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A METHOD FOR PROCESS COMPUTER ALARM ANALYSIS

By

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A Doctoral Thesis

Submitted in partial fulfilment of the requirements

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A B S T R A C T

Computer-controlled process plants are sometimes equipped with alarm systems. The purpose of these systems is to warn the operator of abnormal plant conditions in order that he may take remedial action or shut down the plant. The systems are based on programs which compare the values of process variables with preset alarm limits. Abnormal conditions are usually reported to the operator by means of a special teletype. On most plants, the operator is then expected to analyse the "pattern" of alarms and thereby diagnose the cause of the trouble. The time available for this diagnosis may be extremely limited and the penalty for maloperation may be high. The operator is therefore under considerable stress.

Some of the nuclear power stations currently being built use computer-based alarm analysis systems. These systems require large amounts of information on the cause-and-effect relationships between alarms. The preparation of this data is a laborious task requiring several man-years of effort. The present work is aimed at reducing this effort in order that the use of alarm analysis schemes may become a more attractive proposition.

Methods based on mathematical models have been developed which are applicable to any process plant. The type of model used depends on the nature of the information required for a particular application. Two types of model are considered in detail for the present study. The methods used rely heavily on special computational techniques first developed by workers in the field of Artificial Intelligence. In particular, the use of lists and chained data structures is central to the solution of the problem as presented here.

The present study is entirely based on an off-line computer since the emphasis of the work is on the preparation of the data for the on-line machine although some modifications to the methods used by the on-line machine are proposed. The work is also orientated towards the use of cathode ray tubes as alarm display devices since these are more suited to an orderly presentation of information than the conventional type of alarm panel.

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CHAPTER 1

INTRODUCTION

The modern chemical processing plant is generally an expensive, complex system. The widespread use of analogue controllers and the increased tendency to locate control and monitoring equipment in one central control room has led to a reduction in the number of personnel required to operate such plants.

A consequence of the use of small plant operating teams is that, when a plant fault or disturbance occurs, the available operators are heavily loaded. In many cases, an operator will be required to monitor several hundred variables. In order to direct his attention to the first signs of trouble, many plants are equipped with alarm systems. These systems rely on the assumption that, during normal operation, the measured variables will not stray outside of a certain band of values. The limits within which the plant is deemed to be normal are known as "alarm limits". Equipment manufacturers frequently insist on particular alarm limits. When a variable strays outside of its alarm limits, the operator's attention is drawn to the fact by the use of audible and visual warnings. The audible warning normally consists of a klaxon or siren. The visual warning is displayed to the operator via a coloured (normally white or yellow but sometimes red) glass panel, inscribed with an alarm message appropriate to the variable concerned, which is illuminated from the rear when the alarm is active. When a new alarm occurs, the usual practice is for the alarm panel to flash on and off,

accompanied by the audible warning, until the operator denotes his "acceptance" of the alarm by pushing a button on the panel. This causes the audible warning to stop and also leaves the alarm panel continuously lighted until such time as the variable concerned returns to a normal value.

When a fault occurs, a number of variables will start to move away from their normal values and a succession of alarms will then become active. It is one of the operator's responsibilities to diagnose the cause of the fault from the "pattern" of alarms displayed and from his knowledge of the order in which they appeared. The way in which he arrives at his decision is not clear but, if he is to be consistently successful when performing this task, it is apparent that he must use some kind of conceptual model of the plant. If the operator cannot diagnose the fault or if no remedial action is possible, then the plant may have to be shut down either for safety reasons or in order to prevent or minimise plant damage. Automatic "trip" systems may be employed to shut down the plant when certain combinations of conditions occur or after a fixed time delay if no remedial action is taken.

The amount of plant that a single operator is responsible for is still increasing and so his diagnosis problem is becoming correspondingly more difficult. The penalty for maloperation must also increase with plant size and eventually it becomes necessary to provide the operator with some assistance in his diagnosis task. This point is more likely to be reached first on complex or highly hazardous plants and so it is not surprising that the first known alarm analysis schemes appeared on nuclear power plants. Only one reference to an alarm analysis scheme has been found for chemical processing plants and this was for an experimental computer control

project. The process computer is ideally suited to the rapid logical operations needed to determine causes from effects in such situations. It may be useful to note that, on the nuclear power plants, the alarm analysis and display systems are not part of an integrated computer control system but use a small computer solely for this one function. On computer-controlled chemical processing plants, the required computer and analog inputs are already present for other purposes. Since the hardware costs for a system will be a large fraction of the total cost, it would appear that the addition of an alarm analysis function to an existing computer control system could be comparatively cheap.

The alarm systems used on computer-controlled chemical processing plants are more flexible than those used on plants using conventional controllers. The computer's arithmetic capacity may be conveniently used to provide "deviation" alarms (an alarm occurs if the measured variable moves outside of a band of values above and below the set-point value). The computer alarm system consists of a program which scans the measured variables periodically and compares the values with alarm limits. Off-normal variables are then reported to the operator via a special alarm teleprinter. This appears to be a poor system from an ergonomic viewpoint. No attempt is made to use the powerful logical capacity of the computer to assist the man in his all-important diagnosis of the original fault. This is surprising since the operator may be under considerable stress in this situation and his diagnosis may therefore be erroneous. The computer's operations will not be affected in this way and, for a corresponding sequence of checks, will be considerably faster than the operator.

Several reasons may be postulated for this apparent anomaly:

- 1) The early process computers were slow, small (sometimes with only 4 or 8K of core store), expensive and often unreliable. Many unforeseen problems were encountered and hence some systems never performed to the original specification. Naturally the monitoring and simple control functions were attempted first and many projects did not get beyond this stage. Process computers are now faster, bigger, cheaper and more reliable.
- 2) Partly because of the reasons given in 1), most of the applications in use at the present time were programmed in machine code or low-level language. Since higher order control functions are generally very complex, such applications involve high software production costs. High level languages and software packages are now becoming available in ever-increasing numbers.
- 3) The problems associated with complex programs with noisy input signals in a real-time environment require careful consideration. Experience with such problems is gradually increasing.
- 4) The plant dynamics need to be known for many sophisticated control functions. This data may be very difficult to obtain unless a plant model is available. In recent years, many flowsheeting and simulation packages have been produced. The use of these packages reduces the magnitude of this problem to some extent.

It is therefore becoming more attractive to implement sophisticated control functions, particularly on plants which have high penalties for maloperation.

The present work originated from a more general study of the process operator carried out by Dr. F. P. Lees. It had been realised that the operator was an important component in the control system but that little was known about his activities, particularly with regard to his decision-making functions. An in-plant study of the operator was made by the author as part of this general interest in the operator. Simultaneously, the literature was searched for articles concerning human decision-making in complex situations, such as those encountered on processing plants. Work of interest is carried out in the field of "Operational Research" and it was also noted that work in the field of "Artificial Intelligence" was relevant. This work revealed that problems involved in human and machine chess-playing had been extensively studied because of the complex decisions that must be made. It was found that the computational problems involved were of a completely different type from those encountered in numerical programming problems. The use of special "list-processing" languages is almost universal for Artificial Intelligence problems. It was realised that this type of computational technique was central to the solution of such problems. The in-plant study of the operator had revealed the importance of alarms and it was therefore decided to apply list-processing techniques in order to solve alarm system problems on computer-controlled plants. Lists and data structures have been extensively used as a tool, for the work reported here, and found to be a powerful addition to conventional numerically-orientated programming methods.

The object of the work described in this thesis was to investigate the various problem areas associated with alarm analysis and to propose methods aimed at reducing the effort needed for an alarm analysis application.

The content of this thesis is arranged in a manner that is intended to preserve the central theme of "alarm analysis". Discussion of aspects of the work which are peripheral to this theme will mainly be confined to the Appendices. This is most noticeable in the short literature survey which follows in Chapter 2. The papers considered are all concerned with specific alarm analysis applications rather than artificial intelligence, list-processing, computer control, displays or ergonomics, which are all relevant topics but of lesser interest.

Chapter 3 examines some of the problems involved in alarm analysis and provides background information on many aspects of alarm systems. Chapters 4, 5, 6 and 7 contain details of the work done for the present study. This work is intended to minimise some of the problems introduced in Chapter 3 or to propose alternative methods that circumvent the problems completely. A procedure is recommended for setting up a complete alarm system for any plant. Chapter 8 reviews the problems that remain with some suggestions for further work. Chapter 9 is devoted to a discussion of the work and subject area as a whole.

CHAPTER 2

LITERATURE SURVEY

This chapter will be confined to a review of literature directly concerned with alarm analysis applications. References to articles concerned with other aspects of this topic will be inserted where relevant to the text.

A literature search has revealed only a small number of papers which make any reference to alarm analysis schemes although it is expected that other references may exist.

Welbourne⁽¹⁾ referred to the alarm analysis system to be used at Wylfa nuclear power station as part of a large computer-based system at that plant. This paper was written in 1964 some years before the plant became operational. No details of the procedure were given although it was noted that the computer output was to cathode ray tubes (C.R.T.'s) for display to the plant operators.

Early in 1966, Kay⁽²⁾ published a paper specifically concerned with alarm analysis and display at the Oldbury-on-Severn nuclear power station. He pointed out that the increasing size and complexity of modern process plant was making the operator's job more difficult and that the penalty for incorrect operation was naturally showing a corresponding tendency to increase. Until this time, the practice had been to install a centralised control room containing conventional control equipment and alarm panels. The alarm panels were inscribed with appropriate warning messages to the

operator and were individually illuminated from the rear of the panel. The system used was as follows: when a variable passes its alarm limit, the corresponding panel flashes and an audible warning sounds until the alarm is "accepted" by the operator. The operator accepts the alarm by pushing a button which causes the alarm to become continuously illuminated and the audible warning to cease. It is then the operator's responsibility to diagnose plant faults from the appearance of these alarms. For the system described by Kay, some 3,000 alarms have to be displayed, a large number of which would be triggered almost instantaneously for some faults. It was therefore decided that a different type of alarm system was not merely desirable but necessary. It was decided to use an A.E.I. 1040 process control computer as the basis of the alarm system. The computer is then used to scan all alarm signals and to arrange them for display to the operator in a manner that assists his interpretation of them. C.R.T.'s are used as the display devices.

The Oldbury system employs 2 special Burst Cartridge Detection (B.C.D.'s) computers and 2 temperature scanners in addition to the 3,000 alarm contacts. All of the alarm information from these sources is fed to the central control computer for transmission to the displays. The system is designed to sort the alarms according to their importance with respect to the operator's understanding of the fault and its propagation through the plant. Each C.R.T. may be used to display 32 lines of 39-character messages. The left-hand side of the screen is always used for B.C.D. and temperature information and the right-hand side shows alarm messages derived from the alarm contacts on the reactor units. All important alarms that are related to a particular cause are displayed together in a group with the "cause"

alarm at the head of the group and succeeding "effect" alarms below it. Alarms which are effects are not displayed unless they are considered to be important to the operator's understanding. These alarms are known as "suppressed" alarms.

In order to analyse the alarms as they occur, the computer is provided with data on the cause and effect relationship between alarms. Messages of advice or warning are provided for the analysis program to transmit to the display system as required. These messages can be used either for single alarms or for combinations of alarms. Messages displayed only when particular combinations of alarms are present were known as "deduced" alarms.

One C.R.T. is used for alarms for each of the station's two reactors. The information on these displays is duplicated on the remaining two displays which are situated on the supervisor's desk. Some "station" alarms not associated with either reactor are also displayed on both of these C.R.T.'s. This system ensures that failure of any one of the four displays does not result in any loss of information.

The computer also performs checks on its own equipment and displays appropriate warnings to the operator in the event of an incorrect response. Complete computer failure is monitored by a timing circuit in the scanner and is followed by a warning to the operator. The data used by the analysis program is protected from destruction, in the event of a computer failure, by the isolation of the writing heads of the drum stores on which the data is stored.

This system was stated to be the first power station information-handling system using C.R.T.'s. It was also pointed out that

the main computer was used entirely for purely logical operations.

Kay and Heywood⁽³⁾ presented a paper, also concerning the Oldbury plant, at a conference in March, 1966. In this paper, the authors emphasised the important point that the Oldbury system employs a general alarm analysis program and data corresponding to the particular plant concerned. This system enabled the writing of the program to be started very early in the life of the project before the basic cause-and-effect relationships between process variables was known. The other major advantages are that the basic analysis program is suitable for other plants and that the data may be changed quite simply whereas program alterations may be very inconvenient. This paper also discussed three possible methods of analysis. These methods will be discussed in detail in Chapter 3. For the Oldbury system, a method known as "tree analysis" is used. It is also noted that the messages for display to the operator number 4,000 for this system. This would have required 18,000 (44-bit) words of storage if the messages had been stored intact. In order to reduce this volume, a "dictionary" of required words is used and the various messages assembled as required. The dictionary itself, not including the references to its entries, occupies a mere 256 words.

In 1967, Barth and Maarleveld⁽⁴⁾ presented a paper concerning alarm analysis on chemical process plant. The work reported had been carried out for an experimental computer control project at the Pernis refinery in Holland. The central theme of the analysis scheme used was again based on the separation of cause and effect but the approach used was somewhat different from that discussed previously.

The hardware system used was physically different in that, although C.R.T.'s were used for graphical display of variable history, none were used for the display of alarms which were logged on a typewriter. The authors also placed considerable emphasis on the time-ordering of alarms.

The basis of the approach used is to split the plant into small sections and to deduce the likely effects of various faults originating both inside and outside these sections. For each variable, a list of checks is then obtained which are executed when the variable becomes off-normal. This technique was apparently successful for this experimental project but would be unsuitable for a large plant due to the large number of possible interactions and the correspondingly enormous volume of storage space required by the data.

Barth and Maarleveld also point out that the computational technique known as "list processing" is very convenient for use in the analysis program since it permits the use of non-consecutive core store locations for the formation of a list. The full implications of this point are discussed in Appendix 1.

Welbourne⁽⁵⁾ published a second paper concerning the data processing and computer control system at Wylfa nuclear power station in November, 1968. This paper concerns itself specifically with the alarm analysis and display aspects of the system. This system is similar in many respects to the one described by Kay and Heywood, the major difference being that a standby computer and automatic changeover system is employed in the event of computer failure. The marked similarity in the Wylfa and Oldbury systems is almost certainly due to a common Central Electricity Generating Board specification for new nuclear power stations. At the time that

Welbourne wrote the paper, the system was operational for use in the commissioning stage of the plant. The various possible analysis methods described by Kay and Heywood were discussed and the tree-analysis system again chosen as the most suitable method. Welbourne also noted that the "action phrases" used to guide the operator to the fault were chosen on the assumption that the plant was normally loaded prior to the fault occurring.

The display system adopted at Wylfa is somewhat different from that at Oldbury in that all "prime cause" alarms (those which are deemed to have caused all the others in any related group) are displayed on one C.R.T. and all others on a second. The second display can be cleared by the operator after acceptance of the alarms. It is also stated that up to six independent displays can be provided for each of the two reactor units although only two of these are reserved for alarms. The system is designed so that, if any one of the individual tubes fails, then the relevant information can be displayed on any of the others.

The dictionary system employed at Oldbury is not favoured at Wylfa although some common action phrases (used in addition to the bare alarm indication) are available.

Patterson⁽⁶⁾ published a paper in December, 1968, on the system at Oldbury which was, by then, in use with the first of the two reactors at the station. This paper was concerned with the general aspects of the system previously discussed and with some examples of alarm trees. Some minor display system modifications are also reviewed.

CHAPTER 3

SOME PROBLEMS OF ALARM ANALYSIS AND DISPLAY FOR CONTINUOUS PROCESSES

This Chapter is intended to highlight some of the problem areas in alarm analysis. Possible solutions to some of these problems are suggested in the Chapters which follow. Since the problem areas are interrelated, they must ultimately be viewed in the context of the complete system but, for convenience, they will be considered separately. The problem areas considered are fairly well-defined:

- 1) The "model" of the plant needed to obtain the data.
- 2) The definition of the alarm system details.
- 3) Deduced alarms.
- 4) Storage of alarm data for analysis program.
- 5) Analysis.
- 6) Display.

A subsection will be devoted to each of these areas.

3.1 Plant Models

Alarm analysis methods ultimately depend on a knowledge of the plant characteristics. This requires that either a formal mathematical model is available or that an engineer uses his mental model of the plant. The latter approach is the one used for the applications in Chapter 2. The difficulty with this approach is that extensive consultations are needed between engineers and systems and control personnel. All plant changes during design and commissioning require further consultations. A further problem is that the engineer's mental model may be inaccurate. These problems are reduced if formal mathematical models are used intelligently. There are two main reasons why such models are more convenient for use in alarm analysis schemes:

- 1) The model may be tested prior to use,
- 2) Once the model is correctly defined by the engineer, the systems and control personnel may use it whenever they wish.

The type of mathematical model most commonly used by engineers involves simultaneous solution of equations derived from mass and energy balances on plant streams. For a computer-controlled process plant, the number of equations is likely to be large and hence the time required for model production is likely to be excessive if a complete model is used. In order to reduce the time required to model a plant, some simplifications may be made. These may be split into three distinct categories and are considered in the following three subsections.

3.1.1 Simplifications that Reduce the Order of the Plant Model

The number of equations may be reduced in several ways. The engineer is accustomed to making quite severe simplifications, such as the assumption of perfect mixing, with very little hesitation. Methods of reducing the order of systems of equations (mainly linear systems) are also available⁽⁴⁶⁾, although not yet widely used. It may also be noted that, since the majority of plant measuring devices are for flow, temperature, pressure and level, rather than concentration, then individual component mass balances may not be necessary for models required for alarm systems. It is also useful to note that, since many common process plant failures are of a purely mechanical nature, such as pump failures, leaking or jammed valves, broken thermocouples or faulty level devices, then the models of items such as distillation columns or absorbers may not need to be so accurate.

3.1.2 Simplifications that may be made by Using a Different Type of Plant Model

Plant models may be classified into 5 categories for the purpose of this discussion:

- a) Mental models - only included here for completeness.
- b) Functional models - models based on the knowledge that a particular variable is a function of several others. The function is undefined for this type of model. For the

liquid level in a tank;

$$\dot{L} = f_1(Q_{in}, Q_{out})$$

and for the outflow:

$$Q_{out} = f_2(L)$$

It will be noted that no quantitative information is associated with this type of model. Since the equations, as written, do not indicate whether the left-hand side will increase or decrease when the right-hand side is increased, then they may also be considered as having no "directional" information associated with them. The functional model is the loosest form of equation that may be conveniently expressed on paper. A crude analysis program could be written on the basis of such a model but it would appear more fruitful to use it as a starting-point for a model using plant data, obtained during commissioning.

- c) Enhanced functional models - these models are similar in form to functional models but also contain directional information, if this is known. This type of model may be represented as:

$$\dot{L} = f_1(Q_{in}^+, Q_{out}^-)$$

and:

$$Q_{out} = f_2(\dot{L})$$

In the examples above, a "+" sign indicates that the

dependent variable increases as the parameter concerned increases. A "-" sign indicates the opposite effect. In some cases, the directional information may be unknown or dependent upon other variables:

$$Y = f_3(x_1^+, x_2^-, x_3)$$

The enhanced functional model contains all the necessary information needed to perform a basic cause-and-effect analysis although the lack of quantitative information may cause a diagnostic program to fail for difficult cases. Such models may be derived far more easily than conventional full-equation mathematical models but are unsuitable for obtaining deduced alarm information, particularly if time-ordered alarms are to be used. (A time-ordered alarm is one which is only displayed if, say, "A", "B" and "C" all occur in a particular specified order). An alarm scheme based on an enhanced functional plant model might be set up very economically if an automatic method of producing the cause-and-effect data from such a model were available.

- d) Statistical models - these models are based on regression and correlation of data accumulated by logging plant variables, either during commissioning or on a similar plant elsewhere. They may be represented by least-squares correlations with additional parameters such as standard deviation, correlation coefficient etc. Such models may be used as the basis for alarm analysis schemes and are considered in a similar manner to full-equation mathematical models.

e) Full-equation models - this type of model is more difficult to derive since it requires an accurate conception of the dynamics of the system. The full model will consist of a set of simultaneous differential and algebraic equations. As noted earlier, the production of such a model would be a major effort. This type of model may be available since it might be required for another purpose, such as optimisation.

A comparison of these types of models shows that functional or enhanced functional models require considerably less effort to assemble than full equation or statistical models. The disadvantage of using such functional models is that, by their nature, they are not suitable for simulations of plant behaviour.

3.1.3 Simplifications that may be Made by Assembling the Complete Plant Model from Commonly-Encountered Units

This type of simplification would be particularly useful for a large organisation that intended modelling a number of plants containing many "standard" units. "Modules" of equations corresponding to the units could then be derived and used as required to build up the complete model with any special modules peculiar to a particular plant.

The choice of type of model and simplifications made must ultimately depend on the process involved, the penalty for maloperation and any other relevant data which is available.

3.2 Defining the Alarm System

Three distinct steps are involved in defining an alarm system for a plant:

- (1) The measured variables to be used for alarms are chosen,
- (11) The type of alarm used for each variable must be specified,
- (i11) The levels must be set for each alarm in the system.

These aspects of system design do not appear to have been studied by workers in the field. It is likely that a considerable improvement in alarm systems could be made by devising a method of defining the system as a whole. At this time, some of the problems specific to the individual steps will be considered.

3.2.1 Choosing the Variables to be Used for the Alarm System

During the design stage of a computer control system, the measured variables are selected and arrangements made for their input to the computer. These variables may be measured for a variety of reasons. In some cases, the precise location of the required measuring device will be defined by the major use for which the measurement is intended but in others considerable latitude is available for the choice of location of the measuring device. It is also noted that, in some cases, a measurement in a particular vessel or stream is required but that there is some freedom in the particular property measured (at the time of design). It may be hypothesised that the analysis of alarms might be improved if the

analysis problems are considered at the time of design when these measuring device types and locations are chosen. It is also suggested that since the design engineer is likely to use a different type of mental model of the plant from that of the operator, then the variables that the operator is interested in are likely to be different. It may therefore be worthwhile to investigate different sets of measured variables in order to select the set which maximises the efficiency of the alarm system whilst fulfilling all other criteria. In order to do this, a method of evaluating different sets of measured variables is necessary.

Process computers are also used to derive "inferred" measurements of plant parameters from the measured variables. This facility may be used when the parameter desired is difficult, impossible or costs too much to measure directly. It is again suggested that fuller use of such measurements might lead to improvements in analysis problems. The requirement here is for a method of analysis which would suggest, during trials, a need for inferred measurements of particular parameters.

3.2.2 Choosing Alarm Types

After the measured variables for a particular plant have been selected, and any inferred measurements defined, then the alarms to be associated with the variables must be chosen. The various types that may be specified are as follows:

1. Absolute Alarms - the operator is warned if the variable moves beyond certain fixed limits. These may be fixed by the equipment manufacturer.
2. Deviation Alarms - the operator is warned if the variable moves outside of a band about the set-point value.
3. Zero/Full-Scale Alarms - the operator is warned if the measuring device is at the limit of its range (shows a full-scale or zero reading).
4. Rate-of-Change Alarms - the operator is warned if the rate of change of the measured variable exceeds a certain limit.
5. Deduced Alarms - the operator is warned if a logical statement concerning other alarms is found to be true.

In order to choose the type of alarm best suited to a particular variable, three factors must be considered:

- a) The purpose of any alarm system is to provide the operator with useful information about malfunctions as early as possible but without saturating him with information or giving too many false alarms.
- b) The choice of alarm type will, to some extent, be fixed by the quality of the input signals used. In particular, noisy signals must be carefully treated if used with rate-of-change alarms.

- c) If a variable is very important, then multiple alarms may be associated with it. These may consist of either pre-alarm levels in addition to normal alarms or different types of alarm.

3.2.3 Setting Alarm Levels

Setting the values at which alarms occur is important if the maximum information is to be derived from the system. If the levels are too close to the steady-state operating values, then large numbers of "false" alarms will occur. Although such an approach might be favoured from the "safety first" viewpoint, it may be detrimental for the system if the operator begins to ignore such alarms. In contrast, if the alarm levels are set too far from the steady-state value, then the operator will not receive warnings until the fault is fairly well-developed. Since any alarm analysis scheme is based on cause-and-effect, it is also desirable, but not essential, that alarms are set correctly relative to one another so that "cause" alarms do, in fact, occur before "effect" alarms. The optimum setting for the alarm-level must also depend on the number of other alarms in that region of the plant and on the relationships between the variables involved. In order to set alarm levels that fulfill these criteria either the plant dynamics must be well known or trial runs used during commissioning of the alarm system. In any case, the alarm system should be designed so that a properly authorised person can adjust the alarm levels if necessary.

3.3 Deduced Alarms

Deduced alarms are those which are only displayed to the operator when a combination of other alarms occur. This type of alarm is not directly related to any particular measured variable. For this reason, these alarms are likely to be more widely used on chemical plants than in the nuclear power plant applications already described since chemical plants are not as heavily instrumented. Deduced alarms are particularly suited to the process computer since the conditions for their display may be arranged in the form of a logical statement. If the statement is found to be "true" during analysis, the message is displayed, if "false" then the message is not displayed. Examples of deduced alarms are shown in Fig. 3.1. There are three problems associated with deduced alarms:

- 1) The logical conditions required may not be readily found unless an accurate plant model is available or on-line testing is possible.
- 11) Since there is a strong possibility that the stored conditions will be incorrect, it is necessary to be able to change the conditions easily.
- 111) Unless care is taken when the alarm system programs are organised an excessive number of transfers between core-store and backing store may be required.

This condition will arise if the alarm data for groups of variables that are closely connected in the model is stored in several sections in the backing store.

| Alarm No. | Conditions for Alarm to be displayed |
|-----------|--------------------------------------|
| 1 | A and B |
| 2 | (A and B) or (B and C) or (A and C) |
| 3 | A and (B or C) |
| 4 | A and B and (not C) |
| 5 | (A or B) and (not (C or D)) |

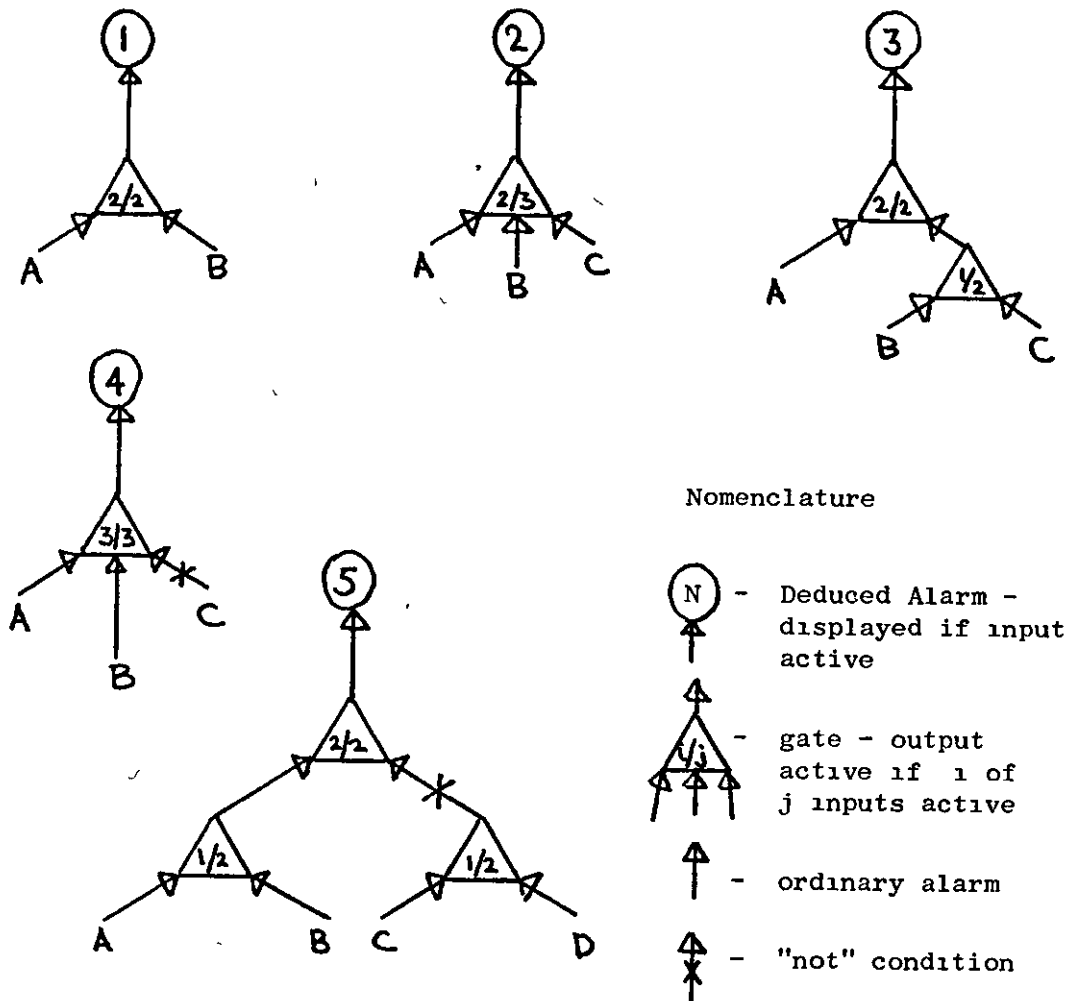


FIG. 3.1

Examples of Deduced Alarms

3.1 Storage of Analysis Data

Kay and Heywood⁽³⁾ draw attention to the important distinction between storing the data in a manner that may be used by a general-purpose analysis program and writing special programs for each set of symptoms. The advantages of a general program are:

- i) The program may be started before the data is available.
- ii) The program may be used for other jobs of the same type.
- iii) Alterations to analysis data are easier than program alterations.
- iv) The data may be easily prepared solely by plant operations personnel rather than in direct collaboration with the software team.

Process computers generally have quite small core-stores when compared to their off-line counterparts. In the past, some machines had only 4 or 8 K and at the present time 24 K is quite large.

Programs which use large volumes of data must therefore be organised so that the data may be kept permanently in backing store. Small portions of the data may be transferred to core store as required.

Welbourne⁽⁵⁾ stated that the data for the Wylfa system occupied approximately 140 K (44-bit word length). The first constraint on the form of alarm analysis data is therefore imposed by the system characteristics. For the remainder of this section, it will be assumed that this constraint is satisfied. It will also be assumed that care has been taken to pack the data in such a way that large numbers of transfers to backing-store are avoided during

analysis and display.

The methods available for storage of alarm data may now be considered in detail.

3.4.1 Probability Method

For this method, each message to be displayed is associated with several conditions. Each condition corresponds to a particular state of one measured variable. An engineer evaluates the probability that each condition is satisfied when the fault described by the message occurs. The probabilities are stored with the corresponding conditions and a "target" sum associated with the whole group. During the analysis, the message is displayed if the sum of the probabilities of all the active alarms within the group exceeds the target sum. The data for such a system might be as in the example shown in Fig. 3.2.

| Message | Conditions and Probabilities | | | | | | Target |
|---------|------------------------------|-----|-----|----|-----|----|--------|
| 1 | A | B | C | D | E | - | 2.1 |
| | .7 | .45 | .8 | .3 | .65 | - | |
| 2 | A | F | B | G | - | - | 1.85 |
| | .3 | .9 | .75 | .8 | - | - | |
| 3 | B | C | E | F | H | I | 1.75 |
| | .2 | .45 | .65 | .7 | .65 | .3 | |

FIG. 3.2

Form of Data for Storage Using Probability Method

This system is very flexible but requires a large amount of storage space. It is also difficult to arrive at the probabilities and target sums, required for each group, with any degree of certainty.

3.4.2 Logical Statement Method: Cause-Effect

This method is similar to the previous one except that instead of probabilities, logical expressions are used. This is equivalent to the use of probabilities 1 or 0. The message associated with each expression is only displayed if the expression is found to be true. An alarm is equivalent to a boolean variable, active alarms are TRUE and inactive alarms are FALSE. The logical expressions are assembled from alarms and the boolean operators AND, OR and NOT. Fig. 3.3(a) shows a logical statement and its value for several sets of conditions. This method avoids the problems involved in estimating the probabilities, as in the previous method, but still involves a large volume of data. The logical statements may also require considerable effort since they are likely to be more complex than in the example. The complexity is magnified by the necessity to include negative conditions in order to avoid displaying multiple messages. This is demonstrated by the logical statements in Fig. 3.3(b). Since the statements corresponding to faults 2 and 3 are contained within the first statement, all three messages would be displayed when fault 1 occurred. In order to avoid this, additional conditions are added to make each statement unique. This is demonstrated by the amended statements shown in Fig. 3.3(c).

Logical statement:

A AND (B OR (C AND NOT(D)))

| A | B | C | D | Value of Statement |
|---|---|---|---|--------------------|
| T | F | F | F | F |
| F | T | F | F | F |
| F | F | T | F | F |
| F | F | F | T | F |
| T | T | F | F | T |
| T | F | T | F | T |
| T | F | F | T | F |
| F | T | T | F | F |
| T | T | T | T | T |

FIG. 3.3(a)

Values of Logical Statement for Various Conditions

| Fault | Logical Statement |
|-------|-----------------------------------------------|
| 1 | A AND (B OR C) AND D AND (E OR F) AND G AND H |
| 2 | D AND (E OR F) AND G |
| 3 | (E OR F) AND G |

FIG. 3.3(b)

Basic Logical Statement Data - Non-Unique

| Fault | Logical Statement |
|-------|-----------------------------------------------|
| 1 | A AND (B OR C) AND D AND (E OR F) AND G AND H |
| 2 | NOT(A) AND D AND (E OR F) AND G |
| 3 | NOT(D) AND (E OR F) AND G |

FIG. 3.3(c)

Enhanced Logical Statement Data - Unique

3.4.3 Logical Statement Method: Effect-Cause

The scheme described in the previous section was essentially based on storing all the effects associated with one cause in one place. During analysis, the statement is checked and displayed if the result is true. An alternative method is based on noting the time-ordering of the effects associated with all of the causes considered. Each effect that occurs last in one or more symptom sets is then considered separately. A number of possible causes are likely to exist when this last alarm has occurred. The data is arranged in the form of a complex logical statement as below for a simple example:

```
IF <some condition occurs>
  THEN IF <some other condition>
    THEN Cause 1
    ELSE Cause 2
  ELSE IF <some further condition>
    THEN Cause 3
    ELSE IF <some final condition>
      THEN Cause 4
      ELSE Cause 5
```

It is seen that this corresponds to storing sets of causes with the last effect. The time ordering of the effects is used to find the form of the logical statement. This type of method was used by Barth and Maarleveld⁽⁴⁾.

3.4.4 Tree Analysis Method

The basic reason why the previous methods require so much space is because much of the stored information is duplicated. The information used to derive the sets of symptoms is obtained from a knowledge of the relationships between the various causes and successive effects. The tree analysis method stores these relationships in the form of a "tree". Each alarm appears in the tree linked, by branches, to other alarms. Alarms in the lower levels of the tree cause alarms on higher levels to occur. Each alarm has its own message and a small block of data giving information on its relations with other alarms. An example is shown in Fig. 3.4. Deduced alarms are handled using supplementary information in the form of a Logical Statement. This allows the volume of data to be considerably reduced but retains the flexibility of the Logical Statement for special cases. The main problem with this method is the production of the tree.

The method used for storage of data also influences the result of on-line analyses. Since the first three methods discussed only store data for specific faults, the analysis program fails if a different fault occurs. With the data stored in a tree, as in the fourth method, the analysis program can at least draw the operator's attention to the prime cause alarm.

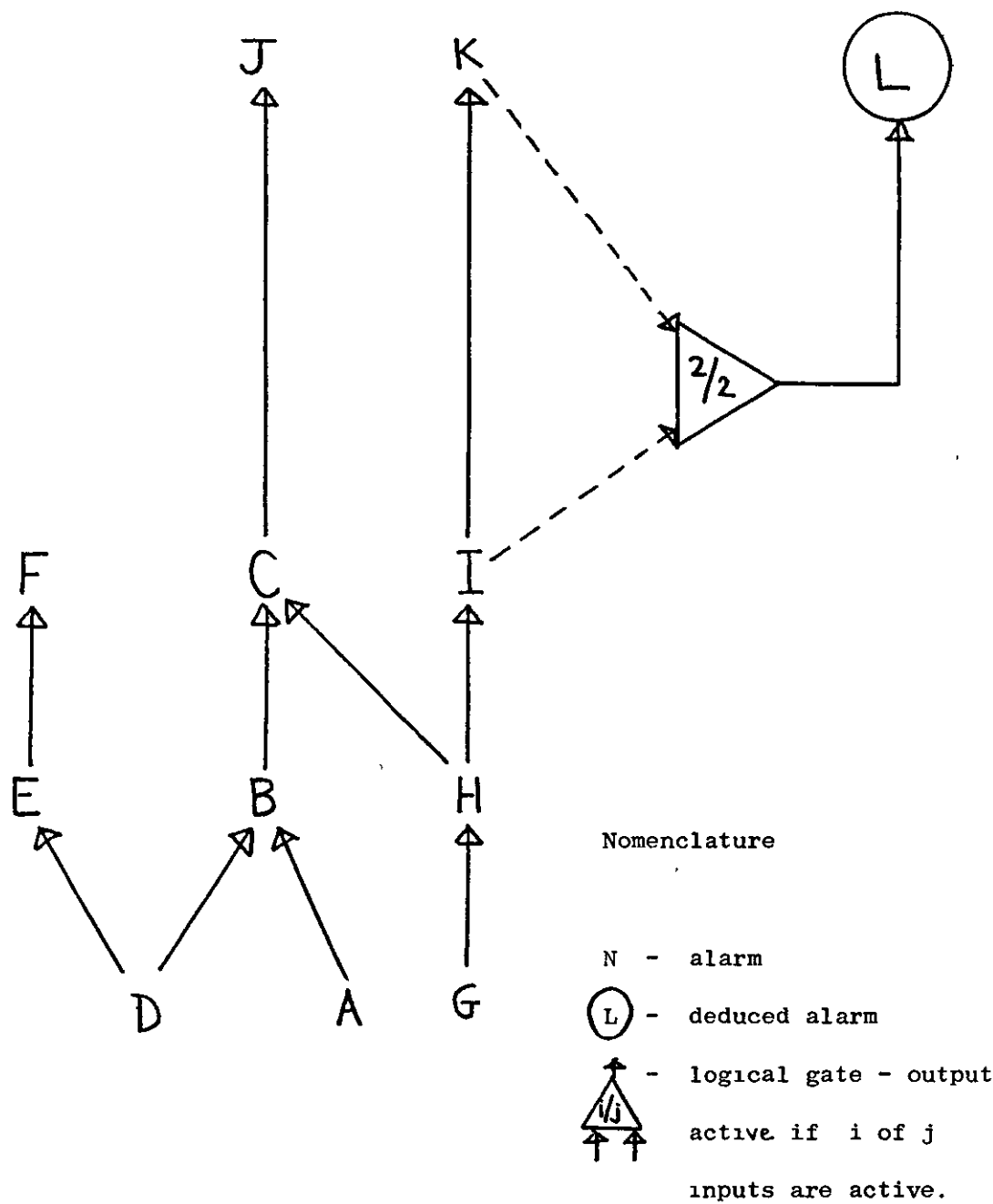


FIG. 3.4

Simple Alarm Tree

3.5 Analysis of Alarms

The problems concerned with the diagnostic program may be conveniently split into 2 categories:

- (1) Those due to a poorly defined system,
- (2) Those due to plant conditions at the time of diagnosis.

Problems in the first category include alarms that occur in a misleading order due to a poor choice of alarm levels and incomplete diagnosis due to the use of too few alarms in a particular area of the plant. These topics are considered elsewhere and are only noted here for completeness. Problems in the second category manifest themselves in the same way but are more difficult to eradicate. These problems include:

- 1) Alarms that are not active due to failure of a measuring device. If the failure is known, the analysis can be modified to minimise the problem. If the failure is not known, the analysis program will not recognise the failure unless a special deduced alarm is provided for the purpose. Malfunction detection techniques may solve this problem but they are not within the province of the alarm analysis program as considered here.

- 11) Noisy input signals may cause alarms to become active in an order that does not correspond to that obtained by cause-and-effect methods. The analysis program would then decide that the new alarm was not a "latest effect" and would then erroneously treat the new alarm as a prime cause. This will be corrected when the missing alarms appear. This problem may be minimised either by incorporating a time delay

before new alarms are considered by the analysis program or by using a modified program that attempts to find possible missing alarms. It is noted that the use of a digital filter to smooth input signals will in any case cause a slight time delay.

i11) During any disturbance, due either to a fault or to a change in the steady-state operating level, the cause and effect data may be incorrect. The analysis program may have extreme difficulty in such cases. The problem here is one of providing the program with the correct data at the time that it is required.

3.6 Display Problems

The value of any alarm analysis system must ultimately be limited by the efficiency of the display system used. It was noted in Chapter 2 that one of the problems of alarm display using panels, inscribed with warning messages, was the large number of these panels required. The other basic problem with this type of system is that the relative positions of the panels are fixed. This leads to a situation where a number of alarms caused by one particular fault may appear scattered around the panel.

If multiple faults occur, the problem is further complicated. The operator becomes confused between cause and effect and his attention may be drawn away from significant alarms by the mass of minor alarms.

Several other problems are associated with the display of alarms:

- (1) The display used must be capable of being rapidly updated, particularly for plants where large numbers of alarms occur in short periods of time, but must not change so quickly that the operator cannot digest the information presented. For this reason, cathode ray tubes are much better than teleprinter's provided that provision is made for "freezing" the display when desired.
- (2) If a C.R.T. is used, it must be "freshened" repeatedly in order to prevent flickering. This introduces a timing constraint into the design of the display system.
- (3) If a C.R.T. display is full, other alarms must be queued and the operator informed that the queue exists. Facilities must also be provided to inspect the queue as desired.
- (4) Since the display system is vital, it must be ensured that adequate standby facilities are provided in case the primary display fails.
- (5) An unchanging display may indicate either a static plant state or an analysis system failure. In order to distinguish between these two possibilities, some indication of computer activity must be given on the display at all times.

In operation, a C.R.T. display, showing purely alphanumeric information might appear as in Fig. 3.5. This display shows two sets of alarms (for a hypothetical plant) which the analysis program considers have been caused by separate events. For the first set of alarms shown, the cause of disturbance appears to be the gassing-up of the reactor feed pump. The deduced alarm corresponding to this condition is displayed because its symptoms are satisfied by the state of the alarms shown above it on the display. For a well-designed alarm system, the three absolute alarms would occur in the order shown, which corresponds to cause-and-effect.

If the alarms did not occur in the correct order, the analysis program might still be able to find the order shown by inspection of the alarm tree.

For the second set of alarms shown, it is assumed that the actual cause of the disturbance is monitored, in this case, the raw material temperature. As for the first example, the alarms appear in cause-and-effect order.

The analysis and display system performs several distinct functions. In order to emphasise this important point, several features of the example will be noted:

- 1) The analysis program has split the active alarms into two distinct groups, corresponding to separate causes.
- 11) The absolute alarms in each group are displayed in cause-and-effect order.
- 111) Deduced alarms may be displayed after all absolute alarms as long as the type of alarm is also shown. This is typical

| | |
|--------|----------------------------|
| * A267 | REACTOR FEED FLOW LOW |
| A132 | COOLING WATER FLOW LOW |
| A096 | SEPARATOR FEED FLOW LOW |
| D041 | REACTOR FEED PUMP GASED UP |
| | |
| * A274 | RAW MATERIAL TEMP. HIGH |
| A004 | SURGE TANK TEMP. HIGH |
| A068 | PREHEATER STEAM FLOW LOW |

Notes: * - indicates prime cause alarm
 A - indicates absolute alarm
 D - indicates deduced alarm

Each alarm has unique 3-figure reference number

FIG. 3.5

C.R.T. Display showing Typical Data Format

of the systems described in Chapter 2.

- iv) It is assumed that, for this example, no suppression of alarms occurs. It is not necessary to reduce the volume of displayed information until a larger number of "minor" alarms are active. Some alarms are marked in order that they will always be displayed when active, irrespective of the prime cause.

C H A P T E R 4

FORMULATION OF THE PROCESS MODEL

It has been noted that the effort required to set up an alarm analysis scheme from an intuitive model of a plant is excessive. It is therefore reasonable to assume that alarm analysis schemes will only be used when an alternative method requiring considerably less effort is used. If a method based on a formal model of the plant is used then the inequality below must be satisfied:

$$E_D + E_S + K.E_M \ll E_I$$

where: E_S is the effort required to define the alarm system from a formal plant model,

E_D is the effort required to produce the analysis data from the alarm system,

E_M is the effort required to produce the plant model,

E_I is the effort required to produce analysis data from an intuitive model,

K is a correction factor such that:

$K = 0$ if a model is already available,

$0 < K < 1$ if a model is needed for other purposes,

$K = 1$ if a model is produced specially for alarm analysis.

Since E_I and K are constant for any given plant, E_S , E_D and E_M must be minimised in order to make the provision of alarm analysis schemes a practical proposition. The remainder of this Chapter is devoted to work done on minimising E_M . Chapters 5 and 6 contain work done on minimising E_S and E_D . Chapter 7 is used to demonstrate the use of functional models for alarm analysis. This type of model may be useful for providing an alarm analysis scheme for plants that do not warrant the production of a full-equation model or do not depend heavily on deduced alarms. Details of the programs used for the work are in the Appendices with listings and data input requirements.

