THE NUMBER OF SOLUTIONS IN THE VARIABLE *
C*  "MAG1"                                                       *
C*****************************************************************

      WRITE(1) '  INPUT NUMBER OF REQUIREMENTS (2 digits) '
      READ(1,302)MAG
      WRITE(1) '  INPUT NUMBER OF SOLUTIONS (2 digits)  '
      READ(1,302)MAG1

C*****************************************************************
C*  THE PROGRAM ACCEPTS THE NAME OF THE FILE CONTAINING THE      *
C*  NAMES OF SOLUTIONS IN THE VARIABLE "SOLFIL"                  *
C*****************************************************************

  420 WRITE(1) ' FILE CONTAINING NAMES OF SOLUTIONS IS = '
      READ(1) SOLFIL
      IF(IOREAD(8,2,0,SOLFIL)) GOTO 420
      DO 430 J=1,MAG1
      READ(8,ENDFILE=440) A(J)
  430 CONTINUE
  440 IF(IOCLOS(8)) GOTO  4030
```

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```
C*****************************************************************
C*  THE PROGRAM ACCEPTS THE NAME OF THE FILE CONTAINING THE      *
C* VALUES OF THE CANDIDATE MATERIALS PROPERTIES IN THE VARIABLE *
C* "DATFIL"                                                      *
C*****************************************************************

 4035 WRITE(1) ' DATA FILE NAME IS = '
      READ(1) DATFIL
      IF(IOREAD(6,2,0,DATFIL)) GOTO 4000
      DO 4005 I=1,MAG
      READ(6,ENDFILE=4010)(RRS(I,J),J=1,MAG1)
      DO 6008 J=1,MAG1
 6008 RS(I,J)=RRS(I,J)
 4005 CONTINUE

C*****************************************************************
C*      PRINTING OF DATA FILE CONTAINED IN THE ARRAY RS(I,J)     *
C*****************************************************************

 4010 IF(IOCLOS(6)) GOTO 4030
      DO 4015 J=1,MAG1
      WRITE(4,4020)(RS(I,J),I=1,MAG)
      WRITE(4,4025)
 4015 CONTINUE

C*****************************************************************
C*  AS THERE ARE TWO TECHNIQUES TO SOLVE THE MATERIAL SELECTION *
C*  PROBLEM,THE VARIABLE "METHOD" IS USED TO CHOOSE ONE OF THEM *
C*****************************************************************

 3001 WRITE(1)'    TO APPLY <LIMITS ON PROPERTIES METHOD> ENTER 1 ,'
      WRITE(1,27)
      WRITE(1)'    TO APPLY <WEIGHTING FACTORS METHOD>    ENTER 2 :'
      READ(1,1130) METHOD

C*****************************************************************
C* 1-TO CALCULATE THE COST USING THE PROVIDED "COST" SUBROUTINE *
C*    ENTER <Y> FOR THE FLAG "KCOST" IF NOT ENTER <N>.           *
C* 2-TO CALCULATE THE RELIABILITY USING THE PROVIDED "MAXREL"    *
C*    AND "MINREL" SUBROUTINES ENTER <Y> FOR THE FLAG "KREL" IF  *
C*    NOT ENTER <N>.                                             *
C* 3-TO RESCALE THE VALUES OF A PROPERTY USING THE PROVIDED      *
C*    "RSCSUB" SUBROUTINE ENTER<Y> FOR THE FLAG "KRES" IF NOT    *
C*    ENTER <N>.                                                 *
C* 4-TO PERFORM THE CALCULATIONS WITH SOME TARGET VALUES ENTER   *
C*    <Y> FOR THE FLAG KTRG IF NOT ENTER <N>.                    *
C*****************************************************************


      WRITE(1,310)
  310 FORMAT(10X,'INPUT <Y> OR <N> FOR flags KCOST,KREL,KRES,KTRG',/)
      READ(1,15) KCOST,KREL,KRES,KTRG
      IF(METHOD.EQ.2) GOTO 3000
      IF(METHOD.EQ.1) GOTO 1300
      GOTO 3001
 3000 IF(KTRG.EQ."N")   GOTO 1300
```

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```
C*********************************************************************
C*  TRGVAL IS THE ARRAY CONTAINING THE TARGET VALUES                 *
C*********************************************************************

        WRITE(1,1100)
  1100 FORMAT(10X,'INPUT F5.1 TARGET VALUES FOR ALL REQUIREMENTS',/)
        READ(1,1110)(TRGVAL(I),I=1,MAG)

C*********************************************************************
C*  KTRGT IS AN ARRAY CONTAINING 1'S OR 0'S TO SPECIFY THE           *
C* PROPERTIES THAT HAVE TARGET VALUES                                *
C*********************************************************************

        WRITE(1,1120)
        READ(1,1130)(KTRGT(I) , I=1,MAG)
        DO 1140 I=1,MAG
        IF(KTRGT(I).EQ.0)   GOTO 1140
        DO 1135 J=1,MAG1
  1135 RS(I,J)=DABS(RS(I,J)-TRGVAL(I))
  1140 CONTINUE
  1300 M=MAG


