MALFUNCTION OF PROCESS INSTRUMENTS AND ITS DETECTION USING A PROCESS CONTROL COMPUTER

SAMUEL NNAEMEKA ANYAKORA

MALFUNCTION OF PROCESS INSTRUMENTS AND ITS DETECTION USING A PROCESS CONTROL COMPUTER

by

SAMUEL NNAEMEKA ANYAKORA

Supervisor: DR. F.P. LEES

A Thesis
Submitted for the degree of
Doctor of Philosophy
Loughborough University of Technology

Department of Chemical Engineering - September 1971

FOR MY MOTHER AND MY FAMILY

CONTENTS

CONTENTS

Section Page

ABSTRACT

From an initial concern with investigation of ways in which the process control computer could learn, the project was narrowed down to instrument malfunction detection.

Preliminary surveys in industry were made and from there general ideas of modes of failure of some instruments were obtained. A wider survey of instruments in different environmental conditions followed. Failure information and reliability data on about 9,500 instruments representing a total of about 4,500 instrument years operating time were obtained.

A study of failure information from industry and study of available theory in the open literature that are amenable to malfunction detection techniques led to a presentation of some general ideas and techniques of instrument malfunction detection. Time series analysis was singled out for special attention because of its promised potential.

The implications of malfunction detection and reliability data for the improvement of plant and control systems are discussed.

Case studies of select instruments - thermocouples, differential pressure transmitters and control valves, were carried out. An instrument malfunction detection algorithm based on the standard deviation, calculated with a running mean, was tested on-line on the thermocouples and proved effective. Power spectral analysis results of signals from a differential pressure transmitter used as a flow measurement show the feasibility of the technique for instrument malfunction detection.

Industrial data on measuring instruments and control valves were obtained and analysed.

On the whole the feasibility and potentials of malfunction detection, particularly by the process control computer is shown.

1. INTRODUCTION

1. INTRODUCTION

This project is essentially an initiation of a program of work on computer control with special emphasis on those functions which are normally not allocated to the computer but which are performed by the human operator.

Even though there are many successful computer control projects, there is need for more useful computer functions as even in these 'successful' computer control projects the potential of the process control computer is not fully exploited. The stage when computer control might be justified as an experiment must now be over for most firms. With the present trend of increasing sophistication in computer design and complexity of process plant design, there is need for a larger number of useful functions to make computer control easier to justify. This program aims to develop some of these.

More specifically, the objective of this program is to obtain more precise definition of the operator's functions, using logical and mathematical methods where possible. It is expected that this will improve understanding of these functions, help in the allocation of functions between the operator and the computer, indicate what aids and interface the operator should be given and lead to the development of techniques for making some of these functions automatic, where this is appropriate.

It is hoped that in this way the operation and availability of the plant will be improved - the upgrading of the performance not only of the instruments but of the plant items as a whole resulting in more reliable installations; that the usefulness of the operator will be increased; that the capability of the computers will be more fully utilised; the operation of the plant with less or even no operator supervision will be made possible.

Within this general program, the work described here began as an investigation of the ways in which the computer could learn. Awareness of the growing literature on learning methods and pattern recognition led to the thought that it was about time development for and application of these techniques to the process industry was attempted. The emphasis here being more on reproducing rather than on improving human learning - the aim being to develop the techniques necessary to allow plants to be run without operators rather than those of making small improvements in efficiency.

With the development of the project, there has been a clearing of thinking and ideas. An initial study and consideration of the current thinking in computer control influenced the further development and defining of the project. The work described here, therefore, has since been narrowed down to methods by which the process control computer can detect the malfunctioning of its instruments.

The current thinking in computer control is that a more realistic trend in the further development of automatic control should be towards a shift from complete automation to achieving a proper balance between the division of labour between automatic equipment and man. This shift has already occurred in the aerospace industry in more recent years. The experience in process control with the emergence of a number of functions which have proved rather difficult to automate and which can often be shown to be well suited to execution by the human operator, points to this shift as a more realistic general direction for the further development of automatic control in the process industry.

1.1 Project

Development of more useful functions which the process control computer can perform and which are considered in the work reported here include: methods by which the computer can detect whether its instruments (measuring elements and control valves) are working properly; methods by which in the event of failure, alternative approximate estimates of the variables can be made; methods of utilising the potential of the computer to maximise system reliability.

The detection techniques for measuring instruments have included generally comparative methods such as comparison between the actual reading and that expected from consideration of the instruments physical constraints, dynamic response and signal properties; and of other measurement readings, process relationships and control valve positions. These techniques could be divided generally into two types, based

(i) on instrument or equipment condition

(ii) on instrument or equipment performance

On this basis the techniques can be classified as passive or active.

The project is part of a continuing program of work in the department on the task of the process operator, on computer control and on reliability engineering..

Faults on the departmental computer, shortage of finance to spend some periods in industry and difficulty in getting on-line computer data from working plants were the main difficulties. Nevertheless, work was done and data were obtained from industry.

The general presentation of the thesis is one of first presenting the ideas and information leading to and the necessary theory developed; followed by a report on the application of the ideas and theory to both industrial and laboratory experimental data.

There is no single literature survey. The very nature of the project does not allow for a single survey. Where appropriate, a survey has been done on the separate subjects.

An initial and background study of the functions performed by both the computer and the process plant operator, the limitations and future trends and development of computer control is presented in Chapter 2. This study was a necessary and first step in the defining and development of the project, and influenced the narrowing down of the work as reported here.

One of the main experimental works carried out was the collection of failure information and reliability data on some 9,000 instruments representing a total of about 4,500 instrument years operating time from three chemical works. This yielded information on failure modes and behaviour of some instruments in their working environment. A report on this survey of instrument reliability carried out in industry is presented in Chapter 3.

The implications of malfunction detection and reliability data for the improvement of the reliability of plant and control systems are discussed in Chapter 4. This is followed in Chapter 5 by the general ideas and techniques of instrument malfunction detection.

Because of the considerable potential of time series analysis as a method of malfunction detection, it has been singled out for special attention in Chapter 6.

The case studies of selected instruments and the application of malfunction detection techniques to both laboratory and industrial experimental data from them are presented in Chapters 7 and 8. The thermocouple was typically and illustratively studied in detail and has been presented on its own in Chapter 7.

Time series analysis of logged signals from a differential pressure transmitter, used as a flow measurement instrument, is contained in Chapter 8. An analysis of logged instrument data from industry is also contained in Chapter 8.

A report (i) below, on thermocouples and their failure described in Chapter 7, was written for the Central Electricity Generating Board. A paper (ii) below, based on the material of the industrial survey of instrument reliability in Chapter 3 has been written and submitted for publication. The title and synopsis of a paper (iii) based on the principles of instrument malfunction detection described in Chapters 5 and 6 has been submitted for publication.

(i) Anyakora, S.N

"Thermocouple installations and Their Failure" A Report Written for C.E.G.B., February, 1970.

(ii) Anyakora, S.N., Engel, G.F. and Lees, F.P.

"Some Data on The Reliability of Instruments in Chemical Plant Environment" Submitted to the Institution of Chemical Engineers for Publication.

(iii) Anyakora, S.N. and Lees, F.P.

"Principles of the Detection of Malfunction Using a Process Control Computer". Title and Synopsis Submitted For Publication, Instn. Chem. Engnrs. Symposium: Decision, Design and the Computer.

2. COMPUTERS AND OPERATORS IN INDUSTRIAL PROCESS CONTROL

2. COMPUTERS AND OPERATORS IN INDUSTRIAL PROCESS CONTROL

Introduction

At the early stages of this project some basic background work was necessary for the better defining and narrowing down of the work reported here, from the general program of work being initiated. The study of computer and operators in industrial process control is in this category. It influenced a more realistic definition of this project. It also, in retrospect, helps bring out the relevance and importance of malfunction detection. The computer functions such as alarm scanning, mathematical modelling, optimisation and sequential control emphasise the relevance of malfunction detection to the proper carrying out of these functions by the computer. Most of the functions performed by the computer rely on accurate and dependable information from its instruments for their meaningful execution.

The study of the functions carried out by the operator shows that a large amount of malfunction detection is carried out by him.

Even though a lot of this work is background work, besides its chronological relevance in the development of the project, it is important in emphasising the relevance of malfunction detection.

Since the advent of automatic equipment the trend has been generally one of trying to replace the human operator with automatic equipment. Most development of automatic control over the years has been in this general direction. Because of the basic difference in intelligence between the man and the machine, it is not surprising that experience from the increasing degree of automation has shown up certain functions which are very well suited to execution by the operator but are rather difficult to automate. It would appear that with the lack of intelligence and creativity of the machine, complete automation in the process industry would remain an ideal for a considerable time to come.

In more recent years, the emphasis in the aerospace industry, one of the main users of automatic systems, has shifted somewhat from complete automation to division of labour between automatic equipment and man. In process control, the achievement of a proper balance in the allocation of functions between the operator and the automatic equipment would be a more realistic future direction in the further development of automatic control. This is the current thinking in this field. It is an objective which can easily be achieved and which could have very desirable and considerable implications for upgrading the performance of plant items and of the plant as a whole.

A necessary first step in this direction would be a study of the functions performed by both the computer and the process plant operator as reported.

A survey of these functions in the chemical process industry is attempted. It starts with a brief discussion of a wide variety of process characteristics which determine computer and operator functions. It covers: functions performed by the process control computer in general; some actual examples of industrial applications of on-line computers, briefly; functions performed by the human operator and in the light of these problems of total computer control; and finally the possibilities and direction of computer control.

All this was relevant in selecting instrument malfunction detection for further development.

2.1. Process Characteristics

The characteristics of any process mainly determine the functions of both the plant operator and the automatic equipment. Before these functions can be defined and/or allocated an understanding of the process to be controlled is very necessary.

A number of circumstances can affect the characteristics of a given process. Factors of variability such as raw materials quality, feed rates, behaviour of plant equipment and instrument systems and overall environmental conditions can affect the process characteristics. These could generally be considered as disturbances to the system. These disturbances are almost inevitable and the process characteristics are subject to these disturbances.

Fouling and deteriorating factors are inevitable in certain circumstances as exemplified by the decaying of catalysts in catalytic reactions. These factors of course, cause disturbances in the process. Certain types of behaviour of process materials cause disturbances when they occur. Solidification in polymerisation and other such processes is a typical example. The materials might be very sensitive to certain parameters such as ambient temperature variations or variations in alkalinity which could arise from raw material variations. In the case of production of silica gels, any of these variations could lead to solidification. The very physical characteristics of the process could lead to disturbances such as the build up of dust particles in a dusty environment such as in a cement kiln could lead to blockages or clogging, or tearing of paper in a paper machine could lead to jamming. Some awareness of these distrubances is very essential for the allocation or defining of functions of either the plant operator or automatic equipment in any given process.

Also very relevant and important are the intrinsic characteristics of the process such as the technical characteristics. Important technical characteristics are those with problems which could be due to the type of control - feedback, feedforward, continuous or sequential, malfunctions or just variation of parameters for optimisation purposes.

Measurement is basic in all process control systems and its many facets make it one of the most difficult aspects of process control. Measurement here includes both inferred and direct measurements. In control such as feedback or feedforward control, which is totally dependent on measurement, difficulties often arise which can make control impossible.

Non-linearity, inherent instability, dead-time, long and short time constants, recycle, limit cycles, strong interaction, to name a few, can pose problems for continuous control. For sequential control the problems depend on whether it is a batch operation, plant start up or shutdown, or even variations in product quality or throughput. All these technical problems can characterise processes.

The malfunctioning of a process, the monitoring to detect the malfunctions, the techniques for diagnosing the malfunctions and the necessary emergency action to be taken can also characterise a process.

In cases where there are scope for optimisation changes in configuration, constraints, process inputs or internal drifts, optimisation of conditions may almost have to be done continuously. Such factors can characterise a given process when applicable.

It would be impossible here to mention all the possible characteristics of a process which are relevant to the allocation of functions, as the relevant characteristics vary from process to process and are also related to the partiuclar objectives. All that has been done here is to mention a few fairly general characteristics to make the point about the necessity and relevance of such considerations in defining and allocating functions to both the plant operator and the automatic equipment.

2.2. Functions Performed by the Process Control Computer

Within the past decade, the process control computer has enjoyed a spectacular growth. The application of computers to the control of separate on-line chemical processes is rapidly becoming an established technique. The literature is full of publications on different aspects and developments of computer control in industry.

The functions carried out by control computers have now reached a certain degree of standardisation. The emphasis placed on individual functions varies with the nature of the process, but on the whole the similarities between systems are greater than the differences. Measurement, computation, communication and control are basic in all process control systems.

The versatility of the nature of the process digital computer equipment renders it applicable to nearly all process industries alike. Its lack of emotions is an invaluable asset. Because of its capability of being programmed with a set of simple, but meaningful commands the process digital computer can perform a myriad of desirable functions.

In general, two types of computer systems are possible with on-line operations.

(i) Fixed program system

(ii) Variable program system

In fixed-program system, the operations of monitoring and control are fully defined before the system is constructed. The required operations are accomplished merely by the inclusion of the necessary equipment. Because the latter can be quite large and the resulting system inflexible and costly to change, fixed-program systems are best applied to such simple operations as data acquisition, data logging and alarm indication.

In variable-program systems, the program is held in the store of the computer and can readily be changed. Hence, as further information becomes available, it is possible to make rapid adjustments to the program with a minimum of interference with the operation of the system. The flexibility of a digital computer and the ease with which its programs can be altered makes it an ideal tool for this type of application. By using sampling and time-sharing techniques, a digital computer can accommodate a large number of inputs or control loops with relative ease. The addition of further inputs or control loops can usually be accomplished with a minimum of effort and expense as, in general, all that is required is to bring signals from the additional points and to feed them into the computer.

The basic function of a process control computer is one of goal maintenance. This entails ensuring that primary and secondary aims of the control are maintained, that specific constraints are adhered to and that the order of priority of these is followed. Its lack of emotions is an invaluable asset in this type of function. More specifically, typical functions performed by the process control computer can be summarised with a brief explanation of each function as follows: (1,2,3)

2.2.1. Measurement and Calculations; scan and convert analog calculations

2.2.2. Data logging and Data processing

2.2.3. Alarm Scanning and Analysis

2.2.4. Indirect and Direct plant control - Equipment regulation

2.2.5. Optimisation

2.2.6. Sequential control

2.2.7. Special system functions

2.2.8. Commercial data handling

2.2.9. Management calculations, information and Background capability

2.2.10. Control by Learning.

2.2.1. Measurements and Calculations; scan and correct analog calculations

With an analog input scan program, the interfacing required for communication between the process and the computer is provided. The analog input signals are converted by the computer to digital values, usually in engineering units (p.s.i., ^{o}C, lb/hr, etc.) and stored in storage locations reserved for the engineering units table. The functional programs use only the engineering units values of the process variables from the engineering unit table and not the actual analog signals transmitted from the process measurement transducers.

Thus, the computer receives crude instantaneous plant measurements which it may modify to eliminate, say, non-linearities such as occur in flow and temperature measurements. These measurements may be smoothed or averaged and other variables can be calculated from them. Such inferred measurements can also be obtained in some cases from say, the amount of control action needed to keep a variable constant and very often are more important than the original measurements (4,5).

The inferred measurements, once calculated can be used exactly as an ordinary measurement and can, in particular, be displayed, logged scanned for alarms or controlled. Hence, particularly at start up of a plant, the computer can be used to provide a temporary solution to measurement problems (1).

2.2.2. Data logging and Data processing

Because of the computer's tireless and reliable ability to perform routine tasks at high speed, it is ideally suited to monitoring plant operations, logging and data processing. The computer is usually better than a special data logger, as it is usually well maintained for other purposes also.

Any data available in the computer - measured values, set points, valve positions, inferred measurements, may be logged on to paper or magnetic tape.

Several logs are generally provided. Typical are the instantaneous log, 8-hour summary log, 24-hour summary log, demand log and trend log.

Instantaneous logs provide the current values within a specified section of the process; the 8-hour log and 24-hour summaries are self explanatory.

The demand log may give mainly smoothed hourly readings of a large number of operational parameters for the eight hours previous to the demand, say. Examples are tables of instrument readings and tables of a computer variable, such as product yield given as weight percentage of feedstock used in eight hours. The latest values of a variable chromatograph analysis and the like can also be printed.

A number of independent tables comprise the trend log. The latest instantaneous readings of an instrument or set of instruments, whose trend of behaviour is wanted, for instance, are typed at optional intervals for some set period.

For a computer executing direct digital control, in addition to logging measurements and readings, it can also record such very informative data as the interventions made by the plant operator such as set point insertions or changes. It can also log information on plant failures such as measurements taken over short intervals for a fixed period in the immediate past. Such information is held in the computer and continuously updated and in the event of a serious plant failure, this information can be retrieved and used to trace the source.

Since the amount of work the computer has to do during non-alarm conditions is smaller than that under alarm conditions, it normally has capacity to do additional work such as data processing. Computer usage of this type is feasible through the application of time-sharing techniques, priority and other routines in arranging computer programs.

2.2.3. Alarm Scanning and Analysis

There are different levels of alarm, starting from preliminary warnings and ending with emergency shutdown. Detection of certain alarm conditions can be used to initiate logging for fault tracing.

The alarm scanning program is used to check the process variables against preset limits for normal and safe process operation. The alarm limit could be an absolute value, a given deviation from set point, a specified rate of change or even a full scale instrument reading.

Even though alarms are usually confined to the process variables there may also be some form of indication that particular plant items are not in operation, either because they have failed or are not required.

In addition to alarm scanning on smoothed direct and inferred measurements, the alarm scanning function includes alarm analysis. (6,7) The latter involves the diagnosis of the possible fault condition and sometimes suggested corrected action by following an appropriate algorithm. This is sometimes known as 'alarm tree' analysis.

Start - stop monitoring and control implies two basic programs: scanning and alarming of equipment operations, and stored logic of all the sequencies of steps involved in start-ups and shutdowns. Scanning and alarming are carried out as usual, except that additional measurements are often required and typed warning messages include restrictions on further steps in the sequence.

To illustrate the nature of the logical start-up sequence, the computer steps required to open a valve may be listed (3): as below

(i) check valve limit switch to assure fully closed condition

(ii) check availability of power supply to operate the valve

(iii) transmit signal for full opening of valve

(iv) check valve limit switch to assure fully open condition

(v) check valve limit switch to assure that "fully-closed" circuit is not energised

(vi) include analog flow signal in scan sequence.

(vii) check flow against high and low limits

(viii) select next logical step

Any of the check steps could give rise to an alarm condition.

2.2.4. Indirect and Direct Plant Control - Equipment Regulation

Increasing use is being made of computers for the control of plants such as in an indirect control capacity i.e. providing information for the adjustment of conventional closed-loop controllers either normally or automatically.

In direct digital control, the computer controls the final control elements, alters set point and control parameters for the control loops at specified time intervals or when process variables exceed preset limits.

The computer can use inferred measurements as the controlled variables. Modified control algorithms including asymmetrical and non-linear gain, and a wider range of control constants can be used in direct digital control. In this way, common analogue controller disadvantages such as derivative kick or integral saturation are eliminated.

In equipment regulation, calculations are designed so as to control a single piece of equipment within an overall process.

2.2.5. Optimisation

Process efficiency, productivity, product distribution or product quality are optimised by the computer. Such techniques as linear programming, search techniques or statistical methods are used to define the operating conditions for process optimisation.

Process optimisation is probably the most important single operation performed by on-line computers. In fact, it is one function which has been the main factor in some of the most successful computer installations.

Models can be updated by the computer at periodic intervals to take into account deterioration factors such as decay of catalysts or fouling of heat exchangers. Some optimisation methods need reliable models and some do not need models at all. Since the original work of Box and Jenkins (8), a variety of techniques based on direct experimentation with the process have been developed.

2.2.6. Sequential Control

The capability of executing logical sequencies swiftly and reproducibly, and of making large numbers of process inputs and outputs, makes the computer adaptable and essential for tasks like high speed sequential control. The program executed by the computer provides a rigid framework for sequential control operations such as batch processes, start-up and shut-down, change of throughput or grade.

For planned experimentation where a high degree of reproducibility is very valuable, for instance, this function is invaluable. Also it ensures a higher degree of safety if conditions are critical.

2.2.7. Special System Functions (3)

These include fill-in-the blank type programs for updating and expanding the basic system functions programs, as well as alarm action programs developed to provide specific actions based on random events occuring in the process. The actions initiated by such programs are both process oriented and operator oriented and may include all or only some of the following actions:

(a) Activate - deactivate single alarm points or entire blocks of alarms.

(b) Activate - deactivate specific control loops

(c) Change control loop parameters

(d) Change coefficients in analog conversion equations

(e) Change the state of contact outputs

(f) Activate central computer programs and other special process programs.

(g) Provide print out or display on specified peripheral devices.

2.2.8. Commercial Data Handling

The computer may be used to produce documents for immediate use, such as consignment notes, and summaries and records for the commercial departments. These records can be produced in printed form for manual operations or as tape suitable for feeding into another computer.

It can also control actual loading operations as exemplified by the use of punched card by lorry drivers.

2.2.9. Management Calculations, Information and Background Capability

The computer can perform many functions for management information. Two of the most important functions are:

(i) calculations of daily production records for individual units and for the entire product,

(ii) developing economic reports for plant management.

Other functions such as production planning and scheduling based on sales demands or raw materials, also may be implemented. In some cases the computer has an important scheduling role. This usually arises in the control of large complexes where changes can occur in raw materials, services or throughputs. In this function there is usually rather less emphasis on dynamic and optimal features.

It is convenient in practice to include on-line certain technical and economic calculations in aid to management even though these can be done off-line.

2.2.10. Control by Learning

Control by learning is certainly not very widely performed by computers in industry as learning processes for computers are not well developed.

As applied to process control, learning could be achieved basically through association of cause and effect. This could be achieved by the controller learning through experimentation and observation which actions are most likely to result in an improvement of process performance. The controller can incorporate in this way, means for adapting the model to changes in the process characteristics.

However, despite great research interest in on-line adaptive modelling techniques, particularly determination of transfer functions by perturbations with psuedo-random binary signals and of state-variable models using the Kalman filter, there are very few practical applications yet.

2.3. Examples of Computer Control in Specific Chemical Industries

Even though the advantages of computer control have been recognised by major companies in the chemical industry for a long time, the limitations and shortcomings of the earlier computers retarded its implementation. Poor reliability problems and generally high installation costs were major setbacks to the early implementation of d.d.c. for instance. With the continuing design evolution of computers the door to the extensive use of both d.d.c. and general computer control has been opened.

A few examples of specific applications of computer to specific industries are briefly reviewed here.

2.3.1. Computer Control in the Cement Industry

As of now, there is very little d.d.c. control in the cement industry but mainly computer control. Most computers in operation in cement plants perform the raw material proportioning calculations and several employ on-line analysers to close the loop. Because of its importance to the quality of the cement and because of the adverse effects of poor blending control on kiln operation, the first area to receive attention in computer application in the cement industry is usually the raw material preparation. Logging of kiln operating data, and supplying the operator with alarm messages for unusual or dangerous conditions, is usually the next application and most current installations include these functions.

The centrallized operating philosophy employed in the cement industry - and the long time lags encountered during the process - lend themselves readily to direct digital control with manual back up. The material blending requirements and the complicated interactions of kiln parameters also contribute to making this an ideal process for d.d.c.

The first applications of a digital computer were in the automatic adjustment of set points in analog systems (9). To achieve proper performance, mathematical models were created. These models are not producing the desired results, so companies are now turning to an empirical approach. The delays created by the inadequacy of mathematical models have hindered most attempts to apply digital computers to a higher level of control. Process measurement and identification problems currently preclude automation.

The first computer reported to have been installed in a cement plant (10), in fact used a linear programming algorithm to determine the least cost of quarry materials. A similar technique is used at Ciments La Farge Azergnes Valley plant near Lyons , France.

In Tokuyama Soda Company's Nanyo, Japan, plant, for instance, continuous proportioning and blending are performed with the aid of a digital control computer (11). Limestone, clay gannister, and stag feeders are set directly by the computer based on the results of a matrix inversion algorithm.

Generally, computers are being used to assist in the proportioning of raw materials, the operation of the rotary kiln, and the raw material and product grinding operations. Several different approaches (11-23) have been used to achieve the benefits from computer control of the cement kiln. However, difficulties in obtaining good measurements and identifying kiln dynamic characteristics have been the limiting factor in realizing the ultimate potential of process control computers in cement kiln operation.

Computer control of grinding involves primarily the monitoring of those variables that can be measured (mill, elevator, separator power and temperatures) and adjusting the fresh feed rate to obtain maximum production at the specified product size distribution or related surface area (24). The separator settings can normally be adjusted manually. Control algorithms vary but are usually simple (25,26). Studies have been directed towards the modelling of the crushing, grinding and separation phenomena, primarily on the basis of the principles of physics and probability theory (27-30).

In a particular installation most recently reported (31), the computer upgrades the plant measurements and calculates inferred or indirect measurements thus solving the problem of difficult important measurements. For instance, the dry solids flows were calculated from the raw materials wet solids flows, using laboratory water analyses; and the fuel oil flow was calculated, using the oil temperature measurement, to correct the flow. In addition all types of quantities - instantaneous, or averaged, including plant, laboratory and inferred measurements, set points and valve positions were logged by the computer. The plant measurements were scanned for alarm condition. Several calculations useful for management such as clinker output, fuel consumption per shift, and clinker compositions were also carried out by the computer.

2.3.2. Computer Control in the Pulp and Paper Industry

The application of digital computers to the pulp and paper industry has been mainly for supervisory control. The application of d.d.c. has been relatively cautious.

Generally, most of the successful development work has been oriented towards the solution of the following problems:

(i) dead-time processes

(ii) feed forward control

(iii) non interacting control

(iv) automatic tuning and

(v) calculated variable control.

A pulp and paper mill contains a wide variety of processes - some with rapidly changing variables and some with long time lags. The processes with rapidly changing variables do not lend themselves to d.d.c., using relatively inexpensive manual back-up. Most companies require analog back up which is relatively expensive. Also companies are reluctant to put all of their faith into one piece of d.d.c. control equipment - without analog back up - especially on a paper machine where a loss of production is very expensive. However, one paper machine with 28 loops on d.d.c. has proved successful (9).

Brewster and Bjerring (32) have dealt in great detail with control computer application in the pulp and paper industries mainly in the U.S.A. but also with significant developments elsewhere from 1961 to 1969. They carried out a detailed review of the control problems and computer control solutions which have been used in a number of important parts of the process.

The function of the Kamyr Digester is to delignify chips. The measure of this is the terminal K number. Keeping a constant K number is the object of the Kamyr regulatory control. The control of this K number has been effected through the control of the wood specie, the initial alkali - to - wood ratio, the initial liquor - to - wood ratio, the initital temperature of the cooking zone, and the residence time in the cooking zone. Further and more detailed information is given in references (33-36).

One of the most widely published and probably the most sophisticated integrated system in the industry is that consisting of two computers installed in Sweden at the Gruvon mill of Billeruds, in joint projects with KMW and IBM (37-49). In addition to the theoretical developments in the field of stochastic control (38,43) and production scheduling (40) an interesting approach to interpolation and extrapolation of real sample quality data, involving Kalman filtering is reported (39,44).

Of interest also is the use of a small slow 8K Elliott ARCH 1000 computer at the Wolvercote Paper Mill, Oxford in 1965 (50,51). This system utilizes digitally directed analog control. A major characteristic of this system is the low capital cost and small number of technical personnel involved.

A rather more specialised development has been reported between English Electric and The Grove Mill Paper Company (52). Here a specially developed combination of analog computing and logic elements is used to perform a number of functions.

2.3.3. Computer Control in the Iron and Steel Industry

In the iron and steel industry, very few digital controls have been applied for the most part. Digital computers are being applied to electric furnace melt shops but only in power demand is d.d.c. being applied. Leading candidates for d.d.c. are blast furnace stores, reheat furnaces, soaking pits, coke ovens and continuous casting operations.

In one computer installation reported (53) the computer has four major functions: the keeping of comprehensive records of each cast of steel produced; the processing of this data to issue reports to various departments of the works; giving a direct read out facility to each of three Quantovac vacuum spectrographs; and predicting using a mathematical process model of the charge and addition weights and oxygen volumes required for each cast. The mathematical model used for these predictions is a combination of theoretical balances with statistical regression on actual plant performance. Considerable accuracy was obtained with this model.

In another (54), an operational computer system controls data flow from a central position in the plant hierarchy. It communicates in one direction with process control and manufacture, and in the other with planning management. In this application the operational computer, given desired final product and its quality, arrives at decisions on selection of available cooking equipment, choice of blooming or slabbing, and choice of rolling with one or with two heats.

Koppel (9) suggests that the reluctance of the iron and steel industry to accept d.d.c. more quickly can perhaps be traced to the lack of success of the computer in controlling the basic oxygen furnace.

2.3.4. Computer Control in the Glass Industry

The glass industry is one industry which is known to have whole-heartedly embraced d.d.c. techniques and are known to be applying the technique to many new installations. The large thermal storage type process operations used in this industry are readily adaptable to d.d.c. Unfortunately very little has been published in the open literature on computer application in this industry as of now.

The illustrative examples of computer control in specific industries above is not a comprehensive representation of such known applications. Some industries have published a lot of such applications in the open literature whereas others still treat such information as classified. Some publications do not contain or give out much information and some have been more on known conventional application lines. With such publications it was not considered worthwhile to include them in this brief survey.

The overall picture that has emerged from the study of the applications of the computer to the chemical industry is that in some cases computer application has been justified by some obvious single function for the computer to perform such as alarm, scanning, optimisation or feedforward control. This picture would fit better, earlier installations as more recent installations have required more than one function to justify them.

Movement now is towards larger and more complicated plants and plants in the former category could be in the minority. With increasing complexity and sophistication of the computer, currently, the computer needs many useful functions to justify it.

2.4. Functions Performed by the Human Operator

The computer has been used principally to complement the human operator. For the full exploitation of the potential of on-line computers, particularly for the optimum division of labour between man and the machine, a study of the functions actually performed by the human operator on the chemical plant is a necessary step.

Generally, the functions performed by the operator are more varied than the corresponding functions currently carried out by the computer. The main reason for this being the fact that man is capable of creative thinking and high-speed correlation but is slow at calculation, reading and writing and is also error - prone whereas the computer has limited intellectual power but is capable of split-second calculations, reading and writing, rarely makes mistakes but also has uncertain reliability.

The choice of terminology for the description of the functions performed by the operator can be similar to those of the computer to bring out the fact that the computer principally complements the operator. The overlap in the functions performed by the operator will not give similar sharp distinctions. The functions performed by the operator can be adequately described to bring out the similarity and main differences with computer functions under the following headings;

(i) Control
(ii) Process optimisation and back-up
(iii) Alarm scanning and malfunction detection
(iv) Learning
(v) Manual operations

2.4.1. Control

The basic mechanism of on-line control is one of comparing the measured status with the desired status; making a decision based on on the comparison; taking action based on the decision; which in turn causes a reaction in the process.

The basic function of the plant operator is to keep the plant running at the desired operating conditions and this involves essentially control. To carry out this function involves measurement, calculation, logging and control, especially.

The plant operator normally carries out a wide variation of measurements both direct and inferred. The off-line analyses he carries out, the samples he takes are all variations of the measurement function. The different variations give either direct and/or inferred measurements. Sometimes he obtains indirect or inferred measurements from variables which are measured directly as exemplified by inferring reaction rate from a pH measurement.

The calculation function the plant operator carries out is basically subsidiary to the other functions. Most of the calculations are either concerned broadly with inferred measurements or with a mental model or correlation.

As the operator gets about making sure that the plant is running at the desired operating conditions, he normally records information, usually instrument readings. This he does partly to provide a proper work load and to monitor the process more efficiently. He also logs on paper certain events which the system cannot pick up, such data as actual changes made and why. Very often, some of these are the most important information on plant operation and can sometimes provide information for interpreting his control of the process.

In the actual control of the plant, the operator can not only understand the system, but he can also learn how to do many things. As one variable changes, he would change the setting of another variable because he had learned that this helped stabilize the process. Based on experience, he would anticipate load changes and help the system to meet the new demand. At different loads he would make different adjustments again based on experience. All this can be described in terms of different types of control terminology. Control engineers have invented these relationships and now refer to them in terms such as 'non-interacting', 'feed-forward' and 'adaptive'. These functions have in fact always existed in the minds of the operators and he has always carried out the different types of on-line control.

2.4.2. Process Optimisation and Back-up

The basic mechanism of process optimisation and back-up is one of intelligence systems (55,56) outside of the on-line control loops making observations (such as observing other measurements, direct or inferential, or making calculations, mental or machine, assisted) which the on-line system cannot make; comparing these with the measured status, determining an inferred actual status (57); comparing the inferred actual status with the desired status; and making a new decision based on the comparison. These are not new ideas as in all control situations, prior to attempts to automate, these functions have been performed by the operator, assisted by safety or interlock systems. In non automated systems it has been, and in automated systems it must be, possible for the operator to intervene without confusion.

The main technique used by process plant operator for optimisation is a form of perturbation or hill-climbing and his application of it is crude, even though he is usually able over the long run to come quite close to the optimum for a given set of conditions. When it comes to short term fluctuations in the optimum, he is less able to cope.

2.4.3. Alarm Scanning and Malfunction Detection

Usually, as the operator gets about his work, he quite unsystematically carries out some alarm scanning and malfunction detection. Much of the effort here is usually devoted to trying to forestall trouble.

He performs a variety of checks on instruments readings. These checks may be based on current or past behaviour of the instrument, for instance, off-scale, completely constant, excessivley noisy readings or readings which do not show expected relation to other measurements may be suspect. Using all human sensing facilities: sight, hearing, smell and touch, he checks continuously on the working of units such as pumps, fans, control valves and such process equipment which can go wrong and which are not instrumented. This in addition to, for instance, scanning inferred measurements to make sure that no variables have reached alarm limit. He usually has his own personal set of early warning conditions at which he starts to take action. This function is one of the operators more routine functions.

2.4.4. Learning

Learning is the most creative part of the operator's task and virtually the whole range of his activities are covered by the learning function.

The main asset here is that when the system feeds out information of a dynamic nature, man can learn and advance at the maximum rate. He usually starts by building up a mental image of the process, by recognising patterns and by devising algorithms: From a knowledge of the usual behaviour of his instrument readings, the operator can recognise divergencies from this either due to abnormal plant conditions or instrument malfunction. He learns to take early action to prevent the development of alarm conditions and when they occur, to cure them. Most of the operator's experience is derived from learning.

2.4.5. Manual Operations

It is the manual operations carried out by the operator that may make him indispensible for some time yet to come. Apart from the functions already mentioned, manual operations of various kinds make up his other work. These may be associated with measurement, such as sampling; with flow control or change-over, such as hand valve adjustments; with process additives such as catalyst addition; with mechanical adjustment, such as tightening bolts; or with replacement of deteriorating items such as filters or spent catalyst.

Not all of the functions of the operator described here are carried out in every case. This is due to differences in the nature of the process controlled and to differences of policy in what the operator is permitted to do and what should be programmed. Thus in a nuclear reactor for instance, the emphasis may be on alarm scanning and analysis, there may be strict limitations on the actions which the operator can take and the programming may be very comprehensive.

Nevertheless, an insight into the functions performed by the process control computer has been attempted.

2.5. Problems of total Computer Control

A general learning algorithm remains a daunting problem for total computer control. The complexity of industrial systems and the limitations of human decision making prevent an explicit application of formalised logical or numerical routines.

The operator sometimes knows how he makes the decision, but he does not usually know how to communicate his full action to someone from a different discipline. He may describe the action which he takes, but the decision-making process leading to the action is far more complex as it correlates all available explicit and implicit information. Since sensors, switches etc. are not perfect devices, he often makes correct decisions based on conflicting and imperfect information.

Any machine system designed to make these decisions as the human operator does, must operate on the same information and make the same, or as good, correlations and evaluations prior to taking action.

A real bottleneck in bringing, a computer controlled installation into being is the manpower needed to do the jobs. Availability of systems engineering talents and the associated costs are factors to be taken into consideration, especially with the decline in computer costs and more than compensative increase in labour costs.

The last and not the least important problem of complete computer control is the achievement of the type of instrument reliability required.

2.6. Possibility and Direction of Computers and Computer Control Development

As confidence grows in the reliability of the modern on-line computer, and in the handling of the versatile software associated with it, it can be expected that the use of on-line systems will rapidly increase. These will not be confined to plants in the chemical industry, but may extend for instance to the shift laboratory and the research department, taking over many of the routine functions done by the laboratory and the staff and giving more accurate results sooner (57).

Recently, there has been discernible trend towards making greater use of minicomputers, because, for the same power, computers are now much smaller and cheaper than they were, say, five years ago. At the same time, there is growing awareness of the merit, in some circumstances, of using a compact, semi-dedicated machine in preference to a small, and possibly busy part of a bigger machine. A survey of digital computers available in the U.K. and costing less than £10,000 has recently been made (58).

New concepts of reliability, modularity and high-speed real time structure and software are boasted by the small digital computer manufacturers. Small economic systems will open up the possibility of control for medium-to-small sized plant and will also provide operators of large industrial plant with much greater flexibility. In this latter area, a rapid growth in small dedicated d.d.c. systems operating in multi-computer configurations running under the control of a larger central computer that provides a background data processing capability, is expected (59,60).

Some work is being accomplished in the field of hierarchies of computers. This concept involves the use of one high powered executive computer to control a number of small computers which operate in satellite fashion. Each small computer can operate automatically and may be located in physical proximity to a process. The master computer has the function of scheduling and coordinating the smaller ones. This approach has already been implemented in the information system and data display area. Eventually the executive computer will schedule the functions between control information and display while the satellite computers retain localised, low level capability functions.

Considerable advances have been made in large-scale integrated circuitory in which from 100 to 200 logic functions are packaged in a ½ by ¾ inch chip. This technology permits reduction in the size of a complete main frame. It will also reduce the price and greatly improve reliability since the number of connections are reduced. This concentration of logic functions will also reduce propagation delays.

Improved displays and better operator interfacing between the computer and the process are a prime consideration in utilizing computer techniques. There is a trend towards more cathode ray tube displays, especially with the development of coloured cathode ray tubes. The use of light pens to make changes in instructions to a process through an operator console should be in effect before long.

Overall, the general direction of development for both the chemical plant and the computer is one of increasing complexity, sophistication and versatility.

2.7. Instrument Malfunction Detection - its Selection for Development

The number of computers on chemical plants now is large and the rate of installation seems to be still growing very rapidly. The current trend in process plants and computers is one of increasing complexity and sophistication. For some processes such as for the production of high quality products and for some highly integrated systems computer control could be regarded as essential.

In the present applications of the computer, the full potentials are not being exploited in most cases; the majority being used for functions such as data logging with the minority perhaps about a fifth of present installations only being truly on-line in the sense that they send out control signals to adjust the controller set point or control valves.

At this stage of computer control new projects are not approved unless they appear to be profitable in some other way, as the stage when computer control might be justified as an experiment must now be over.

Probably to a considerable extent, due to the relatively undeveloped state of the technology at the time when these systems were put in, full potential of the computer was far from exploited even in the systems considered highly successful.

Considerable improvements have since been made on making the equipment cheaper and more reliable as most effort seems to have been concentrated in this area. For the already installed systems this does not improve the exploitation of the computer capabilities, neither does it suffice to ensure that computers be installed as a matter of course.

Even though there is great scope for and value in developing the existing computer control techniques, there is still need for extending the computer's activity to some of the more routine functions carried out by the operator.

There is scope and immediate need to extend the range of useful functions which on-line computers can perform - a need for imaginative development of additional useful functions.

The retention of the human operator as of now and probably for a considerable time to come must be assumed and therefore emphasis should be placed on the allocation to the computer and the operator of the control tasks to which either is most suited.

There is a continuing tendency for the operator to take over the supervision of larger amounts of plants with the result that the attention which he can devote to a given amount diminishes. More recently, he is assuming simple maintenance functions which previously were done by other workers.

In the new situation, it is important that the operator should be well informed about abnormalities in his plant by correctly formulated and appropriately presented messages. If the routine part of off-normal signals or instruments malfunction detection should be done by the computer, the operator can then concentrate on more difficult and more creative jobs for which he is better suited.

Perhaps interplay between man and the machine may be the right way to use the relative strengths of both..

The overall improvement of the instrumentation and control system is one useful function which is relevant to all plants and is a useful added function which the computer can readily perform.

Instrument malfunction detection is a specific aspect of this function.

The prospects of signficantly upgrading the performance not only of the instrumentation but of the plant items as a whole and the desirability of even more reliable installations are some further considerations that make an attempt in this direction worthwhile.

With growing literature on learning methods and pattern recognition, it is time to try to develop these techniques and to apply them to the chemical industry. Instrument malfunction detection is one very relevant field to which these can be applied in the chemical industry.

The meaningful execution of computer functions - logging, alarm scanning, control, optimisation etc. depends on accurate and reliable instrument signals. The implications of malfunction detection are for ensuring this.

At the moment, most malfunction detection is done manually and unaided, by the process operator. The process operator might be superior in specific aspects of malfunction detection requiring intelligence, such as pattern recognition, decision making and taking certain corrective actions that involve manual operations. The routine tasks of off-normal detection, however, can readily be taken over by the computer. In this way a better, function allocation between the machine and man can be achieved leading to a more optimum use of both.

3. INDUSTRIAL SURVEY OF INSTRUMENT RELIABILITY

3. INDUSTRIAL SURVEY OF INSTRUMENT RELIABILITY

3.1. Introduction

Still at the formative stages of the project the need for some data on instrument reliability in the chemical plant environment was realised. These were not available in the open literature.

Also, to realise the objectives of the project, a very necessary first step was to determine what instruments do fail, their mode of failure and their probable behaviour during failure. For the chemical industry, because of the importance and relevance of the working environment, it was very desirable to get the information in the actual working environment. The main difference between the chemical industry and other industries is the severity of the environments to which the instruments can be subjected.

Such information on failure of instruments is not only relevant to methods of instrument malfunction detection but also has very wide implications for the improvement of instrument reliability and maintenance strategies in general.

It will provide background in meeting future engineering requirements and offer clues to inherent weaknesses of materials and manufacturing processes. The failure of an instrument or instrument system is caused by the failure of its components. If the relative rates of failure of these is known, it is possible to design instruments or instrument systems which are less likely to fail and to predict the probability of failure of particular instrument designs. Similarly, if the failure frequency of individual instruments is known, it is possible to design more reliable control instrument systems.

With these considerations and insight gained from preliminary surveys, an instrument reliability survey in the chemical plant environment was initiated with a view to getting some statistically meaningful data which could be published and which will help fill the vacuum created by the dearth of such information, at least in the open literature.

The survey was in two stages, the first being preliminary surveys from which evolved the survey which is reported here.

The problems of collecting and publishing such data were not easy ones. Detailed information on the preliminary surveys mentioned, for instance, cannot be published within the terms of reference of the agreement to carry them out. The author spent some time visiting some chemical works and studying available information on the failure of instruments. The preliminary surveys were a major guidance in the further narrowing down and development of the project.

Industrial secrecy and existence of usable systems of data collection were major problems in getting cooperation and in carrying out the survey.

This chapter is essentially a report on the survey carried out.

The survey covers the main measuring instruments (pressure, level by float as well as by pressure, differential pressure, flow, temperature, density, viscosity, thermal conductivity; analytical); controllers; control valves. It does not cover indicators or recorders.

Data on the reliability of some 9,500 instruments in 3 chemical works with a total operating time of about 4,500 instrument - years have been obtained. For most of the instruments surveyed data have not previously been available, but the data obtained are reasonably consistent with such data as have been published.

Of special interest is very useful information on the nature of the failures of the instruments obtained from one of the works.

This was in the form of comments by the operator on the log tickets. A representative cross-section of these comments is presented in section 3.9.

3.2. Literature Survey

Very little failure rate data for instruments on chemical plants has apparently been published in the open literature. The available information is summarised in Table 3.1. Most of it is based on the publications of the U.K. Atomic Energy Authority, which has pioneered work on instrument reliability in this country.

The failure rate quoted for solenoid valves in Reference (61) is based not on field tests, but on the specification to which industrial solenoid valves are designed. The difference between the two failure rates quoted for temperature trip amplifiers in References (62,63) is at least partially explicable by the fact that the first is a much older design than the second and by the sensitivity of the failure rate of these instruments to performance required, extra facilities provided, such as low margin alarm, and operating conditions. The references quoted do not give information in the number of failures recorded or on confidence limits, except for Reference (63), which gives the latter.

Recent work by the I.S.A. (64) on the number of hours per year required for the maintenance of particular instruments is also relevant, but these data do not appear to correlate directly with failure rates.

Table 3.1.

Previously Published Data on Instrument Reliability

Instrument	Failure Rate		Ref.
	Actual Fault/ year	Assumed Fault/ year	
Control valve (p)	0.25	-	62
Solenoid valve	-	0.26	101
	-	0.1 (design)	61
Controller (p)	0.38	-	102
Differential pressure transmitter (p)	0.76	-	102
Variable area flowmeter transmitter (p)	0.68	-	62
Thermocouple	-	0.088	101
Temperature trip amplifier, type A	2.6	-	102
Temperature trip amplifier, type B	1.7	-	102
Temperature trip amplifier -	0.1	-	63
Pressure switch	0.14	-	62
Oxygen analyser	2.5	-	62
Tachometer	-	0.044	101
Stepper motor	-	0.044	101
Pressure gauge	-	0.088	101
Relay (p)	0.17	-	102
Indicator (moving coil meter)	-	0.026	107
Recorder	-	0.22	101

(p) : pneumatic

(e) : electronic

3.3. Methodology of Survey

Most firms have a system of maintenance job slips and some have also instrument record cards, which could be made the basis of a data collection scheme. With the limitations of time and the difficulties, delays and complications of initiating a new data collecting scheme, already existing methods and organisations for reliability data collection within a given firm were used. Where these were inadequate for the purpose, the firm was avoided. The systems used could be improved but in the circumstances were the best and were considered adequate. From the shortcomings of existing systems could evolve new and better schemes or at least improvements on existing schemes.

In the survey, the instrument records have been used to determine how many instruments of each type were at risk and the instrument job sheets to determine what failures have occurred and any other useful information such as the operator's comments.

3.4. Definition of Failure

From the British Standard concepts of failure (67):

A failure is any inability of a part or of an equipment to carry out its specified function.

An item (any part, sub-system, system or equipment which can be individually considered and separately tested) can fail in many ways but these failures can be generally classified either as:

(i) Misuse failure: when the failures are attributable to the application of stresses beyond the stress capabilities of the item or

(ii) Inherent weakness failure: when the failures are attributable to weakness inherent in the item itself when subjected to stresses within the stated capabilities of that item.

The failures can be sudden or gradual in time. Sudden failures are generally failures that could not be anticipated by prior examination whereas gradual failures are failures that could be anticipated by prior examination.

The degree of failure could be partial or complete. Failures resulting from deviations in characteristic(s) beyond specified limits not such as to cause complete lack of the required function can be classified as partial failures. Failures resulting from deviations in characteristic(s) beyond specified limits such as to cause complete lack of the required functions are classified as complete failures. The limits referred to in this category are special limits specified for this purpose.

The combination of failures could be classified as Catastrophic or as a graceful Degradation. Catastrophic failures, here, are failures which are both sudden and complete, and graceful Degradation failures are failures which are both gradual and partial.

An important type of failure which does not quite fit into any of the above categories is latent failure. These are failures which, even though they may not be detectable could lead to a catastrophic failure. In fact they may be considered as the main causes of sudden failure.

The question of fail to safety or to danger is also relevant. Any of these incidents is a failure.

In the present work the only practical definition and one which has been used is that the instrument is not working to the process operator's satisfaction.

3.5. Organisation of Survey

The survey was carried out in three large chemical works, referred to as A, B, C for security purposes. Works A is a large works producing a wide range of heavy organic chemicals. Works B makes heavy inorganic chemicals and consists of an acid, a sintering, a furnace and a water treatment plant. Works C is a glass works divided into two plants.

The instrumentation in Works A is pneumatic except on one plant, on which electronic instruments are used. Two of the four plants in Works B are computer controlled and electronic instruments are used on all plants. In Works C both pneumatic and electronic instruments are used.

At all three works preventive maintenance is carried out as well as repair of failed equipment. At Works A preventive maintenance comprises three quarters of the work. There are periodic plant shut downs at all three works, the intervals were between six months and two years at Works A and a year at Works B and C, with lesser shutdowns fortnightly at Works B.

The organisation of and information available about the instrument repair were slightly different at each works. At all three works there was a full system of records, so that it was possible to determine how many of each type of instrument were at risk during the survey period, but the information on failures was more variable. At Works A the job sheets gave information on the plant and on the type of instrument which had failed, but unfortunately in the case of measuring instruments it was sometimes possible to determine accurately only the general class of measurement (e.g. flow) and not the specific type of measurement tranducer (e.g. differential pressure transmitter). In every other respect, however, the quality of information available from these job sheets was high. This works has yielded not only the greatest quality of crude failure data, but also the detailed information given later on failure in particular equipment such as control valves and impulse lines and on the effect of different environments.

At Works B the job sheets gave information on the plant and on the type of instrument, including measuring instruments, on which failure occurred. The information available on the sheet in this case, however, was limited to the fact that there has been a failure.

At Works C the information given by the job sheets was similar to that at Works B, but the quality of the information was not quite so good, so that rather a large proportion of faults were attributable only to a control loop in general and not to any particular element in it.

The number of instruments included in the survey and the period of the survey at each works are as follows:

Works	No. of Instruments	Period of Survey
A	7998	October 1 1968 - April 11 1969 = 0.477 yr.
B	951	October 6 1969 - March 23 1970 = 0.398 yr.
C	443	July 1 1968 - May 13 1969 = 0.858 yr.
		March 2 1969 - August 15 1969 = 0.458 yr.

The survey covers a different period in the two plants in Works C.

3.6. Statistical Basis of Survey

The statistical basis of the survey is important for the analysis and meaningful interpretation of the data obtained. The statistical basis of the analysis of the data obtained here derives from reliability theory considerations.

When an equipment is first put into use any inherently weak parts usually fail fairly soon. The early failure rate may, therefore, be relatively high, but falls as the weak parts are replaced. The inherently weak parts may be because the instrument is not standard, has not been fully tested or has been incorrectly installed. There is then a period during which the failure rate is lower and fairly constant, and finally the failure rate rises again as parts start to wear out. This is illustrated in Fig. 3.1., where the high rate of initial failures can be seen. Although the steady rate is often shown as a straight line, in practice it will be wavy and in good (reliable) equipment it may be a long time before the wearout period is reached. The part of main interest is the constant failure rate period. The three parts may be defined as follows: early failure period, when the failure rate is decreasing rapidly as when the equipment is being run in and the failure rate is initially high but declining; the constant failure rate period during which the failure occurs at an approximately uniform rate as when the equipment is operating normally and failure rate is low and fairly constant; the wear-out failure period during which the failure rate is rapidly increasing due to determination processes as when the equipment is wearing out and failure rate is high and rising.

The data obtained in this survey is assumed to correspond to the constant or chance failure rate period. Since the survey was carried out for a fixed time interval during which failed instruments were repaired or replaced, the data can be treated as data from a fixed-time test with replacement of failed items.

If the failure rates measured are significantly affected by either infant mortality or wearout, the assumption of chance failure would not be strictly valid. The instruments considered here are all standard types and are quite exhaustively tested in the works prior to installation. Added to the fact that almost all the instruments had been operating for at least a year, it is believed that infant mortality is not a significant factor. However, the possibility of an effect due to wearout is perhaps rather greater. In Works A there was a wide spread in the age of the

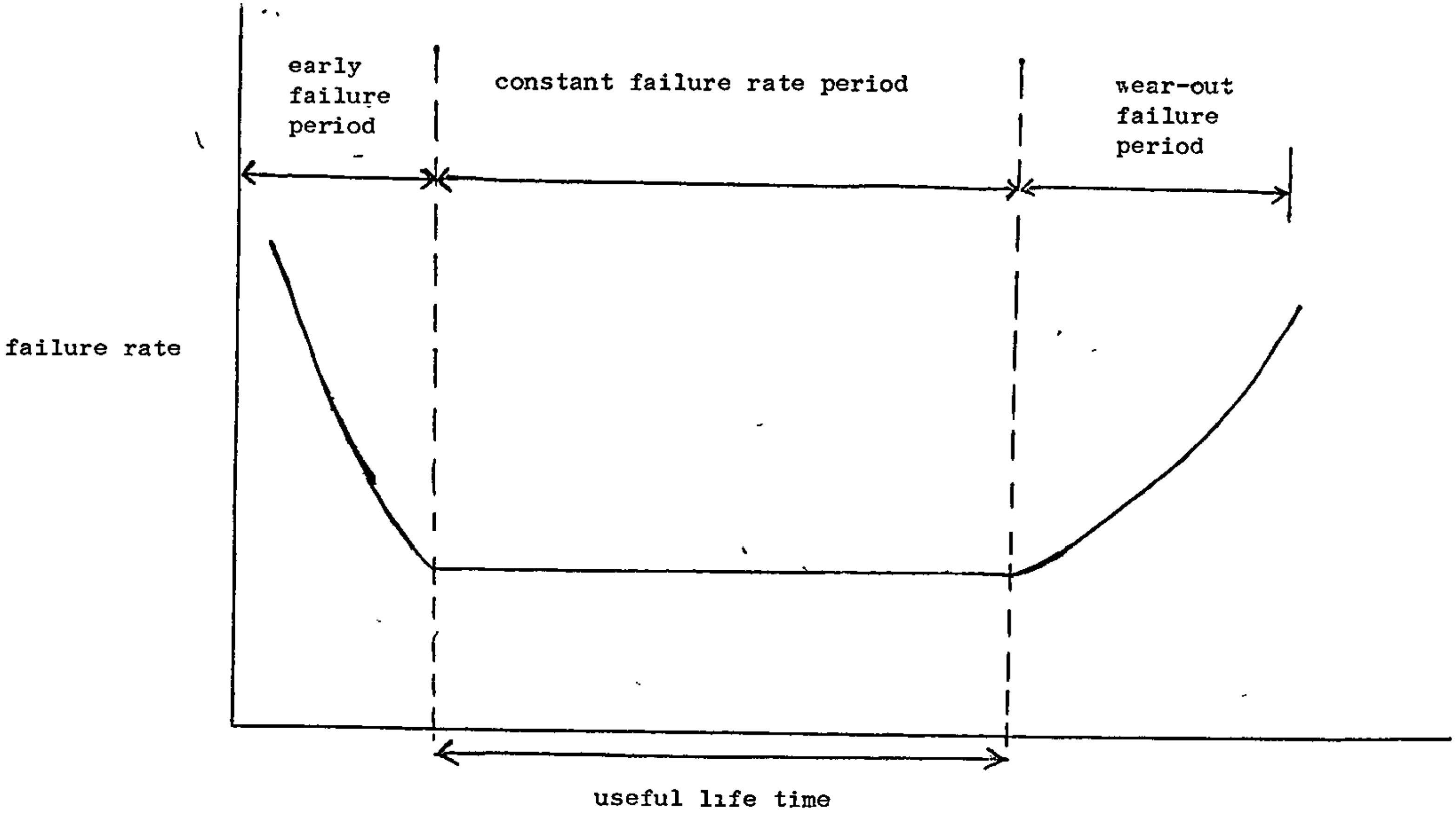


Fig. 3.1 Bath tub curve

instruments, some being about 15 years old, while in Works B and C very few instruments were more than 5 years old. The data obtained may, therefore include some wearout failures. The relevance of this would depend on the use to which the data are to be put, for instance, if it is desired to obtain data on the actual failure rates of instruments in a given works with a given maintenance policy, then the inclusion of some wearout failures is presumably not serious.