4.1 Setting Up the Process Model

It was decided to write a flexible computer program that would allow a relatively inexperienced user to set up a plant model in a form suitable for use with alarm analysis problems. One of the difficulties of other programs used for plant modelling is that the user may have to be quite proficient in the computer language, used for the program, in order to use it successfully. It was therefore decided at the beginning of the work that, as far as possible, all user-supplied information would be input to the program as data in a simple format. This restriction requires that some flexibility will be lost but, in practice, this has not proved to be serious.

In order to reduce the effort required to set up the model, the form of the data must be similar to that which the engineer would use. The subsections which follow describe the basis of the modelling

method used and the program used to assemble the model.

4.1.1 Modelling Method Used

It was decided to use the modular approach, outlined in Section 3.1.3 as the basis of the plant models required. This approach was found to be convenient for 5 reasons:

- i) The individual modules used may be based on the familiar "unit operations" commonly found in text books. Each unit modelled is defined by a name and a series of input and output streams linking it to other units.
- ii) Individual modules may be tested by supplying dummy modules for each input and output stream. In this way, the response of the unit to various process disturbances may be found.
- iii) Simple models of units may be used initially and may be replaced by more complex ones where necessary or as knowledge of the process increases.
- iv) A library of commonly-encountered units may be built up. This naturally leads to a reduction in the amount of effort required to assemble a "new" model.
- v) Modifications to the plant may be copied in the model by addition or subtraction of the corresponding modules. This factor is important and must be borne in mind when writing the program or the desired flexibility will be lost.

The modular approach was used for studies on both full-equation and functional type models.

4.1.2 Conventions used with General-Purpose Models

A constraint on the use of general models is that a convention must be adopted to ensure that, for instance, a variable is not set in more than one unit. The conventions used for the work described here are:

1. Each stream between units has 6 "fields" associated with it. Each field is used to store the value of a particular property in that stream. The individual fields are accessed by use of a "fieldname". For stream "A" the fieldnames are QA, PA, TA, XA, YA and ZA. It is stressed that the number of fields associated with each stream and the fieldnames used to access them may be easily changed.
2. The properties flow (Q), temperature (T) and concentration (X) are set in unit output streams whilst pressure (P) is set in unit input streams. For convenience, the fieldnames used correspond to letters normally used to denote these properties (Y and Z are spare fields).

In certain cases, the strict use of a convention such as this may lead to unnecessarily complicated models. It is recommended that the convention is relaxed in such a situation and the model, if used as part of a library, be marked as one unsuited for general use. The existence of the convention is important, even when such exceptions are made, since it highlights the areas in which difficulties are

likely to occur. An example showing how the convention adopted for the present work may be relaxed is shown in Figs. 4.1(a) and 4.1(b). The former contains a full model of a sliding-stem control valve whilst the latter shows a simplified model. In the latter case, the convention is relaxed by the assumption that the line pressure p_c is set at the controller output.

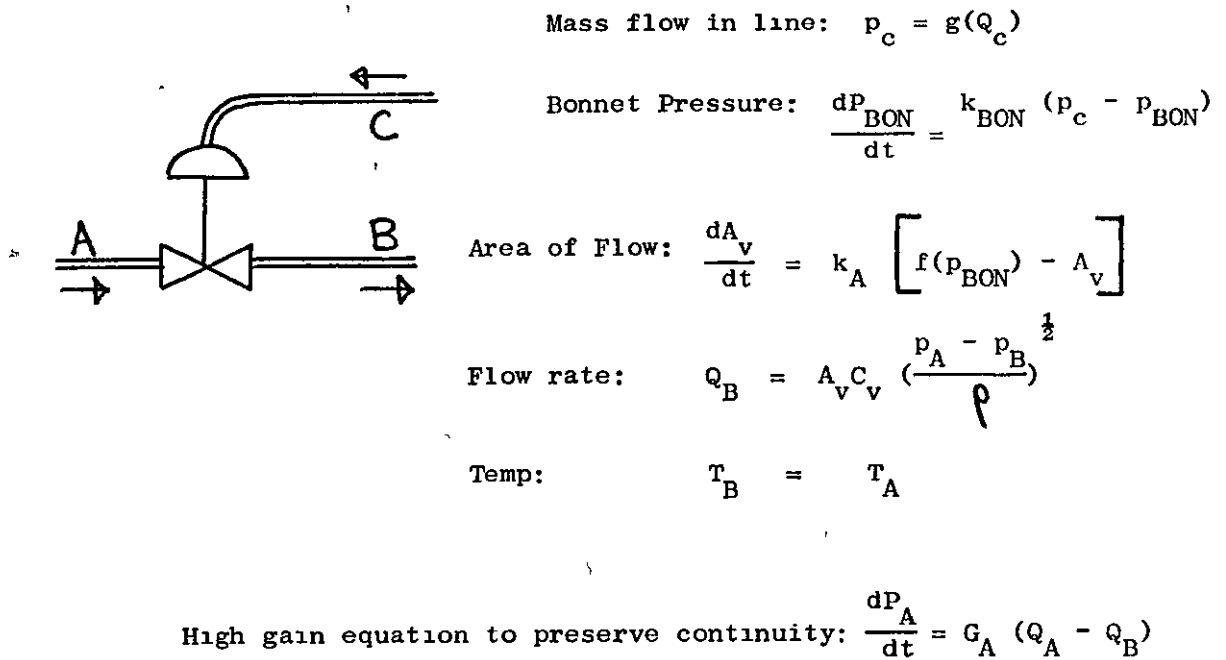


FIG. 4.1 (a)

Sliding-stem Control Valve - Full Model

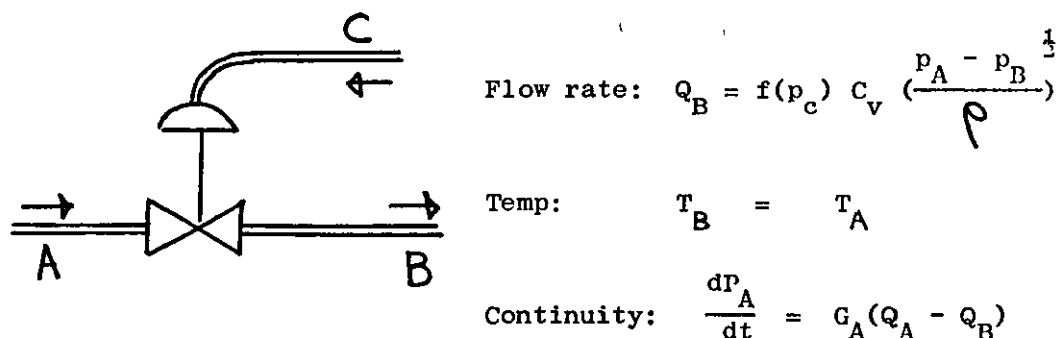


FIG. 4.1 (b)

Sliding-stem Control Valve - Simple Model (Conventions relaxed)

By relaxing the conventions, the model is simplified by ignoring the mass flow of air to the control valve and its effect on the pressure. In the event that the valve dynamics are important, the bonnet pressure change and its effect on the area for flow may be modelled as in Fig. 4.1 (a). For most situations, these effects may be considered as instantaneous which allows the simplification to the model shown in Fig. 4.1 (b).

4.1.3 Executive Program Functions

The function of the executive program is to assemble the complete plant model from the individual unit modules. This function may be subdivided into several distinct operations as follows:

1. Identifying the individual units to be modelled and the process streams linking the units together. For this purpose, each unit is given a unique name consisting of 4 characters, e.g. TANK, CV21, DRY2, BED4 or COND. Each input and output stream to be considered is identified by means of a single character. As an example, consider the distillation column reboiler shown in Fig. 4.2. For all programs for the present study, the unit name, REB1, is used as the unique identifier for the computational module associated with this unit. The decision to classify the process streams linking a unit with its neighbours as "inputs" or "outputs" rather than as "streams" was made for 2 reasons:

- a) the convention adopted for setting variables in input or output streams, depending on the property concerned, is consistent with this classification,
- b) since every input stream must correspond to an output stream on another unit, some simple checks may be written into the executive program.

Using the fieldnames discussed previously, the temperature in the bottoms stream B would be denoted as TB. All names for variables are restricted to 2 characters for the sake of convenience whether or not they are associated with a process stream. It may be noted that, since variables in process streams have one name in each unit, the complete variable consists of two names and one value. The temperature at output B in a unit will be TB and the same variable at input A of the adjacent unit will be called TA. The variable name is stored as the 4 characters TATB. Where 4 characters are printed out, the first 2 are always the name of the variable in the input stream and the last two the corresponding name in the output stream of the other unit concerned.

2. Assembly of the model from the units and streams defined above. The working space required for the stream variables is also created by the executive program during this stage. Fig. 4.3 shows 2 units that are part of a larger model. It may be seen that output stream B on unit REB1 is identical to input stream A on unit CV01. This identity must be preserved in the computer model of the plant and the corresponding stream properties must be common to both units. This means that, in general, stream variables will possess two names. This situation could, of course, be avoided by redefining all stream names until each output was connected to an input with the same identification character but this would have meant that general modules could not be used. The executive program was therefore designed to be able to distinguish between the two variable names used for each stream variable.

Unique unit name: REB1

| | | | |
|---------|---|----------|---|
| Inputs: | L | Outputs: | V |
| | F | | B |
| | | | G |

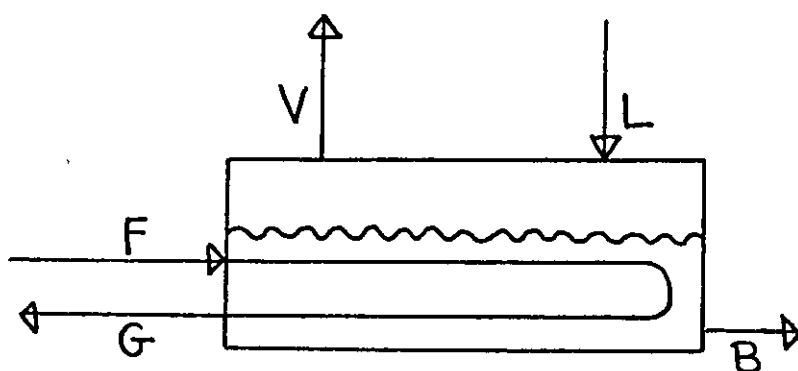


FIG. 4.2

Identifying Units and Process Streams

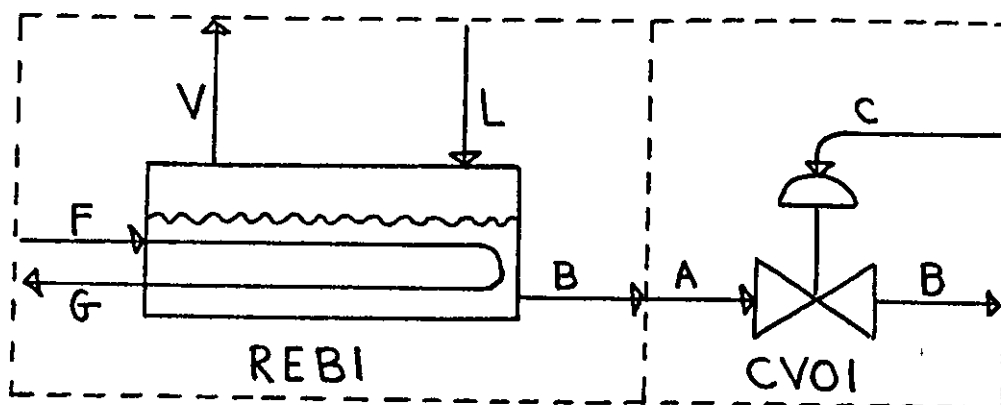


FIG. 4.3

Linking Up the Unit Modules

3. Defining the relationships between the variables for each unit. With the skeleton model set up the model equations are specified for each unit. The executive program must perform several functions on the equations supplied:

- a) Recognise algebraic and differential equations of varying length and complexity,
- b) Distinguish between variables, operators and functions,
- c) Transform the equation into a form suitable for machine evaluation (see Appendix Section A.1.2.3).
- d) Create a set of instructions within core store that correspond to this equivalent form of the equation. This step requires that the program must be able to search through the variables in each unit in order to find those used in the equation. If the variable with the correct name cannot be found among the streams entering and leaving the unit, then a variable local to that unit must be created and stored within the computational module. The search program must also check that the desired variable has not already been created local to the unit due to a previous occurrence in the equations for the unit.

4. The steady-state values of the variables must be fed in and checked. This again requires a search to identify each variable as its value is supplied. The checking is done by integrating all the equations and noting if any of the variables change significantly. The variable values found at this stage are then stored as the "true" steady-state values. Whenever the variables are reinitialised during program use, it is the true values that are restored rather than

the approximate values initially read in.

5. Testing the complete model. In addition to the steady-state check noted above, the complete model must be tested to ensure that its response to various disturbances is similar to that expected of the real plant. This facility is only used for full-equation models since no simulations are possible using functional models.

4.1.4 Example of Program Use

Consider the section of a plant shown in Fig. 4.4. This may be split into units as shown in Fig. 4.5. The particular choice of units shown is rather more detailed than might be required for many applications. Obvious simplifications that could be made are:

- 1) the assumption of constant level in condenser holdup tank (TAN1) and constant flowrate to the column (MTF1, CRO1, CV01) etc.
- 11) the use of empirical equations to describe the overall dynamics of the distillation column if the dynamics of this unit are not important when considered in the context of the complete plant.

The data supplied to the program for this column section is of the type shown in Appendix 3, LISTINGS 2 and 3. LISTING 2 shows the form of the data needed to define a skeleton plant model followed by the equations used for the model. The programs used are completely data-driven and hence certain "keywords" are used to inform the program

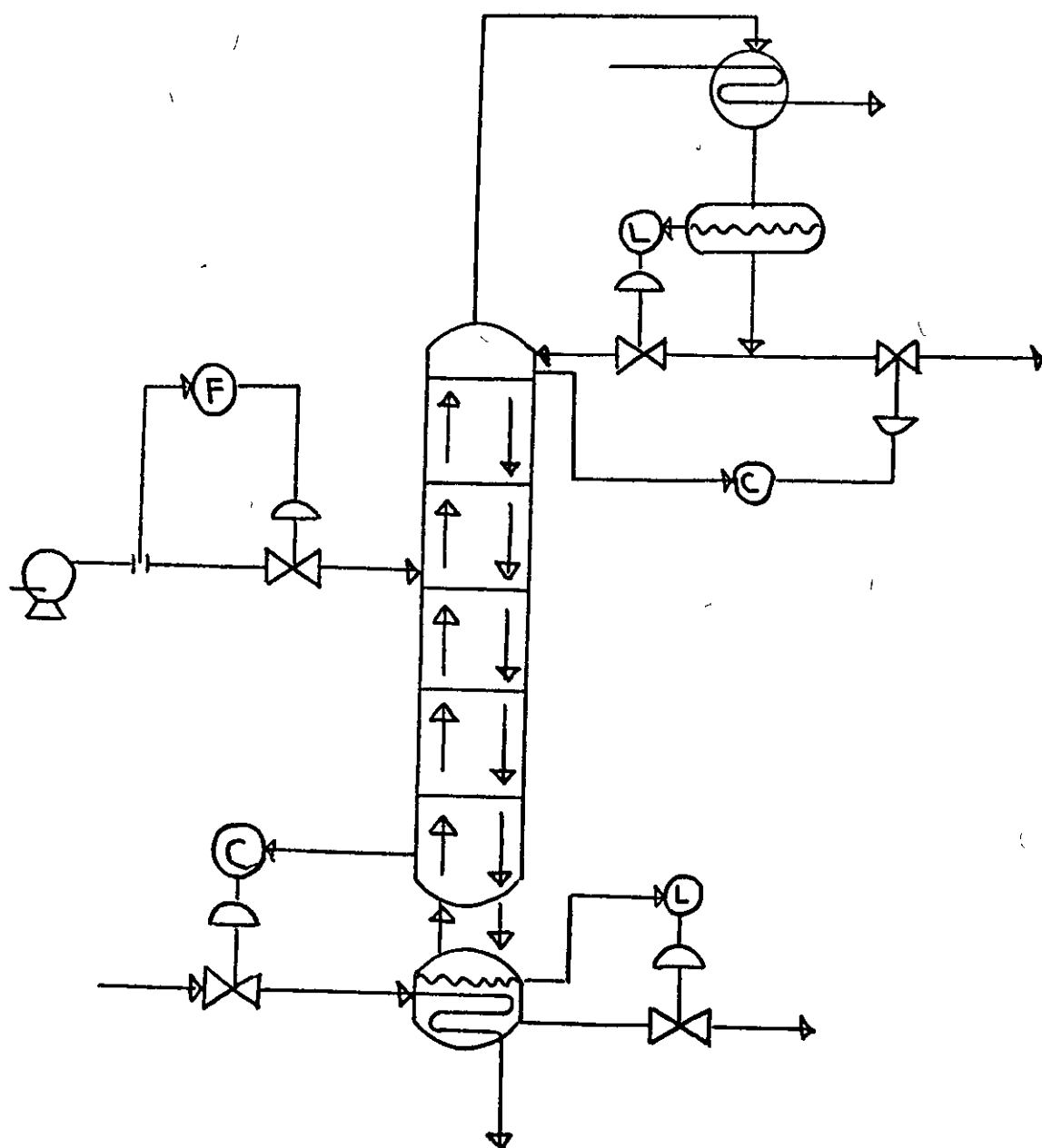


FIG. 4.4(a)

Column Section of Plant-Arranged for
Control of Both Product Compositions

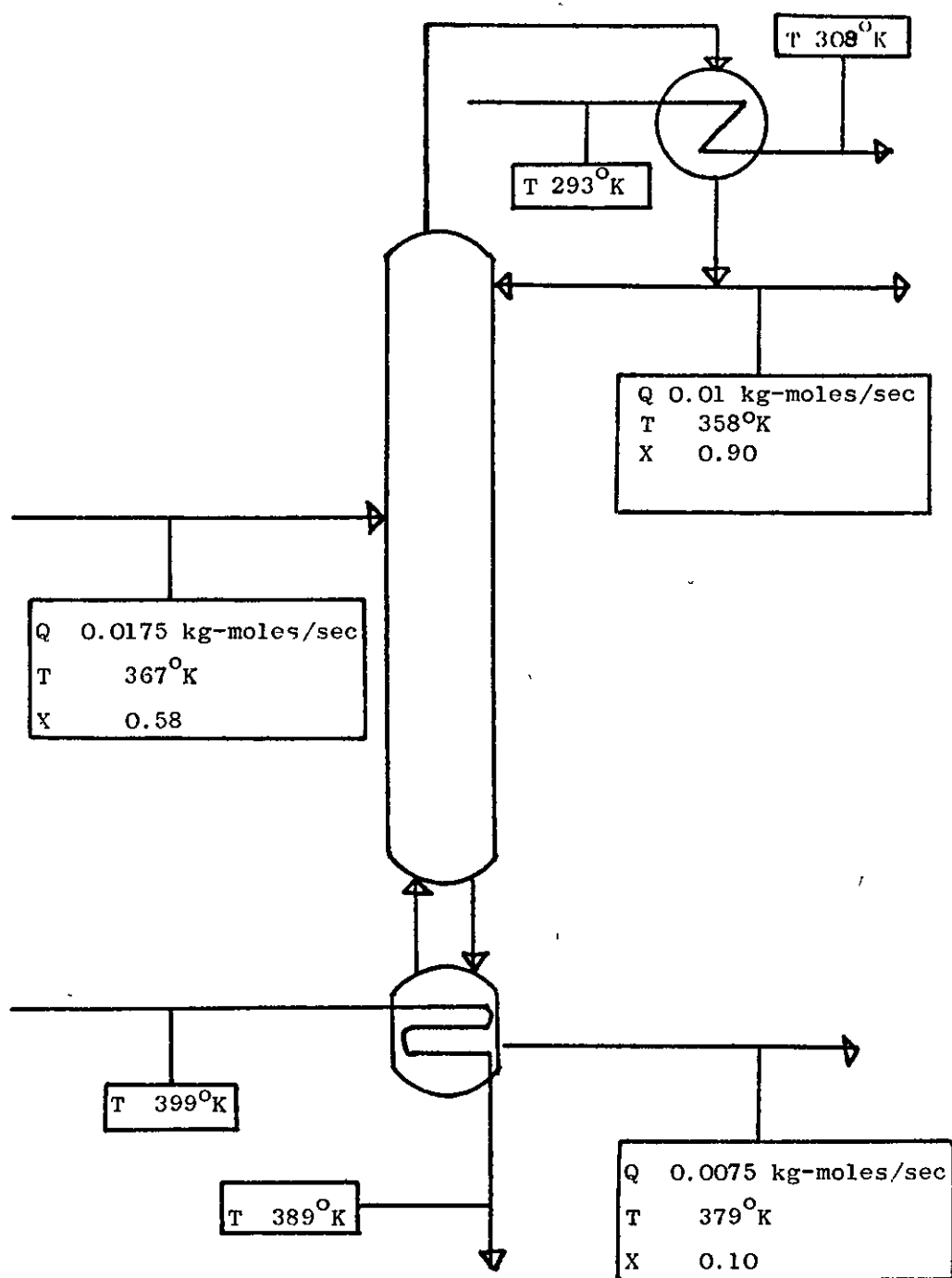


FIG. 4.4(b)

Flow Sheet

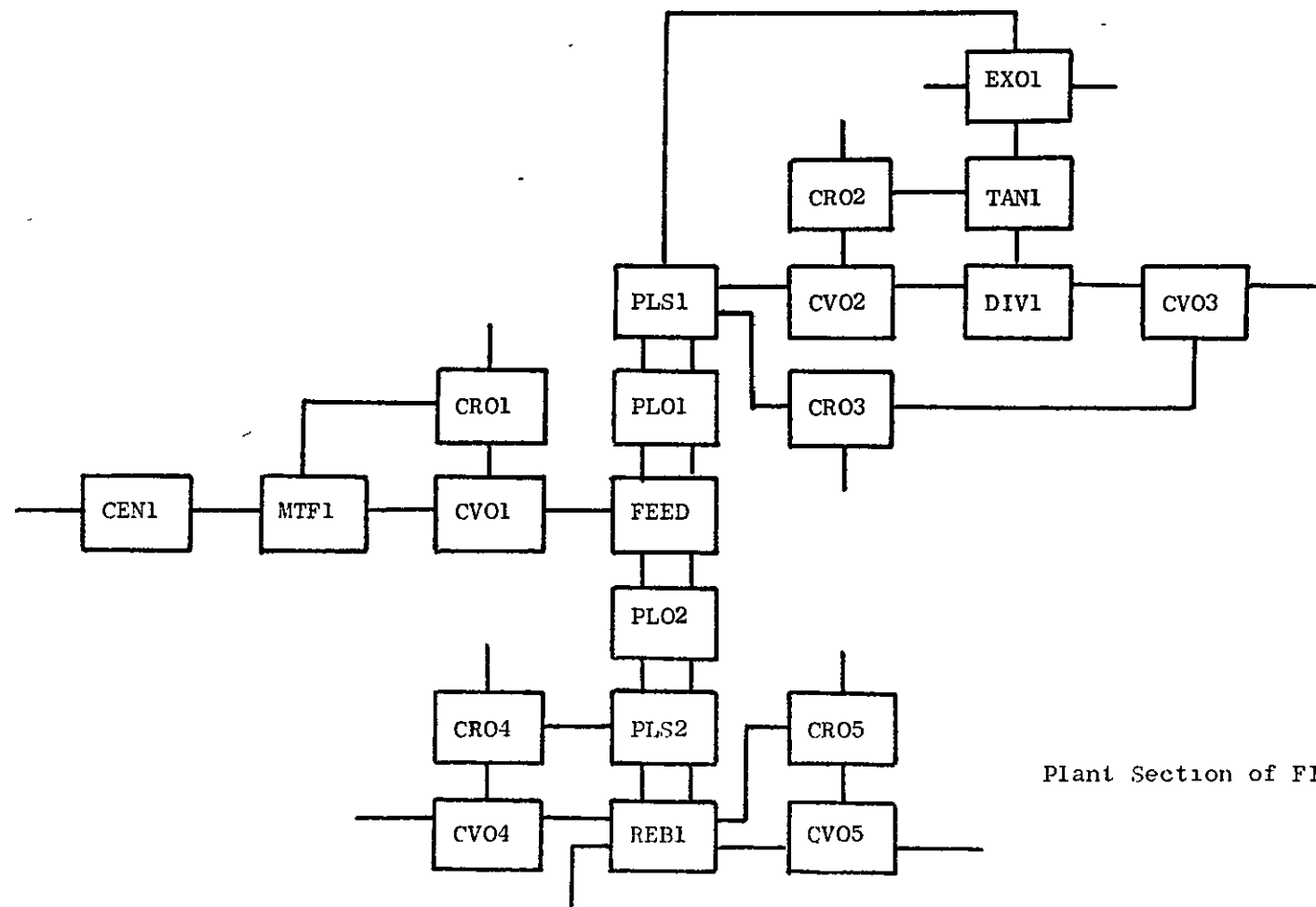


FIG. 4.5

Plant Section of FIG. 4.4 Split into Units

of the details of the facilities required for each run. The keyword used to set up the model in this way is MASTERMODEL. As may be seen from the LISTING, this keyword is the first one used for this particular run of the program. Details of the use of all the keywords available to the user are given in Appendix 2. The program output corresponding to the data for the column section is shown in Figs. 4.6 and 4.7. The correspondence between the streams shown in Fig. 4.5 and the skeleton model data shown in Fig. 4.6 is obvious. The model equations, shown in Fig. 4.7, are also self-explanatory. The system steady-state data is supplied by using the keyword SYSTEMDATA followed by the data for each unit as shown in LISTING 3. The output corresponding to the data for the column section is shown in Fig. 4.8.

The output shown is used for checking purposes and as a convenient listing of unit parameters. Note that stream variables need only be given a value in one of the two units involved but, for the reasons given above, it may be convenient to give these variables the same value in each of the two units concerned. When defining values for this type of variable, only the 2-character name used in the unit currently considered is used even though the complete name consists of 4 characters. The program automatically finds the correct variable by inspecting the stream names for the unit.

The true steady-state, found by integrating the complete model is shown as the final set of values in Fig. 4.9. This output is mainly used for debugging the data.

| LIST UNIT OUTPUT | | | | |
|------------------|-----------------|---------------|------------------|-------|
| UNIT NAME | INPUT OR OUTPUT | POINT ON UNIT | LINKED WITH UNIT | POINT |
| FEED | INPUT | F | CV01 | B |
| | | A | PL01 | C |
| | | D | PL02 | B |
| | OUTPUT | B | PL01 | D |
| | | C | PL02 | A |
| PL01 | INPUT | D | FEED | B |
| | | A | PLS1 | C |
| | OUTPUT | B | PLS1 | D |
| | | C | FEED | A |
| OUT1 | OUTPUT | A | CEN1 | S |
| PL02 | INPUT | A | FEED | C |
| | | D | PLS2 | B |
| | OUTPUT | B | FEED | D |
| | | C | PLS2 | A |
| PLS2 | INPUT | A | PL02 | C |
| | | D | REB1 | D |
| | OUTPUT | B | PL02 | D |
| | | S | CR04 | B |
| | | C | REB1 | C |
| REB1 | INPUT | C | PLS2 | C |
| | | F | CV04 | B |
| | OUTPUT | G | OUT3 | 2 |
| | | D | PLS2 | D |

Program Output Showing Skeleton Plant Model

FIG. 4 6

| | | | | |
|------|--------|---|------|---|
| | | R | CR05 | B |
| | | B | CV05 | A |
| SETC | OUTPUT | 1 | CR01 | A |
| | | 2 | CR02 | A |
| | | 3 | CR03 | A |
| | | 4 | CR04 | A |
| | | 5 | CR05 | A |
| CR04 | INPUT | A | SETC | 4 |
| | | B | PLS2 | S |
| | OUTPUT | C | CV04 | C |
| CV04 | INPUT | A | OUT2 | 1 |
| | | C | CR04 | C |
| | OUTPUT | B | REB1 | F |
| CR05 | INPUT | A | SETC | 5 |
| | | B | REB1 | R |
| | OUTPUT | C | CV05 | C |
| CV05 | INPUT | A | REB1 | B |
| | | C | CR05 | C |
| | OUTPUT | B | OUTF | B |
| OUTF | INPUT | B | CV05 | B |
| | | D | CV03 | B |
| GEN1 | INPUT | S | OUT1 | A |
| | OUTPUT | D | MTF1 | A |
| PLS1 | INPUT | A | CV02 | B |
| | | D | PL01 | B |

FIG. 4.6 (continued)

| | | | | |
|------|--------|---|------|---|
| EX01 | OUTPUT | B | EX01 | A |
| | | C | PL01 | A |
| | | S | CR03 | B |
| EX01 | INPUT | A | PLS1 | B |
| | | C | OUT2 | 3 |
| | OUTPUT | B | TAN1 | A |
| | | D | OUT3 | 4 |
| TAN1 | INPUT | A | EX01 | B |
| | OUTPUT | B | DIV1 | A |
| | | S | CR02 | B |
| CR02 | INPUT | A | SETC | 2 |
| | | B | TAN1 | S |
| | OUTPUT | C | CV02 | C |
| DIV1 | INPUT | A | TAN1 | B |
| | OUTPUT | B | CV02 | A |
| | | C | CV03 | A |
| CV03 | INPUT | A | DIV1 | C |
| | | C | CR03 | C |
| | OUTPUT | B | OUTF | D |
| CR03 | INPUT | A | SETC | 3 |
| | | B | PLS1 | S |
| | OUTPUT | C | CV03 | C |
| OUT2 | OUTPUT | 1 | CV04 | A |
| | | 3 | EX01 | C |
| OUT3 | INPUT | 2 | REB1 | G |

FIG. 4.6 (continued)

| | | | | |
|------|--------|---|------|---|
| | | 4 | EX01 | D |
| CV01 | INPUT | A | MTF1 | B |
| | | C | CR01 | C |
| | OUTPUT | B | FEED | F |
| CR01 | INPUT | A | SETC | 1 |
| | | B | MTF1 | C |
| | OUTPUT | C | CV01 | C |
| MTF1 | INPUT | A | CEN1 | D |
| | OUTPUT | B | CV01 | A |
| | | C | CR01 | B |
| CV02 | INPUT | A | DIV1 | E |
| | | C | CR02 | C |
| | OUTPUT | B | PLS1 | A |

FIG. 4.6 (continued)

READMODEL PRINTOUT

FEED

PL01

PL02

PLS1

PLS2

REB1

EX01

VARIABLES COMMON TO ABOVE UNITS:

M1 ,M2 ,A0 ,A1 ,A2 ,A3 ,A4 ,B0 ,B1 ,B2 ,B3 ,B4 ,HL ,CP

FEED

PL01

PL02

FIG. 4.7

Program Output Showing Equations of Plant Model

PLS1

PLS2

VARIABLES COMMON TO ABOVE UNITS:

HT

PL01

PLS1

VARIABLES COMMON TO ABOVE UNITS:

WL

FEED

PL02

PLS2

VARIABLES COMMON TO ABOVE UNITS:

WL

FIG. 4.7 (continued)

CV01

CV02

CV03

CV04

CV05

QB←KV*PC*(PA-PB)↑KH
D(PA)/DT+GA*(QA-QB)
TB←TA
XB←XA

FEED

$D(XC)/DT+(QD*(XD-XC)+QE*(\lambda F-XC)+QA*(XA-XC)-QB*(XB-XC))/HT$
 $D(QC)/DT+(QA+QE-QC)/WL$
 $TC←A0+XC*(A1+XC*(A2+XC*(A3+XC*A4)))$
 $XB←B0+XC*(B1+XC*(B2+XC*(B3+XC*R4)))$
 $QB←(QA*TA+QD*(TD+HL/CP)+QE*TF-QC*TC)/(TB+HL/CP)$
TB←TC
PF←KP
 $XE←M2*XF/(M2*XF+M1*(WN-XF))$
 $QE←QF*(XF/M1+(WN-XF)/M2)$

CEN1

FIG. 4.7 (continued)

$$QD \leftarrow (K1 * QS \uparrow TT - K2 * (PD - PS) + K3 * QS \uparrow TO) \uparrow KH$$

$$D(PS) / DT \leftarrow KS * (QS - QD)$$

$$XD \leftarrow XS$$

$$TD \leftarrow TS$$

PL01

PL02

PLS1

PLS2

$$D(XC) / DT \leftarrow (QD * (XD - XC) + QA * (XA - XC) - QB * (XB - XC)) / HT$$

$$D(QC) / DT \leftarrow (QA - QC) / WL$$

$$TC \leftarrow A0 + XC * (A1 + XC * (A2 + XC * (A3 + XC * A4)))$$

$$XB \leftarrow B0 + XC * (B1 + XC * (B2 + XC * (B3 + XC * B4)))$$

$$ZS \leftarrow XC * SF$$

$$QB \leftarrow (QA * TA + QD * (TD + HL / CP) - QC * TC) / (TB + HL / CP)$$

$$TB \leftarrow TC$$

CR01

CR02

CR03

CR04

CR05

FIG. 4.7 (continued)

VARIABLES COMMON TO ABOVE UNITS:

W2

$SU \leftarrow SU + (ZA - ZB) * (GT + HH - LT)$
 $PI \leftarrow KH + KC * ((ZA - ZB) + KI * SU)$
 $PC \leftarrow W2 * SLIM[PI]$
 $LT \leftarrow GT + HH$

MTF1

$QB \leftarrow KB * (PA - PB) \uparrow KH$
 $D(PA) / DT \leftarrow GA * (QA - QB)$
 $TB \leftarrow TA$
 $XB \leftarrow XA$
 $ZC \leftarrow SF * QB$

REB1

$D(XR) / DT \leftarrow (QC * (XC - XR) - QD * (XD - XR)) / HR$
 $D(HR) / DT \leftarrow (QC - QD - QR)$
 $LR \leftarrow HR / AR / MD / VF$
 $TR \leftarrow A0 + XR * (A1 + XR * (A2 + XR * (A3 + XR * A4)))$
 $QR \leftarrow KR * ((KP + K1 * LR) - PB) \uparrow KH$
 $FF \leftarrow (TF - TR) / (TG - TR)$
 $EC \leftarrow UC * AC * ((TF - TG) / SLIM[FF])$
 $XD \leftarrow B0 + XR * (B1 + XR * (B2 + XR * (B3 + XR * B4)))$
 $QD \leftarrow EC * RO / HL$
 $TD \leftarrow TR$

FIG. 4.7 (continued)

$ZR \leftarrow LR * SF$
 $QB \leftarrow QR * (M1 * XR + (WN - XR) * M2)$
 $TB \leftarrow TR$
 $XB \leftarrow XR * M1 / (M1 * XR + M2 * (WN - XR))$
 $D(PF) / DT \leftarrow GF * (QF - QG)$
 $QG \leftarrow KG * (PF - PG) \uparrow KH$
 $TG \leftarrow (QT * RF * CF * TF - EC) / QG / RF / CF$

DIV1

$QB \leftarrow KB * (PA - PB) \uparrow KH$
 $QC \leftarrow KC * (PA - PC) \uparrow KH$
 $D(PA) / DT \leftarrow GA * (QA - QB - QC)$
 $TB \leftarrow TA$
 $TC \leftarrow TA$
 $XB \leftarrow XA$
 $XC \leftarrow XA$

TAN1

$D(LC) / DT \leftarrow (QA - QB) / AT$
 $D(TC) / DT \leftarrow QA * (TA - TC) / LC / AT$
 $D(XC) / DT \leftarrow QA * (XA - XC) / LC / AT$
 $QB \leftarrow KB * ((PA + K1 * LC) - PB) \uparrow KH$
 $TB \leftarrow TC$
 $XB \leftarrow XC$
 $PA \leftarrow KP$
 $ZS \leftarrow LC * SF$

SETC

FIG. 4.7 (continued)

Z1←Z1
Z2←Z2
Z3←Z3
Z4←Z4
Z5←Z5

EX01

PA←KP
QB←QA
TB←TA
XB←XA
EC←HL*QA/RO
D(PC)/DT←CC*(QC-QD)
QD←KD*(PC-PD)↑KH
TD←(QC*RC*CC*TC+EC)/(QD*RC*CC)

OUTF

PB←PB
PD←PD

OUT1

TA←TA
QA←KA*(P1-PA)↑KH
XA←XA

FIG. 4.7 (continued)

OUT2

$Q1 \leftarrow K1 * (P0 - P1) \uparrow KH$
 $T1 \leftarrow T1$
 $Q3 \leftarrow K3 * (P0 - P3) \uparrow KH$
 $T3 \leftarrow T3$

OUT3

$P2 \leftarrow P2$
 $P4 \leftarrow P4$

FIG. 4.7 (continued)

| | | | | | | | | |
|----|------------------|----|----|------------------|----|----|------------------|----|
| K1 | +2.000000000000& | +0 | K2 | +1.000000000000& | -1 | K3 | +1.950000000000& | +0 |
| QD | +1.470000000000& | +0 | QS | +1.470000000000& | +0 | PD | +1.500000000000& | +2 |
| PS | +1.034500000000& | +2 | X5 | +5.200000000000& | -1 | XD | +5.200000000000& | -1 |
| TD | +3.670000000000& | +2 | T5 | +3.670000000000& | +2 | K5 | +2.500000000000& | +0 |
| TT | +6.670000000000& | -1 | IO | +2.000000000000& | +0 | | | |

FIG. 4.8

UNIT SETC

| | | | | | |
|----|---------------------|----|---------------------|----|---------------------|
| Z1 | +7.350000000000& +0 | Z2 | +7.500000000000& +0 | Z3 | +1.155000000000& +1 |
| Z4 | +3.000000000000& +0 | Z5 | +7.500000000000& +0 | | |

UNIT PL01

| | | | | | |
|----|---------------------|----|---------------------|----|---------------------|
| SF | +1.500000000000& +1 | WL | +4.500000000000& +2 | XC | +6.200000000000& -1 |
| QC | +3.500000000000& -2 | TB | +3.620000000000& +2 | TC | +3.620000000000& +2 |
| XB | +8.000000000001& -1 | QR | +4.500000000000& -2 | ZS | +9.300000000001& +0 |

UNIT PL02

| | | | | | |
|----|---------------------|----|---------------------|----|---------------------|
| XC | +3.300000000000& -1 | QC | +5.250000000000& -2 | QB | +4.500000000000& -2 |
| ZS | +4.950000000000& +0 | SF | +1.500000000000& +1 | TB | +3.705000000000& +2 |
| TC | +3.705000000000& +2 | XR | +5.350000000001& -1 | | |

FIG 4.8 (continued)

UNIT OUT1

| | | | | | |
|----|---------------------|----|---------------------|----|---------------------|
| 1A | +3.670000000000E +2 | QA | +1.470000000000E +0 | XA | +5.200000000000E -1 |
| KA | +3.170000000000E -1 | PA | +1.034500000000E -2 | P1 | +1.250000000000E +2 |

UNIT PLS1

| | | | | | |
|----|---------------------|----|---------------------|----|---------------------|
| XC | +7.700000000000E -1 | QC | +3.500000000000E -2 | TC | +3.580000000000E +2 |
| XB | +9.000000000000E -1 | QR | +4.500000000000E -2 | TB | +3.580000000000E +2 |
| SF | +1.500000000000E +1 | ZS | +1.155000000000E +1 | | |

UNIT PLS2

| | | | | | |
|----|---------------------|----|---------------------|----|---------------------|
| XC | +2.000000000000E -1 | QC | +5.250000000000E -2 | TC | +3.750000000000E +2 |
| XB | +3.700000000000E -1 | QR | +4.500000000000E -2 | TB | +3.750000000000E +2 |
| ZS | +3.000000000000E +0 | SF | +1.500000000000E +1 | | |

UNIT REB1

| | | | | | |
|----|---------------------|----|---------------------|----|---------------------|
| HR | +6.000000000000E +0 | XR | +1.000000000000E -1 | LR | +1.000000000000E +0 |
|----|---------------------|----|---------------------|----|---------------------|

| | | | | | |
|----|--------------------|----|--------------------|----|---------------------|
| KB | +2.849999999999E-2 | KC | +4.718000000000E-3 | GA | +1.000000000000E+0 |
| PC | +1.045000000000E+2 | PR | +1.075000000000E+2 | KP | +1.013250000000E+2* |
| PA | +1.090000000000E+2 | | | | |

UNIT TAN1

| | | | | | |
|----|--------------------|----|--------------------|----|--------------------|
| AT | +1.500000000000E+1 | QA | +4.500000000000E-2 | LC | +1.000000000000E+0 |
| TA | +3.580000000000E+2 | TC | +3.580000000000E+2 | XA | +9.000000000000E-1 |
| XC | +9.000000000000E-1 | KB | +3.910000000000E-2 | QB | +4.500000000000E-2 |
| PA | +1.013250000000E+2 | K1 | +9.000000000000E+0 | PB | +1.090000000000E+2 |
| IB | +3.580000000000E+2 | XR | +9.000000000000E-1 | KP | +1.013250000000E+2 |
| ZS | +7.500000000000E+0 | SF | +7.500000000000E+0 | | |

UNIT OUTF

| | | | |
|----|--------------------|----|--------------------|
| PB | +9.500000000000E+1 | PD | +1.005000000000E+2 |
|----|--------------------|----|--------------------|

UNIT CV01

| | | | | | |
|----|--------------------|----|--------------------|----|--------------------|
| QB | +1.470000000000E+0 | PA | +1.250000000000E+2 | TB | +3.670000000000E+2 |
| TA | +3.670000000000E+2 | XA | +5.200000000000E-1 | XB | +5.200000000000E-1 |

FIG. 4.8 (continued)

| | | | | | |
|----|-------------------|----|-------------------|----|-------------------|
| KV | +6.0700000000E -3 | PR | +5.0000000000E +1 | PB | +1.0132500000E +2 |
| GA | +1.0000000000E +0 | QA | +1.4700000000E +0 | | |

UNIT MTF1

★ ★ ★ ★ ★ ★ ★ ★

| | | | | | | | | |
|----|----------------|----|----|----------------|----|----|----------------|----|
| QB | +1.4700000000& | +0 | KB | +2.9400000000& | -1 | PA | +1.5000000000& | +2 |
| PB | +1.2500000000& | +2 | GA | +1.0000000000& | +0 | QA | +1.4700000000& | +0 |
| TB | +3.6700000000& | +2 | IA | +3.6700000000& | +2 | XA | +5.2000000000& | -1 |
| XB | +5.2000000000& | -1 | ZC | +7.3500000000& | +0 | SF | +5.0000000000& | +0 |

UNIT CR01

★ ★ ★ ★ ★ ★ ★ ★ ★ ★

| | | | | | | | | |
|----|------------------|----|----|------------------|----|----|------------------|----|
| WZ | +1.000000000000& | +2 | ZA | +7.350000000000& | +0 | ZB | +7.350000000000& | +0 |
| PC | +5.000000000000& | +1 | PI | +5.000000000000& | -1 | SU | +0.000000000000& | +0 |
| KI | +5.000000000000& | -2 | KC | +4.000000000000& | -3 | | | |

UNIT OUT2

★ ★ ★ ★ ★ ★ ★ ★

| | | | | | | | | |
|----|----------------|----|----|----------------|-----|----|----------------|-----|
| Q1 | +1.8750000000& | -1 | T1 | +3.9900000000& | +2 | Q3 | +2.8700000000& | -1 |
| T3 | +2.9300000000& | +2 | P2 | +1.0500000000& | +2* | P4 | +1.0450000000& | +2* |
| K1 | +6.6200000000& | -2 | K3 | +9.0800000000& | -2 | P0 | +1.3000000000& | +2 |

FIG. 4.8 (continued)

P1 +1.2200000000E +2 P3 +1.2000000000E +2 KH +5.0000000000E -1

UNIT CV04

| | | | | | | | | |
|----|----------------|----|----|----------------|----|----|----------------|----|
| QB | +1.8750000000& | -1 | KV | +1.0420000000& | -3 | PC | +5.0000000000& | +1 |
| PB | +1.0900000000& | +2 | PA | +1.2200000000& | +2 | GA | +5.0000000000& | +0 |
| QA | +1.6750000000& | -1 | TB | +3.9900000000& | +2 | TA | +3.9900000000& | +2 |
| XB | +1.0000000000& | +0 | XA | +1.0000000000& | +0 | | | |

UNIT CRO4

| | | | | | | | | |
|----|----------------|----|----|----------------|----|----|----------------|----|
| ZA | +3.00000000008 | +0 | ZR | +3.00000000008 | +0 | PI | +5.00000000008 | -1 |
| PC | +5.00000000008 | +1 | SU | +0.00000000008 | +0 | KI | +1.00000000008 | -3 |
| KC | +5.00000000008 | -1 | | | | | | |

UNIT CV05

| | | | | | | | | |
|----|----------------|----|----|----------------|----|----|----------------|----|
| QB | +6.8000000000& | -1 | KV | +5.5700000000& | -3 | PC | +5.0000000000& | +1 |
| PA | +1.0100000000& | +2 | PR | +9.5000000000& | +1 | GA | +5.0000000000& | -1 |
| QA | +6.8000000000& | -1 | TR | +3.7900000000& | +2 | TA | +3.7900000000& | +2 |
| XB | +8.6099999999& | -2 | XA | +8.6099999999& | -2 | | | |