C*********************************************************************
C*  ARRAYS CONTAINING COST VALUES ARE READ EITHER FROM CRT. OR *
C*  FROM DATA BANK ON MAGNETIC DISC                                  *
C*********************************************************************

        IF(KCOST.EQ."N")    GOTO  1000
        MAG=MAG+1
        WRITE(1) ' INPUT 1 TO PERFORM COSTSUB 0 TO ACCEPT COST FROM CRT'
        READ(1,305) LCOST
        IF(LCOST.EQ.1) GOTO 1170
        WRITE(1,1165)
        READ(1,1180)(RC(J),J=1,MAG1)
        GOTO 1190
  1170 WRITE(1,1150)
        READ(1,1160) INB,IQ
        WRITE(1,307)
        READ(1,5)(CF(J),J=1,MAG1)
        READ(1,5)(CA(J),J=1,MAG1)
        READ(1,5)(CI(J),J=1,MAG1)
        READ(1,5)(CR(J),J=1,MAG1)
        READ(1,5)(CD(J),J=1,MAG1)
        READ(1,5)(CS(J),J=1,MAG1)
        READ(1,5)(CC1(J),J=1,MAG1)
        READ(1,5)(CM(J),J=1,MAG1)
        WRITE(1,313)
        DO 65 I=1,INB
        READ(1,5)(CC(I,J),J=1,MAG
   65 CONTINUE
        DO 75 I=1,INB
        READ(1,5)(CP(I,J),J=1,MAG1)
   75 CONTINUE
        CALL COST(MAG1,INB,QI)
  1190 DO 501 J=1,MAG1
   501 RS(MAG+1,J)=RC(J)
```

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```
C*****************************************************************
C*                  RELIABILITY CALCULATIONS                     *
C*****************************************************************

 1000 IF(KREL.EQ."N")   GOTO  1010
      MAG=MAG+1
      M=MAG-1
      IF(KCOST.EQ."Y")   M=M-1

C*****************************************************************
C*  IRELF  IS A FLAG THAT HAS ZERO VALUE IN CASE OF NO DATA      *
C*  AND 1 VALUE IN CASE OF AVAILABLE DATA FOR RELIABILITY        *
C*****************************************************************

      WRITE(1,3010)
 3010 FORMAT(10X,'TO CALCULATE RELIABILITY ENTER :',/,10X,'0 FOR NODATA
     1',/,10X,'1 FOR AVAILABLE DATA')
      READ(1,3020) IRELF
 3020 FORMAT(I1)
      IF(IRELF.EQ.0) GOTO 3100
      READ(1,3400)T,LAM,ALFA,ST,AV,N
 3400 FORMAT(5F3.1,I1)
      CALL CALREL(T,LAM,ALFA,ST,AV,N)
      GOTO 3050

C*****************************************************************
C* IZ IS THE ARRAY CONTAINING 1,S OR 0'S DEPENDING ON WHETHER   *
C* THE PROPERTY IS REQUIRED TO BE HIGH OR LOW                   *
C*****************************************************************

 3100 WRITE(1,308)
  308 FORMAT(10X,'INPUT 0,1s STRING FOR IZ , 1 FOR HIGH & 0 FOR LOW',/)
      READ(1,305)(IZ(J),J=1,M)
      DO 502 J=1,MAG1
  502 SUMR(J)=0.0
      COUNT=0.0
      DO 503 I=1,M
      IF(IZ(I).EQ.1) CALL MAXREL(I,MAG1,COUNT)
      IF(IZ(I).EQ.0) CALL MINREL(I,MAG1,COUNT)
  503 CONTINUE
      DO 553 J=1,MAG1
      SUMR(J)=SUMR(J)*(9.0/COUNT)
      INTR=IDINT(SUMR(J))
      RS(M+1,J)=FLOAT(INTR)
      DIFFER=SUMR(J)-FLOAT(INTR)
      IF(DIFFER.LT.0.5) GOTO 553
      RS(M+1,J)=RS(M+1,J)+1.0
  553 CONTINUE
 1010 CONTINUE
C*****************************************************************
C*                   SCALING CALCULATIONS                        *
C*****************************************************************

 3050 IF(METHOD.NE.2) GOTO 3003
      IF(KRES.EQ."N")   GOTO 1022
      WRITE(1,559)
```

```
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C*****************************************************************
C* IR IS THE ARRAY CONTAINING 1,S OR 0'S FOR HIGH OR LOW         *
C* SCALING 1 FOR HIGH , 0 FOR LOW , ELSE FOR NO SCALING          *
C*****************************************************************


      READ(1,305)(IR(I),I=1,M)
      DO 167 I=1,M
      CALL RSCSUB(I,MAG1)
  167 CONTINUE
 1022 CONTINUE
      GOTO 1020




C*****************************************************************
C* IR IS THE ARRAY CONTAINING 1,S OR 0'S FOR UPPER OR LOWER      *
C* LIMITING 2 FOR PROPERTIES HAVING TARGET VALUES                *
C*****************************************************************

 3003 WRITE(1,3004)
 3004 FORMAT('   INPUT 0 FOR LOW L.,1 FOR HIGH L.,2 FOR TARGET V.'/)
      READ(1,305)(IR(I),I=1,MAG)

C*****************************************************************
C*  PRINTING A HEADER FOR THE ARRAY CONTAINING THE WEIGHTING     *
C*                         FACTORS                               *
C*****************************************************************

 1020 WRITE(4,1)
      DO 400 I=1,MAG
  400 WRITE(4,9000) I
      WRITE(4,727)
      DO 401 I=1,MAG
  401 WRITE(4,8001)
      WRITE(4,27)

C*****************************************************************
C* THE PROGRAM ACCEPTS THE NAME OF THE FILE CONTAINING THE       *
C* WEIGHTING FCCTORS IN THE VARIABLE "REQFIL"                    *
C*****************************************************************

  410 WRITE(1) ' THE NAME OF WEIGHTING FACTORS FILE IS = '
      READ(1) REQFIL
      IF(IOREAD(7,2,0,REQFIL)) GOTO 410
      DO 5000 I=1,MAG
      READ(7,ENDFILE=5010)(RR(I,J),J=1,MAG)
      DO 1985 J=1,MAG
 1985 R(I,J)=RR(I,J)
 5000 CONTINUE
 5010 IF(IOCLOS(7)) GOTO  4030

C*****************************************************************
C*                  PRINTING THE WEIGHTING FACTORS ARRAY         *
C*****************************************************************

      DO 403 I=1,MAG
      WRITE(4,8002) I
      WRITE(4,8003) (R(I,J),J=1,MAG)
  403 CONTINUE
```

```

C*****************************************************************
C*                 CACULATIONS FOR THE ARRAY "ALPHA"             *
C*****************************************************************

        DO 30 I=1,MAG
        SUM(I)=0.0
        DO 20 J=1,MAG
     20 SUM(I)=SUM(I)+R(I,J)
        ALPHA(I)=SUM(I)/(MAG*(MAG-1)/2)
     30 CONTINUE




C*****************************************************************
C*                 PRINTING THE ARRAY "ALPHA"                    *
C*****************************************************************

        WRITE(4,27)
        DO 92 I=1,MAG
        WRITE(4,4)I,ALPHA(I)
     92 CONTINUE
        IF(METHOD.EQ.1) GOTO 2000

C*****************************************************************
C*  CALCULATIONS FOR THE SOLUTIONS VRS. SOLUTIONS MATRIX "SS"    *
C*  FOR EACH REQUIREMENT                                         *
C*****************************************************************

        WRITE(4,6006)
        DO 130 I=1,MAG
        WRITE(4,6)I
        DO 90 K=1,MAG1
        DO 80 J=K+1,MAG1
        SS(K,K)=0.0
        SS(K,J)=RS(I,K)/(RS(I,K)+RS(I,J))
        GOTO 700
        IF(RS(I,K).EQ.RS(I,J)) GOTO 500
        IF(RS(I,K).GT.RS(I,J)) GOTO 600
        SS(K,J)=0.0
        GOTO 700
    500 SS(K,J)=0.5
        GOTO 700
    600 SS(K,J)=1.0
    700 CONTINUE
        SS(J,K)=1.0-SS(K,J)
     80 CONTINUE
     90 CONTINUE

C*****************************************************************
C*   PRINTING THE SOLUTIONS VRS.SOLUTIONS MATRIX "SS"            *
C*   FOR EACH REQUIREMENT                                        *
C*****************************************************************

        DO 110 J=1,MAG1
        WRITE(4,7)A(J)
        IF(MAG1.LT.10) GOTO 133
        WRITE(4,6007)(SS(J,K),K=1,MAG1)
        GOTO 143