The data on instrument failure rates were obtained by determining the number of each type of instrument at risk and recording the number of failures over a fixed interval.

When the number of instruments at risk and the number of failures recorded is small, there is a degree of uncertainty about the failure rate calculated from the data, so that it is necessary to assign confidence limits to it. Graphs and formulae for the calculation of the confidence limits for the constant failure rate period are given in the literature (65, 66).

Most of the data obtained are presented even though the number of instruments at risk or the number of failures recorded is small. In most such cases the type of instrument involved is such that other works are not likely to have many either. The main hope of obtaining data for such instruments is in the publication of data by a number of firms.

The data are presented as annual failure rates. At Works A the job sheets usually gave enough information to classify a fault as a definite failure or as an incident. Thus a failure was recorded if the process operator stated that the instrument had failed, regardless of whether the instrument fitter found a failure, unless the fitter showed positively that the instrument had not failed and that the matter could be explained in some other way. A failure was also recorded if the operator was uncertain, but the fitter found a failure. All other cases were recorded as incidents. In particular, cases were recorded as incidents where the operator required a check, but the fitter found no failure. In cases where a calibration was requested small errors were recorded as incidents, and large errors as failures. The definition of a large error was taken arbitrarily as 2% full scale or 2^{o}C or 0.1 pH. On this basis 77% of the faults at this works were definite failures and 23% were incidents. At Works B and C it was not possible to distinguish from the job sheets between incidents and failures. The data given here are, therefore, simply in terms of total faults.

When some failures records indicated that an instrument was exhibiting a repeated or intermittent fault over a short period, such cases have been counted as a single failure.

In analysing faults on those plants in works where there is an on-line computer care has been taken as far as possible to avoid assigning to the instruments faults which are properly those of the computer.

3.7. Failure Rate Data

The instruments at risk, the number of faults and the annual failure rates for the three works are given in Tables 3.2.- 3.4. The environment factor quoted is explained in the next section.

As has already been mentioned, there was some difficulty at Works A in determining from the job sheets the type of measurement transducer involved in failures of flow, level and temperature measurement. For this works, therefore, the overall failure rates for these measurements are quite accurate but those for particular types of tranducer are less so.

In analysing the job sheets it was not always possible to assign the fault to a particular instrument in a control loop. In such cases it was necessary initially to assign the fault to the loop as a whole. The proportion of cases of this type was low in Works A, rather higher in Works B and higher still in Works C. These are the faults listed under 'control loop'. These faults were then assigned to the individual elements in the loop by allocating to each element additional faults proportional to those already assinged to it. The original data are given in brackets in the tables and the data after this correction are shown without brackets. The effect of this procedure on the failure rate data obtained is quite small.

In table 3.4. the relationship between the number of instruments at risk, the number of faults and the annual failure rate is complicated by the fact that the survey covers different periods in the two plants. The total number of instrument-years at risk is therefore given in a separate column for each type of instrument.

The temperature measuring elements listed include those on temperature controllers, but not those on the temperature transducers, so that the total number of actual elements is the sum of those quoted as such and of the temperature transducers. In works B and C some temperature measurements, such as those taken inside furnaces or in metal vapour, were not included, but the conditions in which all measurements quoted are taken are still more severe than in Works A. The pyrometer failures recorded in Table 3.4. are not all strictly failures of the measuring instrument itself but include adjustments to the field of view.

Impulse lines on analysers, on pressure and differential pressure transducers and on pressure switches connected to process fluids are listed separately. The lines for differential pressure devices are counted as one item, not two. The purge systems given in Table 3.2. consists of purge lines and small rotameters and are installed on differential pressure transducers measuring liquid flow and level.

The tables show that there are considerable differences in the failure rates obtained for certain types of instrument at the three works.

Most of these differences are explicable in terms of sample size or of environment, which is considered in the next section.

The data for all three works are given in Table 3.5. For most types of instrument the data from Works A, which has much the largest number of instruments, are dominant. This is satisfactory in that this works is probably the most typical of the chemical industry as a whole.

In addition to determining the overall failure rates of the instruments an attempt has been made to obtain data on the nature of the failures in the limited number of cases where this was possible.

In table 3.6. are given data on the failure rates of air supplies, pneumatic and electrical connections. The number of items has been com puter in the following way: The number of air supplies is obtained by assigning one each to control valves, valve positioners, pneumatic controllers or current pressure transducers and pneumatic-output measurement transducers; the number of pneumatic connections by assigning one each to control valves, power cylinders, valve positioners and pneumatic output measurement transducers; and the number of electrical connections by assigning one each to current-pressure transducers, electrical output measurement transducers and temperature measuring elements. These failures are not additional to those given in Tables 3.2 - 3.5.

3.8. Effect of Environment

The method of installation, working environment (corrosion, erosion, vibration) and operating conditions (temperature, pressure) all affect the performance and reliability of an instrument. In a chemical plant, the environment factors are even more important than any other considerations particularly as regards the location of the instrument and whether it is in contact with process materials or not. An instrument may be located in a clean control room or on the plant, where it may be exposed to adverse conditions of temperature, humidity, corrosion, vibration or dust. In a control room and often on the plant it is in contact with instrument air only, but also, on the plant it is frequently in direct contact with process materials fluids or solids. These materials may be relatively harmless or very aggressive - hot, dirty - reactive, corrosive, erosive or prone to freeze or polymerise.

The environment conditions in the three Works A consists of a number of different plants in some of which the fluids are relatively clean (air, water, steam) and in others dirty or liable to block. The overall environment in this works, as regards instrument location, general plant conditions and types of process material, is considered to be very typical of heavy organic chemical plants. Two sets of data obtained in Works A have, therefore, been used in an attempt to arrive at some quantitative estimate of environment.

Works B is an acid, a sinter, a furnace and a water treatment plant. The environment on the first three of these is bad, owing mainly to acid corrosion, solids handling, high temperatures, so that the overall enviornment in the works is considerably more severe than in Works A. Works C is similar to works B but a large fraction of the instrument nominally mounted on the plant consists of equipment for the control of flow of furnace fuel oil and air which is housed in clean rooms adjacent to the control room.

Table 3.7 shows some common types of instruments, grouped according to whether or not they are in direct contact with process fluids. The failure rates of the first group, which are in direct contact with process fluids, are rather similar and have a calculated weighted average of 1.15 faults/ year, while those of the second group, which are not in direct contact with process fluids, are again rather similar but have a weighted average of 0.31 faults/year. Control valves and temperature measurements, although in contact with process fluids, were found to have lower failure rates and are listed separately, while analysers are not listed at all. The second group includes instruments which are normally located in a control room and others which are normally located on the plant. The difference in failure rates between the two appears to be rather small. What the table does bring out is the large difference in failure rates between those instruments which are in contact with process fluids and those which are not

Table 3.8 gives data which offer a comparison between two types of instrument on contact with clean and dirty process fluids. This suggests that the failure rate of an instrument in contact with a clean process fluid differs little from that of an instrument which is not in contact at all, but that the failure rate of an instrument in contact with an aggressive process fluid is much higher. It also implies that the failure rate of the first group of instruments in table 3.7 is determined mainly by those in contact with aggressive fluids.

The data given in these two tables suggest that as a first approximation the severity of the environment of an instrument on a chemical plant can be defined in terms of the aggressiveness of any process materials with which it may be in contact and that other factors are of secondary importance.

The effect of environment may be taken into account by assigning to an instrument a basic failure rate which is then multiplied by a suitable environment factor. For a favourable environment this factor is by definition unity, while for an unfavourable one it is greater than unity.

An attempt has been made to define an environment factor for the main classes of instrument covered in the survey. This factor is determined mainly by the estimated degree of aggressiveness of the process fluids with which the instrument is in contact. The maximum value of the factor, based on the data given in Tables 3.7. - 3.8. was found to be about 4. Since the factor is approximate only integer values are used. These environmental factors are given in Tables 3.2 - 3.5.

The conclusion drawn about the conditions which affect the environment factor and the values assigned to this factor are based on quite slender evidence and are necessarily tentative. The justification for attempting to estimate this factor is that to neglect it entirely would be much more misleading.

Some of the instruments, such as controllers, are normally used, both in the works investigated and elsewhere, in control rooms under clean conditions, while others, such as flame failure devices are used in process fluids under severe conditions. For such instruments the crude failure rates quoted in the last columns of Tables 3.2 - 3.5 will not in general need further correction for environment. Such correction is required mainly where a particular type of instrument may be used in very different conditions. The instruments to which this principally applies are control valves and instruments for measuring fluid flow, fluid level, pressure and temperature.

The data obtained appear to suggest that some types of measurement transducer are much more reliable than others. What has actually been measured in the survey, however, is the reliability of instruments in those functions to which they are normally assigned. It does not necessarily follow that an instrument which has a/low failure rate would in fact perform more reliably if it were used as an alternative to an instrument with a rather higher failure rate. This point is relevant also to the definition of the environment factor. The values quoted for this factor are based on estimates of what constitutes a severe environment for a particular instrument. For instance, the measurement of a moderately high temperature may be a relatively favourable environment for a thermocouple but impossible for a mercury - in - steel thermometer.

3.9. Modes of Failure of the Instruments

In addition to reliability information on the failures of the instruments in their working environments, some information was also obtained on the nature of the failures. This information was expected, and obtaining such information was, in fact, one of the main reasons for carrying out the survey. An insight into the modes of failure of the instruments was expected from such information.

The preliminary survey on control valve failure - not reported here - for instance, showed about half the valve failures in the works to involve either stickiness of the stem or blockage of the body. The failures of the instruments in this particular works were well documented but unfortunately this cannot be fully reported here. However, typical comments as documented on the cards by the operator, on the failures of control valves and differential pressure transmitters obtained from this works are presented in tables 3.9a and 3.9b.

In the work reported here, some information on the nature of the failures at Works A recorded in Table 3.2 was obtained. Such information would not be obtained from either Works B or C. Of the 359 control valve failures 23 were blockages and 53 leakages; of the 185 variable area flowmeter failures 45 were blockages; and of the 364 impulse lines failures 194 were blockages and 99 leakages. The remarks on the failure of the instruments could be much clearer and more informative in a lot of cases, however, a study of the log ticket data as they were gave some insight into the modes of failures of the instruments.

Some more meaningful and relevant comments on log tickets are presented in Tables 3.10 - 3.14. The 'symptoms or comments' column contains remarks as made by the process operator. When the causes of failure can be reconstructed from the comments, they have been included in the 'causes of failures' column.

Not all the comments obtained have been presented. Only a good cross-section of typical comments, to bring out the various useful information which can be got from them, have been presented. Also the comments quoted have been chosen to bring out how the operator executes the function of malfunction detection.

A study of the comments and an attempt to reconstruct probable behaviour of instrument signal suggests that a majority of the instrument malfunctions could be picked up from the instrument signals. Indeed, in most cases, the process operator seems to have detected the failures or malfunction from unusual signal characteristics. It is true that he has sometimes has to use his human senses of sight, smell and sound to sense trouble but even in these cases, perhaps, the symptoms of trouble could equally have been picked up from variations in the instrument signal characteristics.

A majority of the failures were 'hard - over' failures that could have been picked up earlier with a suitable malfunction detection method.

3.10 Discussion

The data given in Tables 3.2 - 3.4 show appreciable differences in the failure rates of particular types of instrument. These differences may be accounted for in most cases either by differences in the environment or by the smallness of the failure sample.

The control valves failure rates at the three works show differences. It is believed that those at Works A are the most typical, as the conditions there are the most typical of a chemical works. The clean environment in which the valves in Works C are housed, and the fact that they regulate only fuel oil and air, could account for the low failure rate recorded there. The high failure rate at Works B may reflect the large proportion of butterfly and diaphragm valves, the large diameter of some of the pipelines and the presence of hot, dirty gases. The environment factor of 4, which is the maximum used in any of the tables, may be an underestimate of the effect of this environment.

A similar underestimate of the effect of this hot, dusty environment may account for the high failure rates of pressure and temperature measuring devices at Works B. These failure rates are much higher than those at Works A, but failure rates at Works B for flow and level measuring devices are closer to those at Works A. This is reasonable since there is probably a greater similarity between the liquids handled at the two works than between the gases. The failure rate of temperature measuring devices at Works C is also higher than at Works A, doubtless for similar reasons.

The very low failure rates obtained for mercury - in - steel thermometers are interesting, but the failure sample size is small and the data for the failure rates of the individual temperature measuring devices are not very accurate. More data are therefore needed on these instruments.

The failure rates of flame failure devices and pH meters are appreciably higher at Works B than at Works A, but in both cases the instrument sample size is small. The figures appear to reflect a small number of rather troublesome instruments.

Somewhat similar considerations seem to apply to the high failure rates of the controllers and controller setting at Works B. These instruments are mostly working in conjunction with a control computer and are on rather critical loops, so that the criteria of failure are probably more stringent.

For Works C the failure rate of the impulse lines is low but that of the flow measurement transducers is high, which suggests that possibly some of the faults in the former have been recorded as faults in the latter.

The confidence limits for the failure rate data are not quoted in the tables. It is considered that in view of the importance of the environmental effect and, for some instruments, the smallness of sample of instruments at risk, the quotation of these limits might indicate a presumption of accuracy which would be spurious. The data required for the calculation of the limits are, however, given in the table.

No distinction has so far been made between electronic and pneumatic instruments. The data obtained does not in fact make it possible to distinguish between the two. Any differences appear to be small in comparison with the effect of environment.

Comparing those items which are common to Tables 3.1 - 3.5., it can be seen that the sets of data are reasonably consistent. In the absence of more information on sample size and environment for the data given in Table 3.1. no more detailed comparison can be made.

Table 3.2. Instrument Reliability Data for Works A

Instrument	No. at Risk	Environment Factor	No. of Faults	Failure Rate faults/yr.
Control valve	1330	2	359 (327)	0.57 (0.51)
Globe (p)	1195			
Butterfly (p)	105			
Diaphragm (p)	30			
Valve positioner (p)	320*	1	62	0.41
Solenoid valve	168	1	24	0.30
Current/pressure transducer	89	1	23	0.54
Pressure measurement:	193	3	89 (82)	0.97 (0.89)
Absolute pressure transducer (p)	124			
Differential pressure transducer (p & e)	69			
Flow measurements (fluids)	1733	3	902 (890)	1.09 (1.08)
Differential pressure transducers (p & e)	473	3	419	1.86
Transmitting variable area flowmeter (p)	100	3	48	1.01
Indicating variable area flowmeter	857	3	137	0.34
Mercury manometer flowmeter	137			
Turbine steam flowmeter	60			
Piston flowmeter	61			
Turbine flowmeter	45			
Level measurements (liquids)	316	4	233 (206)	1.55 (1.37)
Differential pressure transducer (p & e)	130	4	106	1.71
Float-type level transducer	158	4	124	1.64

Table 3.2. (continued)

Capacitance-type level transducer	28	4	3	0.22
Temperature measurement	2391	3	326 (320)	* 0.29 (0.28)
Thermocouple	663	3	127	0.40
Resistance thermometer	441	3	68	0.32
Mercury-in steel thermometer	996	2	13	0.027
Temperature transducer	291	3	118	0.85
Controller	1083	1	133 (120)	0.26 (0.23)
General purpose (p)	767			
General purpose (e)	81			
Temperature	235			
Pressure switch	519	2	75	0.30
Flame failure detector	43	3	28	1.37
Analyser	48		141	6.17
pH meter	29		59	4.27
Gas-liquid chromatograph	3		30	20.9
O_2 analyser	9		30	7.0
CO_2 analyser	4		20	10.5
Infra-red liquid analyser	3		2	1.40
Impulse lines	842	3	364 (341)	0.91 (0.85)
Pressure transducer	124			
Differential pressure transducer	672			
Pressure switch	25			
Analyser	21			
Purge systems	100	4	48	1.00
(Control loop	1083		120	0.23)
Controller setting	1083		66	0.13

* estimated number

Table 3.3. Instrument Reliability Data for Works B

Instrument	No. at Risk	Environment Factor	No. of Faults	Failure Rate faults/yr.
Control valves:	86	4	78 (72)	2.27 (2.10)
Globe (p)	32			
Butterfly (p)	26			
Diaphragm (p)	28			
Power cylinders (p)	83	2	21	0.64
Valve positioner (p)	14	2	7	1.25
Solenoid valve	84	2	24	0.72
Current/pressure transducer	99	1	22	0.56
Pressure measurement	40	4	35 (34)	2.20 (2.14)
(all absolute pressure transducers (e))				
Flow measurement (fluids)	81	4	54 (53)	1.68 (1.64)
Differential pressure transducer (e)	35	4	37	2.66
Magnetic flowmeter	15	4	13	2.18
Indicating variable area flowmeter	31	4		
Flow measurement (solids)				
Load-cells	45		67	3.75
Belt speed measurement & control	19		116	15.3
Level measurement (liquids)	105	4	94 (89)	2.25 (2.12)
Absolute pressure transducer (e)	5	4	0	-
Electrical conductivity probes	100	4	94	2.36
Level measurement (solids)	11		30	6.86
Radioactive gauge	4			
Electrical conductivity probes	5			
Mechanical float	2			

Table 3.3. (continued.)

Instrument	No. at Risk	Environment Factor	No. of Faults	Failure Rate faults/yr.
Temperature measurement	167	4	81 (80)	1.21 (1.20)
Thermocouple	88	4	47	1.34
Resistance thermometer	38	4	24	1.59
Vapour pressure bulb	27	4	4	0.37
Mercury-in-steel thermometer	5	2	0	-
Temperature transducer (e)	9	4	6	1.67
Controller (e) (all general purpose)	21	1	15 (12)	1.80 (1.43)
Pressure switch	30	4	12	1.00
Flow switch	9		4	1.12
Speed switch	6		0	-
Monitor switch	16		0	-
Flame failure detector	2	3	8	10.0
Millivolt-current transducer	12		8	1.67
Analyser:	21		172	20.6
pH meter	5		34	17.1
Gas-liquid chromatograph	5		75	37.7
Electrical conductivity meter (for liquids)	5		33	16.7
Electrical conductivity meter (for water in solids)	3		17	14.3
Water hardness meter	3		13	10.9
Impulse lines	112	4	44 (43)	0.98 (0.96)
Absolute and differential pressure transducer	80			
Pressure switch	27			
Analyser :	5			
(Control loop	21		18	2.16)
Controller setting	21		9	1.08

Table 3.4. Instrument Reliability Data for Works C

Instrument	No. at Risk	Inst. yr.	Environment factor	No. of faults	Failure rate faults/yr.
Control valves (all Globe)	115	78.6	2	10(5)	0.127(0.064)
Power cylinders	15	6.9	3	10	1.45
Current/pressure transducer	12	5.5	1	0	-
Flow measurement (fluids)	128	84.6	2	103(53)	1.22(0.63)
Differential pressure transducer (p)	115				
Differential pressure transducer (e)	13				
Temperature measurement:					
Thermocouple	21	18	4	18	1.00
Radiation pyrometer	43	30.9	4	67	2.17
Optical pyrometer	4	3.4	4	33	9.70
Controllers	88	50.7	1	16(6)	0.32(0.12)
General purpose (p)	76				
General purpose (e)	12				
Analysers	17	7.8		18	2.31
O_2 analyser	3	1.38		2	1.45
H_2 analyser	11	5.04		5	0.99
H_2O analyser (for gas)	3	1.38		11	8.00
Impulse line	145	92.4	2	8(0)	0.08(-)
Differential pressure transducer	128				
Analysers	17				
(Control loops	127			73	0.87)
Controller setting	127	84.2		9	0.11

Table 3.5. Instrument Reliability Data for All Works

Instrument	No. at Risk	Instrument-Years	Environment Factor	No. of Faults	Failure Rate faults/year.
Control valve	1531	747	2	447	0.60
Power cylinder	98	39.9	2	31	0.78
Valve positioner	334	158	1	69	0.44
Solenoid valve	252	113	1	48	0.42
Current/pressure transducer	200	87.3	1	43	0.49
Pressure measurement	233	87.9	3	124	1.41
Flow measurement (fluids)	1942	943	3	1069	1.14
Differential pressure transducer	636	324	3	559	1.73
Transmitting variable area flowmeter	100	47.7	3	48	1.01
Indicating variable area flowmeter	857	409	3	137	0.34
Magnetic flowmeter	15	5.98	4	13	2.18
Flow measurement (solids)					
Load cell	45	17.9	-	67	3.75
Belt speed measurement & control	19	7.58	-	116	15.3
Level measurement (liquids)	421	193	4	327	1.70
Differential pressure transducer	130	62	4	106	1.71
Float-type level transducer	158	75.3	4	124	1.64
Capacitance-type level transducer	28	13.4	4	3	0.22
Electrical conductivity probes	100	39.8	4	94	2.36
Level measurement (solids)	11	4.38	-	30	6.86

Table 3.5.. (continued)

Instrument	No. at Risk	Instrument Years	Environment Factor	No. of Faults	Failure Rate faults/year.
Temperature measurement (excluding pyrometers)	2579	1225	3	425	0.35
Thermocouple	772	369	3	191	0.52
Resistance thermometer	479	227	3	92	0.41
Mercury-in-steel thermometer	1001	477	2	13	0.027
Vapour pressure bulb	27	10.7	4	4	0.37
Temperature transducer	300	142	3	124	0.88
Radiation pyrometer	43	30.9	4	67	2.17
Optical pyrometer	4	3.4	4	33	9.70
Controller	1192	575	1	164	0.29
Pressure switch	549	259	2	87	0.34
Flow switch	9	3.59	-	4	1.12
Speed switch	6	2.39	-	0	-
Monitor switch	16	6.38	-	0	-
Flame failure detector	45	21.3	3	36	1.69
Millivolt-current transducer	12	4.78	-	8	1.67
Analyser	86	39.0	-	331	8.49
pH meter	34	15.8	-	93	5.88
Gas-liquid chromatograph	8	3.43	-	105	30.6
O_2 analyser	12	5.67	-	32	5.65
CO_2 analyser	4	1.90	-	20	10.5
H_2 analyser	11	5.04	-	5	0.99
H_2O analyser (in gases)	3	1.38	-	11	8.00

Table 3.5. (continued)

Instrument	No. at Risk	Instrument Years	Environment Factor	No. of Faults	Failure Rate faults/year.
Infra-red liquid analyser	3	1.43	-	2	1.40
Electrical conductivity meter (for liquids)	5	1.99	-	33	16.70
Electrical conductivity meter (for water in solids)	3	1.20	-	17	14.2
Water hardness meter	3	1.20	-	13	10.9
Impulse lines	1099	539	3	416	0.77
Controller settings	1231	609	-	84	0.14

Table 3.6. Reliability of Air Supply and of Pneumatic and Electrical Connections

	No. at Risk	No. of Faults	Failure Rate faults/year.
Air supply : All works	2651	62	0.048
Works A	2335	51	0.046
B	113	5	0.11
C	203	6	0.046
Pneumatic connections : All works	3137	20	0.013
Works A	2809	19	0.014
B	183	1	0.014
C	145	0	-
Electrical connections : All works	1680	23	0.03
Works A	1329	15	0.024
B	326	8	0.062
C	25	0	-

Table 3.7. Effect of Environment on Reliability : Instruments in Contact with and not in Contact with Process Fluids at Works A.

	No. at Risk	No. of Faults	Failure Rate faults/year.
Instruments in contact with process fluids :	2285	1252	1.15
Pressure measurement	193	89	0.97
Level measurement	316	233	1.55
Flow measurement	1733	902	1.09
Flame failure device	43	28	1.37
Instruments not in contact with process fluids:	2179	317	0.31
Valve positioner	320	62	0.41
Solenoid valve	168	24	0.30
Current-pressure transducer	89	23	0.54
Controller	1083	133	0.26
Pressure switch	519	75	0.30
Control valve	1330	359	0.57
Temperature measurement	2391	326	0.29

Table 3.8. Effect of Environment on Reliability : Instruments in Contact with Clean and Dirty Fluids at Works A

Instrument	No. at Risk	No. of Faults	Failure Rate faults/year.
Control valve :			
Clean fluids	214	17	0.17
Dirty fluids	167	71	0.89
Differential pressure transmitter:			
Clean fluids	27	5	0.39
Dirty fluids	90	82	1.91

Table 3.9a Control Valves

Types of Failure	Symptoms	Causes
1 Fault in gland	Venting to atmosphere, when valve should have been in closed position, other valves off same feed to head O.K.	Spindle seized in gland. P.T.F.E. chevron rings too tight in gland casing
2 Seat failure	Waste brine leaking up through valve spindle	Chemical attack on diaphragm
3 Body failure - blocking	20 psi output from MOD 40 controller and high level in caustic stock tanks	2 inch nail and metal bits blocking valve plug, in body
4 Blocking	No flow	Dirty material caused blockage in valve
5 Seat failure	Passing when valve is closed	Plug and seat to be ground in and valve adjusted
6 Seat and Body failures	Bad leaks on body joint	Seat joint was found to be fractured
7 Relay Body failures	Bad leak from body joint and slow action	Vibration and hydraulic hammering
8 Body failure	Bad leaks about the body	Internal corrosion
9 Blocking	No flow	Solid material in body of valve
10 -	Valve would not close	Large piece of PTFE wedged under seat of control valve

Table 3.9a. Control Valves (Continued)

11 Failure of spindle	Restricted movement of spindle	Bottom guide had seized to spindle
12 Seat failure	Suspected blockage	Lock nut found loose in lower half of spindle

Table 3.9b. Differential Pressure Transmitters

Types of Failures	Symptoms	Causes
Impulse lines	Fluctuating output	Leaking gland on equalising manifold
Diaphragm	None	Diaphragm found to be holed
Body	Incorrect readings	Bad leaks on body joints and manifold
Bellows	Sticktion on calibration	Deposit in High Pressure and low pressure chambers
Flapper/nozzle	Giving a low reading	Flapper and nozzle badly
Bellows	Continuous full output	Bellows unit and casting distorted
Flapper/nozzle	Reading fluctuating badly	Badly fitted nozzle

Table 3.10 Control Valves

	Symptoms or Comments	Causes of failure
1	Not working properly	
2	Valves failed to open	
3	Gland leaking	
4	Pressure connection line broken	
5	Valve not shutting off	
6	Valve leaking	
7	Valve not opening at low flow	
8	Valve passing when closed	packing
9	Steam leak	packing
10	Flow not zero with valve shut	valve passing
11	Valve would not reset	
12	Valve sticking	
13	Cooling valve failure	
14	Heating valve failed to open	sticking
15	No response on control valve damper	shakle pin out of piston
16	Stuffing box blowing	
17	Control valve stem twisted	
18	Operation at low level very faulty	
19	Bottom body joint blowing	
20	Not working, remains shut	bye pass open
21	Control valve ¼ open with full controller output	
22	Bonnet seems disconnected from valve	locking nut adrift
23	Instrument blocked	
24	False reading	sticking
25	Hunting	

Table 3.10 Control Valves (Continued)

26	Valve free but does not move in auto or manual	sticking
27	Valve will not open	
28	Unable to control temperature	
29	Not operating on full stroke	bent trim
30	Not working	blocked
31	Valve jammed	valve seat blocked
32	Passing steam when shut	broken stem and plug
33	Valve connecting link loose	
34	Output from controller rising jumpily	valve sticking
35	Not reading correct	valves seized solid and stem bent
36	Not controlling well, not steady in manual	
37	25% open when should be closed	
38	Unsteady in auto, O.K. in manual	valve sticking
39	Valve will not seat	
40	Valve stuck open	
41	Control valve stem twisted	
42	Level higher than indicated in recorder	
43	Valves blocked	
44	Not working properly	valve alright but no flow in process line
45	Control valve not opening	
46	Not working	blocked

Table 3.11 Valve Positioners

	Symptoms or Comments	Causes of Failure
1	Valve open with controller shut	valve positioner arm loose
2	Valve sluggish	valve positioner out of alignment
3	Control loop not working	valve activator flapper bent and restriction blocked
4	Valve not opening	valve positioner out of alignment
5	Valve not venting when open	valve positioner misaligned
6	Flow swinging	
7	Hunting	
8	Air leaking in valve positioner	relay gasket
9	Raise level keeps hunting	valve positioner output gauge
10	Valve slow on auto	outlet valve positioner screws in valve positioner case tight
11	Valve not closing	fault in valve positioner, baffle adjusting arm loose, relay damaged, trim capillary loose
12	Cycling	
13	Flow unsteady	
14	Arm adrift	
15	Valve not operating properly	valve positioner out of alignment
16	Not working on auto	
17	Seized up	
18	Suspect control	valve positioner faulty
19	Sticking	gland follower rubbing on trim

Table 3.11 Valve Positioners (Continued)

20	Not controlling valve, manual or auto	valve positioner loose
21	Valve positioner out of alignment	
22	Air output falls out on 'seal'	valve positioner relay
23	Flow fluctuating	
24	Valve not controlling level	valve positioner out of calibration
25	Check valve	valve positioner yoke corroded by acid and loose

Table 3.12 Impulse Line failures

	Symptoms or Comments	Cause of Failure
1	Reading unsteady	leak in impulse line
2	No reading	impulse line blocked
3	Faulty reading	impulse line blocked
4	Gland leaking	
5	Transmission gives no output	orifice blocked
6	Reading zero	blockage
7	Reading sluggish	blockage
8	Valve not opening	impulse lines blocked
9	Boiler flow reading with boiler off	bad leak
10	False reading	impulse line frozen
11	Clear rotameter	high pressure leg partly blocked
12	Level indicators not working	high pressure line blocked
13	Steam flow reading low	blockage in low pressure leg
14	Coolant condenser level not recording	impulse line leaking
15	CO_2 analyser not reading	impulse lines blocked
16	D/P transmitter not working	impulse lines partly blocked
17	Level controller faulty	lines blocked
18	Water meter flase reading	lines blocked
19	Vapour flow not recurring	orifice blocked
20	Electro flow D/P transmitter no output	system water-logged
21	Boiler steam meter reading high	low pressure line blocked
22	Faulty transmission in steam blow off	blockage and leaks
23	Flow recorder reading low and unsteady	lines blocked

Table 3.12 Impulse Line Failures (Continued)

24	Vaporiser - false recording	line full of acid
25	Flow indicator reading high	lines blocked
26	Steam flowmeter false reading	lines leaking
27	Erratic readings of flow recorder	lines blocked
28	Flow stream appears stuck	line iced up
29	No recording on steam absorber	lines iced up.
30	Control sluggish	leg blocked
31	Acetone peak high	sample line blocked
32	Reading dropped	lines frozen
33	Reading low	lines frozen
34	Steam input meter not moving	lines blocked
35	Circulation transmitter no reading	high pressure side leaking badly
36	Transmission faulty	
37	Control faulty	
38	Suspect	blocked legs
39	Check	dirt in legs
40	Cock broken	
41	Tapping leaking	
42	Tower 3 circulation flowmeter not reading	blockage
43	Indicator shut off	leak in pipe union
44	Boiler steam flowmeter reading full scale	blocked impulse lines
45	Level recorder reading high	impulse line blocked
46	Air flow reading zero	blockage
47	Steam balance indicates there should be	partial blockage

Table 3.12 Impulse Line Failures (Continued)

48	Export of steam	
49	Boiler CO_2 meter not reading	blockage
50	Clear rotameter	H.P. leg partly blocked
51	Feed to distillation faulty reading	leaking at all joints in impulse lines
52	Treated water flow transmitter - sluggish	
53	Product flow no reading	H.P. line blocked
54	Meter reading low	much dirt in lines
55	Steam meter still working but no steam in main	air trapped in impulse lines
56	Steam meter still reading with no steam flow	klinger corks leaking
57	H_2S meter sluggish	line blocked
58	Boiler CO_2 meter	tapping point blocked
59	Erratic	lines blocked
60	Meter, process stream changes but not recorded	much dirt in lines
61	Air in impulse legs cause trouble	
62	Reading 2,400 lb with line isolated	lines blocked

Table 3.13 Transmitter Failures

	Symptoms or Comments	Cause of Failure
1	Level controller fluctuating	leak in impulse line transmission
2	Faulty reading in flow D/P transmitter	zero error 3%
3	Flow transmitter reading suspect	relay sticking
4	Alarm did not go when decounter	large zero error
5	Filled in level transmitter	
6	Flow transmitter reading not consistent	large zero error
7	With valve position	
8	Flowmeter not reading zero	zero error
9	No reading from flow transmitter	restrictor blocked
10	Valve seemed to have reversed its action	transmission line frozen
11	Flow suddenly gave low reading	
12	Pressure transmitter alarm did not	pressure transmitter
13	Activate when down to 40 psi g	3 psi low
14	Pressure transmitter and gauge disagree	
15	Flow transmitter reading suspect	equalising valve not quite shut
16	Controller output not changing value	
17	Flow controller no reading	
18	Flow transmitter/rotameter	bobbin sticking
19	Flow transmitter zero error	
20	Flow meter faulty	top set of members now jammed
21	Level	purge line blocked
22	Flow transmitter differs from local	
23	Measurement	
24	No reading	
25	Level transmitter reading 16" higher	water purge off

Table 3.13 Transmitter Failures (Continued)

26	than dip	
27	Flow transmitter	water in air system
28	Level transmitter reading constant	
29	Flowmeter sticking	drive wheel loose
30	Meter found not working	
31	Valve does not respond to low level in boiler	
32	Feed and air flow transmitter frozen	
33	Flow cycling in check	
34	Flow transmitter not consistent with level measured	
35	Level control erratic	
36	Flow valve cycling	
37	Flow transmitter will not indicate above 9 on scale	
38	Level transmitter does not read above 82°C	
39	Integrator fully at high constant rates	
40	Flow transmitter reading when valve shut	chamber filled with oil
41	Flow transmitter shut down but still reading flow not zeroing	
42	Level transmitter reading 8 when level zero	
43	Integrator rate does not compare with evaporator rate	
44	Flow will not register above 6	
	Pressure Transmitter Failures	
45	pressure connections	air line broken
46	pressure switch intermittent fault	

Table 3.13 Transmitter Failures (Continued)

47	Pressure control sluggish	perhaps valve blockage
48	No reading	blocked relay
49	Pressure switch, intermittent alarms	zero error
50	Blowing pressure with no pressure in line	line was still under pressure (process)
51	Pressure switch faulty	water in the switch body
52	Transmitter and guage disagree	
53	Pressure switch coming on late	
54	Will not follow load changes	
55	Pressure switch	sticking
56	Reading low	pressure switch corrections in wrong terminals

Table 3.14 Thermocouple Failures

	Symptoms or Comments	Cause of Failure
1	Suspect reading	loose connection in thermocouple head
2	Faulty reading	open circuit in compensating cable
3	Suspect reading	water in thermocouple head
4	Temperature sluggish	loose connection in thermocouple head
5	Reading walking all over	
6	Suspect reading low	contact with surface
7	Leaking thermocouple pocket	
8	Reading 800$^+$ at all levels	
9	Excessive difference in readings between points	
10	Went to 800$^+$	
11	Faulty reading	
12	Temp pocket	leak in pocket
13	Unsteady and low	
14	Loose connection	
15	Difference of 10°C between points	
16	Pocket leaking	
17	No reading	
18	Reading 7°C low	
19	Thermocouple No. 2 low - No. 3 high	
20	Suspect reading low	
21	Check calibration	
22	Temperature hunting	

4. IMPROVEMENT OF RELIABILITY OF PLANT AND CONTROL SYSTEMS

4.0 IMPROVEMENT OF RELIABILITY OF PLANT AND CONTROL SYSTEMS

4.1 Introduction

Reliability is a universal subject, which embraces all fields and technical engineering specialities. The discipline has had broad and profound impact on some industries, such as, the electronics and subsequent military and aerospace industries where it has been successfully applied. Already, a solid foundation for the subject has been laid by these applications. The necessary probability - theory - based structure for its application in other industries has also been provided by these applications

The idea and techniques of malfunction detection developed and discussed in this project have very wide implications for reliability engineering and more especially to its application to the process plant industry. It is mainly these implications that will be discussed in this chapter.

The object here is plant and control systems which are reliable and maintainable. This involves also both initial design for reliability and maintainability, and the use of the computer to improve reliability and maintainability

The primary concern here is with whole systems rather than with very high reliability safety systems even though mention is also made of this.

4.2. Reliability engineering technique application to the process plant industry

'Reliability' means different things in the many differing operational requirements and varying environments. A generally accepted definition of reliability is (67), "Reliability - the characteristic of an item expressed by the probability that it will perform a required function under stated conditions for a stated period of time."

The principles are described in a number of textbooks (69-87). A number of examples of the use of probabilistic methods in general and of the techniques of reliability engineering in particular are well illustrated in references (88-93).

Recently, Pan (94) reviewed the application of reliability engineering to the chemical plant industry. He showed how reliability techniques can be applied in the design, construction, operation, and maintenance of process plants; and what can be done to increase the reliability of existing units. Of particular interest and relevance in his work are the presentation of a statistical method suited for analyzing field failure data for process equipment, and his discussion of maintainability and designing for plant availability. However, his review was primarily concerned with whole equipments in the refinery and petrochemical industries especially.

The basic ideas of reliability engineering and examples of how these techniques can be applied in process design have recently been presented (95).

The need to combat unreliability of equipment is also a maintenance problem. Maintenance and replacement policies have been extensively studied (93,96-98) aiming either at minimising maintenance costs or maximising availability on on-stream time of the equipment or plant, or at optimising both of them. The subject of reliability and maintenance in process plants has been a topic for a recent paper by Freshwater et al (99).

The absence of a data bank adequate for industrial studies has been realised and has been the subject of comment quite recently (100).

The U.K. Atomic Energy Authority, Health and Safety Branch, offers a reliability engineering consulting service and is also building up a data bank on instrument and equipment reliability. It is the most active group in reliability engineering in this country and has issued a number of papers and reports on basic reliability theory, system design and failure data, particularly, for instrument systems (101, 102).

There is no doubt that the field of reliability engineering is now ripe for full exploitation by the process plant industry. There is plenty of room for the improvement of reliability of plant and control systems starting right from the design stages. The absence of the necessary data to enhance such applications is glaring.

The principles of malfunction detection and its implications for reliability engineering have not been considered so far. Yet, the principles of malfunction detection can yield the much needed data for the proper application of already existing theory of reliability engineering.

The effective and proper use of certain ideas such as substitute measurements and self organising control system which augur so well for instrument reliability depends very much on instrument malfunction detection.

The principles of malfunction detection therefore are very relevant for the application of reliability engineering techniques to the process plant industry. The implications of malfunction detection for the improvement of reliability of plant and control systems are discussed in the next section 4 3

4.3. Reliability Implications of Malfunction Detection

The implications of malfunction detection considered here are not only for instruments but also for all plant items.

Failures of instruments and key equipments such as pumps, compressors etc , often can be prevented if the early signs of impending breakdown are recognised. The statistical approach to plant reliability usually assumes that an instrument or equipment fails outright and is then replaced or repaired, and on this basis quite high reliabilities can be obtained. Such figures will become meaningless if an instrument has a fault which is allowed to go on undetected for a long period. This type of situation very easily leads to a catastrophic failure with all the undesirable implications, such as, stoppages, possible accidents, and loss of production. The existence of such a situation falls broadly under conditions of unreliability.

The development of malfunction detection techniques is very necessary for the improvement of plant and control system reliability. The detection of incipient failures can initiate actions that can improve instrument and equipment maintenance, avoid poor control, and avoid catastrophies. Such actions as use of substitute measurements - methods by which in the event of failure being detected, alternative approximate estimates of the variables can be made. Actions such as reorganisation of control systems on the event of failure can also be initiated. These actions when built into the system will, no doubt, improve the reliability of the system.

Maintenance, substitute measurements and self-organising control loops are dealt with, each separately, later

The routine analysis and possible checks that might be involved are functions which the process control computer can very readily take over, thereby contributing to the improvement of the reliability of the whole system. On-line malfunction detection techniques could, indeed, be considered equivalent to providing a redundant system without incurring any further costs, but purely, by using the capabilities of the computer more fully.

In the case of process instruments it is possible that an experience in general malfunction criteria, as is of interest in the present work, can be further developed to include smaller calibration errors or sluggish, response. This will lead to more reliable and accurate instrumentation, which is important, for full exploitation of on-line computers. At this stage, this might sound a bit ambitious but nevertheless it is realistic.

Taking a reciprocating compressor as an example, the detection of the compressor abnormalities, such as, valve leakage, ring blowby and power loss can be detected analytically (103). Such detection can enable the plant operators to schedule repairs and adjustments, thus preventing unscheduled stoppages, possible accidents and lost production.

A recent paper (104), presents a description of experimental investigations which demonstrate the feasibility of on-line monitoring of process vessels for incipient fatigue damage or stress corrosion damage. The possibility of pressure vessel loss prevention by analysis or scientific study of vibrations in rotating machinery, and acoustic emissions from the shells of pressure vessels, has also been pointed out (105).

Even though effort in this project has been principally devoted to developing malfunction detection techniques for instruments, the examples cited above illustrate the wider applications of the principles. Application of the principles and all that evolve from them, no doubt, will reduce the crucial downtime per failure factor in the reliability of equipments and instrument systems.

Because failure in the proper handling of malfunction can lead to catastrophic conditions such as danger to life and body parts, damage to plant and control equipment or loss in production, provision for detection of incipient failure and correction of malfunction within a process should, of necessity, be made at the design stage.

Separation and allocation of function relevant to process malfunction should be considered very carefully. Each stage in the whole process, from detection to action, should be such that as much versatility in behaviour as possible is allowed for. Such versatility may not be necessary during normal operation but in emergency it could be an important ingredient for success.

4.4 Substitute Measurements

It is desirable that all failures when they occur must either be detected and/or absorbed automatically with an efficiency which ensures that any output disturbance is acceptably low When the failure or incipient failure has been detected, it may be possible, very often, to provide substitute measurements. In this way downtime per failure can be drastically reduced

Substitute measurements will involve calculations of the inferred measurement type for which the computer is very well suited. General heat and mass balance type calculations can provide these substitute measurements (223).

Barton et al (31) reported recently programming a method for obtaining approximate alternative measurement for flow, which is generally applicable where there is a constant pressure drop across the system. In their device, during normal operation, the control valve position is calibrated against flow measurement. A divergence between the flow measured and that calculated from the calibration was taken to indicate that a measurement failure may have occurred. In this event the valve position can then be used as a temporary measurement while the suspect instrument is investigated.

Taking the case of flow measurement as an illustrative example, substitute measurements can be got from the valve position as above or from differentiation of a head in storage vessel or from pressure drop in a pipe as shown in figs. 4.1(b) to (c). For a system illustrated in fig. 4.1(a) different calibrations 4.1(b), (c) of (a) flow vs valve position

(b) flow vs head

can be readily built up and stored in the computer and if need be, continuously updated. By such a simple provision, in a situation such as in the cement kiln where the most important measurements are flow measurements, a complete shut-down can be avoided in the event of a failure detection. Different processes have different such critical measurements, which can also be provided for in the event of failure of measurement. Combustion gas oxygen, as another example, can be calculated from fuel flow and fan damper position (31).

For a critical temperature measurement, such as an important controlled temperature of a process feed through a heat exchanger, an alternative approximate estimate of the temperature in the event of failure or malfunction of the temperature measuring device can easily be arranged. Consider a system such as is represented by fig. 4 2. If the feed rate is fixed and the feed temperature also, the temperature of the process feed out of the heat exchanger will be related to the heat flow through the heat exchanger. If the heating medium is steam, this would mean the steam pressure with a simplified arrangement of a fixed feed rate and a fixed feed temperature, The computer could store a calibration of the steam pressure against the heat exchanger outlet feed temperature This arrangement should provide an approximate alternative estimate of the outlet temperature, purely from the steam pressure measurement. For varying conditions, a combination of heat and mass balances can provide an alternative approximate estimate of the temperature in the event of failure of the measuring device.

In the system illustrated in fig. 4.3., the pH in the main line is the controlled variable (215). A chemical solution is added to the flow, the quantity of which must be that required to maintain the pH in the main flow. The amount of chemical solution to be added depends on two factors: (i) the pH of the main line liquid before adding the chemical solution and (ii) the rate of flow in the main line. The pH and rate of flow are measured by separate instruments. If the system is simplified by keeping the flow in the mainline fixed, then the pH measurement will be dependent on the amount of chemical solution added. As the pH of the solution in the tank should be constant, an approximate estimate of the pH measurement can be based on the flow measurement of the added solution. In a general way this is equivalent to obtaining the substitute measurement by a mass balance calculation.

The controlled variable in the above example could have been a concentration measurement. In this case, for a two stream

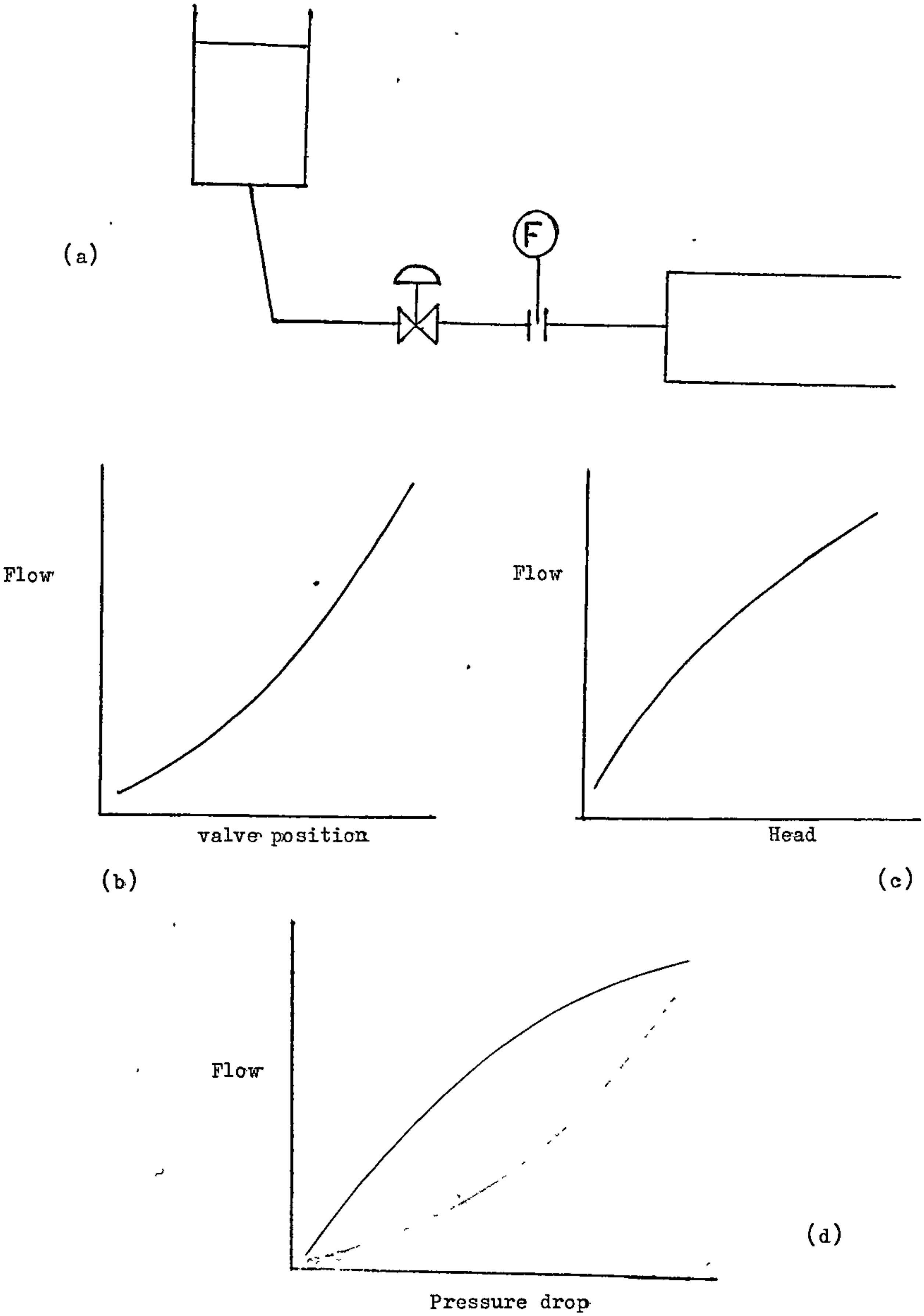


Fig. 4.1 Substitute measurements for flow

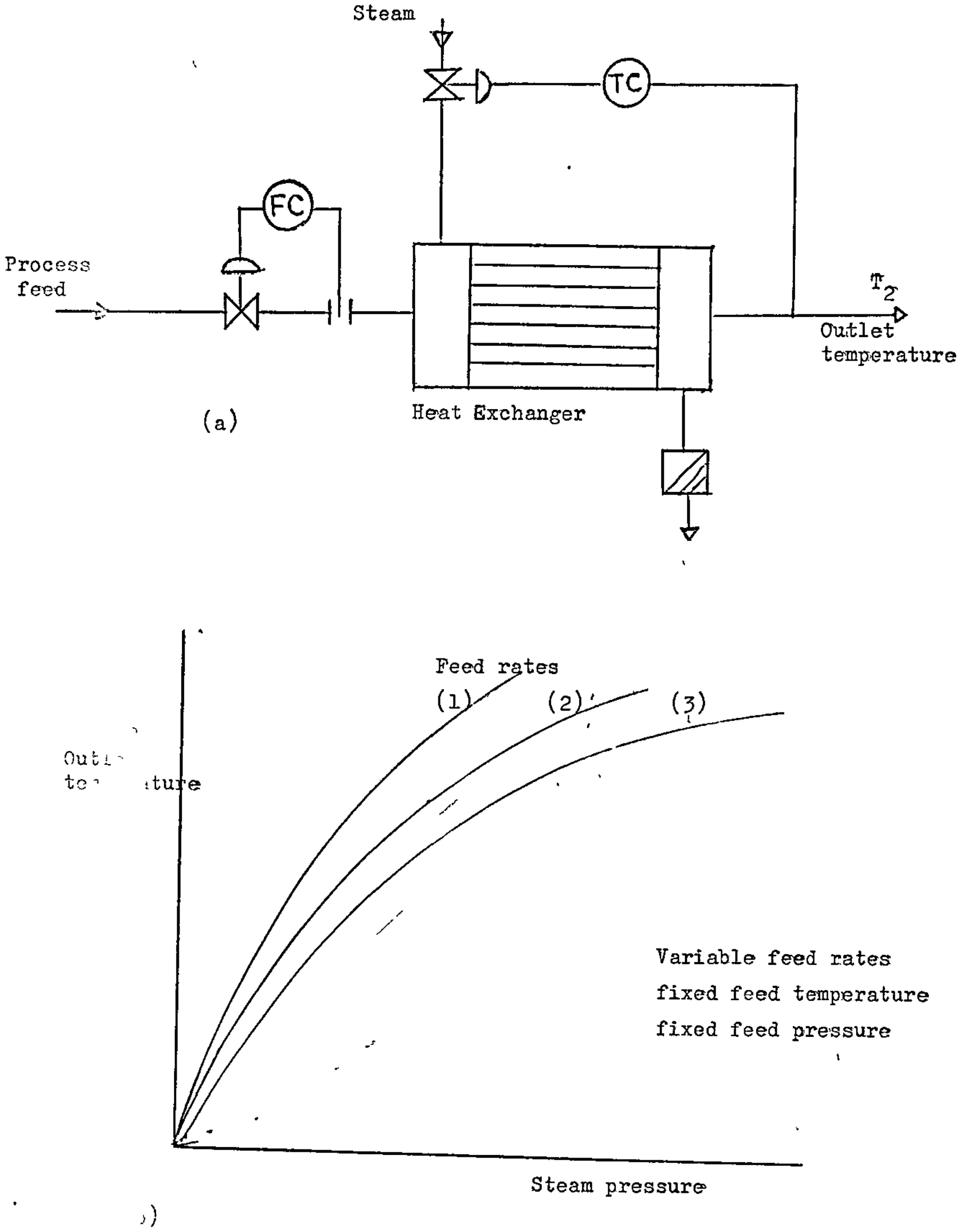


Fig. .2 Substitute measurements for outlet temperature from heat exchanger

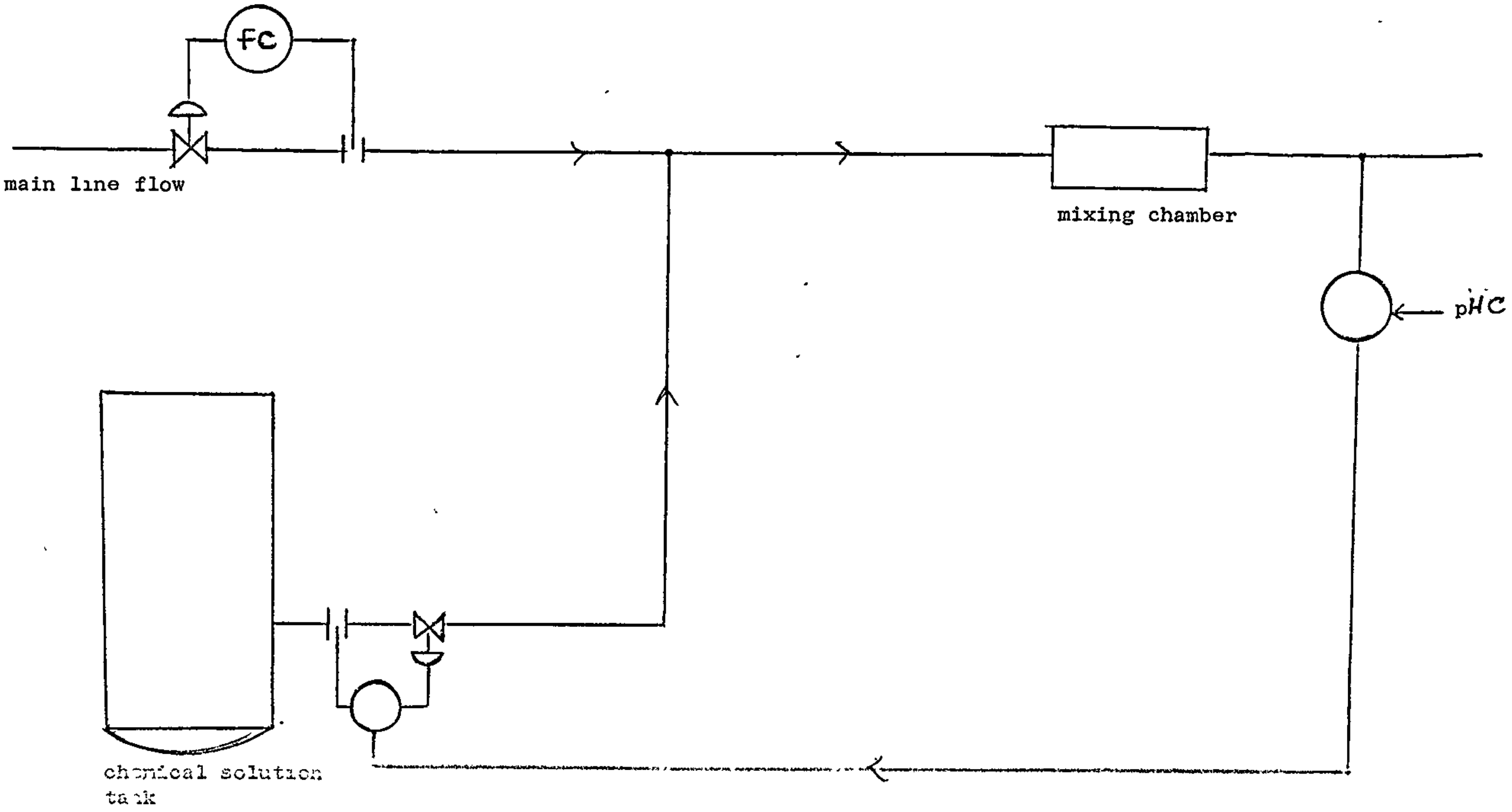


Fig. 4.3 Line diagram for pH control scheme

mixture, the concentration of the mixture will depend on the flows and concentrations of the two streams. A mass balance, with any of the two flows and their concentrations, can yield a substitute measurement for the third. An algorithm to provide these substitute measurements, as an alternative measurement in the event of failure or malfunction of a measuring instrument, can easily be built into the computer.