FIG. 4.8 (continued)

| | | | | | | | | |
|----|----------------|----|----|----------------|----|----|----------------|----|
| QB | +1.0000000000% | -2 | KV | +1.0000000000% | -4 | PC | +5.0000000000% | +1 |
| PA | +1.0450000000% | +2 | PB | +1.0050000000% | +2 | GA | +2.0000000000% | +1 |
| QA | +1.0000000000% | -2 | XA | +9.0000000000% | -1 | XB | +9.0000000000% | -1 |
| TA | +3.5800000000% | +2 | TB | +3.5800000000% | +2 | | | |

P2 +1.05000000008 +2 P4 +1.10000000008 +2

✱ ✱ ✱ ✱ ✱ ✱ ✱ ✱ ✱

| | | | | | | | | |
|----|----------------|----|----|----------------|----|----|----------------|----|
| ZA | +1.15500000008 | +1 | ZB | +1.15500000008 | +1 | PI | +5.00000000008 | -1 |
| PC | +5.00000000008 | +1 | KI | +1.00000000008 | -3 | SU | +0.00000000008 | +0 |
| KC | -9.00000000008 | -1 | | | | | | |

* INDICATES PRECEEDING NAME NOT FOUND IN EQUATIONS

FIG. 4.8 (continued)

RUNSYSTEM PRINTOUT

UNITS AND VARIABLES TO BE USED FOR INTEGRATION
A AND D DENOTE ALG. OR DIF. EQUATION

Program Output after Use of Keyword RUNSYSTEM

FEED

| | | | | | | |
|--------|--------|--------|--------|--------|--------|--------|
| A QE | A XE | A PFPR | A TDTB | A QDQB | A XDXB | A TATC |
| D QAQC | D XAXC | | | | | |

PL01

| | | | | | | |
|--------|--------|------|--------|--------|--------|--------|
| A TDTB | A QDQB | A ZS | A XDXB | A TATC | D QAQC | D XAXC |
|--------|--------|------|--------|--------|--------|--------|

OUT1

| | | |
|--------|--------|--------|
| A XSXA | A QSQA | A TSTA |
|--------|--------|--------|

PL02

| | | | | | | |
|--------|--------|------|--------|--------|--------|--------|
| A TDTB | A QDQB | A ZS | A XDXB | A TATC | D QAQC | D XAXC |
|--------|--------|------|--------|--------|--------|--------|

PLS2

| | | | | | | |
|--------|--------|--------|--------|--------|--------|--------|
| A TDTB | A QDQB | A ZBZS | A XDXB | A TCTC | D QCQC | D XCXC |
|--------|--------|--------|--------|--------|--------|--------|

REB1

FIG. 4.9

| | | | | | | |
|--------|--------|--------|--------|--------|--------|--------|
| A T2TG | A Q2QG | D PFPR | A XAXB | A TATB | A QAQB | A ZRZR |
| A TDYD | A QDQD | A XDAD | A EL | A FF | A QBOR | A TBIR |
| A LR | D HR | D XBXR | | | | |

SETC

| | | | | |
|--------|--------|--------|--------|--------|
| A ZAZ5 | A ZAZ4 | A ZAZ3 | A ZAZ2 | A ZAZ1 |
|--------|--------|--------|--------|--------|

CR04

| | | | |
|------|--------|------|------|
| A LT | A PCPC | A PI | A SU |
|------|--------|------|------|

CV04

| | | | |
|--------|--------|--------|--------|
| A XFXB | A TFTB | D PAP1 | A QFQB |
|--------|--------|--------|--------|

CR05

| | | | |
|------|--------|------|------|
| A LT | A PCPC | A PI | A SU |
|------|--------|------|------|

CV05

| | | | |
|--------|--------|--------|--------|
| A XBXB | A TBTB | D PAPB | A QBQB |
|--------|--------|--------|--------|

OUTF

| | |
|--------|--------|
| A PDPB | A PBPB |
|--------|--------|

CEN1

| | | | |
|--------|--------|--------|--------|
| A TATD | A XAXD | D PSPA | A QAQD |
|--------|--------|--------|--------|

PLS1

A TATB A QAQB A ZBZS A XAXB A TATC D QAQC D XAXC

EX01

A T4TD A Q4QD D PCP3 A EC A XAXB A TATB A QAQB
A PAPB

TAN1

A ZBZS A PAPB A XAXR A TATB A QAQB D XC D TC
D LC

CR02

A LT A PCPC A PI A SU

DIV1

A XAXC A XAXB A TATC A TATB D PAPB A QAQC A QAQB

CV03

A XDXB A TDTB D PAPC A QDOB

CR03

A LT A PCPC A PI A SU

OUT2

A TCT3 A QCQ3 A TAT1 A QAQ1

FIG. 4.9 (continued)

OUT3

A P4PD A P2PG

CV01

A XFXB A TFTB D PAPB A QFQB

CR01

A LT A PCPC A PI A SU

MIF1

A ZBZC A XAXB A TATB D PAPD A QAQB

CV02

A XAXB A TATB D PAPB A QAQB

TIME = +0.000008 +0

VALUES SET BY DIFFERENTIAL EQUATIONS:

| | | | | | | | | | | | |
|------|-----------|----|------|-----------|----|------|-----------|----|------|-----------|----|
| PAPB | +1.075008 | +2 | PAPD | +1.500008 | +2 | PAPB | +1.250008 | +2 | PAPC | +1.045008 | +2 |
| PAPB | +1.090008 | +2 | IC | +1.000008 | +0 | TC | +3.580008 | +2 | XC | +9.000008 | -1 |
| PCP3 | +1.200008 | +2 | XAXC | +7.700008 | -1 | QAQC | +3.500008 | -2 | PSPA | +1.034508 | +2 |
| PAPB | +1.010008 | +2 | PAP1 | +1.220008 | +2 | XBXR | +1.000008 | -1 | HR | +6.000008 | +0 |
| PFPB | +1.090008 | +2 | XCXC | +2.000008 | -1 | QCQC | +5.250008 | -2 | XAXC | +3.300008 | -1 |
| QAQC | +5.250008 | -2 | XAXC | +6.200008 | -1 | QAQC | +3.500008 | -2 | XAXC | +4.800008 | -1 |
| QAQC | +5.250008 | -2 | | | | | | | | | |

VALUES SET BY ALGEBRAIC EQUATIONS:

| | | | | | | | | | | | |
|------|-----------|----|------|-----------|----|------|-----------|----|------|-----------|----|
| QAQB | +3.500000 | -2 | TATB | +3.580000 | +2 | XAXB | +9.000000 | -1 | QAQB | +1.470000 | +0 |
| TATB | +3.670000 | +2 | XAXB | +5.200000 | -1 | ZBZC | +7.350000 | +0 | SU | +0.000000 | +0 |
| PI | +5.000000 | -1 | PCPC | +5.000000 | +1 | LT | +0.000000 | +0 | QFQB | +1.470000 | +0 |
| TFTB | +3.670000 | +2 | XFXB | +5.200000 | -1 | P2PG | +1.050000 | +2 | P4PD | +1.100000 | +2 |
| QAQ1 | +1.875000 | -1 | TAT1 | +3.990000 | +2 | QLQ3 | +2.870000 | -1 | TCT3 | +2.930000 | +2 |
| SU | +0.000000 | +0 | PI | +5.000000 | -1 | PCPC | +5.000000 | +1 | LT | +0.000000 | +0 |
| QDQB | +1.000000 | -2 | TDTB | +3.580000 | +2 | XDXB | +9.000000 | -1 | QAQB | +3.500000 | -2 |
| QAQC | +1.000000 | -2 | TATB | +3.580000 | +2 | TATC | +3.580000 | +2 | XAXB | +9.000000 | -1 |
| XAXC | +9.000000 | -1 | SU | +0.000000 | +0 | PI | +5.000000 | -1 | PCPC | +5.000000 | +1 |
| LT | +0.000000 | +0 | QAQB | +4.500000 | -2 | TATB | +3.580000 | +2 | XAXB | +9.000000 | -1 |
| P4PB | +1.013250 | +2 | ZBZS | +7.500000 | +0 | PAPB | +1.013250 | +2 | QAQB | +4.500000 | -2 |
| TATB | +3.580000 | +2 | XAXB | +9.000000 | -1 | EC | +1.800000 | +4 | Q4QD | +2.870000 | -1 |
| T4TD | +3.080000 | +2 | TATC | +3.580000 | +2 | XAXB | +9.000000 | -1 | ZBZS | +1.155000 | +1 |
| Q4QB | +4.500000 | -2 | TATB | +3.580000 | -2 | QAQD | +1.470000 | +0 | XAXD | +5.200000 | -1 |
| T4TD | +3.670000 | +2 | PBPB | +9.500000 | -1 | PDPB | +1.005000 | +2 | QBQB | +6.800000 | -1 |
| TBTB | +3.790000 | +2 | XBXB | +8.610000 | -2 | SU | +0.000000 | +0 | PI | +5.000000 | -1 |
| PCPC | +5.000000 | +1 | LT | +0.000000 | +0 | QFQB | +1.875000 | -1 | TFTB | +3.990000 | +2 |
| XFXB | +1.000000 | +0 | SU | +0.000000 | +0 | PI | +5.000000 | -1 | PCPC | +5.000000 | +1 |
| LT | +0.000000 | +0 | ZA21 | +7.350000 | +0 | ZA22 | +7.500000 | +0 | ZA23 | +1.155000 | +1 |
| ZA24 | +3.000000 | +0 | ZA25 | +7.500000 | +0 | LR | +1.000000 | +0 | TBTR | +3.790000 | +2 |
| QBQR | +7.500000 | -3 | FF | +2.000000 | +0 | EC | +1.800000 | +4 | XDXD | +2.100000 | -1 |
| QDQD | +4.500000 | -2 | TDTB | +3.790000 | +2 | ZBZR | +7.500000 | +0 | QAQB | +6.800000 | -1 |
| TATB | +3.790000 | +2 | XAXB | +8.610000 | -2 | Q2QG | +1.875000 | -1 | T2TG | +3.890000 | +2 |
| TCTC | +3.750000 | +2 | XDXB | +3.700000 | -1 | ZBZS | +3.000000 | +0 | QDQB | +4.500000 | -2 |
| TDTB | +3.750000 | +2 | TATC | +3.705000 | +2 | XDXB | +5.350000 | -1 | ZS | +4.950000 | +0 |
| QDQB | +4.500000 | -2 | TDTB | +3.705000 | +2 | TSTA | +3.670000 | +2 | QSQA | +1.470000 | +0 |
| XSXA | +5.200000 | -1 | TATC | +3.620000 | -2 | XDXB | +8.000000 | -1 | 7S | +9.300000 | +0 |
| QDQB | +4.500000 | -2 | TDTB | +3.620000 | +2 | TATC | +3.660000 | +2 | XDXB | +6.800000 | -1 |
| QDQB | +4.500000 | -2 | TDTB | +3.660000 | +2 | PFPB | +1.013250 | +2 | XE | +5.800000 | -1 |
| QE | +1.750000 | -2 | | | | | | | | | |

TIME = +1.443758 -1

VALUES SET BY DIFFERENTIAL EQUATIONS:

| | | | | | | | | | | | |
|------|-----------|----|------|-----------|----|------|-----------|----|------|-----------|----|
| PAPB | +1.075008 | +2 | PAPD | +1.500008 | +2 | PAPB | +1.249998 | +2 | PAPC | +1.045008 | +2 |
| PAPB | +1.090008 | +2 | LC | +1.000018 | +0 | TC | +3.580008 | +2 | XC | +8.999988 | -1 |
| PCP3 | +1.200008 | +2 | XAXC | +7.700038 | -1 | QAQC | +3.500008 | -2 | PSPA | +1.034518 | +2 |
| PAPB | +1.010008 | +2 | PAP1 | +1.220008 | +2 | XBXR | +1.000078 | -1 | HR | +5.999858 | +0 |
| PAPB | +1.090008 | +2 | XCXC | +1.999978 | -1 | QCQC | +5.250008 | -2 | XAXC | +3.300008 | -1 |
| QAQC | +5.250008 | -2 | XAXC | +6.200028 | -1 | QAQC | +3.500008 | -2 | XAXC | +4.799958 | -1 |
| QAQC | +5.250008 | -2 | | | | | | | | | |

VALUES SET BY ALGEBRAIC EQUATIONS:

| | | | | | | | | | | | |
|------|-----------|----|------|-----------|----|------|-----------|----|------|-----------|----|
| QAQB | +3.502748 | -2 | TATB | +3.580008 | +2 | XAXB | +8.999988 | -1 | QAQB | +1.470028 | +0 |
| TATB | +3.670008 | +2 | XAXB | +5.200008 | -1 | ZBZC | +7.350108 | +0 | SU | -7.970168 | -6 |
| PI | +5.000008 | -1 | PCPC | +4.999998 | +1 | LT | +1.443758 | -1 | QFQB | +1.476718 | +0 |
| TFTB | +3.670008 | +2 | XFXB | +5.200008 | -1 | P2PG | +1.050008 | +2 | P4PD | +1.100008 | +2 |
| QAQ1 | +1.872478 | -1 | TAT1 | +3.990008 | +2 | QCQ3 | +2.871348 | -1 | TCT3 | +2.930008 | +2 |
| SJ | -2.515518 | -6 | PI | +5.000348 | -1 | PCPC | +5.000548 | +1 | IT | +1.443758 | -1 |
| QCQB | +1.000118 | -2 | TDTB | +3.580008 | +2 | XDXB | +8.999988 | -1 | QAQB | +3.490638 | -2 |
| QAQC | +1.000848 | -2 | TATB | +3.580008 | +2 | TATC | +3.580008 | +2 | XAXB | +8.999988 | -1 |
| XAXC | +8.999988 | -1 | SU | -6.967008 | -6 | PI | +5.002158 | -1 | PCPC | +5.003378 | +1 |
| LT | +1.443758 | -1 | QAQB | +4.500948 | -2 | TATB | +3.580008 | +2 | XAXB | +8.999988 | -1 |
| PAPB | +1.013258 | +2 | ZBZS | +7.500118 | +0 | PAPB | +1.013258 | +2 | QAQB | +4.655988 | -2 |
| TATB | +3.582758 | +2 | XAXB | +8.950628 | -1 | EC | +1.862398 | +4 | Q4QD | +2.868208 | -1 |
| T4TD | +3.088298 | +2 | TATC | +3.582758 | +2 | XAXB | +8.950628 | -1 | ZBZS | +1.155008 | +1 |
| QAQB | +4.655998 | -2 | TATB | +3.582758 | +2 | QAQD | +1.468178 | +0 | XAXD | +5.200008 | -1 |
| TATD | +3.670008 | +2 | PBPB | +9.500008 | +1 | PDPB | +1.005008 | +2 | QBQB | +6.819628 | -1 |
| TBTB | +3.791658 | +2 | XBXR | +8.609888 | -2 | SU | +1.237858 | -5 | PI | +4.999048 | -1 |
| PCPC | +4.998508 | +1 | LT | +1.443758 | -1 | QFQB | +1.878808 | -1 | TFTB | +3.990008 | +2 |
| XFXB | +1.000008 | +0 | SU | +7.674628 | -6 | PI | +5.000588 | -1 | PCPC | +5.000928 | +1 |

| | | | | | | | | | | | |
|------|-----------|----|------|-----------|----|------|-----------|----|------|-----------|----|
| LT | +1.443758 | -1 | ZA21 | +7.350008 | +0 | ZA22 | +7.500008 | +0 | ZA23 | +1.155008 | +1 |
| ZA24 | +3.000008 | +0 | ZA25 | +7.500008 | +0 | LR | +9.999758 | -1 | TBTR | +3.791658 | +2 |
| QBQR | +7.484208 | -3 | FF | +1.908888 | +0 | EC | +1.845118 | +4 | XDXD | +2.075668 | -1 |
| QDQD | +4.612768 | -2 | TDTD | +3.791658 | +2 | ZBZR | +7.499818 | +0 | QAQB | +6.780678 | -1 |
| TATB | +3.791658 | +2 | XAXB | +8.609888 | -2 | Q2QG | +1.875018 | -1 | T2TG | +3.895568 | +2 |
| TCTC | +3.751928 | +2 | XDXB | +3.746768 | -1 | ZBZS | +2.999888 | +0 | QDQB | +4.602178 | -2 |
| TDTB | +3.751928 | +2 | TATC | +3.705188 | +2 | XDXB | +5.459248 | -1 | ZS | +4.950008 | +0 |
| QDQB | +4.596508 | -2 | TDTB | +3.705188 | +2 | TSTA | +3.670008 | +2 | QSQA | +1.471548 | +0 |
| XSXA | +5.200008 | -1 | TATC | +3.619458 | +2 | XDXB | +8.033928 | -1 | ZS | +9.300048 | +0 |
| QDQB | +4.626178 | -2 | TDTB | +3.619458 | +2 | TATC | +3.657918 | +2 | XDXB | +6.957258 | -1 |
| QDQB | +4.617618 | -2 | TDTB | +3.657918 | +2 | PFPB | +1.013258 | +2 | XE | +5.609768 | -1 |
| QE | +1.754938 | -2 | | | | | | | | | |

MAXIMUM STEPSIZE = +1.44162597668 -1

TIME = +1.001648 +0

VALUES SET BY DIFFERENTIAL EQUATIONS:

| | | | | | | | | | | | |
|------|-----------|----|------|-----------|----|------|-----------|----|------|-----------|----|
| PAPB | +1.074998 | +2 | PAPD | +1.499988 | +2 | PAPB | +1.249938 | +2 | PAPC | +1.045008 | +2 |
| PAPB | +1.090008 | +2 | LC | +1.000128 | +0 | TC | +3.580018 | +2 | XC | +8.999858 | -1 |
| PCP3 | +1.200018 | +2 | XAXC | +7.700168 | -1 | QAQC | +3.500028 | -2 | PSPA | +1.034588 | +2 |
| PAPB | +1.009988 | +2 | PAP1 | +1.219978 | +2 | XBXR | +1.000448 | -1 | HR | +5.998668 | +0 |
| PFPB | +1.090008 | +2 | XCXC | +1.999438 | -1 | QCQC | +5.250008 | -2 | XAXC | +3.299988 | -1 |
| QAQC | +5.250008 | -2 | XAXC | +6.200158 | -1 | QAQC | +3.500008 | -2 | XAXC | +4.799598 | -1 |
| QAQC | +5.250028 | -2 | | | | | | | | | |

VALUES SET BY ALGEBRAIC EQUATIONS:

| | | | | | | | | | | | |
|------|-----------|----|------|-----------|----|------|-----------|----|------|-----------|----|
| QAQB | +3.519738 | -2 | TATB | +3.580018 | +2 | XAXB | +8.999858 | -1 | QAQB | +1.470138 | +0 |
| TATB | +3.670008 | +2 | XAXB | +5.200008 | -1 | ZBZC | +7.350678 | +0 | SU | -3.671808 | -4 |
| PI | +4.999978 | -1 | PCPC | +4.999968 | +1 | LT | +1.001648 | +0 | QFQB | +1.476528 | +0 |

FIG 4.9 (continued)

| | | | | | | | | | | | |
|------|-----------|----|------|-----------|----|------|-----------|----|------|-----------|----|
| TFTB | +3.679008 | +2 | XFXB | +5.200008 | -1 | P2PG | +1.050008 | +2 | P4PD | +1.100008 | +2 |
| QAQ1 | +1.872838 | -1 | TAT1 | +3.990008 | +2 | QCQ3 | +2.871268 | -1 | TCT3 | +2.930008 | +2 |
| SU | -1.131978 | -4 | PI | +5.002218 | -1 | PCPC | +5.003478 | +1 | LT | +1.001648 | +0 |
| QDQB | +1.000718 | -2 | TDTB | +3.580018 | +2 | XDXB | +8.909858 | -1 | QAQB | +3.491718 | -2 |
| QAQC | +1.000848 | -2 | TATB | +3.580018 | +2 | TATC | +3.580018 | +2 | XAXB | +8.999858 | -1 |
| XAXC | +8.999858 | -1 | SU | -3.891388 | -4 | PI | +5.018208 | -1 | PCPC | +5.028608 | +1 |
| LI | +1.001648 | +0 | QAQB | +4.502448 | -2 | TATB | +3.580018 | +2 | XAXB | +8.999858 | -1 |
| PAPB | +1.013258 | +2 | ZBZS | +7.500918 | +0 | PAPB | +1.013258 | +2 | QAQB | +4.722478 | -2 |
| TATB | +3.582748 | +2 | XAXB | +8.950698 | -1 | EC | +1.888998 | +4 | Q4QD | +2.868278 | -1 |
| T4TD | +3.090358 | +2 | TATC | +3.582748 | +2 | XAXB | +8.950698 | -1 | ZBZS | +1.155028 | +1 |
| QAQB | +4.722478 | -2 | TATB | +3.582748 | +2 | QAQD | +1.467898 | +0 | XAXD | +5.200008 | -1 |
| TATD | +3.679008 | +2 | PBPB | +7.500008 | +1 | PDPB | +1.005008 | +2 | QBQB | +6.802898 | -1 |
| TBTB | +3.791638 | +2 | XBXB | +8.613088 | -2 | SU | +7.063728 | -4 | PI | +4.991598 | -1 |
| PCPC | +4.936798 | +1 | LT | +1.001648 | +0 | QFQB | +1.880738 | -1 | TFTB | +3.990008 | +2 |
| XFXB | +1.000008 | +0 | SU | +3.897718 | -4 | PI | +5.004288 | -1 | PCPC | +5.006728 | +1 |
| LI | +1.001648 | +0 | ZAZ1 | +7.350008 | +0 | ZAZ2 | +7.500008 | +0 | ZAZ3 | +1.155008 | +1 |
| ZAZ4 | +3.000008 | +0 | ZAZ5 | +7.500008 | +0 | LR | +9.997778 | -1 | TBTR | +3.791638 | +2 |
| QBQR | +7.484098 | -3 | FF | +1.860198 | +0 | EC | +1.866718 | +4 | XDXD | +2.076348 | -1 |
| QDQD | +4.666778 | -2 | TDTD | +3.791638 | +2 | ZBZR | +7.498338 | +0 | QAQB | +6.780548 | -1 |
| TATB | +3.721638 | +2 | XAXB | +8.613088 | -2 | Q2QG | +1.875118 | -1 | T2TG | +3.898278 | +2 |
| TCTC | +3.751948 | +2 | XDXB | +3.746028 | -1 | ZBZS | +2.999148 | +0 | QDQB | +4.656508 | -2 |
| TDTB | +3.751948 | +2 | TATC | +3.705188 | +2 | XDXB | +5.459218 | -1 | ZS | +4.949978 | +0 |
| QDQB | +4.651308 | -2 | TDTB | +3.705188 | +2 | TSTA | +3.670008 | +2 | QSQA | +1.471298 | +0 |
| XSHA | +5.200008 | -1 | TATC | +3.619458 | +2 | XDXB | +8.034018 | -1 | ZS | +9.300238 | +0 |
| QDQB | +4.681648 | -2 | TDTB | +3.619458 | +2 | TATC | +3.657928 | +2 | XDXB | +6.956958 | -1 |
| QDQB | +4.672698 | -2 | TDTB | +3.657928 | +2 | PFPB | +1.013258 | +2 | XE | +5.609768 | -1 |
| QE | +1.754718 | -2 | | | | | | | | | |

FIG. 4.9 (continued)

CHAPTER 5

DEFINITION OF THE ALARM SYSTEM

5.1 Introduction

Using the program facilities described in the preceding Chapter, the plant model may be assembled in a useful form within the computer core store. Additional programs were written that use this basic model as a tool for the production of the data needed for an alarm analysis application. The primary aim of these programs was to provide facilities that would enable various alarm system configurations to be tested with little additional effort from the user. Emphasis was also placed on the acquisition of time-ordered alarm data and the definition of symptom sets for deduced alarms.

5.2 Methods Used to Define and Improve Alarm Systems

The problems involved when designing a complete alarm system are many and varied, as noted in Section 3.2. In such circumstances, it is unlikely that any "one shot" method will produce the best result and hence an iterative technique is recommended for finding the best system. As a starting point, the features of the system which are fixed must be specified. These features include:

1. The majority of the measured variables,
2. The alarm types and levels which are required by the equipment manufacturers,
3. The locations and ranges of most of the measuring devices required for the above purposes.

The system, as defined by these conditions, will be referred to as the "basic" system. The basic system is then improved by adding other alarms on existing measured variables that are important for the process. The levels for some of these alarms may be obvious.

In particular, full-scale alarms are easily set but will only be useful if the full range of variable values is less than the scale range of the measuring device. In order to pinpoint such restrictions, it may be useful to define a "basic" system consisting of all fixed characteristics of the plant and its instrumentation and then using the analysis programs to test the effectiveness of additions to the basic system. Such a definition of the system would include all alarm types and levels in addition to the measuring devices and their locations.

5.3 Executive Program Functions

The functions of the executive program may be classified as follows:

1. A facility to allow the user to specify the measured variables and to set their types and levels.
2. A facility to allow the system to be tested by simulation of normal operating conditions.
3. A facility for finding deduced alarm symptoms.

These functions will be described in detail in the sections which follow.

5.3.1 Defining the Alarm System

A program facility is provided which allows the user to input the following information:

- a) The unit name of a module which has one or more measured variables equipped with alarms. The details of the individual alarms are specified as below.
- b) The message to be associated with each variable.
- c) The name of each variable to be equipped with alarms.
- d) The type of alarm used for each variable.
- e) The alarm levels for each alarm.

The program which carries out these functions is a procedure called "ADDALARMS". The format of the data required by this procedure is given in Appendix Section A.2.3 and an example of this type of data is given in LISTING A.4.4.

5.3.2 Testing the Alarm System

The system may be tested by simulation of normal operating conditions. Even at "steady state" process variables on real plants fluctuate slightly. If such fluctuations cause alarms to occur then the alarm levels must be reset. Other alarm levels might be set too far from normal operating values. These may also be reset if desired. In order to carry out such tests, the program may be used to apply disturbances to variables in input and output streams.

This function may be performed by use of selected model equations and/or the use of additional data input. Two procedures are used to perform these functions, "RUNSYSTEM" and "SYSTEMDATA". The former is described in Appendix Section A.2.3 and the latter in Appendix Section A.2.2. Examples of such inputs are shown in Fig. 5.1. Tests carried out for the column section shown in Fig. 4.4 gave the results shown in Fig. 5.2.

Tests such as these given above are used to define approximate levels for individual alarms. In general, this leads to a band of values in which a particular alarm limit must be set. The relative alarm limits of adjoining alarms may be tested by use of the same program facilities noted above. For this type of test the disturbance applied to the plant will be more drastic than before. As each disturbance is applied, the system equations are evaluated and alarms checked at specified time intervals. The user adjusts the alarm levels until the order of the alarms corresponds as closely as possible to that deduced by cause-and-effect methods.

Steady-state equation: $TA \leftarrow KT$

Sinusoidal variations: $TA \leftarrow KT + GF * \$ SIN [GT]$

Functional variation: $TA \leftarrow A1 + AT * GT + \$ LIN [GT]$

For a step change: $TA \leftarrow KT$

For the latter case, KT is set in the normal way when steady-state values are input to the program but the setting used differs from the steady-state value.

FIG. 5.1

Perturbation of Input Stream Variables

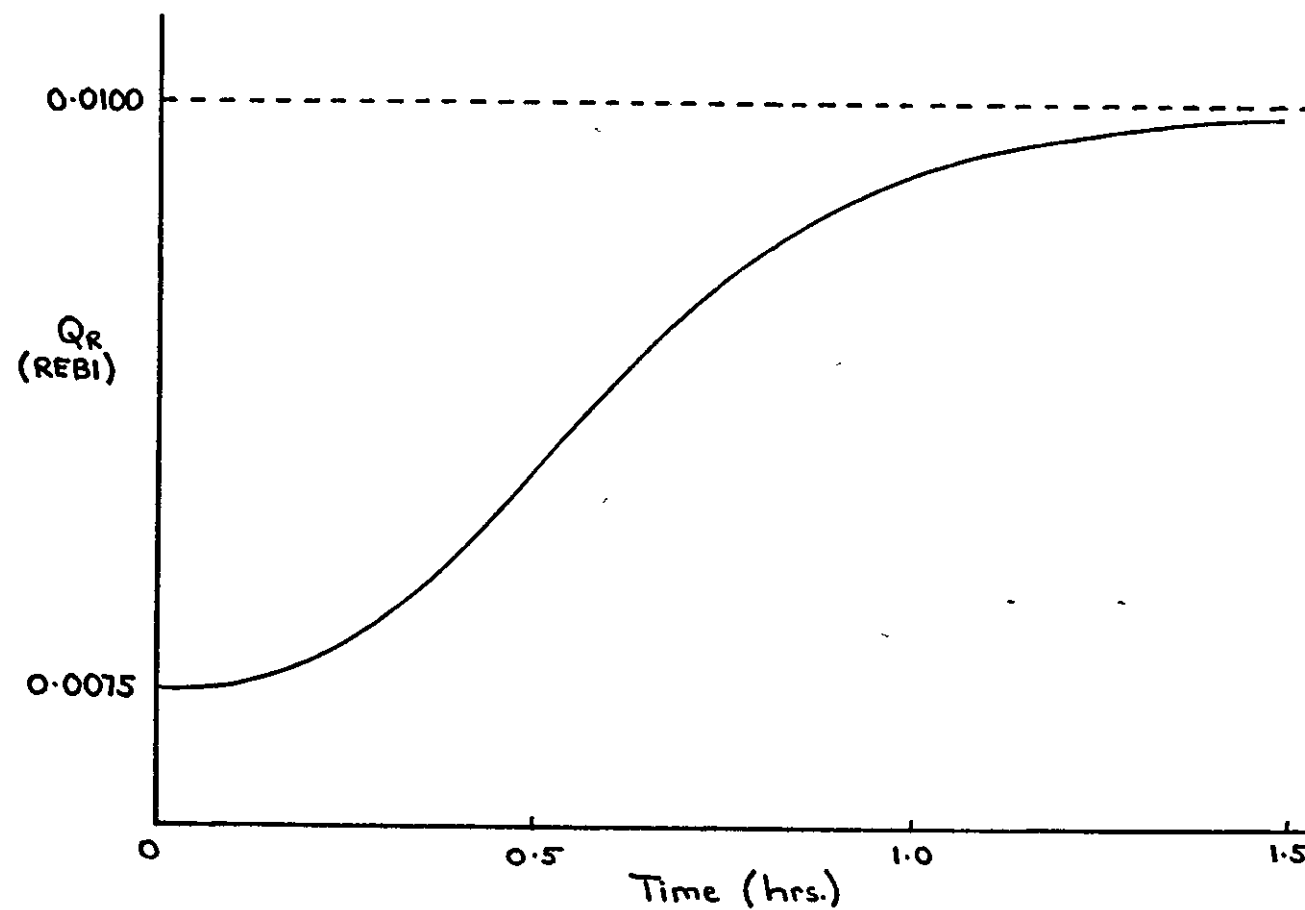


FIG. 5.2

Response of Bottoms Flowrate to Step Change in Feed Flow
from 0.0175 to 0.0200 Kg-moles/sec.

When setting up the alarm system, several points may be considered:

- i) Important alarm levels should be set first.
- ii) Results from a series of simulations may be used to find alarms which occur too frequently or in an incorrect cause-and-effect order.
- iii) If good relative alarm limits cannot be found, the system may have to be changed. When considering what changes to make, it is convenient to start with alarms that are less important or fit least well into the present system.
- iv) When considering system changes, several possible courses of action are available apart from the obvious ones of scrapping the alarm or changing its levels:
 - a) Alter type of alarm,
 - b) Resite measuring device,
 - c) Measure different property,
 - d) Use multiple levels or separate type of alarm on "copy" of the variable.

5.3.3 Finding Symptom Sets for Deduced Alarms

In order to find symptoms for deduced alarms, a complex program has been developed that allows the simulation of a series of plant faults with minimum effort on the part of the user. The program used to carry out this function, MASTEREFFECT, is shown in LISTING A.3.11.

A flowchart of the program is also shown in Fig. A.4.2. This program carries out the following tasks:

- i)
- ii) Initialises all variables at the start of each simulation,
- iii) Accepts information on process faults in the form of equations and/or variable changes,
- iiii) Selects the system of equations to be used for the simulation. (This facility is used where a fault will only propagate through a limited part of the model. In the event of the system selected by the program being inadequate, the program automatically alters the system used and restarts the simulation - for a more complete discussion of this facility see Section A.2.1).
- v)
- vi) Runs the simulation and prints the results obtained,
- vii) Stores all symptoms found, in the manner needed by the analysis program,
- viii) At the end of the simulation, any equations changed for the run are restored to their initial form.

The disadvantage with using this facility is that the integration time involved is very long. The use of algebraic and high-gain differential equations gives rise to a "stiff" problem. The integration steplength is therefore reduced considerably and the integration proceeds very slowly. If time-ordered deduced alarms are required, this must be tolerated since the cost of computer time is likely to be considerably lower than the cost of plant failure. A fuller discussion of this topic is included in Chapter 9.

This facility may also be used to find controller settings, using the reaction-curve method. In this case, the disturbance considered is a step change in control valve bonnet pressure. The response of the measured variable is then plotted as a function of time and the controller settings found in the normal way.

5.4 Example of Program Use

The example for this Section uses the section of plant shown in Fig. 4.4. The program output following the use of keyword ADDALARMS is shown in Fig. 5.3. The alarms are defined in sets for each unit. After the unit name, each variable to be equipped with alarms, whose value is set in that unit, is considered separately. The basic alarm title (excluding qualifiers such as "low", "high", "very low" etc.) is given first and, on the line following, the variable name in that unit and 4 real numbers. The full interpretation of these numbers is given in Section A.2.3 but, as a guide, they may be subdivided into 3 classes:

- i) For a simple absolute alarm, the last two numbers are zero.
- ii) For a rate alarm, the first two numbers are zero.
- iii) For an absolute alarm with two high levels and two low levels, all four numbers are non-zero.

Fig. 5.4 shows the program output during use of keyword MASTEREFFECT. An example of the data used with this keyword is shown in LISTING A.3.6. The fault considered is a control valve with a leaking port. A short discussion of this type of fault is given

in Section A.5.3.

Fig. 5.5 shows a selection of possible faults and input disturbances for the plant section of the example.

★ ★ ★ ★ ★

TC +3.600000000000E+2 +3.700000000000E+2 +0.000000000000E+0 +0.000000000000E+0

XC +7.5000000000% -1 +7.9000000000% -1 +0.0000000000% +0 +0.0000000000% +0

TC +3.5200000000E +2 +3.6400000000E +2 +0.0000000000E +0 +0.0000000000E +0

★ ★ ★ ★ ★ ★ ★ ★

XC +1.9500000000E-1 +2.0500000000E-1 +0.0000000000E+0 +0.0000000000E+0

TC +3.7000000000E +2 +3.8000000000E +2 +0.0000000000E +0 +0.0000000000E +0

UNIT MTF1

FEED STREAM TEMP

TB +3.4865000000& +2 +3.5782500001& +2 +3.7617500000& +2 +3.8535000000& +2

FEED STREAM FLOWRATE

QB +1.4000000000& +0 +1.5400000000& +0 +0.0000000000& +0 +0.0000000000& +0

UNIT TAN1

CONDENSER CATCHPOT LEVEL

LC +0.0000000000& +0 +0.0000000000& +0 -1.0000000000& -2 +1.0000000000& -2

CONDENSER CATCHPOT TEMP

TC +3.5000000000& +2 +3.6500000000& +2 +0.0000000000& +0 +0.0000000000& +0

CONDENSER CATCHPOT CONC

XC +8.7500000001& -1 +9.2500000001& -1 +0.0000000000& +0 +0.0000000000& +0

UNIT EX01

CONDENSER COOLANT FLOW

QD +2.8000000000& -1 +2.9500000000& -1 +0.0000000000& +0 +0.0000000000& +0

CONDENSER COOLANT TEMP

TD +3.0000000000& +2 +3.1500000000& +2 +0.0000000000& +0 +0.0000000000& +0

UNIT DIV1

TOP PRODUCT FLOW

QC +9.74999999998 -3 +1.02500000008 -2 +0.00000000008 +0 +0.00000000008 +0

REFLUX FLOW

QB +3.40000000008 -2 +3.55000000008 -2 +0.00000000008 +0 +0.00000000008 +0

UNIT RFB1

REBOILER CONC

XR +9.75000000008 -2 +1.02500000008 -1 +0.00000000008 +0 +0.00000000008 +0

REBOILER LEVEL

LR +9.50000000008 -1 +1.05000000008 +0 +0.00000000008 +0 +0.00000000008 +0

REBOILER TEMP

TR +3.70000000008 +2 +3.90000000008 +2 +0.00000000008 +0 +0.00000000008 +0

BOTTOMS FLOW

QB +6.60000000008 -1 +7.00000000008 -1 +0.00000000008 +0 +0.00000000008 +0

REBOILER EXCHANGER FLOW

QG +1.80000000008 -1 +1.95000000008 -1 +0.00000000008 +0 +0.00000000008 +0

REBOILER EXCHANGER EXIT TEMP

TG +3.80000000008 +2 +4.00000000008 +2 +0.00000000008 +0 +0.00000000008 +0

Fig. 5.3 (continued)

MASTEREFFECT OUTPUT

FAULT MESSAGE:
VALVE CV02 LEAKING BADLY

CV02 NEW EQUATION:

$D(PA)/DT+GA*(KH*QA-QB)$

CV02 VALUE OF QB IS NOW = +1.75000000008 -2

CV01 CV04 PL02 PLS2 REB1 CV05 FEED OUT3 OUT2 OUTF CR01 CR04
CR05 SETC CV03 TAN1 EX01 CR03 PL01 PLS1 DIV1 CR02 CV02

CV01 CV04 PL02 PLS2 REB1 CV05 FEED OUT3 OUT2 OUTF CR01 CR04
CR05 SETC CV03 TAN1 EX01 CR03 PL01 PLS1 DIV1 CR02 CV02

CV01 CV04 PL02 PLS2 REB1 CV05 FEED OUT3 OUT2 OUTF CR01 CR04
CR05 SETC CV03 TAN1 EX01 CR03 PL01 PLS1 DIV1 CR02 CV02

CV01 CV04 PL02 PLS2 REB1 CV05 FEED OUT3 OUT2 OUTF CR01 CR04
CR05 SETC CV03 TAN1 EX01 CR03 PL01 PLS1 DIV1 CR02 CV02

CV01 CV04 PL02 PLS2 REB1 CV05 FEED OUT3 OUT2 OUTF CR01 CR04
CR05 SETC CV03 TAN1 EX01 CR03 PL01 PLS1 DIV1 CR02 CV02

CV01 CV04 PL02 PLS2 REB1 CV05 FEED OUT3 OUT2 OUTF CR01 CR04
CR05 SETC CV03 TAN1 EX01 CR03 PL01 PLS1 DIV1 CR02 CV02

CV01 CV04 PL02 PLS2 REB1 CV05 FEED OUT3 OUT2 OUTF CR01 CR04
CR05 SETC CV03 TAN1 EX01 CR03 PL01 PLS1 DIV1 CR02 CV02

Program Output after Use of Keyword MASTEREFFECT

FIG. 5.4

CV01 CV04 PL02 PLS2 REB1 CV05 FEED OUT3 OUT2 OUTF CR01 CR04
 CR05 SETC CV03 TAN1 EX01 CR03 PL01 PLS1 DIV1 CR02 CV02

CV01 CV04 PL02 PLS2 REB1 CV05 FEED OUT3 OUT2 OUTF CR01 CR04
 CR05 SETC CV03 TAN1 EX01 CR03 PL01 PLS1 DIV1 CR02 CV02

CV01 CV04 PL02 PLS2 REB1 CV05 FEED OUT3 OUT2 OUTF CR01 CR04
 CR05 SETC CV03 TAN1 EX01 CR03 PL01 PLS1 DIV1 CR02 CV02

UNITS AND VARIABLES TO BE USED FOR INTEGRATION
 A AND D DENOTE ALG. OR DIF. EQUATION

CV01

A XFXB A TFTB D PAPB A QFQB

CV04

A XFXB A TFTB D PAP1 A QFOB

PL02

A TDTB A QDQB A ZS A XDXB A TATC D QAQC D XAXC

PLS2

A TDTB A QDQB A ZBZS A XDXB A TCTC D QCQC D XCXC

REB1

FIG. 5.4 (continued)

| | | | | | | |
|--------|--------|--------|--------|--------|--------|--------|
| A T2TG | A Q2QG | D PFPB | A XAXB | A TATB | A QAQB | A ZEZR |
| A TDTB | A QDQD | A XDxD | A EC | A FF | A QBQR | A TBTB |
| A LR | D HR | D XBXR | | | | |

CV05

| | | | |
|--------|--------|--------|--------|
| A XBXB | A TBTB | D PAPB | A QBQB |
|--------|--------|--------|--------|

FLED

| | | | | | | |
|--------|--------|--------|--------|--------|--------|--------|
| A QE | A XE | A PFPB | A TDTB | A QDQB | A XDxB | A TATC |
| D QAQC | D XAXC | | | | | |

OUT3

| | |
|--------|--------|
| A P4PD | A P2PG |
|--------|--------|

OUT2

| | | | |
|--------|--------|--------|--------|
| A TCT3 | A QCQ3 | A TAT1 | A QAQ1 |
|--------|--------|--------|--------|

OUTF

| | |
|--------|--------|
| A PDPB | A PBPB |
|--------|--------|

CR01

| | | | |
|------|--------|------|------|
| A LT | A PCPC | A PI | A SU |
|------|--------|------|------|

CR04

| | | | |
|------|--------|------|------|
| A LT | A PCPC | A PI | A SU |
|------|--------|------|------|

CR05

A LT A PCPC A PI A SU

SETC

A ZAZ5 A ZAZ4 A ZAZ3 A ZAZ2 A ZAZ1

CV03

A XDXB A TDTB D PAPC A QDQB

TAN1

A ZBZS A PAPB A XAXB A TATB A QAQB D XC D TC
D LC

EX01

A T4TD A Q4QD D PCP3 A EC A XAXB A TATB A QAQB
A PAPB

CR03

A LT A PCPC A PI A SU

PL01

A TDTB A QDQB A ZS A XDXB A TATC D QAQC D XAXC

PLS1

A TATB A QAQB A ZBZS A XAXB A TATC D QAQC D XAXC

FIG. 5.1 (continued)

DIV1

A XAXC A XAXB A TATC A TATB D PAPB A QAQC A QAQB

CR02

A LT A PCPC A PI A SU

CV02

A XAXB A TATB D PAPB A QAQB

TIME = +0.000008 +0

VALUES SET BY DIFFERENTIAL EQUATIONS:

| | | | | | | | | | | | |
|------|-----------|----|------|-----------|----|------|-----------|----|------|-----------|----|
| PAPB | +1.074998 | +2 | PAPB | +1.090008 | +2 | XAXC | +7.700168 | -1 | QAQC | +3.500028 | -2 |
| XAXC | +6.200158 | -1 | QAQC | +3.500008 | -2 | PCP3 | +1.200018 | +2 | LC | +1.000128 | +0 |
| TC | +3.580018 | +2 | XC | +8.999858 | -1 | PAPC | +1.045008 | +2 | XAXC | +4.799598 | -1 |
| QAQC | +5.250028 | -2 | PAPB | +1.009988 | +2 | XBXR | +1.000448 | -1 | HR | +5.998668 | +0 |
| PAPB | +1.090008 | +2 | XCXC | +1.999438 | -1 | QCQC | +5.250008 | -2 | XAXC | +3.299988 | -1 |
| QAQC | +5.250008 | -2 | PAP1 | +1.219978 | +2 | PAPB | +1.249938 | +2 | | | |

VALUES SET BY ALGEBRAIC EQUATIONS:

| | | | | | | | | | | | |
|------|-----------|----|------|-----------|----|------|-----------|----|------|-----------|----|
| QAQB | +1.750008 | -2 | TATB | +3.580018 | +2 | XAXB | +8.999858 | -1 | SU | -3.891388 | -4 |
| PI | +5.018208 | -1 | PCPC | +5.028608 | +1 | LT | +1.001648 | +0 | QAQB | +3.491718 | -2 |
| QAQC | +1.000848 | -2 | TATB | +3.580018 | +2 | TATC | +3.580018 | +2 | XAXB | +8.999858 | -1 |
| XAXC | +8.999858 | -1 | TATC | +3.582748 | +2 | XAXB | +8.950698 | -1 | ZBZS | +1.155028 | +1 |
| QAQB | +4.722478 | -2 | TATB | +3.582748 | +2 | TATC | +3.619458 | +2 | XDXB | +8.034018 | -1 |