```

```
  133 WRITE(4,6002)
      WRITE(4,6003)(SS(J,K),K=1,MAG1)

C****************************************************************
C*    CALCULATIONS FOR THE SOLUTIONS WEIGHTING ARRAY "BETA"     *
C*    FOR EACH REQUIREMENT                                      *
C****************************************************************

  143 SUMB(J)=0.0
      DO 100 L=1,MAG1
  100 SUMB(J)=SUMB(J)+SS(J,L)
  110 BETA(I,J)=SUMB(J)/(MAG1*(MAG1-1)/2.0)



C****************************************************************
C*    PRINTING THE SOLUTIONS WEIGHTING ARRAY "BETA"             *
C*    FOR EACH REQUIREMENT                                      *
C****************************************************************

      WRITE(4,27)
      WRITE(4,27)
      DO 120 MM=1,MAG1
      WRITE(4,8)I,MM,BETA(I,MM)
  120 CONTINUE
      WRITE(4,6006)
  130 CONTINUE

C****************************************************************
C*    PRINTING THE SOLUTIONS WEIGHTING ARRAY "BETA"             *
C*    FOR ALL THE REQUIREMENTS                                  *
C****************************************************************

      WRITE(4,1)
      DO 417 I=1,MAG
  417 WRITE(4,8000) I
      WRITE(4,727)
      DO 418 I=1,MAG
  418 WRITE(4,8001)
      WRITE(4,27)
      DO 140 IM=1,MAG1
      WRITE(4,9)A(IM)
      WRITE(4,409)(BETA(L,IM),L=1,MAG)
  140 CONTINUE

C****************************************************************
C*            CALCULATIONS & PRINTING FOR THE ARRAY "GAMA"      *
C****************************************************************

      WRITE(4,27)
      DO 160 J=1,MAG1
      GAMA(J)=0.0
      DO 150 I=1,MAG
  150 GAMA(J)=GAMA(J)+ALPHA(I)*BETA(I,J)
  160 CONTINUE
      DO 95 J=1,MAG1
      WRITE(4,11)J,GAMA(J)
   95 CONTINUE
```

```
C*****************************************************************
C*    SORTING PROCEDURE FOR THE ARRAY "GAMA"                     *
C*    THEN CALCULATING THE ARRAY "GAMAR"                         *
C*****************************************************************

      DO 666 KK=1,MAG1-1
      DO 333 I=1,MAG1-1
      J=I+1
      IF(GAMA(I).GT.GAMA(J)) GO TO 333
      XXX=GAMA(I)
      GAMA(I)=GAMA(J)
      GAMA(J)=XXX
      XXZ=A(I)
      A(I)=A(J)
      A(J)=XXZ
  333 CONTINUE
  666 CONTINUE
      DO 190 I=1,MAG1
  190 GAMAR(I)=(GAMA(I)*100.0)/GAMA(1)

C*****************************************************************
C*   PRINTING THE FINAL RESULTS IN THE FORM OF 3 COLUMNS         *
C*   THE NAME OF THE MATERIAL , ITS GAMA & GAMAR VALUES.         *
C*****************************************************************

      WRITE(4,6006)
      DO 200 I=1,MAG1
  200 WRITE(4,12)A(I),GAMA(I),GAMAR(I)

C*****************************************************************
C*                END OF WEIGHTING FACTORS METHOD                *
C*****************************************************************
      STOP

C*****************************************************************
C*                START OF LIMITS ON PROPERTIES METHOD           *
C*****************************************************************

 2000 DO 2010 J=1,MAG1
      DELTA(J)=0.0
 2010 CONTINUE

C*****************************************************************
C*    TRGVAL IS THE ARRAY THAT ACCEPTS THE UPPER LIMIT VALUES    *
C*    THE LOWER LIMIT VALUES & THE TARGET VALUES                 *
C*****************************************************************

      WRITE(1,1999)
 1999 FORMAT(10X,'INPUT F9.4 LIMITS & TARGET VALUES ',/)
      READ(1,1110)(TRGVAL(I),I=1,MAG)

C*****************************************************************
C*    THE FOLLOWING IS THE SCREENING OPERATION PERFORMED         *
C*    BY INTRODUCING AN INTEGER ARRAY "IRJCT" HAVING 0 OR 1      *
C*    VALUES FOR "REJECTED" OR "ACCEPTED" MATERIALS .            *
C*    "REJECTED" MATERIALS ARE THOSE HOW TRANSGRESS LIMITS.      *
C*****************************************************************

      DO 2222 J=1,MAG1
      IRJCT(J)=1
```

```
 2222 CONTINUE