The specific examples considered above mainly serve to illustrate the ideas of substitute measurements. The provisions for different processes will differ, and will depend on the particular process and its requirements.

The provision of such substitute measurements is, in fact, equivalent to providing, stand-by or redundant systems in the event of failure. This, without incurring any further costs but by exploiting the capabilities of the computer.

Ability to provide such substitute measurements, no doubt, will increase overall plant availability, even in the event of failure of its measuring instruments. These substitute measurements could be quite simple sometimes and this may therefore be a fruitful area to explore further.

4.5. Self organising control systems

The operator normally carries out some reorganisation of control systems in the event of a failure or malfunction detection by him. One of the simple reorganisations of control systems carried out by the operator is when a measurement fails and he puts the loop on manual control. In this way, the failure or malfunction can be coped with on its detection. It is an effective way of coping with a failure without increasing the downtime per failure.

This type of function can be taken over by the computer. To do this, it is desirable that provision be made for the computer to be able to reorganise the control loop or control organisation to cope with a failure in the event of malfunction detection.

Grant (106) has very recently suggested a supervisory programme, one of whose duties is to inhibit control action from incorrect information by closing paths in the redundancy network which include failed equipment, and to divert the information flow through a path which is known to be functioning correctly. This duty may be fairly easily designed into a simple program for the computer equipment and in this way, plant availability can be improved even in the event of instrument or equipment failure.

Barton et al in their report on the operation of a DDC computer on a cement plant (31) indicated that DDC made their implementation of alternative control loop configuration easier.

Reorganisation of alternative control loop configuration can be to

(i) switch over to single loops or auto-manual
(ii) making or breaking ratio controllers
(iii) making or breaking cascades
(iv) switching over to substitute measurement algorithm

It is evident that a combination of malfunction detection by computer with the ability to reorganise the control loop or control organisation to cope with a failure on detection, will improve computer system effectiveness and overall reliability of the whole plant system.

4.6. Design of reliable system

A typical breakdown (94) of difficulties and troubles experienced in most process plant commissioning and normal operation is given below, from various sources (216-218) as

Problem Area	Percentage of Problem
General plant design	10% - 20%
Faulty erection	15% - 20%
Faulty equipment	40% - 75%
Faulty direction of operator and Human factor	10% - 30%

The above analysis points at faulty equipment as the major source of troubles.

There is plenty of room for the improvement of the reliability of plant and control systems starting right from the design stages. After the design stage, factors such as installation, operability and maintainability, can affect the reliability of an equipment or system. The factor of maintainability will be discussed separately in the next section.

Systems such as the electrical system, especially the power supply and control system, which are of extreme importance in the smooth and continuous operation of any process plant should be designed with extreme care and for high reliability. Detailed studies of this problem have been done and certain design criteria relating the reliability of such systems to the safe operation of refineries and chemical plants (219-221).

Bodine (222) has suggested the idea of suppliers' systems responsibility approach for achieving integrated reliability in instrumentation and control. Hensley (62) has shown how the performance of emergency shut down systems for process plants can be assessed numerically in relation to the safety and reliability of the plant operations.

Indispensable items in process plant operations, such as compressors, should be chosen very carefully and for reliability.

Simplicity, high component reliability, interchangeability and standardisation, rapid and positive identification of malfunction, minimum maintenance time, operability and other human engineering considerations are some points that should be aimed at and designed for.

Grant (106) in a recent paper suggested how, using standard contemporary equipment, it is possible to design computer control system of high reliability at acceptable cost. He suggested how, still at the design stage, the criticism that savings in plant manning is upset by need for highly skilled computer maintenance mechanics can be countered by the use of replaceable modules. Such replaceable modules which reduce repair to a plug - in replacement carried out by a non-specialist The replaceable modules should be such that they can be taken off or replaced without shutting down the plant; should be such that a test exists which allows the computer to report a fault within a small group of modules which can easily be replaced by the operator and should be readily available either from the stores or the manufacturers, without much time lag from detection of failure.

All that have been discussed in this chapter on instrument malfunction detection and all that can evolve from it —— instrument reliability data, substitute measurement techniques and so on—have implications for design of reliable systems. If the techniques are available, then it is possible to imagine designing systems so that a much higher degree of availability is achieved. This means building these techniques in, right at the design stage.

Much effectiveness of designing for more reliable computer——instrument system will be lost without consideration of the features of operability and maintainability. Operability here, is used in the common sense of ease and convenience of operation. Neither operability nor maintainability features are usually considered within the scope of reliability. Yet poor operability can lead to equipment failure, and poor maintainability can reduce the time during which an equipment is functioning normally. To be reliable therefore, equipments must be so designed as to minimise the probability of the operator making an error. This brings in ergonomics (the study of man in relation to work or human engineering) considerations.

The more comfortable the operator is, the less likely he is to make mistakes which will introduce an element of unreliability into the equipment he is controlling because, through faulty operation, it may fail to perform its specified function.

Ensuring correct operation involves more than just making the operator comfortable. Most times, the operator's main responsibility is to assess an equipment's performance through displays such as chart recorders, meters, indicators, and to control it through the movement of knobs, switches and the like. The displays must be so designed that the operator will quickly and accurately understand the information they convey, and the controls must operate in a way which will, as far as possible, ensure that when the operator moves them he will produce the required change in the performance of the equipment. The techniques of malfunction detection can make a considerable contribution in the displays for the operator. This is one of the main ways of using the techniques envisaged, and one which should be brought in right at the design stage.

Therefore, in addition to the reliability of the component and whole system considerations at the design stage, operability considerations are also relevant at this stage to the improvement of the overall plant system reliability.

4.7. Design of Maintainable Systems

Very often, the user is more interested in availability, which is the period during which an equipment is functioning normally, than in reliability. Since no design can be made absolutely reliable, when an equipment or machine fails, as is inevitable sooner or later, it is important that it should be repaired quickly so as to become available for use again in the shortest time possible.

Equipments must therefore have good maintainability, maintainability used here in the sense that it is a measure of the speed with which loss of performance is detected, the fault located, repairs completed and a check made that the equipment is functioning normally again. Maintainability must be built into the original design since like other reliability factors, attempts to incorporate it as an after thought by modifications to the manufactured equipment, will never produce a satisfactory solution. Features which improve maintainability can often be made part of the original design without a great deal of extra cost.

As a process plant is composed of a wide range of highly engineered, manufactured and technical systems, and components which do not all wear out or require maintenance at the same time, good maintenance strategy is very important for routine maintenance as it is for repair, since maintenance also represents a period of non-availability which must be made as short as possible. In complicated equipments, or where faulty operation may not be immediately obvious, some means must be provided to indicate quickly and clearly that a fault has occured, and the region where it is situated. Early detection of error therefore makes it easier to plan maintenance.

Grant's idea of a system to be modularised for repair by replacement (106) has already been mentioned as one way of cutting down repair time and improving system maintenance. Hoyte (107) has presented a discussion of how regular checks on instrument performance can be planned, based on, and carried out by a simple process - application digital computer, to use manpower very efficiently. The discussion has implications for maintenance. The programs for checking the instruments are held in the computer, and the process operator initiates a check by keying in an instrument designation. Instrument faults will be reported to the maintenance group on their printer. Their report will contain full results of the instrument check. Previous check results will be stored in the computer, to assist in diagnosing a fault. The storage of check results will provide accurate statistics to the design department on the long-term performance of different instruments, assisting them to select instruments for new plants and providing information for planning an optinum maintenance strategy.

A computer based, 'tight' maintenance system can be built in at the design stage. Such a maintenance system will have advantages of systematic notification, objective trend record and such useful and important information as operator's diagnosis;——this can be typed into the computer by the operator.

Malfunction detection techniques are likely to yield more precise reliability data; and the information from reliability data can be used to cure faults and so reduce maintenance and perhaps even more important, can be used to plan maintenance. When based on the computer, malfunction detection techniques will be invaluable for a computer based maintenance system as mentioned above.

4.8. Reporting Failures

No matter how carefully a design has been conceived and manufactured, failures which reduce the reliability are inevitable in particular parts, sooner or later, when the equipment or system is in use. Accurate reporting of the nature of these failures is invaluable to the designer for making improvements which can increase reliability . This improved reliability may not be produced only in future designs of the same or similar equipments; the failure reports may also be useful for improving the reliability of other equipments or machines which use the same parts In addition, reports will provide the designer with background information which will assist his constant search for improved reliability. Collection of this information is largely routine work for which the computer is very well suited.

Reporting failures in use might well establish the shortcomings in one particular part, and so indicate how a minor and inexpensive modification could produce a substantial improvement in reliability. On the spot failure reporting can often save time and money by avoiding unnecessary laboratory analysis when failures are caused by improper operation or the cause of failure is obvious.

The need for reporting failures and its relevance for improving the reliability of a system is therefore obvious. Failure reporting should not be confined to those defects which actually lead to a breakdown. Incipient failure or unduly rapid deterioration in a part which may be revealed by malfunction detection techniques or normal maintenance is clearly a failure of the part, even though any necessary action may be taken while the equipment or system is still functioning normally and so not have caused a breakdown. The presence of such situations is obviously a potential cause of equipment unreliability, and in addition, the need to take corrective or preventive action at relatively frequent intervals increases maintenance time and reduces the equipment availability.

The importance of accuracy and speed of reporting cannot be over emphasised, as wrong information about the nature of the failure may do more harm than good. This means that the nature of the failure must be accurately diagnosed, the part which has failed must be identified, and the information clearly conveyed, making it clear which are facts and which are opinions or deductions about the cause of failure if done by the operator. A failure reporting system based on the computer should be most satisfactory. For this, computer based malfunction detection techniques are invaluable.

4.9. High Integrity Systems

High integrity systems such as those used for safety shut down are outside the scope of this work but even though the main concern in this work has not been with such systems, it is likely that in due course the techniques may make a contribution here also.

5. PRINCIPLES AND TECHNIQUES OF INSTRUMENT MALFUNCTION DETECTION

5. PRINCIPLES AND TECHNIQUES OF INSTRUMENT MALFUNCTION DETECTION

5.1. Introduction

With the advancement of modern technology, the growing number of problems whose solutions is demanded of engineering instruments in general and measuring instruments in particular, and the high reliability requirements imposed on acquired information from them, have led both to a greater complication of instruments and to the extensive incorporation of conceptually new elements. These factors tend to lower the reliability of measuring devices. The reliability of a measuring device is interpreted here as its ability to provide dependable information on the measured object under specified operational conditions.

For computer control, without the building of reliable instruments or improvement of the reliability of existing instruments, it would be impossible to solve many of the most important scientific and engineering problems in the further advancement of computer control.

The overwhelming majority of instruments have been manufactured, to date, without the provision of quantitative reliability or longevity specifications in the technical documentation. Information on their malfunctioning - mode of failure, exact behaviour when failing or when failed-are hard to come by. Hard to come by also, are works on the techniques of detection of the malfunctioning of the instruments. Yet, the problems of instrument systems cannot hope for an auspicious solution without regard for the particular features associated with the specific characteristics of these very relevant considerations.

At present, the function of malfunction detection is done predominantly by the process plant operator. The operator has to observe a large number of plant variables, watching the instruments in order to detect any off-normal condition that may develop. Even though the operator performs this task fairly well despite its monotonous and therefore boring nature, the computer has definite advantages over the human operator in this type of routine work. The computer can perform the scanning function tirelessly, imperturbably, and faster. Even though the operator's malfunction detection functions cannot be taken over completely by the computer, as tasks such as detection of small leakages, cracks in valve body etc., have to be detected on the spot during inspection tours of the plant; if the computer can take over the routine part of the interpretation of off-normal signals, then the operator can concentrate on more difficult jobs for which he is better suited.

The automatic detection of faulty behaviour of its own instruments is an added function which the process control computer can readily perform. The object here will be to detect the error before it is obvious and perhaps disastrous. This will obviously improve the maintenance and reliability of the instruments, more so, as the instrument will be tested in its actual working environment. Even though highly automated or very high integrity systems are not of main interest in this project, the ability of the computer to carry out this function would seem to be an essential requirement in such systems.

When an off-normal condition is detected, the operator normally decides on the probable cause by making some routine checks, in addition to checking relationships with other variables, that may also have become off-normal. If the computer takes over the off-normal detection, it can also handle these routine checks and deduce the most probable cause.

It is thought that any check must be some kind of comparison. There is quite a wide variety of possible comparisons. The checks could be on the equipment or instrument performance or condition. The checks can be broadly looked at either as passive tests or active tests, even though such a demarcation may not be very sharp sometimes.

Detecting and establishing the cause of an off-normal condition calls for a remedial action decision. More information and intelligence are required for the remedial action decision. More information and intelligence are required for the remedial action than for the interpretation. Because of the complexity and nature of the decisions to be taken the human operator is sometimes superior to the computer. Complete automation of this function is therefore not envisaged in this project but even when the decision has to be taken by the operator the task is expected to be enhanced by displays or computer warnings, all arising from off-normal interpretations by the computer. Some form of interplay between the man and machine and a proper allocation of functions between them in this respect is envisaged.

A set of algorithms of increasing complexity and sophistication would be required for this function.

An approach to the development of some of these algorithms has been two pronged, namely from

(i) a study of data on instrument failure, covering as wide a range of instruments as could be obtained and

(ii) looking at available relevant techniques and theories in the literature which can either be directly applied or adapted to this end.

A review and development of these techniques and possible applications of the techniques follows.

5.2. Literature Survey

Experience has shown that a great many instrument failures are caused by periodic variations in their working parameters, until finally their values exceed the permissible limits. This indicates that failure can result not only from sudden breakdown in the physical properties of an element in an instrument (disconnection, shorting, breakage etc.), but also from gradual variation of the parameters of the instrument elements due to aging and wear. Wear is associated with the partial breakdown of materials (abrasion and change in the geometry of moving parts) with aging and variation of the internal structure of materials (change in the resistance of insulation, embrittlement etc.) (108).

Most electronic objects are characterised by errors due to sudden failures. In well built products of this type, particularly those in which provision has been made for preventive replacement of parts having short service times, gradual failures constitute a negligible fraction (5-10%) of the total error. (109).

The distinction between sudden and gradual failure is an important one, because the nature of the failure affects the choice of analytical method, the technique of instrument system design, the techniques for detecting and locating failures etc. Another important consideration is the fact that sudden failures are generally explicit (Failure can be detected as soon as it happens) whereas gradual failures are latent by their very nature. The occurrence of this kind of failure in an instrument usually produces uncorrected error whose magnitude grows larger the greater the time that elapses between its occurrence and its detection. When there is interrelationship between elements (as is of course typical of many instruments) the gradual failure of one of them may not lead to the failure of the total system, but it can change the operating conditions of the other elements and thus change the quantitative reliability characteristics with respect to sudden failure.

At the present time the theory of gradual failures has not been adequately developed. There are a number of factors responsible for this state of affairs. (110) The majority of specialists so far concerned with reliability problems have concentrated their attention on the theory of sudden failure; it is far more complex to organise an ensemble of statistical data on the gradual failures of systems and constituent parts than on sudden failures, thus explaining the almost total lack of such data. The testing of products and components for the investigation of gradual failures is generally a protracted and costly process, it is often very difficult to ascertain the transformation operator (factor) between the input and output parameters of the instrument.

Not much work has been done in the field of instrument or equipment malfunction detection. Some work has been done by Rollins and Martin (111,112) to produce efficient calibration systems. They postulated that the decisions necessary to accomplish calibration can be made effectively when instrument data are interpreted as probabilistic phenomena. With case histories of two instruments, they showed how small samples of data could imply most of the knowledge necessary to manage instrument quality. Overall controls were given to verify the validity of samples of data interpretation. Hoyte (106) has discussed how instrument checks can be carried out by a process control computer. Using specific examples of how the operator carried out some checks, he showed how these checks could be carried out by the computer. He suggested that the specific examples illustrate general methods of using a computer to carry out automatic instruments checks. Doing a cost analysis with a specific example, he showed the feasibility of these checks by computer at justifiable costs. He did not, however, go further than defining the operator's checks logically and showing how these could be carried out in these specific examples by the computer.

Baarth and Maarleveld (7) have discussed the feasibility of including the function of off-normal interpretation by the computer in a d.d.c. project started at Pernis Refinery in 1966. The object of the off-normal interpretation program is to be able to warn the operator that an off-normal condition has arisen in the plant: one or more measured variables have passed beyond their limiting values. Calculated quantities have not been incorporated. Their proposal is based mainly on interrelationships between readings.

The Central Electricity Generating Board requirement for alarm analysis has been detailed and the different methods used have been reviewed by Welbourne (113). The method used at Wylfa is described, covering the different display and printing facilities available from the computer system. Both the alarm and data facilities are described and a brief account of the computer equipment is given, and the methods of alarm detection are described.

Alarms are detected by the data-processing system from the contact scanner inputs and by comparison of analogue scanner inputs, and by simple and calculated levels. The data processing system raises alarms, generated by program, on detection of faulty peripheral devices. Alarm grouping is done by the system programs.

Failure of peripheral devices, when used by the computer, is detected and alarmed. These alarms are, in most cases, fault incidents rather than fault states which persist.

Patterson (114) has described the alarm analysis by digital - computer system which has been installed and is now operating at Oldbury power station. In this plant, alarm information is presented to the operator by cathode ray tube displays. How the predicted alarm fault patterns, on which the analysis is based, were prepared for programming is described and some details of operational experience are also given.

The function of alarm trees (An alarm tree is defined by the Oldbury system, is any pattern of any number of real or derived alarms which can be interconnected in a predefined manner to demonstrate the relationship between cause and effect, and to show paths along which faults may develop from partiuclar causes) was divided into three parts in the way of the three things the analyser can be asked to do in processing a particular fault pattern, as follows:

(i) to analyse an alarm pattern and produce an analysis of cause and effect.

(ii) to consider the real alarms that are active, and display deduced alarms whose conditions for initiation are satisfied by these active real alarms

(iii) to darken any information which is superflous to the operator's requirements for operation of the plant and determination of fault causes.

The primary aim at the Oldbury and Wylfa applications was for an alarm-analysis system to be able to detect the prime cause of any fault and able to display this to the operator with any significant associated alarms.

5.3. Types of Malfunction Detection Techniques

The different types of malfunction detection techniques can be based generally on

(i) the condition or state of the equipment or instrument

(ii) the performance of the equipment or instrument.

Two general types of malfunction detection techniques

(i) Active

(ii) Passive

can be based on the above classification.

A specific definition here for Active and Passive techniques could run into interpretation problems and therefore will not be attempted.

As a general guide, by active type of malfunction detection, here, is meant the type of check procedure that is carried out either on routine basis or by some sort of initiation on either the equipment or instrument performance or on its condition. A pressure gauge installation for instance may be checked manually or automatically, on routine, for leakages, impulse line blockages or calibration errors. Impulse line may be tested manually by, isolating the line at the main and watching for a fall in the indicated pressure which would indicate a leak whose measure could be got from timing the rate; or by opening valve B see figure 5.1 (106) to change the indicated pressure, closing valve B and opening valve A. A slow rate of pressure rise when timed would indicate a blockage in impulse line.

The condition of a thermocouple can be tested by checking one of the characteristics of the thermocouple wire, say, the resistance. A dose of current can be passed through the wire and the resistance measured and compared with what is expected.

The dynamic response of a valve stem to a step change can be used to check for stickiness. All these are examples of active malfunction detection checks. The checks are carried out to probe the condition or performance of the instrument or equipment, to observe any incident failure or failed modes.

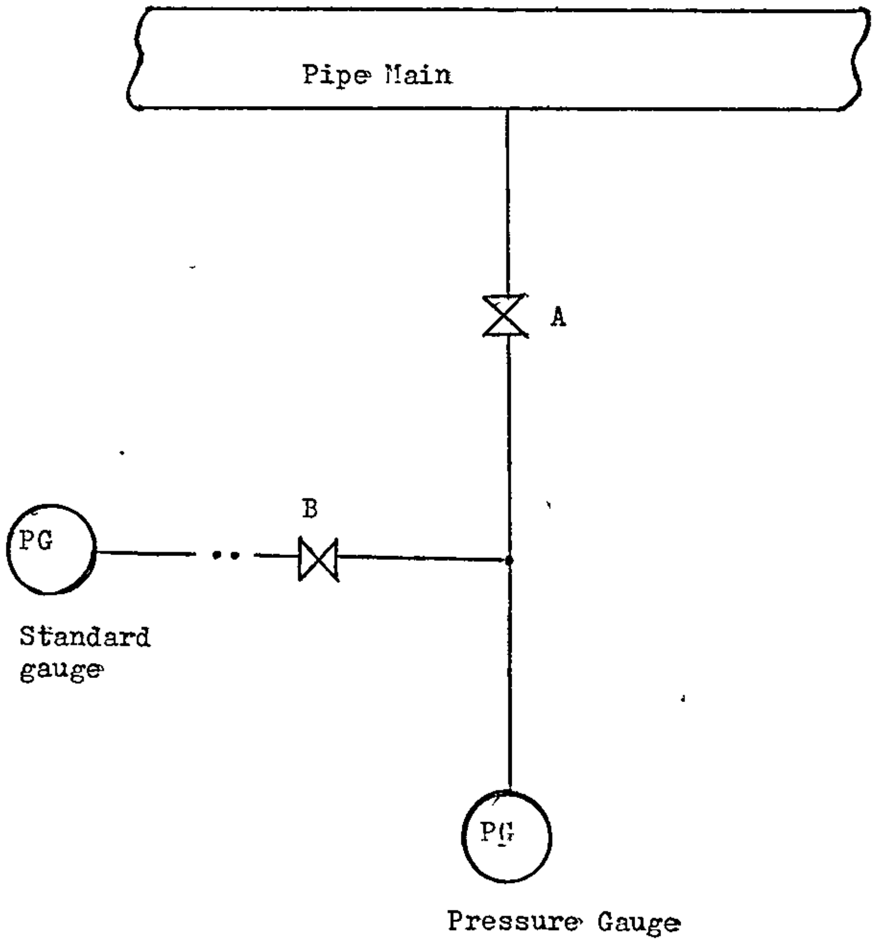


Fig. 5.1 Manual check of impulse line

On the other hand passive checks may rely on some form of signal analysis or relationship between readings, to signify an incident or total failure. The off-normal type interpretations suggested by Baarth and Maarleveld (7), or the alarm analysis type checks at Oldbury and Wylfa (113,114), could fall generally within this category.

It would appear that the main distinguishing factor would be how the check is carried out; so that checks whereby the failures or malfunctions are picked up, can generally be called passive, and checks whereby the failures or malfunctions are picked up by probing, called active.

No attempts will be made to classify the methods of malfunction detection discussed in this chapter as some of the methods could fall into either category depending on how they are used and for what purpose they are used. General basis and methods of malfunction detection only will be discussed.

5.4. Comparison as basis of detection

For measuring instruments, comparison method of malfunction detection includes the comparison between the actual reading and the expected, from considerations of the instruments physical constraints, dynamic response and signal properties, and of other measurement readings, process relationships, and control valve positions. For control valves, they include the comparison of the actual and expected values of the valve positions and of the force needed to position the valve.

Two main features of correct instrument signal which may be chosen for comparison are absolute value and first derivative. All instruments have variation in all their responses which can be classified as:

(i) Random variation (related to the design)

(ii) Permissible bias

(iii) Excessive variation

Excessive variation may be variability greater than normal but still random, time dependent variation or drift, or excessive bias.

Distinction between normal variation and excessive variation would be key requirements in detecting instrument malfunctioning. This could be done within the general premises of

(i) the instrument capability

(ii) the instrument use tolerance and/or

(iii) the instrument performance requirement.

The comparison of signals may be

(a) with expected correct signal

(b) with correct signal of duplicate instrument

(c) with correct signal of another instrument (using some simple model).

(d) with correct control valve position

(e) with own past signals

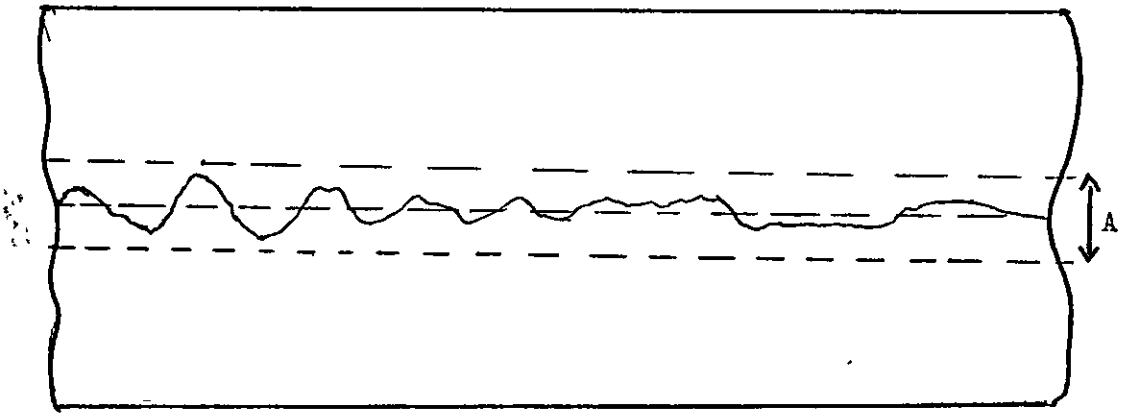
(f) with past signals of other types of instrument (using some complex model or filter).

Simple comparisons of correct signal with expected values include checks on zero or full-scale deflection, or excessively rapid rate of change.

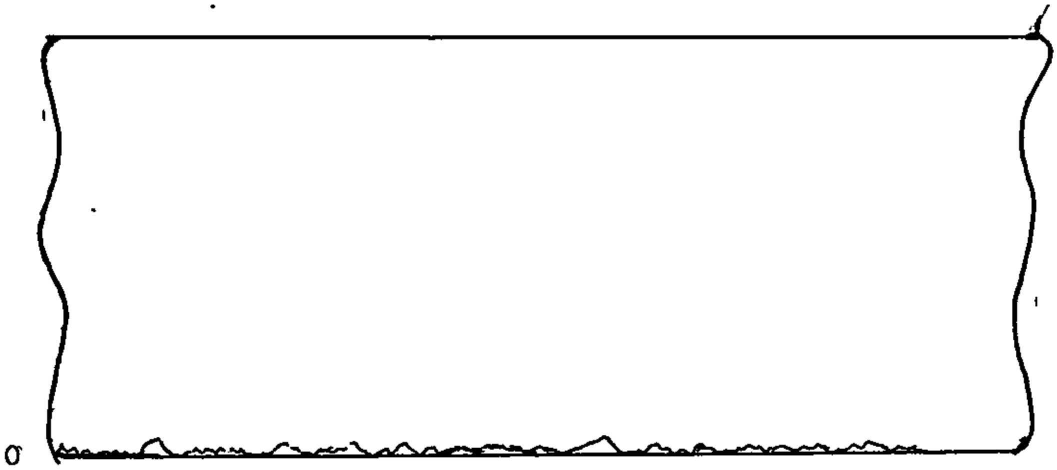
Proof-testing, in which once again there is an expected response, also comes in this category of comparison.

5.5. Detection by the Operator

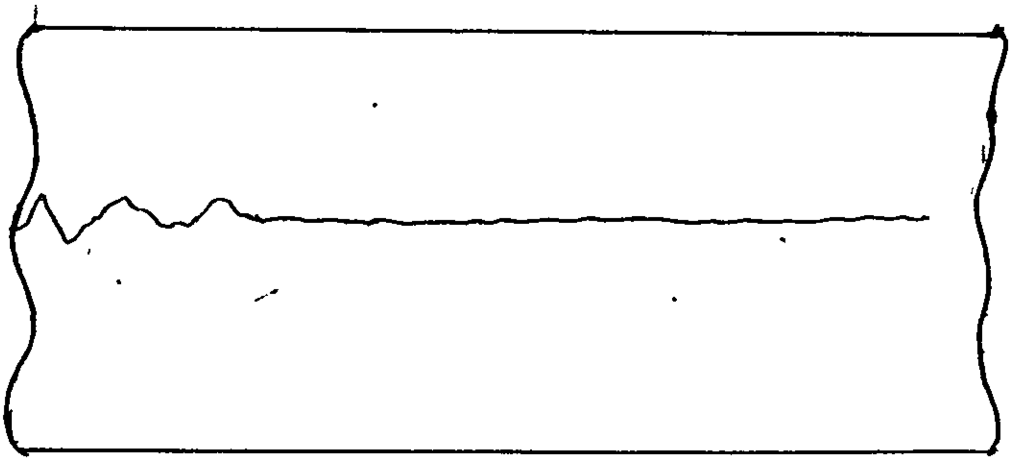
The operator uses many of the methods just mentioned with the exception of (f). The survey on failure of instruments carried out in industry and reported in Chapter 3 indicates that sometimes the



(a) Normal Signal A = Instrument capability

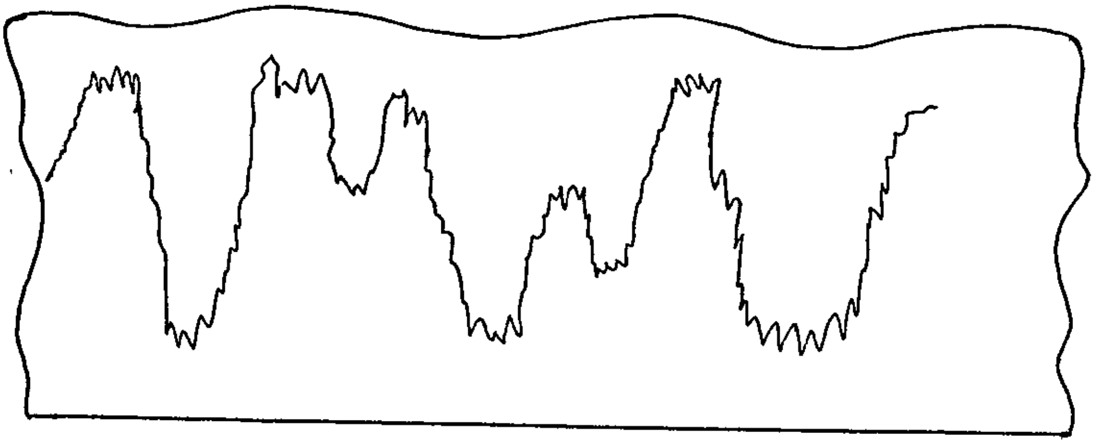


(b) 'Live' Zero signal

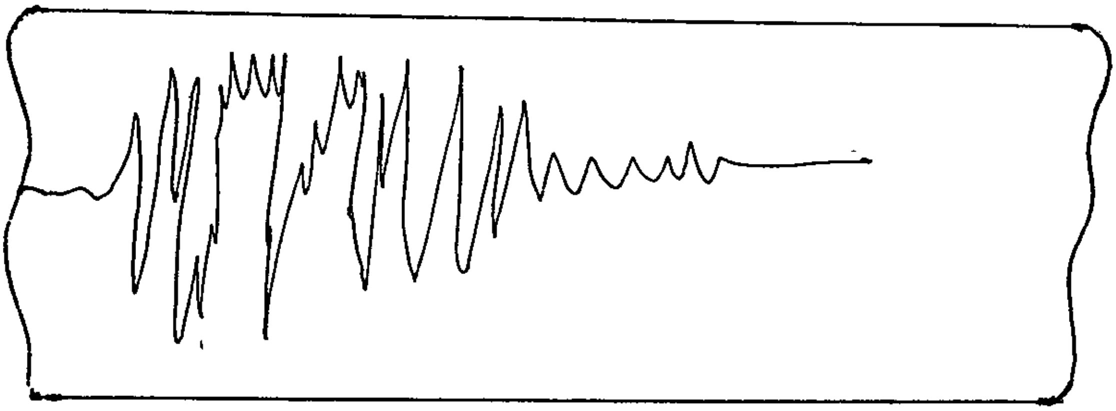


(c) Constant Signal

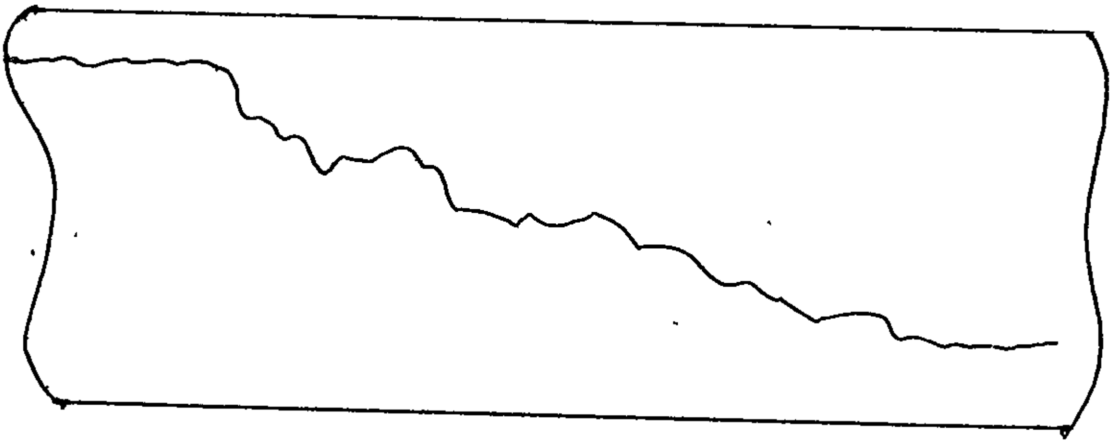
Fig. 5 Typical instrument signals



(d) Cycling Signal



(e) Excessively noisy signal



(f) Drifting signal

Fig. 5 contd. Typical Instrument Signals operator has to use his human senses of sight, smell and sound in addition. Such visual aids as chart recorders are very useful to him in sensing trouble. Displays, therefore, would be an important aspect of any malfunction detection technique that will use the operator

Typical sketches of a recorder chart of normal signal, zero signal, full scale deflection, excessively noisy signal, cyclic signal and a drifting signal are shown fig. 5.0 as typical examples.

The chart recorder represents the common type of visual aid normally provided which aid the operator in his malfunction detection function. Displays specifically designed to help the operator carry out the malfunction detection part of his job, should greatly enhance this function. It is normally the initiation of departure from some pattern of systems performance which may first give rise to the suspicion that a fault may exist or will shortly exist.

The first step for the effective use of the display method of malfunction detection would be to examine the system for possible parameters, indicative of changing states, which would have significance for fault anticipation or detection. Proper display of such a parameter, to quickly show up any abnormally, should very much enhance the operator's task of interpreting off-normal conditions.

A typical example of displays serving this end is that given by Bowen (115). He uses the effect of changing display parameters to illustrate how almost unnoticeable non-linearities in an abnormal engine gimbal response to a step change, as displayed on a pen recorder, show up clearly and in real-time in the phase plane display. (see Fig. 5.2.).

Figs 5.2. (a) and (c) show the smooth or normal engine gimbal response to step function as displayed on pen recorder and phase plane respectively.

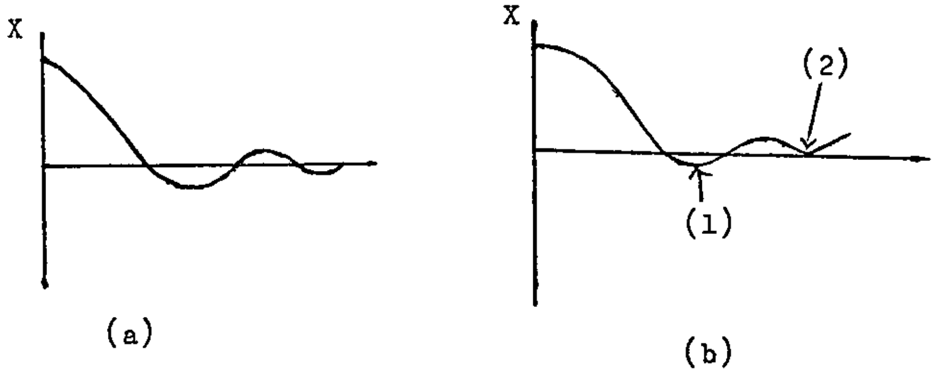
(b) and (d) show the corresponding non-linear or abnormal response. It would be extremely difficult to spot the beginning of the abnormally development before it would reach, probably, a state of malfunction. The almost unnoticeable non-linearities at points labelled (1) and (2) on the pen recording show up clearly in the phase plane display. Bowen also illustrated a method of displaying very large numbers of test data points in a way that facilitates the detection of the locus of a malfunction and the spread of its effect.

Further general illustrative examples of displays to this end are shown in Figs. 5.3. (a) to (d).

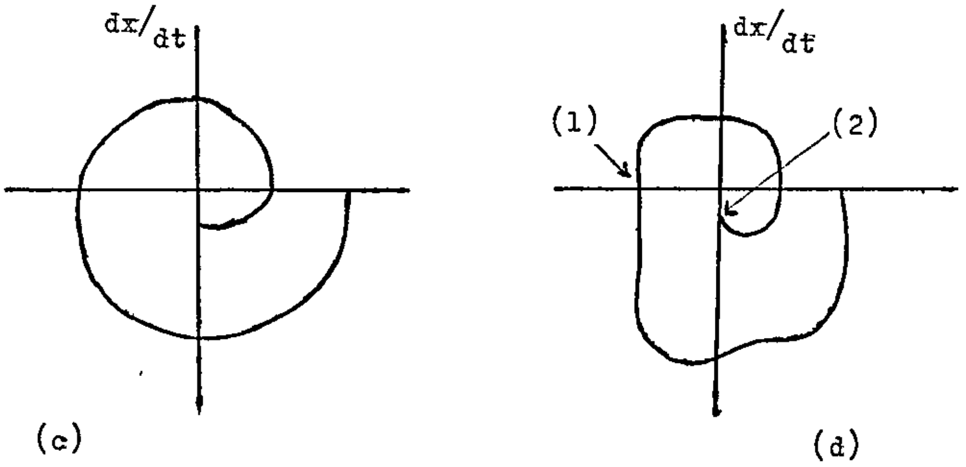
Fig 5.3. (a) shows a display of the noise level of a signal with the mean substracted. The average power or standard deviation of the signal could have done as well. With a noisy or rapidly changing signal, where it would be difficult otherwise to sense possibility or actual malfunction, this type of display should greatly enhance the task.

Some deviations from normal, of a signal, may not show up very well on a single statistical parameter but may on the other hand show up very well in the frequency domain. Frequency analysis based displays such as the line spectrum illustrated in Fig. 5.3 (b) should be most useful.

A powerful display technique which has been developed and is in use in the medical profession is the Wolf's "face" type display (116) shown in Fig 5.3. (c). This makes use of the well known psychological fact that man finds it easier to recognice round shapes like the face and deviations from them. Different critical system parameters which can indicate the behaviour of one system can be displayed in scaled form, as an axis or radius of the circle. Thus if the four main radii, for instance, represent measurements of temperature and pressure, these measurements are represented

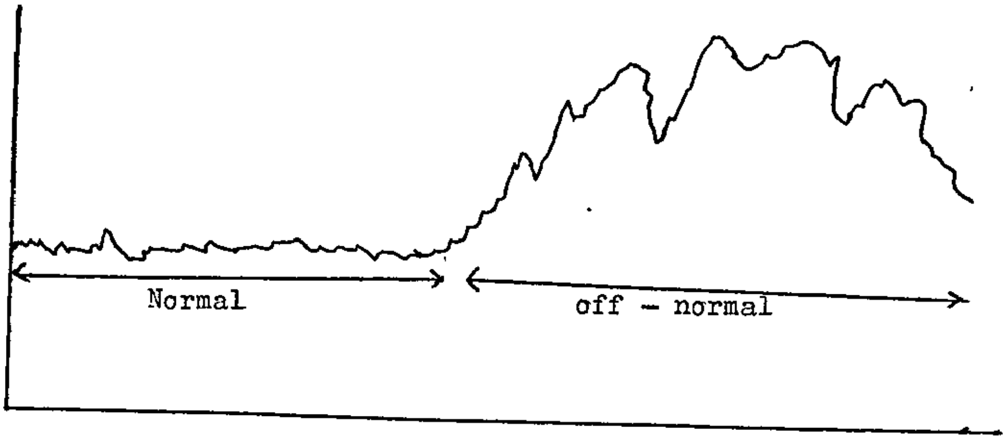


Pen recorder displays

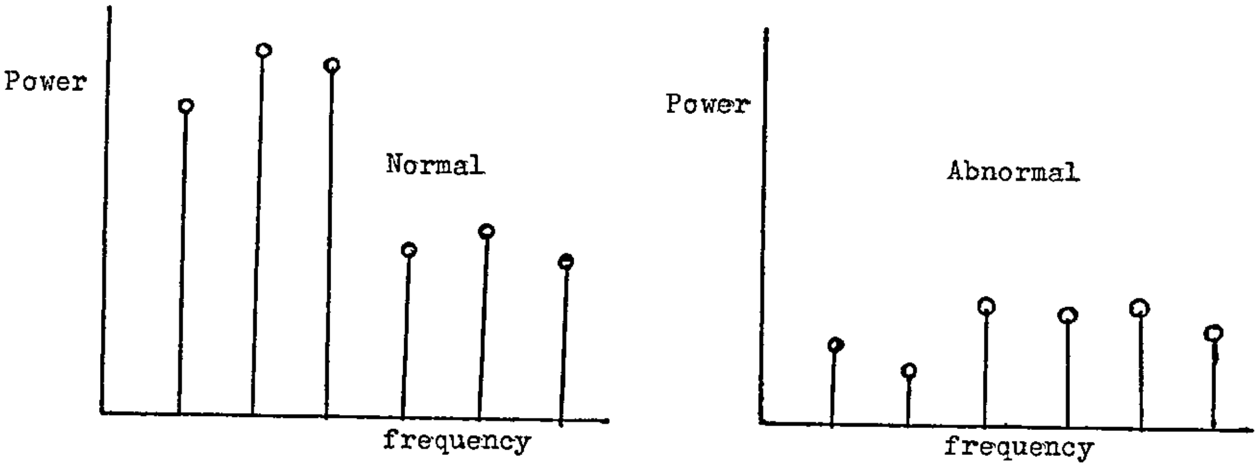


Phase plane displays

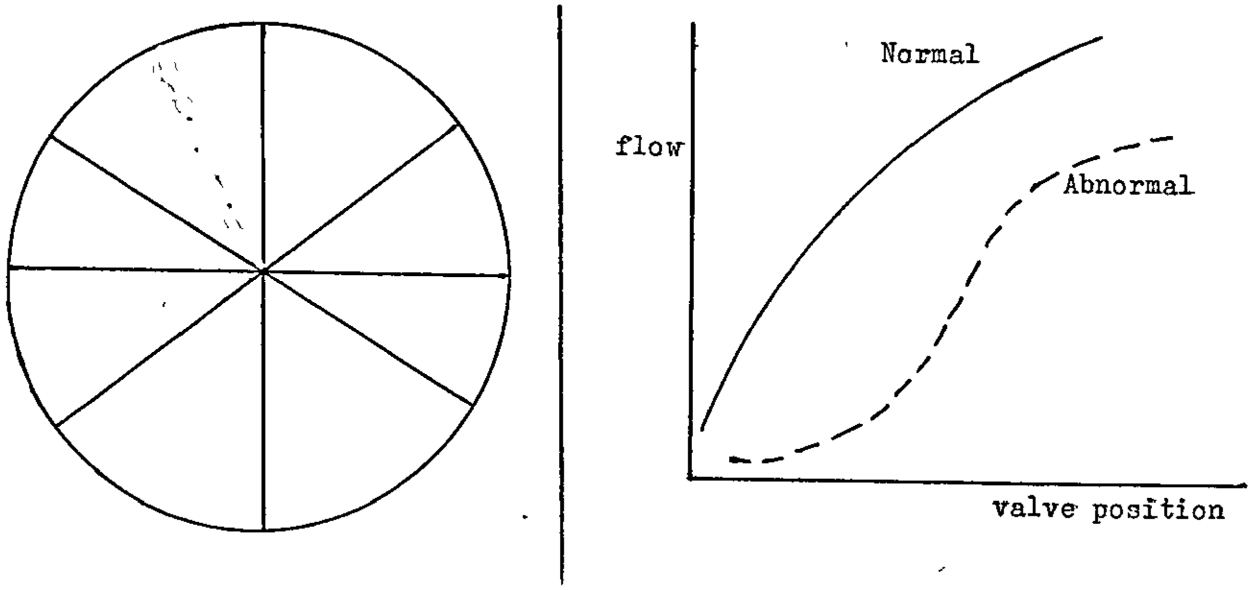
Fig. 5.2 Effect of changing display parameters



(a) Noise (with mean subtracted)



(b) Line spectrum display



(c) Hugo Wolf's 'face'

(d) Trend log display

Fig. 5.3 Displays

in such a way that a circular display is shown. A deviation from normal of any of the parameters, would lead to a distortion of the circular shape and this could very easily be picked up. Thus an initiation or actual failure can easily be seen on such a display.

A simple display such as a graph of some trend log by the computer, such as flow against valve position, for instance, can show up a deviation better. Fig. 5.3. (d).

The power of such display techniques would be in their optimising and efficiently employing the operator's most powerful tools namely, his intelligence and his ability to learn.

The routine task of producing the displays is a task the computer is very well suited to.

5.6. Detection by Computer

Before the machine can be asked to analyse any situation, it must be furnished with some criteria such as algorithms. These could be based within the general premises of checking some critical parameter to see if it is within desired quality level or expected family capability.

It is desirable that general principles of detection methods suitable for the computer should be as economic, general, and robust as possible. In this respect such methods as based on duplicated instruments are not very economic; mass balances are not general; zero scale or full scale deflection methods tend to give false alarms.

Nevertheless all the methods given in section 5.4. (a) to (f) appear applicable in some form.

5.7. Comparison with expected signal

5.7.1. Zero or Full Scale Signal

For a zero signal, there are two types (i) a 'dead' zero and (ii) a 'live' zero. A dead zero, is when there is no output at all and the pen recorder for instance is not moving. A live zero, is when there is an output but the output is hovering around zero. A pen recorder would be moving but around zero. A distinction between the two zero readings is important for diagnosing the fault. A dead zero signal could mean a failure in the electronics of the system whereas a live zero could eliminate this possibility. An algorithm to differentiate between the two will enhance fault diagnosis. Nevertheless, they both could represent malfunction behaviour.

With development to suppress false detection, an algorithm based on zero or full scale signal could probably be a valid check. 'Hardover' checks such as zero or full scale signal, however, have the disadvantages of false alarms and the fact that they very often represent and tend to occur with total failure.

The computer could learn to suppress false detection by observing which detections came up during some specified period. Suppression could be permanent or brought in only during start-up and shut down.

5.7.2. High Rate of Change of Signal

The maximum permissible rate of change can be specified in advance and learnt during specified period of running, thus making this a feasible valid check.

5.7.3. Proof-testing

The criteria of success in a proof test is achievement of an expected response, so that this comes into this category.

The intrinsic characteristics of the process can be used as perturbations. For a batch process with known cycles, for instance, the start of a cycle could be used as a perturbation. If this cycle is a heat cycle, for instance, in the case of a batch polymerisation process, the start of the heat input or the turn off of heat can be used as a perturbation to test the response or behaviour of a temperature measuring device such as a resistance thermometer. The check procedure can be initiated by the start or finish of the cycle.

Within the general criteria of achievement of an expected response, dynamic tests can be initiated and situations of malfunction can be detected.

5.8. Comparison with Duplicate Instrument

This comparison may be based mainly on the premises of the instrument family capability. In a suspect situation, the reading of the duplicate instrument could be used for a check. The reading of the duplicate instrument could be used to set the limits of the normal instrument family capability. The deviation from the duplicate instrument reading could be one parameter indicative of a normal or off-normal condition.

5.9. Comparison with another Instrument

This comparison may be based on relations specified in advance, for instance, mass balance, or on relations learnt such as some plant pressures and temperatures being related to throughput.

5.10 Comparison with Valve Position

Although this is mainly a means of checking flow meters in situations where valve pressure drop is constant, or else measurable, flowmeters are so common that this is virtually a general technique.

5.11. Comparison with Past Signals

This is a general technique which depends on the fact that instrument and process noises are likely to have different characteristics. In this case a deviation from normal could very easily be detected from a frequency resolution of the signal. This is dealt with in the next chapter.

5.12. Comparison with other Instruments Using Unsteady State Model or Filter

This again is a general technique which depends on the fact that there are necessary relations between process variables. This technique is also dealt with in the next chapter.

5.13. Action taken on Detection

Detection of an off-normal condition should result in action. It can initiate a warning or a display for the operator. If measurement is used in control, either an approximate measurement may be actuated, or control organisation must be changed. These possibilities have already been discussed in Chapter 4. If it is used in some kind of model, some action is again required.

It is also then desirable that full information on the failure should be made available to the maintenance department. An 'alarm tree' type analysis can be triggered off. This offers hope of getting much more precise reliability data, because the computer's reason for declaring a failure will be quite precise.

5.14. Feasible Algorithms based on some Ideas of the Foregoing General Outline

5.14.1. Zero or Full Scale Reading Detection

The lower limit of scale L, the upper limit of scale U, the lower limit margin δl and the upper limit margin δu can be set as parameters for this algorithm. δl and δu set the dead band for hovering readings and should ensure that false alarms are not raised in such situations.

A check on the instanteneous measured value M_k, with respect to these parameters, can then be made to see either if

$$M_k < (L + \delta l)$$

or

$$M_k > (U - \delta u)$$

Satisfaction of either of these conditions could be a suggestion of some spurious or unreliable signal.

In the case of a continuously fluctuating variable, the fluctuation should be within certain limits of tolerance. The upper and lower limits of this band together with the upper and lower margins can be designed as above and the algorithm similarly applied.

Continuous satisfaction of either or both of these above conditions could be a simple indication of trouble.

5.14.2. Large or Sudden and Large Excursion

For signals where the readings should remain reasonably steady within a certain limit, large, or sudden and large excursions, could be an indication of malfunctioning of the instrument. For an algorithm to deal with this type of situation, a running mean value of the signal ($\bar{M}_k$) would be required as well as a stipulation of the excursion limit (e max).