FIG. 5.4 (continued)

| | | | | | | | | | | | |
|------|-----------|----|------|-----------|----|------|-----------|----|------|-----------|----|
| ZS | +9.300238 | +0 | QDQB | +4.681648 | -2 | TDYB | +3.619458 | +2 | SU | -1.181978 | -4 |
| PI | +5.002218 | -1 | PCPC | +5.003478 | +1 | LT | +1.001648 | +0 | PAPB | +1.013258 | +2 |
| QAQB | +4.722478 | -2 | TATB | +3.582748 | +2 | XAXB | +8.950698 | -1 | EC | +1.888998 | +4 |
| Q4QD | +2.868278 | -1 | T4TD | +3.090358 | +2 | QAQB | +4.502448 | -2 | TATB | +3.580018 | +2 |
| XAXB | +8.999858 | -1 | PAPB | +1.013258 | +2 | ZBZS | +7.500918 | +0 | QDQB | +1.000718 | -2 |
| TDTB | +3.580018 | +2 | XDXB | +8.999858 | -1 | ZA21 | +7.350008 | +0 | ZA22 | +7.500008 | +0 |
| ZA23 | +1.155008 | +1 | ZA24 | +3.000008 | +0 | ZA25 | +7.500008 | +0 | SU | +7.063728 | -4 |
| PI | +4.991598 | -1 | PCPC | +4.986798 | +1 | LT | +1.001648 | +0 | SU | +3.897718 | -4 |
| PI | +5.004288 | -1 | PCPC | +5.006728 | +1 | LT | +1.001648 | +0 | SU | +3.671808 | -4 |
| PI | +4.999978 | -1 | PCPC | +4.999968 | +1 | LT | +1.001648 | +0 | PBPB | +9.500008 | +1 |
| PDPB | +1.005008 | +2 | QAQ1 | +1.872838 | -1 | TAT1 | +3.990008 | +2 | QCQ3 | +2.871268 | -1 |
| TCT3 | +2.930008 | +2 | P2PG | +1.050008 | +2 | P4PD | +1.100008 | +2 | TATC | +3.657928 | +2 |
| XDXB | +6.956958 | -1 | QDQB | +4.672698 | -2 | TDTB | +3.657928 | +2 | PFPB | +1.013258 | +2 |
| XE | +5.609768 | -1 | QE | +1.754718 | -2 | QBQB | +6.802898 | -1 | TBTB | +3.791638 | +2 |
| XBXB | +8.613088 | -2 | LR | +9.997778 | -1 | TBTR | +3.791638 | +2 | QBQR | +7.484098 | -3 |
| FF | +1.860198 | +0 | EC | +1.866718 | +4 | XDXD | +2.076348 | -1 | QDQD | +4.666778 | -2 |
| TDTD | +3.751638 | +2 | ZBZR | +7.498338 | +0 | QAQB | +6.780548 | -1 | TATB | +3.791638 | +2 |
| XAXB | +8.613088 | -2 | QZQG | +1.875118 | -1 | T2TG | +3.898278 | +2 | TCTC | +3.751948 | +2 |
| XDXB | +3.746028 | -1 | ZBZS | +2.999148 | +0 | QDQB | +4.656508 | -2 | TDTB | +3.751948 | +2 |
| TATC | +3.705188 | +2 | XDXB | +5.459218 | -1 | ZS | +4.949978 | +0 | QDQB | +4.651308 | -2 |
| TDTB | +3.705188 | +2 | QFQB | +1.880738 | -1 | TFTB | +3.990008 | +2 | XFxB | +1.000008 | +0 |
| QFQB | +1.476528 | +0 | TFTB | +3.670008 | +2 | XfXB | +5.200008 | -1 | | | |

TIME = +2.915048 -1

VALUES SET BY DIFFERENTIAL EQUATIONS:

| | | | | | | | | | | | |
|------|-----------|----|------|-----------|----|------|-----------|----|------|-----------|----|
| PAPB | +1.074748 | +2 | PAPB | +1.090008 | +2 | XAXC | +7.700208 | -1 | QAQC | +3.500038 | -2 |
| XAXC | +6.200198 | -1 | QAQC | +3.500008 | -2 | PCP3 | +1.200018 | +2 | LC | +1.000168 | +0 |
| TC | +3.580018 | +2 | XC | +8.999808 | -1 | PAPC | +1.045008 | +2 | XAXC | +4.799468 | -1 |
| QAQC | +5.250028 | -2 | PAPB | +1.009988 | +2 | XBXR | +1.000548 | -1 | HR | +5.998168 | +0 |

PFPB +1.090012 +2 XCXC +1.999252 -1 QCQC +5.250002 -2 XAXC +3.299962 -1
QAQC +5.250002 -2 PAP1 +1.219952 +2 PAPB +1.249922 +2

VALUES SET BY ALGEBRAIC EQUATIONS:

| | | | | | | | | | | | |
|------|-----------|----|------|-----------|----|------|-----------|----|------|-----------|----|
| QAQB | +3.506322 | -2 | TATB | +3.580012 | +2 | XAXB | +8.999802 | -1 | SU | +2.127792 | -4 |
| PI | +5.024692 | -1 | PCPC | +5.038782 | +1 | LT | +2.915042 | -1 | QAQB | +3.521272 | -2 |
| QAQC | +1.000842 | -2 | TATB | +3.580012 | +2 | TATC | +3.580012 | +2 | XAXB | +8.999802 | -1 |
| XAXC | +8.999802 | -1 | TATC | +3.582742 | +2 | XAXB | +8.950722 | -1 | ZBZS | +1.155032 | +1 |
| QAQB | +4.733492 | -2 | TATB | +3.582742 | -2 | TATC | +3.619452 | +2 | XDXB | +8.034032 | -1 |
| ZS | +9.300282 | +0 | QDQB | +4.700962 | -2 | TDTB | +3.619452 | +2 | SU | +4.622652 | -5 |
| PI | +5.002752 | -1 | PCPC | +5.004322 | +1 | LT | +2.915042 | -1 | PAPB | +1.013252 | +2 |
| QAQB | +4.733492 | -2 | TATB | +3.582742 | +2 | XAXB | +8.950722 | -1 | EC | +1.893402 | +4 |
| QXQD | +2.868302 | -1 | TATD | +3.090662 | +2 | QAQB | +4.503122 | -2 | TATB | +3.580012 | +2 |
| XAXB | +8.999802 | -1 | PAPB | +1.013252 | +2 | ZBZS | +7.501242 | +0 | QDQB | +1.000882 | -2 |
| TDTB | +3.580012 | +2 | XDXB | +8.999802 | -1 | ZA21 | +7.350002 | +0 | ZA22 | +7.500002 | +0 |
| ZA23 | +1.155002 | +1 | ZA24 | +3.000002 | +0 | ZA25 | +7.500002 | +0 | SU | -3.955872 | -4 |
| PI | +4.988532 | -1 | PCPC | +4.981982 | +1 | LT | +2.915042 | -1 | SU | -1.824402 | -4 |
| PI | +5.005612 | -1 | PCPC | +5.008802 | +1 | LT | +2.915042 | -1 | SU | +1.076152 | -4 |
| PI | +4.999972 | -1 | PCPC | +4.999962 | +1 | LT | +2.915042 | -1 | PBPB | +9.500002 | +1 |
| PDPB | +1.005002 | +2 | QAQ1 | +1.872972 | -1 | TAT1 | +3.990002 | +2 | QCQ3 | +2.871242 | -1 |
| TCT3 | +2.930002 | +2 | P2PG | +1.050002 | +2 | P4PD | +1.100002 | +2 | TATC | +3.657922 | +2 |
| XDXB | +6.956832 | -1 | QDQB | +4.691872 | -2 | TDTB | +3.657922 | +2 | PFPB | +1.013252 | +2 |
| XE | +5.609762 | -1 | QE | +1.754642 | -2 | QBQB | +6.796172 | -1 | TBTB | +3.791632 | +2 |
| XBXB | +8.613982 | -2 | LR | +9.996932 | -1 | TBTR | +3.791632 | +2 | Q8QR | +7.483912 | -3 |
| FF | +1.843692 | +0 | EC | +1.874232 | +4 | XDXD | +2.076532 | -1 | QDQD | +4.685582 | -2 |
| T0TD | +3.791632 | +2 | ZBZR | +7.497702 | +0 | QAQB | +6.780372 | -1 | TATB | +3.791632 | +2 |
| XAXB | +8.613982 | -2 | Q2QG | +1.875152 | -1 | T2TG | +3.899222 | +2 | TCTC | +3.751952 | +2 |
| X0XB | +3.745762 | -1 | ZBZS | +2.998882 | +0 | QDQB | +4.675422 | -2 | TDTB | +3.751952 | +2 |
| TATC | +3.705182 | +2 | XDXB | +5.459182 | -1 | ZS | +4.949942 | +0 | QDQB | +4.670382 | -2 |
| TDTB | +3.705182 | +2 | QFQB | +1.881422 | -1 | TFTB | +3.990002 | +2 | XFXB | +1.000002 | +0 |
| QFQB | +1.476462 | +0 | TFTB | +3.670002 | +2 | XFXB | +5.200002 | -1 | | | |

FIG. 5.4 (continued)

TIME = +5.283728 +0

VALUES SET BY DIFFERENTIAL EQUATIONS:

| | | | | | | | | | | | |
|------|-----------|----|------|-----------|----|------|-----------|----|------|-----------|----|
| PAPB | +1.070878 | +2 | PAPB | +1.089898 | +2 | XAXC | +7.700178 | -1 | QAQC | +3.499128 | -2 |
| XAXC | +6.200108 | -1 | QAQC | +3.500008 | -2 | PCP3 | +1.200038 | +2 | LC | +1.001528 | +0 |
| TL | +3.580058 | +2 | XC | +8.999018 | -1 | PAPC | +1.044998 | +2 | XAXC | +4.796358 | -1 |
| QAQC | +5.250098 | -2 | PAPB | +1.010188 | +2 | XBXR | +1.000518 | -1 | HR | +5.980058 | +0 |
| PFPB | +1.090078 | +2 | XCXC | +1.995288 | -1 | QCQC | +5.250008 | -2 | XAXC | +3.298518 | -1 |
| QAQC | +5.250008 | -2 | PAP1 | +1.219618 | +2 | PAPB | +1.249628 | +2 | | | |

VALUES SET BY ALGEBRAIC EQUATIONS:

| | | | | | | | | | | | |
|------|-----------|----|------|-----------|----|------|-----------|----|------|-----------|----|
| QAQB | +3.352668 | -2 | TATB | +3.580058 | +2 | XAXB | +8.999018 | -1 | SU | -2.265798 | -2 |
| PI | +5.199588 | -1 | PCPC | +5.313298 | +1 | LT | +5.283728 | +0 | QAQB | +3.930338 | -2 |
| QAQC | +9.996968 | -3 | TATB | +3.580058 | +2 | TATC | +3.580058 | +2 | XAXB | +8.999018 | -1 |
| XAXC | +8.999018 | -1 | TATC | +3.582748 | +2 | XAXB | +8.950708 | -1 | ZBZS | +1.155038 | +1 |
| QAQB | +5.026288 | -2 | TATB | +3.582748 | +2 | TATC | +3.619458 | +2 | XDXB | +8.033978 | -1 |
| ZS | +9.300158 | +0 | QDQB | +5.087148 | -2 | TDTB | +3.619458 | +2 | SU | -2.115078 | -3 |
| PI | +5.002298 | -1 | PCPC | +5.003608 | +1 | LT | +5.283728 | +0 | PAPB | +1.013258 | +2 |
| QAQB | +5.026288 | -2 | TATB | +3.582748 | +2 | XAXB | +8.950708 | -1 | EC | +2.010518 | +4 |
| Q4QD | +2.868668 | -1 | T4TD | +3.099658 | -2 | QAQB | +4.539378 | -2 | TATB | +3.580058 | +2 |
| XAXB | +8.999018 | -1 | PAPB | +1.013258 | +2 | ZBZS | +7.509878 | +0 | QDQB | +1.000638 | -2 |
| TDTB | +3.580058 | +2 | XDXB | +8.999018 | -1 | ZA21 | +7.350008 | +0 | ZA22 | +7.500008 | +0 |
| ZA23 | +1.155008 | +1 | ZA24 | +3.000008 | +0 | ZA25 | +7.500008 | +0 | SU | +5.191788 | -2 |
| PI | +4.870118 | -1 | PCPC | +4.796028 | +1 | LT | +5.283728 | +0 | SU | +1.768378 | -2 |
| PI | +5.035498 | -1 | PCPC | +5.055758 | +1 | LT | +5.283728 | +0 | SU | -3.230178 | -3 |
| PI | +4.999978 | -1 | PCPC | +4.999958 | +1 | LT | +5.283728 | +0 | PBPB | +9.500008 | +1 |
| PDPB | +1.005008 | +2 | QAQ1 | +1.876938 | -1 | TAT1 | +3.990008 | +2 | QCQ3 | +2.870878 | -1 |
| TCT3 | +2.930008 | +2 | P2PG | +1.050008 | +2 | P4PD | +1.100008 | +2 | TATC | +3.658018 | +2 |
| XDXB | +6.954148 | -1 | QDQB | +5.075968 | -2 | TDTB | +3.658018 | +2 | PFPB | +1.013258 | +2 |
| XE | +5.609768 | -1 | QE | +1.753558 | -2 | QBQB | +6.553288 | -1 | TBTB | +3.791638 | +2 |

| | | | | | | | | | | | |
|-------|-----------|----|-------|-----------|----|-------|-----------|----|------|-----------|----|
| XBXB | +8.613708 | -2 | LR | +9.966758 | -1 | TBTR | +3.791638 | +2 | QBQR | +7.464198 | -3 |
| FF | +1.556528 | +0 | EC | +2.024758 | +4 | XD XD | +2.076478 | -1 | QDQD | +5.061878 | -2 |
| TOTD | +3.791638 | +2 | ZBZR | +7.475068 | +0 | QAQB | +6.762508 | -1 | TATB | +3.791638 | +2 |
| XAXB | +8.613708 | -2 | Q2QG | +1.876618 | -1 | T2TG | +3.919078 | +2 | TCTC | +3.752108 | +2 |
| XD XB | +3.739798 | -1 | ZBZS | +2.992978 | +0 | QDQB | +5.054048 | -2 | TDTB | +3.752108 | +2 |
| TATC | +3.705238 | +2 | XD XB | +5.457528 | -1 | ZS | +4.947778 | +0 | QDQB | +5.052218 | -2 |
| TDTB | +3.705238 | +2 | QFQB | +1.896118 | -1 | TFTB | +3.990008 | +2 | YFXB | +1.000008 | +0 |
| QFQB | +1.475558 | +0 | TFTB | +3.670008 | +2 | XFXB | +5.200008 | -1 | | | |

MAXIMUM STEPSIZE = +9.23632425068 -1

TIME = +1.005898 +1

VALUES SET BY DIFFERENTIAL EQUATIONS:

| | | | | | | | | | | | |
|------|-----------|----|------|-----------|----|------|-----------|----|------|-----------|----|
| pApB | +1.067778 | +2 | pApB | +1.089658 | +2 | XAXC | +7.698798 | -1 | QAQC | +3.497418 | -2 |
| XAXC | +6.198558 | -1 | QAQC | +3.499988 | -2 | PCP3 | +1.200058 | +2 | LC | +1.003478 | +0 |
| TC | +3.580108 | +2 | XC | +8.998218 | -1 | PAPC | +1.045008 | +2 | XAXC | +4.791488 | -1 |
| QAQC | +5.250138 | -2 | PAPB | +1.011158 | +2 | XBXR | +9.967898 | -2 | HR | +5.942848 | +0 |
| PfPB | +1.070208 | +2 | XCXC | +1.989448 | -1 | QCQC | +5.250008 | -2 | XAXC | +3.294828 | -1 |
| QAQC | +5.250008 | -2 | PAP1 | +1.219008 | +2 | PAPB | +1.249388 | +2 | | | |

VALUES SET BY ALGEBRAIC EQUATIONS:

| | | | | | | | | | | | |
|------|-----------|----|------|-----------|----|------|-----------|----|-------|-----------|----|
| Q4QB | +3.343538 | -2 | TATB | +3.580108 | +2 | XAXB | +8.998218 | -1 | SU | -9.814368 | -2 |
| P1 | +5.529708 | -1 | PCPC | +5.828218 | +1 | LT | +1.005898 | +1 | QAQB | +4.215378 | -2 |
| QAQC | +9.969838 | -3 | TATB | +3.580108 | +2 | TATC | +3.580108 | +2 | XAXB | +8.998218 | -1 |
| XAXC | +8.998218 | -1 | TATC | +3.582798 | +2 | XAXB | +8.949958 | -1 | ZBZS | +1.154828 | +1 |
| Q4QB | +5.504128 | -2 | TATB | +3.582788 | +2 | TATC | +3.619498 | +2 | XD XB | +8.032918 | -1 |
| ZS | +9.297838 | +0 | QDQB | +5.566548 | -2 | TDTB | +3.619498 | +2 | SU | +1.665578 | -3 |
| P1 | +4.983688 | -1 | PCPC | +4.974368 | +1 | LT | +1.005898 | +1 | PAPB | +1.013258 | +2 |

FIG. 5.4 (continued)

| | | | | | | | | | | | |
|------|-----------|-----------|------|-----------|--------|------|-----------|--------------------------|------|-----------|----|
| QAQB | +5.504128 | -2 | TATB | +3.582788 | +2 | XAXB | +8.949958 | -1 | EC | +2.201658 | +4 |
| Q4QD | +2.868938 | -1 | T4TD | +3.115008 | -2 | QAQB | +4.611918 | -2 | TATB | +3.580108 | +2 |
| XAXB | +8.998218 | -1 | PAPB | +1.013258 | +2 | ZBZS | +7.525998 | +0 | QDQB | +9.048168 | -3 |
| TDTB | +3.580108 | +2 | XDXB | +8.998218 | -1 | ZA21 | +7.350008 | +0 | ZA22 | +7.500008 | +0 |
| ZA23 | +1.155008 | +1 | ZA24 | +3.000008 | +0 | ZA25 | +7.500008 | +0 | SU | +2.530768 | -1 |
| PI | +4.617418 | -1 | PCPC | +4.400488 | +1 | LT | +1.005898 | +1 | SU | +6.774528 | -2 |
| PI | +5.070548 | -1 | PCPC | +5.124938 | +1 | LT | +1.005898 | +1 | SU | +6.422878 | -3 |
| PI | +4.999968 | -1 | PCPC | +4.999948 | +1 | LT | +1.005898 | +1 | PBPB | +9.500008 | +1 |
| PDPB | +1.005008 | +2 | QAQ1 | +1.884048 | -1 | TAT1 | +3.990008 | +2 | QCQ3 | +2.870608 | -1 |
| TCT3 | +2.930008 | +2 | P2PG | +1.050008 | +2 | P4PD | +1.100008 | +2 | TATC | +3.658168 | +2 |
| XDXB | +6.947928 | -1 | QDQB | +5.553128 | -2 | TDTB | +3.658168 | +2 | PFPB | +1.013258 | +2 |
| XE | +5.609768 | -1 | QE | +1.752668 | -2 | QBQB | +6.061078 | -1 | TBTB | +3.791788 | +2 |
| XBXU | +8.581208 | -2 | LR | +9.904738 | -1 | TBTR | +3.791788 | +2 | QBQR | +7.398038 | -3 |
| FF | +1.268458 | +0 | EC | +2.711598 | +4 | XDXD | +2.069588 | -1 | QDQD | +5.528978 | -2 |
| TOTD | +3.791788 | +2 | 7BZR | +7.428548 | +0 | QAQB | +6.702948 | -1 | TATB | +3.791788 | +2 |
| XAXB | +8.581208 | -2 | Q2QG | +1.879718 | -1 | T2TG | +3.945628 | +2 | TCTC | +3.752328 | +2 |
| XDXB | +3.731008 | -1 | 7BZS | +2.984168 | +0 | QDQB | +5.524138 | -2 | TDTB | +3.752328 | +2 |
| TATC | +3.705358 | +2 | XDXB | +5.453248 | -1 | ZS | +4.942228 | +0 | QDQB | +5.526228 | -2 |
| TDTB | +3.705358 | +2 | QFQB | +1.916548 | -1 | TFTB | +3.940008 | +2 | XFXB | +1.000008 | +0 |
| QFQB | +1.474808 | +0 | TFTB | +3.670008 | +2 | XFXB | +5.200008 | -1 | | | |
| TAN1 | LC | +1.003478 | +0 | +1 | 000128 | +0 | +1 | CONDENSER CATCHPOT LEVEL | | | |
| DIV1 | QAQB | +4.215378 | -2 | +3 | 491718 | -2 | +1 | REFLUX FLOW | | | |

FIG. 5.4 (continued)

| Mechanical Faults: | |
|----------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------|
| Unit(s) | Fault Name |
| Valves: CV01 } CV02 } CV03 } CV04 } CV05 } | Jammed open Jammed shut Jammed at intermediate or s.s. position Blocked Leaking (process stream) Leaking (bonnet) |
| Pump CEN1 | Gassed Up Leaking (process stream) |
| Tank TAN1 | Discharge blocked Level device failure |
| Reboiler REB1 | Discharge blocked Level device failure Leaking jacket |
| Flow meter MTF1 | Blocked (process stream) Transducer failure |
| Plates PLS1 PLS2 | Measuring device failure |
| Input Disturbances: | |
| Loss of process air Cooling water temperature Feed stream temperature Feed stream composition Feed stream flowrate | |

FIG. 5.5

Typical Plant Faults for Plant Section of Fig. 4.4

C H A P T E R 6

PRODUCTION OF THE ALARM TREE

The aim of the work done for this study was to provide a method of setting up alarm analysis systems with a much smaller effort than that required previously. The preceding two chapters have largely been concerned with the use of plant models with particular reference to defining the alarm system and finding symptoms for deduced alarms.

One of the features of the modelling method used in the programs is that, since the unit modules are supplied as data, the program may inspect and manipulate the variables in the model. This would be very difficult to do if the unit modules used were in the form of subprograms.

This chapter is concerned directly with producing analysis data for an on-line program. The type of model used was chosen primarily so that it would be suitable for use with a program that would automatically produce the analysis data directly from the model. It was shown in Chapter 3 that the data is stored most efficiently in a tree-like form but that the setting up of the tree was a time-consuming task. The processing of data in such a form is entirely different from the processing of numerical data commonly encountered by engineers and scientists. "List processing" is the name given to that branch of computer science devoted to the manipulation of data in this form. The computer language used for the work, ALGOL 68-R, incorporates list-processing facilities in addition to all the normal facilities of a high-level language. The type of model used was therefore chosen so that it could be manipulated using the

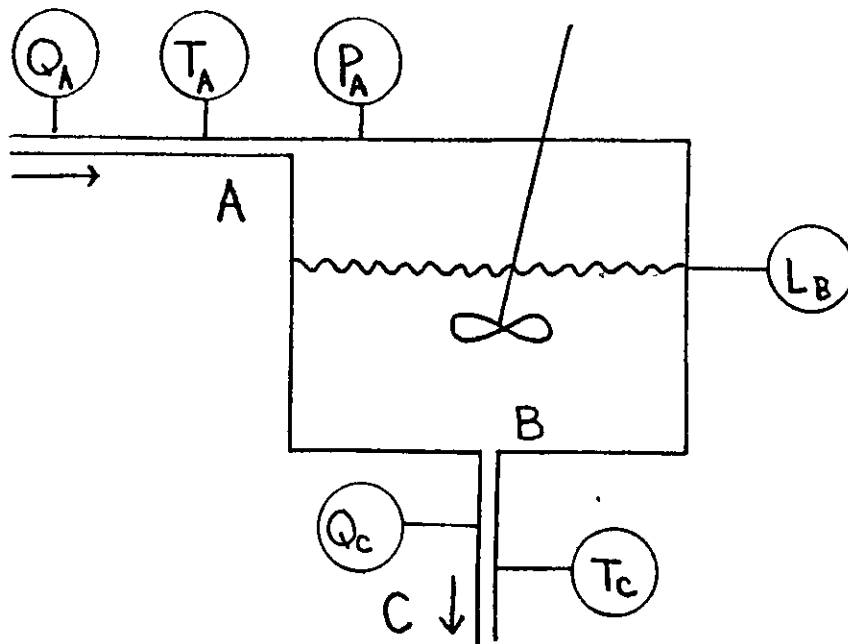
list-processing capabilities of the language.

A moment's reflection shows that an alarm tree is really a special type of plant model since both are based on the interactions between process variables. The major difference is that plant models are commonly used to find the effects of an event occurring on the plant whilst alarm trees are used to find the event that caused a series of effects. A less significant difference is that the alarm tree uses only the measured variables and inferred measurements.

6.1 The Analogy Between the Alarm Tree and the Plant Model

Consider the mixing tank shown in Fig. 6.1. The simple equations show the dependence of the output stream variables on those in the input stream. An information flow diagram for the same system is shown in Fig. 6.2. The type of alarm system depicted in the references given in Chapter 2 is shown in Fig. 6.3. In alarm-tree diagrams, effects generally appear above causes. The arrows indicate that the information stored with the effects is used to find the cause. For convenience, it is assumed that all of the measured variables as shown in Fig. 6.1 are equipped with both high and low alarms. In general, this is not true but the example serves to illustrate most clearly the point that, in the type of representation shown in Fig. 6.3, each variable occurs once for each alarm limit used. Each "node" in Fig. 6.3 corresponds to an alarm.

The information flow diagram may be set up by inspection of the plant model and it is therefore desirable to find a transformation to convert the information flow diagram into the alarm tree. At this stage, it is convenient to consider the form of the desired alarm tree.



Functional model:

$$\dot{L}_B = f_1(Q_A, Q_C)$$

$$\dot{T}_C = f_2(T_A, L_B, Q_A)$$

$$P_A = f_3(T_C, L_B)$$

$$P_B = f_4(P_A, L_B)$$

$$Q_C = f_5(P_B, P_C)$$

Full-equation model:

$$A_T \frac{dL_B}{dt} = (Q_A - Q_C)$$

$$A_T L_B \frac{dT_C}{dt} = Q_A (T_A - T_C)$$

$$P_A = \frac{K_4 T_C}{A_T (L_{\max} - L_B)}$$

$$P_B = P_A + K_1 L_B$$

$$Q_C = K_2 (P_B - P_C)^{\frac{1}{2}}$$

FIG. 6.1

Simple Model of Mixing Tank

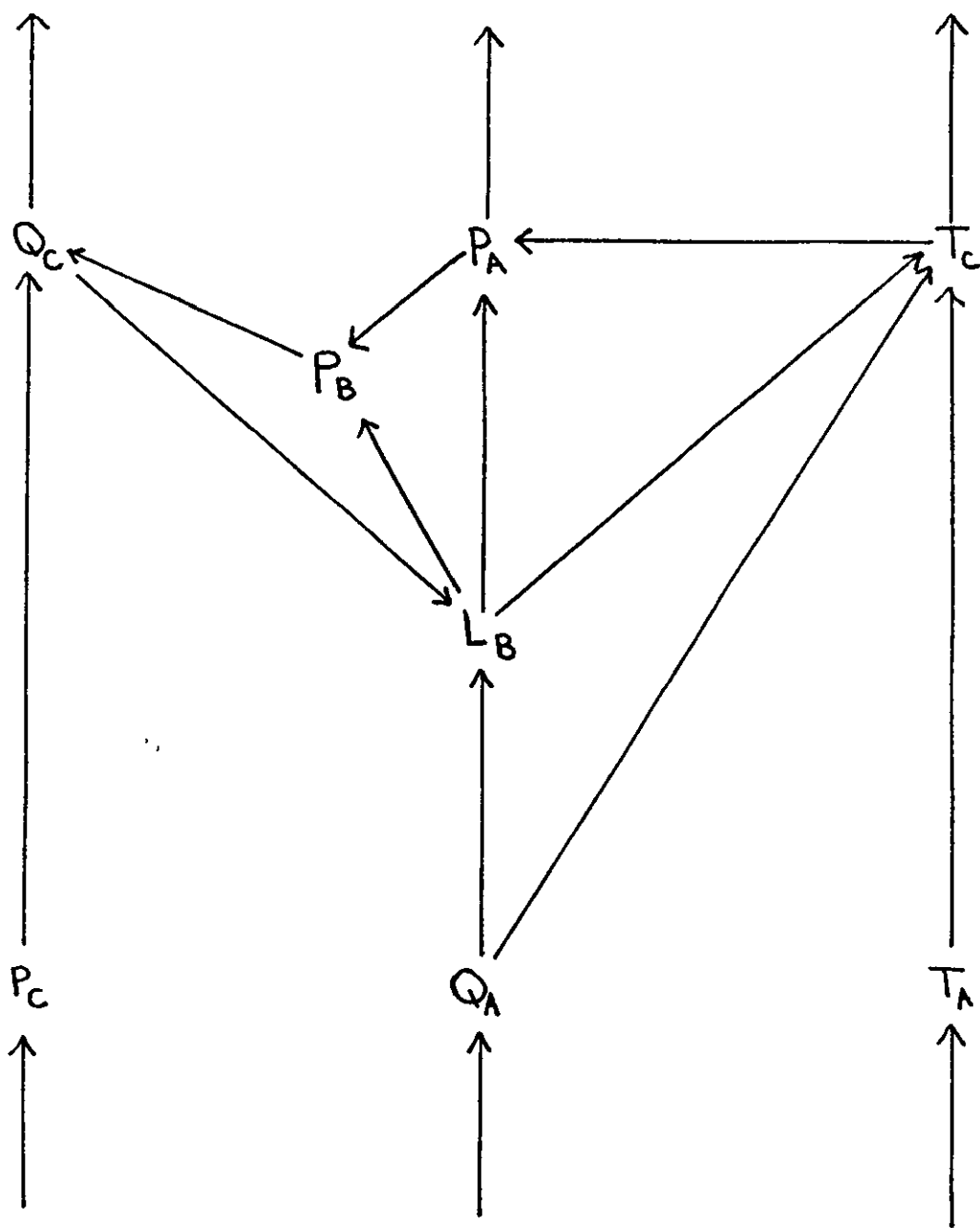


FIG. 6.2

Information Flow Diagram for the System of Fig. 6.1

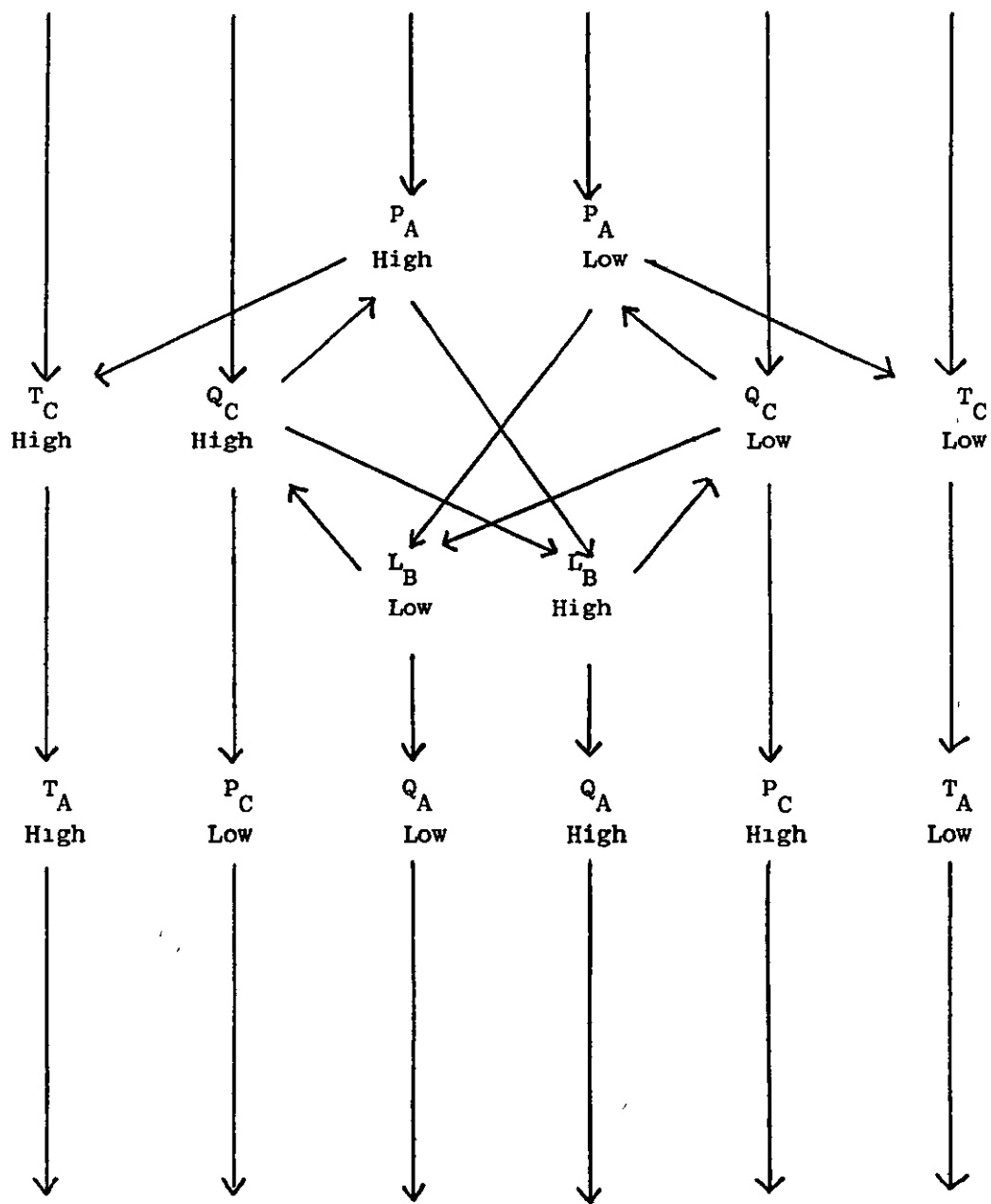


FIG. 6.3

Standard Alarm Tree Representation for the System of Fig. 6.1

As noted earlier, the type of tree shown in Fig. 6.3 contains a node for each alarm. The reason for this is that the tree was produced as a means of diagnosing the cause-and-effect relationships between a particular set of alarms. A more general result may be obtained by considering the cause-and-effect relationships between the variables involved. This approach leads to a tree with variables at the nodes and is the one used for this study. This reduces the complexity of the tree considerably, as shown by the representation in Fig. 6.4. A "plus" sign alongside the pointer between two nodes indicates that a high alarm will tend to cause a high alarm and a low alarm will tend to cause a low alarm. A "minus" sign indicates that a high alarm will tend to cause a low alarm and vice-versa. These signs must be included in order to prevent any loss of information. This type of information will be called "directional information" (in order to be consistent with Chapter 3) and is available directly from the plant model.

It may be seen that this new representation is very similar to the information flow diagram of Fig. 6.2. The most obvious difference is that the alarm tree shown contains less pointers than the information flow diagram. The missing pointers fall into 2 categories:-

1. Those that are not included in the alarm tree because one of the variables at the ends of the pointer is not measured. For the example shown P_B is not measured. The equivalent form of the equations is obtained by algebraic elimination of P_B . This is important since a large number of variables will not be measured for most applications.

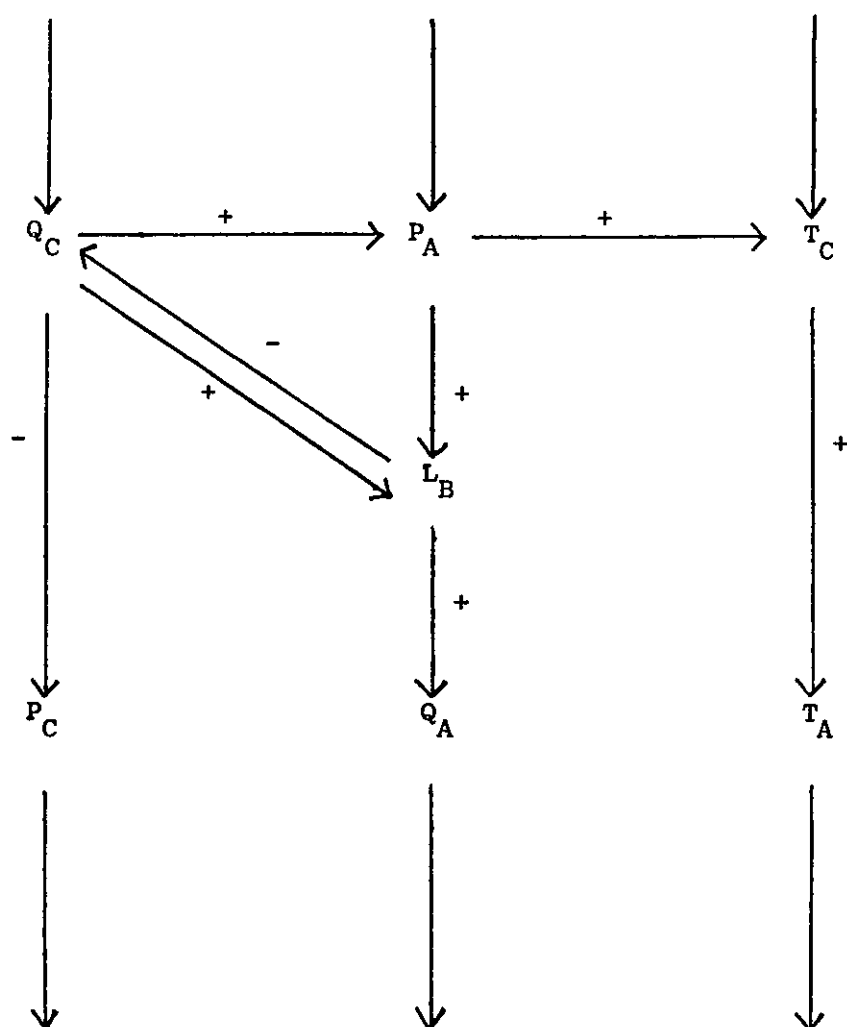


FIG. 6.4

Alternative Alarm Tree Representation
with Variables at Nodes

2. Those not included in the alarm tree because there is no direct cause and effect relationship between the variables concerned. For the example shown in Fig. 6.2, the pointers from L_B and Q_A to T_C do not represent possible reasons for changes in T_C . Variations in L_B and Q_A will only serve to magnify or diminish changes in T_C caused by T_A . Such situations frequently occur in systems involving hydraulic delay and mass (or volume) flows.

All of the information in the alarm tree can therefore be obtained either directly from the plant model or its associated information flow diagram.

6.2 The Proposed Form of the Analysis Tree

It was decided to use the general form of the alarm tree (with variables at the nodes) as discussed in the last section. The method used for storing data, as discussed below, was partly dictated by the nature of the work done for the study in that it was desirable to be able to experiment with different types of analysis schemes. It is expected that an on-line analysis scheme employing a similar type of tree would use a different storage scheme. In particular, an on-line scheme would have to use backing-store for the large amount of data associated with a complete plant. The form of the analysis tree would therefore be dependent on such considerations.

The information needed at each node for the alarm analysis simulation is as follows:

- 1) The variable name and value,
- 2) The alarm types and levels directly associated with it,
- 3) The deduced alarms which involve the variable at the node,
- 4) The alarm message for the variable,
- 5) The addresses of other nodes where the corresponding variables are likely to cause the variable at this node to become off-normal,
- 6) The address of any entry in the list of fault messages currently displayed that corresponds to the variable at the node,
- 7) The result of the previous use of the scanning program for the variable at the node. (This could be avoided but is convenient for detecting changes in variables needed for use by the analysis program).

6.3 Derivation of the Alarm Tree

The production of the analysis tree directly from the plant model may be split into two distinct steps:

- i) Use of the model equations to set up in core store data equivalent to the information flow diagram with directional information.
- ii) Conversion of the data produced in the first step into a form that contains only measured variables.

Program facilities are provided to carry out these steps separately. A separate facility provides for a print-out of the tree produced by either step. By using this facility between the two steps, the user may inspect the information-flow data produced and the associated directional information. The two steps will now be considered separately.

6.3.1 Production of the Information Flow Data

This step requires that the model equations are inspected by the program. A node is created that corresponds to each variable that appears on the left-hand side of each equation in the model. The variables on the right-hand side of each equation are identified and the addresses of the corresponding nodes are stored in a list of possible "causes". Each of the addresses stored at a node corresponds to a "branch" of the tree. Directional information is stored with each branch for possible use in the analysis program. For full-equation models, the directional information is obtained

by perturbation of the variables in the equation. The program notes the probability that an increase in the variable causes an increase in the value delivered by the right-hand side and also stores the magnitude of the change. For functional models, the directional information must be included when the equation is supplied as noted in Chapter 4. A simple flowchart of the procedure used to perform this function, SETUPTREE, is shown in Fig. 6.5. The number of perturbations needed to produce statistically significant values for the directional information of full-equation models is found from the number of variables in the equation:

$$\text{No. of tests} = N(N + 2)$$

where N is the number of variables. This formula assumes that all of the variables are perturbed for each test. The significance of the results has been demonstrated by using the same data set for several program runs. For the majority of cases, the directional information obtained is identical for each run but slight deviations are noted.

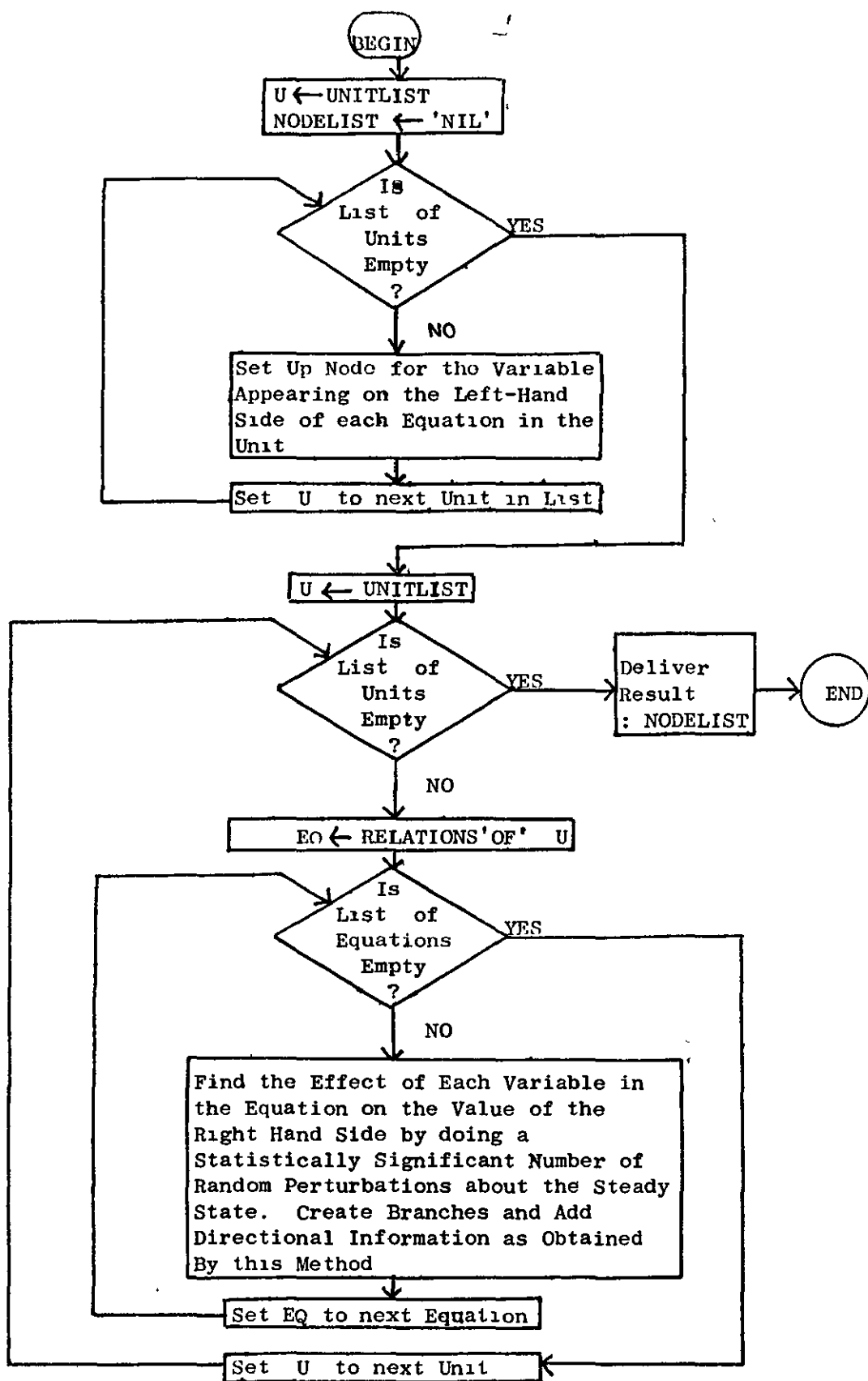


FIG. 6.5

Simple Flowchart of Procedure SETUP TREE

6.3.2 Production of the Alarm Tree

This step involves removing all the nodes which correspond to variables which are not measured. A method was developed and tested to carry out this function. The procedure to be applied to each node in turn is shown in the form of a flowchart in Fig. 6.6. The procedure is repeated for the entire list of nodes until no new branches are created during one pass through the list. The nodes corresponding to the non-measured variables are also removed from the list of nodes at this stage. An example showing the form of the tree at various stages of this process is given in Fig. 6.7 for a hypothetical case.

Each node in Fig. 6.7 is denoted by a circle and a number, measured variables are denoted by a cross through the circle at the appropriate node. Pointers are used to indicate branches to other nodes.