      DO 2200 I=1,MAG
      IF(IR(I).EQ.2) GOTO 2400
      IF(IR(I).EQ.1) GOTO 2300
      DO 2210 J=1,MAG1
      IF(RS(I,J).LT.TRGVAL(I)) IRJCT(J)=0
 2210 CONTINUE
      GOTO 2200
 2300 DO 2310 J=1,MAG1
      IF(RS(I,J).GT.TRGVAL(I)) IRJCT(J)=0
 2310 CONTINUE
      GOTO 2200
 2400 DO 2410 J=1,MAG1
      IF(RS(I,J).GT.(10*TRGVAL(I))) IRJCT(J)=0
 2410 CONTINUE
 2200 CONTINUE
C************************************************************************
C*                 CALCULATIONS OF THE ARRAY "DELTA"                   *
C************************************************************************
      DO 2500 I=1,MAG
      IF(IR(I).EQ.2) GOTO 2700
      IF(IR(I).EQ.1) GOTO 2600
      DO 2510 J=1,MAG1
      DELTA(J)=DELTA(J)+(TRGVAL(I)/RS(I,J))*ALPHA(I)
 2510 CONTINUE
      GOTO 2500
 2600 DO 2610 J=1,MAG1
      DELTA(J)=DELTA(J)+(RS(I,J)/TRGVAL(I))*ALPHA(I)
 2610 CONTINUE
      GOTO 2500
 2700 DO 2710 J=1,MAG1
      VALUE=TRGVAL(I)/RS(I,J)-1
      DELTA(J)=DELTA(J)+(ABS(VALUE))*ALPHA(I)
 2710 CONTINUE
 2500 CONTINUE
C************************************************************************
C*  DELTA ENTRIES CORRESPONDING TO "REJECTED" MATERIALS ARE             *
C*  GIVEN LARGE VALUES (100) TO MAKE THEM FALL TO THE BOTTOM            *
C*                         OF THE LIST                                  *
C************************************************************************
      DO 2800 J=1,MAG1
      IF(IRJCT(J).EQ.1) GOTO 2800
      DELTA(J)=100.0
 2800 CONTINUE
C************************************************************************
C*                DELMIN CONTAINS THE MINIMUM VALUE                     *
C*                     FOR THE ARRAY "DELTA"                            *
C************************************************************************
      DELMIN=DELTA(1)
      DO 2100 J=1,MAG1
      DELMIN=AMIN1(DELMIN,DELTA(J))
 2100 CONTINUE
```

```
C*********************************************************************
C*                 CALCULATIONS OF 'DELTAR'                          *
C*********************************************************************

      DO 2110 J=1,MAG1
      DELTAR(J)=(DELMIN/DELTA(J))*100.0
 2110 CONTINUE

C*********************************************************************
C*             SORTING PROCEDURE FOR DELTA ARRAY                     *
C*********************************************************************

      DO 2120 KK=1,MAG1-1
      DO 2130 II=1,MAG1-1
      JJ=II+1
      IF(DELTAR(II).GT.DELTAR(JJ)) GOTO 2130
      XXX=DELTAR(II)
      DELTAR(II)=DELTAR(JJ)
      DELTAR(JJ)=XXX
      XXX=DELTA(II)
      DELTA(II)=DELTA(JJ)
      DELTA(JJ)=XXX
      XXZ=A(II)
      A(II)=A(JJ)
      A(JJ)=XXZ
 2130 CONTINUE
 2120 CONTINUE

C*********************************************************************
C*                 PRINTING THE FINAL RESULTS                        *
C*********************************************************************

      DO 2150 J=1,MAG1
      IF(DELTA(J).EQ.100.0) GOTO 2830
      WRITE(4,12) A(J),DELTA(J),DELTAR(J)
      GOTO 2150
 2830 WRITE(4,2888) A(J)
 2150 CONTINUE

C*********************************************************************
C*             END OF LIMITS ON PROPERTIES METHOD                    *
C*********************************************************************
      STOP

C*********************************************************************
C*                   DISPLAYED MESSAGES                              *
C*********************************************************************

 4000 WRITE(1) ' THERE IS NO FILE UNDER THAT NAME '
      GOTO 4035
 4030 WRITE(1) ' CANNOT CLOSE THE FILE '

C*********************************************************************
C*             THE FORMATS USED THROUGHOUT THE PROGRAM               *
C*********************************************************************

   12 FORMAT('0',2X,A11,2(5X,F14.10))
 2888 FORMAT('0',2X,A11,5X,'REJECTED')
   11 FORMAT(5X,'GAMA(',I2,') = ',F14.12)
    9 FORMAT('0',2X,A11,':'$
```