One equation for averaging (smoothing) the current value with the past values, in order to eliminate the effects of noise, is the single-exponential smoothing (17) and is given by

$$\bar{M}_k = \alpha M_k + (1-\alpha)\ \bar{M}_{k-1}$$

where the smoothing constant α, lies in the range $0 \leqslant \alpha \leqslant 1$. Thus the smoothed value $\bar{M}_k$ is constructed by taking some fraction of the present unsmoothed value and the complementary fraction of the previous smoothed value. A low value of smoothing constant should be used when it is suspected that the signal has large random fluctuations, since the weight placed on the current unsmoothed value will be sufficiently low to smooth out the effects of the fluctuations. On the other hand, an excessively low value of α will also cause the smoothed signal $\bar{M}_k$ to be unrepresentative of the actual signal if a steady real trend is present. Choosing $\alpha = 1$ is clearly equivalent to not smoothing. The choice of α requires a compromise between noise rejection and speed of signal tracking. The lower the smoothing constant α, the better the noise rejection, but the slower the smoothed signal compared to the original. Typical values of commonly used in industry, are $\frac{1}{2}$, $\frac{1}{4}$ and $\frac{1}{3}$. This type of smoothing is normally done in d.d.c.

Having calculated the running mean, the excursion e_k can then be calculated as

$$e_k = M_k - \bar{M}_{k-1}$$

check if

$$e_k > e_{max}$$

where e_{max} is the permissible excursion limit as defined.

5.14.3. Large Derivative

Provided the mean does not move too rapidly this is virtually the same as above (5.14.2).

5.14.4. Variation in Variance or Standard Deviation

The variance σ^2 or the second moment about the mean is a measure of the spread of a distribution about the mean which can be defined in the discrete form as

$$\sigma^2 = \frac{1}{n} \sum_{i=1}^{n} (M_k - \bar{M}_k)^2$$

[illegible]

If the fluctuation of the signal tends to be narrow and concentrated about the mean, σ^2 will be small. Conversely if there are large fluctuations of the instantaneous reading far from the mean value, σ^2 will be large.

The standard deviation σ is simply the square root of the variance.

Therefore the single parameter σ can be used as a measure of the scatter of the instantaneous readings about the mean value over a period of time. Normally, there would be a limit for the fluctuation of the readings about the mean. A rise in level of σ above this limit would indicate unusually large fluctuations. The maximum tolerable value of σ, σ_{max} can be pre-specified.

For a continuously varying signal, a running mean would be preferable to a fixed mean.

Using single, exponential smoothing, a variance estimating algorithm could be as follows

(i) Calculate the running mean $\bar{M}_k$ as

$$\bar{M}_k = \alpha M_k + (1 - \alpha) \bar{M}_{k-1}$$

(ii) Calculate error

$$e_k = M_k - \bar{M}_{k-1}$$

and hence

(iii) $$\sigma^2 = \frac{\Sigma e_k^2}{n}$$

or $$\sigma = \sqrt{\sigma^2}$$

$$= \frac{1}{\sqrt{n}} \sqrt{(\sum e_k^2)}$$

(iv) Check if

$$\sigma > \sigma_{max}.$$

This technique should bring out an excessively noise-free as well as an excessively noisy signal. It has been used in this project for thermocouple signal malfunction detection and for the detection of off-normal conditions from industrial control valve data.

6. ON-LINE TIME SERIES ANALYSIS OF INSTRUMENT SIGNALS

6. ON-LINE TIME SERIES ANALYSIS OF INSTRUMENT SIGNALS

6.1. Introduction

By definition, a statistical time series is a signal or function of time, x (t), which exhibits random or fluctuating properties. In most situations the fluctuation x(t) will be a function of time, but in other situations it may be a function of some other physical parameter t, for example, space.

Two simple concepts of time series are the discrete and continuous series as shown in Figs. 6.1. (a) and (b).

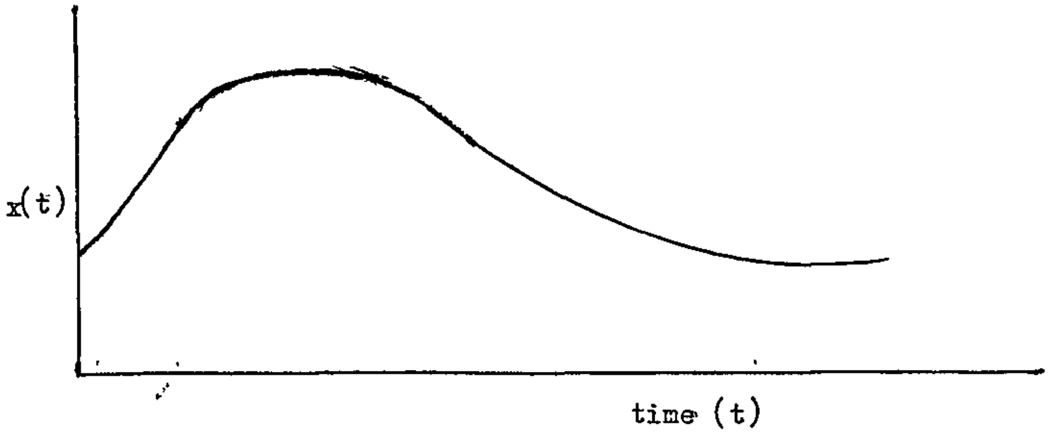


Fig. 6.1(a) Continuous time series

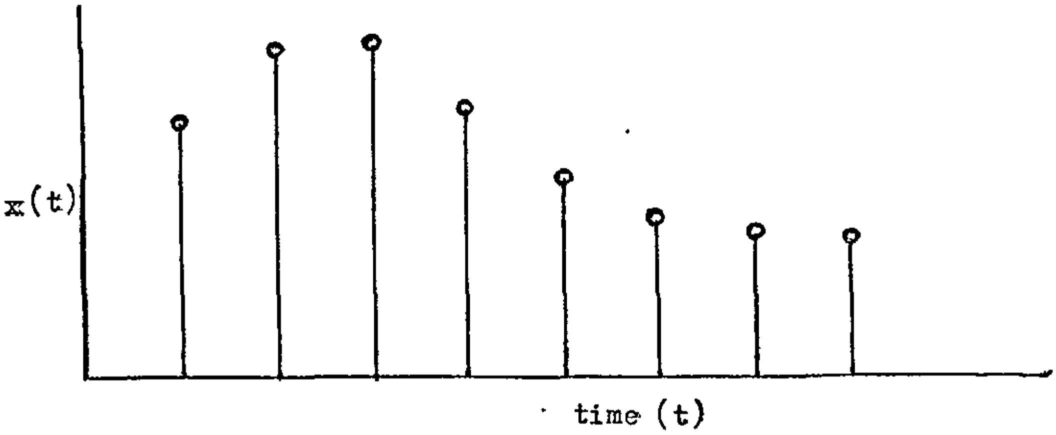


Fig. 6.1(b) Discrete time series

Continuous time series: Time series with continuous measurements for instance fluctuating yield from a chemical reactor as measured on a continuous basis by an infra-red sprectrometer.

Discrete time series: Time series for which the values are given only at specific instants of time. One way in which a discrete time series may be obtained is by sampling a continuous time series at equal intervals of time. It may also arise when a physical quantity does not have an instantaneous value but has meaning only when accumulated or integrated over a suitable time interval.

The main characteristics of on-line computer signals are that the signals are discrete and potentially of almost un-limited length; and also they contain both process and measurement noise. Each of these characteristics is important and it is these characteristics that make them amenable to the treatments discussed here.

This is divided into two main areas: various methods of analysis for simple signals and Kalman filters for multiple signals. It is on the former that most work has been done but the potential of the latter is pointed out.

The particular phenomena of interest here is power at particular frequencies. This involves resolving a signal into the frequency domain either by the Fast Fourier transform (FFT) techniques or by the use of digital filtering techniques.

It is expected that the behaviour of the power spectrum at a particular frequency or the power spectra over a range of particular frequencies of a given signal will show up any significant deviation in signal behaviour from normal which might indicate malfunctioning. It might amplify or show up the deviations better than, say, the average power in certain cases.

One such situation and one which has been used as an illustrative example here is the signal from a differential pressure (D/P) transmitter.

Normal and abnormal signals from a D/P transmitter have been subjected to frequency domain analysis using the FFT to calculate an equivalent of the power at particular frequencies. This analysis is not discussed in this chapter but is discussed later.

The necessary theoretical background and possible applications of FFT type analysis and digital filters to instrument malfunction detection are discussed in this chapter.

6.2. Methods of Analysis for Simple Signals

6.2.1. Autocorrelation Function and Power Spectral density function

Among the various statistical parameters associated with random processes, two stand out as being of greatest importance, namely, the power spectral density functions (also simply called power spectra) and correlation functions.

6.2.2. The Autocorrelation Function

If $x_1(t)$ is a time series, the concept of comparison of two signals, applied to the comparison of a signal with itself when shifted by an amount τ, is called the autocorrelation function $Q_{11}(\tau)$ and is defined as

$$Q_{11}(\tau) = \int_{-\infty}^{\infty} x_1(t)\; x_1(t-\tau)\, dt \tag{6.1.}$$

$$= \int_{-\infty}^{\infty} x_1(t+\tau)\; x_1(t)\, dt \tag{6.2.}$$

From equations 6.1. and 6.2. it is obvious that

$$Q_{11}(\tau) = Q_{11}(-\tau)$$

Evidently, the autocorrelation function is an even function of τ.

For a given process, there is a unique autocorrelation function but the converse is not true. A given autocorrelation function may correspond to a large number of different processes. This is because an autocorrelation function is not a complete measure of a random process but is one of the average parameters, and a certain average can correspond to an infinitely large number of situations.

The autocorrelation function, however, is one of the most significant quantities in the spectral analysis of random signals. It is a measure of the rapidity of variation of a given signal.

It has noise minimising properties which are extensively used in the detection of signals in the presence of noise (118,119). Applications have ranged from the detection of periodicities to the reception of weak signals from deep space vehicles.

The autocorrelation function is not of primary interest here but is relevant to one of the methods of estimating the power spectral density function.

6.2.3. The Power Spectral density function

The power spectrum P(f) and autocorrelation $Q(\tau)$ functions are related according to the Fourier transform relation

$$P(f) = \int_{-\infty}^{\infty} Q(\tau) \cos 2\pi f \tau \, d\tau \qquad (6.3.)$$

and hence knowledge of the autocorrelation function of a process is equivalent to knowledge of the spectrum of the process.

However, in the analysis of a finite length of record, the power spectrum is often preferable to the autocorrelation function. First, estimates of the spectrum at neighbouring frequencies are approximately independent, and hence the interpretation of the sample spectrum is usually easier than that of the sample autocorrelation function. More important, in many physical problems, the spectrum is of direct interest.

The power spectral density for a process indicates the contribution to mean-squared fluctuation due to signal components in any specified frequency interval.

It is not a complete measure of a signal but is just an average parameter of the signal. This is because the power density spectrum by definition is a power density averaged over a large time interval T.

6.2.4. Practical Procedures for estimating spectra from observed time series:

The statistical theory of spectral analysis is normally derived assuming the data x(t) are continuous. In many situations, the data are essentially discrete and hence digital formulae are required. The accuracy, flexibility and relative availability of digital computers, today, make them the ready choice for most spectral analysis. The use of computers for spectral analysis implies quantizing (the process of converting from the analog to the digital form) and it will be assumed that the quantizing is fine enough so that no errors are introduced in the conversion from analog to digital form.

In practice, numbers are only represented to some finite degree of precision, due to the finite word length of a computer.

In a digital filter, the effect of numerical error has two main effects:

(i) the finite accuracy with which the coefficients can be specified limits the accuracy with which the frequency response can be defined.

(ii) the effect of round-off which is inevitable at each computational stage produces error in the output number sequence. The error can often be regarded as being due to a uniformly distributed random number added to the result of each computation.

In many applications, particularly when a general purpose computer with large word length is used, the effect of quantization error in digital filters is negligible in comparison with the effects involved in analogue/digital conversion.

However, when the signal waveform as such is not of interest, as in power spectrum analysis, then the effect of quantization error is negligle to a large extent.

It may be necessary to filter the data before estimating the autocorrelation function or the power spectrum from the autocorrelation function.

Even though the power spectrum can be estimated via the autocorrelation, this method is much inferior to the method of estimating the power spectrum by fast fourier transform techiques, particularly with the implementation of the latter by digital computer.

The practical procedures for estimating spectra from observed time series that are discussed here, therefore, are those using the more efficient and more economical (with computer application) fast Fourier transform methods.

6.2.5. The Fast Fourier Transform (FFT)

The fast Fourier transform is a computational tool which facilitates signal analysis such as power spectrum analysis and filter simulation by means of digital computers. It is not a transform as such but a collective term for a number of algorithms which facilitate the efficient computation of the discrete Fourier transform of a series of data samples or a time series.

6.2.6. The Discrete Fourier Transform (DFT)

The discrete Fourier transform is the sampled-data equivalent of the conventional Fourier transform.

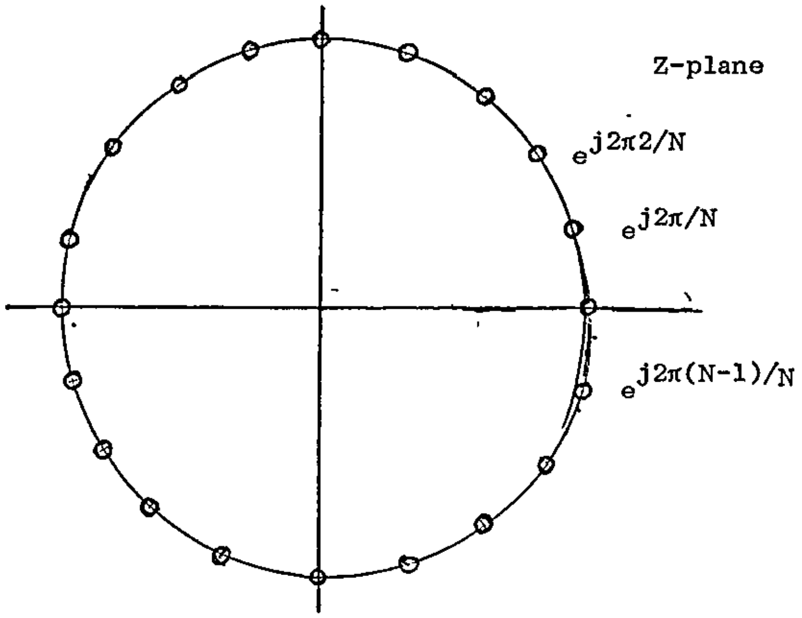
A finite sequence (x_n) has a z - transform

$$X(Z) = x_o + x_1 Z^{-1} + \ldots\ldots + x_{N-1} Z^{-(N-1)} \qquad (6.5.)$$

If the Z - transform is evaluated at values of z given by

$$(1,\ e^{j2\pi/N},\ e^{j4\pi/N},\ \ldots\ldots\ldots\ldots,\ e^{j2\pi(N-1)/N})$$

a new sequence is obtained. These values of Z lie at regular angular intervals around the unit circle in the Z - plane.



Using W to represent $e^{-j2\pi/N}$ these values of the Z- transform are given by the equations

$$\begin{aligned}
X_o &= x_o + x_1 + \ldots\ldots + x_{N-1} \\
X_1 &= x_o + x_1W + \ldots\ldots + x_{N-1}W^{N-1} \\
X_2 &= x_o + x_1W^2 + \ldots\ldots + x_{N-1}W^{2(N-1)} \\
&\bullet \quad \bullet \quad \bullet \quad \bullet \quad \bullet \quad \bullet \quad \bullet \quad \bullet \\
X_{N-1} &= x_o + x_1W^{N-1} + \ldots\ldots\ldots + x_{N-1}W^{(N-1)^2}
\end{aligned} \tag{6.6.}$$

The sequence $(X_o , \ldots\ldots\ldots X_{N-1})$ is the discrete Fourier transform of the sequence $(x_o , \ldots\ldots\ldots\ldots , x_{N-1})$.

The equations (6.6) can be written as a matrix equation

$$\underline{X} = \underline{W} \; \underline{x}$$

where the column vectors $\underline{X}$ and $\underline{x}$ contain the elements of the sequence (X_n) and (x_k). The matrix $\underline{W}$ is given by

$$W = \begin{bmatrix} 1 & 1 & 1 & \cdots & 1 \\ 1 & W & W^2 & \cdots & W^{N-1} \\ 1 & W^2 & W^4 & \cdots & W^{2(N-1)} \\ 1 & W^3 & W^6 & \cdots & W^{3(N-1)} \\ \cdot & \cdot & \cdot & \cdots & \cdot \\ 1 & W^{N-1} & W^{2(N-1)} & \cdots & W^{(N-1)^2} \end{bmatrix}$$

The DFT is written as

$$X_n = \sum_{k=o}^{N-1} x_k W^{nk} \quad , \quad n = o , 1 , \ldots\ldots , N-1$$

Since the x_k's are often values of a function at discrete time points, the index, n , is sometimes called the 'frequency' of the DFT.

There exists the usual inverse of the DFT and, because the form is very similar to that of the DFT, the FFT may be used to compute it.

It can be verified that the inverse of the matrix $\underline{W}^*$ is given by $^1/N\ W^{-1}$. Thus the DFT is an invertible transform in its own right: given (x_n) the sequence (X_n) can be computed and vice versa.

The Inverse Discrete Fourier Transform (IDFT) can be written as

$$x_l = \frac{1}{N} \sum_{n=o}^{N-1} X_n W^{-nl} \quad l = o , 1 , \ldots\ldots\ldots\ldots , N-1.$$

6.2.7. Useful properties of the DFT

An important property that makes the DFT very useful is the relationship between the DFT of a sequence of Nyquist samples and the Fourier transform of a continuous waveform, that is represented by the Nyquist smaples.

(The Nyquist frequency $f_N = \frac{1}{2}\Delta$ is the highest frequency which can be detected with data sampled at intervals Δ).

Another very useful property of the DFT is the convolution relationship. That is, the IDFT of the product of two DFT's is the periodic mean convolution of the two DFT's. This relationship proves very useful when computing the filter output as a result of an input waveform; it becomes especially effective when computed by the FFT.

Other properties of the DFT are in agreement with the corresponding properties of the Fourier integral transform, perhaps with slight modifications. These properties have been compiled by Gentleman and Sande (120).

6.2.8. Applications of the Fast Fourier Transform

Before the advent of the fast Fourier transform, the Fourier transform served as a bridge between the time domain and the frequency domain. With the development of the FFT it is now possible to go back and forth between waveform and spectrum with enough speed and economy to create a whole new range of applications for this classic mathematical device.

The FFT can be used in place of the continuous Fourier transform only to the extent that the DFT could before but with a substantial reduction in time.

If the set (X_o , X_1 , ... , X_{N-1}), equation 6.6., are computed directly, N operations (counting one complex multiplication as an operation, are required for each X_k, and N^2 for the whole set of N members. The fast Fourier transform reduces the number of operations for DFT evaluation to the order of $N \log_2 N$. For large N the saving can be dramatic. For example it has been calculated that a transform of 2^{17} complex points requiring 24 minutes of FFT computation on an IBM 7090 would run for about 65 days performing a direct evaulation. A fewer number of operations results in a reduction of cumulative round off error and hence the FFT is both faster and more accurate than the direct method.

The operations usually associated with the FFT are

(i) computing a spectrogram (a display of the short-term power spectrum as a function of time);

(ii) the convolution of two time series to perform digital filtering; and (iii) the correlation of two time series.

Although all of these operations can be performed without the FFT, its computational savings have significantly increased the interest in performing them digitally.

(i) Spectrograms: In this case the square of the magnitude of the set of complex Fourier coefficients (that is, the periodogram) is used to estimate the power spectrum of the original signal.

A snapshot of the spectrum of the signal can always be computed from the last T seconds of data. By taking a series of these snapshots, estimates of the power spectrum can be displayed as a function of time.

When the spectrum of a signal contains a periodic component, this spectrum can be compressed by taking the logarithm, and then the fast Fourier transform can be taken. The result is called a cepstrum (121,122). For a more complete discussion of short-term spectrum and cepstrum analysis see references (121 - 132).

(ii) Use of the FFT for Digital filtering: The problems of either determining the output, given the input and the impulse response, or finding the impulse response, given the input and the output, frequency confronted in a linear system, can be approached rather easily in the frequency domain.

The output of the general nonrecursive filter is given by,

$$y_n = \sum_{r=0}^{L} a_r \, x_{n-r}$$

The output sequence, $(y_o , y_1 , \ldots\ldots)$ is said to be the discrete convolution of the input sequence $(x_o , x_1 , \ldots\ldots)$ and the filter impulse response, $(a_o , a_1 , \ldots\ldots , a_L)$.

Taking as an example, a three-coefficient filter of fig. 6.3 (L = 2), successive outputs are given by,

$$\begin{aligned} y_o &= a_o x_o \\ y_1 &= a_o x_1 + a_1 x_o \\ y_2 &= a_o x_2 + a_1 x_1 + a_2 x_o \\ y_3 &= a_o x_3 + a_1 x_2 + a_2 x_1 \\ y_4 &= a_o x_4 + a_1 x_3 + a_2 x_2 \end{aligned} \qquad (6.7.)$$

etc.

The input sequence, $(x_o , x_1 , ...)$ may be very large or not entirely available before filter outputs are required and therefore to achieve a 'continuous' filtering action it is necessary to consider successive N - point segments of the input.

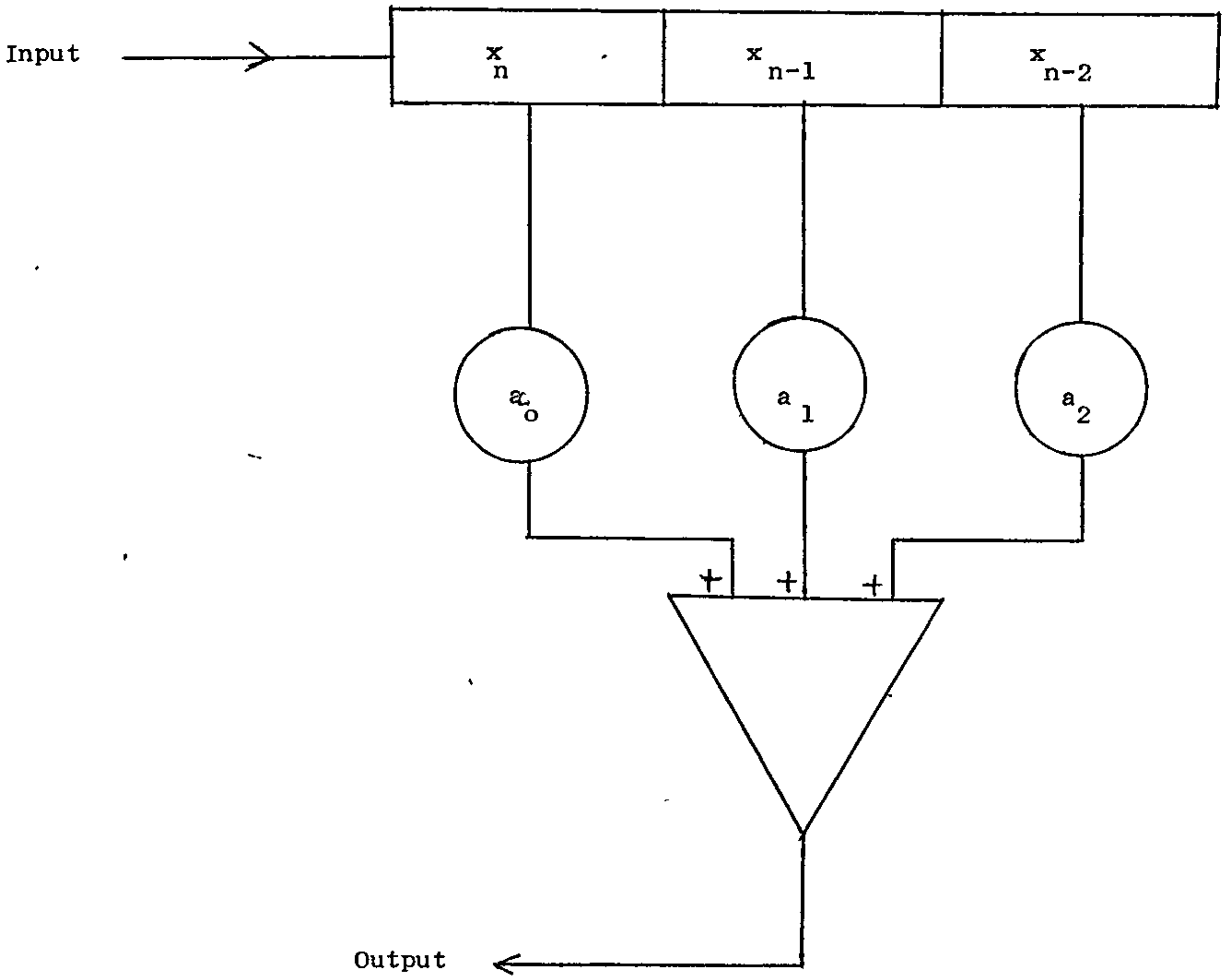
To implement the filter of fig. 6.3 by FFT methods, with N=8 the DFT of the sequence $(x_o , x_1 , ... x_7)$ is taken and multiplied by the DFT of a_o , a_1 , a_2. The IDFT of the product sequence then yields the <u>circular</u> convolution values. (a discrete convolution of the input sequencies (x_n) and (y_n) defined as

$$P_r = \sum_{n=0}^{N-1} y_n \cdot x_{r-n}$$

where $x_n = x_{n+N}$ is said to be a <u>circular convolution</u> if x_n is treated as a periodic input).

$$\begin{array}{l} (a_o x_o + a_1 x_1 + a_2 x_6) \\ (a_o x_1 + a_1 x_o + a_2 x_7) \\ (a_o x_2 + a_1 x_1 + a_2 x_o) \\ (a_o x_3 + a_1 x_2 + a_2 x_1) \\ \quad\vdots \\ (a_o x_7 + a_1 x_6 + a_2 x_5) \end{array}$$

A comparison with equation 6.7 indicates that the first two (in general L)



$$y_n = a_o x_n + a_1 x_{n-1} + a_2 x_{n-2}$$

Fig. 6.3   3-Coefficient non-recursive filter results above do not agree with any of the required values and must therefore be discarded. The remaining results, however, are correct for y_2, y_3, ..., y_7. To apply the FFT method continuously it is therefore necessary to 'overlap' successive input segments by L points so that the first L erroneous convolutions associated with each segment can be discarded in favour of the correct values saved from the last L results of the previous segment. In terms of the example, this implied that the next DFT input is the sequence $(x_6, x_7, ..., x_{13})$ in which case the first two results of the circular convolution are discarded in favour of y_6 and y_7 which are available as the last two results from the previous segment. This procedure has been termed the overlap-save method (133). Other methods of comparable efficiency have been discussed in the literature (133). Tests (134) have shown that FFT methods of computing convolutions are faster than standard nonrecursive methods when L is greater than about 32.

Other Applications of FFT

A sampled power spectrum is given by the modulus squared of the frequency samples. Thus, $(|X_0|^2, |X_1|^2, ..., |X_{N-1}|^2)$ is amenable to rapid calculation by FFT methods.

Autocorrelation or cross - correlation is similar in mathematical structure to convolution. The same approach to FFT computation can therefore be applied.

6.2.9. Implementation of the fast Fourier transform

The number of variations of the FFT algorithm appears to be directly proportional to the number of people using it (135 - 153). Most of these algorithms are based on either the Cooley - Tukey or the Sande - Tukey algorithm (124), but are formulated to exploit properties of the series analysed or properties of the computer used.

A variety of different FFT programs for performing one - dimensional and multidimensional fast Fourier transforms have been made available by

Cooley (141, 142) Sande (148), Singleton (149 - 152) and Brenner (139), who have programmed most of the options available.

Bergland (154) has reported a survey of FFT processors and their characteristics.

The FFT program used for the analysis of the signals from the D/P transmitter in the present work is based on the decimation in frequency method algorithm (133, 155).

6.3. DIGITAL FILTERS

Digital filters, here, will be taken to imply linear digital filters. In this case the output number sequence is always some linear combination of past and present inputs and past imputs.

Digital filters employ digital hardware and software (delays, adders, multipliers) to perform spectral - shaping operations on signals represented by number sequencies (usually binary). For conceptual purposes a digital filter can be regarded as a system constructed from unit delay elements, adding units and coefficient multipliers. The only permitted operations are delay or storage, addition and multiplication by a constant coefficient. Therefore a digital filter, here, is regarded as an entity whose input and output are sequencies of numbers.

In general, the present output from a digital filter is related to the present input number and the past inputs and outputs by a difference equation of the form

$$y_n = \sum_{k=0}^{L} a_k x_{n-k} - \sum_{k=1}^{M} b_k y_{n-k} \quad \ldots\ldots \quad (6.8.)$$

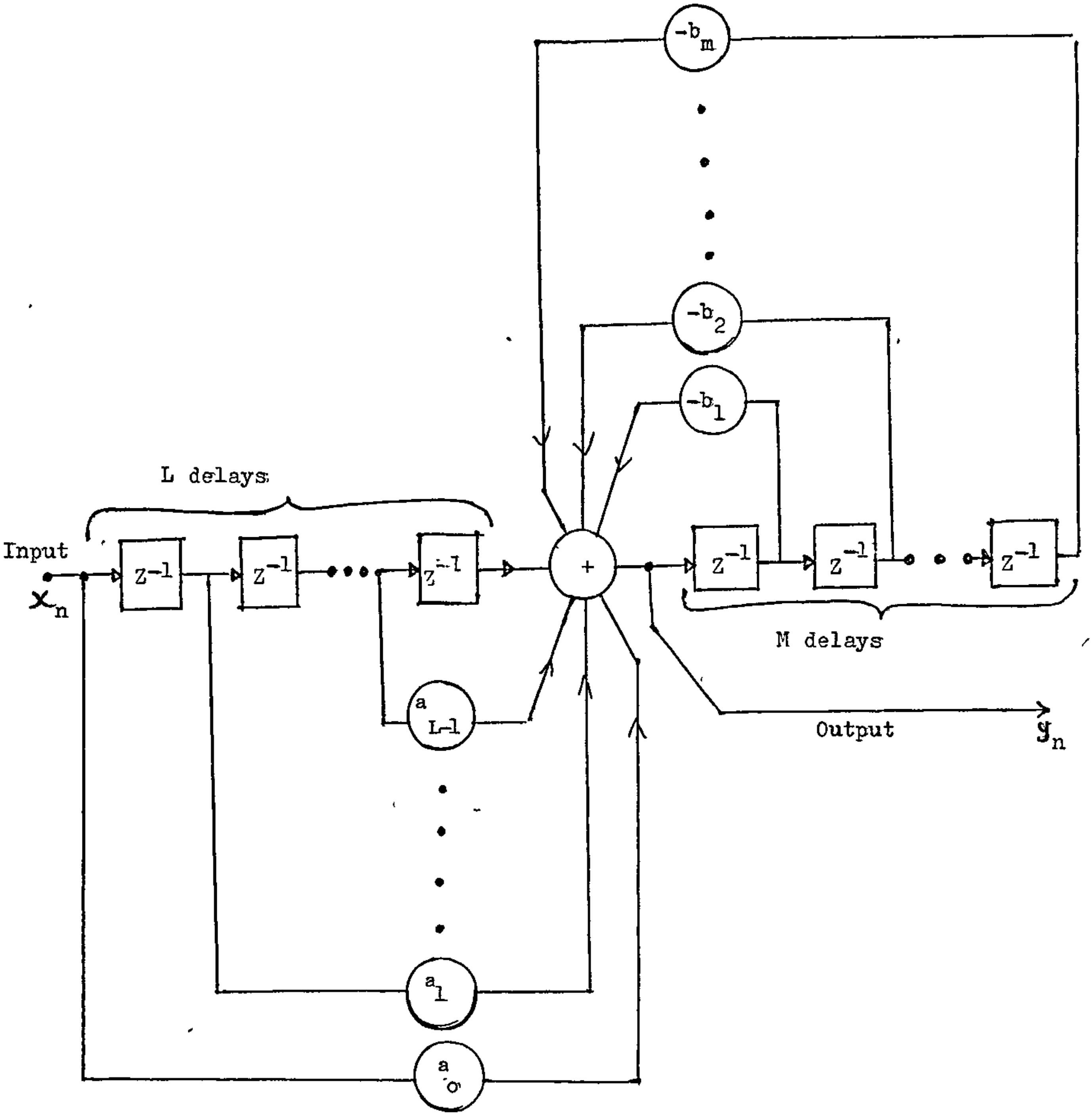


Fig 6.4 General digital filter – Direct realisation

where,

x_n is the nth input number

y_n is the nth output number

a_k and b_k are the kth of (L + 1) and M coefficients respectively which are real constants determining the particular filtering action performed.

The input and output sequences, x_n and y_n , $n = 0$, 1, 2, ... may be conceived as sampled and digitized values of analogue waveforms but this viewpoint is by no means necessary since the digital filter of equation 6.8 is fully specified by its action on input and output number sequencies. The coefficients (a_o , ..., a_L) and (b_1 , ..., b_M) suffice to specify the filter. A digital filter can also be specified by its impulse response (the impulse response of a digital filter is defined later).

A direct realisation of the general digital filter in terms of digital hardware is illustrated in fig. 6.4. The index n is incremented by one every T seconds.

In this section, basic properties of digital filters are summarised. This leads to a discussion of the digital resonator and an examination of two synthesis procedures which facilitate the design of a wide variety of filter types.

6.3.1. The Pulse Transfer Function, Poles and Zeroes

Digital filter design methods make use of the theory of functions of a complex variable.

The pulse transfer function, (p.t.f., denoted here by H(Z)) is defined as the ratio of the Z - transform of the output of a digital filter to the Z - transform of the input.

For equation 6.8., taking Z - transforms of both sides gives

$$Y(Z) = X(Z)\sum_{k=0}^{L} a_k Z^{-k} - Y(Z)\sum_{k=1}^{M} b_k Z^{-k}$$

$$\therefore H(Z) = Y(Z)/X(Z)$$

$$= \sum_{K=0}^{L} a_k Z^{-k} \Big/ \sum_{K=0}^{M} b_k Z^{-k} , \quad (b_o = 1) \qquad (6.9.)$$

A ZERO of H(Z) is a value of Z for which H(Z) is zero. A POLE of H(Z) is a value of Z for which H(Z) (which is the ratio of the polynomials in Z^{-1}) becomes infinite i.e. a value of Z for which the denominator polynomial is zero.

If the poles and zeroes are known then the nominator and denominator polynomials may be written in factoral form:

$$H(Z) = K \frac{(1 - \alpha_1 Z^{-1})(1 - \alpha_2 Z^{-1}) \ldots\ldots (1 - \alpha_L Z^{-1})}{(1 - \beta_1 Z^{-1})(1 - \beta_2 Z^{-1}) \ldots\ldots (1 - \beta_M Z^{-1})} \qquad (6.10.)$$

or

$$H(Z) = \frac{K \; (Z - \alpha_1)(Z - \alpha_2) \ldots\ldots (Z - \alpha_L)}{(Z - \beta_1)(Z - \beta_2) \ldots\ldots\ldots (Z - \beta_M)} Z^{-(L - M)} \qquad (6.11.)$$

where K is a constant coefficient and α_1 , ... ,α_L are the zeroes and β_1 , ..., β_M are the poles of H(Z).

It may be shown (123) that for stability the poles of H(Z) should be within the Z - plane unit circle (i.e.$|\beta_k| < 1$, k = 1 , 2, ... M). Also because the coefficient a_k and b_k are real numbers the poles and zeroes of H(Z) are either real or else fall in conjugate pairs (123) Fig. 6.5. below shows the poles and zeroes of a typical stable filter

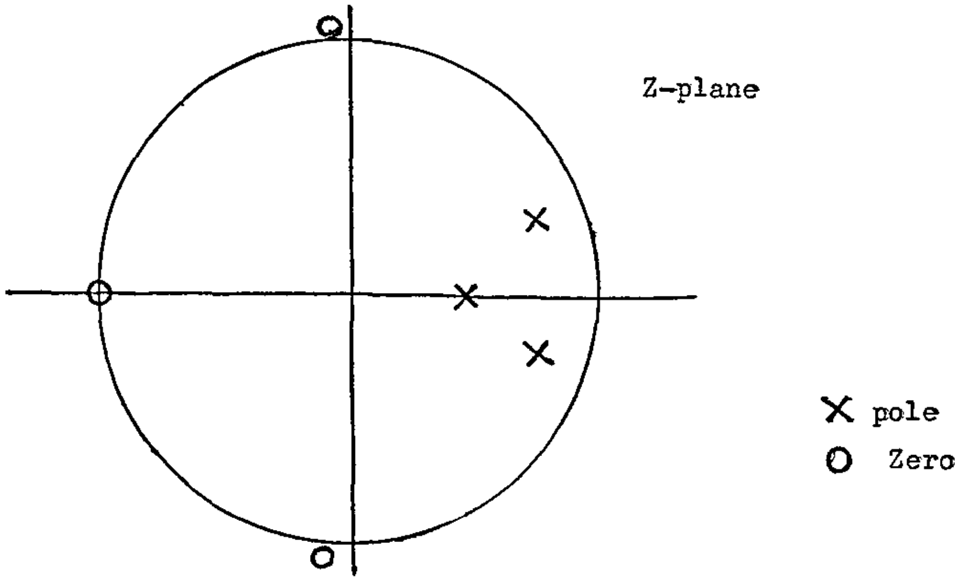


Fig. 6.5 Poles and Zeroes of a typical Stable Digital Filter

Frequency Response of a Digital filter: The frequency characteristic of a digital filter is determined by evaluating the p.t.f. H(Z) on the unit circle of the Z - plane. From equation 6.9. therefore, with $Z = e^{j2\pi ft}$ where f is the real frequency variable in Hertz (cycles per second) the frequency characteristic is given by,

$$H(e^{j2\pi ft}) = \sum_{k=0}^{L} a_k e^{-kj2\pi ft} \Big/ \sum_{k=0}^{M} b_k e^{-kj2\pi ft}$$

Amplitude Characteristic: In general, the frequency characteristic is a complex function which can be expressed as

$$H(e^{j2\pi ft}) = R(e^{j2\pi ft}) + j\, I(e^{j2\pi ft}) \qquad (6.12.)$$

where R and I denote real functions. The amplitude characteristic is given by,

$$\left|H(e^{j2\pi ft})\right| = \sqrt{R^2(e^{j2\pi ft}) + I^2(e^{j2\pi ft})} \qquad (6.13.)$$

It determines the gain or attenuation imposed by the digital filter on a sinusoidal input sequence of frequency f H_z .

Phase Characteristic: From equation 6.12, the phase characteristic of a digital filter is given by,

$$\arg\left[H(e^{j2\pi ft})\right] = \tan^{-1}\left[I(e^{j2\pi ft}) / R(e^{j2\pi ft})\right]$$

This characteristic determines the phase shift between output and input for a sinusoidal input sequence of frequency f Hz .

Recursive Digital Filter: If $M \neq 0$ in equation 6.9. the filter described by H(Z) is said to be recursive since feedback is implied. Under this condition poles appear in the p.t.f. (see equation 6.10) and instability will occur if they fall outside the z - plane unit circle.

Nonrecursive Digital Filter: If $M = 0$ in equation 6.9. then the filter is said to be nonrecursive since no feedback is involved. The p.t.f. (equation 6.11) possesses no poles and consequently the filter is stable under all conditions.

Impulse Response: This is the response of the digital filter to the input sequence,

$$(1 , 0, 0, \ldots\ldots)$$

The Z - transform of this sequence is given by

$$X(Z) = 1$$

From the definition of the p.t.f., H(Z)

$$Y(Z) = H(Z)\cdot X(Z)$$

Thus, with $X(Z) = 1$ the Z transform of the output sequence is simply H(Z) and it follows that the p.t.f. is the Z- transform of the impulse response.

If the filter is nonrecursive then it is evident from equation 6.8 that the impulse response is the (L + 1) length sequence given by the coefficients (a_o , a_1 , ... , a_L). If the filter is recursive then in principle the impulse response will never terminate due to the action of feedback. In this case it is usually simpler to derive the impulse response by taking the inverse Z - transform of the p.t.f.

Summary of some important points

Without going into any details a summary of some important points at this juncture is thought more useful than going deeper into the mathematics. The points to be made here are

(i) Poles on the real axis give rise to non oscillatory components in the impulse response

(ii) Complex poles give rise to oscillatory impulse responses.

(iii) The nearer a pole lies to the origin of the Z - plane, the more rapidly the associated component decays.

(vi) The frequency of the oscillatory component associated with complex poles increases with their angle measured from the real axis.

(v) The impulse response of a digital filter will decay (i.e. the filter will be stable) if and only if all the poles of the filter lie within the unit circle in the Z - plane. It is thus possible to test whether a filter is stable by factoring the denominator of its transfer function and observing the magnitudes of the poles.

6.3.2. The Digital Resonator

A digital filter can be specified by either the poles, zeroes and/or impulse response. The direct realisation of the second order difference equation

$$y_n = x_n - b_1 y_{n-1} - b_2 y_{n-2}$$

is shown below Fig. 6.6 and the Pole positions are shown in Fig. 6.7.

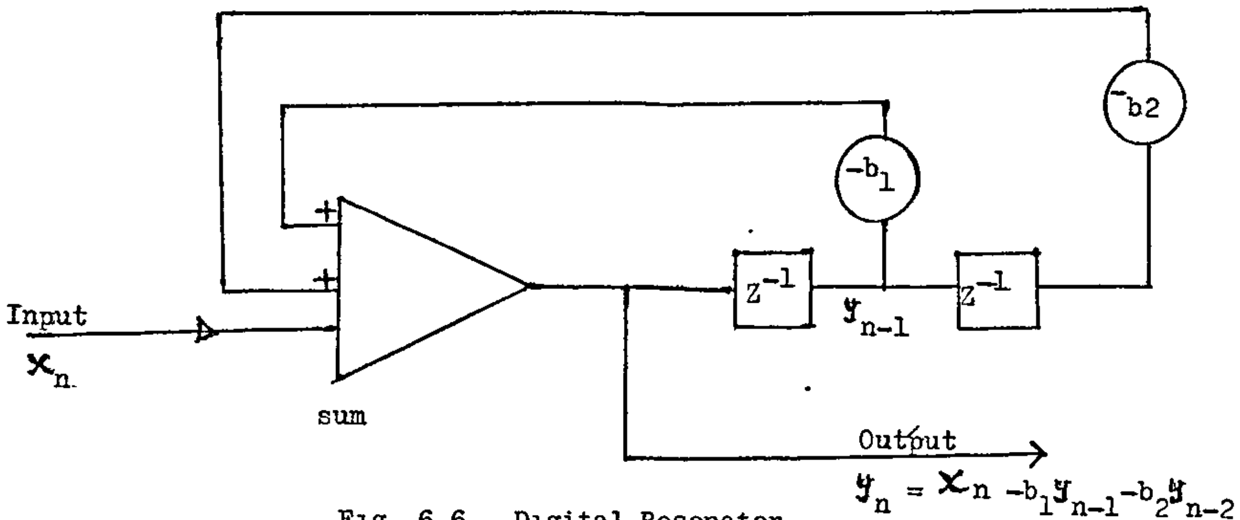


Fig. 6.6. Digital Resonator

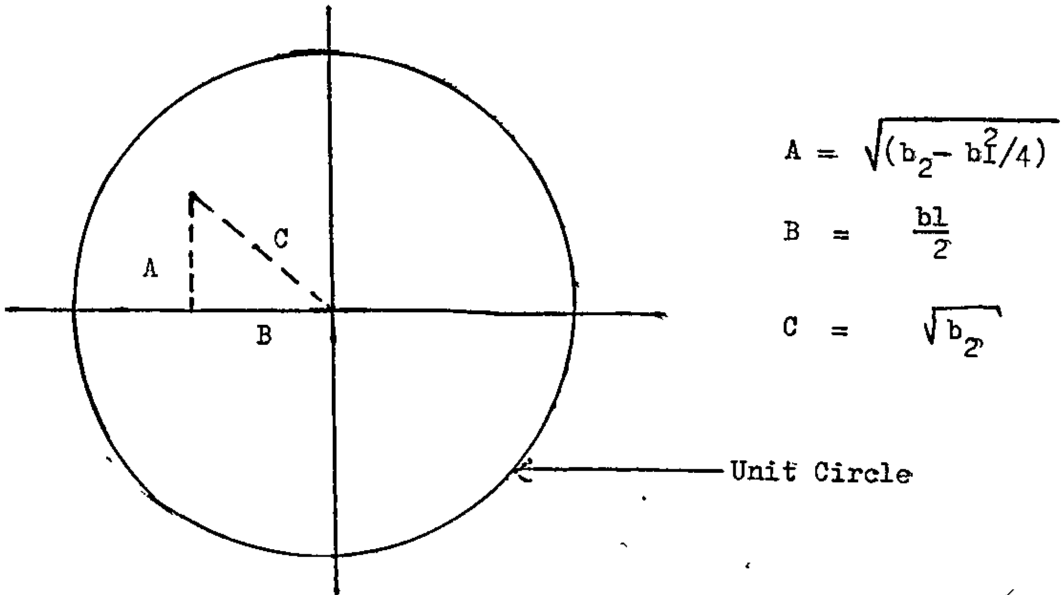


Fig. 6.7. Resonator Pole Positions

The p.t.f. is given by,

$$H(Z) = \frac{1}{1 + b_1 Z^{-1} + b_2 Z^{-2}}$$

$$= \frac{Z^2}{(Z - \beta_1)(Z - \beta_2)}$$

where,

$$\beta_{1,2} = \frac{-b_1}{2} \pm j\sqrt{\left\{b_2 - \left(\frac{b_1}{2}\right)^2\right\}} \qquad (6.14.)$$

If $b_2 > \left(\frac{b_1}{2}\right)^2$ then β_1 and β_2 form a conjugate pole pair as shown in fig 6.7. For stability the poles must fall within the unit circle and therefore,

$$\therefore |\beta_1| \cdot |\beta_2| < 1$$

i. e. from equation 6.14.

$$\left(-\frac{b_1}{2}\right)^2 + \left[b_2 - \left(\frac{b_1}{2}\right)^2\right] < 1$$

or $b_2 < 1$

The frequency characteristic is given by,

$$H(e^{j2\pi ft}) = \frac{e^{j4\pi ft}}{(e^{j2\pi ft} - \beta_1)(e^{j2\pi ft} - \beta_2)} \qquad (6.15.)$$

For positive f, $|H(e^{j2\pi ft})|$, the amplitude characteristic, will exhibit a single maximum value at a resonant frequency given by

$$\cos 2\pi ft = \frac{-b_1}{2\sqrt{b_2}}$$

Also, the closer $|\beta_1|$ and $|\beta_2|$ approach unity i.e. ($b_2 \rightarrow 1$), the closer the denominator of equation 6.15 will approach zero at the resonant frequency and the sharper will be the peak of the amplitude characteristic. b_2 therefore controls the degree of damping.

The digital resonator is the digital equivalent of the simple analogue inductance, capacitor, resistor resonator.

6.3.3. Design of Digital Filters

The design of a digital filter involves two main steps, synthesis and realisation. Synthesis is concerned with finding a suitable p.t.f. from design requirements such as frequency or impulse response specifications.

When the p.t.f. has been determined a particular arrangement of digital filter elements (delays, multipliers, adders) must be selected to realise the pulse transfer function.

Two approaches which together are applicable to a wide range of filters will be discussed.

6.3.3.1. Indirect Method

Here, use is made of knowledge of analogue filters.

The transfer function of a linear analogue filter comprising inductance, capacitance and resistance is normally expressed as a rational function, A(s), say (i.e. A(s) is the ratio of two polynomials in s). In this case the frequency characteristic is derived by evaluating A(s) on the s plane imaginary axis (i.e. set $s = j2\pi f_A$ where f_A is the real analogue frequency variable). Suppose a method is available for synthesising A(s), (perhaps A(s) poles and zeroes are tabulated over a range of frequency domain design requirements) then, if s in A(s) is replaced by a rational function of Z which maps the s plane imaginary axis unto the Z plane unit circle the resulting function of Z (p.t.f.) will assume a set of values along the Z plane unit circle as A(s) along the S plane imaginary axis. There will therefore be a correspondence between the frequency characteristic of the analogue filter and the digital filter which is specified by the derived p.t.f.

The bilinear transformation is the simplest transformation, with the above property and is defined by,

$$S = \frac{Z - 1}{Z + 1}$$

The procedure for synthesizing a digital filter by analogue techniques using the bilinear transformation is summarised as follows:

(i) Note the critical frequencies and ranges of the required digital filter (i.e. the cut-off frequencies, pass band, stop band regions, etc.) thus defining, f_{D1}, f_{D2}, ... Compute the corresponding set of frequencies for the analogue filter through,

$$f_{A_i} = \frac{1}{2\pi} \tan\left[\pi . f_{D_i} T\right], \quad i = 1, 2, \ldots\ldots$$

(ii) Determine the analogue transfer function, A(S) from the f_{A_i} specifications by some convenient analogue synthesis procedure.

(iii) Replace A(S) by $(Z - 1/Z + 1)$ to obtain the required digital filter.

The bilinear transformation transforms a lowpass analogue filter into a lowpass digital filter, a highpass into a highpass etc. Other transformations are available (133, 156) which transform lowpass to highpass, lowpass to bandpass, lowpass to bandstop etc. so that a wide variety of digital types may be synthesised from the basic analogue lowpass.

6.3.3.2. Direct Method:

Synthesis of the various classical filters (Butterworth, Chebyshev, Elliptic etc.) in the S plane begins with the specification of suitable squared amplitude characteristics. Applying the same technique in the Z plane results in a direct synthesis procedure for digital filters. The squared amplitude characteristic of a digital filter $(|H(e^{j2\pi ft})|^2)$ is a real function of frequency which can be expressed as a real rational function in $\tan^2(\pi f t)$ (133, 156). A suitable lowpass filter function is then,

$$|H(e^{j2\pi ft})|^2 = \frac{1}{1 + \dfrac{\tan^{2n}(\pi ft)}{\tan^{2n}(\pi f_c t)}} \qquad (6.16.)$$

f_c is the cutoff frequency and n denotes the order of the filter.

By analogy with the analogue form, equation 6.16 may be regarded as the definition of a digital Butterworth amplitude characteristic. The poles and zeroes of $H(Z)\cdot H(Z-1)$ are found by setting

$$Z = e^{j2\pi ft}$$

in equation 6.16 and factorising. They are given by

$$U_m = \frac{2(1 - \tan^2(\pi f_c t))}{1 - 2\tan(\pi f_c t)\cos(m\pi/n) + \tan^2(\pi f_c t)} \qquad (6.17.)$$

$$V_m = \frac{2\tan(\pi f_c t)\sin(m\pi/n)}{1 - 2\tan(\pi f_c t)\cos(m\pi/n) + \tan^2(\pi f_c t)} \qquad (6.18.)$$

$$m = 0, 1, \ldots\ldots\ldots, (2n-1)$$

where the mth pole is given by,

$$Z_m = U_m + j\,Vm$$

Replacing $m\pi/n$ by $(2m+1)\pi/2n$ gives equivalent expressions for n even. $2n$ zeroes are also located at $Z = -1$.

Having located the poles and zeroes of $H(Z)\cdot H(Z^{-1})$ the required p.t.f. $H(Z)$ is constructed by selecting those poles which lie within the unit circle and an nth order zero at $Z = -1$.

Application of the direct method of synthesis to a wide variety of filter types is discussed in the literature (133, 156, 158).

The direct form has the advantage that it uses the coefficients of the transfer function without modification. It suffers from the disadvantage that it is sensitive to computational error. This is usually only an important consideration in computers with small word length.

Non - recursive filters are almost always implemented in the direct form.

6.3.4. Programming Digital Filters

A digital filter can be implemented as a computer program by the following procedure.

(i) Label the variable which is held in each delay unit.

(ii) Set the initial values of these state variables as zero.

(iii) Each number is computed as a linear combination of the present input and the state variables.

(iv) The state variables are transferred to auxilliary storage and their new values are computed.

6.4. Use of Simple Filters to detect Instrument Malfunction

The relevant theory for the use of digital filters has been reviewed in the foregoing sections. The specific use of the digital filter for instrument malfunction detection will now be discussed. The basis has already been mentioned but the point will be amplified here.

An instrument signal would have a range of frequency components from low to high. The frequency components of the instrument signal would be considerably higher than that of the process.

When the instrument is behaving normally the characteristics of the frequency components would be expected to show a pattern. If the instrument begins to malfunction, the likelihood also would be that the characteristics of the frequency components would change, and probably, considerably from that at normal behaviour. There might be an unusual rise or fall in the level of the components at a certain frequency.

Because of the inertia of a given process, excessive fluctuations in the process signal would not be expected. The overall contributions of the process signal to the frequency components of both the process and the instrument would be expected to be fairly steady and more in the low frequency region.

The frequency component contribution of a normal instrument would be expected to be within some tolerance band. A considerable rise or fall in the high frequency components, say, would almost certainly be from the instrument and could therefore be an indication of an abnormality in the instrument behaviour.

By looking at the contributions of the components at specific frequencies, it should be possible to detect a significant change in frequency level. This is the whole basis of the application of this technique to the detection of instrument malfun ction.

A simple system to do this is illustrated below Fig. 6.8.