Fig. 6.7(a) shows the form of the tree after use of keyword SETUPTREE. Fig. 6.7(b) shows the form of the tree after the first use of the "pruning" procedure, described above, to node 1. Note that the branch to node 4 has been replaced by two branches to nodes 6 and 8. Since branches already existed from node 4 to nodes 6 and 8, two additional branches had to be created or information at node 1 would have been lost. The new branch to node 8 is satisfactory because node 8 corresponds to a measured variable but the branch to node 6 will have to be replaced during the next pass through the list of nodes.

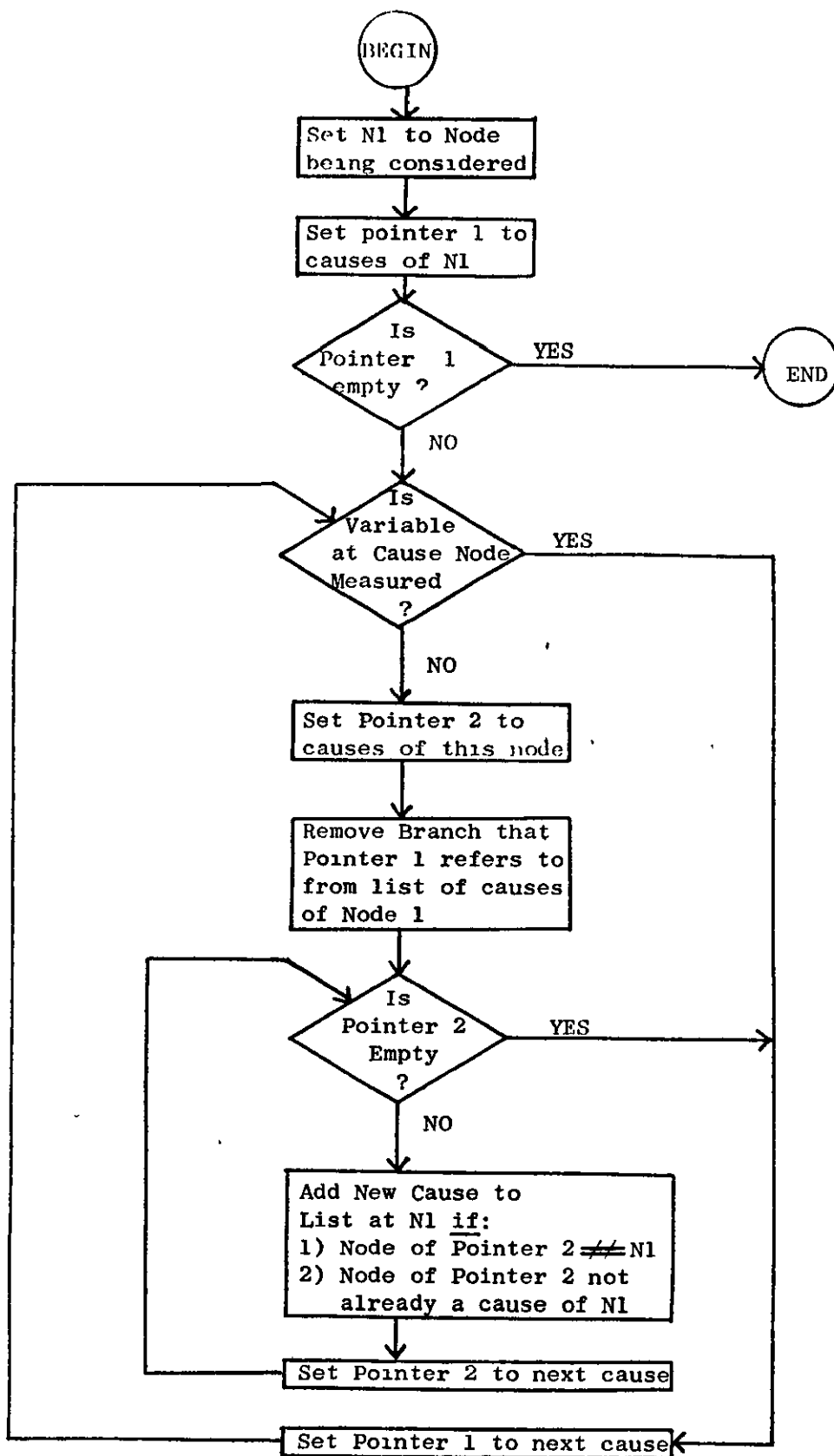


FIG. 6.6

Simple Flow Chart showing Logic Used Inside Procedure "ALTERTREE"

FIG. 6.7(a)

Example showing Use of
Procedure ALTERTREE

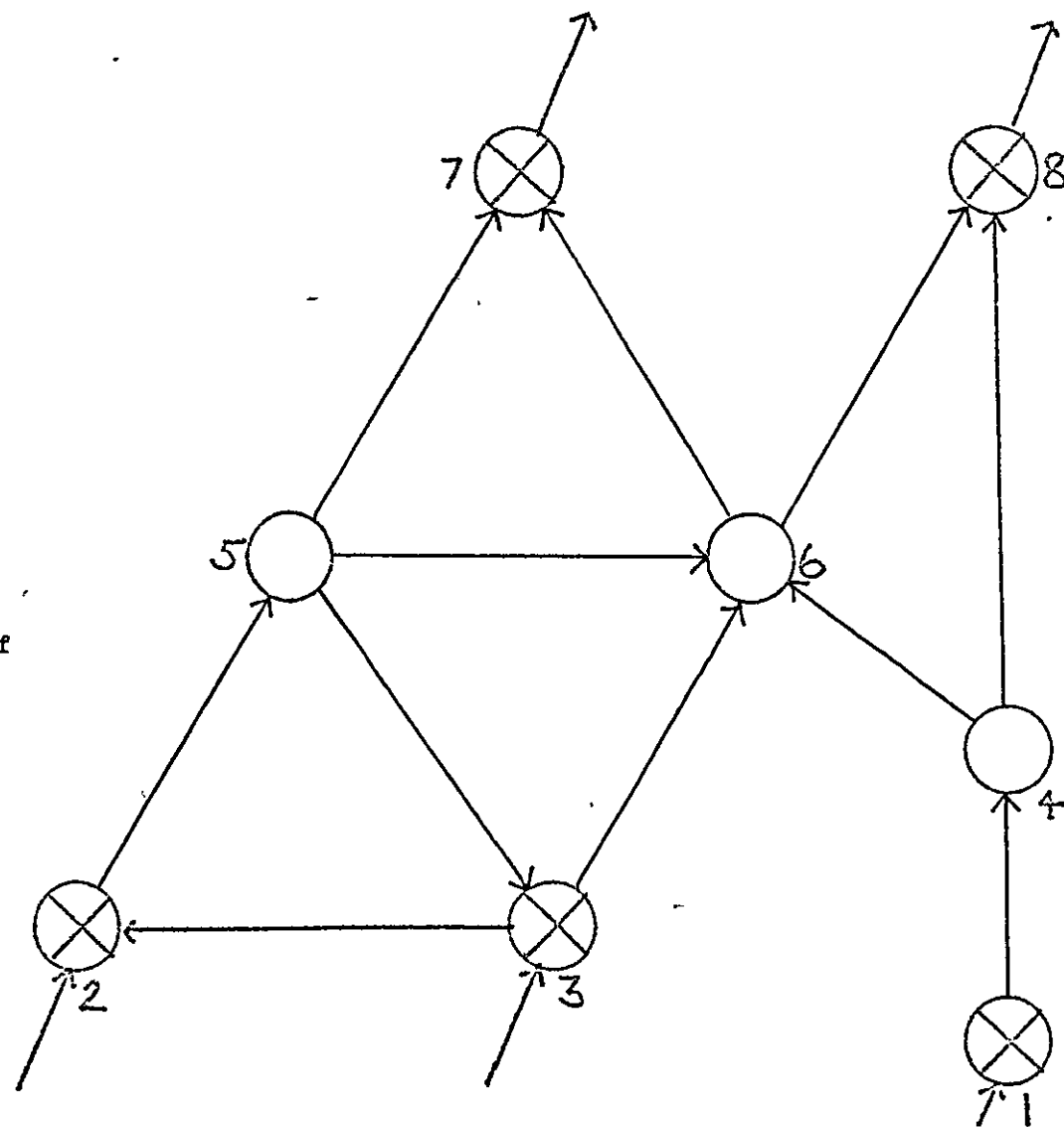
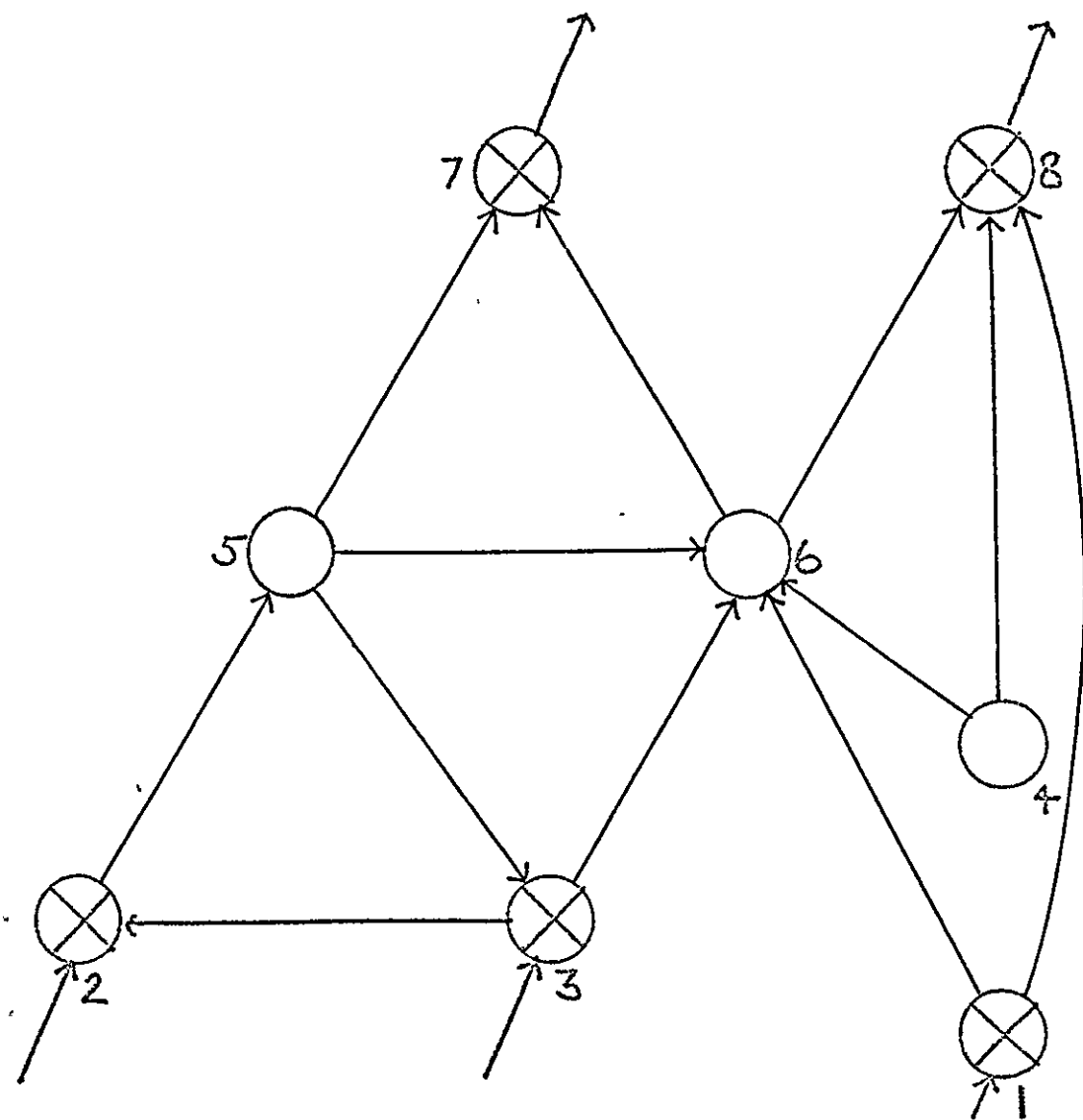


FIG. 6.7(b)



In shorthand notation, this tree pruning step may be written as:

$$1 - 4 : 4 - 6 \longrightarrow 1 - 6$$

and:

$$1 - 4 : 4 - 8 \longrightarrow 1 - 8$$

or in contracted form:

$$1 - 4 : (4 - 6, 4 - 8) \longrightarrow (1 - 6, 1 - 8)$$

Fig. 6.7(c) shows the tree after the pruning procedure has been used on node 2 for the first time. In the shorthand notation, this step may be written as:

$$2 - 5 : 5 - 3 \longrightarrow 2 - 3$$

$$2 - 5 : 5 - 6 \longrightarrow 2 - 6$$

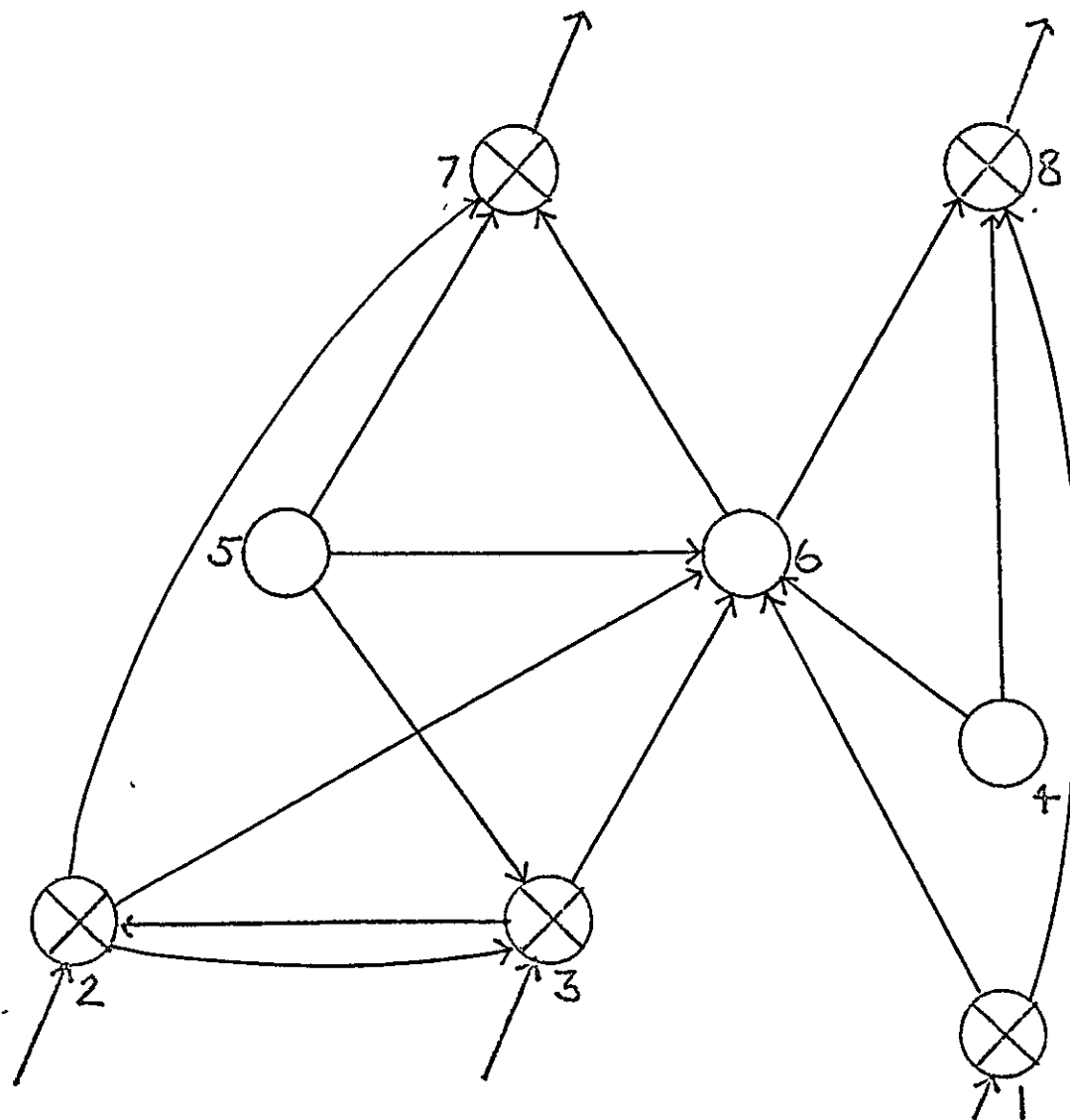
$$2 - 5 : 5 - 7 \longrightarrow 2 - 7$$

or:

$$2 - 5 : (5 - 3, 5 - 6, 5 - 7) \longrightarrow (2 - 3, 2 - 6, 2 - 7)$$

Again, it is noted that one of the new branches created, 2 - 6, will have to be replaced on the next pass of the procedure through the list of nodes. Fig. 6.7(d) shows the tree after use of the pruning procedure on node 3. This node has two branches from it to other nodes and so the pruning operation is potentially more complex but in this case one of the two branches, 3 - 2, points to a node which corresponds to a measured variable and will not therefore need to be replaced. The result of the procedure at this node may be summarised as:

$$3 - 6 : (6 - 7, 6 - 8) \longrightarrow (3 - 7, 3 - 8)$$

FIG. 6.7(c)

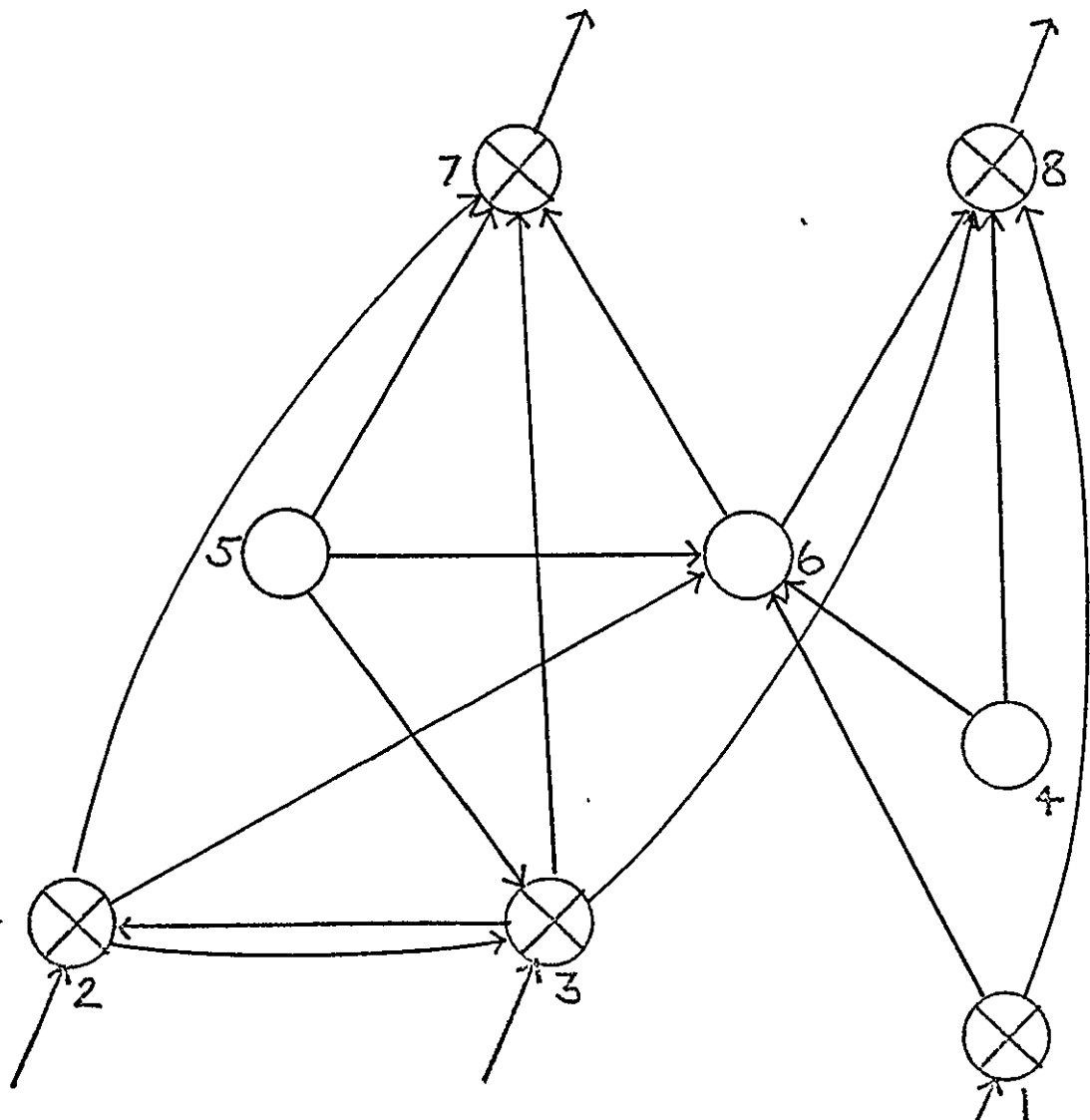


FIG. 6.7(d)

Fig. 6.7(e) may be written as:

$$4 - 6 : (6 - 7, 6 - 8) \longrightarrow (4 - 7, \quad)$$

No new branch 4 - 8 is created because one already exists between these nodes.

Fig. 6.7(f) may be written as:

$$5 - 6 : (6 - 7, 6 - 8) \longrightarrow (\quad , 5 - 8)$$

No alterations to the tree are made during the first use of the pruning operation on nodes 6, 7 and 8. After this first pass through the list of nodes, no branches point to nodes 4 and 5 and so they are removed from the list of nodes to leave the tree as shown in Fig. 6.7(g). The other node corresponding to a non-measured variable, node 6, cannot be removed at this stage since there are still pointers to it from nodes 1 and 2. Fig. 6.7(h) shows the tree after two passes of the pruning procedure and removal of node 6. This is the final form of the tree.

The shorthand representation used here only shows changes in the tree. A more complete notation, which shows branches that are not replaced and also denotes measured variables by means of an overbar, may be written in the form below for the first use of the pruning procedure on node 3:

$$\begin{aligned} &(\bar{3} - \bar{2}, \\ &\bar{3} - 6 : (6 - \bar{7}, 6 - \bar{8}) \longrightarrow (\bar{3} - \bar{7}, \bar{3} - \bar{8})) \end{aligned}$$

For the first use on node 4, this notation gives:

$$\begin{aligned} &(4 - 6 : (6 - \bar{7}, 6 - \bar{8}) \longrightarrow (1 - \bar{7}, \quad), \\ &4 - \bar{8}) \end{aligned}$$

FIG. 6.7(e)

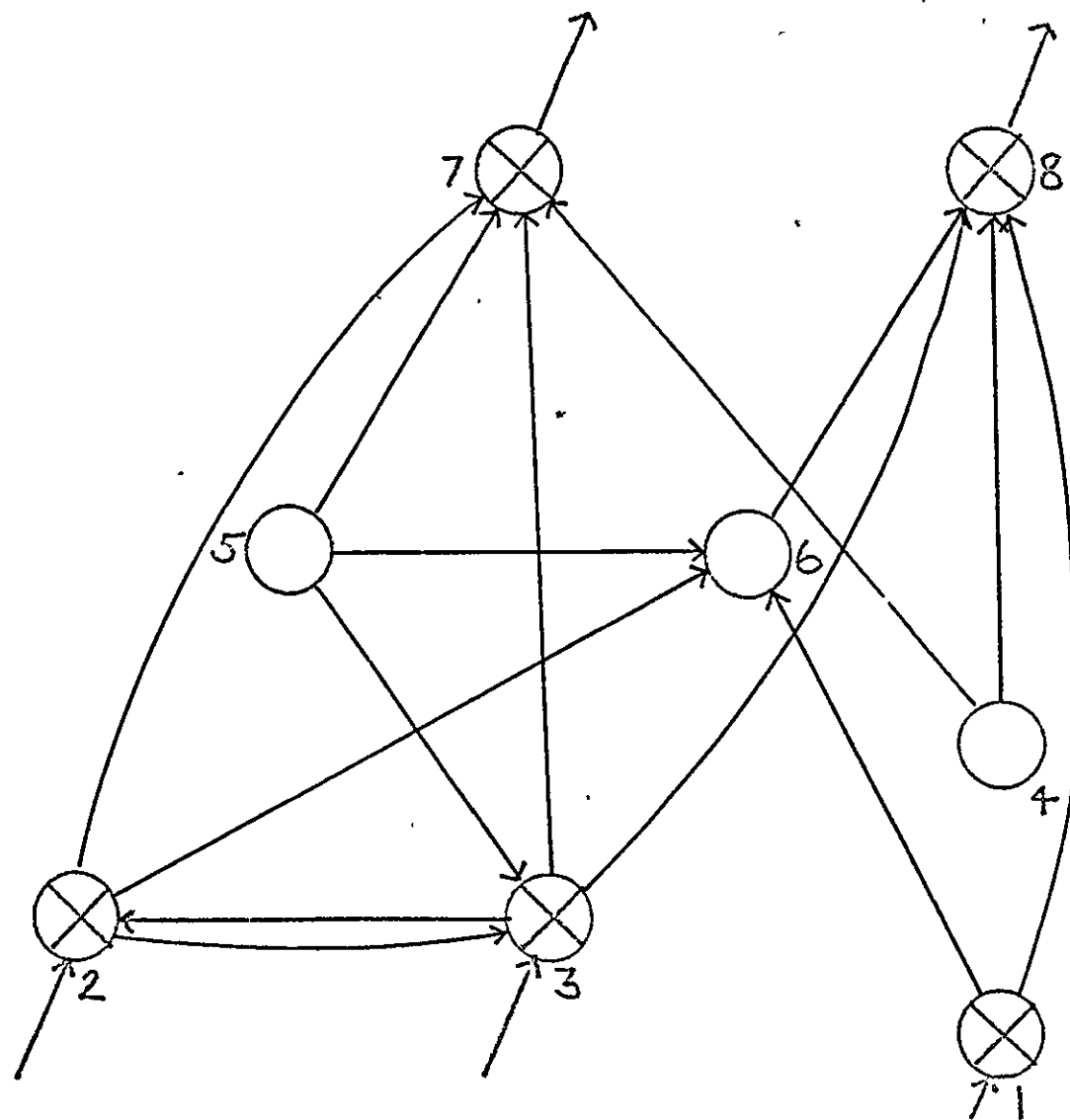


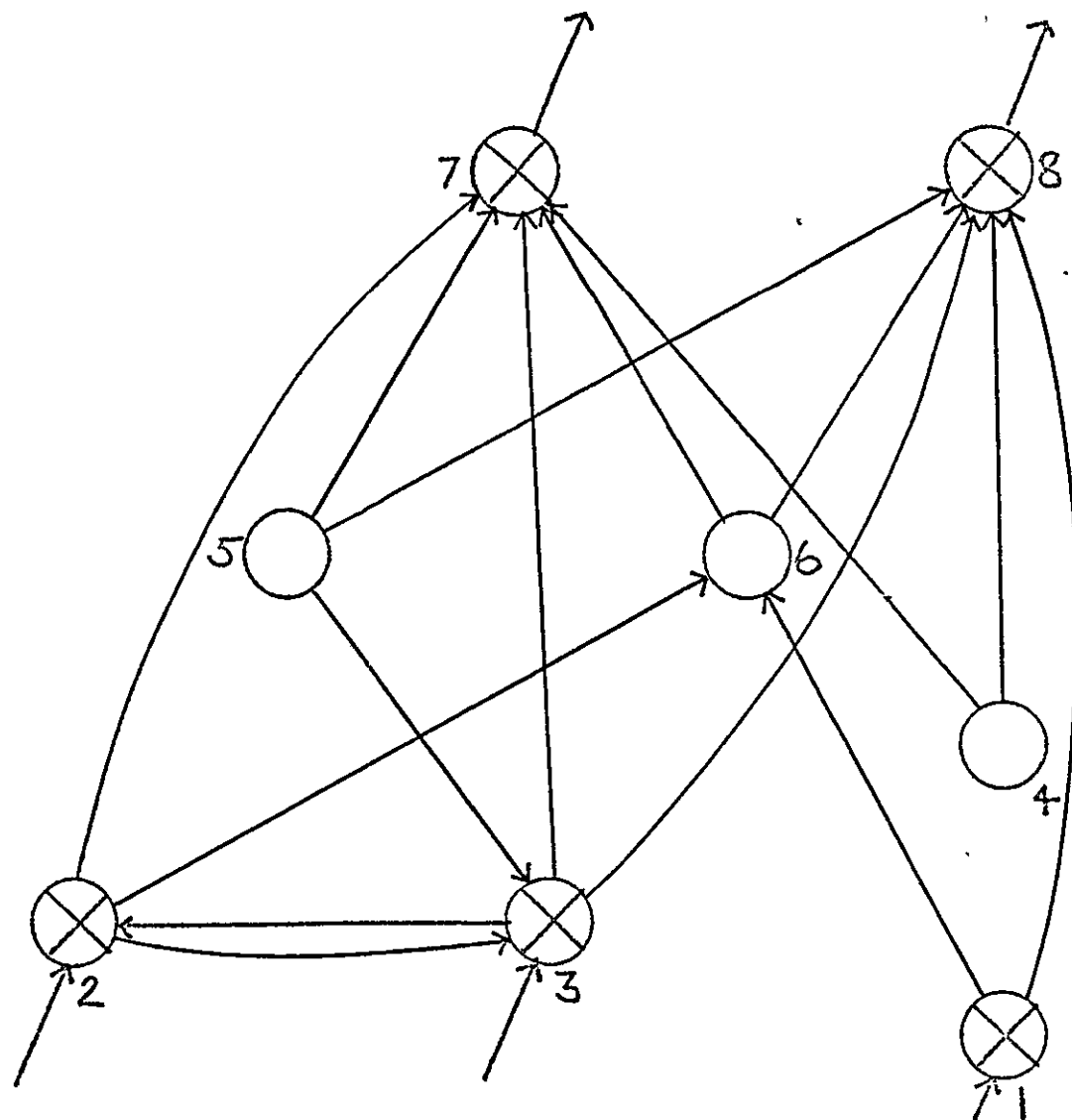
FIG 6.7(f)

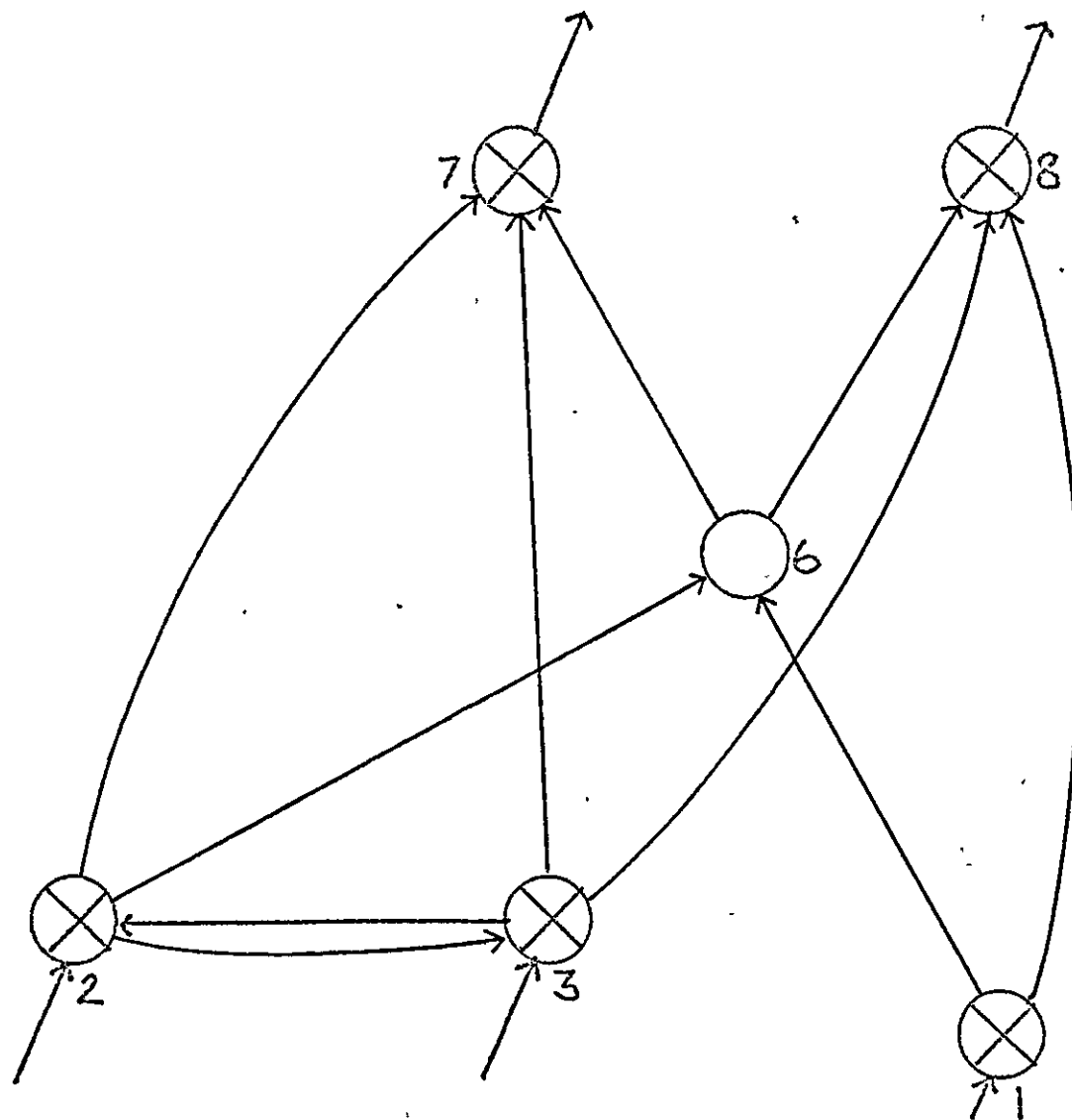
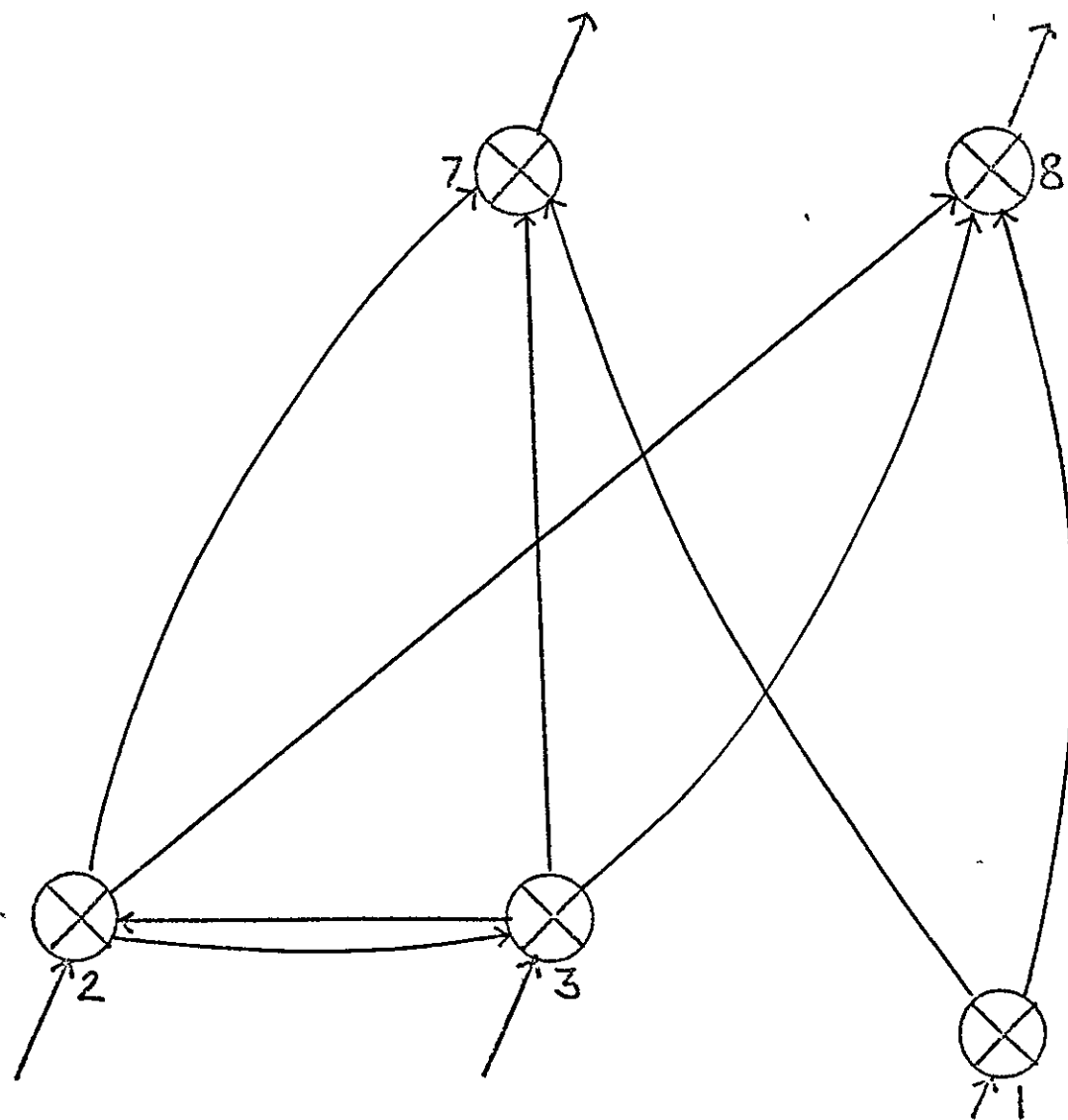
FIG. 6.7(g)

FIG. 6.7(h)

The use of this method of pruning the alarm tree always leads to a unique result, irrespective of the order of the nodes in the list since the pruning process is only a logical equivalent of algebraic substitution. For small systems, this may be shown by use of the notation above but for large systems the number of operations involved is excessive.

6.3.3 Definition of Deduced Alarms

Deduced alarm symptoms may be found either by using the program facilities described in Section 5.3.3 or by use of intuitive models. In order to use the symptoms, the corresponding data must be added to the alarm tree data. If the symptoms are not found during the same program run, they must be input as data. The use of keyword INPUTCHECKS, described in Section A.2.3, allows the user to specify the symptoms and the associated deduced alarm message. The program stores the message with the symptoms in core-store and sets pointers to the complete set of symptoms from each variable concerned.

These variables are at the nodes of the alarm tree and the relevant symptom lists may therefore be inspected, during analysis, when the scanning program detects that a variable has crossed one of its alarm limits.

The difference in the storage schemes used for basic alarm tree data and the deduced alarm symptoms partly reflects the difference in the two types of information. The information contained in the alarm tree represents the basic cause-and-effect relationships between the measured variables whilst deduced alarm symptoms represent

the active alarms when the appropriate condition occurs.

6.3.4 Transfer of Data to the On-Line Machine

After the alarm tree has been set up and deduced alarm symptoms, if any, added the data needed for the on-line analysis program is complete. At this stage, the tree may be printed out using keyword PRINTREE, as described in Section A.2.4, or tested using keyword TESTREE, as noted in the following section. For a real application, the data produced must now be converted to the form which is compatible with the on-line machine to be used. It is expected that this stage will consist of transferring the data to a magnetic tape and then running a short program to process the tape. This work has not been done for the present study since no real application was involved. The important point to note is that no effort is required by the user, at this stage, apart from the production of the short program to process the magnetic tape.

6.4 Testing the Analysis Tree

In order to test the analysis tree produced by the method, a further program was written that allows simulations of various disturbances while using the analysis data to diagnose the root cause. The main program used for this facility is called TESTREE and may be used by inputting the appropriate keyword as described in Section A.2.6. In order to test the data thoroughly, slight changes to model parameters may be used so that the model used for testing is not

identical to that from which the data was derived. Tests of this nature are necessary since, for a real application, the model used would be far from perfect.

6.5 Example of Program Use

The program was tested using the plant model used in the preceding two Chapters. Fig. 6.8 shows the program output after use of keywords SETUPTREE and PRINTREE. This output corresponds to the information flow diagram and therefore contains all model variables. Measured variables are denoted by inclusion of the unit name, in brackets, after the variable name. If any other model variable causes changes in the variable considered, two numbers appear on the same line as the variable name. The first number gives a measure of the direction of change that the variable (whose name appears on the line below), causes when perturbed (+1 for increase in B causes increase in A). The second number gives a measure of the size of the change that occurs ($\Delta A / \Delta B$). The output shown contains two levels of causes and therefore the second variable may also be followed by 2 numbers. The number of levels of causes printed may be set by the use of keyword MAXLEVEL as described in Section A.2.1. Variables at the same level in the tree are printed inset from the left side the same number of spaces. This output is only shown for the sake of completeness. Fig. 6.9 shows the same example after use of keywords ALTERTREE and PRINTREE. In this figure, two levels of the tree are again printed. Note that this is only a feature of the print-out rather than the structure of the tree itself.

PRINTREE OUTPUT

| | | | |
|------|-------------|-------------|-------------|
| XAXC | +1.0000E +0 | +4.2726E -3 | |
| ODQB | | +1.0000E +0 | +1.0000E +0 |
| | | ODQB | |
| | +1.0000E +0 | +2.9259E -3 | |
| XDXB | | +1.0000E +0 | +1.1557E +0 |
| | | XAXC | |
| | +1.0000E +0 | +6.5255E -3 | |
| OF | | +1.0000E +0 | +1.1922E -2 |
| | | OFQB | |
| | | +1.0000E +0 | +2.8884E -3 |
| | | XFXB | |
| | +1.0000E +0 | +1.1177E -3 | |
| XE | | +1.0000E +0 | +0.7811E -1 |
| | | XFXB | |
| | +1.0000E +0 | +8.8709E -3 | |
| QAQC | | +1.0000E +0 | +7.2222E -3 |
| | | QAQC | |
| | +1.0000E +0 | +2.2222E -3 | |
| XAXC | | +1.0000E +0 | +4.7775E -3 |
| | | ODQB | |
| | | +1.0000E +0 | +2.9221E -3 |
| | | XDXB | |
| | | +1.0000E +0 | +9.5797E -3 |
| | | QAQC | |
| | | +1.0000E +0 | +2.2172E -3 |

Tree for Complete Plant Model

FIG. 6.8

| | | | |
|-----------|-------------|-------------|-------------|
| | | YC (PLS1) | |
| | | -1.00000 +0 | -1.18238 -2 |
| | | ODOB | |
| | | -1.00000 +0 | -2.92618 -3 |
| | | XDXB | |
| | -1.00000 +0 | -1.35628 -2 | |
| | ODQB | +1.00000 +0 | +1.00000 +0 |
| | | ODQB | |
| | -1.00000 +0 | -2.91908 -3 | |
| | XDXB | +1.00000 +0 | +8.70158 -1 |
| | | XAXC | |
| Q400 | +1.00000 +0 | +3.33338 -3 | |
| | Q400 | +1.00000 +0 | +2.27228 -3 |
| | | Q400 | |
| | +1.00000 +0 | +3.33338 -3 | |
| | QF | +1.00000 +0 | +1.19228 -2 |
| | | QFQB | |
| | | +1.00000 +0 | +2.88248 -3 |
| | | XFXB | |
| TC (FEED) | -1.00000 +0 | -2.91928 +1 | |
| | YAXC | +1.00000 +0 | +4.27268 -3 |
| | | ODQB | |
| | | +1.00000 +0 | +2.92598 -3 |
| | | XDXB | |
| | | +1.00000 +0 | +6.52558 -3 |
| | | QF | |

FIG. 6.8 (contd.)

| | |
|--------------|--------------|
| +1.00000E +0 | +1.11772E -3 |
| XF | |
| +1.00000E +0 | +8.83098E -3 |
| Q2QC | |
| +1.00000E +0 | +2.22222E -3 |
| XAYC | |
| -1.00000E +0 | -1.35628E -2 |
| ODQB | |
| -1.00000E +0 | -2.91098E -3 |
| YDXE | |

| | | |
|------|--------------|--------------|
| XDXB | +1.00000E +0 | +8.70158E -1 |
| YAYC | | |
| | +1.00000E +0 | +4.27262E -3 |
| ODQB | | |
| | +1.00000E +0 | +2.92598E -3 |
| XDXB | | |
| | +1.00000E +0 | +6.52558E -3 |
| OF | | |
| | +1.00000E +0 | +1.11772E -3 |
| XF | | |
| | +1.00000E +0 | +8.83098E -3 |
| Q2QC | | |
| | +1.00000E +0 | +2.22222E -3 |
| XAYC | | |
| | +1.00000E +0 | -1.35628E -2 |
| ODQB | | |
| | +1.00000E +0 | -2.91098E -3 |
| YDXB | | |

| | | |
|------|--------------|--------------|
| ODQB | +1.00000E +0 | +1.00000E +0 |
| QDQB | | +1.00000E +0 |

FIG. 6.8 (contd.)