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```
6006 FORMAT('1')
   8 FORMAT(5X,'BETA(',I2,',',I2,') = ',F10.9)
6007 FORMAT(5X,15(F4.2,1X))
6002 FORMAT(5X$
6003 FORMAT(F3.1,' '$
   7 FORMAT(3X,A11)
   6 FORMAT(35X,'REQUIREMENT NO. ',I2)
   5 FORMAT(16F5.1)
   4 FORMAT(5X,'ALPHA(',I2,') = ',F4.3)
   1 FORMAT(12X$
 559 FORMAT(10X,'INPUT 0,1s VALUES FOR IR(I) ,0 FOR LOW & 1 FOR HIGH',/)
  27 FORMAT('0')
  17 FORMAT(3X,F14.10$
 305 FORMAT(I1)
 313 FORMAT(10X,'INPUT 16F5.1 VALUES FOR CC(I,J)&CP(I,J)',/)
 307 FORMAT(10X,'INPUT 16F5.1 VALUES FOR CF.CA,CI,CR,CD,CS,CC,CM',/)
1160 FORMAT(2I2)
1150 FORMAT(10X,'INPUT I2 VALUES FOR INB & IQ',/)
1180 FORMAT(F5.1)
1165 FORMAT(10X,'INPUT F5.1 VALUES FOR THE COSTS',/)
1130 FORMAT(I1)
1120 FORMAT(10X,'INPUT 0,1s VALUES FOR KTARGET(I) 1 IF ANY 0 IF NOT',/)
1110 FORMAT(F9.4)
  15 FORMAT(4A1)
4025 FORMAT('0')
4020 FORMAT(3X,F8.3$
 302 FORMAT(I2)
8000 FORMAT(3X,'R',I2,2X$
 727 FORMAT('0',11X$
8001 FORMAT(8(1H=)$
8002 FORMAT('0',7X,'R',I2$
8003 FORMAT(4X,F4.2$
 409 FORMAT(2X,F6.5$
     STOP
     END
```