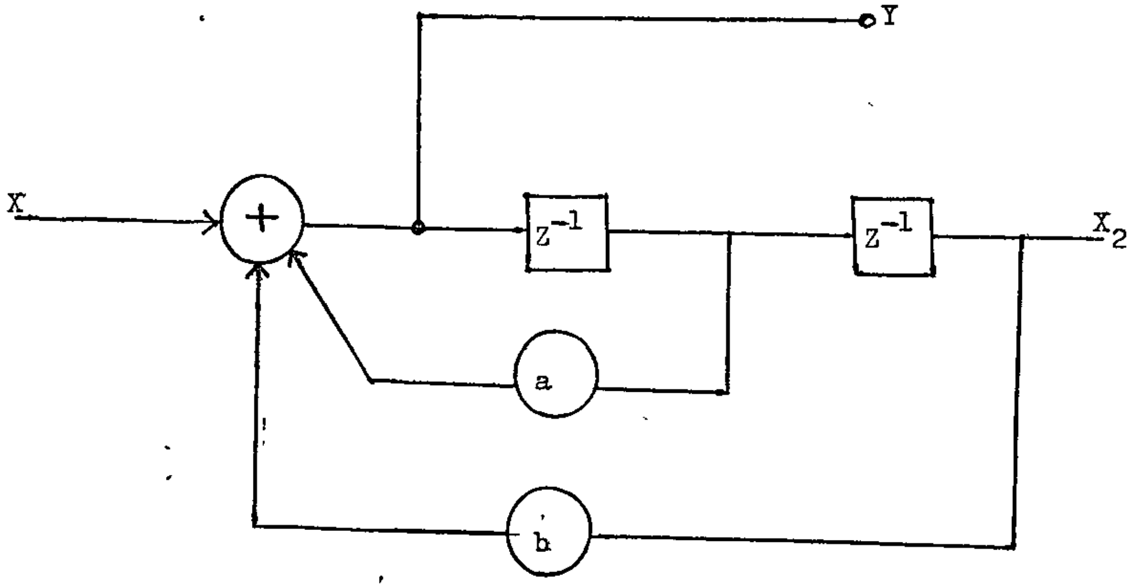


Fig. 6.8. Simple Second order filter

$$Y = X + a Z^{-1} Y + b Z^{-2} Y$$

represents a simple second order filter. The output of the system Y is a combination of the outputs of the two filters in series. By the setting of the constants a and b, the attenuation of the outputs of the filters will be set and hence the contribution of the two frequency components would be set relative to each other.

For normal behaviour, the contribution of one of the filters might be negligible to the overall characteristics of the output of the system, say. The status quo could be a basis for the normal behaviour criterion.

A significant rise or fall in the contribution of the components could then be an indication of an abnormality.

Because the system suggested above is a recursive filter, the stability aspects as dealt with in section 6.3.1. have to be considered. The system can easily be programmed.

Unfortunately, a digital filter technique for instrument malfunction detection was not tested in the practical work done in this project. This was mainly due to the shortage of time and the loss of the on-line computer on which this work was based. Also because the digital filter technique involves resolution of signals in the frequency domain, as do the fast Fourier transform based techniques; and because the digital filter might be considered more special in application than the FFT techniques, the practical work of testing the techniques was started with testing the more general fast Fourier transform, in the hope that there might be time for the digital filters.

The digital filter techniques and the fast Fourier transform techniques are nevertheless not the same. The two approaches are different in conception and realisation.

The digital filters can look at a specific or specific frequencies; they can be selective in the particular frequencies or band of frequencies to look at from a range of available or detectable frequencies. The fast Fourier transform can generally analyse a whole range of available or detectable frequencies.

The information offered by and the computational requirements of the two are different.

6.5. Use of the Power Spectrum to detect Instrument Malfunction

The fact that the power spectral density for a process indicates the contribution to mean-squared fluctuation due to signal components in any specified frequency interval can be used as a criterion for instrument malfunction detection.

Because of the inertia of a given process, the spectral density plot of a normal process instrument signal would have a shape pattern for a given frequency interval or range. This might be a characteristic concentration of most of the power in a certain frequency region, say, high or low. For instance Fig. 6.9. can represent a typical power spectrum plot for a normal process instrument signal.

The instrument signal contribution to mean-squared fluctuation in a specified frequency interval and hence the spectral density plot would not be the same for normal and malfunctioning instruments.

A parameter of the spectral density plot such as the area under the curve or the ratio of the areas A_1 and A_2 on either sides of a specified critical frequency, f_c , can characterise normal or abnormal instrument signal.

It is envisaged that one possible way of using the technique is to set threshold values for one of such parameters, as mentioned above, for normal or abnormal instrument behaviour.

In the present work, the fast Fourier transform has been used to estimate the power spectrum of some normal and abnormal signals from a D/P transmitter. The results are discussed in Chapter 8.

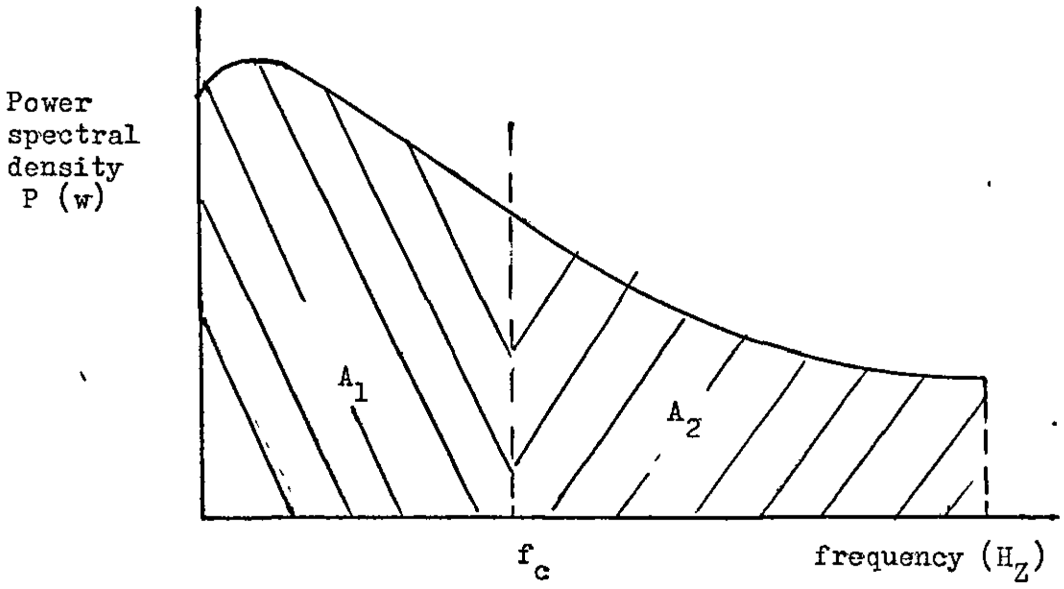


Fig. 6.9. Illustrative Power Spectrum Plot

6.6. Use of an adaptive model for instrument Malfunction detection

The findings of Sargent and Goldman (222) in a feasibility study of using linear recursive least - squares estimators for on-line state and parameter estimation suggest the possible implications of such techniques for instrument malfunction detection. They used a simulation of a binary distillation column to investigate how effective the filter is in detecting bias or drift in a particular instrument or a slow drift in plant conditions before this otherwise becomes obvious. Their findings indicate that the least squares filter could provide a means of detecting instrument malfunction.

The Kalman filter is a general model relating, in principle, all plant variables, in contrast to mass and heat balance type models and therefore promises to be a very powerful technique for instrument malfunction detection. It is envisaged that it will be suitable for analysing multiple instrument signals as opposed to single signals as have been dealt with mainly in the present work.

Even though no work has been done on this in the present work, there has been all along, awareness of the potential of the Kalman filter in this direction.

7. CASE STUDIES OF INSTRUMENT MALFUNCTION AND MALFUNCTION DETECTION (1) THERMOCOUPLES

7. CASE STUDIES OF INSTRUMENT MALFUNCTION AND MALFUNCTION DETECTION (1) - THERMOCOUPLES

7.1. Introduction

From case studies of instrument malfunction, malfunction detection techniques can be developed and tested. Such case studies can throw light into the instruments' mode of failure, symptoms shown before or at failure, with their possible implications, and methods of forestalling undesirable consequences or disaster in such an event.

Ideally, study of as many instruments as possible, under as widely varying environmental condition as can be achieved, is desirable. With the limitation of time and facilities this is not possible in the present work.

Some select instruments, therefore, were studied. The systems studied were

(i) Thermoconples

(ii) Differential pressure transmitters as flow measuring instruments

(iii) Control valves

The reasons for their choice are that the thermocouple and the D/P transmitter can easily both offer signals to analyse, but it was also expected that the. thermocouple might provide a signal easily amenable to simple algorithms or analysis, while the differential pressure transmitter might require more sophisticated time series analysis. Some failure modes of the two instruments can easily be simulated in the laboratory.

Control valves differ from the thermocouple and D/P transmitter in that they are not measuring instruments and again a different technique might be needed.

All the systems studied are important systems in process control.

Of the three systems chosen for study, the thermocouple was typically and illustratively studied in detail. For this reason, the case study of the thermocouple has been presented on its own in this chapter. The other two systems were not studied in such detail and their case studies are presented in chapter 8.

Freezing of the impulse lines of the D/P transmitter was simulated in the laboratory and the signals obtained analysed using the fast fourier transform method.

For the control valves, data were obtained from industry and analysed.

7.2. THERMOCOUPLE INSTALLATIONS, NATURE AND CAUSES OF THERMOCOUPLE FAILURE

7.2.1. General

The thermocouple is not a new device, the thermoelectric effect having been demonstrated as far back as 1821 by Seebeck (159). It consists essentially of two dissimilar electrical conductors either or both of which may be pure metals, alloys or non-metals, having a common junction where the conductors are in good thermal and electrical contact (hot junction).

The other ends of the leads from this junction are kept at a common temperature (cold junction) and are connected to an instrument measuring the electromotive force which is developed. For thermoelectric thermometry theory one only has to turn to the literature (160-164).

Beyond the simple operating principle of the thermocouple lies much important information which instrumentation men must know to ensure accurate, reliable and reproducible measurement and minimum maintenance with thermocouples. The purpose of the background work 7.2.1. - 7.2.10.5 is mainly to bring out this information.

7.2.2. Industrial Thermocouples (165)

The two conductors constituting the thermocouple are chosen such that changes caused by the physical and chemical conditions to which they are exposed do not cause any appreciable departure of the calibrated values of the e.m.f. generated at certain known temperatures of the hot junction and cold junction respectively.

The conductors constituting the thermocouple have physical characteristics which are suitable for the temperature to which they are exposed, and must not melt or change in composition by evaporation at those temperatures.

A thermocouple may be used bare, but in the majority of applications it is necessary to insert it in a metallic pocket with a protecting head, Fig. 7.1.

The following factors are of particular importance when relating the basic principles of thermoelectricity to practical applications.

(i) A thermocouple is installed directly (usually with a protecting tube) in the process medium, which can be corrosive and at high temperatures or pressures.

(ii) Hundreds of temperature points are measured by thermocouples in many processes. This is a sizeable maintenance responsibility, even when minimum attention is required.

(iii) Thermocouples are expendable, and replacement costs must be minimised by proper protection and care of those in service.

(iv) A thermocouple involves an electric current, often with a path hundreds of feet long, with connections to remote panel-boards. Failure of these connections at any point means failure of the entire instrument system and consequent loss of automatic recording and control.

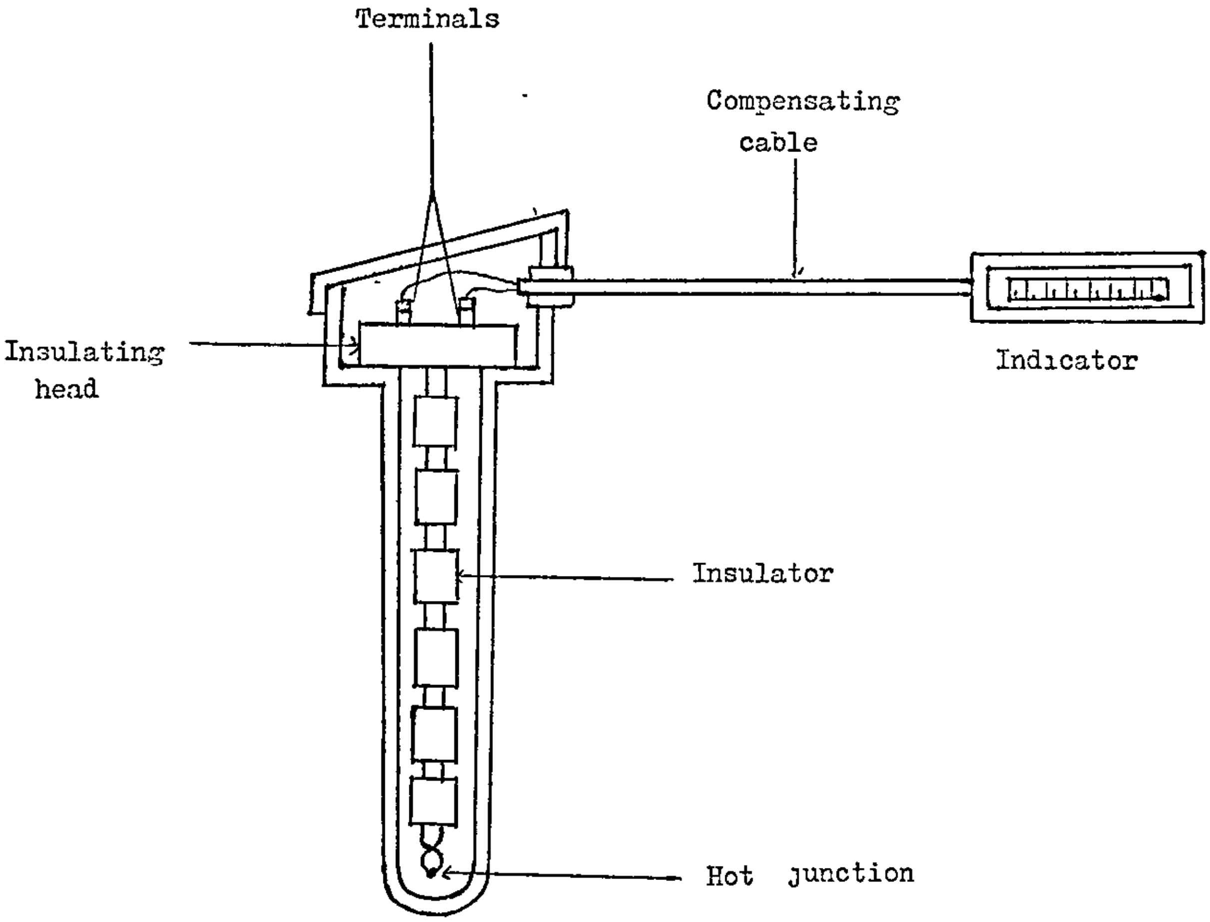


Fig 7.1 Basic arrangement of thermocouple installation in industrial plant

7.2.3. Use Characteristics of Thermocouples

Thermocouples can be used over a very wide range from below $0^{o}C$ to $2600^{o}C$ and provide accurate, reliable and reproducible temperature measurements. The characteristics of the thermocouple method may be listed as follows

(i) Many thermocouple combinations exist and each has an optimum temperature range. Selections may be made from tho variety of base and rare metal types to meet the requirements of most operating conditions.

(ii) Most thermocouple materials are readily available with the electromotive force/temperature characteristics guaranteed to within stated tolerances.

(iii) Thermocouples may be made from very fine wires and hence are of low thermal capacity. They can therefore respond rapidly to fluctuating temperatures.

(iv) No external electrical supply is required except where highly accurate potentiometric methods of electromotive force measurements must be used.

(v) Sensitivity of response may be increased by using several thermocouples in series.

(vi) Measuring junctions may be easily made by the user and thermocouples may be easily installed and maintained.

(vii) Usually only simple methods of measuring the electromotive force are required.

(viii) The thermocouple method requires the use of a reference junction and special precautions may be adopted to compensate for variations in the temperature of this junction.

7.2.4. Types and Methods of Use (166,167)

There are three usual methods of using thermocouples corresponding to three types namely

(a) Surface contact type - With this type, thermal equilibrium is established between the solid body, whose temperature is being measured, and hot junction of the thermocouple by means of a contact plate. Here it is important that the temperature of the thermocouple is not affected to any appreciable extent by heat exchange between the thermocouple contact system and any adjacent surfaces other than those of the hot body whose temperature is being measured.

(b) Immersion type - The hot junction is immersed or inserted into the body whose temperature is being measured, the body being either a liquid, a gaseous atmosphere, or a gaseous atmosphere in an enclosure in which the body whose temperature is to be measured is also enclosed. With a liquid, thermal equilibruim between the liquid and the thermocouple is established by direct conduction. In a gaseous atmosphere, this thermal equilibrium is maintained by direct contact between the hot junction and the gas. However, unless conditions are favourable, radiation from other gaseous zones and surrounding solids affect the measurement, and the temperature measured will be that of the gas only if the other radiating bodies are at the same temperature as the gas in the immediate neighbourhood of the hot junction of the thermocouple.

In the third instance thermal equilibrium between the body whose temperature is being measured and the hot junction of the thermocouple is established partly by gaseous heat transfer and partly by radiation from the hot body, and errors may occur from the same causes as previously mentioned.

(c) The suction type : is used for the measurement of temperature of a gas in a furnace (or other enclosure) where the walls are not in thermal equilibrium with the gas. A small portion of gas under measurement is extracted so that it flows continuously past the hot junction during measurement, both the mounting and surroundings of the hot junction being designed to reduce thermal exchange by radiation to a minimum so that a measured temperature approximating as closely as possible to the actual gas temperature is obtained.

7.2.5. Thermocouple Selection (168)

Even though any two dissimilar conductors can form a thermocouple and develop an e.m.f. when their junctions are at different temperatures, only a relative few thermoelement combinations are used. Some of the reasons for a choice of a pair of materials are evident while others may not be quite so obvious (168-170). Finch (168) suggests that the characteristics of an acceptable pair of materials should be such that:

(1) Their melting points are higher than the higest temperature at which the thermocouple is to be used.

(2) Their thermal e.m.f. is large enough to be measured with reasonable accuracy.

(3) Their thermal e.m f. increases continuously with increasing temperature over the temperature range in which the thermocouple is to be used, preferably approximating a straight line relationship.

(4) They are resistant to oxidation and corrosion in the medium and at the temperature to which they are to be exposed.

(5) They are homogeneous.

(6) Their electrical resistances are not too high to limit their use.

(7) They maintain their e.m.f. stability during calibration and use, within acceptable limits.

(8) Their thermal e.m.f. is not appreciably altered during use by internal physical or chemical changes, or by contamination from materials of their environment.

(9) They can be melted from their raw materials and fabricated into wire or any other desired shape without undue difficulty.

(10) They are reproducible in the quantities desired, and of uniform quality.

(11) They can be fabricated with actual thermocouples with relative ease.

(12) Their cost must bear a reasonable relationship to the degree with which they meet the optimum of the above requirements.

Every added restriction narrows the choice of pairs of materials until only a few are left. Of these, the majority may be eliminated by consideration of the economics of procurement which weigh heavily in the final choice for industrial applications.

7.2.6. Connecting Circuits (166)

The protection of the compensating leads from mechanical damage, from burning or from the effects of damp and from electrolytic action, electrical leakage or induced voltages from power or lighting circuits is vital to the performance of the measuring system. The conductors should have adequate strength appropriate to the nature of the installation. The conductor cross section is also governed by considerations of the electrical resistance acceptable to the measuring instrument.

The insulation between the conductors must be reliable and that normally used for high voltage is satisfactory. In damp situations lead covering may be employed but its tendency to sag must be guarded against. In hot, dry situations woven asbestos covering by itself is satisfactory provided those coverings are never exposed to damp, but if conditions of dampness are unavoidable the only safeguard is to use asbestos covering outside rubber or plastics insulation and this double covering should encase each of the conductors individually. Permanent installations are preferably protected in conduit.

Copper Cables Where copper connecting cables are used in place of, or in addition to, the compensating leads referred to above, the same remarks as to protection and conditions for installation apply. A method of protection sometimes used is that in which the conductors are embedded in compressed magnesia in a copper tube.

Switches : Switch contacts and the contacts at all other points where the circuit may be broken and reconnected should preferably be of corrosion resisting metals as the available voltages are seldom sufficient to break down even an invisible film of oxide. Care should be taken to ensure that the switch itself does not give rise to unwanted thermal electromotive forces. The act of making the connections between contact and contact should involve some degree of wiping action between the two elements. On installations involving alternative connections of several thermocouples to one measuring instrument, double-pole switches are essential if there is any risk of an earth connection in the thermocouple circuit. The type of switch making contact between mercury and mercury in hermetically sealed capsules has been found to provide a very reliable form of contact.

7.2.7. Materials for Thermocouples

Of the infinite combinations of metals, alloys, semiconductors, and non metals that can form thermocouples, only a few have found use as temperature sensors. Because of the needs of the new technologies-jet engine, reactor, and rocket technologies in the higher temperature ranges and cryogenics in the lower temperature ranges, new thermocouples are being developed to meet these recent requirements.

The emphasis in this paper is on industrial type thermocouples.

The materials considered here can be classified into four groups for convenience.

1. Noble or Rare Metals.
2. Base Metals
3. Refractory Metals
4. Carbon and Carbides

The Noble and Base Metals represent the vast majority of thermocouples now in use. Fewer data are available on Refractory metal thermocouples, but a considerable effort is being exerted in the field of refractory metals to meet the high temperature needs of recent technological developments. Relatively little work has been done on Carbon and Carbides, but some thermocouples employing graphite, carbon, and carbides are used.

Table 7·1 shows materials most widely used (165,166,174). The base metal thermocouples are used at temperatures up to 1,200°C and the rare metals up to 1,500°C, while non-metallic thermocouples, because of their other limitations, are only used for temperatures too high for either of the other groups. (167) In both the Rare and Base metal groups, the limiting minimum electromotive force which can be employed with measuring instruments usually decides the low temperature limit. In this respect base-metal thermocouples have the advantage in general of developing relatively large electromotive forces and Coxon (167) in fact gives - 200°C as their lower temperature limit.

Schulze (172) has made an extensive review of many thermocouple combinations for operation at high temperatures, particularly platinum: molybdenum, platinum: tungsten, platinum: tantalum, and various alloys of the platinum metals coupled with either pure platinum, rhodium or iridium. The high cost and difficulty of manufacture of many of these metals and alloys in the form of wire prevent their having any commercial applications.

Descriptions and properties of thermocouples of the refractory metals are found in the works of Sanders (173), Kuether (174), Lachman and Kuether (175), Kuether and Lachman (176), Lachman and McGurty (178).

For the carbon and carbides group, work has been done mainly by Thielke and Shepard (179), Ubbelhode (180), Bidwell (181), Watson and Abrams (182), Fitterer (183) and Shepard and Westbrook (184). Even though carbon and carbides have been subjects of investigation, for many years, to avoid problems inherent in the use at high temperatures of thermocouples of metals and alloys; thermocouples of this kind have not yet, from the number in use, assumed an important position in the temperature measuring field; but some are used now, and the possibility exists that more will be used in the near future (185).

TABLE 7.1

COMPOSITIONS AND OPERATING TEMPERATURES OF THERMOCOUPLES (166)

1	2	3	4	5	6	7	8
THERMOCOUPLE	NOMINAL COMPOSITION	OPERATING TEMPERATURES °C		APPROXIMATE E.M.F. (MICROVOLTS/ DEG. C.)	TOLERANCE	TEMPERATURE RANGE °C	RELEVANT B.S REFERENCE TABLES
		NORMAL RANGE FOR CONTINUOUS USE °C	MAXIMUM 'SPOT' READINGS °C				
<u>Base Metals</u> *Copper v Constantan	Cu v Cu-Ni (40/45% Ni)	- 250 to 400	500	56	± 1 deg C ± 1%	0 - 100 100 - 400	B.S. 1828
*Iron v Constantan	Fe v Cu-Ni (40/45% Ni)	- 200 to 850	1100	57	± 3 deg C ± 1%	0 - 300 300 - 850	B.S. 1829
*Nickel/Chromium v Constantan	Ni 90%, Cr 10% v Cu-Ni (40/45% Ni)	See Note 2 - 200 to 850	1100		± 3 deg C ± 0.75%	0 - 400 400 - 850	Refer to Manufacturer's Data B.S. 1827
*Nickel/Chromium v Nickel/Aluminium	Ni 90%, Cr 10% v Ni 95% balance Al, Si, Mn	See Note 2 - 200 to 1100	1300	40	± 3 deg C ± 0.75%	0 - 400 400 - 1100	
Tungsten/rhenium v Tungsten rhenium (See Note 4)	W 95%, Re 5% v W 7 4% Re 26%	See Note 2 0 to 2,300	2600		Tolerances should be agreed between user and manufacturer		Refer to Manufacture's Dat
Tungsten v Molybdenum (See Notes 4 and 5)	W v Mo	1250 to 2600	2600		ditto		
<u>Rare Metals</u> Platinum/rhodium v Platinum	Pt 90% Rh 10% v Pt 100%	0 to 1400	1650	12	± 1 deg C ± 2 deg C ± 3 deg C	0 - 1100 1100 - 1400 above 1400	B.S. 1826

Table 7.1.
Compositions and Operating Temperatures of Thermocouples (166) (Continuation)...

Platinum/rhodium v Platinum	Pt 87% Rh 13% v Pt 100%	0 - 1400	1650	11			
Platinum/rhodium v Platinum/rhodium	Pt 8P% Rh 20% v Pt 95% Rh 5%	0 to 1500	1700		± 3 deg C ± 4 deg C	0 to 1100 1100 to 1550	Refer to Manufact-urer's Data
Platinum/rhodium v Platinum/rhodium	Pt 70% Rh 30% v Pt 94% Rh 6%	0 to 1500	1700				
Platinum/rhodium v Platinum/rhodium	Pt 60% Rh 40% v Pt 80% Rh 20%	1000 to 1600	1800				
Rhodium/iridium v iridium	See Note 3	See Note 6 0 to 2,000	2100				

7.2.8. Thermocouple Insulation (166)

Electrical insulation between the two conductors is essential except at their measuring junction, and except in certain cases (e.g. when used with some electronically operated indicators, recorders or controllers) they should be each insulated from earth or from any high electric potential that may exist in the plant or apparatus in which the thermocouple is installed.

The form and nature of the insulation will depend on the use to which the thermocouple will be put. Table 7.2 shows the maximum temperatures to which various forms of insulation may be taken without suffering deterioration.

The insulating resistance between conductors and earth or between the two conductors must be high enough to prevent unacceptable reduction of the electromotive force measured. As reduction is likely to be more pronounced with increasing temperature a general guide (8) would be to select the insulating material such that the reduction of the generated electromotive force at the maximum operating temperature should be less than 0.1 cent.

Cotton, silk, woven glass or asbestos when used should be in a relatively dry atmosphere because if they should absorb moisture, a voltaic cell will be formed, the electromotive force of which will modify the normal electromotive force of the thermocouple and so may give rise to incorrect results.

TABLE 7.2.

Maximum Limiting Temperatures For Various Insulating Materials

(Continuous use in dry air)

P.V.C.	70-100°C according to grade.
Rubber	80-100°C according to grade.
Cotton	100°C) (if varnished 150°C)
Silk	100°C) (if varnished 150°C)
Enamel (Synthetic base)	150°C
P.T.F.E.	250°C (Intermittent use up to 300°C)
Woven glass	350°C (Varnish impregnated) (Intermittent use up to 400°C).
Woven Silica	1000°C
Aluminous Porcelain	1400°C (Electrical resistance begins to decline appreciably at 900°C)
Recrystallized alumina	1950°C (Electrical resistance begins to decline appreciably at 1200°C).

7.2.9. Protection of Thermocouples (166)

In order to preserve the electromotive force/temperature characteristics of a thermocouple and also to protect it from the effects of rapid oxidation or other deterioration due to the action of gases or liquids in which it is immersed, it is essential, at temperatures where such deterioration is possible, to provide protection which usually takes the form of a tubular sheath closed at the immersed end.

Generally, for temperatures exceeding 500°C unless very rapid response to change of temperature is essential, the mechanical protection provided by a sheath is desirable and in some circumstances a sheath of ordinary mild steel is suitable. For

TABLE 7.3

THERMOELECTRIC SHEATHS (184)

GENERAL DESCRIPTION AND/ OR TRADE NAME	MAXIMUM TEMP. °C	PROTECTION AFFORDED AGAINST	USUAL CAUSE OF FAILURE	REMARKS
Metallic Mild Steel, solid-drawn or welded.	°C 800	Oxidation, but emits metal vapour above 500°C.	Oxidation and/or fluxing in metals.	Welded end, or bored from solid.
Mild Steel, solid-drawn, surface treated, e.g., by 'calorizing'.	900	Oxidation, but emits metal vapour above 500°C.	Oxidation and/or fluxing in metals. (Less rapid than above).	Welded end, before surface treatment.
Nickel-free stainless iron.	800	Low temperature molten metals, but emits vapour above 500°C.	Oxidation.	Bored from solid.
High chromium-nickel stainless steels.	1,000	Oxidation, but emits metal vapour above 500°C.	Oxidation and/or fluxing in metals (less rapid than above).	Welded end or bored from solid.
Nickel-chromium alloy with some iron, solid-drawn.	1,000	Oxidation but emits metal vapour above 500°C, may also re-emit absorbed SO_2 or CO.	Oxidation, slow, and attack by SO_2 or CO, fluxing in metals.	Welded-end.
Nickel-chromium alloy with some iron cast.	1,000	Oxidation, but emits metal vapour above 500°C, may also re-emit absorbed SO_2 or CO.	Oxidation slow, and attack by SO_2 or CO, fluxing in metals.	Cast with closed end, bore must be freed from core-wires.
Nickel-chromium alloy, nominally pure, cast.	1,100	Oxidation but emits metal vapour above 500°C, may also re-emit SO_2 or CO.	Oxidation, slower than above and attack by SO_2 or CO, fluxing in metals.	Cast with closed end, bore must be freed from core-wires.
Nickel-chromium alloy with 1 to 2 percent W.	1,100 in most circumstances	Generally similar to nickel-chromium alloy, but more resistant to corrosion attack.		

Table 7.3

Thermoelectric Sheaths (184) (Continuation)...

Refractory				
Fused silica, milky.	1,000	Oxidation, gas entry, but may emit silicon above 800°C.	Devitrification, fluxing in slag, etc.	End closed by fusing, withstands temperature shock.
Fused silica, clear.	1,100	Oxidation, gas entry, but may emit silicon above 800°C.	Devitrification, fluxing in slag etc.	End closed by fusing, withstands temperature shock.
Fire Clay	1,400	Oxidation	Cracking, fluxing or building up.	Usually open-ended outer sheath.
Porcelain, glazed and unglazed.	1,400	Oxidation, gas entry.	Cracking, fluxing or building up.	Closed and moulded firing. Manufacturer recommendations shoul be followed in the us of porcelain.
Recrystallized alumina.	1,700	Oxidation and gas entry.	Cracking, fluxing or building up, slow, failure usually traceable to builders.	-
Silicon carbide.	2,000	Oxidation to 1,400°C	Fluxing, or disintegration or binder.	Not much used except as outer sheath.
Alundum	1,550	Oxidation	Cracking, fluxing of building up.	American.

temperatures not exceeding 900°C, a sheath of steel suitably treated, e.g., by 'calorizing', can be used or, for prolonged exposure up to this temperature, a sheath of nickel-chromium alloy. Some heat-resistant metals are used, on occasion, up to 1100°C, and at even higher temperatures. For prolonged service where the temperatures may exceed 1100°C a sheath of refractory material is necessary.

The liability of rare-metals to become contaminated by metal vapours and by gases in the hot zone in which the thermocouple is immersed, makes it desirable to use a sheath of refractory material with a rare-metal thermocouple for all temperatures and, further, to ensure that the sheath used has low permeability to gases.

Table 7.3 as indicated in B.S.1041: 1943 (184) gives a guide to choice of a suitable sheath. Brass and copper can be used up to 250°C and 500°C respectively.

7.?.10. Thermocouple Failure

Because the use of thermocouples in industry is of almost infinite variation, it is difficult to express an exact service life to be expected, but generally the nearer the maximum recommended temperatures for the thermocouples are approached, the shorter their life. Rare metal thermocouple materials are almost immune from chemical attack, but they have a tendency to self-contamination which increases as the temperature increases. In normal use thermocouples fail by many extraneous causes, the occurence of which is often unpredictable.

Observed types of failure can be divided roughly into four categories.

1. Chemical
2. Mechanical
3. Electrical
4. Miscellaneous

Main causes of the different types of failure are briefly outlined below.

(i) Chemical

Oxidation of thermocouple wires.

Diffusion of metal (particularly rhodium).

Volatilisation of thermocouple material.

Gain or loss of impurities.

Contamination - Gas absorption in the metals in reducing atmospheres, chemical fumes attack and metal vapour attacks.

Corrosion.

(ii) Mechanical

Cracking of sheaths.

Fracture of thermocouple wire due to embrittlement.

Plastic strain.

Stress fatigue.

Vibrational fatigue.

(iii) Electrical

Open circuit in loop.

Electrical leakage to earth.

Electrolytic effects in immersed thermocouples.

Pick up from mains.

Shorting of hot junction.

(iv) Miscellaneous

Moisture or dust in thermocouple head.

Bad contact at terminals.

Neutron irradiation at high temperatures.

Work hardening of thermocouple material.

Poor annealing of thermocouple material.

Not a lot of work has been done on the specific study of the failure of thermocouples. The bulk of what work has been done has been on the noble metal thermocouples. For convenience the studies will be treated under their thermocouple material groups.

7.2.10.1. Noble Metal Thermocouple Failures

Rare metals do not oxidise appreciably but there is a tendency for rhodium to transfer from the alloy to the pure platinum. This may be either a diffusion process via the hot junction or volatilization. The effect is continuous, increases with temperature and duration of heating and results in a progressive decrease of the electromotive force (166). This fall may be considerable before any mechanical failure calls attention to its existence. In addition to this self-contamination, a similar and much more rapid fall in electromotive-force follows exposure to metal vapours or contact with metallic oxides in reducing atmosphere. The atmosphere may be accidentally generated by the burning of carbonaceous substances. Of the metallic oxides, silica is the most common cause of trouble.

(i) Contamination of the Thermocouples

Contamination of the pure platimum leg in service is perhaps the main reason for loss of calibration (186,187). Diffusion of rhodium increases with the temperature and the time during which the thermocouple is exposed to the temperature Its effect is negligible if the furnace temperature is uniform (188), and if there is sufficient depth of uniform temperature, as then the zone containing the diffused rhodium acts only as a connector between the legs of the thermocouple and so does not interfere with the indications of the thermocouple. Should the diffused zone enter a region of non-uniform temperature, the result would be to reduce the e.m.f. output of the thermocouple, thus making the indicated temperature lower than the true temperature of the furnace.

At temperatures over 1200°C, diffusion of rhodium into the platinum leg by volatilization from platinum - rhodium wire and deposition on to the platinum occurs significantly, (196) particularly in oxidising atmospheres (168,188).

According to Finch (168), a common fault in thermocouple materials at temperatures above 1000°C, and the most outstanding fault of the Pt - $Pt_{90}Rh_{10}$ thermocouple is rapid deterioration in reducing atmospheres which results from gas adsorption in the metals, from the reduction of metallic oxides in its environment, and the absorption of the reduced metals by the platinum, tending to change the e.m.f.

Contact between any metals (solids, liquid or vapour) and the thermocouple leads to alloying which will change the e.m.f. of thermocouple and render it unfit for further use (186). Furnace gases or chemical fumes, particularly those carrying sulphur or sulphur compounds, may cause embrittlement of the wires in addition to affecting the e.m.f. output. (186,189) (190), but there is no evidence that sulphur alone will contaminate platinum from an experiment by Bennett (187) in which samples of platinum were heated at 1200°C for half an hour in atmospheres of H_2S and SO_2 without an embrittlement being observed.

Attack by lead or zinc vapours are frequently encountered. This attack produces embrittlement and hot shortness, so that if the wires are subject to any stress even at a relatively low temperature they are liable to fracture, with a very crystalline break (187). This often occurs at the places where insulating tubes meet and the platinum wire is exposed to the contaminating vapour. This kind of contamination often occurs when scrap that contain lead or zinc bearing solders is being melted. In such instances it is generally found that the thermocouple sheath has cracked or the vapours have had access to the thermocouple system in some unsuspected way. Refractory cement when used sometimes have been found to contain lead which volatilises and contaminates the thermocouple. Heated brass and galvanised iron sheets may be a source of contamination through volatilization of zinc.

(ii) Reducing Atmosphere

Under reducing atmosphere conditions the silica in silica and siliceous refractories is reduced to silicone which alloys with platinum lowering the melting point. It has been shown that a thermocouple contaminated with silicon in this way has failed at as low a temperature as 1200°C due to melting of grain-boundary films of platinum - platinum silicide eutectic (191,192). Chausian (193) has reported some experiments in which platinum: 10% rh/pt thermocouples were heated in various refractory oxides. He observed high e.m.f. outputs.

(iii) Prolonged heating at high temperatures

There appears to be disagreement as to which metal (platinum or rhodium) volatilizes preferentially from the platinum - rhodium alloys. Several experimenters (186,194,195) have found that slightly more platinum volatilizes than rhodium. Others (196-199) have found a slight preference for rhodium volatilization. Work done to 1400°C (200) in a moving dry air atmosphere on pure platinum group metals indicates that slightly more platinum than rhodium will volatilize. Generally, however, after prolonged heating at a high temperature, platinum thermocouples tend to produce a decreasing e.m.f. due chiefly to the pick up on the pure platinum wire of rhodium volatilised from the alloy wire (187). Powell (201) critically reviews work on this subject up to 1958 and describes some original experimental work.

It has been observed that heating under load at 1400°C produced very large grain growth in the pure platinum, the wire consisting of a chain of large crystals of the diameter of the wire. Under prolonged stress at low loads grain - boundary sliding occurs and ultimately leads to a brittle type of fracture, which is occasionally found in a couple after long service at a high temperature (187).

In service the platinum wire is subject to grain growth which eventually causes the wire to consist of a series of crystals each occupying its entire cross-section. This has little effect on the e.m.f. of the thermocouple, but contamination and volatilization proceed more rapidly and the wire becomes brittle, resulting eventually in failure. Thermocouples left permanently in a fixed position last longer than those subject to mechanical disturbance (167).

Because many factors are involved in the evaluation of a thermocouple, references (183,191,197,198) only give a guide from experiments in the cases where volatilization appears to be the main problem.

7.2.10.2. Base Metal Thermocouple Failures

Oxidation is the main cause of failure for this group of metal thermocouples (166,204 - 206). The thermocouple deteriorates rapidly due to oxidation and the oxidation process is continuous. Nickel/Chromium and nickel/aluminium are less readily oxidised; these alloys are, however, susceptible to atmospheres containing active compounds of sulphur. Nickel/chromium is also susceptible to compounds of carbon and cyanide fumes.

Inherent inhomogeneity in the as received metals and plastic strain are known to cause a drift in the thermocouple e.m.f. (205-207). Dahl's (204) stability tests in air indicate that long-time exposure to high temperatures causes the em.f. corresponding to a given temperature to increase, or the temperature corresponding to a given e.m.f. to decrease.

Roeser and Dahl (208) found that the thermoelectric changes in copper due to coldworking was not very large, this they attributed to the exceptionally uniform thermoelectric properties of the commercial metal. The assumption therefore being that the greater part of the change in service of copper v constantan thermocouples is due to damages in the constantan wire (204).

Experience in Rolls-Royce Limited (Aero-Engine Division) (209) where Ni Cr/Ni Al thermocouple is very widely used at well under the maximum recommended temperature is that there are two main types of failures.

(i) Mechanical: Usually in the form of Intergranular or Transgranular fractures.

(ii) Electrical: Reduction in thermoelectric output in extreme high temperature and oxidising conditions.

The behaviour of the thermocouple at failure has been complete loss of output, although intermittent signals, as a result of make and break action of fractured section, can be received. These effects were more pronounced on current drawing readout equipment due to time resistance changes.

Causes of failure were attributed to Gas and/or Stress corrosion, small stress fatigue, high temperature creep and vibrational fatigue.

7.2.10.3. Thermocouple Failure in Nuclear Environment

The stability of platinum vs platinum 10% rhodium thermocouples has been reported poor when they were exposed to neutron irradiation for fairly long periods of time at high neutron flux (210). The cause of the instability has been attributed to nuclear conversion. Because the rhodium in the alloy leg has a large cross section, neutrons transform part of the rhodium to palladium, effectively producing a platinum vs platinum, rhodium palladium couple (211).

Weaving (212) draws attention to problems and experience in reactor temperature measurement. From his experience the main problems are

(i) Drift

Considerable drift can occur in a thermocouple calibration following extended periods at high temperature because of lack of or inadequate annealing on completion of manufacture and possibly also due to work hardening during installation.

(ii) Sulphur embrittlement

Thermocouple conductor failures have occured due to sulphur embrittlement, the sulphur attack being negligible at room temperature and accelerating at high temperatures. If sulphur is present the attack often occurs during the annealing processes and failure occurs due to subsequent cold work.

(iii) Effect of Moisture

Contamination of magnesia insulation by moisture, by exposure to atmosphere, will probably lead to embrittlement of the conductors following exposure to high temperature for an extended period.

The moisture has a further effect in that it can bring about a low insulation resistance when the thermocouple is at a high temperature. The insulation resistance may be sufficiently low to create difficulties in obtaining a satisfactory temperature measurement.

7.2.10.4. Experience at the National Engineering Laboratory

Three main modes of failure namely (i) open circuit in loop, (ii) Electrical leakage to earth or adjacent metal work and (iii) Hot junction shorted out have been experienced in the National Engineering Laboratory (213). A signal may be developed across part of the thermocouple to give a reading either higher or lower than expected in the case of electrical leakage to earth. A special case of this had been observed where bare thermocouples were immersed in water. Electrolytic effects can arise and are most noticeable in a differential configuration (large error signals, often of a random but varying nature, are observed).

If the instrument is not isolated from earth, large signals may be developed due to its own power supply in an earth loop where the thermocouple lead forms a path for the error current. High or low readings may be expected.

Where a.c. currents are adjacent, such as form the mains, effects may be observed if the equipment is sensitive to rapidly changing signals. On an oscilloscope or an ultra violet recorder the effect will be a trace of a periodic nature superimposed on the expected signal. If the equipment is a digital voltmeter performing repeated scans in a data logging system, a scatter of readings is obtained about an expected mean.

7.2.10.5. Other Sources of Possible Failures in the Thermocouple Installation — Electrical Instruments used with thermocouples

In the overall reliability consideration of the thermocouple system, consideration of the electrical instruments and connections that go with the thermocouple is relevant. Errors arising from the electrical instruments used with the thermocouple would result in outputting of eroneous signals.

There are two main types of electrical instruments used with thermocouples.

(i) Direct deflection instruments e.g. Millivoltmeter

(ii) Potentiometer type instrument e.g. Null Potentiometer.

Associated with these could be voltage amplifiers.

Errors in the indications given by a millivoltmeter may arise due to parasitic or stray electromotive forces. Such electromotive forces may be caused by leakage currents from neighbouring power and lighting circuits; by breakdown of electrical furnaces at high temperatures; by electrolytic effects occuring as a result of dampness at any junctions, including switchgear; to thermoelectric effects arising from temperatures differences between the junction of similar metals other than in the thermocouple itself; and to thermionic effects.

The above sources of error also apply to instruments recording an out-of-balance current from a potentiometer system. For the null method potentiometers there are other sources of possible error. These are (i) A change in e.m.f. of the standard cell against which the potentiometer current is adjusted (ii) a change in the potentiometer current during intervals between adjustments; (iii) indefinite or slack mechanical linkage between the slide wire contact and the pointer of indicator or of the pen of the recorder; (iv) insensitivity of the balancing mechanism to the galvanometer deflections.

7.3. Thermocouple Failure rate data

There is not much published work on thermocouple failure rates in the open literature. The only published figure on thermocouple failure rate known to the author is that by

Green and Bourne (101) where they quoted an assumed failure rate of 0.088 faults per year. However, actual data from the survey carried out by the author and already reported in Chapter 3 show much higher failure rates. Relevant extracts of summary of the survey are given below. Table 7.4. Interpretation of the tables and other background information are as given in Chapter 3.

Table 7.4.

Thermocouple Reliability Data

Works	Number at Risk	Instrument Years	Environment factor	Number of faults	Failure rate, faults/year
A	663	-	3	127	0.40
B	88	-	4	47	1.34
C	22	18	4	18	1.00
All	772	369	3	191	0.52

The figures shown above point at the influence of environment on the failure rate. Obviously, the severer the environmental conditions, the higher the failure rate expectation.

7.4. Experimental Laboratory Work on Thermocouple Failure

The temperature range limitation of the experiments carried out were imposed by the furnace available in the laboratory. Because of this temperature range limitation the choice of possible thermocouples for testing to failure under severe temperature conditions was limited to only copper vs constantan and possibly iron vs constantan and nickel/10% chromium vs constantan thermocouples. The copper vs constantan thermocouple was easily the best choice in the circumstances as its recommended range of operation is well below that of the furnace and it was easily available, hence its choice for the experiments. For similar reasons Chromel vs Alumel thermocouple was used as the reference or comparator thermocouple as its range of operation is outside the range of the furnace and it was also readily available.

7.4.1. Description of Apparatus

A line diagram of the apparatus set up is shown in Fig. 7.2.

The copper vs constantan (Cu/Const) thermocouples were part insulated by ceramic sleeves and part by insulating tape. Most of the thermocouple in the furnace and out of the furnace was insulated by ceramic sleeves and the remainder by insulating tape. The Chromel vs Alumel (Cr/Al) thermocouples already had fibre glass insulation.

The Cu/Const thermocouples were made up in the laboratory by braising the two wires together while the CR/Al thermocouples were spot welded. The Cu/Const wires were 18 gauge and the Cr/Al about 19 gauge.

A constant temperature water bath was used to maintain a 'cold junction'. The temperature of the bath was controlled at 22°C.

The thermocouples therefore had their cold junctions in the water bath, their hot junction in the furnace and the

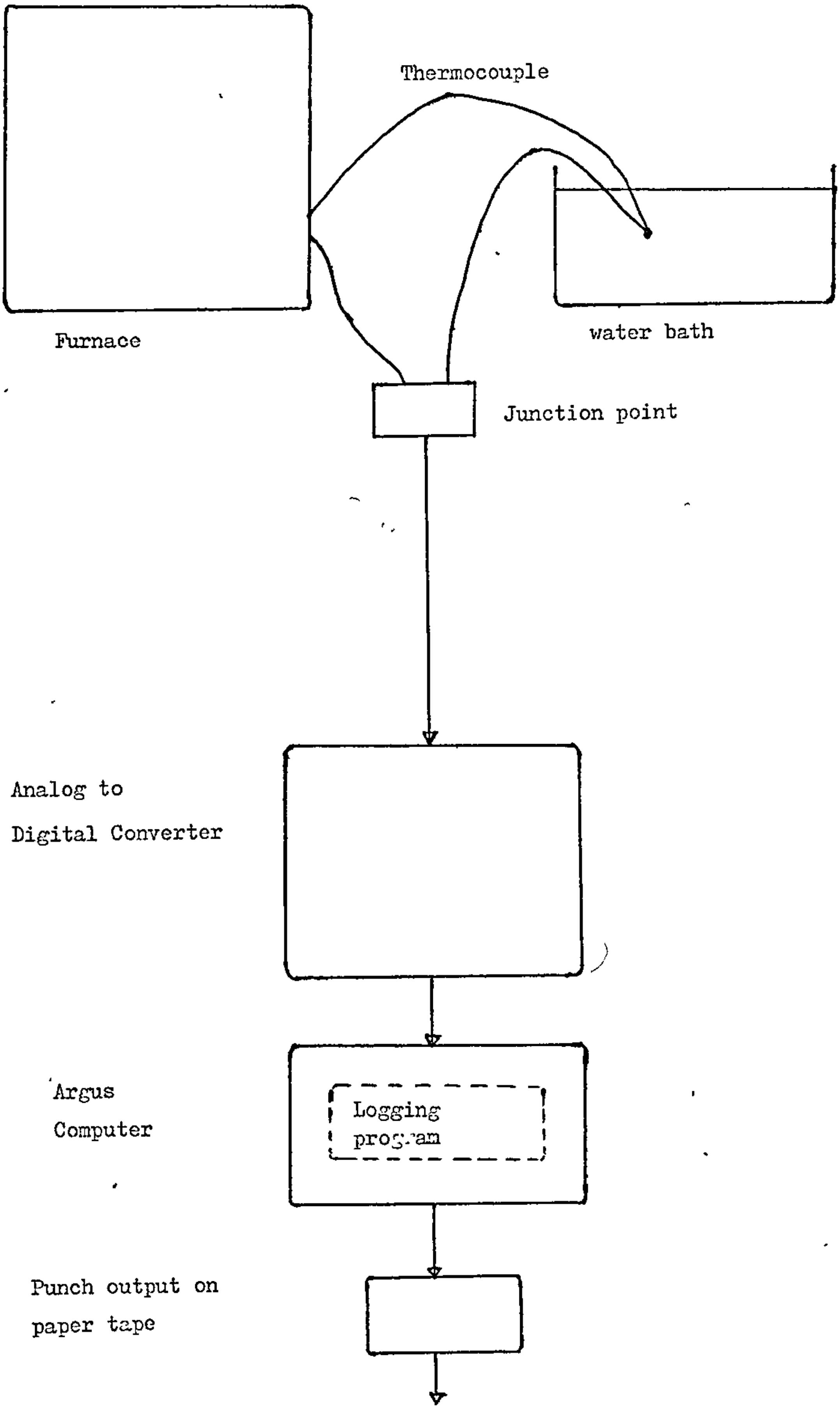


Fig 7.2 Line diagram of thermocouple failure logging rig.

loose ends connected up to a junction point from which they were linked directly by cable to the analogue to digital converter and hence to the computer.

The analogue to digital converter incorporates amplifiers which were set to an amplification of 100 and had an internal resistance of 10k ohms.

The power input to the furnace is controlled by an energy regulator which is a periodic current interruptor having a continuously variable ratio of the 'on' to the total cycle time. Because the energy regulator compensates automatically for voltage variations and the furnace winding has a large heat capacity, quite accurate temperature control can be expected but because the regulator only controls the power input, it does not operate in the same way as a thermostat and the temperature will only remain constant if the ambient temperature does not change and the furnace is not exposed to draughts.

The furnace is fitted with a Cr/Al thermocouple which is connected to a temperature indicator at the front of the furnace by a compensating cable.

There was provision for four channels into the computer from the junction point so that four thermocouple readings could be logged simultaneously.

7.4.2. Experimental Work Carried Out

All the laboratory experimental work was done on-line using the departmental Argus 100 computer.

Initial experimental runs were carried out to develop the best way of logging the thermocouple signal by the computer. From the initial runs and the difficulties encountered, modifications were made until a satisfactory logging state - as was used - was achieved.

Cu/Const thermocouples were then subjected to severe temperature conditions and tested to failure; the behaviour before, during, and after failure was thus recorded and observed.

A series of experimental runs were then carried out from fairly high temperatures (860°C) for Cu/Const thermocouples to just above the recommended upper temperature (400°), to observe the approximate relations for times to failure and the general pattern of behaviour at failure at these various environmental conditions.

Following the analysis of the earlier runs, a simple algorithm, based on the standard deviation of the signal, was developed to detect thermocouple malfunction.

It is easy to detect total failure but the object of the algorithm was to detect the start of failure. Fuller details on the algorithm are given in the next section 7.4.3.

The logging program was then modified to incorporate and test the algorithm on-line. A series of experimental runs were carried out to do this. The parameters of the algorithm were investigated on-line also.

In addition to simulating thermocouple failure under severe temperature environmental conditions, open circuit or loose end failure was also simulated. Finally, chemical attack or severe corrossive atmosphere environment effect was simulated. The latter two simulations were done using the Cr/Al thermocouple and working well within its recommended temperature range.

The results of the experimental runs carried out are presented later in section 7.4.4.

7.4.3 Thermocouple Failure detection algorithm as tested on-line:

Invariably a thermocouple failure would result in its giving out erroneous signals. From the work carried out in the laboratory and from data from industry, an excessive rate of change of readings of the thermocouple is almost a common characteristic. This can easily be picked up by looking at the variation in the standard deviation of the signal, calculated by using a running mean.

A running mean is important as the thermocouple mean may move. A mean is necessary for the effectiveness of the algorithm as it is important to damp out spurious signal noises and avoid false alarms by spurious spikes.

The procedure for calculating standard deviation is the same as that for average power. The variance and average power are effectively the same.

The standard deviation based algorithm was developed and tested both off-line and on-line. The algorithm is exactly on similar lines as that described in Chapter 5 Section 5.14.4.

The running mean is calculated by using a single exponential smoothing as follows:

(i) running mean $\bar{m}_k$

$$\bar{m}_k = \alpha m_k + (1-\alpha) \bar{m}_{k-1}$$

(ii) error e_k

$$e_k = m_k - \bar{m}_{k-1}$$

(iii) variance σ^2

$$\sigma^2 = \frac{\Sigma e_k^2}{N}$$

(iv) standard deviation σ

$$\sigma = \sqrt{\sigma^2}$$
$$= \frac{1}{\sqrt{N}}\sqrt{(\Sigma e_k^2)}$$

In the present work, the standard deviation was simply calculated and displayed as a function of time This was adequate for the objectives of illustrating the feasibility of the use of the technique It could be displayed in various ways to aid the operator in malfunction detection Some display types have already been described in Chapter 5 section 5.5 . For automatic detection by computer, threshold values can be set for the standard deviation values calculated

The Astral programs to carry out the operations both off-line and on-line are given in the Appendix (2)

Values of α used were the common type values used in industry ——— $\frac{1}{2}$, $\frac{1}{4}$, and 1/8. The values of N used were 20, 30, 60, 120 The sampling times were 1, 5, 10, 20, 30 seconds. The speed of the punch out-put was a limiting factor to how fast the logging could be. For the investigation of a particular parameter, the other two were held constant.

7.4.4. Experimental results and analysis

The cold junction was a water bath maintained at 22°C.

The tolerance for copper/constantan (Cu/Const) thermocouple in the range +100 to +400°C is ± $\frac{3}{4}$%. That for chromel/Alumel (Cr/Al) thermocouple in the range 300°C to 1000°C is ± $\frac{3}{4}$% (184). There is nothing in the literature for the tolerance of the Cu/const thermocouples in the temperature ranges to which they were subjected in the laboratory tests (400°C to 860°C) as this was outside their recommended range of operation. The environmental conditions in which the Cu/Const thermocouples were tested were drastic for them.