0000

TDTG
+1.00002 +0
TC (FFFD) -1.00002 +0
YAXC -2.01922 +1

Prp.
LE
+1.00002 +0
YEXB
+0.78112 -1
+1.00002 +0
YAXB +1.00002 +0

QE
+1.00002 +0
DFQR
+1.10222 -2
+1.00002 +0
PCPC
+1.00002 +0
PAPB
-1.00002 +0
PFPR -3.10762 -2

+1.00002 +0
YFYB
+2.82842 -3
+1.00002 +0
YAYB +1.00002 +0

YXC
+1.00002 +0
DDQR
+4.77752 -5
+1.00002 +0
DDQB +1.00002 +0

+1.00002 +0
XDYB
+2.07212 -3
+1.00002 +0
+8.70152 -1

FIG. 6.8 (contd.)

V4YC

| | | |
|-------------|-------------|-------------|
| +1.0000E +0 | +0.5707E -3 | |
| Q4JC | +1.0000E +0 | +2.2222E -3 |
| | Q4QB | |

| | | |
|-------------|-------------|-------------|
| +1.0000E +0 | +2.2172E -3 | |
| YC (DLS1) | +1.0000E +0 | +2.0022E -3 |
| | QDQB | |
| | +1.0000E +0 | +2.0147E -3 |
| | XDXP | |
| | +1.0000E +0 | +8.1942E -3 |
| | Q4QB | |
| | +1.0000E +0 | +2.2173E -3 |
| | X4YE | |
| | +1.0000E +0 | +7.0847E -3 |
| | Q4QB | |
| | +1.0000E +0 | +2.0275E -3 |
| | YEXB | |

| | | |
|-------------|-------------|-------------|
| +1.0000E +0 | +1.1823E -2 | |
| YDQB | +1.0000E +0 | +1.0000E +0 |
| | QDQB | |

| | | |
|-------------|-------------|-------------|
| +1.0000E +0 | +2.0261E -3 | |
| X7YB | +1.0000E +0 | +6.6670E -1 |
| | X4XC | |

| | | | |
|------|-------------|-------------|-------------|
| Q4QC | +1.0000E +0 | +2.2222E -3 | |
| | Q4JC | +1.0000E +0 | +2.2222E -3 |
| | | Q4QB | |

FIG. 6.8 (contd.)

| | | | |
|------|----------------------|--------------|-------------|
| TATC | -1.00000E +0 YAXC | -2.5625E +1 | |
| | | +1.00000E +0 | +4.7775E -3 |
| | | 0000 | |
| | | +1.00000E +0 | +2.4221E -3 |
| | | XDXB | |
| | | +1.00000E +0 | +0.5797E -3 |
| | | 0AQC | |
| | | +1.00000E +0 | +2.2172E -3 |
| XDXB | +1.00000E +0 YAXC | YC (PLS1) | |
| | | -1.00000E +0 | -1.1823E -2 |
| | | 0000 | |
| | | -1.00000E +0 | -2.0261E -3 |
| | | XDXB | |
| | | +6.6670E -1 | |
| | | +1.00000E +0 | +4.7775E -3 |
| | | 0000 | |
| ZS | +1.00000E +0 YAXC | +1.00000E +0 | +2.0221E -3 |
| | | YDXB | |
| | | +1.00000E +0 | +0.5797E -3 |
| | | 0AQC | |
| | | +1.00000E +0 | +2.2172E -3 |
| | | YC (PLS1) | |
| | | -1.00000E +0 | -1.1823E -2 |
| | | 0000 | |
| | | -1.00000E +0 | -2.0261E -3 |
| | | YDXB | |
| | | +1.50000E +1 | |
| | | +1.00000E +0 | +4.7775E -3 |

FIG. 6.8 (contd.)

| | | | | | | |
|------|--------------|--|--------------|--|--------------|--|
| | | | 0000 | | | |
| | | | +1.00000E +0 | | +2.4221E -3 | |
| | | | X0X0 | | | |
| | | | +1.00000E +0 | | +0.5707E -3 | |
| | | | 0400 | | | |
| | | | +1.00000E +0 | | +2.2172E -3 | |
| | | | X0 (PLS1) | | | |
| | | | -1.00000E +0 | | -1.1823E -2 | |
| | | | 0000 | | | |
| | | | -1.00000E +0 | | -2.9261E -3 | |
| | | | X0X0 | | | |
| 0000 | +1.00000E +0 | | +1.00000E +0 | | | |
| | 0000 | | +1.00000E +0 | | +1.00000E +0 | |
| | | | 0000 | | | |
| T0T0 | +1.00000E +0 | | +1.00000E +0 | | | |
| | TATC | | -1.00000E +0 | | -2.5625E +1 | |
| | | | XAXC | | | |
| TSTA | | | | | | |
| Q000 | -1.00000E +0 | | -3.5075E -2 | | | |
| | P000 | | +1.00000E +0 | | +2.50000E +0 | |
| | | | 0000 | | | |
| | | | -1.00000E +0 | | -2.50000E +0 | |
| | | | 0400 | | | |
| XSYA | | | | | | |
| XAYC | +1.00000E +0 | | +2.0540E -3 | | | |

FIG. 6.8 (contd.)

| | | |
|--------------|--------------|--------------|
| 0000 | +1.000000 +0 | +1.000000 +0 |
| | 0000 | |
| +1.000000 +0 | +2.05232 -3 | |
| 0000 | +1.000000 +0 | +1.49600 +0 |
| | XC (PLS2) | |
| +1.000000 +0 | +0.527732 -3 | |
| 0000 | +1.000000 +0 | +3.33333 -3 |
| | 0000 | |
| | +1.000000 +0 | +3.33333 -3 |
| | 00 | |
| +1.000000 +0 | +3.32242 -3 | |
| YAXC | +1.000000 +0 | +4.27762 -3 |
| | 0000 | |
| | +1.000000 +0 | +2.92592 -3 |
| | YAXC | |
| | +1.000000 +0 | +4.52552 -3 |
| | 00 | |
| | +1.000000 +0 | +1.11772 -3 |
| | YF | |
| | +1.000000 +0 | +2.83992 -3 |
| | 0000 | |
| | +1.000000 +0 | +2.22222 -3 |
| | YAXC | |
| | -1.000000 +0 | -1.35622 -2 |
| | 0000 | |
| | -1.000000 +0 | -2.01092 -3 |
| | YFYS | |
| -1.000000 +0 | -1.37712 -2 | |
| 0000 | +1.000000 +0 | +1.000000 +0 |

FIG. 6.8 (contd.)

| | | | |
|------|-------------|-------------|-------------|
| | | QDQD | |
| | -1.7707E +0 | -2.0267E -3 | |
| | XDYE | +1.0000E +0 | +1.1557E +0 |
| | | XDYE | |
| QDQC | +1.0000E +0 | +3.3333E -3 | |
| | QDQC | +1.0000E +0 | +3.3333E -3 |
| | | QDQC | |
| | +1.0000E +0 | +3.3333E -3 | |
| | | OF | |
| TATC | -1.0000E +0 | -3.3808E +1 | |
| | XDYE | +1.0000E +0 | +2.9540E -3 |
| | | QDQD | |
| | +1.0000E +0 | +2.9323E -3 | |
| | XDYE | | |
| | +1.0000E +0 | +0.5773E -3 | |
| | QDQC | | |
| | +1.0000E +0 | +3.3224E -3 | |
| | XDYE | | |
| | -1.0000E +0 | -1.3771E -2 | |
| | QDQD | | |
| | -1.0000E +0 | -2.0267E -3 | |
| | XDYE | | |
| XDYE | +1.0000E +0 | +1.1557E +0 | |
| | XDYE | +1.0000E +0 | +2.9540E -3 |
| | | QDQD | |
| | +1.0000E +0 | +2.9323E -3 | |

FIG. 6.8 (contd.)

| | | | | |
|------|-------------|-------------|-------------|--|
| | | XBXB | | |
| | | +1.0000E +0 | +0.5773E -3 | |
| | | QAOB | | |
| | | +1.0000E +0 | +3.3224E -3 | |
| | | YAYC | | |
| | | -1.0000E +0 | -1.3771E -2 | |
| | | QOQB | | |
| | | -1.0000E +0 | -2.0267E -3 | |
| | | ZLXB | | |
| 7S | +1.0000E +0 | +1.5000E +1 | | |
| | XAXB | +1.0000E +0 | +2.9540E -3 | |
| | | QOQB | | |
| | | +1.0000E +0 | +2.9323E -3 | |
| | | YBXB | | |
| | | +1.0000E +0 | +0.5773E -3 | |
| | | QAOB | | |
| | | +1.0000E +0 | +3.3224E -3 | |
| | | YAYC | | |
| | | -1.0000E +0 | -1.3771E -2 | |
| | | QOQB | | |
| | | -1.0000E +0 | -2.0267E -3 | |
| | | YBXB | | |
| OCQB | +1.0000E +0 | +1.0000E +0 | | |
| | QOQB | +1.0000E +0 | +1.0000E +0 | |
| | | QOQB | | |
| TDTE | +1.0000E +0 | +1.0000E +0 | | |
| | TATC | -1.0000E +0 | -3.3808E +1 | |

FIG. 6.8 (contd.)

XAXC

| | | | |
|-----------|---------------------|-----------------------------------------|-------------|
| XC (P192) | +0.35318 -1 9000 | +4.48118 -4 +1.00002 +0 80 | +2.50002 -6 |
| | +1.00002 +0 X0Y0 | +2.21202 -3 +1.00002 +0 XR (2EB1) | +1.85712 +0 |
| | +1.00002 +0 0AQC | +3.21422 -3 +1.00002 +0 0AQC | +3.33332 -3 |
| | +1.00002 +0 XAXC | +3.33002 -3 +1.00002 +0 0PQ3 | +2.25402 -3 |
| | | +1.00002 +0 X0YR | +2.93232 -3 |
| | | +1.00002 +0 0AQC | +0.57732 -3 |
| | | +1.00002 +0 XAXC | +3.32242 -3 |
| | | +1.00002 +0 0PQ3 | -1.37712 -2 |
| | | +1.00002 +0 X0YR | -2.92672 -3 |
| | -1.00002 +0 0PQ3 | -1.11312 -2 +1.00002 +0 0000 | +1.00002 +0 |

FIG. 6.8 (contd.)

| | | | |
|-----------|--------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------|
| | -1.0000E +0 XDAB | -2.0250E -3 +1.0000E +0 XC (PLS2) | +1.4060E +0 |
| QDQC | +1.0000E +0 QDQC | +7.3333E -3 +1.0000E +0 QDQC | +3.3333E -3 |
| TC (PLS2) | -1.0000E +0 XC (PLS2) | -3.8125E +1 +0.5833E -1 QDQC +1.0000E +0 XDAB +1.0000E +0 QDQC +1.0000E +0 XDAB -1.0000E +0 QDQC -1.0000E +0 XDAB | +4.6811E -4 +2.9180E -3 +8.2142E -3 +3.3300E -3 -1.1131E -2 -2.0250E -3 |
| QDQC | +1.0000E +0 XC (PLS2) | +1.4060E +0 +0.5833E -1 QDQC +1.0000E +0 XDAB +1.0000E +0 QDQC +1.0000E +0 | +4.6811E -4 +2.9180E -3 +8.2142E -3 +3.3300E -3 |

FIG. 6.8 (contd.)

| | | | |
|-----------|-------------|-------------|-------------|
| | | XAXC | |
| | | -1.00008 +0 | -1.11318 -2 |
| | | 0000 | |
| | | -1.00008 +0 | -2.92508 -3 |
| | | XDXB | |
| 252S | +1.00008 +0 | +1.50008 +1 | |
| | YC (PLS2) | +0.58338 -1 | +4.68118 -4 |
| | | 0000 | |
| | | +1.00008 +0 | +2.91808 -3 |
| | | XDXD | |
| | | +1.00008 +0 | +8.21428 -3 |
| | | 0A0C | |
| | | +1.00008 +0 | +3.33008 -3 |
| | | XAXC | |
| | | -1.00008 +0 | -1.11318 -2 |
| | | 0008 | |
| | | -1.00008 +0 | -2.92508 -3 |
| | | XDXB | |
| 000B | +1.00008 +0 | +1.00008 +0 | |
| | 0000 | +1.00008 +0 | +2.50008 -6 |
| | | FC | |
| T07B | +1.00008 +0 | +1.00008 +0 | |
| | TC (PLS2) | -1.00008 +0 | -3.80258 +1 |
| | | XC (PLS2) | |
| XR (PE91) | +1.00008 +0 | +1.64748 -2 | |

FIG. 6.8 (contd.)

| | | |
|-------------|-------------|-------------|
| 0000 | +1.0000E +0 | +3.3333E -3 |
| | 0400 | |
| +1.7777E +0 | +8.7687E -3 | |
| XC (DLS2) | +9.5833E -1 | +4.6811E -4 |
| | 0500 | |
| | +1.0000E +0 | +2.9180E -3 |
| | XD XD | |
| | +1.0000E +0 | +6.2142E -3 |
| | 0600 | |
| | +1.0000E +0 | +3.3300E -3 |
| | XAXC | |
| | -1.0000E +0 | -1.1131E -2 |
| | 00Q3 | |
| | -1.0000E +0 | -2.9250E -3 |
| | XD XD | |
| -1.0000E +0 | -1.7845E -2 | |
| 0000 | +1.0000E +0 | +2.5000E -6 |
| | FC | |
| -1.0000E +0 | -7.6644E -3 | |
| YD XD | +1.0000E +0 | +1.8571E +0 |
| | XR (REB1) | |
| -7.1428E -1 | -7.0388E -6 | |
| HR | +1.0000E +0 | +1.0000E +0 |
| | 0000 | |
| | -1.0000E +0 | -1.0000E +0 |
| | 0000 | |
| | -1.0000E +0 | -1.0000E +0 |
| | 0800 | |

FIG. 6.8 (contd.)

| | | | |
|-----------|-------------|-------------|-------------|
| HF | +1.00000 +0 | +1.00000 +0 | |
| | QCQC | +1.00000 +0 | +3.33332 -3 |
| | | QAQC | |
| | -1.00000 +0 | -1.00000 +0 | |
| | QDQD | +1.00000 +0 | +2.50000 -6 |
| | | FC | |
| | -1.00000 +0 | -1.00000 +0 | |
| | QPOR | +1.00000 +0 | +3.66092 -3 |
| | | 14 (REQ1) | |
| | | -1.00000 +0 | -4.55092 -4 |
| | | PAPB | |
| LR (REQ1) | +1.00000 +0 | +1.66672 -1 | |
| | LR | +1.00000 +0 | +1.00000 +0 |
| | | QCQC | |
| | | -1.00000 +0 | -1.00000 +0 |
| | | QDQD | |
| | | -1.00000 +0 | -1.00000 +0 |
| | | QPOR | |
| | | | |
| | | | |
| | | | |
| TR (REQ1) | -1.00000 +0 | -4.13222 +1 | |
| | X4 (PEB1) | +1.00000 +0 | +1.64742 -2 |
| | | QCQC | |
| | | +1.00000 +0 | +8.76872 -3 |
| | | YC (PLS2) | |
| | | -1.00000 +0 | -1.78452 -2 |
| | | QDQD | |
| | | -1.00000 +0 | -7.66442 -3 |

FIG. 6.8 (contd.)

VDDYD
-7.14228 -1 -7.03388 -6
HR

QBOP +1.00008 +0 +5.56208 -3
LR (REF1) +1.00008 +0 +1.66678 -1
HR

-1.00008 +0 -4.55208 -4
PAPS +1.00008 +0 +5.00008 -1
OP (REF1)
-1.00008 +0 -5.00008 -1
ORQR

FF +7.33332 -1 -3.20558 -1
TFTR +1.00008 +0 +1.00008 +0
TAT1

+4.66672 -1 -4.61002 -1
TR (REF1) -1.00008 +0 -4.13222 +1
XR (REF1)

-7.33332 -1 -1.41532 +0
TG (REF1) +1.00008 +0 +2.14012 +3
OFQ8
+1.00008 +0 +1.00278 +0
TFTR
-1.00008 +0 -5.54412 -4
FC
-1.00008 +0 -2.03832 +3
OG (REF1)

FIG. 6.8 (contd.)

| | | | |
|------|--------------------------|------------------------------------------------------------------------------------------------------------|----------------------------------------------------------|
| EC | +1.00002 +0 TFT8 | +1.04478 +3 +1.00008 +0 TAT1 | +1.00008 +0 |
| | -1.00002 +0 YG (REF1) | -1.02752 +3 +1.00008 +0 OFQ8 +1.00002 +0 TFT8 -1.00002 +0 EC -1.00003 +0 OG (REF1) | +2.14018 +3 +1.00272 +0 -5.54412 -4 -2.03832 +3 |
| | -7.33338 -1 CF | -1.91312 +4 +7.33338 -1 TFT8 +4.66678 -1 TR (REF1) -7.33338 -1 TG (REF1) | -3.29552 -1 -4.61602 -1 -1.41532 +0 |
| XDXD | +1.00002 +0 XR (REF1) | +1.85712 +0 +1.00008 +0 OFQ8 +1.00008 +0 XC (PLS2) -1.00002 +0 OFQ8 -1.00008 +0 | +1.64742 -2 +8.76878 -3 -1.78452 -2 -7.66442 -3 |

FIG. 6.8 (contd.)

| | | | |
|-----------|--------------------------|-------------------------------------------------------------------------------------|-------------------------------------------|
| | | XYXD -7.1429E -1 UR | -7.0388E -6 |
| OCOD | +1.0000E +1 FC | +2.5000E -6 +1.0000E +0 YFTS -1.0000E +0 TG (REF1) -7.3333E -1 PF | +1.9467E +3 -1.0275E +3 -1.0151E +4 |
| YSTD | +1.0000E +1 TR (REF1) | +1.0000E +0 -1.0000E +0 XR (REF1) | -4.1322E +1 |
| ZBZF | +1.0000E +0 LR (REF1) | +7.5000E +0 +1.0000E +0 HP | +1.6667E -1 |
| OB (REF1) | +1.0000E +1 ORGR | +0.0600E +1 +1.0000E +0 IP (REF1) -1.0000E +1 PAPB | +3.6609E -3 -4.5509E -4 |
| | -1.0000E +0 XR (REF1) | -1.0430E -1 +1.0000E +0 QCQC | +1.6474E -2 |

FIG. 6.8 (contd.)

| | | | |
|------|-------------|-------------|-------------|
| | | +1.00002 +0 | +2.76878 -3 |
| | | XC (PLS2) | |
| | | -1.00002 +0 | -1.78452 -2 |
| | | QD3D | |
| | | -1.00002 +0 | -7.66442 -3 |
| | | XD4D | |
| | | -7.14202 -1 | -7.03882 -6 |
| | | 4R | |
| TATB | +1.00002 +0 | +1.00002 +0 | |
| | YR (REF1) | -1.00002 +0 | -4.13222 +1 |
| | | YR (REF1) | |
| YACB | +1.00002 +0 | +8.74542 -1 | |
| | XD (REF1) | +1.00002 +0 | +1.64742 -2 |
| | | QD9C | |
| | | +1.00002 +0 | +2.76872 -3 |
| | | XC (PLS2) | |
| | | -1.00002 +0 | -1.78452 -2 |
| | | QD3D | |
| | | -1.00002 +0 | -7.66442 -3 |
| | | XD4D | |
| | | -7.14202 -1 | -7.03882 -6 |
| | | 4R | |
| PFPB | +1.00002 +0 | +1.00002 +0 | |
| | QFQS | +1.00002 +0 | +3.76822 -3 |
| | | QD9C | |
| | | +1.00002 +0 | +7.34552 -3 |
| | | PA01 | |

FIG. 6.8 (contd.)

| | | | | |
|-----------|--------------------------|------------------------------------|---------------------|-------------|
| | | | -1.0000E +0 PFDB | -7.6162E -3 |
| | -1.0000E +0 QG (REF1) | -1.0000E +0 +1.0000E +0 PFDB | | +2.4755E -2 |
| | | -1.0000E +0 P2DG | | -2.8157E -2 |
| UG (REF1) | +1.0000E +0 PFDB | +2.4755E -2 +1.0000E +0 PFDB | +1.0000E +0 | |
| | | -1.0000E +0 QG (REF1) | -1.0000E +0 | |
| | -1.0000E +0 P2DG | -2.8157E -2 | | |
| TG (REF1) | +1.0000E +0 PFDB | +2.1401E +3 +1.0000E +0 PCDB | +3.7682E -3 | |
| | | +1.0000E +0 P2D1 | +7.3455E -3 | |
| | | -1.0000E +0 PFDB | -7.6162E -3 | |
| | +1.0000E +0 TFTB | +1.0027E +0 +1.0000E +0 TAT1 | +1.0000E +0 | |
| | -1.0000E +0 EC | -5.5441E -4 +1.0000E +0 | +1.0467E +3 | |

FIG. 6.8 (contd.)

TFTB
 -1.00000 +0 -1.92758 +3
 TG (REF1)
 -7.33332 -1 -1.91318 +4
 EF

-1.00002 +0 -2.03832 +3
 QG (PER1) +1.00003 +0 +2.47558 -2
 PFOB
 -1.00002 +0 -2.81572 -2
 Q2QG

ZA71
 ZA72
 ZA73
 ZA74
 ZA75
 SU

154

+1.00002 +0 +1.47562 -7
 ZA74
 -1.00002 +0 -1.71262 -7
 ZR2S +1.00003 +0 +1.50002 +1
 XC (PLS2)

+3.33332 -1 +4.23582 -3
 LT

PI +1.00002 +0 +5.00002 -1
 ZA74
 -1.00002 +0 -5.00002 -1
 ZR2S +1.00003 +0 +1.50002 +1
 XC (PLS2)

FIG. 6.8 (contd.)

155

| | | |
|--------------|--------------|--------------|
| -1.000000 +0 | +0.000000 +0 | |
| SH | +1.000000 +0 | +1.675000 -7 |
| | PAZL | |
| | -1.000000 +0 | -1.712600 -7 |
| | PRIS | |
| | +3.333333 -1 | +4.835800 -3 |
| | IT | |

| | | |
|------|--------------|--------------|
| PCPC | +1.000000 +0 | +1.570300 +2 |
| PI | +1.000000 +0 | +5.000000 -1 |
| | PAZL | |
| | -1.000000 +0 | -5.000000 -1 |
| | PRIS | |
| | -1.000000 +0 | +0.000000 +0 |
| | SH | |

| | | |
|------|--------------|--------------|
| LT | | |
| 9FUP | +1.000000 +0 | +3.760200 -3 |
| | PCPC | +1.000000 +0 |
| | PI | +1.570300 +2 |
| | | |
| | +1.000000 +0 | +7.343500 -3 |
| | PAPI | -1.000000 +0 |
| | | +0.000000 +0 |
| | PAPI | |
| | -1.000000 +0 | -5.000000 +0 |
| | OFOS | |
| | | |
| | -1.000000 +0 | -7.416200 -3 |
| | PCPC | +1.000000 +0 |
| | | +1.000000 +0 |
| | OFOS | |
| | -1.000000 +0 | -1.000000 +0 |

FIG. 6.8 (contd.)

| | | | |
|------|-------------|-------------|-------------|
| | | OG (PEB1) | |
| DAP1 | -1.00002 +0 | +0.00002 +0 | |
| | UAG1 | -1.00002 +0 | +0.00002 +0 |
| | | DAP1 | |
| | -1.00002 +0 | -5.00002 +0 | |
| | UEUR | +1.00002 +0 | +3.76822 -3 |
| | | DCPC | |
| | | +1.00002 +0 | +7.34552 -3 |
| | | DAP1 | |
| | | -1.00002 +0 | -7.61622 -3 |
| | | DEUR | |
| TFTB | +1.00002 +0 | +1.00002 +0 | |
| | TAT1 | | |
| YFXE | | | |
| SU | +1.00002 +0 | +1.60102 -7 | |
| | ZIZ5 | | |
| | -1.00002 +0 | -1.60242 -7 | |
| | ZER2 | +1.00002 +0 | +7.50002 +0 |
| | | IP (PEB1) | |
| | +4.66472 -1 | +5.26472 -2 | |
| | LT | | |
| PI | -1.00002 +0 | -5.00002 -1 | |
| | ZAZ5 | | |
| | +1.00002 +0 | +5.00002 -1 | |
| | ZER2 | +1.00002 +0 | +7.50002 +0 |

FIG. 6.8 (contd.)

IR (REF1)

| | | |
|-------------|-------------|-------------|
| -1.0000E +0 | +0.0000E +0 | |
| SI | +1.0000E +0 | +1.6910E -7 |
| | 7A75 | |
| | -1.0000E +0 | -1.6924E -7 |
| | 7B7E | |
| | +4.6667E -1 | +5.2647E -2 |
| | IT | |

PCPC

| | | |
|-------------|-------------|-------------|
| +1.0000E +0 | +1.5706E +2 | |
| DJ | -1.0000E +0 | -5.0000E -1 |
| | 7A75 | |
| | +1.0000E +0 | +5.0000E -1 |
| | 7B7E | |
| | -1.0000E +0 | +0.0000E +0 |
| | SI | |

LT
QBQR

| | | |
|-------------|-------------|-------------|
| +1.0000E +0 | +1.4441E -2 | |
| PCPC | +1.0000E +0 | +1.5706E +2 |
| | PI | |
| +1.0000E +0 | +5.7116E -2 | |
| PAPR | +1.0000E +0 | +5.0000E -1 |
| | QB (REF1) | |
| | -1.0000E +0 | -5.0000E -1 |
| | QBQB | |
| -1.0000E +0 | -6.4397E -2 | |
| PBPR | | |

FIG. 6.8 (contd.)

| | | | |
|------|-------------|-------------|-------------|
| PAPB | +1.00072 +0 | +5.00002 -1 | |
| | OP (REF1) | +1.00002 +0 | +9.06002 +1 |
| | | OPOR | |
| | | -1.00002 +0 | -1.04392 -1 |
| | | XR (REF1) | |
| | -1.00002 +0 | -5.00002 -1 | |
| | OPOR | +1.00002 +0 | +1.44412 -2 |
| | | PCPC | |
| | | +1.00002 +0 | +5.71162 -2 |
| | | PAPB | |
| | | -1.00002 +0 | -6.43972 -2 |
| | | PRPB | |
| TSTR | +1.00002 +0 | +1.00002 +0 | |
| | TATR | +1.00002 +0 | +1.00002 +0 |
| | | TR (REF1) | |
| XBAB | +1.00002 +0 | +1.00002 +0 | |
| | XAYB | +1.00002 +0 | +8.74542 -1 |
| | | XR (REF1) | |
| PBPR | | | |
| OPOR | | | |
| Q4OD | +1.00002 +0 | +2.33822 +0 | |
| | QSOA | -1.00002 +0 | -3.50752 -2 |
| | | PSPA | |
| | -1.00002 +0 | -3.44452 -2 | |

FIG. 6.8 (contd.)

| | | | |
|-----------|--------------|--------------|--------------|
| | PAPD | +1.70000E +0 | +1.00000E +0 |
| | QAPD | -1.00000E +0 | -1.00000E +0 |
| | QD (ITF1) | | |
| | +1.70000E +0 | +3.31458E -2 | |
| | PSPD | +1.00000E +0 | +2.50000E +0 |
| | QSDA | -1.00000E +0 | -2.50000E +0 |
| | QAPD | | |
| PSPD | +1.00000E +0 | +2.50000E +0 | |
| | QSCA | -1.00000E +0 | -3.50758E -2 |
| | PSPD | | |
| | -1.00000E +0 | -2.50000E +0 | |
| | QAPD | +1.00000E +0 | +2.33828E +0 |
| | QSDA | -1.00000E +0 | -3.44458E -2 |
| | PAPD | +1.00000E +0 | +3.31458E -2 |
| | PSPD | | |
| X=XD | +1.00000E +0 | +1.00000E +0 | |
| | XSXA | | |
| TATD | +1.00000E +0 | +1.00000E +0 | |
| | TSTA | | |
| XC (PLS1) | +1.00000E +0 | +2.00228E -3 | |
| | QDQR | +1.00000E +0 | +1.00000E +0 |

FIG. 6.8 (contd.)

| | | | |
|-----------|--------------|--------------|--------------|
| | | ODQ3 | |
| | +1.00000E +0 | +2.0147E -3 | |
| | YDYR | +1.00000E +0 | +6.6670E -1 |
| | | XAYC | |
| | +1.00000E +0 | +8.1942E -3 | |
| | QAD3 | +7.50000E -1 | +7.2253E -4 |
| | | DCPC | |
| | | +1.00000E +0 | +0.4243E -3 |
| | | DAOB | |
| | +1.00000E +0 | +2.2173E -3 | |
| | XAXR | +1.00000E +0 | +1.00000E +0 |
| | | XAXR | |
| | -1.00000E +0 | -7.9847E -5 | |
| | QAD3 | +1.00000E +0 | +1.00000E +0 |
| | | ODQ3 | |
| | -1.00000E +0 | -2.0225E -3 | |
| | XAX3 | +1.00000E +0 | +5.3259E -1 |
| | | XC (PLS1) | |
| QAD3 | +1.00000E +0 | +2.2222E -3 | |
| | DAOB | +7.50000E -1 | +7.2253E -4 |
| | | DCPC | |
| | | +1.00000E +0 | +0.4243E -3 |
| | | DAOB | |
| TC (PLS1) | -1.00000E +0 | -2.3420E +1 | |

FIG. 6.8 (contd.)

| | | |
|-------------|-------------|-------------|
| XC (PLS1) | +1.0000E +0 | +2.0922E -3 |
| 0003 | | |
| +1.0000E +0 | +2.9147E -3 | |
| X0Y3 | | |
| +1.0000E +0 | +3.1942E -3 | |
| 0408 | | |
| +1.0000E +0 | +2.2173E -3 | |
| Y4X3 | | |
| -1.0000E +0 | -7.9847E -3 | |
| 0403 | | |
| -1.0000E +0 | -2.9225E -3 | |
| X4Y3 | | |

| | | |
|-------------|-------------|-------------|
| XC (PLS1) | +1.0000E +0 | +5.3250E -1 |
| 0003 | | |
| +1.0000E +0 | +2.9147E -3 | |
| X0Y3 | | |
| +1.0000E +0 | +3.1942E -3 | |
| 0408 | | |
| +1.0000E +0 | +2.2173E -3 | |
| X4Y3 | | |
| -1.0000E +0 | -7.9847E -3 | |
| 0403 | | |
| -1.0000E +0 | -2.9225E -3 | |
| X4Y3 | | |

| | | |
|-------------|-------------|-------------|
| XC (PLS1) | +1.0000E +0 | +1.5000E +1 |
| 0003 | | |
| +1.0000E +0 | +2.9147E -3 | |
| X0Y3 | | |
| +1.0000E +0 | +3.1942E -3 | |

FIG. 6.8 (contd.)

| | | |
|--------------|----------|----|
| XDX3 | | |
| +1.000002 +0 | +3.10428 | -3 |
| Q4Q3 | | |
| +1.000009 +0 | +2.21738 | -3 |
| XDX3 | | |
| -1.000002 +0 | -7.28478 | -3 |
| Q4Q3 | | |
| -1.000002 +0 | -2.92258 | -3 |
| XDX3 | | |

| | | | |
|------|--------------|--------------|--------------|
| Q4Q3 | +1.000002 +0 | +1.000002 +0 | |
| | Q4Q3 | +1.000002 +0 | +1.000002 +0 |
| | | Q4Q3 | |

| | | | |
|------|--------------|--------------|-------------|
| TATR | +1.000002 +0 | +1.000002 +0 | |
| | TC (PLS1) | -1.000002 +0 | -2.34298 +1 |
| | | TC (PLS1) | |

| | | | |
|------|--------------|--------------|--------------|
| Q4Q3 | +1.000002 +0 | +1.000002 +0 | |
| | Q4Q3 | +1.000002 +0 | +1.000002 +0 |
| | | Q4Q3 | |

| | | | |
|------|--------------|--------------|--------------|
| TATR | +1.000002 +0 | +1.000002 +0 | |
| | TATR | +1.000002 +0 | +1.000002 +0 |
| | | TC (PLS1) | |

| | | | |
|------|--------------|--------------|--|
| XDX3 | +1.000002 +0 | +1.000002 +0 | |
|------|--------------|--------------|--|

FIG.6.8. (contd.)

| | | | |
|-----------|--------------------------|----------------------------------------------------------------|----------------------------|
| | X4XB | +1.19008 +0 XC (PLS1) | +5.32598 -1 |
| EC | +1.00008 +0 QAB8 | +4.00008 +5 +1.00008 +0 Q003 | +1.00008 +0 |
| PC03 | -1.00008 +0 Q003 | +0.00008 +0 -1.00008 +0 PC03 | +0.00008 +0 |
| | -1.00008 +0 Q0 (EX01) | -2.00008 +0 +1.00008 +0 PC03 -1.00008 +0 Q400 | +1.42298 -2 -1.58088 -2 |
| Q0 (EX01) | +1.00008 +0 PC03 | +1.42298 -2 -1.00008 +0 Q003 -1.00008 +0 Q0 (EX01) | +0.00008 +0 -2.00008 +0 |
| | -1.00008 +0 P400 | -1.58088 -2 | |
| TD (EX01) | -1.00008 +0 Q003 | +0.00008 +0 -1.00008 +0 PC03 | +0.00008 +0 |

FIG. 6.8 (contd.)

| | | | |
|-----------|--------------|--------------|--------------|
| | -1.000000 +0 | +0.000000 +0 | |
| | TCT3 | | |
| | +1.000000 +0 | +2.31238 -4 | |
| | EC | +1.000000 +0 | +4.000000 +5 |
| | | Q4Q3 | |
| | -1.000000 +0 | -5.28738 +1 | |
| | QD (F401) | +1.000000 +0 | +1.42298 -2 |
| | | PCP3 | |
| | | -1.000000 +0 | -1.58088 -2 |
| | | Q4D0 | |
| LC (TAN1) | +1.000000 +0 | +6.66678 -2 | |
| | Q4Q8 | +1.000000 +0 | +1.000000 +0 |
| | | Q4Q8 | |
| | -1.000000 +0 | -6.66678 -2 | |
| | Q4Q8 | +6.000000 -1 | +1.33378 -2 |
| | | Q4Q8 | |
| | | +7.33338 -1 | +1.00308 -1 |
| | | IC (TAN1) | |
| | | -1.000000 +0 | -1.60468 -2 |
| | | Q4Q8 | |
| TL (TAN1) | -2.000000 -1 | +2.54508 -2 | |
| | Q4Q8 | +1.000000 +0 | +1.000000 +0 |
| | | Q4Q8 | |
| | +1.000000 +0 | +3.04758 -3 | |
| | TATB | +1.000000 +0 | +1.000000 +0 |
| | | TATB | |

FIG. 6.8 (contd.)

| | | | |
|-----------|-------------------------------------------------|------------------------------------------------------------------------------|------------------------------------|
| | -4.6667E -1 LC (TAN1) | -1.1761E -2 +1.0000E +0 Q1Q1 -1.0000E +0 Q4Q3 | +4.6667E -2 -6.6667E -2 |
| XC (TAN1) | -6.6667E -2 Q2Q3 | -1.1220E -4 +1.0000E +0 Q1Q5 | +1.0000E +0 |
| | +1.0000E +0 X4XB | +3.0496E -3 +1.0000E +0 Y4YB | +1.0000E +0 |
| | +6.6667E -2 LC (TAN1) | +1.7445E -5 +1.0000E +0 Q2Q3 -1.0000E +0 Q4Q3 | +6.6667E -2 -6.6667E -2 |
| Q4QB | +6.0000E -1 PAPB +7.3333E -1 LC (TAN1) | +1.3337E -2 +1.0030E -1 +1.0000E +0 Q2Q3 -1.0000E +0 Q4Q3 | +6.6667E -2 -6.6667E -2 |
| | -1.0000E +0 PAPB | -1.6040E -2 +1.0000E +0 | +1.0000E +0 |

FIG. 6.8 (contd.)

| | | | | |
|------|-------------|-------------|-------------|--|
| | | QAQB | | |
| | | -1.0000E +0 | -1.0000E +0 | |
| | | QB (DIV1) | | |
| | | -1.0000E +0 | -1.0000E +0 | |
| | | QC (DIV1) | | |
| TATB | +1.0000E +0 | +1.0000E +0 | | |
| | TC (TAN1) | -2.0000E -1 | +2.5459E -2 | |
| | | QAQB | | |
| | | +1.0000E +0 | +3.0475E -3 | |
| | | TATB | | |
| | | -6.6667E -1 | -1.1761E -2 | |
| | | LC (TAN1) | | |
| XAXB | +1.0000E +0 | +1.0000E +0 | | |
| | XC (TAN1) | -6.6667E -2 | -1.1226E -4 | |
| | | QAQB | | |
| | | +1.0000E +0 | +3.0456E -3 | |
| | | XAXB | | |
| | | +6.6667E -2 | +1.7445E -5 | |
| | | LC (TAN1) | | |
| DABD | | | | |
| ZB7S | +1.0000E +0 | +7.5000E +0 | | |
| | LC (TAN1) | +1.0000E +0 | +6.6667E -2 | |
| | | QAQB | | |
| | | -1.0000E +0 | -6.6667E -2 | |
| | | QAQB | | |

FIG. 6.8 (contd.)

| | | | |
|------|-------------|-------------|-------------|
| SJ | +1.00002 +0 | +1.65468 -7 | |
| | 7A72 | | |
| | -1.00002 +0 | -1.73108 -7 | |
| | 7B7S | +1.00002 +0 | +7.50008 +0 |
| | | LC (TAB.1) | |
| | +6.66672 -2 | +2.38032 -2 | |
| | LT | | |
| PI | -1.00002 +0 | -2.00002 +0 | |
| | 7A22 | | |
| | +1.00002 +0 | +2.00002 +0 | |
| | 7B7S | +1.00002 +0 | +7.50002 +0 |
| | | LC (TAB.1) | |
| | -1.00002 +0 | +0.00002 +0 | |
| | SH | +1.00002 +0 | +1.65468 -7 |
| | | 7A72 | |
| | | -1.00002 +0 | -1.73108 -7 |
| | | 7A22 | |
| | | +6.66672 -2 | +2.38032 -2 |
| | | LT | |
| PCPC | +1.00002 +0 | +1.57022 +2 | |
| | PI | -1.00002 +0 | -2.00002 +0 |
| | | 7A72 | |
| | | +1.00002 +0 | +2.00002 +0 |
| | | 7B7S | |
| | | -1.00002 +0 | +0.00002 +0 |
| | | SH | |

FIG. 6.8 (contd.)

| | | | | |
|-----------|-------------|-------------|-------------|--|
| LT | | | | |
| OB (DIV1) | +7.50000 -1 | +1.01552 -2 | | |
| | P400 | +1.00000 +0 | +1.00000 +0 | |
| | | 0A00 | | |
| | | -1.00000 +0 | -1.00000 +0 | |
| | | 00 (DIV1) | | |
| | | -1.00000 +0 | -1.00000 +0 | |
| | | 00 (DIV1) | | |
| | -1.00000 +0 | -5.42500 -3 | | |
| | P400 | +1.00000 +0 | +5.00000 +0 | |
| | | 00 (DIV1) | | |
| | | -1.00000 +0 | -5.00000 +0 | |
| | | 0A00 | | |
| OC (DIV1) | +1.00000 +0 | +1.11140 -3 | | |
| | P400 | +1.00000 +0 | +1.00000 +0 | |
| | | 0A00 | | |
| | | -1.00000 +0 | -1.00000 +0 | |
| | | 00 (DIV1) | | |
| | | -1.00000 +0 | -1.00000 +0 | |
| | | 00 (DIV1) | | |
| | -1.00000 +0 | -1.43660 -3 | | |
| | P400 | +1.00000 +0 | +2.00000 +1 | |
| | | 00 (DIV1) | | |
| | | -1.00000 +0 | -2.00000 +1 | |
| | | 0000 | | |
| P400 | +1.00000 +0 | +1.00000 +0 | | |
| | 0A00 | +6.00000 -1 | +1.33370 -2 | |

FIG. 6.8 (contd.)

| | | | | |
|------|-------------|-------------|-------------|--|
| | | DAPB | | |
| | | +7.7333E -1 | +1.0039E -1 | |
| | | LC (TAN1) | | |
| | | -1.0000E +0 | -1.6046E -2 | |
| | | DAPB | | |
| | -1.0000E +0 | -1.0000E +0 | | |
| | GB (DIV1) | +7.5000E -1 | +1.0155E -2 | |
| | | DAPB | | |
| | | -1.0000E +0 | -5.4258E -3 | |
| | | DAPB | | |
| | -1.0000E +0 | -1.0000E +0 | | |
| | LC (DIV1) | +1.0000E +0 | +1.1114E -3 | |
| | | DAPB | | |
| | | -1.0000E +0 | -1.4366E -3 | |
| | | DAPB | | |
| TATE | +1.0000E +0 | +1.0000E +0 | | |
| | TATE | +1.0000E +0 | +1.0000E +0 | |
| | | TC (TAN1) | | |
| TATC | +1.0000E +0 | +1.0000E +0 | | |
| | TATC | +1.0000E +0 | +1.0000E +0 | |
| | | TC (TAN1) | | |
| XAXB | +1.0000E +0 | +1.0000E +0 | | |
| | XAXB | +1.0000E +0 | +1.0000E +0 | |
| | | XC (TAN1) | | |

FIG. 6.8 (contd.)

| | | | |
|------|--------------------------|----------------------------------------------------------------------------------|-------------------------------------------|
| XAYC | +1.00002 +0 XAXR | +1.00002 +0 +1.00002 +0 YC (TAG1) | +1.00002 +0 |
| Q000 | +1.00002 +0 PCPC | +2.15432 -4 +1.00002 +0 PI | +1.56972 +2 |
| | +1.00002 +0 PAPC | +1.53642 -3 +1.00002 +0 QC (DIV1) -1.00002 +0 Q000 | +2.00002 +1 -2.00002 +1 |
| | -1.00002 +0 P0PR | -1.36072 -3 | |
| PAPC | +1.00002 +0 QC (DIV1) | +2.00002 +1 +1.00002 +0 PAPC -1.00002 +0 PAPC | +1.11142 -3 -1.43662 -3 |
| | -1.00002 +0 Q000 | -2.00002 +1 +1.00002 +0 PCPC +1.00002 +0 PAPC -1.00002 +0 P0PR | +2.15432 -4 +1.53642 -3 -1.36072 -3 |

FIG. 6.8 (contd.)

| | | | |
|------|-------------|-------------|-------------|
| TDTG | +1.0000E +0 | +1.0000E +0 | |
| | TATC | +1.0000E +0 | +1.0000E +0 |
| XDXE | +1.0000E +0 | +1.0000E +0 | |
| | XAXC | +1.0000E +0 | +1.0000E +0 |
| SU | +1.0000E +0 | +1.6597E -7 | |
| | ZAZZ | | |
| | -1.0000E +0 | -1.6839E -7 | |
| | ZBZS | +1.0000E +0 | +1.5000E +1 |
| | | XC (PLS1) | |
| PI | -6.6667E -2 | -2.8525E -2 | |
| | LT | | |
| | -1.0000E +0 | -9.0000E -1 | |
| | ZAZZ | | |
| | +1.0000E +0 | +9.0000E -1 | |
| | ZBZS | +1.0000E +0 | +1.5000E +1 |
| | | XC (PLS1) | |
| | -1.0000E +0 | +0.0000E +0 | |
| | SU | +1.0000E +0 | +1.6597E -7 |
| | | ZAZZ | |
| | | -1.0000E +0 | -1.6839E -7 |
| | | ZBZS | |
| | | -6.6667E -2 | -2.8525E -2 |
| | | LT | |

FIG. 6.8 (contd.)

| | | | |
|------|-------------|-------------|-------------|
| PCPC | +1.0000E +0 | +1.5697E +2 | |
| PI | | -1.0000E +0 | -9.0000E -1 |
| | | ZA73 | |
| | | +1.0000E +0 | +9.0000E -1 |
| | | 7875 | |
| | | -1.0000E +0 | +0.0000E +0 |
| | | SI | |
| LT | | | |
| Q401 | -1.0000E +0 | +0.0000E +0 | |
| QAP1 | | -1.0000E +0 | +0.0000E +0 |
| | | QAP1 | |
| | | -1.0000E +0 | -5.0000E +0 |
| | | QF05 | |
| TAT1 | | | |
| QCG3 | -1.0000E +0 | +0.0000E +0 | |
| PCP3 | | -1.0000E +0 | +0.0000E +0 |
| | | QCG3 | |
| | | -1.0000E +0 | -2.0000E +0 |
| | | QD (EXC1) | |
| TCT3 | | | |
| Q2PC | | | |
| Q4PD | | | |
| QF03 | +1.0000E +0 | +2.0888E +2 | |
| PCPC | | +1.0000E +0 | +1.5697E +2 |
| | | PI | |

FIG. 6.8 (contd.)

| | | | |
|------|---------------------------|--------------------------------------------------------------------------------------|--------------------------------------------------|
| | +1.00000E +0 PAPR | +3.11682E -2 +1.00000E +0 OR (MTF1) -1.00000E +0 OF28 | +1.00000E +0 -1.00000E +0 |
| | -1.00000E +0 PAPR | -3.10768E -2 | |
| PAPR | +1.00000E +0 OR (MTF1) | +1.00000E +0 +1.00000E +0 PAPD -1.00000E +0 OAPR | +2.94452E -2 -2.97578E -2 |
| | -1.00000E +0 QFUR | -1.00000E +0 +1.00000E +0 PCPC +1.00000E +0 PAPR -1.00000E +0 DFD3 | +2.98882E -2 +3.11682E -2 -3.10768E -2 |
| TFYB | +1.00000E +0 TB (MTF1) | +1.00000E +0 +1.00000E +0 TAYD | +1.00000E +0 |
| XFYB | +1.00000E +0 XAXR | +1.00000E +0 +1.00000E +0 XAXD | +1.00000E +0 |

FIG. 6.8 (contd.)

| | | | |
|------|--------------|--------------|--------------|
| SU | +1.00000E +0 | +1.67556E -7 | |
| | 7A21 | | |
| | -1.00000E +0 | -1.7277E -7 | |
| | 7B7C | +1.00000E +0 | +5.00000E +0 |
| | | OR (MTF1) | |
| | +2.00000E -1 | +7.9882E -3 | |
| | LT | | |
| PI | +1.00000E +0 | +4.00000E -3 | |
| | 7A21 | | |
| | -1.00000E +0 | -4.00000E -3 | |
| | 7B7C | +1.00000E +0 | +5.00000E +0 |
| | | OR (MTF1) | |
| | -1.00000E +0 | +0.00000E +0 | |
| | SU | +1.00000E +0 | +1.67556E -7 |
| | | 7A21 | |
| | | -1.00000E +0 | -1.7277E -7 |
| | | 7B7C | |
| | | +2.00000E -1 | +7.9882E -3 |
| | | LT | |
| PCDC | +1.00000E +0 | +1.5627E +2 | |
| | PI | +1.00000E +0 | +4.00000E -3 |
| | | 7A21 | |
| | | -1.00000E +0 | -4.00000E -3 |
| | | 7B7C | |
| | | -1.00000E +0 | +0.00000E +0 |
| | | SU | |

FIG. 6.8 (contd.)

| | | | | |
|-----------|-------------|-------------|-------------|--|
| LT | | | | |
| QE (MTF1) | +1.00000 +0 | +2.04458 -2 | | |
| | PAPB | +1.00008 +0 | +1.00008 +0 | |
| | | QAOB | | |
| | | -1.00008 +0 | -1.00008 +0 | |
| | | QB (MTF1) | | |
| | -1.00008 +0 | -2.07578 -2 | | |
| | PAPB | +1.00008 +0 | +1.00008 +0 | |
| | | QB (MTF1) | | |
| | | -1.00008 +0 | -1.00008 +0 | |
| | | QFQB | | |
| PAPB | +1.00008 +0 | +1.00008 +0 | | |
| | QAOB | +1.00008 +0 | +2.33828 +0 | |
| | | QSOA | | |
| | | -1.00008 +0 | -3.44458 -2 | |
| | | PAPB | | |
| | | +1.00008 +0 | +3.31458 -2 | |
| | | PSPB | | |
| | -1.00008 +0 | -1.00008 +0 | | |
| | QB (MTF1) | +1.00008 +0 | +2.04458 -2 | |
| | | PAPB | | |
| | | -1.00008 +0 | -2.97578 -2 | |
| | | PAPB | | |
| TB (MTF1) | +1.00008 +0 | +1.00008 +0 | | |
| | PATB | +1.00008 +0 | +1.00008 +0 | |

FIG. 6.8 (contd.)