```
**************************************************************
*                                                            *
*      REFERENCE TO ALL LABLES USED THROUGHOUT               *
*              THE MAIN PROGRAM                              *
*                                                            *
**************************************************************

000302-3D1E   000420-003C   000430-007F          000440-0082
004030-110B   004035-008D   004000-10FA          004005-010D
004010-0110   006008-00F3   004015-0158          004020-3D18
004025-3D12   003001-015B   000027-3CC4          001130-3CFA
000310-3C04   000015-3D0C   003000-01D4          001300-0292
001100-3C10   001110-3D06   001120-3D00          001140-028F
001135-0268   001000-0513   000305-3CD0          001170-030D
001165-3CF4   001180-3CEE   001190-04EE          001150-3CE8
001160-3CE2   000307-3CDC   000005-3CAC          000313-3CD6
000065-04AE   000075-04E6   000501-04F8          001010-06BF
003010-3C2E   003020-3C34   003100-05A5          003400-3C3A
003050-06BF   000308-3C40   000502-05DF          000503-062A
000553-06BC   003003-0720   001022 07[illegible] 00055[illegible]-3CBE
000167-071A   001020-0750   003004-3C4C          000001-3C88
000400-0762   008000-3D24   000727-3D2A          000401-0785
008001-3D30   000410-0798   005000-0818          005010-081B
001985-07FE   000403-0869   008002-3D36          008003-3D3C
```

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000030-08CB      000020-088D      000092-08F8      000004-3CB2
002000-0D45      006006-3C82      000130-0B3F      000006-3CA6
000090-0A0E      000080-0A0B      000700-09F0      000500-09CD
000600-09E0      000110-0AD0      000007-3CA0      000133-0A69
006007-3C8E      000143-0A9C      006002-3C94      006003-3C9A
000100-0AB3      000120-0B34      000003-[illegible]      000417-0B54
000418-0B77      000140-0BD1      000009-3C7C      000409-3D42
000160-0C22      000150-0BFD      000095-0C47      000011-3C76
000666-0CDA      000333-0CD7      000190-0CE7      000200-0D19
000012-3C6A      002010-0D5A      001999-3C58      002222-0DA2
002200-0E69      002400-0E35      002300-0E04      002210-0DFE
002310-0E2F      002410-0E66      002500-0F64      002700-0F16
002600-0ED8      002510-0ED2      002610-0F10      002710-0F61
002800-0F8E      002100-0FB6      002110-0FDA      002120-109A
002130-1097      002150-10F4      002830-10E2      002888-3C70
000017-3CCA

*****************************************************************
*                                                               *
*            LIST OF ALL VARIABLES USED THROUGHOUT              *
*                      THE MAIN PROGRAM                         *
*                                                               *
*                                                               *
*****************************************************************

SS     -3A42,.DATA. D A             SUMS   -3A48,.DATA. D A
BETA   -3A4E,.DATA. D A             GAMA   -3A54,.DATA. D A
A      -3B0E,.DATA. S A             R      -3B14,.DATA. D A
SUM    -3B1A,.DATA. D A             ALPHA  -3B20,.DATA. D A
GAMAR  -3B26,.DATA. D A             IZ     -3B2C,.DATA. I A
TRGVAL-3B32,.DATA. D A              KTRGT  -3B38,.DATA. I A
DELTA  -3B3E,.DATA. R A             DELTAR-3B44,.DATA. R A
RR     -3B4A,.DATA. R A             IRJCT  -3B50,.DATA. I A
CF     -3B56,.DATA. R A C           CA     -3B5C,.DATA. R A C
CI     -3B62,.DATA. R A C           CR     -3B68,.DATA. R A C
CD     -3B6E,.DATA. R A C           CS     -3B74,.DATA. R A C
CCI    -3B7A,.DATA. R A C           CM     -3B80,.DATA. R A C
CC     -3B86,.DATA. R A C           CP     -3B8C,.DATA. R A C
RC     -3B92,.DATA. R A C           RS     -3B98,.DATA. D A C
SUMR   -3B9E,.DATA. D A C           IR     -3BA4,.DATA. I A C
RRS    -3BAA,.DATA. R A C           COUNT  -3106,.DATA. D     VD
DIFFER-310E,.DATA. D     VD         XXX    -3116,.DATA. D     VD
DATFIL-3BB0,.DATA. S      D         REQFIL-3BB6,.DATA. S      D
SOLFIL-3BBC,.DATA. S      D         XXZ    -3BC2,.DATA. S     VD
KCOST  -3BC8,.DATA. S     VD        KREL   -3BCE,.DATA. S     VD
KRES   -3BD4,.DATA. S     VD        KTRG   -3BDA,.DATA. S     VD
MAG    -3189,.DATA. I     VD        MAGI   -31C8,.DATA. I     VD
IOREAD-0000,IOREAD I     E          J      -320D,.DATA. I     VD
IOCLOS-0000,IOCLOS I     E          I      -3246,.DATA. I     VD
METHOD-32D8,.DATA. I     VD         DABS   -0000,DABS   R    E
M      -3360,.DATA. I     VD        LCOST  -33BD,.DATA. I     VD
INB    -33DB,.DATA. I     VD        IQ     -33E4,.DATA. I      D
COST   -0000,COST   R    E          Q:     -343A,.DATA. R      D
IRELF  -34AC,.DATA. I     VD        1      -34B9,.DATA. R      D
LAM    -34C4,.DATA. I      D        ALFA   -34C6,.DATA. R      D
ST     -34CA,.DATA. R      D        AV     -34CE,.DATA. R      D
N      -34D2,.DATA. I      D        CALREL-0000,CALREL R    E
MAXREL-0000,MAXREL I    E           MINREL-0000,MINREL I    E
INTR   -3556,.DATA. I      D        IDINT  -0000,IDINT  I    E
FLOAT  -0000,FLOAT  R    E          RSCSUB-0000,RSCSUB R    E
K      -365D,.DATA. I     VD        L      -367D,.DATA. I     VD
```