The computer loggings are the actual e.m.f. outputs of the thermocouples. The outputs are in millivolts because of an amplification factor of 100 of the signal by the analogue to digital converter before the signal is read into the computer. The computer outputs can easily be converted into actual temperature readings in engineering units by using standard calibration curves for the particular thermocouples. Because the Cu/Const thermocouples were tested outside their recommended temperature range of operations, there is no such calibration data in this range. Nevertheless the signal outputs were considered adequate for representing a normal and failing instrument signal pattern and for the purposes of testing the standard deviation algorithm. Analyses have therefore been done directly on the actual e.m.f. outputs of the thermocouples partly because it was not considered necessary to work in engineering temperature units and partly because the e.m.f. outputs are the actual signals that reach the computer and the behaviour of which is of primary interest.

A check on the fluctuations of the Cr/Al thermocouple readings(for which there are standard calibration data in the literature) showed the fluctuations to be within the recommended tolerance limits for the range of operation. The fluctuations were generally of the order of 0.1 and 0.2 millivolt. A change of 0.1 millivolt in the Cr/Al thermocouple output as logged by the computer is equivalent to a change of approximately 2.5°C. On this basis, the laboratory set up was found sufficiently accurate for the purposes of this project. The logging is only accurate to 3 decimal places and the fourth decimal place is liable to round off error in the computer.

The level of tolerance in the fluctuations of the Cu/Const thermocouples would be expected to be higher than those of the Cr/Al thermocouples as the Cu/Const thermocouples were run at temperatures above their recommended range of operation. The general level was about 2 or 3 times that of the Cr/Al for temperatures around 800°C.

All the data analysed are given in the appendix tables A 7 to A 20 .

Fig. 7.3 is a computer plot of a failing Cu/Const thermocouple signal. Fig. 7.4 is the computer plot of the corresponding standard deviation as calculated on-line by the algorithm.

Period A in fig. 7.3 corresponds to D in fig. 7.4 and represents the period of normal instrument behaviour just before failure. For this region, the signal fluctuations and the standard deviation values are within limits of tolerance and reasonably steady. At point B the instrument signal was beginning to go off-normal. In this particular case, this was characterised by spikes such as B and C, a general rise in the magnitude of the fluctuations and an upward drift in the thermocouple output signal. There was no corresponding rise or change of conditions in the furnace temperature as indicated by both Cr/Al thermocouple output and the furnace temperature indicator. This type of signal behaviour would therefore signify the beginning of an off-normal behaviour of the instrument signal. This off-normal trend was immediately picked up by the standard deviation calculations and clearly shown by peaks E and F, and by the general upward trend of the values thereafter. This type of behaviour of the standard deviation would not be expected for a normal instrument signal. Because of the thermal inertia of the furnace, temperature fluctuations of the furnace would be slower and more gradual. If it is a drift due to varying ambient temperature or change in the measured temperature, the running mean should be able to cope with it. Fig. 7.5 (a) shows the computer plot for normal behaviour Cu/Const and Cr/Al thermocouples for varying measured temperature conditions. There was a rise in the measured temperature from 580°C to 860°C. The rise was gradual and the fluctuations were within limit. The standard deviation calculations fig. 7.5 (b) remained within tolerance and showed a steady pattern.

For off-normal detection purposes, a combination of peaks such as E and F, and a general rise in the level of the standard deviations could be indicative of the beginning of an off-normal condition.

As the general instrument signal fluctuations rose in level and the spikes increased in frequency, more high peaks and generally high values of the standard deviation appear in fig. 7.4. The standard deviation calculations alone could have clearly and positively indicated the off-normal condition in the signal long before it was obvious from the signal itself. A display of the standard deviation calculations would have shown up the on set of off-normal behaviour in the instrument signal well and long before the total failure. Such a display would be superior to a display of the actual signal or pure instantaneous error as neither could differentiate between a normal drift in the measured temperature and spurious excursions and spikes.

The running and continuously updated mean of the algorithm is designed to cope with spurious spikes or normal varying conditions in the measured instrument signal. The standard deviation plot of the rising temperature signal of fig. 7.5 (a) given in fig. 7.5 (b) shows how well the algorithm can cope with such temperature variations. The standard deviation, because it is an average parameter of the signal, tends to damp out any spurious excursions and spikes and therefore when they show up significantly on the standard deviation, they must be significant and can be interpreted as such.

Fig. 7.5 (b) is the standard deviation plot of the signal shown in fig. 7.5 (a) for the normal behaviour of a Cu/Const thermocouple at above 800°C. Even at such severe tenperature conditions, fig. 7.5 (b) shows a steady pattern for the standard deviation. For varying environmental conditions, the computer can learn such patterns and this would increase the versatility of the standard deviation-based malfunction detection algorithm. Fig. 7.6 shows the standard deviation for the failing instrument signal whose normal behaviour is shown in fig. 7.5 (b). The general pattern is the same — a combination of large peaks and general rise in the level of the standard deviations at the on set of off-normal condition.

A crude plot of the times to failure of different Cu/Const thermocouples at different temperatures is given in fig. 7.7. An attempt at an Arhenius type plot, fig. 7.8, suggests that the temperature vs time to failure relationship does not readily fit a chemical rate type equation. Nevertheless, the pattern was one of rapidly decreasing time to failure with increasing temperature ⟶ a drastic drop from under 1000 hrs. at 400°C to about 10 hrs. at 860°C, see table 7.5.

The investigation of the effects of the parameters in the standard deviation algorithm was carried out on Cr/Al thermocouples behaving normally and well within their operating temperature range. The investigations were done on the Cr/Al thermocouples because in the above temperature range of operation, they would be more reliable and would be expected to be more reproducible. The different plots of the standard deviations for the investigations have been included not only to show the effect of varying the parameters but also to show the type of consistency and pattern of the standard deviation to be expected for normal instrument behaviour.

The variations of the smoothing constants figs. 7.9 and 7.10 did not affect the general pattern or values of the standard deviations. The values tested were the normal type of values used in industry. They all seem adequate for the purposes of the algorithm. Choosing $\alpha = 1$ is equivalent to no smoothing whereas an excessively low value of α will cause the smoothed signal to be unrepresentative of the actual signal when a steady real trend is present. A low valve of α should be used to smooth out large random fluctuations. The choice of α therefore requires a compromise between noise rejection and speed of signal tracking.

The effect of varying the sampling times and the sample sizes figs. 7.11 to 7.18 did not show on the general pattern or values of the standard deviations. The sampling times tested appear, therefore, adequate for satisfactory representation of the signal for the purposes of calculating representative values of the standard deviation. Because the standard deviation is an average parameter of the signal, the larger the sample size, the better statistically would be the standard deviation estimate. The choice of the sample size and sampling time, therefore, appears, on the basis of the above findings, to be a rational decision with considerations of how soon the off-normal condition should be detected on occurence and a good representation of the signal characteristics for standard deviation estimation, borne in mind.

Loose connection would typify such sudden thermocouple failures and was simulated in the laboratory. The thermocouple contacts were broken and reconnected while logging the instrument signal. Fig. 7.19 shows how rapidly the algorithm positively picks up such an effect. The thermocouple contacts were disturbed twice in the experimental run shown and the values of the standard deviations between and after the disturbances show how quickly the algorithm recovers from, and its sensitivity to such a fault. Even though the values of the standard deviation shot up on loss of contact, on reconnection, the values quickly came down to the normal level. Again, the general behaviour of the standard deviation at off-normal condition was excessive deviation of the value from normal or expected values.

A similar pattern of behaviour was shown by the standard deviation calculations when a chemical attack of the Cr/Al thermocouple was simulated even though the general behaviour of the instrument signal was different in this case. Instead of a rise in output of the thermocouple, there was a downward drift until total failure when the instrument went open circuit. The on-set of chemical attack was characterised by the high level of fluctuations in the instrument signal. This was followed by a general drop and downward drift of e.m.f. output. The beginning of chemical attack was immediately picked up by the algorithm fig. 7.20 and the off-normal state of the signal was also clearly shown.

Generally, the patterns of the standard deviations for both the Cu/Const and Cr/Al thermocouple signals in the normal and failed states were consistent. When the thermocouples were in their normal states, the standard deviations fluctuated within tolerable limits. As soon as off-normal conditions arose, large excursions showed up as peaks and as the condition deteriorated the excursions were larger and persistent.

The standard deviation algorithm tested here, therefore, could be effectively used for a display technique to aid the operator in malfunction detection or as a computer based technique. For the latter use, two or three consecutive large excursions could be used as a basis for malfunction. Threshold values of tolerance can be set a priori but the computer could learn and set its values with varying environmental conditions. Ability to do the latter would increase the versatility of the algorithm.

The conditions simulated here may be considered too drastic and a bit artificial, nevertheless, they are representative of the pattern of behaviour that would be expected albeit less drastically.

Table 7.5 Cu/Const thermocouple failure time and temperature

Temperature	Time to failure (hrs.)	Absolute temperature $(\frac{1}{T})$	$\frac{1}{t}$ hrs^{-1}
400	840	1.49×10^{-3}	1.19×10^{-3}
600	300	1.14×10^{-3}	3.34×10^{-3}
680	170	1.05×10^{-3}	5.90×10^{-3}
800	20	0.935×10^{-3}	5.0×10^{-2}
860	10	0.885×10^{-3}	1.0×10^{-1}

For Figs. 7.5 to 7.20 the values of the Standard deviation σ are in millivolts x 10.

The points marked x stand for values of $\sigma > 100$.

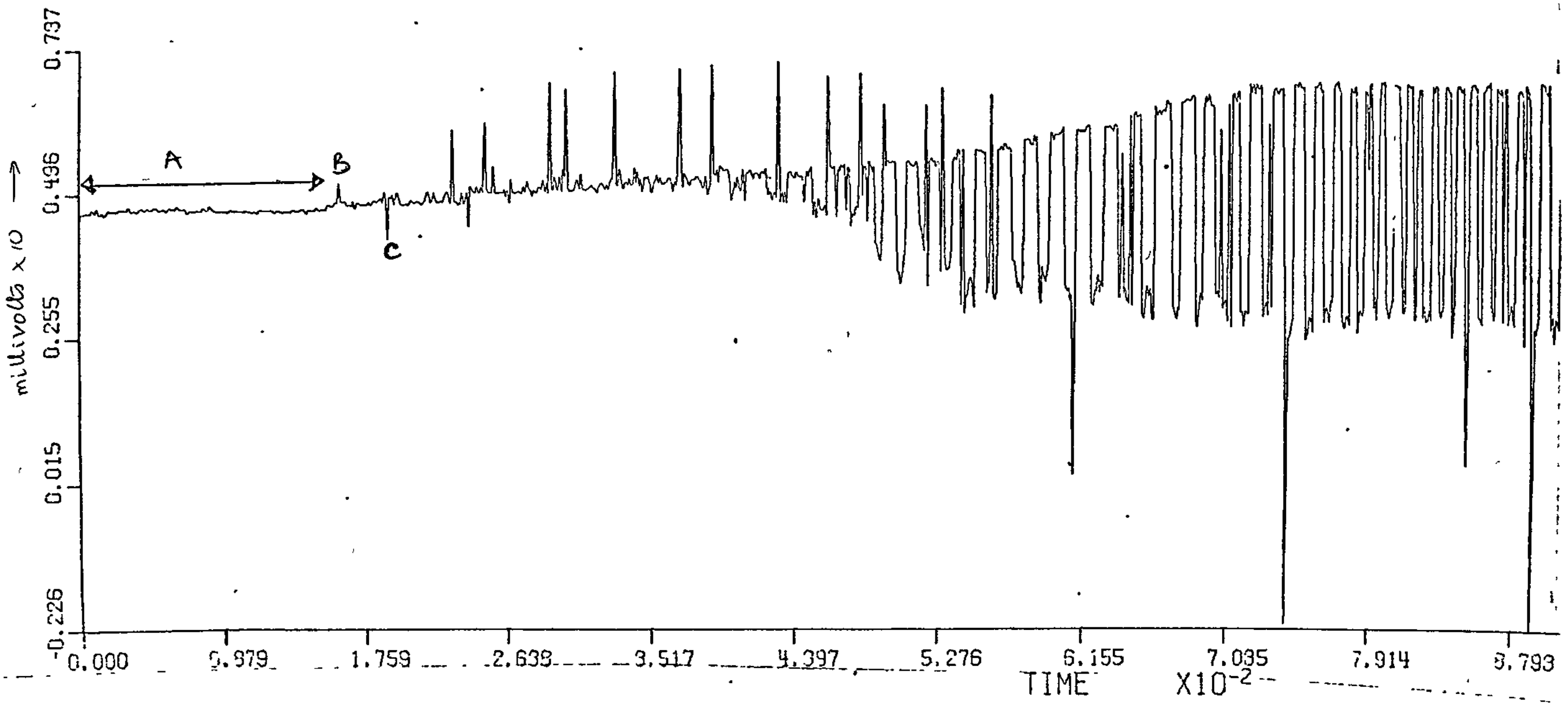
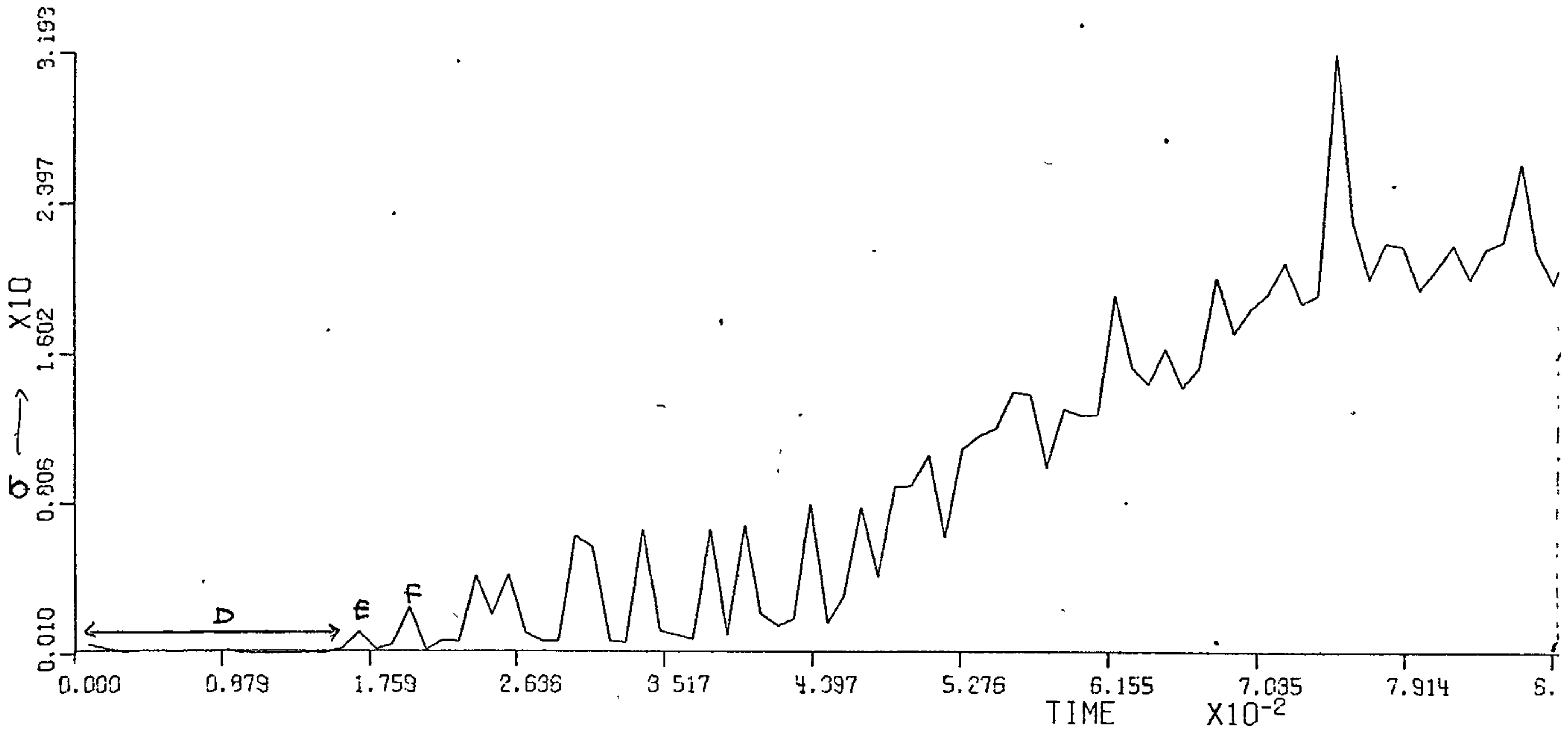


Fig. 7.3. Computer plot of a failing Cu/Const thermocouple



<u>Fig. 7.4. Standard deviation of failing Cu/Const thermocouple fig. 7.3</u>.

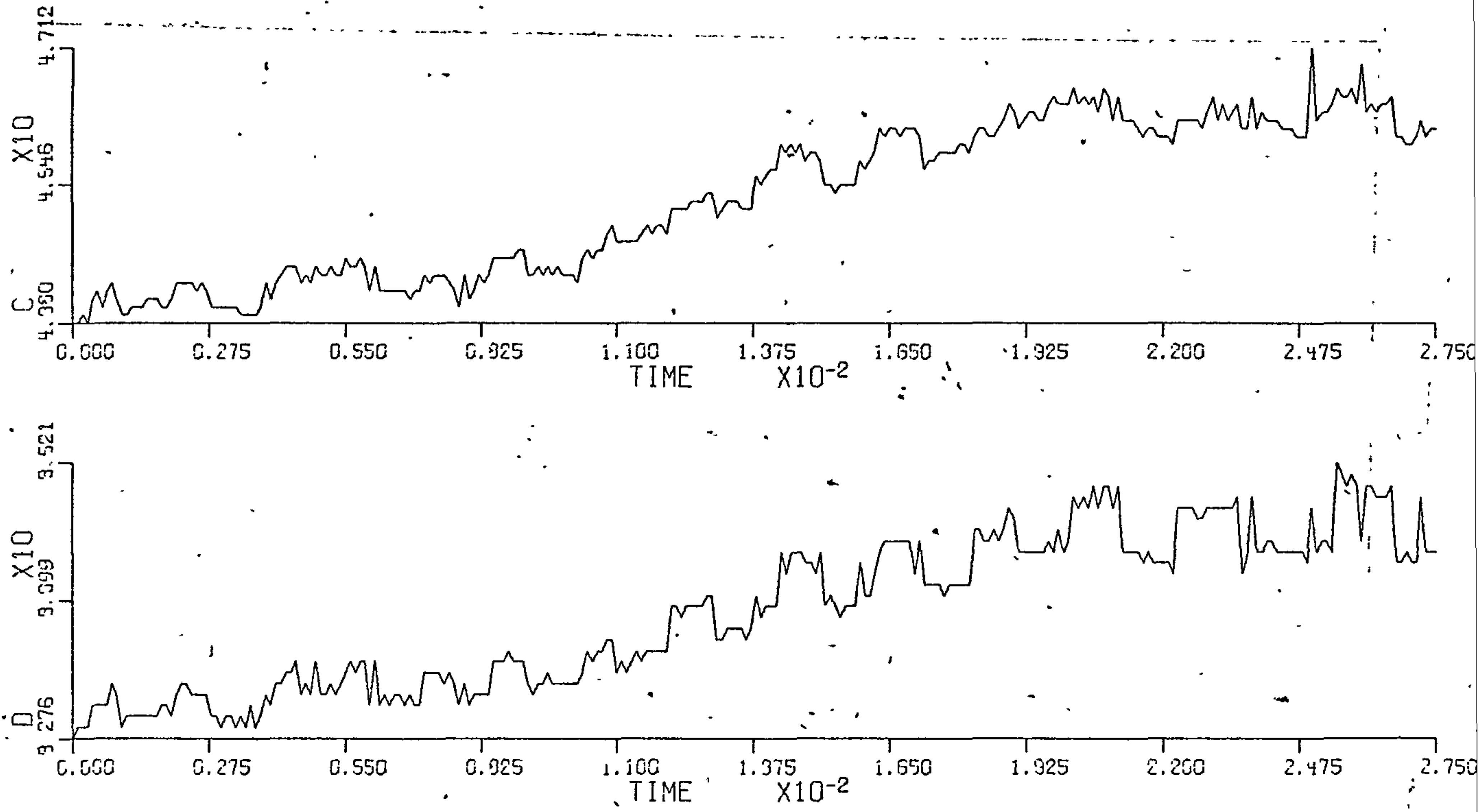


Fig. 7.5. (a) Normal Cu/Const (C) and Cr/Al (D) Thermocouple signals for a 580°C to 860°C furnace temperature rise

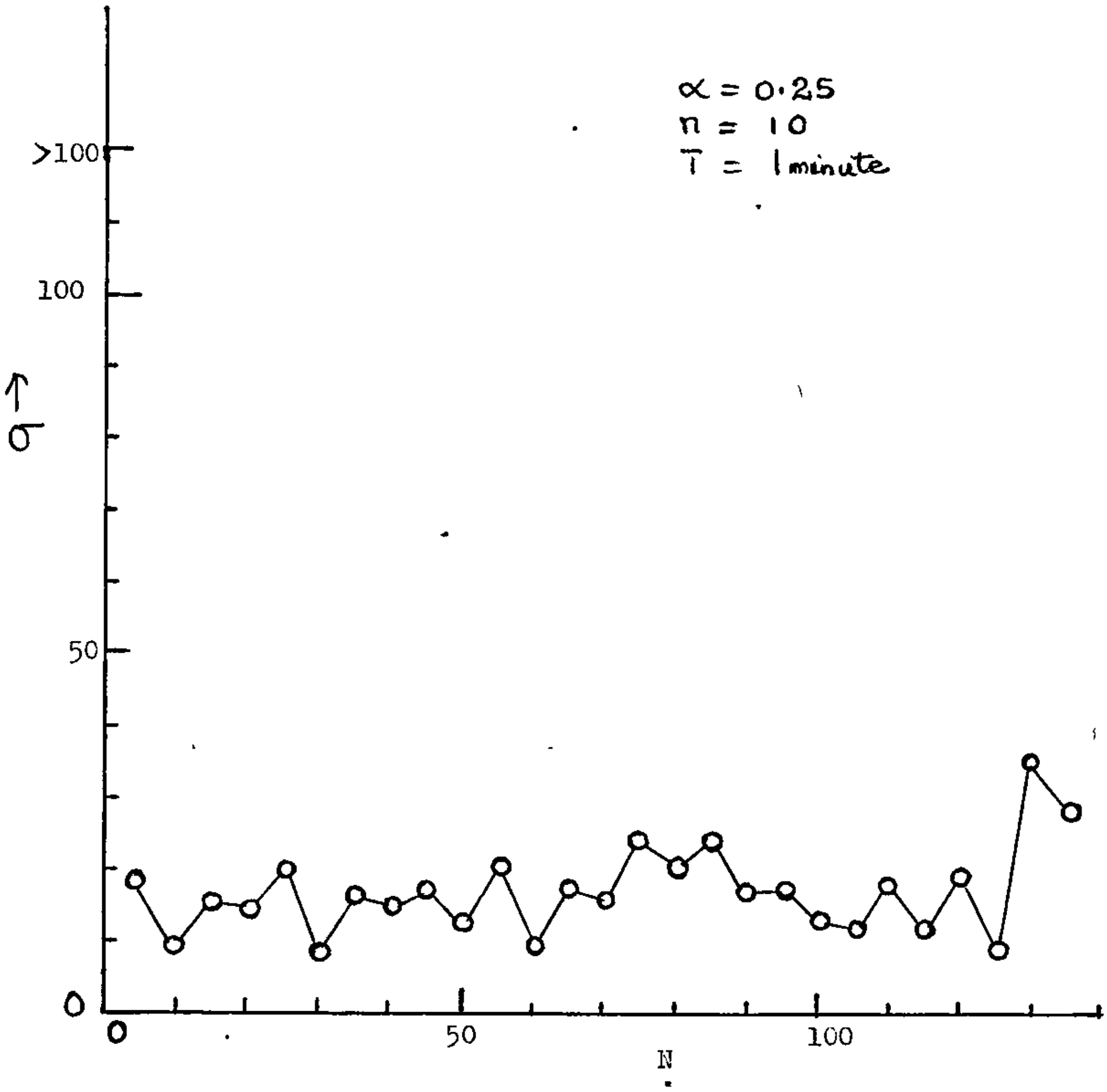


Fig 7.5 (b) Normal Cu/Const thermocouple signal standard deviation at 860 °C

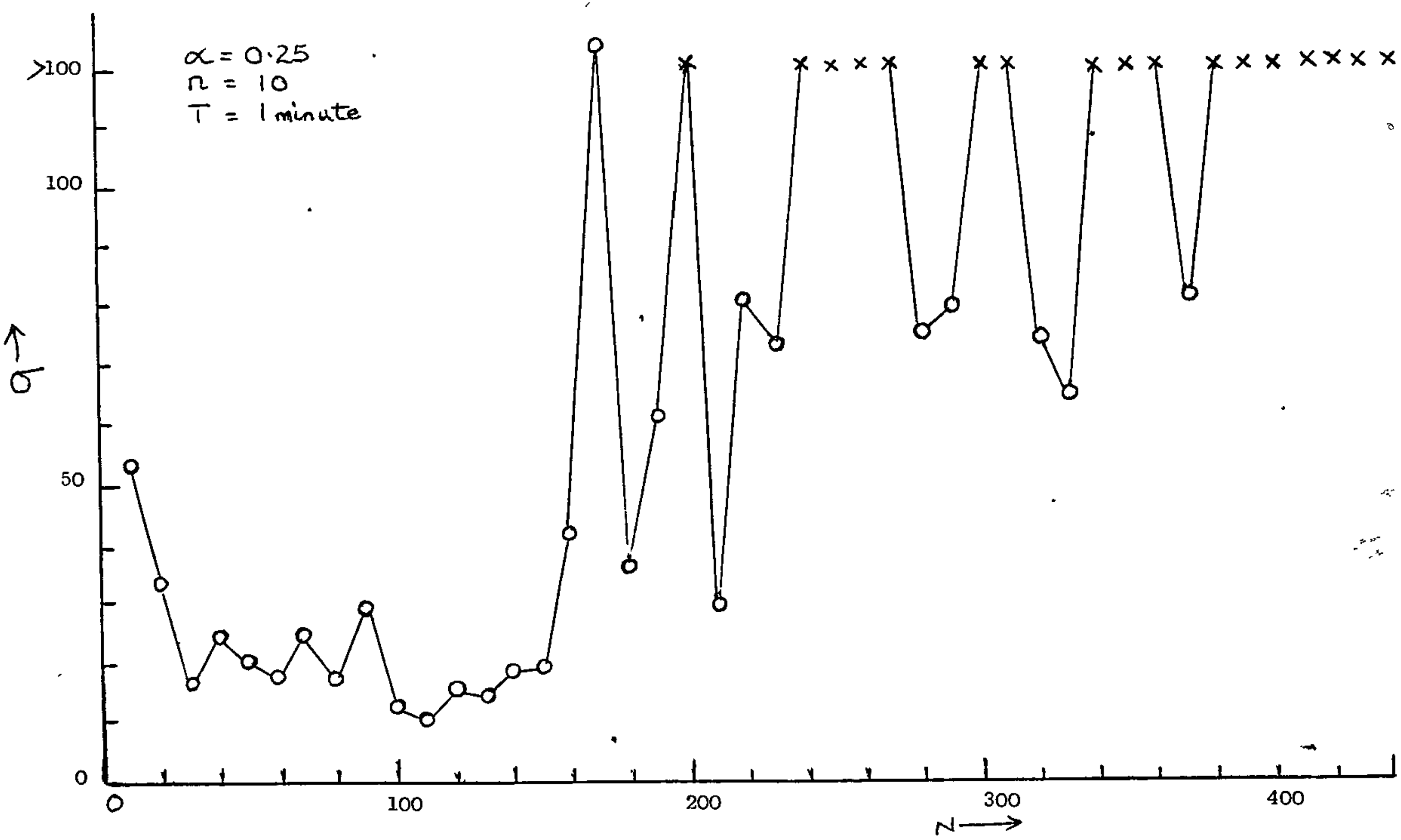


Fig. 7.6 Failure of Cu/Const thermocouple

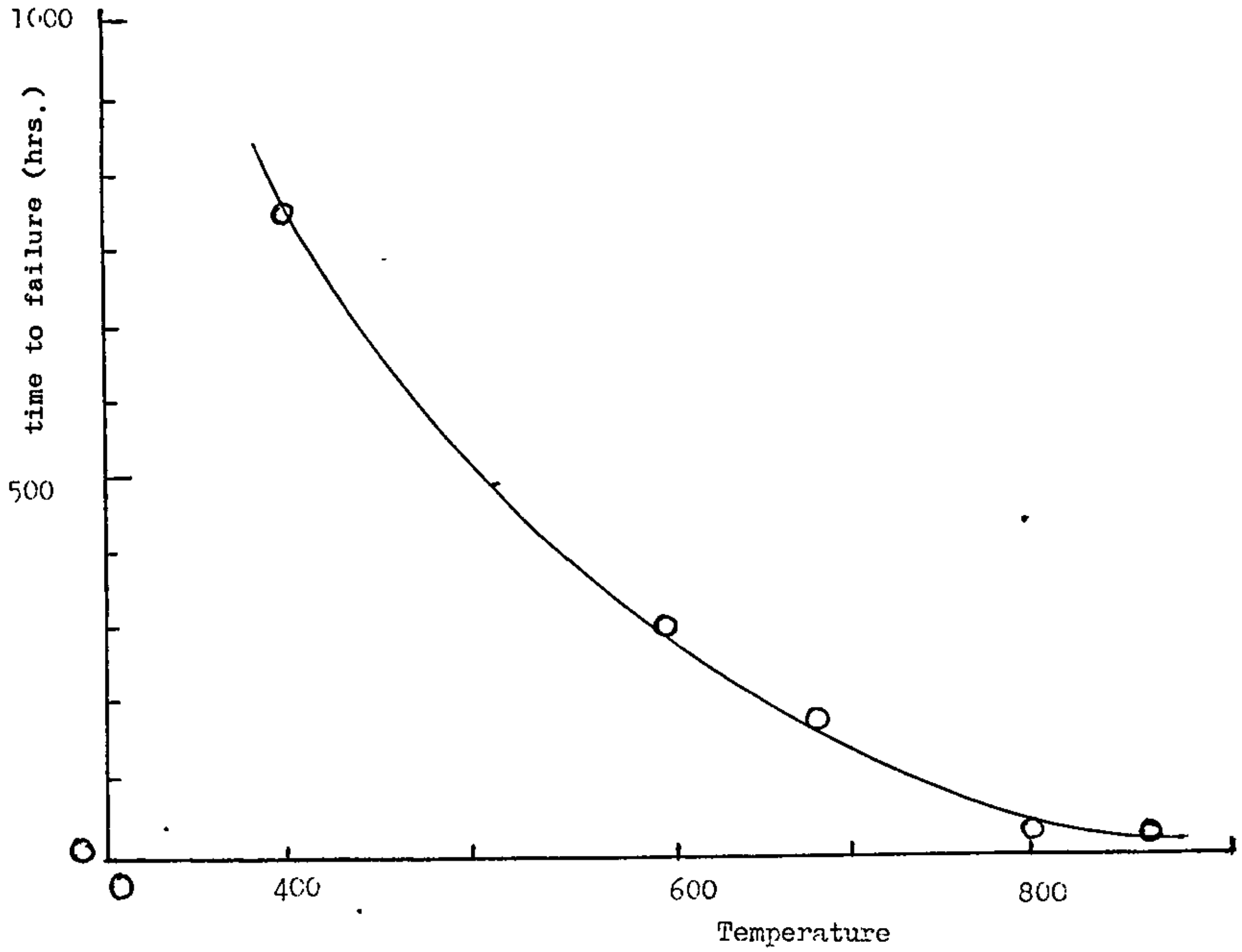


Fig 7.7 Time before failure vs temperature

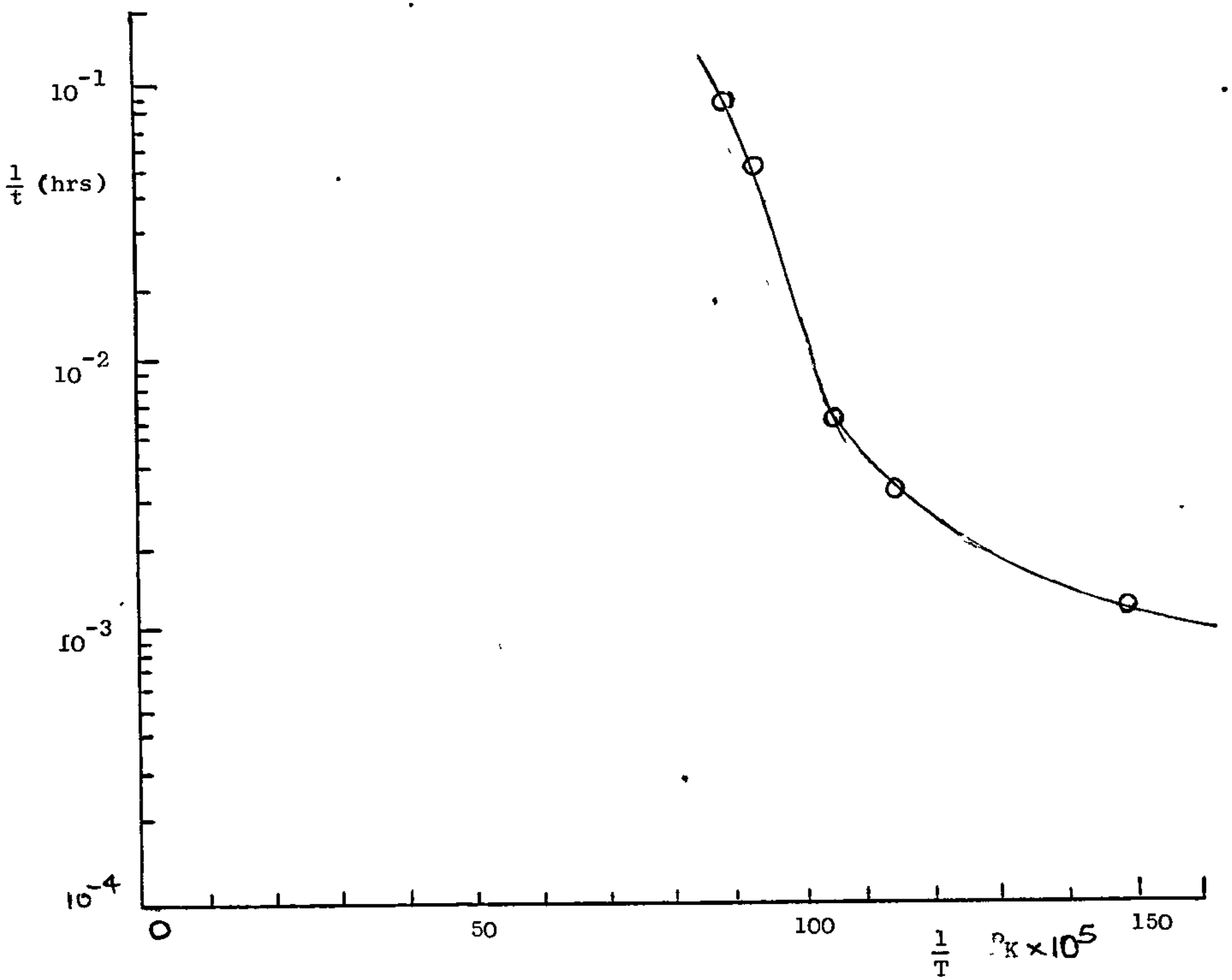


Fig. 7.8. Arhenius type plot for time to failure vs temperature

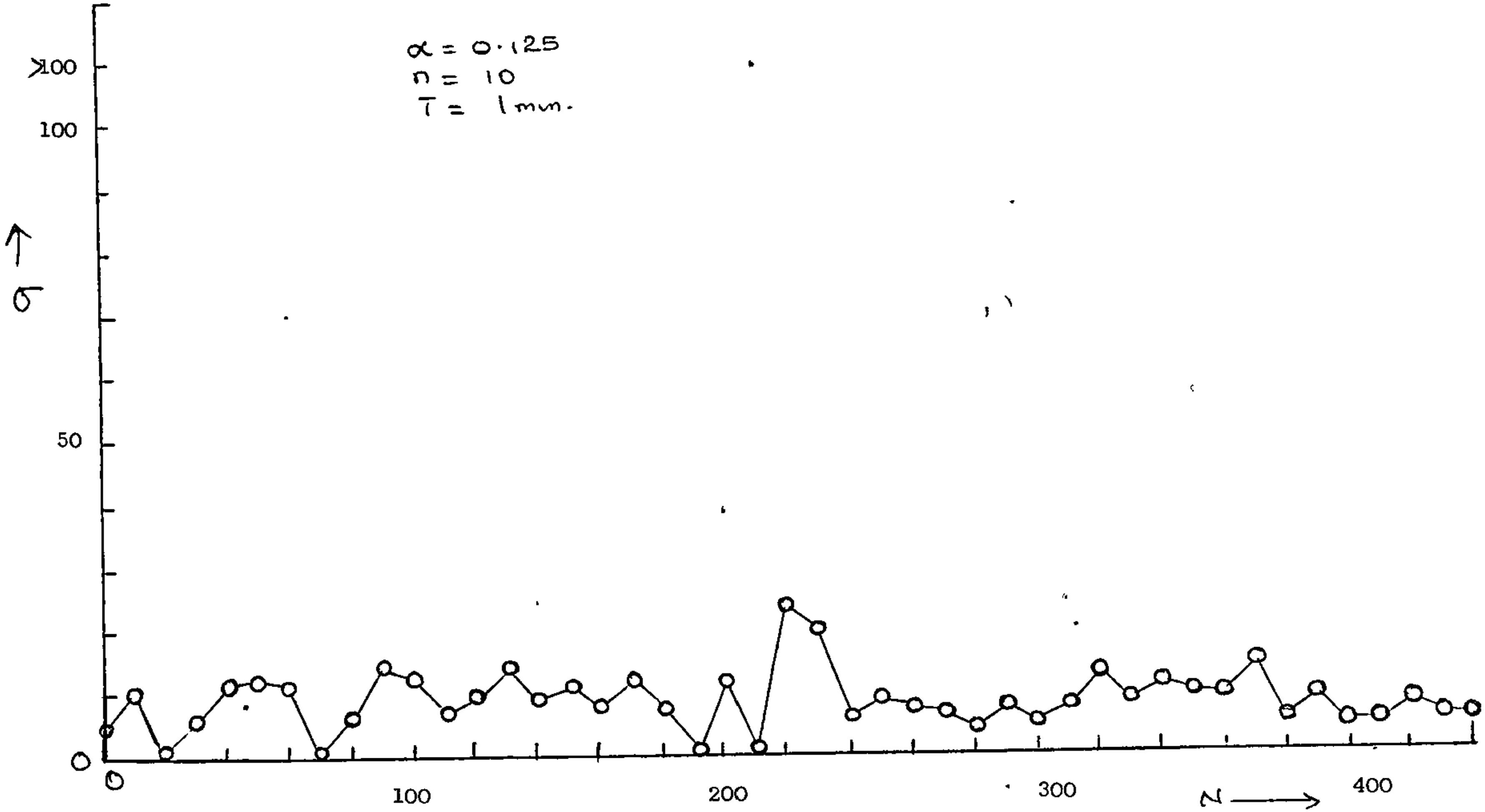


Fig. 7 9 Effects of varying α $\alpha = 0{\cdot}125$

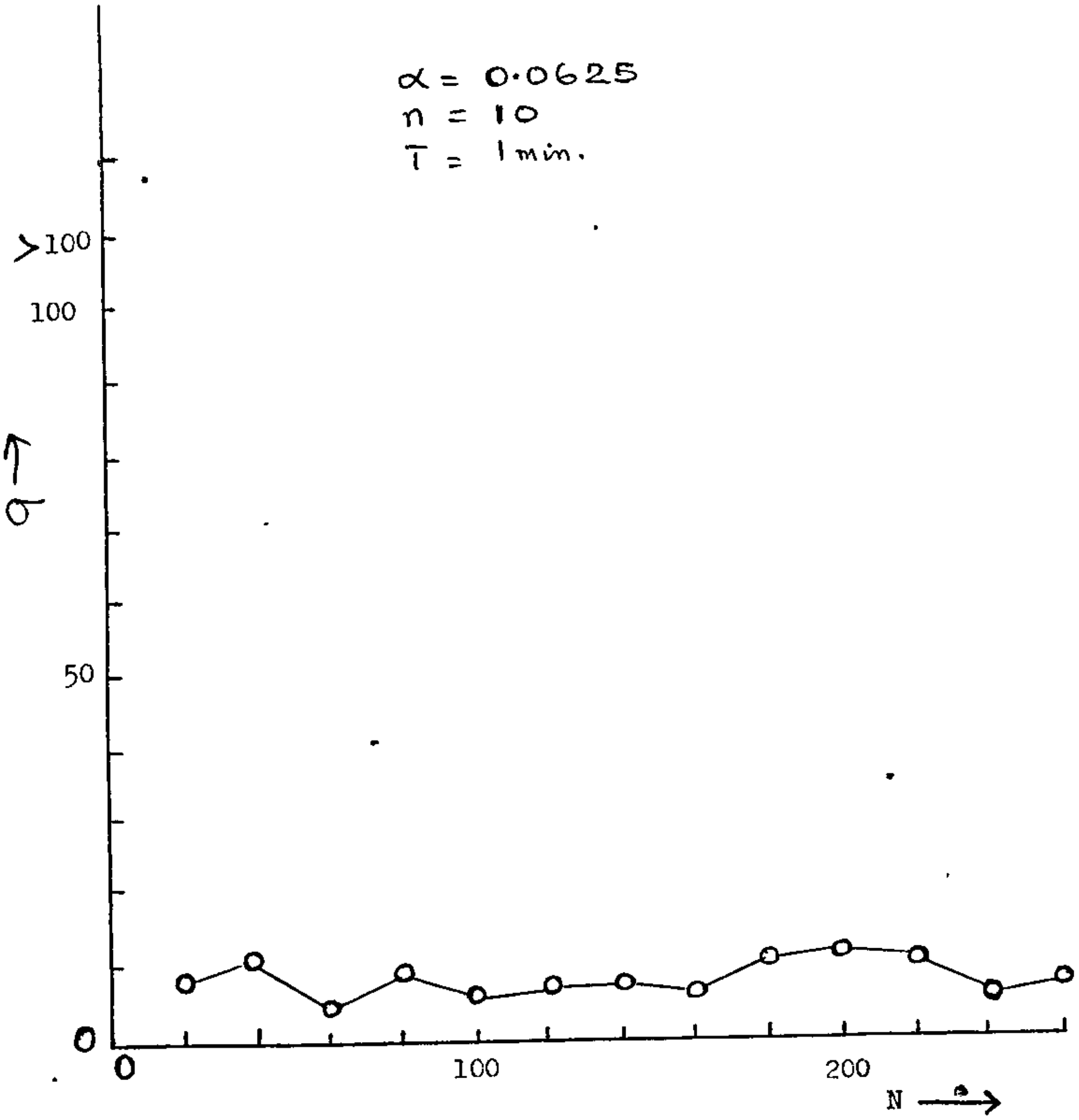


Fig 7.10 Effect of varying α $\alpha = 0.0625$

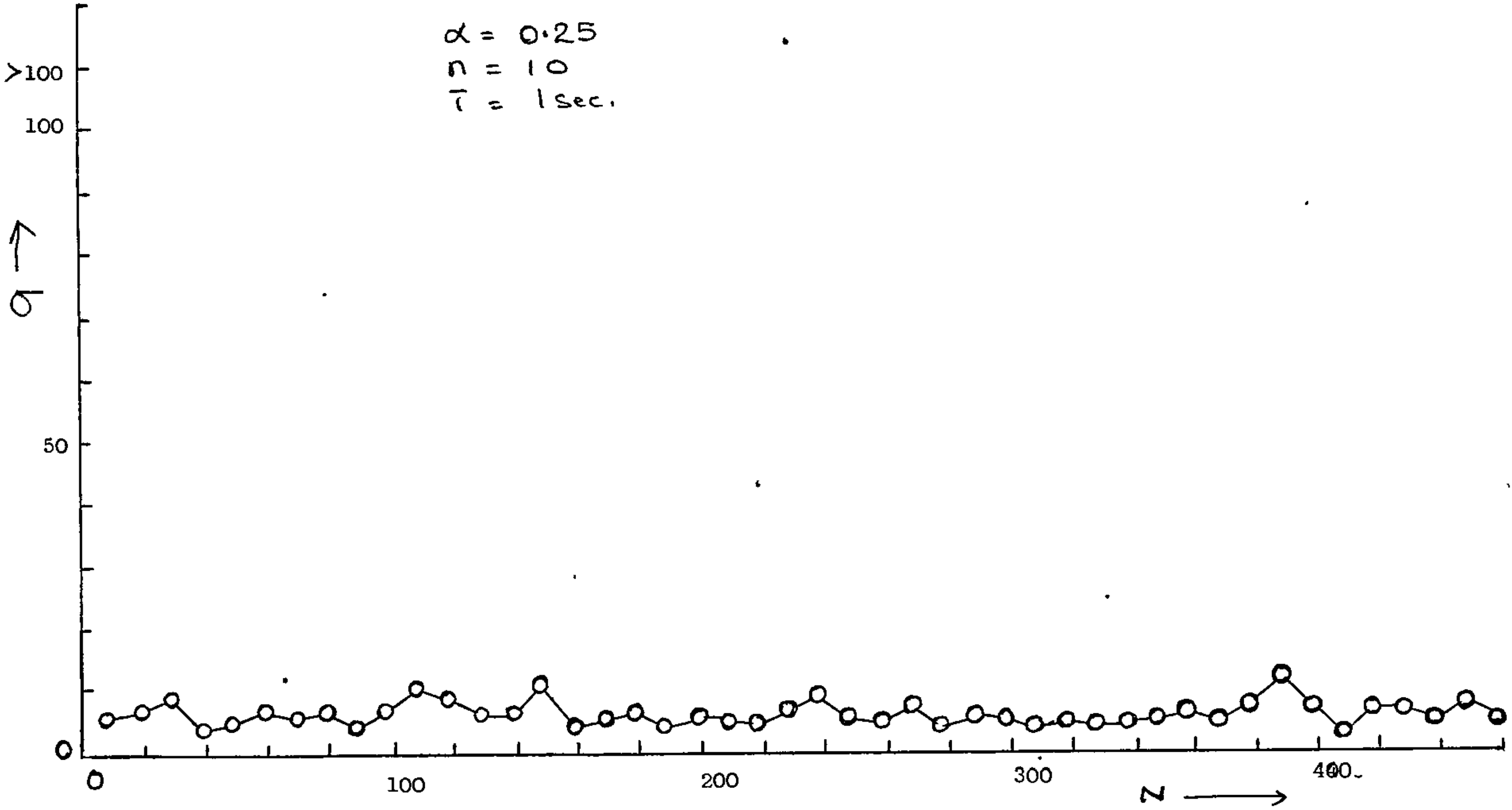


Fig. 7.11 Effect of sampling time T = 1 sec.