TSTA

| | | | |
|----------|-------------|-------------|-------------|
| X4XJ | +1.00000 +0 | +1.00000 +0 | |
| | YAXD | +1.00000 +0 | +1.00000 +0 |
| | | XSYA | |
| ZB7C | +1.00000 +0 | +5.00000 +0 | |
| | UB (MTF1) | +1.00000 +0 | +2.04450 -2 |
| | | PAPD | |
| | | -1.00000 +0 | -2.07570 -2 |
| | | PAPB | |
| 176 Q4UP | +7.50000 -1 | +7.22500 -4 | |
| | PCPC | +1.00000 +0 | +1.57020 +2 |
| | | PI | |
| | +1.00000 +0 | +0.42000 -3 | |
| | QSPB | +1.00000 +0 | +5.00000 +0 |
| | | GP (DIV1) | |
| | | -1.00000 +0 | -5.00000 +0 |
| | | QAPB | |
| PAPJ | +1.00000 +0 | +5.00000 +0 | |
| | OR (DIV1) | +7.50000 -1 | +1.01550 -2 |
| | | PAPB | |
| | | -1.00000 +0 | -5.42500 -3 |
| | | PAPB | |
| | -1.00000 +0 | -5.00000 +0 | |

FIG. 6.8 (contd.)

| | | |
|------|--------------|-------------|
| QABR | +7.50000E -1 | +7.2255E -4 |
| | BCBI | |
| | +1.00000E +0 | +9.4283E -3 |
| | PAFE | |

| | | | |
|------|--------------|--------------|--------------|
| TATP | +1.00000E +0 | +1.00000E +0 | |
| | TATP | +1.00000E +0 | +1.00000E +0 |
| | | TATB | |

| | | | |
|------|--------------|--------------|--------------|
| XAXP | +1.00000E +0 | +1.00000E +0 | |
| | XAXP | +1.00000E +0 | +1.00000E +0 |
| | | XAXB | |

CHECK FOR GARBAGE
CHECK FOR GARBAGE
CHECK FOR GARBAGE
CHECK FOR GARBAGE
CHECK FOR GARBAGE

FIG. 6.8 (contd.)

PRINTREE OUTPUT

| | | | |
|----------|-------------|-------------|-------------|
| TC (FFB) | -1.00002 +0 | -1.54202-14 | |
| | TG (REB1) | -1.00002 +0 | -2.65662 +0 |
| | | YC (PLS2) | |
| | | +3.42222 -1 | -4.89602 +0 |
| | | TR (REB1) | |
| | | -1.00002 +0 | -2.03832 +3 |
| | | QG (REB1) | |
| | -3.42222 -1 | +7.00442-14 | |
| | TR (REB1) | -1.00002 +0 | -4.13222 +1 |
| | | YR (REB1) | |
| | +7.50002 -1 | +4.58462 -0 | |
| | LC (TAB1) | -3.42222 -1 | +1.47182 -3 |
| | | TR (REB1) | |
| | | -1.00002 +0 | -3.21242 -4 |
| | | TG (REB1) | |
| | | -1.00002 +0 | -1.06072 -3 |
| | | QC (DIV1) | |
| | | -1.00002 +0 | -1.06072 -3 |
| | | QB (DIV1) | |
| | +1.00002 +0 | +1.27002-1) | |
| | QB (DIV1) | +7.50002 -1 | +4.61072 -2 |
| | | LC (TAB1) | |
| | | -7.50002 -1 | -1.01552 -2 |
| | | QC (DIV1) | |
| | -1.00002 +0 | -7.07852 -5 | |
| | QB (MTF1) | | |

Alarm Tree Data from Plant Model

FIG. 6.9

| | | |
|-------------|-------------|-------------|
| -1.00000 +0 | -4.33048 -4 | |
| XC (PLS2) | -1.00000 +0 | -2.95718-15 |
| | OR (MTF1) | |
| | -1.00000 +0 | -4.81328-17 |
| | OR (DIV1) | |
| | -7.50000 -1 | -1.73758-15 |
| | IC (TAN1) | |
| | -3.42222 -1 | +2.17178 -7 |
| | TR (REF1) | |
| | -1.00000 +0 | -4.74008 -8 |
| | TG (REF1) | |
| | +1.00000 +0 | +5.45118-11 |
| | XC (PLS1) | |
| | +1.00000 +0 | +5.41018 -3 |
| | XR (REF1) | |
| -1.00000 +0 | -4.43838 -4 | |
| XC (PLS1) | +1.00000 +0 | +7.32048-11 |
| | XC (PLS2) | |
| | +1.00000 +0 | +1.19818-11 |
| | OR (MTF1) | |
| | +1.00000 +0 | +3.22898-10 |
| | TG (REF1) | |
| | -3.42222 -1 | -1.47048 -9 |
| | TR (REF1) | |
| | +1.00000 +0 | +3.86298 -4 |
| | OR (DIV1) | |
| | -7.50000 -1 | -6.57378 -4 |
| | IC (TAN1) | |
| | +1.00000 +0 | +2.21738 -3 |
| | XC (TAN1) | |

FIG. 6.9 (contd.)

| | | | |
|-----------|-------------|-------------|-------------|
| XC (PLS2) | -1.00002 +0 | -2.95718-19 | |
| | QB (TYPE1) | | |
| | -1.00002 +0 | -4.81322-17 | |
| | QB (DIV1) | +7.51102 -1 | +4.61672 -2 |
| | | LC (TAV1) | |
| | | -7.50002 -1 | -1.01552 -2 |
| | | QC (DIV1) | |
| | -7.50002 -1 | -1.73252-15 | |
| | LC (TAV1) | -3.42222 -1 | +1.47122 -3 |
| | | TR (REB1) | |
| | | -1.00002 +0 | -3.21242 -4 |
| | | TG (REF1) | |
| | | -1.00002 +0 | -1.06072 -3 |
| | | QC (DIV1) | |
| | | -1.00002 +0 | -1.06072 -3 |
| | | QB (DIV1) | |
| | -3.42222 -1 | +7.17172 -7 | |
| | TR (REB1) | -1.00002 +0 | -4.13222 +1 |
| | | YQ (REB1) | |
| | -1.00002 +0 | -4.74002 -3 | |
| | TG (REF1) | -1.00002 +0 | -2.65662 +0 |
| | | XC (PLS2) | |
| | | +3.42222 -1 | -4.89602 +0 |
| | | TR (REB1) | |
| | | -1.00002 +0 | -2.03832 +3 |
| | | QC (REB1) | |
| | +1.00002 +0 | +5.45112-11 | |
| | XC (PLS1) | +1.00002 +0 | +7.32942-11 |
| | | XC (PLS2) | |

FIG. 6.9 (contd.)

| | |
|-------------|--------------|
| +1.00000 +1 | +1.10318 -11 |
| OP (HTF1) | |
| +1.00000 +0 | +3.22202 -10 |
| TC (REF1) | |
| +3.42222 -1 | -1.47042 -9 |
| TR (REF1) | |
| +1.00000 +0 | +3.86292 -4 |
| OR (DIV1) | |
| -7.50000 -1 | -6.57372 -4 |
| LC (TAN1) | |
| +1.00000 +0 | +2.21732 -3 |
| XC (TAN1) | |

| | |
|-------------|--------------|
| +1.00000 +0 | +3.41012 -3 |
| AR (REF1) | |
| -7.14202 -1 | -0.84402 -20 |
| OB (DIV1) | |
| +5.35712 -1 | +1.16492 -19 |
| LC (TAN1) | |
| -7.14202 -1 | -1.09262 -16 |
| OB (MYF1) | |
| -2.44442 -1 | +1.75272 -7 |
| TR (REF1) | |
| -7.14202 -1 | -3.82542 -8 |
| TG (REF1) | |
| +7.14202 -1 | +2.01342 -8 |
| IR (REF1) | |
| -7.14202 -1 | -1.81002 -9 |
| OR (REF1) | |
| +1.00000 +0 | +8.76872 -3 |
| YC (PLS2) | |

| | | |
|-----------|-------------|-------------|
| TC (PLS2) | -1.00002 +0 | -3.80252 +1 |
|-----------|-------------|-------------|

FIG. 6.9 (contd.)

| | | |
|-----------|-------------|-------------|
| XC (PLS2) | -1.00000 +0 | -2.05718-19 |
| QB (DIV1) | -1.00000 +0 | -4.81322-17 |
| QB (DIV1) | -7.50000 -1 | -1.73752-15 |
| LC (TAN1) | -3.42722 -1 | +2.17178 -7 |
| TR (REF1) | -1.00000 +0 | -4.74008 -8 |
| TG (REF1) | +1.00000 +0 | +5.45118-11 |
| XC (PLS1) | +1.00000 +0 | +5.41918 -3 |
| XR (REF1) | | |
| XR (REF1) | -7.14292 -1 | -5.84408-20 |
| QB (DIV1) | +7.50000 -1 | +4.61678 -2 |
| LC (TAN1) | -7.50000 -1 | -1.01558 -2 |
| QB (DIV1) | | |
| LC (TAN1) | +5.35712 -1 | +1.16408-19 |
| LC (TAN1) | -3.42222 -1 | +1.47188 -3 |
| TR (REF1) | -1.00000 +0 | -3.21248 -4 |
| TG (REF1) | -1.00000 +0 | -1.06078 -3 |
| QB (DIV1) | -1.00000 +0 | -1.06078 -3 |
| QB (DIV1) | | |
| QB (DIV1) | -7.14292 -1 | -1.09268-16 |

FIG. 6.9 (contd.)

| | | |
|-------------|-------------|--------------|
| Q3 (ITE1) | | |
| -2.44442 -1 | +1.75272 -7 | |
| TR (REF1) | -1.00002 +0 | -4.13222 +1 |
| | XP (REF1) | |
| -7.14292 -1 | -3.82542 -8 | |
| TG (REF1) | -1.00002 +0 | -2.65662 +0 |
| | XC (PLS2) | |
| | +3.42222 -1 | -4.89602 +0 |
| | TP (REF1) | |
| | -1.00002 +0 | -2.03832 +3 |
| | QG (REF1) | |
| +7.14292 -1 | +2.01342 -9 | |
| LR (REF1) | +1.00002 +0 | +1.43702 -15 |
| | QB (DIV1) | |
| | +7.50002 -1 | +5.18752 -14 |
| | IC (TAN1) | |
| | +1.00002 +0 | +3.80002 -5 |
| | OB (REF1) | |
| | +1.00002 +0 | +8.03112 -4 |
| | TG (REF1) | |
| | +3.42222 -1 | -3.67952 -3 |
| | TP (REF1) | |
| | +1.00002 +0 | +2.20372 -12 |
| | OR (ITE1) | |
| -7.14292 -1 | -1.81062 -9 | |
| OB (REF1) | +1.00002 +0 | +3.32492 -1 |
| | IR (REF1) | |
| | -1.00002 +0 | -1.04302 -1 |
| | XP (REF1) | |

FIG. 6.9 (contd.)

| | | |
|-------------|-------------|--------------|
| +1.00000 +0 | +8.76878 -3 | |
| XC (PLS2) | -1.00000 +0 | -2.95718 -19 |
| | OP (MTF1) | |
| | -1.00000 +0 | -4.81328 -17 |
| | OR (DIV1) | |
| | -7.50000 -1 | -1.73758 -15 |
| | IC (TAN1) | |
| | -3.42222 -1 | +2.17178 -7 |
| | TR (REF1) | |
| | -1.00000 +0 | -4.74008 -8 |
| | TG (REF1) | |
| | +1.00000 +0 | +5.45118 -11 |
| | XC (PLS1) | |
| | +1.00000 +0 | +5.41018 -3 |
| | XP (REF1) | |

| | | | |
|-----------|-------------|--------------|-------------|
| LR (REF1) | +1.00000 +0 | +1.43708 -15 | |
| | QB (DIV1) | -7.50000 -1 | +4.61678 -2 |
| | | IC (TAN1) | |
| | | -7.50000 -1 | -1.01558 -2 |
| | | OC (DIV1) | |
| | +7.50000 -1 | +5.18758 -14 | |
| | LC (TAN1) | -3.42222 -1 | +1.47188 -3 |
| | | TP (REF1) | |
| | | -1.00000 +0 | -3.21248 -4 |
| | | TG (REF1) | |
| | | -1.00000 +0 | -1.06978 -3 |
| | | OC (DIV1) | |
| | | -1.00000 +0 | -1.06978 -3 |
| | | QB (DIV1) | |

FIG. 6.9 (contd.)

| | | |
|--------------|--------------|--------------|
| +1.00000E +0 | +3.80000E -5 | |
| QB (REF1) | +1.00000E +0 | +3.3249E -1 |
| | LR (REF1) | |
| | -1.00000E +0 | -1.0439E -1 |
| | YR (REF1) | |
| +1.00000E +0 | +5.0311E -4 | |
| TG (REF1) | -1.00000E +0 | -2.6540E +0 |
| | XC (PLS2) | |
| | +3.4222E -1 | -4.8960E +0 |
| | TR (REF1) | |
| | -1.00000E +0 | -2.0383E +3 |
| | QG (REF1) | |
| +3.4222E -1 | -3.6705E -3 | |
| TR (REF1) | -1.00000E +0 | -4.1322E +1 |
| | YP (REF1) | |
| +1.00100E +0 | +2.2937E -12 | |
| QB (MTF1) | | |
| TR (REF1) | -1.00000E +0 | -4.1322E +1 |
| | XR (REF1) | -6.8449E -20 |
| | QB (DIV1) | |
| | +5.3571E -1 | +1.1649E -19 |
| | IC (TAN1) | |
| | -7.1420E -1 | -1.0926E -16 |
| | QB (MTF1) | |
| | -2.4444E -1 | +1.7527E -7 |
| | TR (REF1) | |
| | -7.1420E -1 | -3.8254E -8 |
| | TG (REF1) | |
| | +7.1420E -1 | +2.9134E -8 |

FIG. 6.9 (contd.)

IR (REF1)
 -7.14228 -1 -1.81008 -9
 Q2 (REF1)
 +1.00008 +0 +2.76878 -3
 XC (PLS2)

QB (REF1) +1.00008 +0 +3.32408 -1
 LR (REF1) +1.00008 +0 +1.43708 -15
 OR (DIV1)
 +7.50008 -1 +5.18758 -14
 IC (TAN1)
 +1.00008 +0 +3.80008 -5
 OR (REF1)
 +1.00008 +0 +8.03118 -4
 TG (REF1)
 +3.42228 -1 -3.67958 -3
 TR (REF1)
 +1.00008 +0 +2.29378 -12
 QB (MTF1)

-1.00008 +0 -1.04398 -1
 XR (REF1) -7.14228 -1 -0.84498 -20
 OR (DIV1)
 +5.35718 -1 +1.16498 -19
 LC (TAN1)
 -7.14228 -1 -1.09268 -16
 QB (MTF1)
 -2.44468 -1 +1.75278 -7
 TR (REF1)
 -7.14228 -1 -3.82548 -8
 TG (REF1)
 +7.14228 -1 +2.01348 -8

FIG. 6.9 (contd.)

IR (REB1)
 -7.1420E -1 -1.3100E -9
 OR (REB1)
 +1.0000E +0 +8.7687E -3
 XC (PLS2)

QG (REB1) -1.0000E +0 -1.0985E -1
 XC (PLS2) -1.0000E +0 -2.0571E -19
 OR (MTF1)
 -1.0000E +0 -4.8132E -17
 OR (DIV1)
 -7.5000E -1 -1.7375E -15
 IC (TAN1)
 -3.4222E -1 +2.1717E -7
 TR (REB1)
 -1.0000E +0 -4.7400E -8
 TG (REB1)
 +1.0000E +0 +5.4511E -11
 XC (PLS1)
 +1.0000E +0 +5.4101E -3
 XR (REB1)

TG (REB1) -1.0000E +0 -2.6560E +0
 XC (PLS2) -1.0000E +0 -2.0571E -19
 OR (MTF1)
 -1.0000E +0 -4.8132E -17
 OR (DIV1)
 -7.5000E -1 -1.7375E -15
 IC (TAN1)
 -3.4222E -1 +2.1717E -7
 TR (REB1)

FIG. 6.9 (contd.)

| | | | |
|-----------|-------------|--------------|--------------|
| | | -1.00000 +0 | -4.74000 -8 |
| | | TG (REB1) | |
| | | +1.00000 +0 | +5.45110 -11 |
| | | XC (PLS1) | |
| | | +1.00000 +0 | +5.41010 -3 |
| | | XR (REB1) | |
| | +3.42220 -1 | -4.80600 +0 | |
| | TR (REB1) | -1.00000 +0 | -4.13220 +1 |
| | | XR (REB1) | |
| | -1.00000 +0 | -2.03830 +3 | |
| | QG (REB1) | -1.00000 +0 | -1.09850 -1 |
| | | XC (PLS2) | |
| XC (PLS1) | +1.00000 +0 | +7.32040 -11 | |
| | XC (PLS2) | -1.00000 +0 | -2.95710 -19 |
| | | QB (MTF1) | |
| | | -1.00000 +0 | -4.81320 -17 |
| | | QB (DIV1) | |
| | | -7.50000 -1 | -1.73750 -15 |
| | | IC (TAN1) | |
| | | -3.42220 -1 | +2.17170 -7 |
| | | TR (REB1) | |
| | | -1.00000 +0 | -4.74000 -8 |
| | | TG (REB1) | |
| | | +1.00000 +0 | +5.45110 -11 |
| | | XC (PLS1) | |
| | | +1.00000 +0 | +5.41010 -3 |
| | | XR (REB1) | |
| | +1.00000 +0 | +1.19310 -11 | |

FIG. 6.9 (contd.)

| | | |
|-------------|--------------|-------------|
| QA (MTF1) | | |
| +1.00000 +1 | +3.22800 -10 | |
| TG (REF1) | -1.00000 +0 | -2.65660 +0 |
| | XC (PLS2) | |
| | +3.42228 -1 | -4.89600 +0 |
| | TP (REF1) | |
| | -1.00000 +0 | -2.03830 +3 |
| | OG (REB1) | |
| +2.42220 -1 | -1.47940 -0 | |
| TR (REF1) | -1.00000 +0 | -4.13220 +1 |
| | XR (REF1) | |
| +1.00000 +0 | +3.26290 -4 | |
| QR (DIV1) | +7.50000 -1 | +4.61670 -2 |
| | IC (TAN1) | |
| | -7.50000 -1 | -1.01550 -2 |
| | QC (DIV1) | |
| -7.50000 -1 | -6.57370 -4 | |
| LC (TAN1) | -7.42220 -1 | +1.47180 -3 |
| | TR (REB1) | |
| | -1.00000 +0 | -3.21240 -4 |
| | TG (REF1) | |
| | -1.00000 +0 | -1.06070 -3 |
| | QC (DIV1) | |
| | -1.00000 +0 | -1.06070 -3 |
| | QR (DIV1) | |
| +1.00000 +0 | +2.21730 -3 | |
| XC (TAN1) | +2.28150 -2 | -2.47840 -6 |
| | TR (REB1) | |
| | +6.66670 -2 | +5.40930 -7 |

FIG. 6.9 (contd.)

| | |
|-------------|-------------|
| TG (REF1) | |
| +1.00000 +0 | +1.62428 -3 |
| XC (PLS1) | |
| +6.66678 -2 | +1.74458 -5 |
| IC (TAN1) | |

| | | | |
|-----------|-------------|-------------|--------------|
| TC (PLS1) | -1.00000 +0 | -2.34298 +1 | |
| | XC (PLS1) | +1.00000 +0 | +7.32048 -11 |
| | | XC (PLS2) | |
| | | +1.00000 +0 | +1.19818 -11 |
| | | OR (MTF1) | |
| | | +1.00000 +0 | +3.22398 -10 |
| | | TG (REF1) | |
| | | +3.42222 -1 | -1.47048 -9 |
| | | TR (REF1) | |
| | | +1.00000 +0 | +3.86298 -4 |
| | | OR (DIV1) | |
| | | -7.50000 -1 | -6.57378 -4 |
| | | IC (TAN1) | |
| | | +1.00000 +0 | +2.21738 -3 |
| | | XC (TAN1) | |

| | | | |
|-----------|-------------|-------------|-------------|
| QD (EX01) | | | |
| TD (EX01) | -3.42222 -1 | +7.34718 +0 | |
| | TR (REF1) | -1.00000 +0 | -4.13228 +1 |
| | | XP (REF1) | |
| | -1.00000 +0 | -1.60368 +0 | |
| | TG (REF1) | -1.00000 +0 | -2.65668 +0 |
| | | XC (PLS2) | |
| | | +3.42222 -1 | -4.80608 +0 |

FIG. 6.9 (contd.)

| | | | |
|-----------|-------------|-------------|-------------|
| | | TP (REF1) | |
| | | -1.00002 +0 | -2.03832 +3 |
| | | OG (REF1) | |
| | | -1.00002 -1 | 25.22732 +1 |
| | | OD (REF1) | |
| LC (TAN1) | -3.42222 -1 | +1.47152 -3 | |
| | TR (REF1) | -1.00002 +0 | -4.13222 +1 |
| | | XP (REF1) | |
| | | -1.00002 +0 | -3.21242 -4 |
| | YG (REF1) | -1.00002 +0 | -2.65662 +0 |
| | | XC (PLS2) | |
| | | +3.42222 -1 | -4.39602 +0 |
| | | TX (REF1) | |
| | | -1.00002 +0 | -2.03832 +3 |
| | | OG (REF1) | |
| | | -1.00002 +0 | -1.06972 -3 |
| | QC (DIV1) | +1.00002 +0 | +1.31172 -2 |
| | | YC (PLS1) | |
| | | +7.33332 -1 | +2.11602 -4 |
| | | IC (TAN1) | |
| | | -1.00002 +0 | -1.11142 -3 |
| | | OB (DIV1) | |
| | | -1.00002 +0 | -1.06972 -3 |
| | QB (DIV1) | +7.50002 -1 | +4.61672 -2 |
| | | IC (TAN1) | |
| | | -7.50002 -1 | -1.01552 -2 |
| | | QC (DIV1) | |

FIG. 6.9 (contd.)

| | | | |
|-----------|-------------|-------------|-------------|
| TC (TAN1) | +6.54448 -2 | +5.62058 -4 | |
| TR (REB1) | -1.00000 +0 | -4.13228 +1 | |
| | | XP (REB1) | |
| | +2.00000 -1 | -1.22638 -4 | |
| YG (REB1) | -1.00000 +0 | -2.65668 +0 | |
| | | XC (PLS2) | |
| | | +3.42228 -1 | -4.80608 +0 |
| | | TR (REB1) | |
| | | -1.00000 +0 | -2.03338 +3 |
| | | OG (REB1) | |
| | +1.00000 -0 | +3.04758 -3 | |
| TC (PLS1) | -1.00000 +0 | -2.34298 +1 | |
| | | XC (PLS1) | |
| | -4.66678 -1 | -1.17618 -2 | |
| LC (TAN1) | -3.42228 -1 | +1.47188 -3 | |
| | | TR (REB1) | |
| | | -1.00000 +0 | -3.21248 -4 |
| | | TG (REB1) | |
| | | -1.00000 +0 | -1.06978 -3 |
| | | OC (DIV1) | |
| | | -1.00000 +0 | -1.06078 -3 |
| | | OB (DIV1) | |
| XC (TAN1) | +2.28158 -2 | -2.47848 -6 | |
| TR (REB1) | -1.00000 +0 | -4.13228 +1 | |
| | | XP (REB1) | |
| | +6.66678 -2 | +5.40938 -7 | |

FIG. 6.9 (contd.)

| | | |
|-------------|-------------|--------------|
| TG (REF1) | -1.0000E +0 | -2.6566E +0 |
| | XC (PLS2) | |
| | +3.4222E -1 | -4.8960E +0 |
| | TR (REF1) | |
| | -1.0000E -0 | -2.0383E +3 |
| | QG (REF1) | |
| +1.0000E +0 | +1.6242E -3 | |
| XC (PLS1) | +1.0000E +0 | +7.3294E -11 |
| | XC (PLS2) | |
| | +1.0000E +0 | +1.1981E -11 |
| | OR (MTF1) | |
| | +1.0000E +0 | +3.2280E -10 |
| | TG (PER1) | |
| | +3.4222E -1 | -1.4794E -9 |
| | TR (PER1) | |
| | +1.0000E +0 | +3.3629E -4 |
| | OR (DIV1) | |
| | -7.5000E -1 | -6.5737E -4 |
| | LC (TAN1) | |
| | +1.0000E +0 | +2.2173E -3 |
| | YC (TAN1) | |
| +1.6667E -2 | +1.7445E -5 | |
| LC (TAN1) | -3.4222E -1 | +1.4718E -3 |
| | TR (REF1) | |
| | -1.0000E +0 | -3.2124E -4 |
| | TG (REF1) | |
| | -1.0000E +0 | -1.0607E -3 |
| | QC (DIV1) | |
| | -1.0000E +0 | -1.0697E -3 |
| | QB (DIV1) | |

FIG. 6.9 (contd.)

| | | | |
|-----------|-------------|-------------|--------------|
| QB (DIV1) | +7.5000E -1 | -4.6167E -2 | |
| LC (TAN1) | | -3.4222E -1 | +1.4718E -3 |
| | | TP (REF1) | |
| | | -1.0000E +0 | -3.2124E -4 |
| | | TG (REF1) | |
| | | -1.0000E +0 | -1.0607E -3 |
| | | QC (DIV1) | |
| | | -1.0000E +0 | -1.0607E -3 |
| | | OB (DIV1) | |
| | | | |
| | -7.5000E -1 | -1.0155E -2 | |
| | QC (DIV1) | +1.0000E +0 | +1.3117E -2 |
| | | XC (PLS1) | |
| | | +7.3333E -1 | +2.1160E -4 |
| | | LC (TAN1) | |
| | | -1.0000E +0 | -1.1114E -3 |
| | | OB (DIV1) | |
| | | | |
| QC (DIV1) | +1.0000E +0 | +1.3117E -2 | |
| | XC (PLS1) | +1.0000E +0 | +7.3294E -11 |
| | | XC (PLS2) | |
| | | +1.0000E +0 | +1.1081E -11 |
| | | OP (MTF1) | |
| | | +1.0000E +0 | +3.2289E -10 |
| | | TG (REF1) | |
| | | +3.4222E -1 | -1.4704E -0 |
| | | TR (REF1) | |
| | | +1.0000E +0 | +3.8629E -4 |
| | | OP (DIV1) | |
| | | -7.5000E -1 | -6.5737E -4 |
| | | LC (TAN1) | |

FIG. 6.9 (contd.)

+1.0000E +0 +2.2173E -3
XC (TAN1)

+7.3333E -1 +2.1140E -4
LC (TAN1) -3.4222E -1 +1.4718E -3
TR (REF1)
-1.0000E +0 -3.2124E -4
TG (RES1)
-1.0000E +0 -1.0607E -3
QC (DIV1)
-1.0000E +0 -1.0607E -3
QB (DIV1)

-1.0000E +0 -1.1114E -3
QB (DIV1) +7.5000E -1 +4.6167E -2
IC (TAN1)
-7.5000E -1 -1.0155E -2
QC (DIV1)

QB (ITE1)
TB (ITE1)

FIG. 6.9 (contd.)

It may be noted that mechanical faults do not fit directly into the tree which represents links between the variables equipped with alarms. The bare tree structure produced in this way is only useful for finding the cause-and-effect links between the alarms and to thereby direct the operator's attention to the prime cause alarm. If this is not considered sufficient for the operator to trace the fault itself, then a deduced alarm must be provided for the fault. The method of storage of deduced alarm symptoms used for the present study allows all deduced alarms involving a variable to be accessed from the corresponding node. In this way, all relevant deduced alarms may be quickly checked when an alarm becomes active.

6.6 Summary of Procedure for Full-Equation Models

The following steps outline the complete procedure to be used if full-equation models are used with the programs described in this work:

1. Split plant into units and identify each unit with a unique 4-character name. Similar units may be denoted by using names consisting of two or three common characters followed by a number, e.g. CVO1, CVO2.

For each unit type:

- 1) Identify each stream entering or leaving unit by means of a unique 1-character name.
- 11) Identify all variables relevant to each unit.

Each variable must be set in one of the units of

the model. Use the convention defined in Chapter 4 to find those variables that are set in the unit. Each variable is given a 2-character name. For variables in streams, the second character in the variable name is the same as the stream name.

- 111) Define equation for each variable set in unit in terms of other variables and constants (i.e. quantities not set in any unit. Note that constants have the same 2-character form as variables).

- 2. Define measured variables and choose those to be equipped with alarms. For each variable with alarms:
 - i) Choose alarm type,
 - ii) Choose alarm levels,
- 3. Find steady state data - this will normally be obtained from the plant flow-sheet and design data.
- 4. Put data into form required by programs. All data formats are given in Appendix 2.
- 5. Run programs to check steady-state data and test system response to various inputs. If deduced alarms are to be found by simulation, this is also done at this stage.
- 6. Run programs to set up alarm tree from plant model. Any deduced alarm symptoms found either by simulation during other

program runs or by intuitive methods may be inserted before or after this step.

7. Run test programs to check alarm tree data if desired.
8. Run further program to convert alarm-tree data into form suitable for on-line machine.

The last step has not been done for the present study.

C H A P T E R 7

THE USE OF ENHANCED FUNCTIONAL MODELS

7.1 Introduction

In Chapter 3, it was noted that "functional" models contain the basic cause-and-effect data needed for alarm analysis and that "enhanced functional" models also contained directional information. The use of models of this type is attractive because the model formulation may be carried out far more rapidly than for the corresponding full-equation model. The disadvantages are:-

- i) Functional models cannot be easily tested. The engineer must ensure that the model is correctly formulated.
- ii) Time-ordered deduced alarm symptoms cannot be found by simulation. If deduced alarms are to be incorporated into the alarm analysis scheme, they must be found intuitively.
- iii) The alarm-analysis data produced by the program cannot be tested, although visual inspection of the data produced for alarm analysis may be sufficient to detect major errors.

It was decided to include facilities in the alarm analysis programs that would enable functional models to be handled. For the sake of generality, the enhanced functional model was chosen. The cost of adding the required directional information to the basic functional model is low and the benefit is high. Most of the program facilities needed to produce alarm analysis data from enhanced functional models

have already been noted in the preceding three Chapters. Only differences in the use of these common facilities will be considered in detail here.

7.2 Model Formulation

The modular method described in Chapter 4 forms the basis of the modelling method used. The conventions adopted for the setting of variables in unit input or output streams is also retained. In order to make use of the program facilities provided for full-equation models, it was necessary to define the enhanced functional model equations in the form shown in Fig. 7.1 for the example of Fig. 6.1.

Note that, for the functional model:

- 1) The constants K_1 , K_2 , K_4 , A_T , L_{\max} and $\frac{1}{2}$ from the full-equation model are absent.
- ii) Three new constants A_W , S_W and Z_0 are included. These have the values +1, -1 and 0 respectively and are used to define the directional information associated with the variable preceding them in the function. These constants will be known as "directional constants". The user may define other directional constants, if needed for special cases.
- iii) The variable and directional constant are "paired" by the use of the standard arithmetic priorities of * and +.
- iv) The capacitance terms in the second function, Q_A and L_B , are denoted by their pairing with the directional constant Z_0 .

Full Equation Model:

$$\frac{dL_B}{dt} = (Q_A - Q_C)/A_T$$

$$\frac{dT_C}{dt} = Q_A(T_A - T_C)/(A_T/L_B)$$

$$P_A = \frac{K_4 T_C}{A_T(L_{\max} - L_B)}$$

$$P_B = P_A + K_1 L_B$$

$$Q_C = K_2(P_B - P_C)^{\frac{1}{2}}$$

Enhanced Functional Model:

$$\frac{dL_B}{dt} = (Q_A * A_W + Q_C * S_W)$$

$$\frac{dT_C}{dt} = (T_A * A_W + Q_A * Z_O + L_B * Z_O)$$

$$P_A = (T_C * A_W + L_B * A_W)$$

$$P_B = (P_A * A_W + L_B * A_W)$$

$$Q_C = (P_B * A_W + P_C * S_W)$$

FIG. 7.1

Comparison between full-equations and Enhanced Functional
Models of Mixing Tank shown in Fig 6.1

If desired, these terms may be omitted completely so that the function would become:

$$\frac{d T_c}{dt} = (T_A * P_W)$$

- v) The use of parentheses to draw attention to the fact that a function, rather than an equation, is being specified. The use of brackets for this purpose is not mandatory for program use (since the brackets do not affect the operator priorities in this situation, the program will merely discard them).

The keyword MASTERMODEL is used to assemble the model within core store as described in Chapter 4. The use of dollarword COMMONVARS is convenient for defining the directional constants A_W , S_W (and any others required by the user) and making the constants available to all units in the model. These facilities are described in Appendix Section A.2.2.

Keyword SYSTEMDATA may then be used to give values to the directional constants defined as above. This keyword is described in Section A.2.2.

Keyword PRINTMODELS may be used to produce a record of the model assembled by the program if required although this facility is not particularly useful for functional models. The keyword is described in Section A.2.7.

7.3 Definition of Alarms and Deduced Alarm Symptoms

The variables to be equipped with alarms may be defined using keyword ADDALARMS as described in Section A.2.2. For the present study, definitions of the alarm types and levels were not necessary since no testing of this form of model was possible but, if the data produced by the program were to be transferred directly to an on-line machine, then the alarm types and levels could be specified at this stage in the normal way. For the same reasons, it might be convenient to specify any deduced alarm symptoms (found intuitively) at this stage. The use of keyword INPUTCHECKS, described in Section A.2.3, enables the user to carry out this function in exactly the same way as for full-equation models.

The deduced alarm symptoms stored by the program may be printed out, as a check, by the use of keyword PRINTUNIEFS as described in Section A.2.7.

7.4 Production of Alarm Tree

In order to produce the alarm tree from the model in this form, an extra keyword is required. This keyword is needed to inform the program that the model used is in functional form and that the directional data is therefore obtained from the directional constants rather than by perturbation of the variables in the model. The keyword, FUNCMODELS, corresponds to a boolean variable in the program which is normally set to FALSE. The keyword is inserted in the data, followed by at least two spaces (to make its length up to the 12 characters read by the program when expecting a keyword) and a T.

The keywords SETUPTREE, ALTERNETREE and PRINTREE are used in the same manner as for full-equation models. These keywords are all described in Section A.2.5.

7.5 Example of Program Use

As an example, consider the plant section of Fig. 4.4. The plant is again split into the units as shown in Fig. 4.5. The data required by procedure LISTUNIT (called after use of keyword MASTERMODEL) is the same as for the full-equation model and the output produced by the program is as shown in Fig. 4.6. The second part of the data used with keyword MASTERMODEL consists of the functional model relations. The program output for this data is shown in Fig. 7.2. Comparison of the functions shown in this output with that given in Fig. 4.7 shows the correspondence between the two types of model used. For convenience, the functions are given in the same order as the equations in Fig. 4.7.

The data for the directional constants is fed in using the keyword SYSTEMDATA. The program output is shown in Fig. 7.3. The same alarm data is used as for the full-equation model and the program output is therefore as in Fig. 5.3. The keyword corresponding to this output is ADDALARMS. The next four data cards contain the keywords FUNCMODELS, SETUPTREE, ALTERNETREE and PRINTREE. The program output corresponding to the last keyword is shown in Fig. 7.4. It may be seen that the output is similar to that shown in Fig. 6.9 except that the second of the two real numbers associated with each branch is always zero. This field is intended to contain some quantitative measure of the relationship between the two variables at the ends of the

FIG. 7.2

MASTERMODEL output for Enhanced Functional Model

| LISTUNIT OUTPUT | | | | |
|-----------------|-----------------|---------------|------------------------|---|
| UNIT NAME | INPUT OR OUTPUT | POINT ON UNIT | LINKED WITH UNIT POINT | |
| FEED | INPUT | F | CV01 | B |
| | | A | PL01 | C |
| | | D | PL02 | B |
| | OUTPUT | B | PL01 | D |
| | | C | PL02 | A |
| PL01 | INPUT | D | FEED | B |
| | | A | PLS1 | C |
| | OUTPUT | B | PLS1 | D |
| | | C | FEED | A |
| OUT1 | OUTPUT | A | CEN1 | S |
| PL02 | INPUT | A | FEED | C |
| | | D | PLS2 | B |
| | OUTPUT | B | FEED | D |
| | | C | PLS2 | A |
| PLS2 | INPUT | A | PL02 | C |
| | | D | REB1 | D |
| | OUTPUT | B | PL02 | D |
| | | S | CR04 | B |
| | | C | REB1 | C |
| REB1 | INPUT | C | PLS2 | C |
| | | F | CV04 | B |
| | OUTPUT | G | OUT3 | 2 |
| | | D | PLS2 | D |

FIG. 7.2

MASTER MODEL output for Enhanced Functional Model

| LISTUNIT OUTPUT | | | | |
|-----------------|-----------------|---------------|------------------------|---|
| UNIT NAME | INPUT OR OUTPUT | POINT ON UNIT | LINKED WITH UNIT POINT | |
| FEED | INPUT | F | CV01 | B |
| | | A | PL01 | C |
| | | D | PL02 | B |
| | OUTPUT | B | PL01 | D |
| | | C | PL02 | A |
| | | | | |
| PL01 | INPUT | D | FEED | B |
| | | A | PLS1 | C |
| | OUTPUT | B | PLS1 | D |
| | | C | FEED | A |
| OUT1 | OUTPUT | A | CEN1 | S |
| PL02 | INPUT | A | FEED | C |
| | | D | PLS2 | B |
| | OUTPUT | B | FEED | D |
| | | C | PLS2 | A |
| PLS2 | INPUT | A | PL02 | C |
| | | D | REB1 | D |
| | OUTPUT | B | PL02 | D |
| | | S | CR04 | B |
| | | C | REB1 | C |
| REB1 | INPUT | C | PLS2 | C |
| | | F | CV04 | B |
| | OUTPUT | G | OUT3 | 2 |
| | | D | PLS2 | D |

| | | | | |
|------|--------|---|------|---|
| | | R | CR05 | B |
| | | B | CV05 | A |
| SETC | OUTPUT | 1 | CR01 | A |
| | | 2 | CR02 | A |
| | | 3 | CR03 | A |
| | | 4 | CR04 | A |
| | | 5 | CR05 | A |
| CR04 | INPUT | A | SETC | 4 |
| | | B | PLS2 | S |
| | OUTPUT | C | CV04 | C |
| CV04 | INPUT | A | OUT2 | 1 |
| | | C | CR04 | C |
| | OUTPUT | B | REB1 | F |
| CR05 | INPUT | A | SETC | 5 |
| | | B | PEB1 | R |
| | OUTPUT | C | CV05 | C |
| CV05 | INPUT | A | REB1 | B |
| | | C | CR05 | C |
| | OUTPUT | B | OUTF | B |
| OUTF | INPUT | B | CV05 | B |
| | | D | CV03 | B |
| CEN1 | INPUT | S | OUT1 | A |
| | OUTPUT | D | MTF1 | A |
| PLS1 | INPUT | A | CV02 | B |
| | | D | PL01 | B |

FIG. 7.2 (contd.)

| | | | | |
|------|--------|---|------|---|
| | OUTPUT | B | EX01 | A |
| | | C | PL01 | A |
| | | S | CR03 | B |
| EX01 | INPUT | A | PLS1 | B |
| | | C | OUT2 | 3 |
| | OUTPUT | B | TAN1 | A |
| | | D | OUT3 | 4 |
| TAN1 | INPUT | A | EX01 | B |
| | OUTPUT | B | DIV1 | A |
| | | S | CR02 | B |
| CR02 | INPUT | A | SETC | 2 |
| | | B | TAN1 | S |
| | OUTPUT | C | CV02 | C |
| DIV1 | INPUT | A | TAN1 | B |
| | OUTPUT | B | CV02 | A |
| | | C | CV03 | A |
| CV03 | INPUT | A | DIV1 | C |
| | | C | CR03 | C |
| | OUTPUT | B | OUTF | D |
| CR03 | INPUT | A | SETC | 3 |
| | | B | PLS1 | S |
| | OUTPUT | C | CV03 | C |
| OUT2 | OUTPUT | 1 | CV04 | A |
| | | 3 | EX01 | C |
| OUT3 | INPUT | 2 | REB1 | G |

FIG. 7.2 (contd.)

| | | | | |
|------|--------|---|------|---|
| | | 4 | EX01 | D |
| CV01 | INPUT | A | MTF1 | R |
| | | C | CR01 | C |
| | OUTPUT | R | FEED | F |
| CR01 | INPUT | A | SETC | 1 |
| | | B | MTF1 | C |
| | OUTPUT | C | CV01 | C |
| MTF1 | INPUT | A | CEN1 | D |
| | | B | CV01 | A |
| | OUTPUT | C | CR01 | B |
| CV02 | INPUT | A | DIV1 | B |
| | | C | CR02 | C |
| | OUTPUT | B | PLS1 | A |

FIG. 7.2 (contd.)

READMODEL PRINTOUT

FEFD

PL01

OUT1

PL02

PLS2

RES1

SETC

CR04

CV04

CR05

CV05

OUTF

CEN1

210

FIG. 7.2 (contd.)

PLS1

EX01

TAN1

VARIABLES COMMON TO ABOVE UNITS:

AW ,SW

211

CR02

DIV1

CV03

CR03

OUT2

OUT3

CV01

CR01

MTF1

CV02

FIG. 7.2 (contd.)

VARIABLES COMMON TO ABOVE UNITS:

AA, SW

CV01

CV02

CV03

CV04

CV05

$QB+(PA*AW+PF*SW+PC*AJ)$

$D(PA)/DT+(QA*AW+QB*SW)$

$TB+(TA*AW)$

$XB+(XA*AJ)$

FEED

$D(XC)/DT+(QD*AW+XD*AW+QF*AJ+XF*AW+QA*AW+QB*SW+XR*SW)$

$D(QC)/DT+(QA*AW+QE*AW+QC*SW)$

$TC+(XC*SW)$

$XB+(XC*AW)$

$QB+(QD*AW)$

$TB+(TC*AW)$

$XE+(XF*AW)$

$QE+(QF*AW+XF*AW)$

FIG. 7.2 (contd.)