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MM     -3691,.DATA. I       VD     IM     -36C4,.DATA. I      VD
KK     -36E2,.DATA. I        D     VALUE -3734,.DATA. R        D
ABS    -0000,ABS     R    E        DELMIN-373C,.DATA. R       VD
AMIN1  -0000,AMIN1   R    E        II     -3749,.DATA. I      VD
JJ     -374D,.DATA. I       VD

>>> PRGM LEN = 111C     >>> DATA LEN = 3D48

END MODULE




C****************** SUBROUTINE COST *************************

      SUBROUTINE COST(N,NB,Q)
      DIMENSION UCF(30),SPF(30)
      COMMON/COR/CF(30),CA(30),CI(30),CR(30),CD(30),CS(30),CC1(30)
      COMMON/COR1/CM(30),CC(30,30),CP(30,30)
      COMMON/OUT/RC(30)
      DO 40 J=1,N
      SUM=0.0
      DO 30 L=1,NB
      SUM=SUM+CC(L,J)*CP(J,J)
   30 CONTINUE
      FIXEDC=CF(J)+CA(J)+CI(J)
      VRIBLC=CR(J)+CD(J)+CS(J)+CC1(J)
      UCF(J)=FIXEDC+VRIBLC+SUM
      SPF(J)=(1+CM(J))*UCF(J)
      IF(Q.EQ.1) GO TO 40
      RC(J)=UCF(J)
      RETURN
   40 RC(J)=SPF(J)
      CONTINUE
  999 RETURN
      END
********** LABLE REFERENCES IN SUBROUTINE COST ************

000040-00D4      000030-0043      000999-00E6

********** LIST OF VARIABLES IN SUBROUTINE COST **********

N      -0000,.DATA. I     P V      NB     -0002,.DATA. I     P V
Q      -0004,.DATA. R     P V      UCF    -0110,.DATA. R A
SPF    -0116,.DATA. R A            CF     -011C,.DATA. R A C
CA     -0122,.DATA. R A C          CI     -0128,.DATA. R A C
CR     -012E,.DATA. R A C          CD     -0134,.DATA. R A C
CS     -013A,.DATA. R A C          CC1    -0140,.DATA. R A C
CM     -0146,.DATA. R A C          CC     -014C,.DATA. R A C
CP     -0152,.DATA. R A C          RC     -0158,.DATA. R      VD
J      -00F6,.DATA. I      VD      SUM    -00FC,.DATA. R      VD
L      -0104,.DATA. I      VD      FIXEDC-0108,.DATA. R
VRIBLC-010C,.DATA. R       VD
>>> PRGM LEN = 00E7     >>> DATA LEN = 015E

END MODULE
```

```
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C***************** SUBROUTINE MAXREL **********************

      SUBROUTINE MAXREL(I,MAG1,COUNT)
      COMMON/REL/RS(10,30),SUMR(30)
      REAL*8 RS,SUMR,COUNT,REMAX,DMAX1
      COUNT=COUNT+1.0
      REMAX=RS(I,1)
      DO 550 L1=2,MAG1
  550 REMAX=DMAX1(REMAX,RS(I,L1))
      DO 551 L1=1,MAG1
  551 SUMR(L1)=SUMR(L1)+RS(I,L1)/REMAX
      RETURN
      END
********* LABLE REFERENCES IN SUBROUTINE MAXREL ***********

000550-002E      000551-0051

********* LIST OF VARIABLES IN SUBROUTINE MAXREL **********

                                       MAG1   -0002,.DATA. I      P V
I      -0000,.DATA. I      P V         RS     -0023,.DATA. D A C
COUNT  -0004,.DATA. D      P VD        REMAX  -0006,.DATA. D        VD
SUMR   -0029,.DATA. D A C              L1     -0014,.DATA. I        VD
DMAX1  -0000,DMAX1  D        E