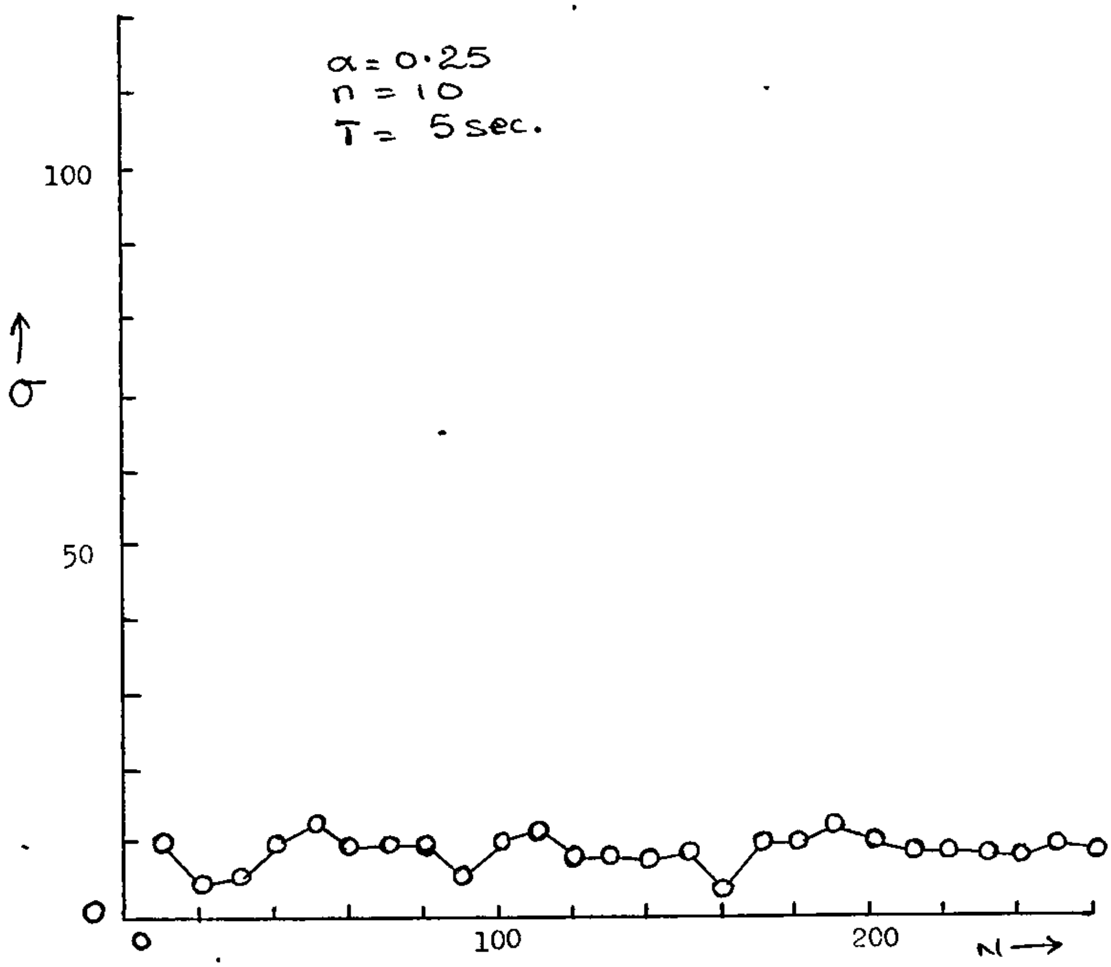


Fig 7.12 Effect of sampling time T = 5 secs

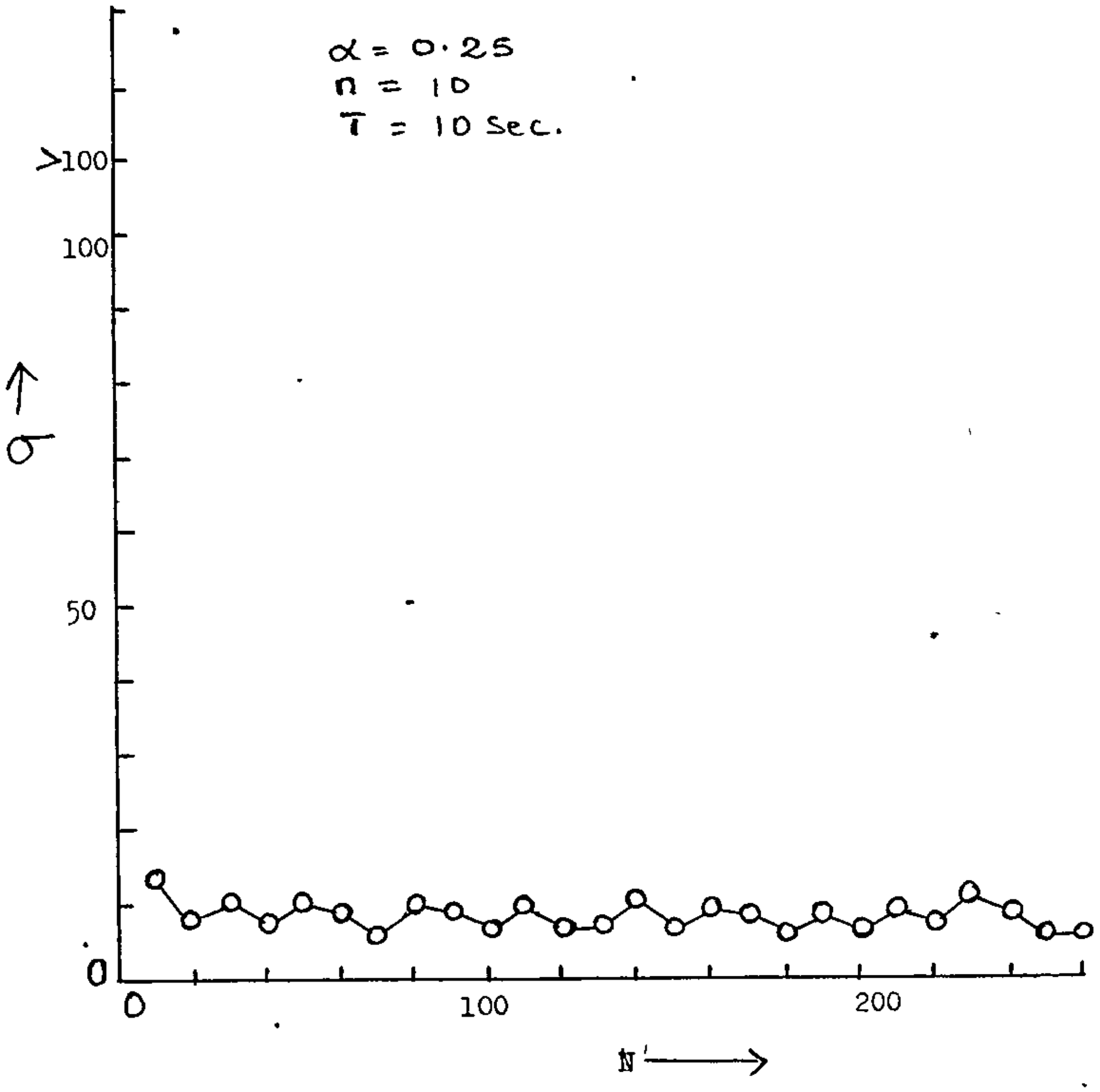


Fig 7.13 Effect of sampling time T = 10 secs

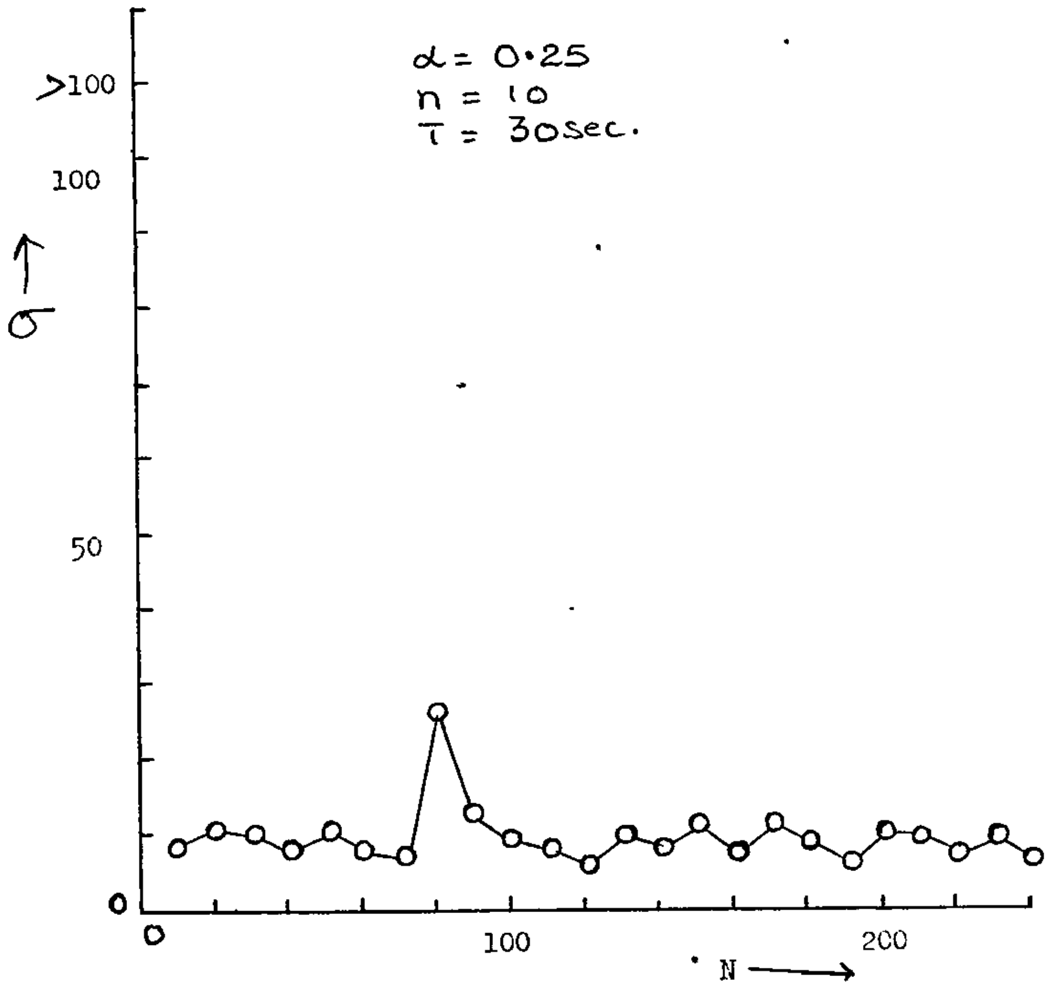


Fig 7.14 Effect of sampling time T = 30 secs

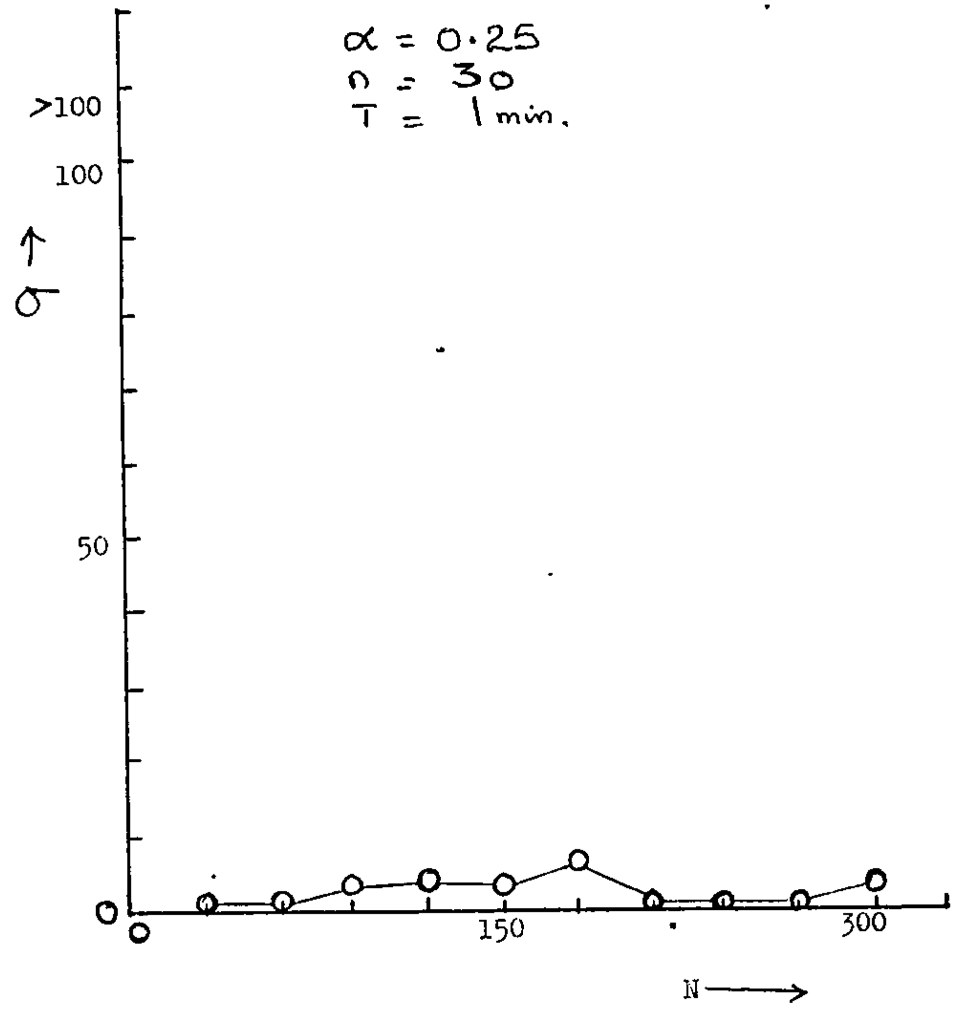


Fig 7.15 Effect of sample size . n = 30

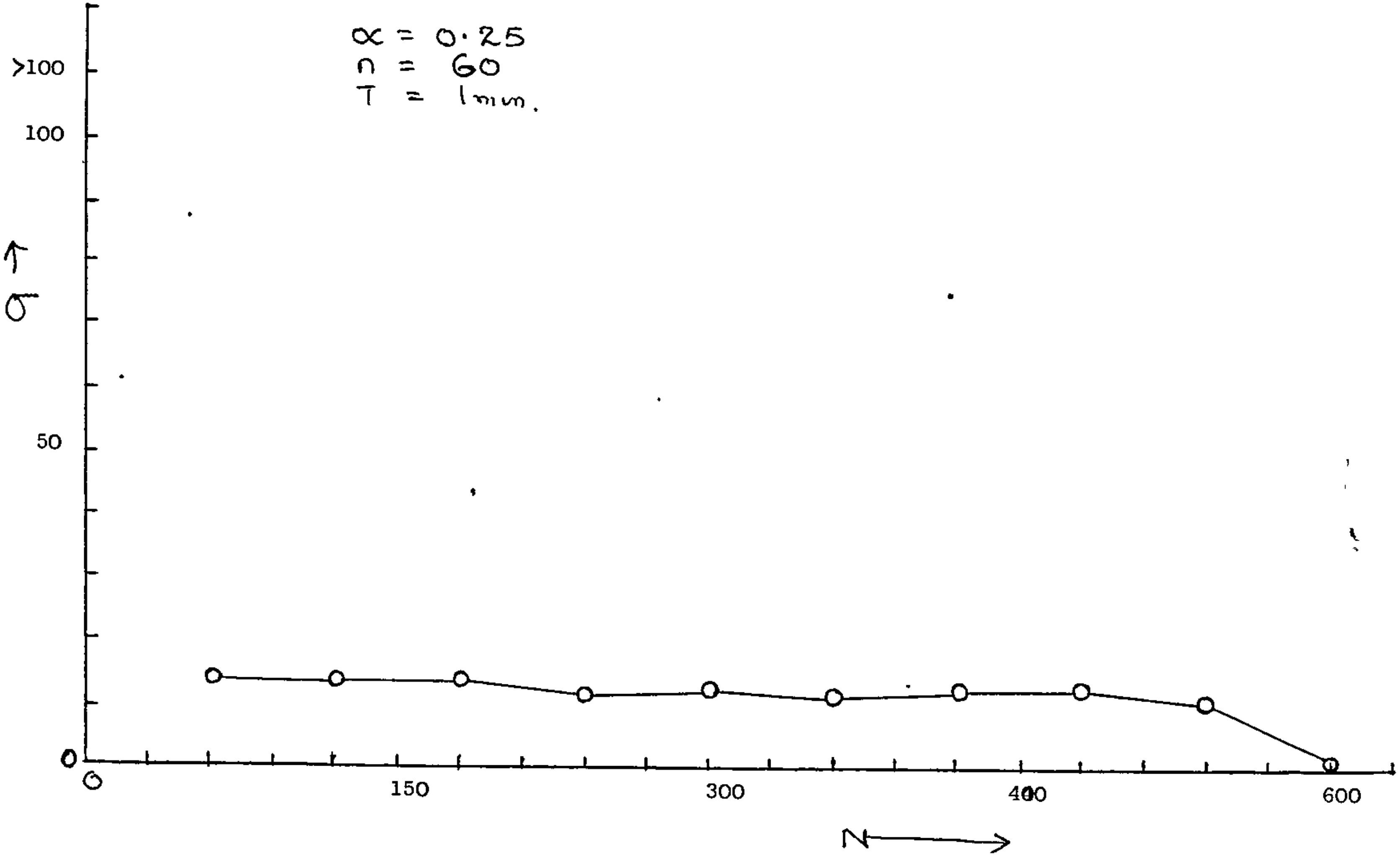


Fig. 7 16 Effect of Sample Size $n = 60$

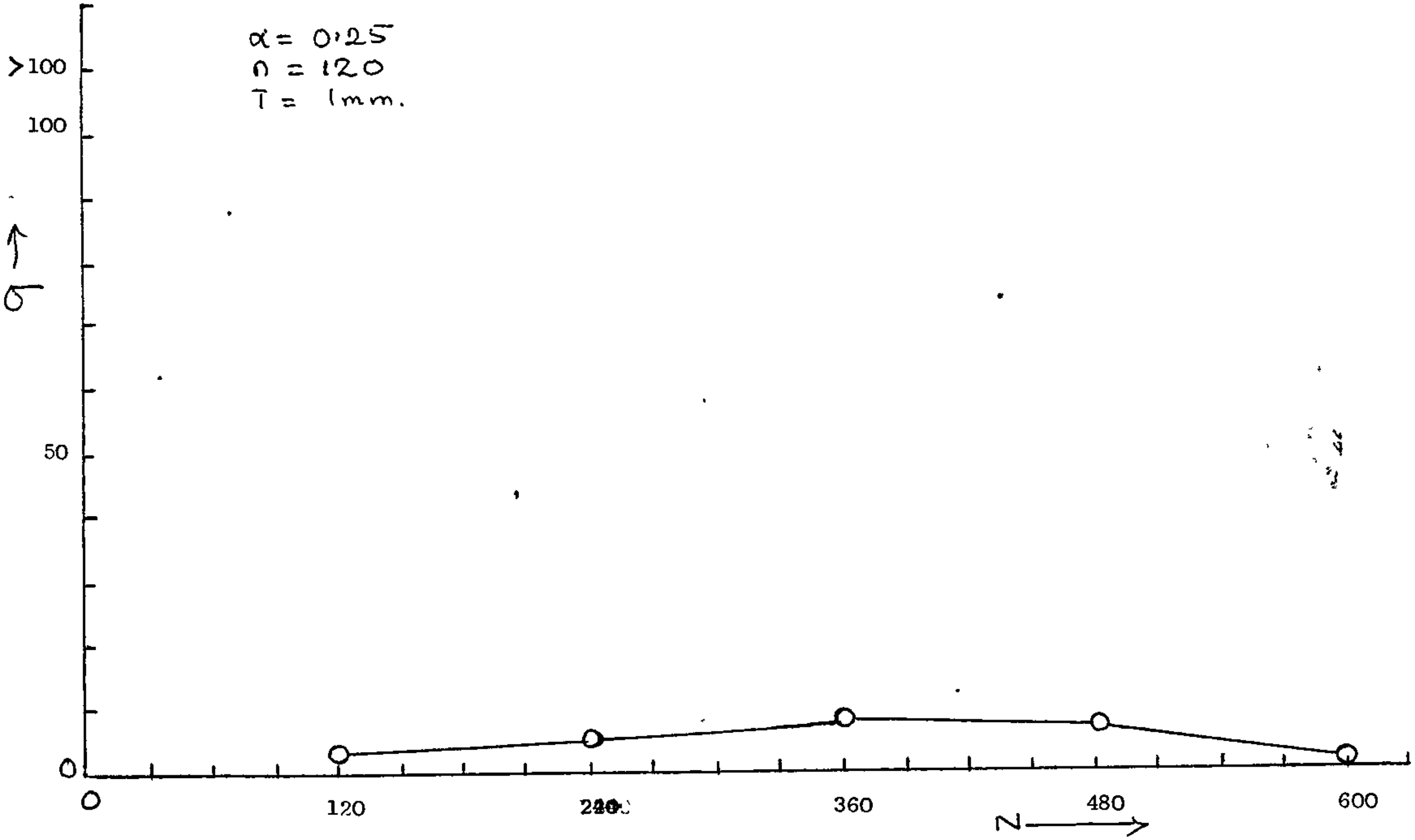


Fig. 7.17 Effect of Sample Size n = 120

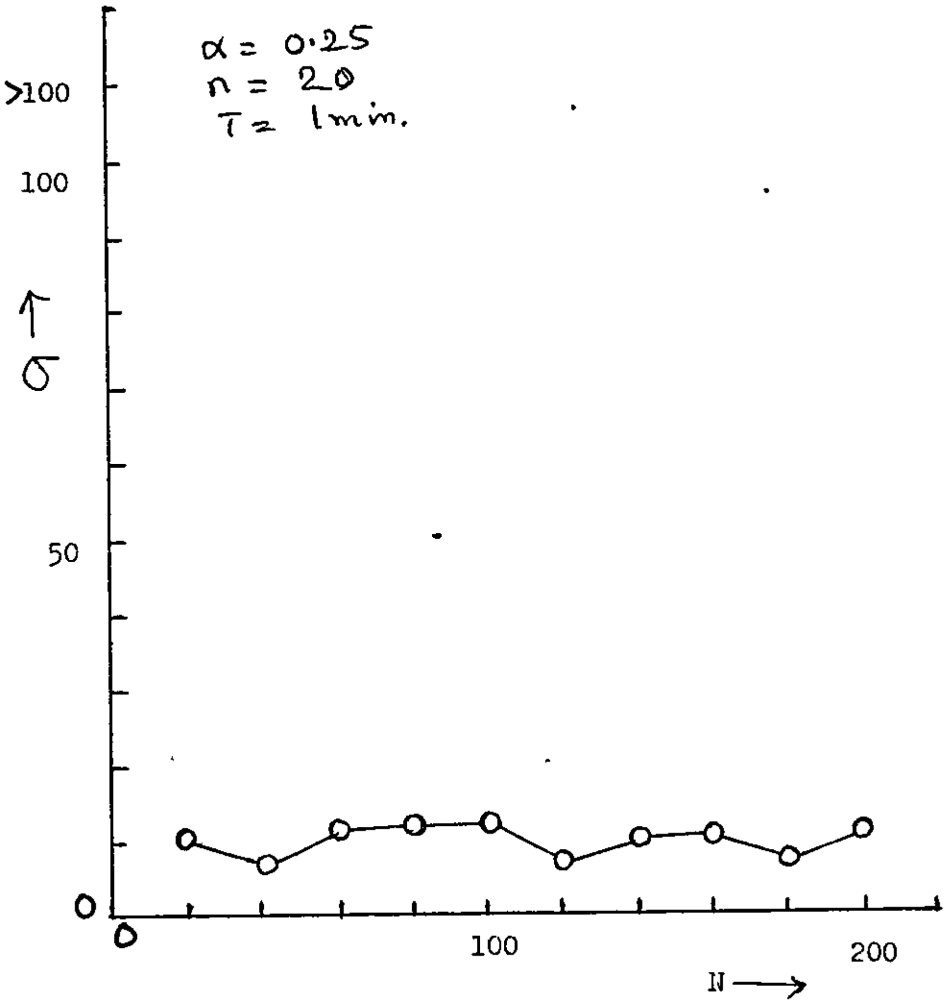


Fig 7.18 Effect of sample size . n =20

$\alpha = 0{\cdot}25$
$n = 20$
$T = 0{\cdot}2$ Sec.

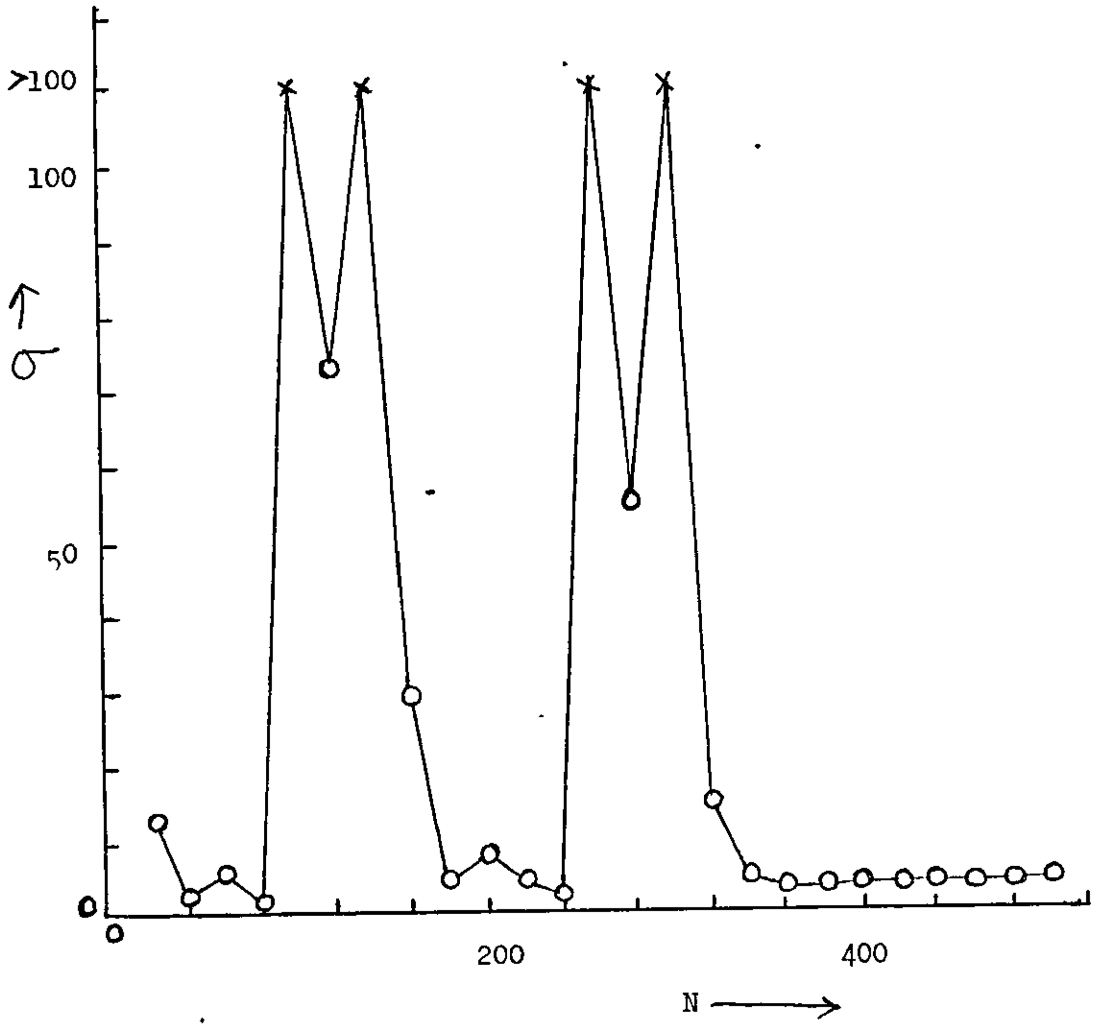


Fig 7.19 Simulation of loose connection

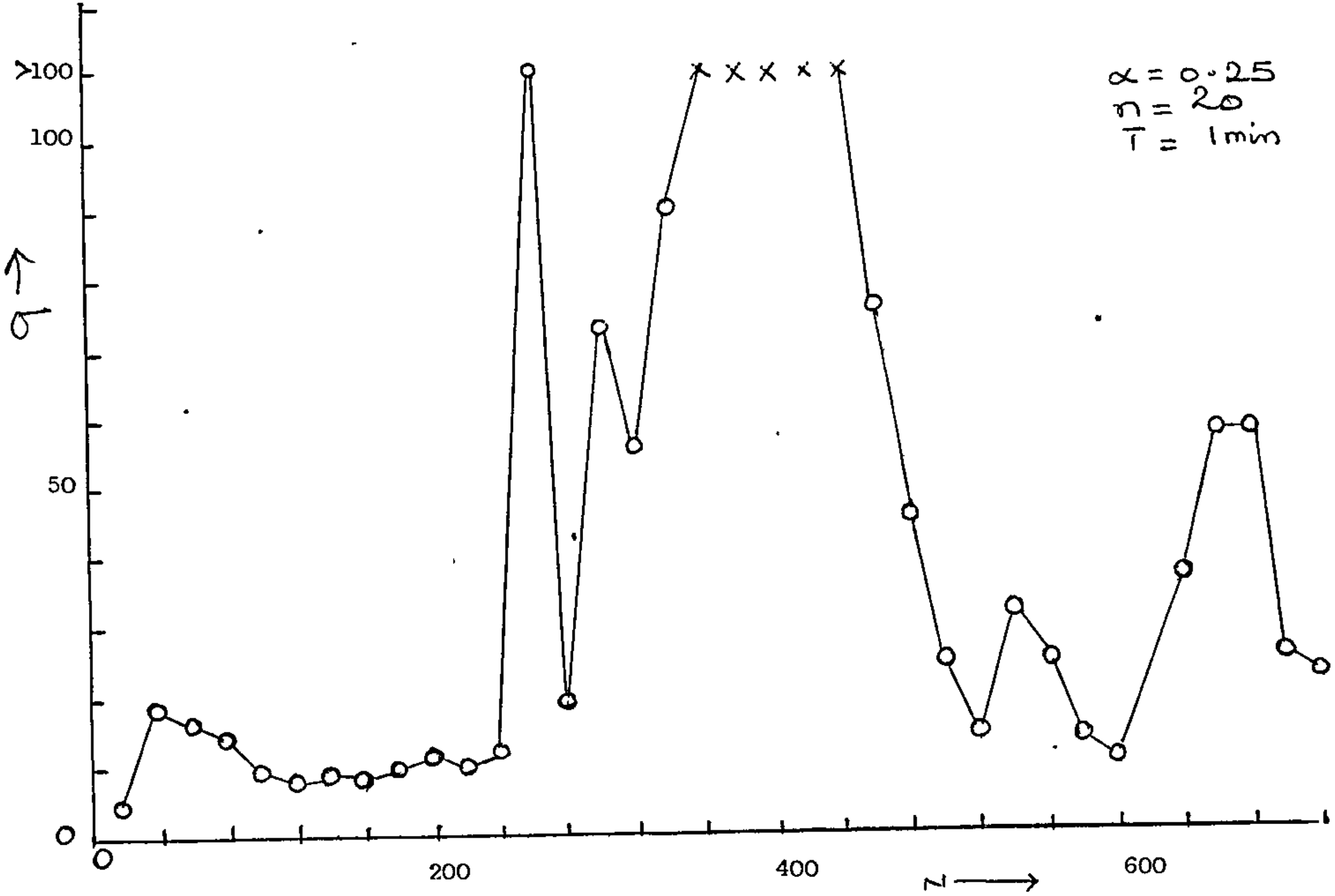


Fig. 7.20 Simulation of chemical attack by concentrated Nitric acid

8. CASE STUDIES OF INSTRUMENT MALFUNCTION AND MALFUNCTION DETECTION (2) - DIFFERENTIAL PRESSURE TRANSMITTERS AND CONTROL VALVES

8. Case Studies of Instrument Malfunction and Malfunction Detection (2) - Differential Pressure Transmitters and Control Valves

8.1. DIFFERENTIAL PRESSURE TRANSMITTERS

Differential pressure (D/P) transmitters are very simple but widely used measuring instruments in industry. The purpose of the instrument is to receive a differential pressure from some primary element such as an orifice or from a liquid level installation.

Some hints on symptoms and causes of failure of the Taylor instruments (214) D/P transmitters is given below;

Hints on Failure of Taylor Instruments D/P transmitters

Symptom	Cause
Output pressure low	(i) leak in output line (ii) plugged orifice
Output pressure high	plugged nozzle
Transmitter fails to respond to change in differential	leak in impulse lines
Output oscillates	Sensing diaphragm

There is, otherwise, not much in the open literature on their failures.

From the preliminary survey of instrument failures in industry and from the survey reported in chapter 3, the majority of D/P transmitter malfunctions were associated with the impulse lines connecting it to the primary element. Blockage of the impulse lines was a predominant cause of malfunction.

The D/P transmitter was primarily chosen for study because it was expected to offer suitable signals for analysis. The signals would be different from those offered by the thermocouple and might be amenable to more sophisticated time series analysis. Impulse line blockage was chosen because it is important and easy to simulate in the laboratory.

8.1.1. D/P Transmitter Failure rate data

Green and Bourne (101) published a failure rate for pneumatic differential pressure transmitters of 0.76 actual calculated fault per year. A summary of the failure rate data, already presented, in details in chapter 3, is given below.

Table 8.1. Summary of D/P transmitter failure rate data

Works	Type of Measurement	Number at risk	Instrument years	Environment factor	No. of faults	Failure rate faults/year
	Pressure	69	-	-	-	-
A	Flow (fluids) (P and e)	473	-	3	419	1.86
	Level (liquids) (P and e)	130	-	4	106	1.71
B	Flow (fluids) (e)	35	-	4	37	2.66
C	Flow (fluids) (e)	13	-	-	-	-
	(p)	115	-	-	-	-
All	Flow (fluids)	636	324	3	359	1.73
	Level (liquids)	130	62	4	106	1.71

e = electronic
p = pneumatic

Table 8.2. Effect of environment on Reliability of D/P transmitters in contact with Clean and Dirty fluids in works A

	No. at Risk	No. of faults	Failure rate, faults/year
Clean fluids	27	5	0.39
Dirty fluids	90	82	1.91

The background and full explanation of the figures have already been given in chapter 3. A direct comparison of the failure rates obtained by the author and that published by Green and Bourne (101) cannot be made, as not enough information on how the latter obtained their figure is given. Also their figure is for pneumatic D/P transmitters. From the figures in table 8.1, the failure rate for the electronic transmitters are much higher than those for combined electronic and pneumatic instruments. This could be explained by the fact that the electronic D/P transmitters were on severe enviornment plant.

The effect of environment does show a marked difference in the failure rates of D/P transmitters in contact with clean or dirty fluids, see table 8.2.

Of the 364 impulse line failures recorded at works A, 194 were blockages and 99 were leakages.

More information on the nature of the failures of the instruments at works A was obtained, a cross-section of the operators comments on the log tickets for the impulse line and transmitter failures, are given in tables 3.12 and 3.13 of chapter 3.

Most of the D/P transmitter failures and failures associated with it such as impulse line failures were 'hard-over' type failures. Most of these failures could have been picked up earlier with a suitable malfunction detection technique, and in cases involving loss of variable measurement, alternative approximate substitute readings could have been easily calculated, particularly in the cases of flow and level measurement.

8.1.2. Experimental laboratory work on impulse line blockage

The primary objective of the laboratory experimental work on impulse line blockage was to obtain signals that would be amenable to time series analysis. The noisy signals from a differential pressure transmitter responding normally as a flow measurement instrument, under conditions of turbulence in the orifice flowmeter, was considered suitable. The signal with the impulse lines blocked or frozen was expected to be less noisy or damped down. Freezing of the impulse lines could be easily simulated in the laboratory and this set-up would be adequate for, the limited objective of, showing the feasibility of time series analysis for instrument malfunction detection. The fact that freezing of impulse lines in industry during the winter is one of the main causes of blockage type malfunction of the differential pressure transmitter, made the choice a better one.

It was hoped that subsequently an algorithm based on frequency analysis (time series) methods could be developed and tested on-line. All the impulse line blockage experiments were done on-line using the Departmental computer. The early loss of the computer towards the end of this project and the shortage of time limited the experimental work that could be done. However, there was time to obtain data, to show the feasibility of frequency analysis, for instrument malfunction detection, and to investigate some relevant considerations in the application of the technique.

Data for analysis were obtained for the unfrozen impulse lines, frozen impulse lines and freezing impulse lines. Experiments to investigate the effect of sampling frequency were also carried out. The fastest logging time was limited to 5 samples per second by the output paper punch used with the computer.

8.1.2.1. Description of apparatus

A line diagram of the impulse line freezing apparatus is given in fig. 8.1.

The orifice meter was designed according to British Standard 1042; Part 1 : 1964 specification for use with a Taylor Instruments fixed range D/P transmitter. The input range of the transmitter is 0-30 inches, water gauge for a 3-15 p.s.i. output.

The pneumatic output from the transmitter was converted into an electric signal by a fast pressure to current transducer. Because of the low signal output from the pressure to current transducer, it had to be amplified before going into the analogue to digital converter and hence to the computer for output on punched paper tape.

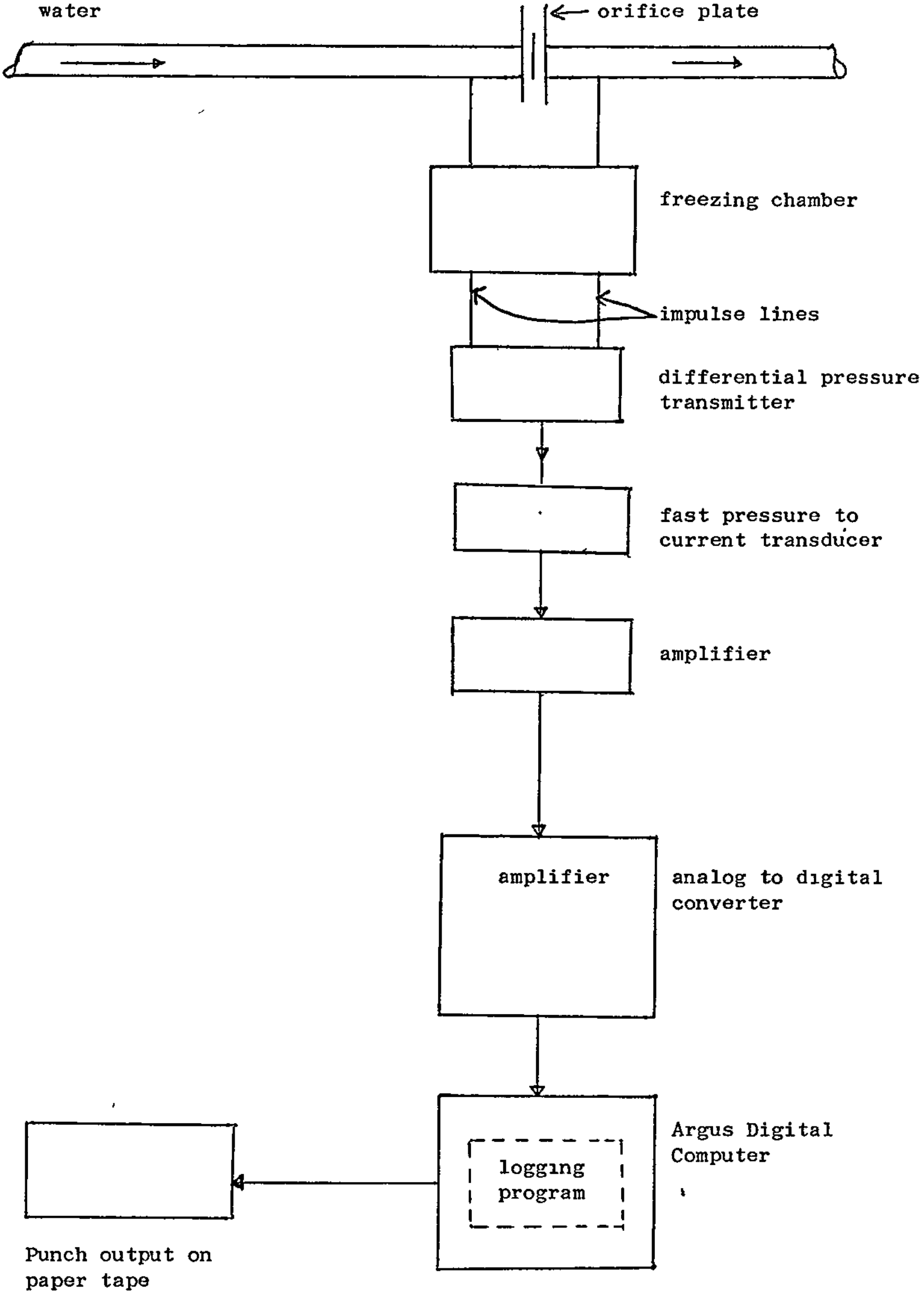


Fig. 8.1 Impulse Line freezing Rig

The freezing of the impulse lines was done more gradually initially by circulating a low temperature ethylene glycol/water mixture through shells round the impulse lines. With the rise in ambient temperature, this became inadequate and the freezing arrangement was modified to a solid carbon dioxide chamber. The freezing was more drastic than with the circulation of ethylene glycol/water mixture. The rate of freezing could be controlled by the amount of solid carbon dioxide in the chamber.

Water was circulated through the orifice plate, and the liquid in the impulse lines was water also. The flow of water could be varied to create laminar or turbulent conditions around the orifice plate. In this way the noisiness of the signal output of the D/P transmitter for normal operation, could be varied and set.

8.1.2.2. Experimental work carried out

The experimental work carried out consisted essentially of automatically logging signals from the differential pressure transmitter using an Argus 100 digital computer.

When the logging technique was adequately developed, the flow rate of water through the orifice plate was adjusted to the turbulent regime so as to give a sufficiently noisy signal output from the transmitter.

With this setting, a series of loggings were done. The normal noisy instrument signals, the instrument signal variation during freezing and the instrument signal with the impulse lines frozen. All these were logged at the fastest logging interval that could be achieved - which was

0.2 second interval. These signals were the important and relevant ones for an instrument malfunction algorithm.

To investigate possible aliasing effects and the effect of the sampling interval on the frequency analysis of the signals, a series of freezing runs were logged at various sampling intervals of 0.2 second, 1 second, 5 second and 1 minute. The use of the computer for on-line experiments was lost shortly after this series of experiments. At this stage sufficient data for analysis had been obtained.

8.1.2.3. Experimental results and analysis

Instrument signals of a differential pressure transmitter were obtained for analysis by the fast Fourier transform methods. The signals analysed were the signals for normal instrument operation and when the impulse lines were frozen. The standard deviations of these two signals were also calculated for comparison with the above analysis.

The data analysed were logged at the maximum achievable frequency which was 0.2 second interval logging time. The highest detectable or available frequency in the analysis therefore was 2.5 cycles per second.

The signals were analysed principally to investigate the general patterns of the power spectrum plots and signal power distribution over the detectable frequency range. It was envisaged that from these, the practical use of the FFT analysis for instrument malfunction detection could be assessed.

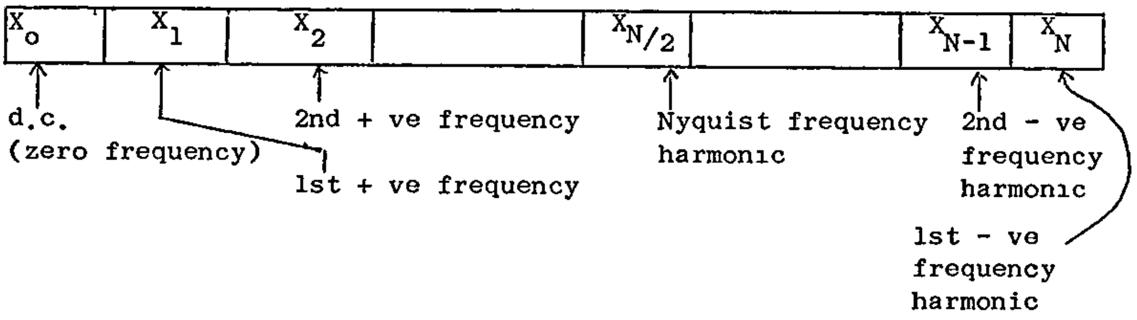
Signals were obtained from different experimental runs and analysed for reproducibility of the patterns of power spectra distribution. Some of the practical considerations for the application of the technique were made.

The Fortran IV coded FFT program used for the analysis of the signals is given in the appendix (I). The algorithm is based on the decimation in frequency method (155). It computes the discrete Fourier transform given by

$$X_n = \sum_{K=0}^{N-1} x_k W^{nk} \quad , n = 0, 1, \ldots\ldots , N - 1$$

where $W = e^{-j2\pi/N}$

The X_n computed using the FFT program are the Fourier coefficients of the corresponding exponential series of the N samples of the signal.



A sampled power spectrum estimate is given by the modulus squared of the frequency samples. Thus, ($|X_o|^2$, $|X_1|^2$, ... $|X_{N-1}|^2$) are the power spectrum estimates for the zero frequency, 1st positive frequency harmonic, 2nd positive frequency harmonic etc.

In this work the power spectra have been calculated for fractions ($\frac{1}{8}$ parts) of the highest detectable frequency. This is effectively normalising the frequency axis for the purpose of comparison of the parts. The calculations of power spectra were normalised also to avoid the dependence of the power spectra values on the sample size.

The only limitation of the program used is that N, the sample size must be an integer of 2. This is purely for program simplicity.

Real time plots of the D/P transmitter signal for normal instrument behaviour and for instrument signal with the impulse lines frozen are shown in the appendix Figs A1 and A2. These are typical signals for the two states and the type of signals analysed.

The calculated power spectra estimates for the line spectra plots of Figs 8.1 to 8.4 are given in the appendix tables A1 to A3.

Figures 8.1 and 8.2 show the type of reproducibility obtained for the plots of the line spectra of different portions but the same value of N, the sample size, for a typical instrument signal. They also represent the general pattern of the line spectra plots for the two states of instrument signal.

The signal power distribution for the same analyses are given in tables 8.3(a) and 8.3(b), for both the normal instrument signal and for the instrument signal when the impulse lines were frozen. Not all the data of tables 8.3(a) and 8.3(b) were plotted. The general pattern was the same and so only three plots each are shown. The data for all the tables, however, are given in the appendix A1 to A3.

Data from different experimental runs were analysed for normal instrument behaviour and for the instrument signal with the impulse lines frozen. The line spectra plots are given in Figs. 8.3

and 8.4. The corresponding signal power distribution calculations are given in tables 8.4(a) and 8.4(b).

A typical signal for each of the two instrument states considered here, were subjected to analysis for different values of N, the sample size. The average values of the line spectra for each value of N were calculated. They have not been plotted as the general pattern is the same. The calculated values, however, are given in the appendix. The signal power distribution are given in tables 8.5(a) and 8.5(b).

The ratios of the total signal power, for frequencies below half the highest detectable frequency to the total signal power for frequencies above, were also calculated and are given in tables 8.3. to 8.5. The total power was calculated as the area under the line spectra plots.

The data shown in Figs. A1) and A2 were analysed using the standard deviation algorithm of chapter 7. The value of the smoothing constant used was 0.25 and the sample size was chosen as 32 to correspond to the predominant value of N used in the above analyses. The values of the standard deviation calculated are given in the appendix, table A4. The plots of these values are shown in Fig. 8.5.

8.1.2.4. Discussion of results

There is a striking difference in the shapes of the line spectra of the instrument signals for the two states of normal behaviour and instrument signal with the impulse lines frozen.

In the results obtained, the general pattern for the normal instrument signal is one of concentration of power in the low frequency region - at frequencies below half the highest detectable available frequency. There are characteristic high values of the line spectra at these low frequencies and a drop in values at higher frequencies. This pattern was reasonably reproducible for all the samples analysed.

With the results for the instrument signal with the impulse lines frozen, this pattern is not there. There are characteristic low values over the entire frequency range for all the frozen impulse lines, instrument signals.

Fluctuations in the absolute values of the line spectra at specific frequencies were observed, but even then, the magnitude and overall pattern was consistent.

A striking difference in patterns as obtained could be an effective means of detecting off-normal behaviour of the instrument malfunction by visual display of these plots.

There is more consistency in the magnitudes of the total power. The total power for the normal instrument signals were generally about an order of magnitude higher than the total power for instrument with the frozen impulse lines. Tables 8.3(a) and 8.3(b) bring out the point very well.

The ratios of the total power on either side of half the highest detectable frequency show reasonable consistency in magnitude and absolute values. The values for the normal instrument signal were generally over 10 while those for the instrument signal with frozen impulse lines were generally below or around 1. When the values for the ratios have varied outside the general values, the values of the total power of the instrument signal have been consistent with general patterns.

With the type of consistency obtained, for the total instrument signal power and ratios of instrument power on either side of a critical frequency, the setting of threshold values for these could be an effective computer based check for detecting off-normal conditions in the instrument signal behaviour. The routine task of calculating these values is well suited to the computer.

The pattern for different experimental runs, Figs. 8.3 and 8.4, are consistent with the general shape of the line spectra plots for the two instrument states. Even though the absolute values of the total power showed some variation, the ranges were consistent and the ratios also consistent with the general pattern observed for any one signal of either state of the instrument.

When the same signal was subjected to analysis with different values of N, the sample size, the results were consistent with the general patterns observed. They showed a good measure of reproducibility of pattern. This would be expected as the length of record determines the extent to which peaks in the line spectra may be distinguished. It is the sampling interval that determines the maximum frequency which can be distinguished. When the general shape of the line spectra is of main interest, any value of N should give the general shape but the value of N will determine the number of line spectra, over the range of highest detectable frequency. Thus if N = 32 for a maximum detectable frequency of 5 cycles per second gives 16 line spectra, for that frequency range at intervals of $\frac{1}{16}$ parts of the highest frequency, N = 16 will give 8 at intervals of $\frac{1}{8}$ parts of the highest frequency while N = 64 will give 32 at intervals of $\frac{1}{32}$ parts of the highest frequency. Each analysis should give the same general shape of the line spectra plot. Therefore, it would be adequate, normally, to select N such that at least the frequencies or fractions of the maximum detectable frequency of interest in the line spectra are contained in the results of the analysis.

Aliasing is the key problem that occurs with sampled data. Frequencies which are really above the samplang frequency are observed at a frequency below. The spectral effect is to fold back the spectrum about the Nyquist frequency. In practice aliasing always occurs to some extent because band limited signals are an ideal not real. Therefore a first requirement for digital analysis is to sample at a high enough rate so that all frequencies of interest are identified properly. The part of the spectrum which is folded back must be sufficiently low in magnitude, that it does not interfere with any part of the spectrum for which information is desired. The effects of aliasing are very relevant to high resolution frequency analysis requirements and interpretation. The frequency analysis requirements for malfunction detection - patterns of line spectra and total power distribution - are relatively coarse. The effect of aliasing therefore, is negligible or not so important for this type of analysis.

The standard deviation plots for the normal instrument behaviour and the instrument signal with the impulse lines frozen, Fig. 8.5 are rather similar in shape. The magnitude of the absolute values are different, however. For visual display the plots will not be as effective as the line spectra plots. The setting of threshold values for the standard deviation of the signal could be an effective check for off-normal instrument behaviour but the difference in magnitudes is not as marked as, say, the difference in magnitudes of the total power or power distribution ratios.

For the type of signals analysed here, even though the standard deviation algorithm could be effective for off-normal signal detection, the method of FFT analysis would be more superior.

TABLES

Tables 8.3 to 8.5 represent total signal power distribution for normal instrument signal and for instrument signal with impulse lines frozen.

A1 represents the total signal power in the range of frequencies above ½ the highest detectable frequency

A2 represents the total signal power in the range of frequencies below ½ the highest detectable frequency

A TOTAL represents the total signal power over the entire range of detectable frequencies.

The units of power are volts^2/hertz.

The total signal power over a range of frequency has been calculated as the area under the line spectra curve for the given frequency range.

For Table 8.3., the numbers 1, 2, ... 6 are different portions of the same signal.

Table 8.3: Same value of N but different portions of the same signal

Table 8.3 (a): Normal instrument signal

Power X 10^{+9}

	A TOTAL	A1	A2	A2/A1
1	7812	135	7676	58
2	5349	314	5035	16
3	6718	405	6313	15.6
4	6503	387	6116	15.8
5	4734	136	4598	33.8
6	5330	348	4982	14.3

Table 8.3 (b): Instrument signal with impulse lines frozen

Power X10^{+9}

	A TOTAL	A1	A2	A2/A1
1	347	197	150	0.76
2	330	177	153	0.86
3	257	101	155	1.53
4	275	166	119	0.72
5	265	115	150	1.30
6	292	204	88	0.45

Table 8.4 <u>Different experimental runs</u>

Table 8.4 (a) <u>Normal Instrument signal</u>

Power x10 $^{+9}$

Experimental Run	A TOTAL	A1	A2	A2/A1
1	1372	83	1289	15.5
2	9029	365	8664	23.8
3	734	79	655	8.4

Table 8.4 (b) <u>Instrument signal with frozen impulse lines</u>

Power X10^{+9}

Experimental Run	A TOTAL	A1	A2	A2/A1
1	242	123	119	0.97
2	209	129	80	0.62
3	167	34	133	3.92

Table 8.5 Different values of N for the same instrument signal

Table 8.5 (a): Normal instrument Signal

Power X10^{+9}

N	ATOTAL	A1	A2	A2/A1
32	6503	387	6116	15.8
64	5504	366	5138	14.0
128	6218	193	6015	31.0

Table 8.5 (b): Instrument Signal with impulse lines frozen

Power X10^{+9}

N	ATOTAL	A1	A2	A2/A1
32	196	106	90	0.85
64	227	101	126	1.23
128	244	135	109	0.82

Figs. 8.1. to 8.4. are line spectra plots of normal instrument signals and instrument signals with the impulse lines frozen.

The units of power P_w are volts^2/hertz.

Fig 8.1 (a) Normal instrument signal; N = 32, different portions of the same signal logging.

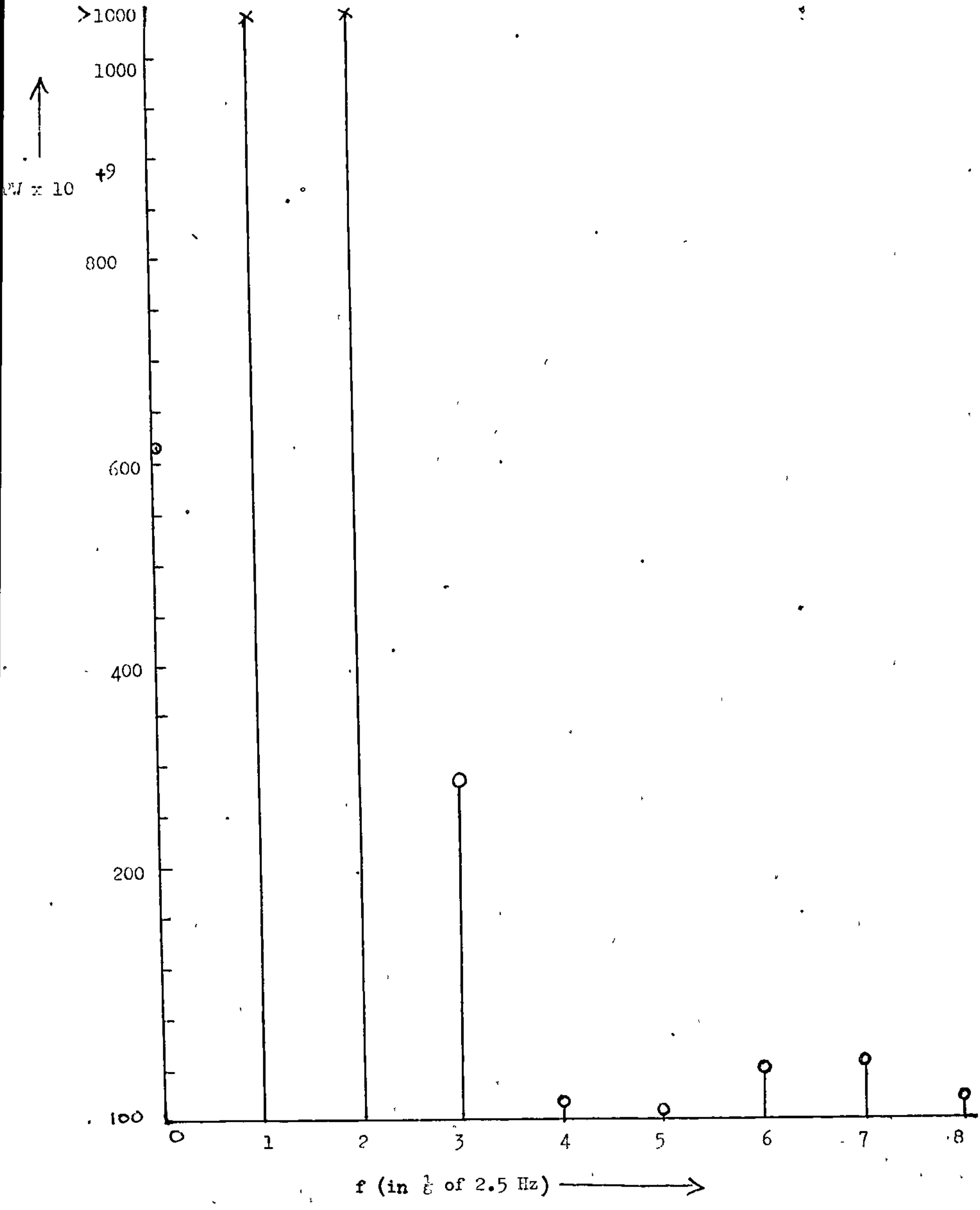


Fig 8.1 (b) Normal instrument signal; N = 32, different portions of the same signal logging.

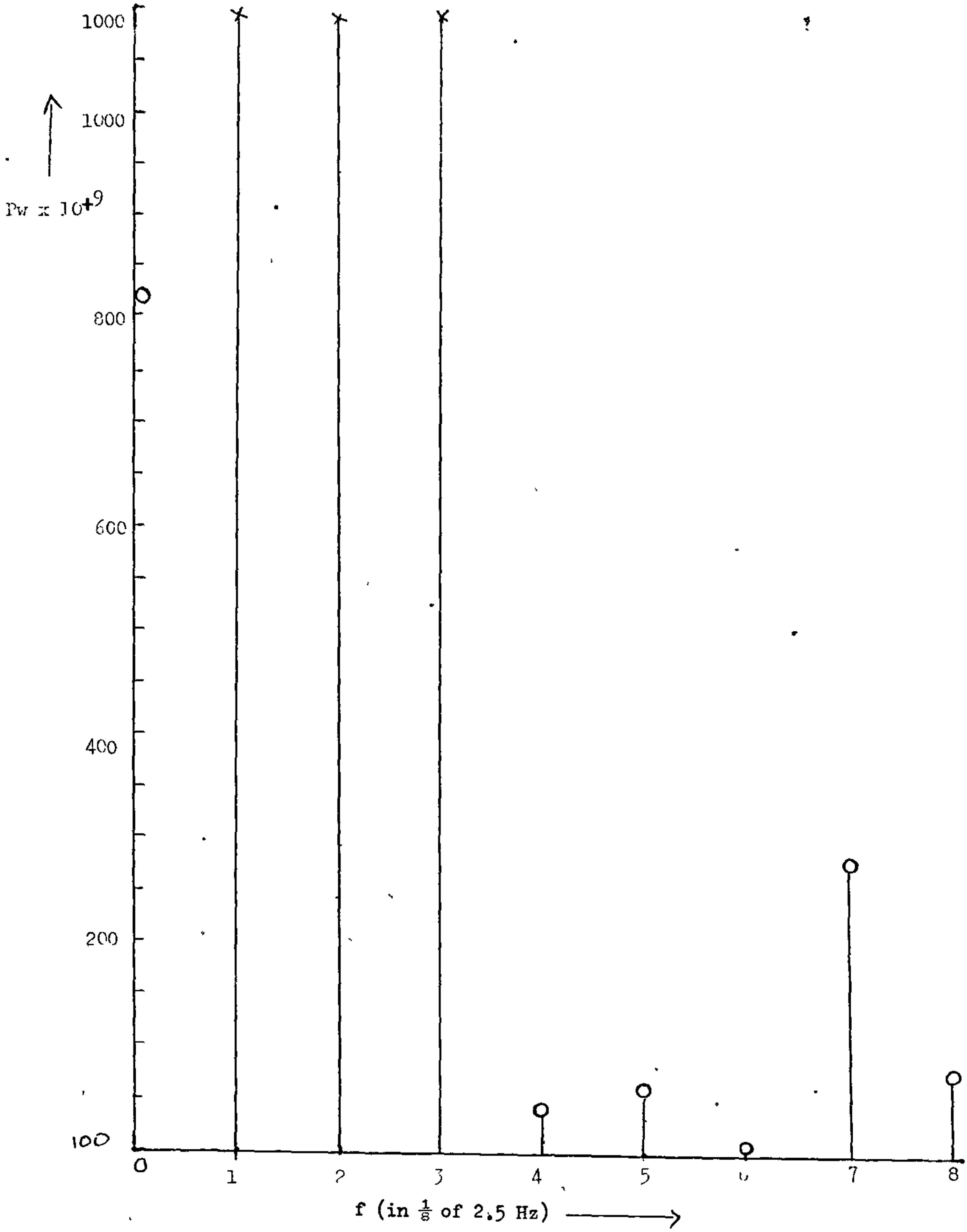


Fig 8.1 (c) Normal instrument signal; N = 32, different portions of the same signal logging.