PF←KP

CEN1

$QD \leftarrow (QS \cdot AW + PC \cdot SW + PS \cdot AW)$
 $D(PS)/DT \leftarrow (QS \cdot AU + QD \cdot SU)$
 $XD \leftarrow (XS \cdot AW)$
 $TD \leftarrow (TS \cdot AW)$

PL01

PL02

PLS1

PLS2

$D(XC)/DT \leftarrow (QD \cdot AW + XD \cdot AJ + ZA \cdot AU + XA \cdot AW + QB \cdot SW + XB \cdot SW)$
 $D(OC)/DT \leftarrow (QA \cdot AW)$
 $TC \leftarrow (XC \cdot SW)$
 $XB \leftarrow (XC \cdot AW)$
 $ZS \leftarrow (XC \cdot AW)$
 $QB \leftarrow (QD \cdot AJ)$
 $TB \leftarrow (TC \cdot AW)$

CR01

CR04

$PC \leftarrow (ZA \cdot AW + TB \cdot SW)$

FIG. 7.2 (contd.)

CR02

CR03

CP05

PC+(ZA*SW+ZF*AU)

MTF1

QB+(PA*AW+PB*SW)
D(PA)/DT+(QA*AU+QB*SW)
TB+(TA*AW)
XB+(XA*AU)
ZC+(QB*AW)

REB1

D(XF)/DT+(QC*AW+XC*AU+XD*SW+XD*SW+HR*ZO)
D(HR)/DT+(QC*AU+QD*SW+QR*SW)
LP+(HR*AU)
TR+(XP*SW)
QR+(LR*AW+PE*SW)
FF+(TF*AW+TP*AU+TG*SW)
EC+(TF*AW+TC*SW+FF*SW)
XD+(XR*AW)
QD+(EC*AW)
TD+(TR*AW)
ZR+(LR*AW)

FIG. 7.2 (contd.)

$QB \leftarrow (QR * AW + XP * SW)$
 $TB \leftarrow (TR * AU)$
 $XB \leftarrow (XR * AU)$
 $D(PF) / DT \leftarrow (QF * AW + QG * SW)$
 $QG \leftarrow (PF * AU + PG * SW)$
 $TG \leftarrow (QF * AU + TF * AW + EC * SW + QG * SW)$

DIV1

$QB \leftarrow (PA * AU + PB * SW)$
 $QC \leftarrow (PA * AU + PC * SW)$
 $D(PA) / DT \leftarrow (QA * AU + QB * SW + QC * SW)$
 $TB \leftarrow (TA * AU)$
 $TC \leftarrow (TA * AU)$
 $XB \leftarrow (XA * AU)$
 $XC \leftarrow (XA * AU)$

TAN1

$D(LC) / DT \leftarrow (QA * AU + QB * SW)$
 $D(TC) / DT \leftarrow (QA * ZQ + TA * AU + IC * ZQ)$
 $D(XC) / DT \leftarrow (QA * ZQ + XA * AU + IC * ZQ)$
 $QB \leftarrow (PA * AU + LC * AU + PB * SW)$
 $TB \leftarrow (TC * AU)$
 $XB \leftarrow (XC * AU)$
 $ZS \leftarrow (LC * AU)$
 $PA \leftarrow KP$

SFTC

FIG. 7.2 (contd.)

Z1+Z1
Z2+Z2
Z3+Z3
Z4+Z4
Z5+Z5

EX01

PA+VP
QB+(QA+AW)
TB+(TA+AW)
XB+(XA+AW)
EC+(QA+AW)
D(PC)/DT+(QC+AW+QD+SW)
QD+(PC+AW+PD+SW)
TD+(QC+AW+TC+AW+EC+AW+QD+SW)

OUTF

PB+PB
PD+PD

OUT1

TA+TA
QA+(PA+SW)
XA+XA

OUT2

FIG. 7.2 (contd.)

$Q1 \leftarrow (P1 * SW)$
 $T1 \leftarrow T1$
 $Q3 \leftarrow (P3 * SW)$
 $T3 \leftarrow T3$

OUT3

$P2 \leftarrow P2$
 $P4 \leftarrow P4$

FIG. 7.2 (contd.)

PRINTREE OUTPUT

| | | | |
|-----------|-------------|-------------|--|
| TC (FFED) | +1.00000 +0 | +0.00000 +0 | |
| TR (REF1) | -1.00000 +0 | +0.00000 +0 | |
| | | XR (REF1) | |
| | +1.00000 +0 | +0.00000 +0 | |
| TG (REF1) | -1.00000 +0 | +0.00000 +0 | |
| | | XC (PLS2) | |
| | +1.00000 +0 | +0.00000 +0 | |
| | | TR (REF1) | |
| | -1.00000 +0 | +0.00000 +0 | |
| | | QG (REF1) | |
| | +0.00000 +0 | +0.00000 +0 | |
| QS (DIV1) | +0.00000 +0 | +0.00000 +0 | |
| | | IC (TAN1) | |
| | +0.00000 +0 | +0.00000 +0 | |
| | | QC (DIV1) | |
| | +0.00000 +0 | +0.00000 +0 | |
| LC (TAN1) | -1.00000 +0 | +0.00000 +0 | |
| | | TR (REF1) | |
| | -1.00000 +0 | +0.00000 +0 | |
| | | TG (REF1) | |
| | +0.00000 +0 | +0.00000 +0 | |
| | | QC (DIV1) | |
| | +0.00000 +0 | +0.00000 +0 | |
| | | OP (DIV1) | |
| | +0.00000 +0 | +0.00000 +0 | |
| ZC (MTF1) | | | |

PRINTREE Output for Enhanced Functional Model

FIG. 7.4

| | | |
|--------------|--------------|--------------|
| -1.00000E +0 | +0.00000E +0 | |
| XC (PLS2) | +0.00000E +0 | +0.00000E +0 |
| | QB (DIV1) | |
| | +0.00000E +0 | +0.00000E +0 |
| | IC (TAN1) | |
| | +0.00000E +0 | +0.00000E +0 |
| | ZC (MTF1) | |
| | -1.00000E +0 | +0.00000E +0 |
| | TR (PER1) | |
| | -1.00000E +0 | +0.00000E +0 |
| | TG (PER1) | |
| | +1.00000E +0 | +0.00000E +0 |
| | XR (RE21) | |

| | | |
|-----------|--------------|--------------|
| XC (PLS2) | +0.00000E +0 | +0.00000E +0 |
| | QB (DIV1) | +0.00000E +0 |
| | IC (TAN1) | |
| | +0.00000E +0 | +0.00000E +0 |
| | QC (DIV1) | |

| | | |
|--------------|--------------|--------------|
| +0.00000E +0 | +0.00000E +0 | |
| LC (TAN1) | -1.00000E +0 | +0.00000E +0 |
| | TR (PER1) | |
| | -1.00000E +0 | +0.00000E +0 |
| | TG (PER1) | |
| | +0.00000E +0 | +0.00000E +0 |
| | QC (DIV1) | |
| | +0.00000E +0 | +0.00000E +0 |
| | QB (DIV1) | |

| | |
|--------------|--------------|
| +0.00000E +0 | +0.00000E +0 |
| ZC (MTF1) | |

FIG. 7.4 (contd.)

| | | |
|-------------|-------------|-------------|
| -1.0000E +0 | +0.0000E +0 | |
| TR (REF1) | -1.0000E +0 | +0.0000E +0 |
| | XR (REF1) | |
| -1.0000E +0 | +0.0000E +0 | |
| TG (REF1) | -1.0000E +0 | +0.0000E +0 |
| | XC (PLS2) | |
| | +1.0000E +0 | +0.0000E +0 |
| | TR (REF1) | |
| | -1.0000E +0 | +0.0000E +0 |
| | QG (REF1) | |
| +1.0000E +0 | +0.0000E +0 | |
| YR (REF1) | +0.0000E +0 | +0.0000E +0 |
| | OB (DIV1) | |
| | +0.0000E +0 | +0.0000E +0 |
| | IC (TAY1) | |
| | +0.0000E +0 | +0.0000E +0 |
| | ZC (MTF1) | |
| | +0.0000E +0 | +0.0000E +0 |
| | TR (REF1) | |
| | +0.0000E +0 | +0.0000E +0 |
| | TG (REF1) | |
| | +0.0000E +0 | +0.0000E +0 |
| | IR (REF1) | |
| | +0.0000E +0 | +0.0000E +0 |
| | OB (REF1) | |
| | +1.0000E +0 | +0.0000E +0 |
| | XC (PLS2) | |
| TC (PLS2) | -1.0000E +0 | +0.0000E +0 |
| | XC (PLS2) | +0.0000E +0 |

FIG. 7.4 (contd.)

| | | | | |
|-----------|-------------|-------------|-------------|--|
| | | QB (DIV1) | | |
| | | +0.00002 +0 | +0.00002 +0 | |
| | | IC (TAN1) | | |
| | | +0.00002 +0 | +0.00002 +0 | |
| | | ZC (HTF1) | | |
| | | -1.00002 +0 | +0.00002 +0 | |
| | | TR (REF1) | | |
| | | -1.00002 +0 | +0.00002 +0 | |
| | | TG (REF1) | | |
| | | +1.00002 +0 | +0.00002 +0 | |
| | | XR (REF1) | | |
| | | | | |
| XR (REF1) | +0.00002 +0 | +0.00002 +0 | | |
| | QB (DIV1) | +0.00002 +0 | +0.00002 +0 | |
| | | IC (TAN1) | | |
| | | +0.00002 +0 | +1.00002 +0 | |
| | | QC (DIV1) | | |
| | +0.00002 +0 | +0.00002 +0 | | |
| | LC (TAN1) | -1.00002 +0 | +0.00002 +0 | |
| | | TR (REF1) | | |
| | | -1.00002 +0 | +0.00002 +0 | |
| | | TG (REF1) | | |
| | | +0.00002 +0 | +0.00002 +0 | |
| | | QC (DIV1) | | |
| | | +0.00002 +0 | +0.00002 +0 | |
| | | QP (DIV1) | | |
| | | | | |
| | +0.00002 +0 | +0.00002 +0 | | |
| | ZC (HTF1) | | | |
| | +0.00002 +0 | +0.00002 +0 | | |
| | TR (REF1) | -1.00002 +0 | +0.00002 +0 | |

FIG. 7.4 (contd.)

XP (RFB1)

| | | |
|-------------|-------------|-------------|
| +0.00002 +0 | +0.00002 +0 | |
| TG (RFB1) | -1.00002 +0 | +0.00002 +0 |
| | XC (PLS2) | |
| | +1.00002 +0 | +0.00002 +0 |
| | TR (RFB1) | |
| | -1.00002 +0 | +0.00002 +0 |
| | QG (RFB1) | |

| | | |
|-------------|-------------|-------------|
| +0.00002 +0 | +0.00002 +0 | |
| LW (RFB1) | +0.00002 +0 | +0.00002 +0 |
| | OR (DIV1) | |
| | +0.00002 +0 | +0.00002 +0 |
| | IR (TAN1) | |
| | +1.00002 +0 | +0.00002 +0 |
| | OP (RFB1) | |
| | +1.00002 +0 | +0.00002 +0 |
| | TG (RFB1) | |
| | +1.00002 +0 | +0.00002 +0 |
| | TP (RFB1) | |
| | +0.00002 +0 | +0.00002 +0 |
| | ZC (MTF1) | |

| | | |
|-------------|-------------|-------------|
| +0.00002 +0 | +0.00002 +0 | |
| OP (RFB1) | +1.00002 +0 | +0.00002 +0 |
| | IR (RFB1) | |
| | -1.00002 +0 | +0.00002 +0 |
| | XP (RFB1) | |

| | | |
|-------------|-------------|-------------|
| +1.00002 +0 | +0.00002 +0 | |
| XC (PLS2) | +0.00002 +0 | +0.00002 +0 |
| | OR (DIV1) | |

FIG. 7.4 (contd.)

| | |
|-------------|-------------|
| +0.00002 +0 | +0.00002 +0 |
| IC (TAN1) | |
| +0.00002 +0 | +0.00002 +0 |
| ZC (4TF1) | |
| -1.00002 +0 | +0.00002 +0 |
| TR (REB1) | |
| -1.00002 +0 | +0.00002 +0 |
| TG (REB1) | |
| +1.00002 +0 | +0.00002 +0 |
| XR (REB1) | |

| | | | |
|-----------|-------------|-------------|-------------|
| LP (REP1) | +0.00002 +0 | +0.00002 +0 | |
| | QB (DIV1) | +0.00002 +0 | +0.00002 +0 |
| | | IC (TAN1) | |
| | | +0.00002 +0 | +0.00002 +0 |
| | | QC (DIV1) | |
| | +0.00002 +0 | +0.00002 +0 | |
| | LC (TAN1) | -1.00002 +0 | +0.00002 +0 |
| | | TR (REB1) | |
| | | -1.00002 +0 | +0.00002 +0 |
| | | TG (REB1) | |
| | | +0.00002 +0 | +0.00002 +0 |
| | | QC (DIV1) | |
| | | +0.00002 +0 | +0.00002 +0 |
| | | QB (DIV1) | |
| | +1.00002 +0 | +0.00002 +0 | |
| | QB (REB1) | +1.00002 +0 | +0.00002 +0 |
| | | IR (REB1) | |
| | | -1.00002 +0 | +0.00002 +0 |
| | | XR (REB1) | |

FIG. 7.4 (contd.)

| | | | |
|-----------|-------------|-------------|-------------|
| | +1.00002 +0 | +0.00002 +0 | |
| | TG (REF1) | -1.00002 +0 | +0.00002 +0 |
| | | XC (PLS2) | |
| | | +1.00002 +0 | +0.00002 +0 |
| | | TP (REF1) | |
| | | -1.00002 +0 | +0.00002 +0 |
| | | QG (REF1) | |
| | +1.00002 +0 | +0.00002 +0 | |
| | TR (REF1) | -1.00002 +0 | +0.00002 +0 |
| | | XP (REF1) | |
| | +0.00002 +0 | +0.00002 +0 | |
| | ZC (MTF1) | | |
| TR (REF1) | -1.00002 +0 | +0.00002 +0 | |
| | XR (REF1) | +0.00002 +0 | +0.00002 +0 |
| | | QB (DIV1) | |
| | | +0.00002 +0 | +0.00002 +0 |
| | | IC (TAN1) | |
| | | +0.00002 +0 | +0.00002 +0 |
| | | ZC (MTF1) | |
| | | +0.00002 +0 | +0.00002 +0 |
| | | TR (REF1) | |
| | | +0.00002 +0 | +0.00002 +0 |
| | | TG (REF1) | |
| | | +0.00002 +0 | +0.00002 +0 |
| | | IP (REF1) | |
| | | +0.00002 +0 | +0.00002 +0 |
| | | QP (REF1) | |
| | | +1.00002 +0 | +0.00002 +0 |
| | | XC (PLS2) | |

FIG. 7.4 (contd.)

| | | | |
|-----------|-------------|-------------|-------------|
| 03 (REB1) | +1.00002 +0 | +0.00002 +0 | |
| | LR (REB1) | +0.00002 +0 | +0.00002 +0 |
| | | OR (DIV1) | |
| | | +0.00002 +0 | +0.00002 +0 |
| | | LC (TAN1) | |
| | | +1.00002 +0 | +0.00002 +0 |
| | | OR (REB1) | |
| | | +1.00002 +0 | +0.00002 +0 |
| | | TG (REB1) | |
| | | +1.00002 +0 | +0.00002 +0 |
| | | TR (REB1) | |
| | | +0.00002 +0 | +0.00002 +0 |
| | | ZC (MTF1) | |
| | -1.00002 +0 | +0.00002 +0 | |
| | XR (REB1) | +0.00002 +0 | +0.00002 +0 |
| | | OR (DIV1) | |
| | | +0.00002 +0 | +0.00002 +0 |
| | | LC (TAN1) | |
| | | +0.00002 +0 | +0.00002 +0 |
| | | ZC (MTF1) | |
| | | +0.00002 +0 | +0.00002 +0 |
| | | TR (REB1) | |
| | | +0.00002 +0 | +0.00002 +0 |
| | | TG (REB1) | |
| | | +0.00002 +0 | +0.00002 +0 |
| | | LR (REB1) | |
| | | +0.00002 +0 | +0.00002 +0 |
| | | OR (REB1) | |
| | | +1.00002 +0 | +0.00002 +0 |
| | | XC (PLS2) | |

FIG. 7.4 (contd.) /

| | | | |
|-----------|-------------|-------------|-------------|
| GG (REB1) | +1.00002 +0 | +0.00002 +0 | |
| | XC (PLS2) | +0.00002 +0 | +0.00002 +0 |
| | | OB (DIV1) | |
| | | +0.00002 +0 | +0.00002 +0 |
| | | LC (TAN1) | |
| | | +0.00002 +0 | +0.00002 +0 |
| | | ZC (MTF1) | |
| | | -1.00002 +0 | +0.00002 +0 |
| | | TR (REB1) | |
| | | -1.00002 +0 | +0.00002 +0 |
| | | TG (REP1) | |
| | | +1.00002 +0 | +0.00002 +0 |
| | | XR (REB1) | |

| | | | |
|-----------|-------------|-------------|-------------|
| TG (REB1) | -1.00002 +0 | +0.00002 +0 | |
| | XC (PLS2) | +0.00002 +0 | +0.00002 +0 |
| | | OB (DIV1) | |
| | | +0.00002 +0 | +0.00002 +0 |
| | | LC (TAN1) | |
| | | +0.00002 +0 | +0.00002 +0 |
| | | ZC (MTF1) | |
| | | -1.00002 +0 | +0.00002 +0 |
| | | TR (REB1) | |
| | | -1.00002 +0 | +0.00002 +0 |
| | | TG (REB1) | |
| | | +1.00002 +0 | +0.00002 +0 |
| | | XP (REB1) | |
| | +1.00002 +0 | +0.00002 +0 | |
| | TR (REP1) | -1.00002 +0 | +0.00002 +0 |

FIG. 7.4 (contd.)

XR (REB1)

-1.00002 +0
OG (REB1) +0.00002 +0
+1.00002 +0 +0.00002 +0
XC (PLS2)

XC (PLS1) +1.00002 +0 +0.00002 +0
XC (PLS2) +0.00002 +0 +0.00002 +0
GR (DIV1)
+0.00002 +0 +0.00002 +0
IC (TAN1)
+0.00002 +0 +0.00002 +0
7C (MTF1)
-1.00002 +0 +0.00002 +0
TR (REF1)
-1.00002 +0 +0.00002 +0
TG (REF1)
+1.00002 +0 +0.00002 +0
XR (REB1)

+0.00002 +0 +0.00002 +0
ZC (MTF1)
+1.00002 +0 +0.00002 +0
TG (REF1) -1.00002 +0 +0.00002 +0
XC (PLS2)
+1.00002 +0 +0.00002 +0
TR (REF1)
-1.00002 +0 +0.00002 +0
OG (REF1)

+1.00002 +0 +0.00002 +0
TR (REF1) -1.00002 +0 +0.00002 +0

FIG. 7.4 (contd.)

| | | | |
|-----------|-------------|-------------|-------------|
| | | XF (REF1) | |
| | +0.00002 +0 | +0.00002 +0 | |
| | QB (DIV1) | +0.00002 +0 | +0.00002 +0 |
| | | IC (TAN1) | |
| | | +0.00002 +0 | +0.00002 +0 |
| | | OC (DIV1) | |
| | +0.00002 +0 | +0.00002 +0 | |
| | LC (TAN1) | -1.00002 +0 | +0.00002 +0 |
| | | TR (REF1) | |
| | | -1.00002 +0 | +0.00002 +0 |
| | | TG (REF1) | |
| | | +0.00002 +0 | +0.00002 +0 |
| | | QC (DIV1) | |
| | | +0.00002 +0 | +0.00002 +0 |
| | | OB (DIV1) | |
| | +0.00002 +0 | +0.00002 +0 | |
| | XC (TAN1) | +0.00002 +0 | +0.00002 +0 |
| | | TF (REF1) | |
| | | +0.00002 +0 | +0.00002 +0 |
| | | TG (REF1) | |
| | | +1.00002 +0 | +0.00002 +0 |
| | | XC (PLS1) | |
| | | +0.00002 +0 | +0.00002 +0 |
| | | IC (TAN1) | |
| TC (PLS1) | -1.00002 -0 | +0.00002 +0 | |
| | XC (PLS1) | +1.00002 +0 | +0.00002 +0 |
| | | XC (PLS2) | |
| | | +0.00002 +0 | +0.00002 +0 |

FIG. 7.4 (contd.)

7C (MYF1)
 +1.00000E +0 +0.00000E +0
 TG (REB1)
 +1.00000E +0 +0.00000E +0
 TR (PEB1)
 +0.00000E +0 +0.00000E +0
 DF (DIV1)
 +0.00000E +0 +0.00000E +0
 IC (TAN1)
 +0.00000E +0 +0.00000E +0
 XC (TAN1)

QD (EX01)
 TD (EX01) -1.00000E +0 +0.00000E +0
 TR (REB1) -1.00000E +0 +0.00000E +0
 XR (REB1)
 -1.00000E +0 +0.00000E +0
 TG (REB1) -1.00000E +0 +0.00000E +0
 XC (PLS2)
 +1.00000E +0 +0.00000E +0
 TR (REB1)
 -1.00000E +0 +0.00000E +0
 QG (REB1)
 -1.00000E +0 +0.00000E +0
 QD (EX01)
 LC (TAN1) -1.00000E +0 +0.00000E +0
 TR (PEB1) -1.00000E +0 +0.00000E +0
 XR (REB1)

FIG. 7.4 (contd.)

| | | |
|-------------|-------------|-------------|
| -1.0000E +0 | +0.0000E +0 | |
| TG (REF1) | -1.0000E +0 | +0.0000E +0 |
| | XC (PLS2) | |
| | +1.0000E +0 | +0.0000E +0 |
| | TR (REF1) | |
| | -1.0000E +0 | +0.0000E +0 |
| | QC (REF1) | |
| +0.0000E +0 | +0.0000E +0 | |
| QC (DIV1) | +0.0000E +0 | +0.0000E +0 |
| | XC (PLS1) | |
| | +0.0000E +0 | +0.0000E +0 |
| | IC (TAN1) | |
| | +0.0000E +0 | +0.0000E +0 |
| | OR (DIV1) | |
| +0.0000E +0 | +0.0000E +0 | |
| OR (DIV1) | +0.0000E +0 | +0.0000E +0 |
| | IC (TAN1) | |
| | +0.0000E +0 | +0.0000E +0 |
| | QC (DIV1) | |
| TC (TAN1) | +0.0000E +0 | +0.0000E +0 |
| | TP (REF1) | -1.0000E +0 |
| | XR (REF1) | +0.0000E +0 |
| +0.0000E +0 | +0.0000E +0 | |
| -TG (REF1) | -1.0000E +0 | +0.0000E +0 |
| | XC (PLS2) | |
| | +1.0000E +0 | +0.0000E +0 |
| | TR (REF1) | |
| | -1.0000E +0 | +0.0000E +0 |

FIG. 7.4 (contd.)

| | | | |
|-------------|-------------|-------------|-------------|
| | | OG (REB1) | |
| +1.00002 +0 | +0.00002 +0 | | |
| TC (PLS1) | -1.00002 +0 | +0.00002 +0 | |
| | XC (PLS1) | | |
| +0.00002 +0 | +0.00002 +0 | | |
| LC (TAN1) | -1.00002 +0 | +0.00002 +0 | |
| | TR (PEB1) | | |
| | -1.00002 +0 | +0.00002 +0 | |
| | TG (REB1) | | |
| | +0.00002 +0 | +0.00002 +0 | |
| | OC (DIV1) | | |
| | +0.00002 +0 | +0.00002 +0 | |
| | OE (DIV1) | | |
| XC (TAN1) | +0.00002 +0 | +0.00002 +0 | |
| | TR (PEB1) | -1.00002 +0 | +0.00002 +0 |
| | | XP (PEB1) | |
| +0.00002 +0 | +0.00002 +0 | | |
| TG (PEB1) | -1.00002 +0 | +0.00002 +0 | |
| | XC (PLS2) | | |
| | +1.00002 +0 | +0.00002 +0 | |
| | TP (REB1) | | |
| | -1.00002 +0 | +0.00002 +0 | |
| | OG (REB1) | | |
| +1.00002 +0 | +0.00002 +0 | | |
| XC (PLS1) | +1.00002 +0 | +0.00002 +0 | |
| | XC (PLS2) | | |
| | +0.00002 +0 | +0.00002 +0 | |

FIG. 7.4 (contd.)

| | | | |
|-----------|-------------|-------------|-------------|
| | | 7C (MTF1) | |
| | +1.0000E +0 | | +0.0000E +0 |
| | | TG (REF1) | |
| | +1.0000E +0 | | +0.0000E +0 |
| | | TP (REF1) | |
| | +0.0000E +0 | | +0.0000E +0 |
| | | OB (DIV1) | |
| | +0.0000E +0 | | +0.0000E +0 |
| | | LC (TAN1) | |
| | +0.0000E +0 | | +0.0000E +0 |
| | | XC (TAN1) | |
| | | | |
| | +0.0000E +0 | +0.0000E +0 | |
| | LC (TAN1) | -1.0000E +0 | +0.0000E +0 |
| | | TP (REF1) | |
| | | -1.0000E +0 | +0.0000E +0 |
| | | TG (REF1) | |
| | | +0.0000E +0 | +0.0000E +0 |
| | | OC (DIV1) | |
| | | +0.0000E +0 | +0.0000E +0 |
| | | OR (DIV1) | |
| | | | |
| QB (DIV1) | +0.0000E +0 | +0.0000E +0 | |
| | LC (TAN1) | -1.0000E +0 | +0.0000E +0 |
| | | TP (REF1) | |
| | | -1.0000E +0 | +0.0000E +0 |
| | | TG (REF1) | |
| | | +0.0000E +0 | +0.0000E +0 |
| | | QC (DIV1) | |
| | | +0.0000E +0 | +0.0000E +0 |
| | | OB (DIV1) | |

FIG. 7.4 (contd.)

| | | | |
|-----------|--------------|--------------|--------------|
| | +0.00000E +0 | +0.00000E +0 | |
| | WC (DIV1) | +0.00000E +0 | +0.00000E +0 |
| | | XC (PLS1) | |
| | | +0.00000E +0 | +0.00000E +0 |
| | | IC (TAN1) | |
| | | +0.00000E +0 | +0.00000E +0 |
| | | QR (DIV1) | |
| QC (DIV1) | +0.00000E +0 | +0.00000E +0 | |
| | XC (PLS1) | +1.00000E +0 | +0.00000E +0 |
| | | XC (PLS2) | |
| | | +0.00000E +0 | +0.00000E +0 |
| | | ZC (ITE1) | |
| | | +1.00000E +0 | +0.00000E +0 |
| | | TG (REF1) | |
| | | +1.00000E +0 | +0.00000E +0 |
| | | TR (PEB1) | |
| | | +0.00000E +0 | +0.00000E +0 |
| | | OP (DIV1) | |
| | | +0.00000E +0 | +0.00000E +0 |
| | | IC (TAN1) | |
| | | +0.00000E +0 | +0.00000E +0 |
| | | XC (TAN1) | |
| | +0.00000E +0 | +0.00000E +0 | |
| | LC (TAN1) | -1.00000E +0 | +0.00000E +0 |
| | | TR (REF1) | |
| | | -1.00000E +0 | +0.00000E +0 |
| | | TG (REF1) | |
| | | +0.00000E +0 | +0.00000E +0 |
| | | QC (DIV1) | |
| | | +0.00000E +0 | +0.00000E +0 |

FIG. 7.4 (contd.)

| | | |
|-------------|-------------|-------------|
| | OR (DIV1) | |
| +0.00002 +0 | +0.00002 +0 | |
| QR (DIV1) | +0.00002 +0 | +0.00002 +0 |
| | IC (TAB1) | |
| | +0.00002 +0 | +0.00002 +0 |
| | QC (DIV1) | |

| |
|----------|
| TS (TF1) |
| ZC (TF1) |

END OF PROGRAM

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FIG. 7.4 (contd.)

branch. This information cannot be obtained from the functional models used.

7.6 Summary of Procedure for Enhanced Functional Models

The following steps outline the complete procedure to be used if functional models are used with the programs described in this work:

1. Split plant into units and identify each unit with a unique 4-character name. Similar units may be denoted by using names consisting of two or three common characters followed by a number, e.g. CV01, CV02.

For each unit type:

- i) Identify each stream entering or leaving unit by means of a unique 1-character name.
- ii) Identify all variables relevant to each unit. Each variable must be set in one of the units in the model. Use the convention defined in Chapter 4 to find those variables that are set in the unit. Each variable is given a 2-character name. For variables in streams, the second character in the variable name is the same as the stream name.
- iii) Define function for each variable set in unit.

2. Define measured variables and choose those to be equipped with alarms. For each variable with alarms:
 - 1) Choose alarm type,
 - 11) Choose alarm levels.
3. If deduced alarms are to be used, the symptoms must be defined at this stage in terms of the measured variables defined above.
4. Put data into form required by program. All data formats are given in Appendix 2.
5. Run program to produce alarm tree data. Check program output for obvious errors due to poor choice of functions or incorrect data format.
6. Run further program to convert alarm tree data into form suitable for on-line machine.

The last step has not been done for the present study.

CHAPTER 8

REVIEW OF OUTSTANDING PROBLEMS

Since the work done for the present study has been completely theoretical, the remaining problems are mostly those associated with practical aspects of applications. The form of the program written for this study is also considered, since it is inevitable that, if programs of this type are to be extensively used, then many alterations will be needed as experience is gained.

8.1 Off-Line Program Problems

The programs used for the study were written so that the ideas involved could be tested and program modifications made easily. This approach inevitably requires that a modular system is employed using many special-purpose subprograms. The programs also rely entirely on core-stored data. These two factors combine to give a large core-store requirement for the analysis programs. The data space required for a particular program depends on both the size of the plant section considered and the program segments used whilst the space available depends solely on the program segments used. It therefore follows that larger plant sections can only be considered if the program space is reduced.

It is expected that the use of the program for a pilot plant study will lead to further changes in both the form of the program and the facilities available. If such studies show that the use of

a program of this type is a practical proposition, then it may be desired to produce a version of the program requiring less core-store, thereby enabling larger plant sections to be considered. Various possible methods are available.

8.1.1 Alteration of Basic Program Form

The program used at present assembles the model in core-store and subsequently manipulates it as required. A completely different approach would be to use a set of programs communicating with each other via a backing store. Such a set might be made up in the following way for use with (for instance) magnetic tape:

- a) A program to assemble a plant model, complete with steady-state data and alarms. The program would end by transferring the complete model onto magnetic tape.
- b) A program to retrieve the model from tape and allow the user to simulate faults in order to obtain deduced alarm data. (Note that the model on tape is not destroyed). The symptoms obtained would be stored on a second tape.
- c) A program to retrieve the model from tape and set up the alarm tree. This tree could be stored on a third tape.
- d) A program to retrieve the model from tape and simulate various conditions. At predetermined times, the values of all process variables would then be stored on a fourth tape.
- e) A program to retrieve the analysis data stored on tapes 2 and 3 and use the run data stored on tape 4 to test the

alarm system.

This method avoids using core-store for programs no longer required although the programs needed to communicate with the backing-store and to assemble the model will themselves use extra space. A preliminary review of the problems involved suggests that considerable space savings may be made in this way.

8.1.2 Improving Efficiency of Present Programs

This method uses the same basic program form as the present program but relies on considerable improvements to the subprograms used to carry out the various functions. There are many places in the program where small savings of space can be obtained with a moderate amount of effort. Inspection of the programs also shows that some procedures are similar in many respects to others. A saving of space may be obtained by carefully combining such procedures. A further possibility is the use of different MODES to build the model. The present arrangement is by no means unique but does have the virtue of being flexible. The savings of space accomplished using these three strategies are not expected to be as great as that achieved by altering the basic program form. The other major improvement that may be made to the present program is the provision of a faster integration program. The routine used at present, a predictor-corrector, is very slow due to the small step length needed for "stiff" problems. Other integration methods considered were:

1. Runge-Kutta methods
2. Kutta-Merson (a method suitable for some stiff problems)
3. Gear's method

The first two were both tested with the programs at an early stage in the project but were rejected because of the larger number of function evaluations needed per step. The results obtained with both of these methods were very close to that given by the predictor-corrector. Gear's method would be faster but would involve a much larger program and was therefore rejected. A simple modification to improve the present method would be to increase the order from 4th to 8th or higher.

8.1.3 Use of Better Algorithms with the Present Program Structure

The amount of data space required by the program is affected by the algorithms used to carry out each function. This may be seen by examining the flowchart of procedure ALTERNATE (Fig. 6.6).

This procedure removes some nodes, with their associated branches, from the tree but also adds new branches in order to preserve the information contained in the tree. The algorithm used was designed so that the unwanted nodes could be released for garbage collection as soon as no branches to them were included in the tree. This enables a larger size of problem to be handled using a given amount of "heap" storage (see Appendix 1 for a discussion of "stack" and "heap" storage).

A combination of these three methods would probably be most effective but will require a large programming effort. At the present time, it appears more profitable to devote such efforts to a compromise solution. This would entail using the backing-store as outlined earlier but only splitting the program into 2 major sections:

- a) Sets up complete model and may be used to find deduced alarm symptoms and run data for tree testing. Finally transfers data to one or more magnetic tapes.
- b) Retrieves data from tape(s), sets up tree and tests tree.

An entirely new program would then be used to combine analysis trees for different sections of plant, stored on tape, into the form required for a complete plant. The final product would be a magnetic tape, compatible with the on-line machine to be used for analysis, containing all the data required.

8.2 On-line Program Problems

The comments in this section are necessarily of a more speculative nature than those in the previous section. Since alarm analysis systems are in operation on nuclear power plants, it will be assumed that the usual problems associated with computer operation in a real-time environment do not present any insurmountable obstacles for alarm analysis applications. For the purpose of discussion, it will also be assumed that the analysis data used is of reasonable quality.

The quality of the incoming signals from the measuring devices is obviously of prime importance to the program. The complexity of the algorithms used to analyse the off-normal situation depends on the signal quality. The overriding constraint on the analysis program must be the time in which an analysis must be completed. The time

for analysis will also be dependent on the way in which the analysis data is stored. An excessive number of backing-store transfers during any operation will increase the time requirement out of all proportion to the other operations carried out (approximately 20 milliseconds for a disc transfer and longer for tape transfers).

Since maintenance is being carried out on a virtually continuous basis on many plants, it follows that some of the measurements normally available cannot be used at such times. Provision should therefore be made to input to the program details of signals that must be ignored for analysis purposes. This facility may need to be protected in order to prevent improper use although, if the alarm levels are correctly set, the temptation to suppress alarms in this way should not arise.

Deduced alarms may be used to warn the operator of measuring instrument malfunction before the instrument fails completely. Alternatively, a separate malfunction detection program might be used to warn of impending failure.

8.3 Display Problems

The papers considered in Chapter 2 review the display systems used in detail. For all practical purposes, the displays available at the time were suitable for alpha-numeric information only. In recent years, considerable advances have been made in the technology of display systems (32). Of particular interest to this work is the improved facilities now available for C.R.T. displays.

Graphical and multi-colour displays are now more common and hence there is now considerably more choice in the type of display system used.

The nuclear power station systems involve multiple display units with a number of formats available for the operator to choose from. If this practice is followed on chemical plant applications, it is suggested that the use of C.R.T. displays showing mimic diagrams, or even the alarm trees themselves, might be a useful addition to the range of formats available. The schemes currently being prepared for the Heysham and Hartlepool reactors include the use of graphical histories of measured variable behaviour and mimic diagrams. It is suggested that, rather than displaying variable values, as is proposed for these power station schemes, a more useful approach might be to merely display alarm states for each variable. This system would allow a greater area of plant to be shown on each diagram and would also allow much easier comprehension of the overall state of the plant. The alarm states shown could be divided into 4 categories:

1. Prime cause alarms
2. Effect alarms
3. Latest effect alarms
4. Deduced alarms

A multi-colour display would probably be the best way to do this if the cost and reliability of such displays makes them acceptable for the system concerned. A further display that would be useful involves the same mimic diagrams but with an additional facility to display only those alarms associated with one particular cause.

It is emphasised that this type of facility is proposed in addition to the more normal display showing alarms and messages grouped according to cause. The use of the two types of display side by side should allow the operator to digest the overall "picture" much more rapidly than at present. Displays showing selected sections of alarm trees would be useful during commissioning since alarms occurring in an incorrect order (on a cause-and-effect basis) are readily pinpointed.

8.4 Uses of Alarm Analysis Systems for Sequential Operations

The work done for the present study has been concerned primarily with alarm systems designed for process plants normally running at steady state. The use of alarm systems on plants during start-up, shut-down or batch operation obviously leads to additional complications. The most significant differences appear to be:

1. Although the measuring instruments are the same, no matter what condition the plant is in, the quantity measured may have a different significance (for instance a temperature measuring device in an empty pipe is not measuring a liquid temperature).
2. Some instruments may be frequently outside of their operational range during some stages of operation.
3. The alarm limits must be dynamic.
4. The corresponding model equations may change considerably for different stages of the operation.

The net result of these considerations is that the information in the alarm tree must be time-dependent. This, in itself, does not appear to present any particular problems. A more difficult problem is that during analysis changes in the tree data (due to the changing plant condition) will require changes in the links in the previously computed cause-and-effect chain if the present type of analysis method is used. It is tentatively suggested that a more suitable method may be to assign a fraction of the cause of an alarm to each of 2 or more other alarms. These fractions might be dependent either on time (since the operation began) or other key process variables. This is equivalent to using one alarm tree for all stages of operation but with dynamic directional information for each branch.

DISCUSSION

The work described in this thesis gives rise to many questions of a general nature due to the fact that much of the content is concerned with areas of research that have remained largely unexplored. The basic tools used for the study are themselves well known; list-processing is an established technique among Artificial Intelligence workers and simulation programs are frequently encountered. The examples in texts on list-processing show little in common with the programs used here because of the specialised nature of the application. The simulation methods used also bear little resemblance to the more widely-used simulation packages. The comparison with these "pure" topics is only valid in terms of the basic ideas on which they depend. The significant feature of list-processing is the concept of run-time storage allocation whilst that of simulation packages is the use of unit modules. These two tools are central to the work reported here.

From an overall viewpoint, it is perhaps surprising that so little work has been done on studying the design and use of conventional alarm systems when, in so many cases, the penalty for maloperation or enforced shutdown is high. It is this penalty which determines the program facilities, if any, which may be economically used for a particular application. Fig. 9.1 shows the major questions that must be answered at the start of an alarm analysis study.

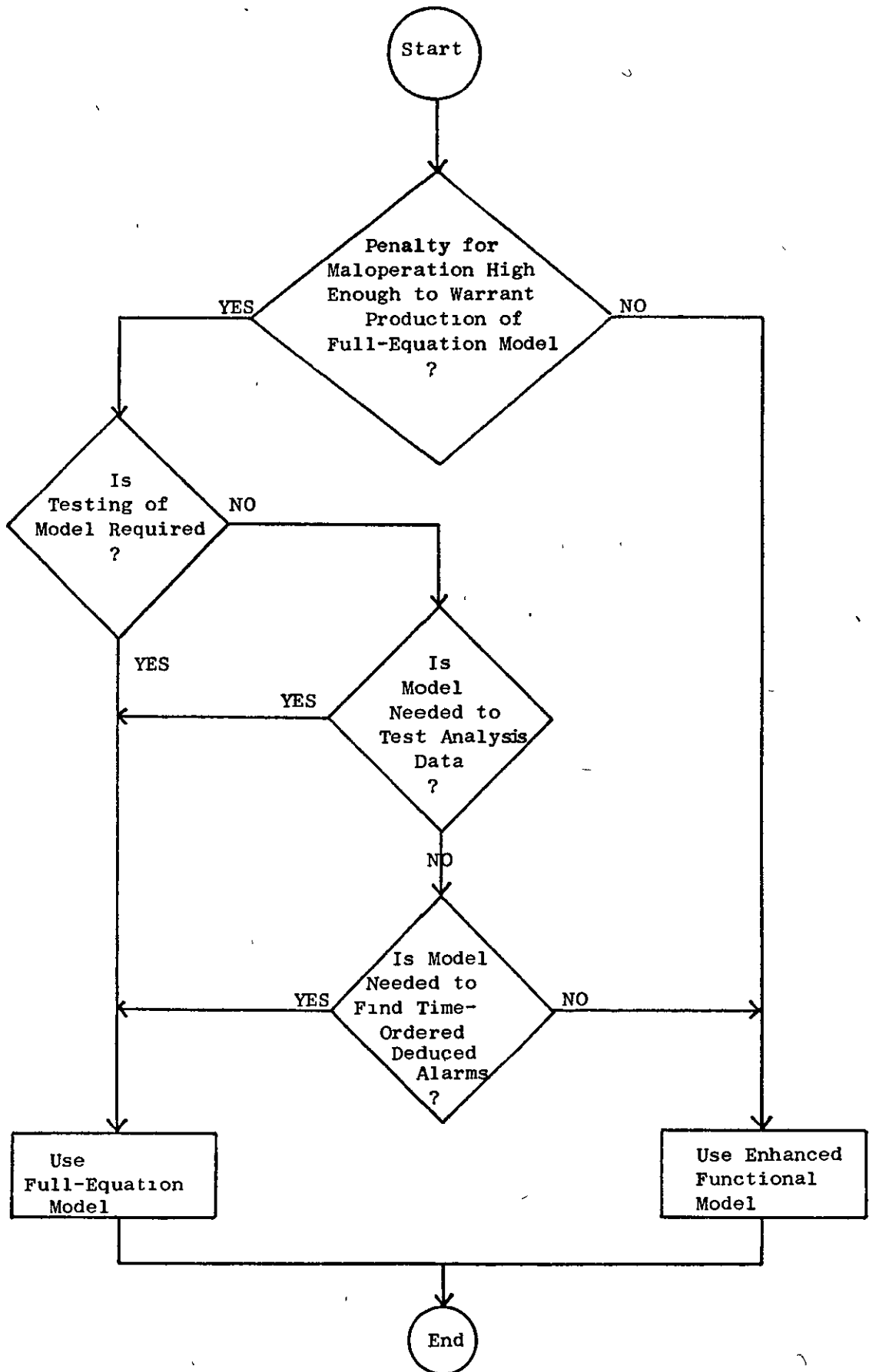


FIG. 9.1

It may be seen from the Figure that the most crucial decision concerns the type of plant model to be used. This is understandable since the effort involved in formulating a realistic full-equation process model is formidable for many plants. The need for this type of model in some situations is the weak point of the method presented. The integration of large sets of differential equations is a time-consuming process particularly for stiff systems. In recent years, sophisticated programs have appeared, such as that produced by Professor Gear, which perform such operations efficiently. The use of such methods for the scheme presented here is largely impractical because of the large amount of program space required. If the program were split up into sections, as described in Chapter 8, the use of such a method might be a worthwhile proposition. It must be noted that deduced alarms are only needed if the analysis program is required to detect faults rather than to reduce the information overload on the operator (by suppression of some alarm messages) or to split the active alarms up into groups based on cause-and-effect.

In many cases, it is likely that the use of enhanced functional models is necessary but that some deduced alarms would also be useful. If the symptoms for these alarms cannot be obtained intuitively then it may be worthwhile for the user to incorporate additional measuring devices on the plant to monitor the appropriate variables. The use of digital alarms, consisting of alarm signals generated by pairs of contact points closing on the plant, may be sufficient in such cases. The use of such alarms has not been considered explicitly here although the treatment of the alarm obtained is essentially similar to absolute alarms.

Several areas of study related to the present work have been considered only briefly during the project. Those may be summarised as:

1. The transfer of data to the on-line machine. This problem was considered and appears to present no particular difficulty.
2. The on-line analysis program. A program was used to test the data obtained by the method but has not been considered in detail since programs of this type are already used on the applications reviewed in Chapter 2. The prime object of the present study was to produce the analysis data required for such a program. The flowcharts of the main procedures used for testing are given in Appendix 4 and the program segment used for testing is given in Appendix 3, LISTING 13.
3. The human-factors problems associated with the design and operation of the display system. These problems are best treated by ergonomists.
4. Possible use of the method for operability studies. This use was suggested late in the study but was not considered in detail since it is not of direct interest.

As would be expected, a number of problems hampered the progress of the work to a greater or lesser extent. With any project involving a moderately large program, there will inevitably be some program "bugs" that are difficult to trace. In this case the language used

was itself new (only draft copies of the basic parts of the language documentation were initially available) which, coupled with the fact that there were no other users in the University, gave rise to additional problems. Some compiler bugs also existed but these were gradually eliminated with succeeding versions of the system. The Royal Radar Establishment at Malvern, where the language originated, was also kind enough to supply an advance version of the ALGOL 68-R system which incorporated a more sophisticated "loader" when the existing version failed, during compilation, due to the large size of the program.

The only other problem that caused a noticeable delay concerned the formulation of general-purpose unit modules. The use of high-gain differential equations to set input stream pressures was central to the solution of this problem.

It is hoped that the method produced will provide the basis for alarm analysis applications on chemical process plants at less cost than has hitherto been possible.

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