>>> PRGM LEN = 0073     >>> DATA LEN = 002F

END MODULE


C***************** SUBROUTINE MINREL **********************

      SUBROUTINE MINREL(I,MAG1,COUNT)
      COMMON/REL/RS(10,30),SUMR(30)
      REAL*8 RS,SUMR,COUNT,REMIN,DMIN1
      COUNT=COUNT+1.0
      REMIN=RS(I,1)
      DO 552 L1=2,MAG1
  552 REMIN=DMIN1(REMIN,RS(I,L1))
      DO 553 L1=1,MAG1
  553 SUMR(L1)=SUMR(L1)+REMIN/RS(I,L1)
      RETURN
      END
********* LABLE REFERENCES IN SUBROUTINE MINREL ***********

000552-002E      000553-0051

********* LIST OF VARIABLES IN SUBROUTINE MINREL **********

                                       MAG1   -0002,.DATA. I      P V
I      -0000,.DATA. I      P V         RS     -0023,.DATA. D A C
COUNT  -0004,.DATA. D      P VD        REMIN  -0006,.DATA. D        VD
SUMR   -0029,.DATA. D A C              L1     -0014,.DATA. I        VD
DMIN1  -0000,DMIN1  D        E

>>> PRGM LEN = 0073     >>> DATA LEN = 002F
```

```
END MODULE



C***************** SUBROUTINE RSCSUB ***********************

      SUBROUTINE RSCSUB(I,MAG1)
      COMMON/REL/RS(10,30),SUMR(30)
      COMMON/RES/IR(10),RRS(10,30)
      REAL*8 VALU,BMIN,BMAX,DMAX1,DMIN1,RS
      BMAX=RS(I,1)
      BMIN=RS(I,1)
      DO 554 J=2,MAG1
      BMAX=DMAX1(BMAX,RS(I,J))
      BMIN=DMIN1(BMIN,RS(I,J))
  554 CONTINUE
      DO 555 J=1,MAG1
      VALU=(RS(I,J)-BMIN)*(100-1)/(BMAX-BMIN)
      IF(IR(I).EQ.0) RS(I,J)=100.0-VALU
      IF(IR(I).EQ.1) RS(I,J)=1.0 + VALU
  555 CONTINUE
      RETURN
      END

********* LABLE REFERENCES IN SUBROUTINE RSCSUB ***********

000554-0055      000555-00CF

********* LIST OF VARIABLES IN SUBROUTINE RSCSUB **********

I      -0000,.DATA. I    P V      MAG1   -0002,.DATA. I    P V
RS     -0040,.DATA. D A C         SUMR   -0046,.DATA. R A C
IR     -004C,.DATA. I A C         RRS    -0052,.DATA. R A C
VALU   -0004,.DATA. D      VD     BMIN   -000C,.DATA. D      VD
BMAX   -0014,.DATA. D      VD     DMAX1  -0000,DMAX1  D    E
DMIN1  -0000,DMIN1  D    E        J      -001E,.DATA. I      VD

>>> PRGM LEN = 00D3    >>> DATA LEN = 0058

END MODULE


C***************** SUBROUTINE CALCREL **********************

      SUBROUTINE CALREL(T,LAM,ALFA,ST,AV,N)
      PI=3.14159
      IF(N.EQ.1) GOTO 3310
      IF(N.EQ.2) GOTO 3320
      PDF=(T**2-AV**2)
      BBB=(2*(2*PI)**.5)*((ST**2)*AV*(T**2))
      BBB=BBB*((T/AV)**.5)-((AV/T)**.5)
      PDF=PDF/BBB
      PDF=PDF*EXP(-(T/AV+AV/T-2)/(2*ALFA**2))
      RLIBL=1-PDF
      GOTO 3330
 3310 RL!BL=EXP(-LAM*T)
      GOTO 3330
 3320 BBB=(((ALOG(T)-AV)**2)/(2*ST**2))/(T*ST*(2*PI)**.5)
      PDF=EXP(BBB)
```

```
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0019        RLIBL=1-PDF
0020   3330 RETURN
0021        END

******** LABLE REFERENCES IN SUBROUTINE CALCREL ***********

003310-00E1     003320-00F7     003330-0148

******** LIST OF VARIABLES IN SUBROUTINE CALCREL **********

T      -0000,.DATA. R    P VD    LAM   -0002,.DATA. I    P V
ALFA   -0004,.DATA. R    P V     ST    -0006,.DATA. R    P V
AV     -0008,.DATA. R    P V     N     -000A,.DATA. I    P V
PI     -000C,.DATA. R      VD    PDF   -0018,.DATA. R     VD
BBB    -001C,.DATA. R      VD    EXP   -0000,EXP    R     E
RLIBL  -0028,.DATA. R       D    ALOG  -0000,ALOG   R     E

>>> PRGM LEN = 014C     >>> DATA LEN = 0034

END MODULE

END COMPILATION PHASE 1
```