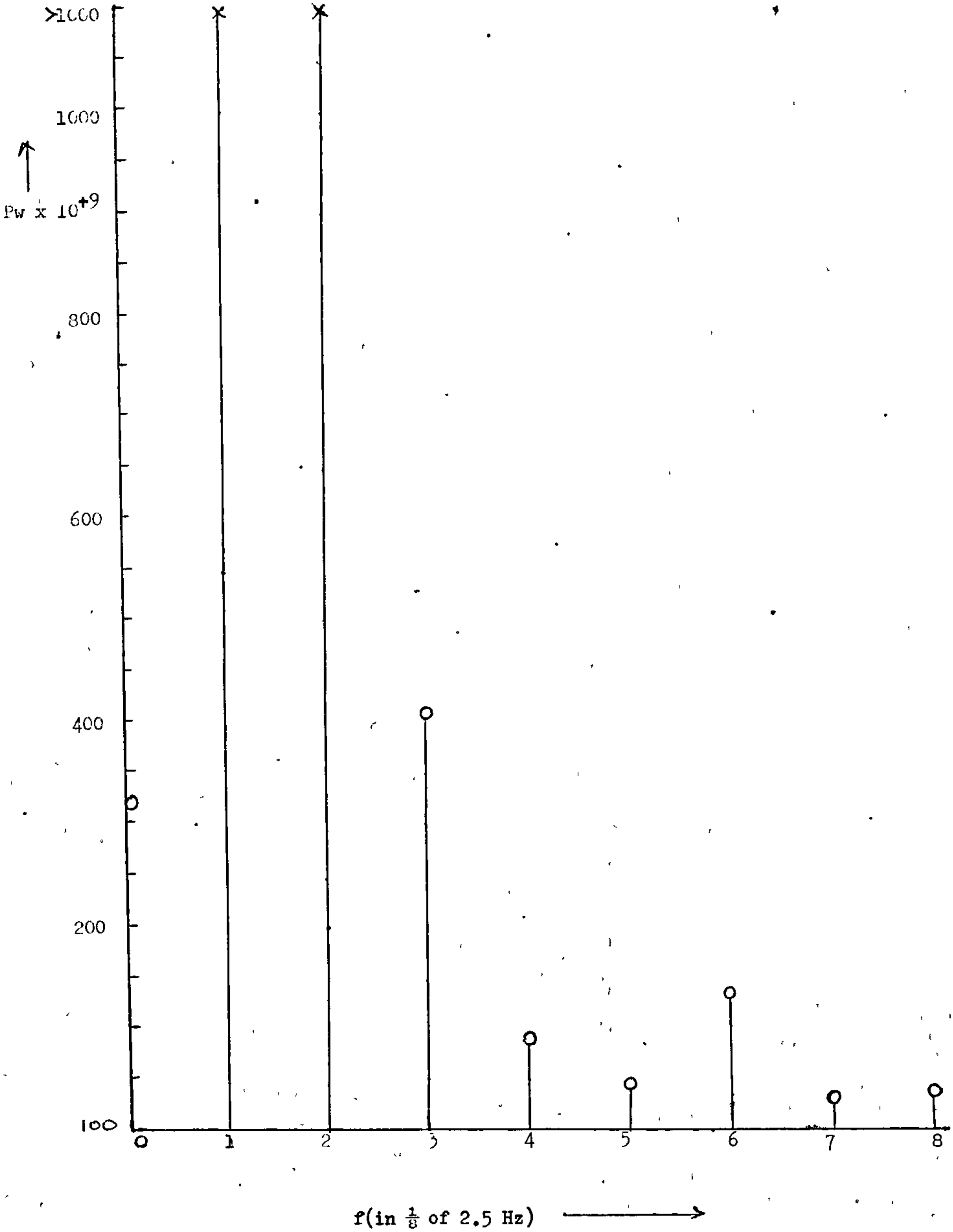
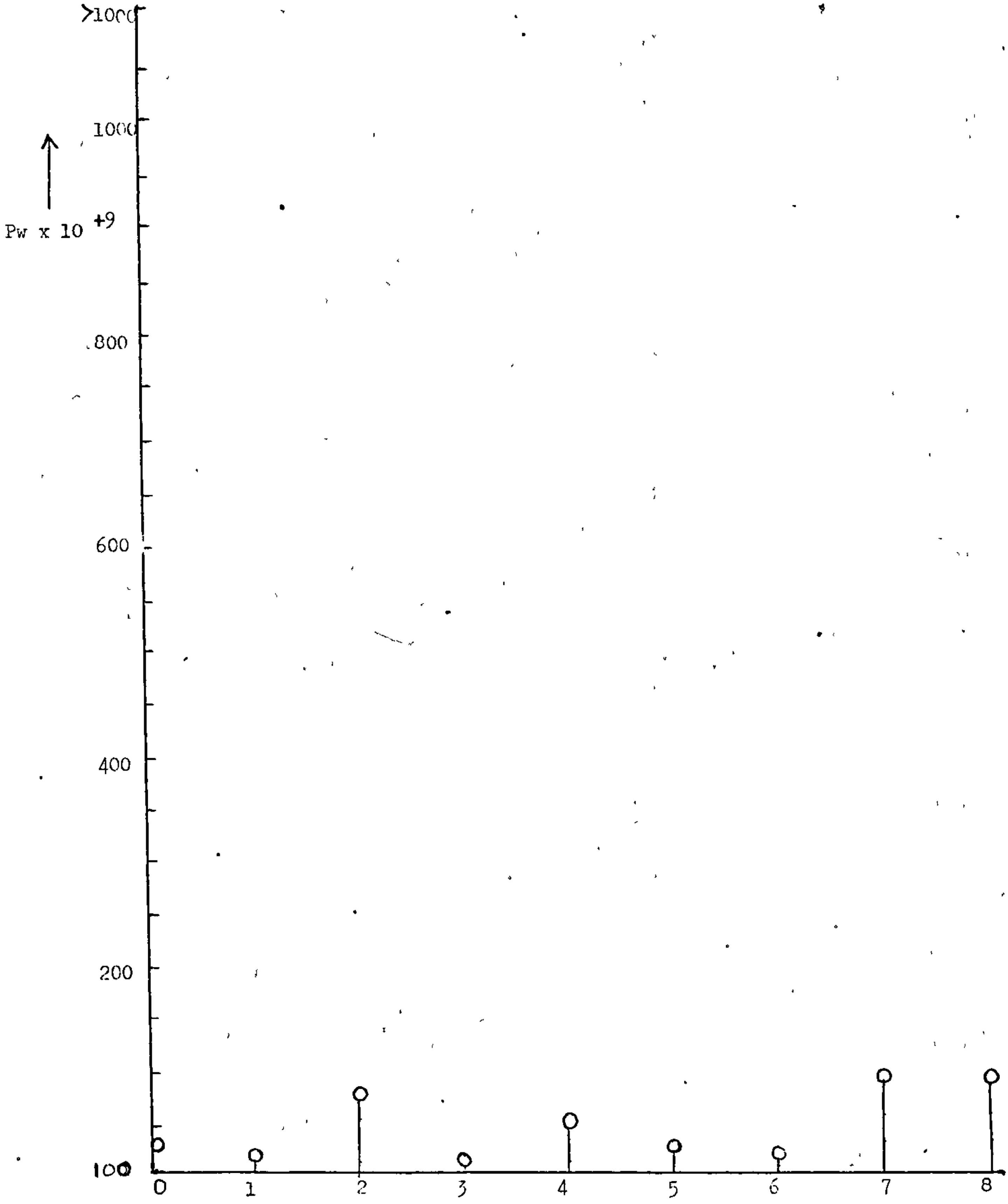


Fig 8.2 (a) Frozen impulse lines; N = 32, different portions of the same signal logging.



f(in $\frac{1}{8}$ of 2.5 Hz) ⟶

Fig 8.2 (b) Frozen impulse lines; N = 32, different portions of the same signal

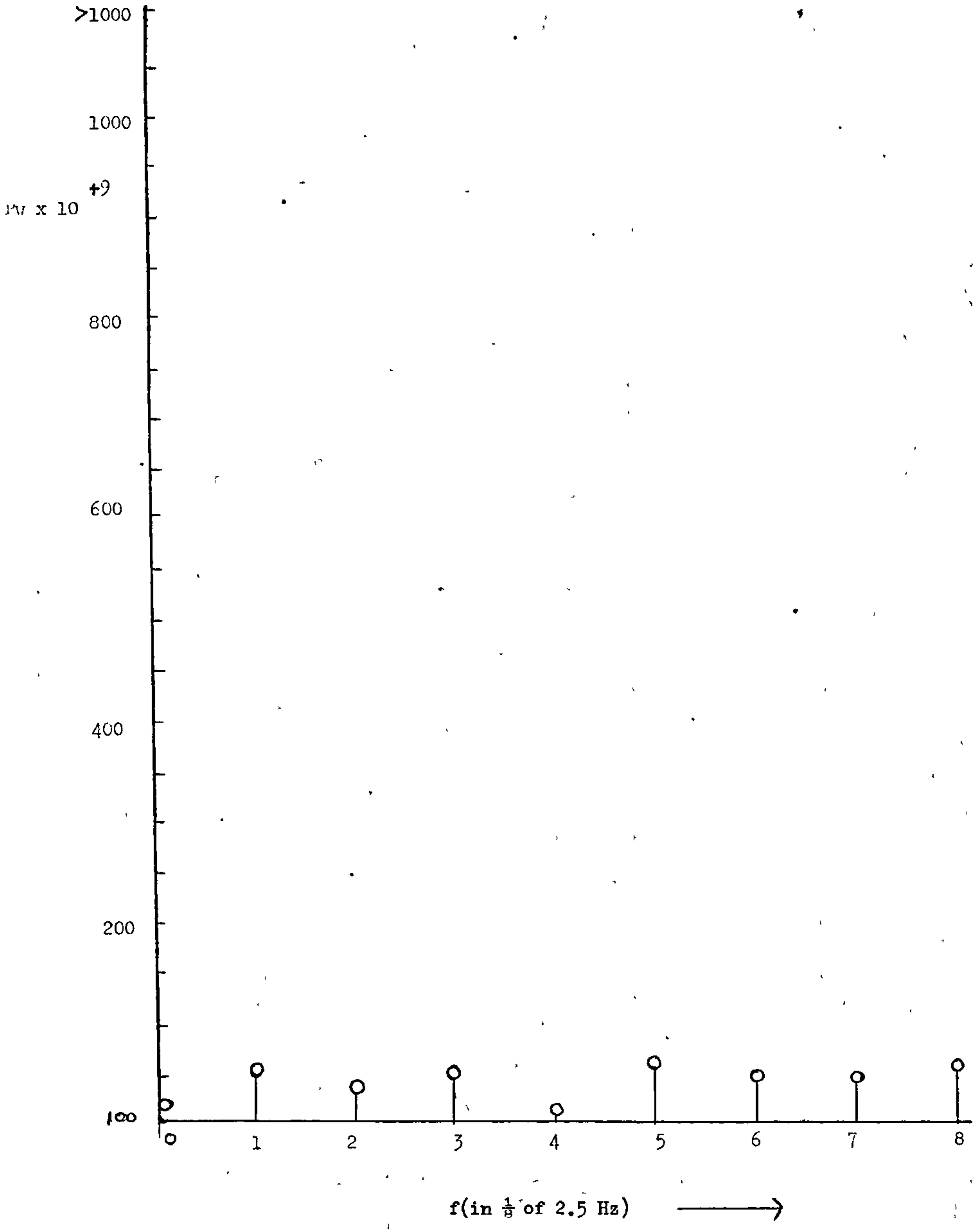


Fig 8.2 (c) Frozen impulse lines; N = 32, different portions of the same signal

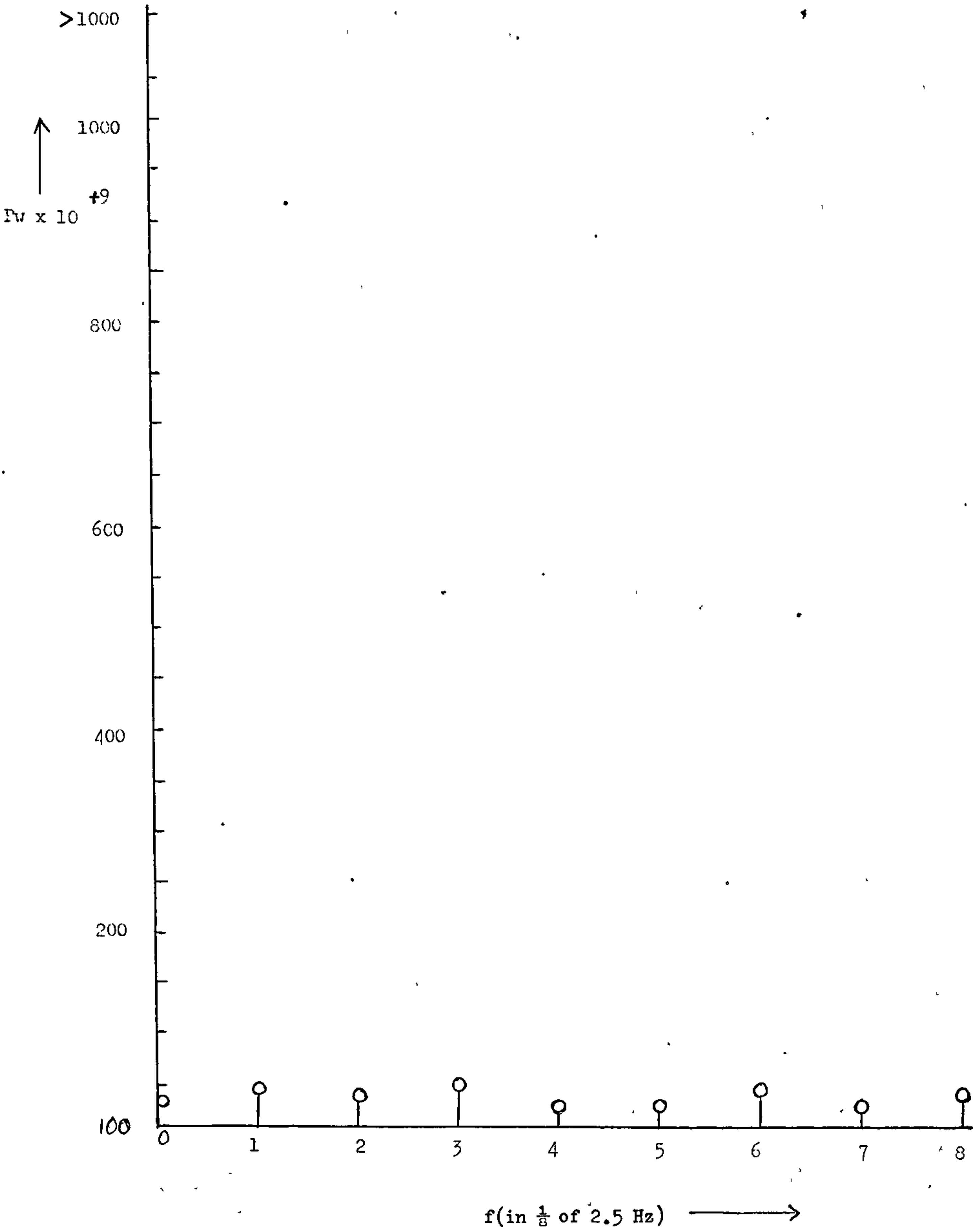


Fig 8.3 (a) Normal signal different experimental run

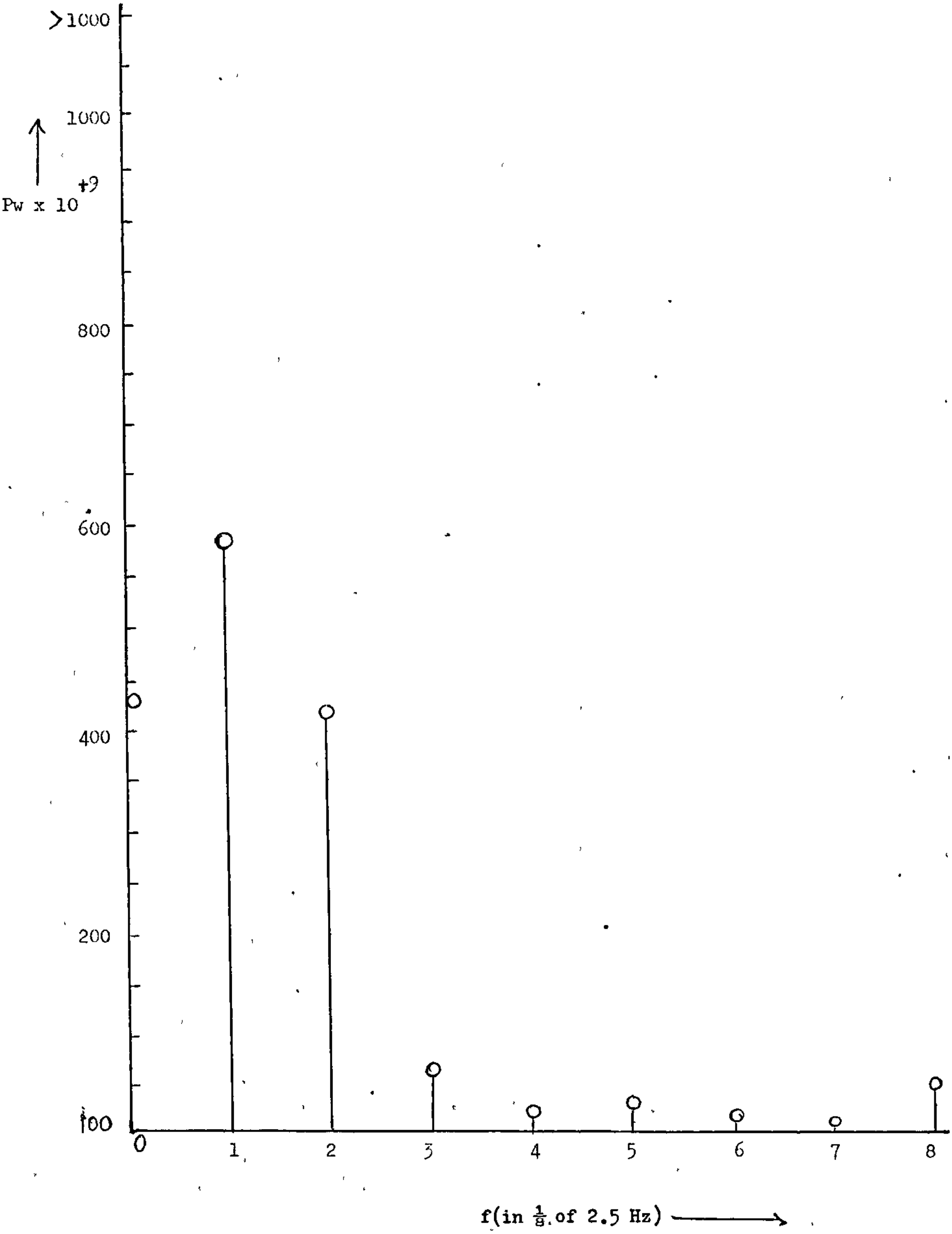


Fig 8.3 (b) Normal signal; different experimental run

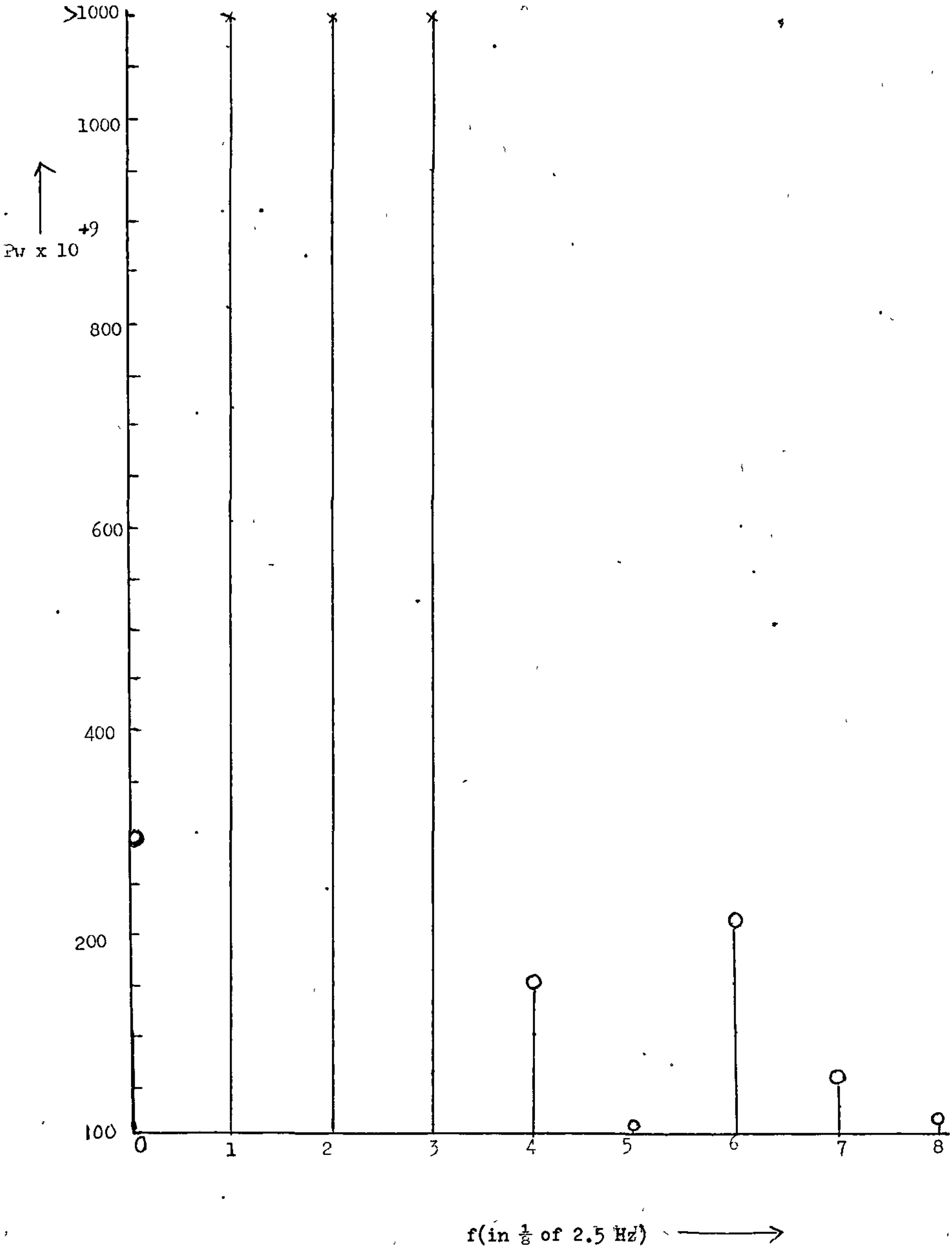


Fig 8.3 (c) Normal signal; different experimental run

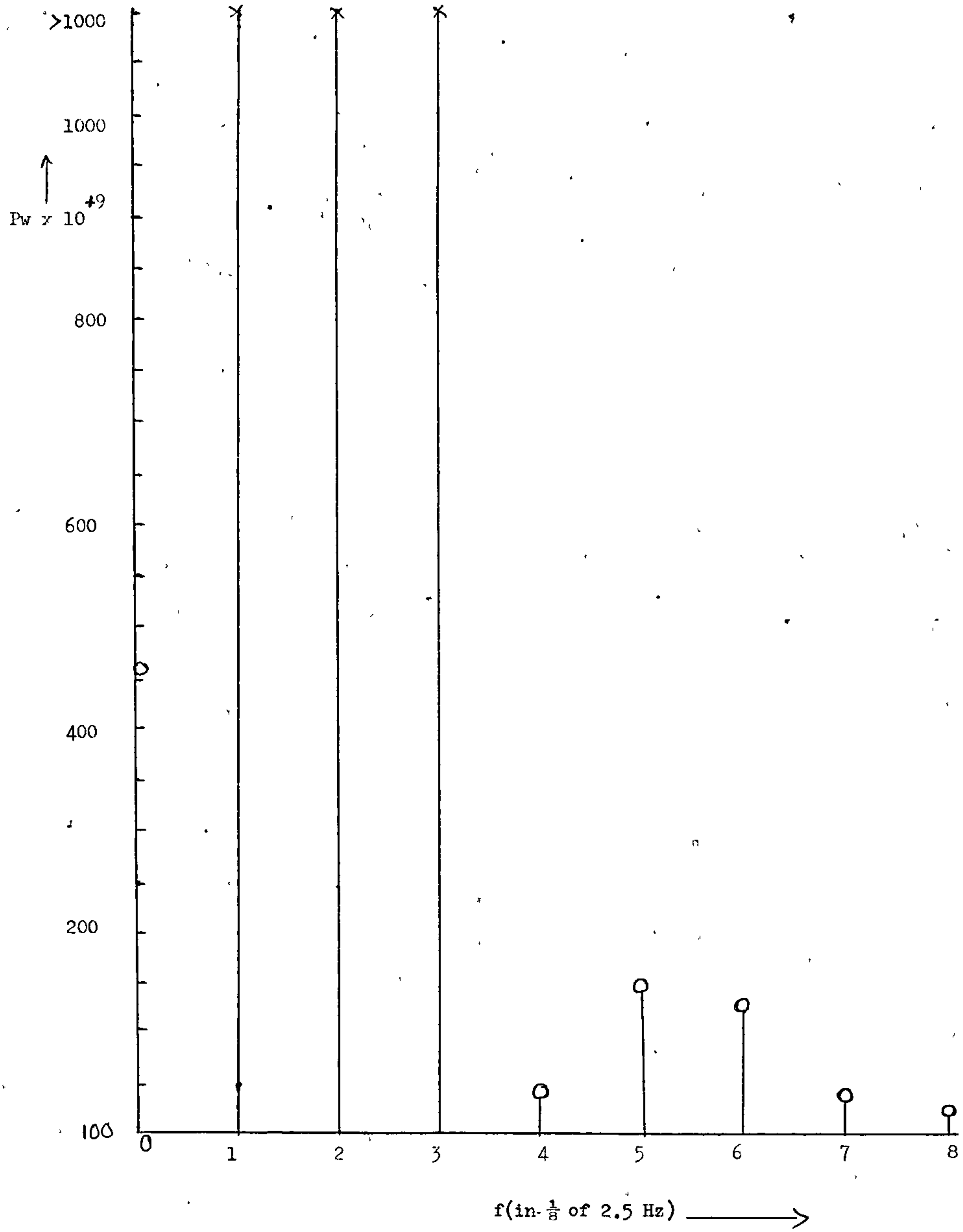


Fig 8.4 (a) Frozen impulse lines; different experimental run

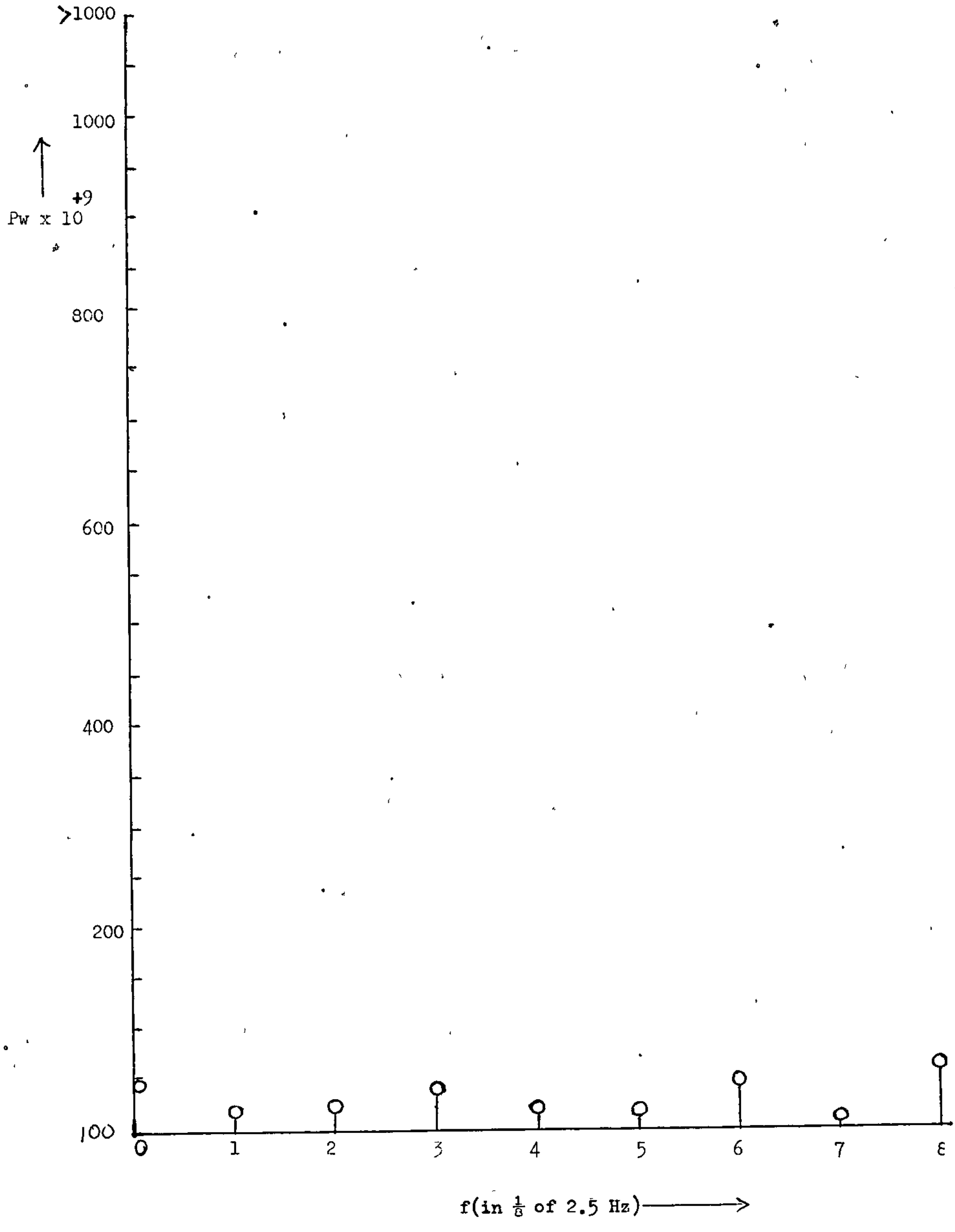


Fig 8.4 (b) Frozen impulse lines; different experimental run

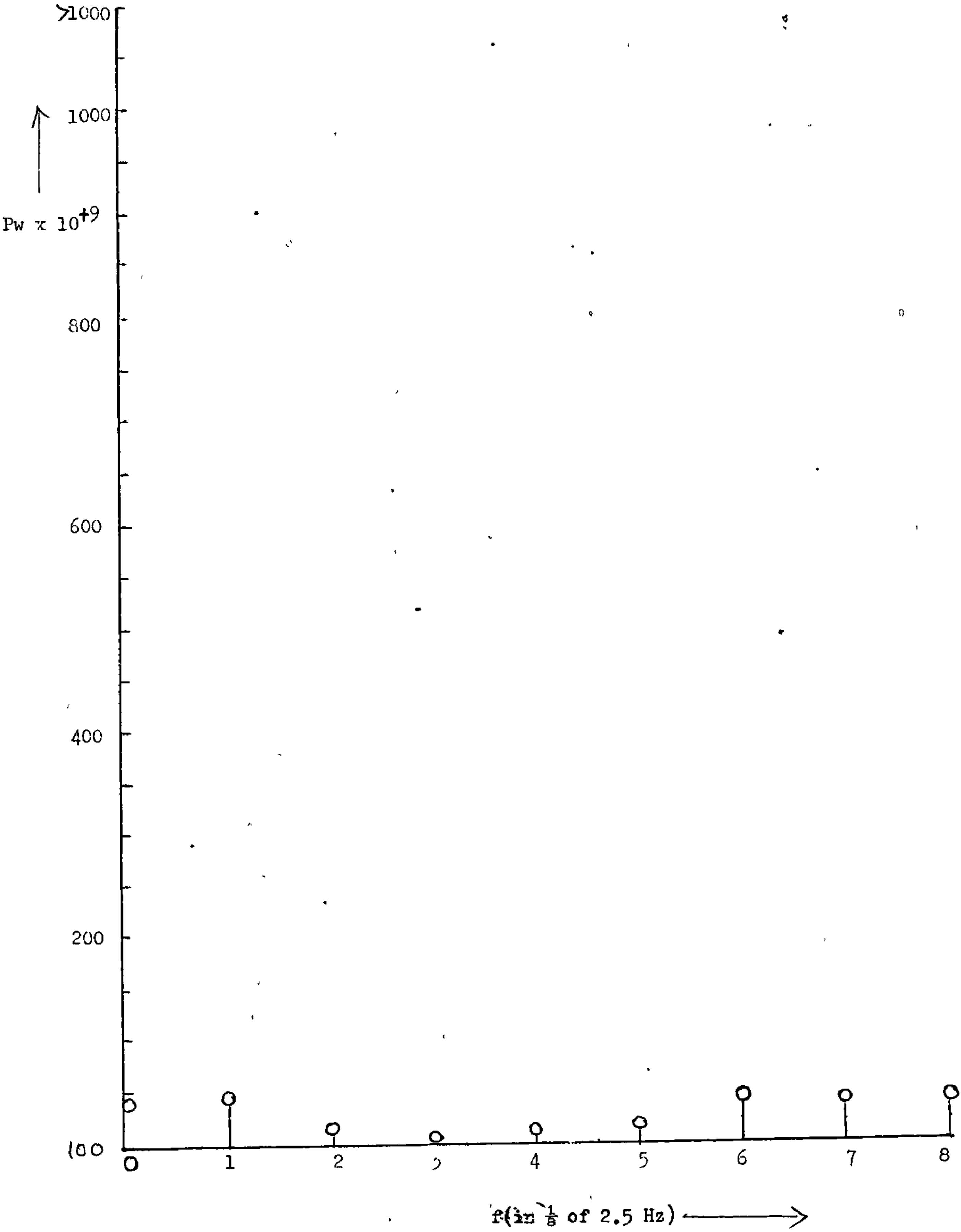
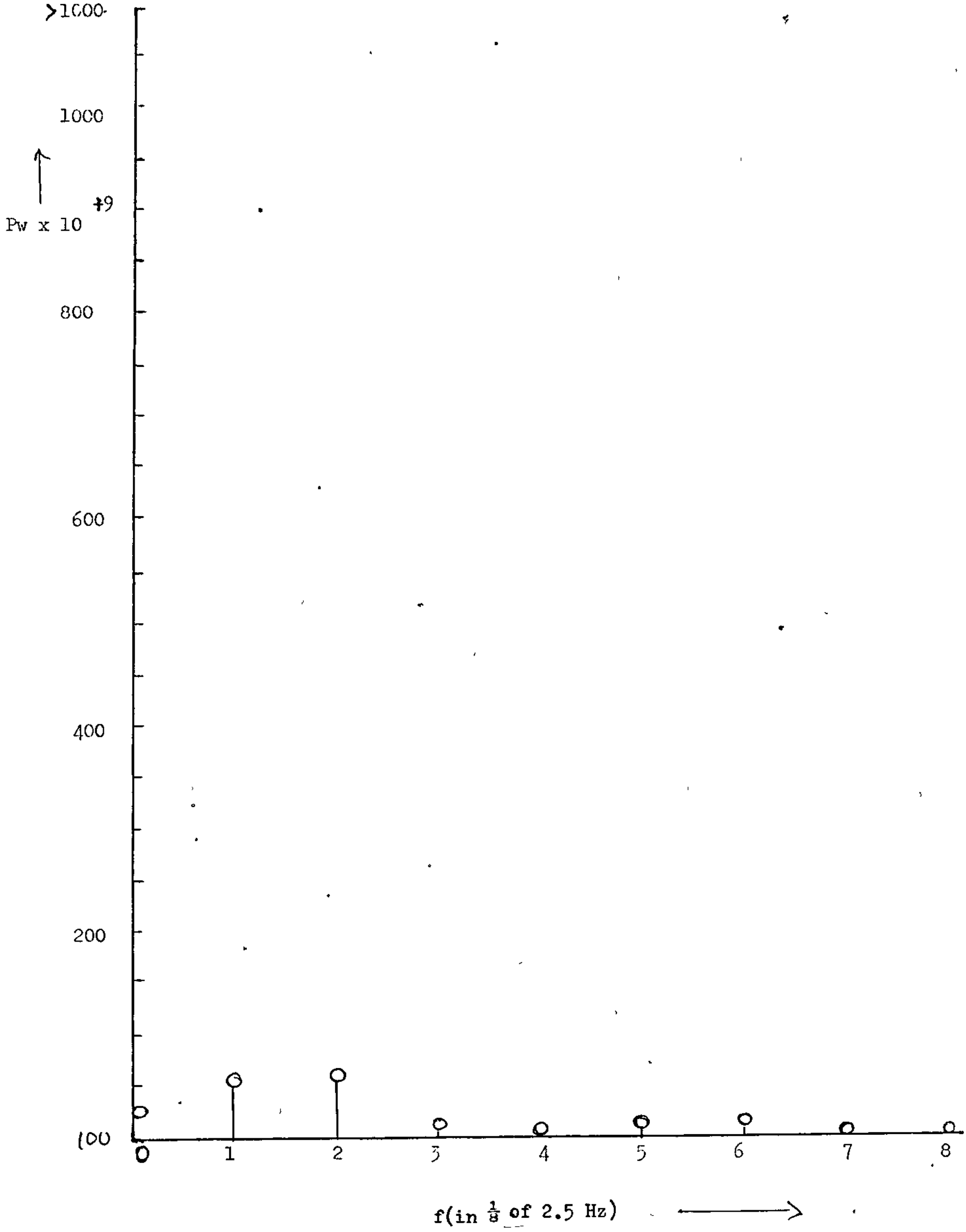


Fig 8.4 (c) Frozen impulse lines; different experimental run



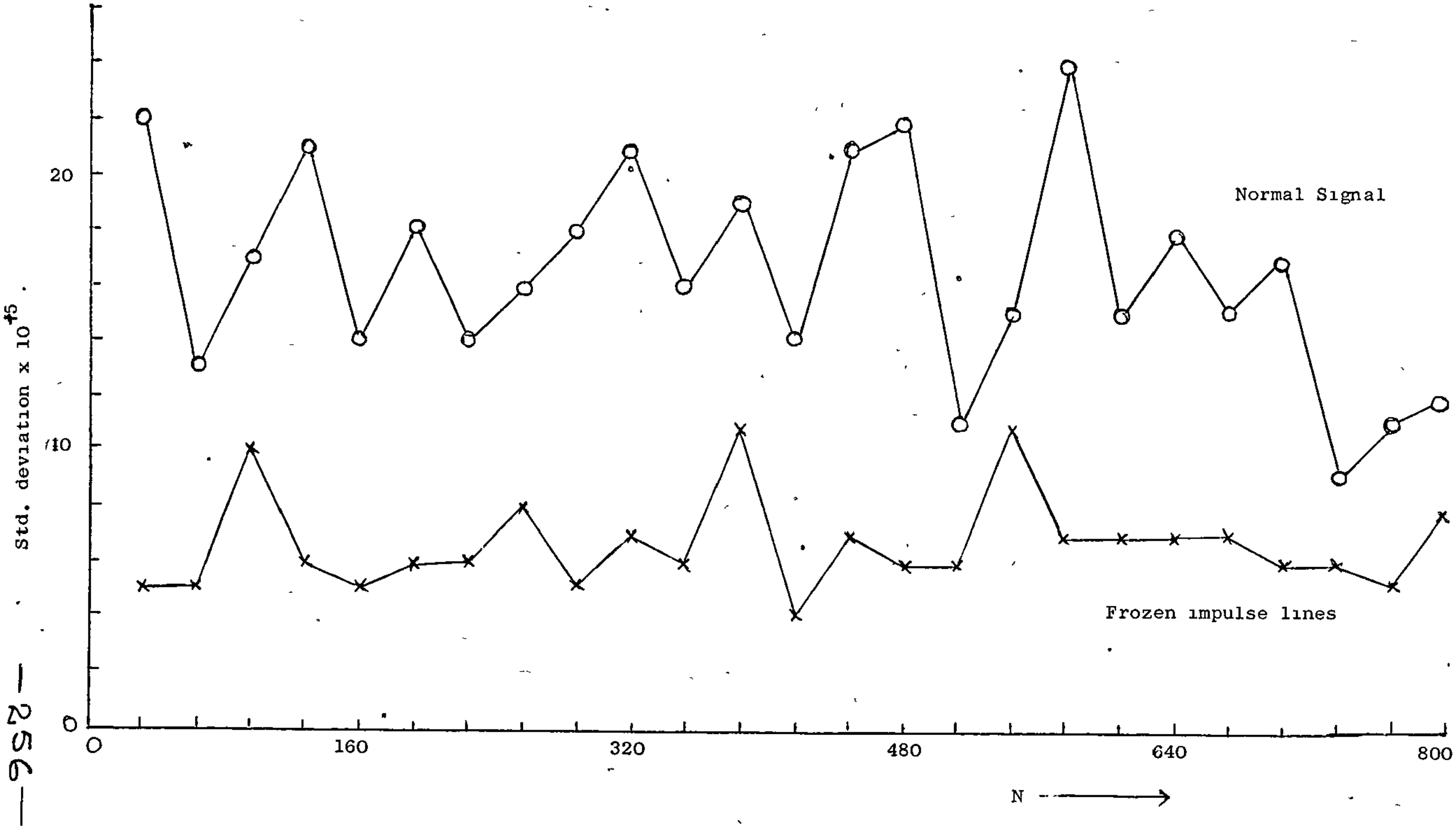


Fig. 8.5 Standard deviation plots for Normal and Frozen Impulse line signals

8.2 INDUSTRIAL CONTROL VALVES

Control valves are the most common form of final control element in a control loop and may be considered the muscle of automatic process control. Modern processes depend a great deal on the correct distribution and control of flowing liquids and gases — a majority of the industrial control loops use the control valve as the final control element for increasing mass flow or steam supply as the case may be. The importance of the control valve in the process industry cannot therefore be over-emphasised.

This importance of control valves was recognised at the formative stages of this project and this coupled with the fact that it was not a measuring instrument made it a ready choice for study. It was expected to offer different signals and perhaps a different malfunction detection approach from that used for measuring instruments.

8.2.1 Nature and causes of Control valve malfunction

From the preliminary survey of failure of plant instruments, the limited data on control valves failure showed about half the valve failures to involve either stickiness of the stem or blockage of the body. Leakages in body and joint were also major causes of malfunction.

In the work reported in Chapter 3, of 359 control valve failures in Works A, 23 were blockages and 53 leakages. Sluggishness of the valves were often traced to sticking. Sometimes the malfunctions of the valves derived from faults in the valve positioner, see Table 3.11, Chapter 3. Valve positioner misalignment, being out of calibration or loose, often affected the behaviour of the control valve.

Hysteresis or dead-zone caused by valve friction is often a source of difficulty in some control valves. This is a specific aspect of valve stickiness which has been recognised in the literature (224). It can lead either to lack of sensitivity to small process disturbances or to sustained oscillations around the dead zone. The friction is largely caused by the gland packing and it has the insidious feature that when the spindle has been static for some time, the problem becomes worse due to congealing of process material in the gland packing. These effects are particularly severe in some temperature control systems, where the valve may be static for many hours, and then, when a small load change occurs, the friction is so great that the valve will not move to the desired new position.

The survey reported in Chapter 3 revealed a lot of random failures such as bending or breakage of spindles or breakage of pressure connection line, etc. There are perhaps no obvious methods of predicting such failures. Incipient stickiness, leakages or blockages can lend themselves to the techniques of malfunction detection.

8.2.2 Control valve failure rate data

A brief summary of the data already given in detail in Chapter 3 will be made here.

The only available figure on control valve failures found in the literature is a figure of 0.25 actual fault/year for pneumatic control valves quoted by Hensley (62).

Reference table 8.6. All the valves were pneumatic. Of Of the 1330 valves in works A, 1195 were globe valves, 105 butterfly and 30 diaphragm; of 86 in works B, 32 were globe, 26 were butterfly and 28 diaphragm valves. All the valves in works C were globe.

Table 8.6(a) Summary of Control valve failure rate data

Works	Number at Risk	Instrument Years	Environment factor	Number of faults	Failure rate faults/year
A	1330	-	2	359	0.57
B	86	-	4	78	2.27
C	115	78.6	2	10	0.127
ALL	1531	747	2	447	0.60

Table 8.6(b) Effect of environment on reliability of control valves

	Number at risk	Number of faults	Failure rate faults/year
Clean fluids	214	17	0.17
Dirty fluids	167	71	0.89

The environment - whether the valve is in contact with clean fluids or dirty fluids has a marked effect on the reliability of control valves, see Table 8.6(b). The failure rate of 0.17 faults/year for valves in contact with clead fluids compares with Hensley's 0.25 faults per year. Again there is not enough information on his figure for comparison with the findings of the survey reported in Chapter 3.

8.2.3 Detection of control valve stickiness

At the formative stages of this work, it was thought desirable to be able to detect stickiness of control valves as soon as it occurs because of its insidious nature and the fact that it might be expected in a lot of the more serious and frequent control valve failures. The object of detecting valve stickiness being, as has been the central theme of this work, to avoid poor control, avoid catastrophies and improve instrument maintenance.

Preliminary analysis of control valve data collected, suggested that a simple detection of error between valve demand and valve position was not good enough for malfunction detection. A significant error after a change in valve demand was thought likely. A compensation for the uncorrected error was thought necessary for estimating a significant error and this required a knowledge of valve dynamics. Hence it was thought necessary to study the dynamics of control valves. In addition to the malfunction detection implications, such a study would be of value itself since many of the most difficult industrial control problems involve fast gas control loops on reactors, compressors, electrolysis cells, where control valve dynamics is significant. Account has not been taken, hitherto, of the control valve dynamics in the design of such loops and better knowledge of the control valve dynamics can only improve the design of such loops. Also knowledge of the actual movement of control valves in practice was thought of interest, as such information could not be found in the open literature. The manufacturers contacted could not provide such information either.

The above considerations led to an attempt, at the early stages of this project, at the modelling of control valves. The aim of the modelling was primarily to see how valves should respond to signal if they are not faulty. Considerable time was spent on this but work was progressing slowly and it appeared that the malfunction detecting objectives could be better achieved by studying control valve signals, and so emphasis was shifted to obtaining and analysing control valve signals from an industrial installation.

Normally, there will be a unique relation between the air pressure on the valve bonnet and the valve stem position. The relation between instrument signal and valve stem movement is usually linear. If there is stickiness, none of these relations will hold. It was therefore thought that a method of detecting stickiness might be based on comparison of signal to bonnet and stem position.

This comparison might be carried out while the valve is in a working control loop or while the loop is broken. It may often be possible to break the loop for the purpose of doing a test; but it might be expected that when stickiness is just beginning it will be intermittent and will often not show up. Hence even if the loop is taken off, nothing may be detected. It is not desirable to have to break the loop too much. This suggested that it is desirable to have a method of detection which will be effective while the loop is working.

At the initiation of the industrial experimental work, a simple comparison of the desired valve position and the actual valve position was envisaged to provide a satisfactory method of malfunction detection. The industrial experimental work was therefore designed to measure these two quantities in working control loops. It is the result of the analysis of the data collected from this experiment that is reported here, in the following sections.

8.2.4 Experimental industrial work on control valve signals

Data were obtained from an industrial computer installation in which positional algorithm is used, valves are positioned by air pressure regulated by solenoids, and valve stem positions are measured.

The general configuration of valves is as shown in Fig. 8.6. There are twelve towers. The computer was the same; so was the method of valve positioning as was described in details by Thompson (225). The computer was originally at Fleetwood and was transferred to Winnington. It was on an ammonia - soda plant in both cases. Data were collected at Winnington.

Two sets of data were obtained. In 1967 the top and bottom cooling valves were found to be sticking, Data on the 1967 valves were obtained. By 1970 all the faulty valves had been replaced. Data on the 1970 valves were also collected.

Valve types: The carb vat liquour (CVL) valves are Saunders 3 inch diaphragm valves. The top and bottom cooling valves are Audco [illegible] "slimseal" butterfly valves. Draw valves are Saunders [illegible] diaphragm valves. No valve positioners are used.

Frequency of calculation of valve demand: CVL and draw valves' demands were calculated every one second. Top and bottom cooling valves' demands were calculated every 5 seconds. The frequency of output of signal to position the valves was 6 times per second. The frequency of output of data was 20 seconds.

Smoothing: Valve demands were smoothed using algorithm

$$\bar{P}_n = \bar{P}_{n-1} + K(P_n - \bar{P}_{n-1})$$

where P_n is the instantaneously measured pressure and $\bar{P}_n$ is the smoothed estimate. K is the smoothing constant with values 1, 1/2, 1/4, 1/8. It is believed that K = 1/4 was used. There was no smoothing in valve position measurement.

Dead band: An allowance of 0.7% is made for the "dead band" range, that is, there is no output to valve unless

$$|\text{valve demand} - \text{valve position}| > 0.7\%$$

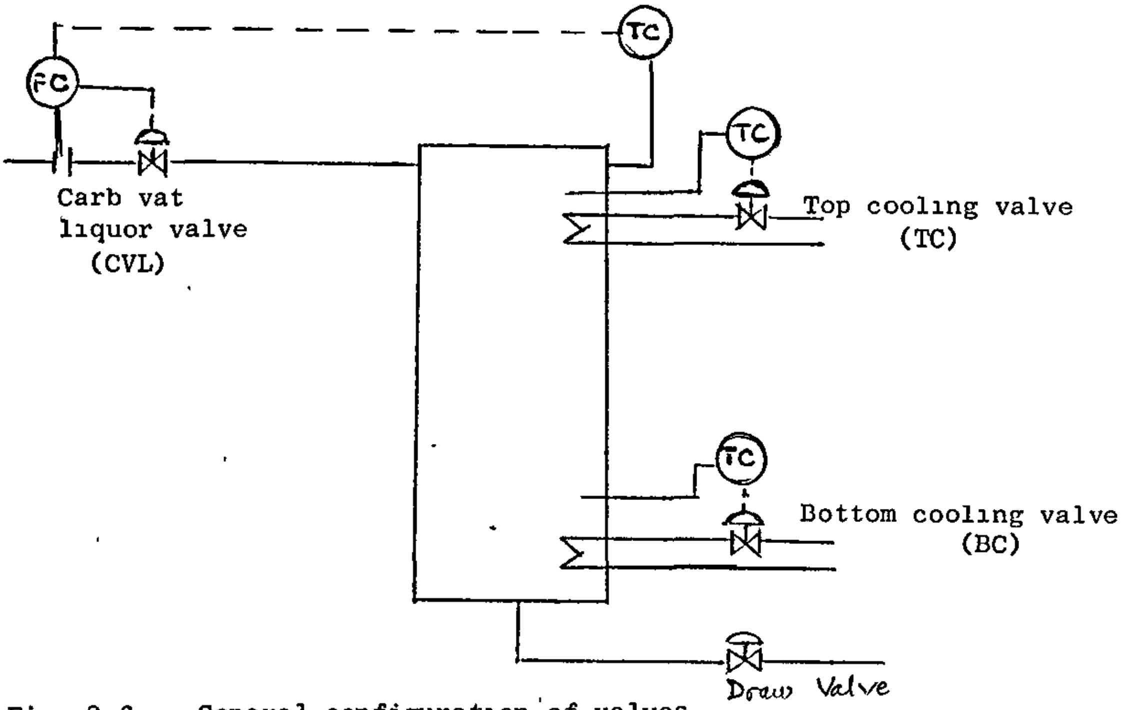


Fig. 8.6 General configuration of valves

8.2.5 Analysis of industrial valve data

At the time of the initiation of the collection of control valve data, a simple comparison of the desired valve position and the actual valve position was envisaged to provide a satisfactory method of malfunction detection. At that initial stage, the parameter of primary interest was the error between the desired and actual valve positions. The computer plots of the valve analysis were carried out to study this.

The valve demand (V_D), valve position (V_p), error between valve position and valve demand (error) and change in valve demand (delta) were plotted for all the data. The aim of the plots was for a visual appreciation of the correlation of the different plotted values. The correlation was not very good and so less emphasis was placed on these plots, instead the emphasis was shifted to the plots of the standard deviation of the error calculations. Typical complete computer plots of the above mentioned variables, for four different valves are shown in Figs. 8.7 to 8.10. The plots are shown mainly to illustrate the type of correlation that was obtained for the plotted variables and the basis for the preliminary conclusions. For ease of comparison of the different plots, these were repeated on a common scale. Figs. 8.11 to 8.14 show only the computer plots of errors for some further data, all plotted on the same scale. Figs. 8.7 to 8.10 are not on the same scale, but on different scales to best represent the values of the variables plotted.

The preliminary analysis and the above plots suggested that a simple check on error between desired and actual valve position might not be enough for malfunction detection. It was thought that the standard deviation of the errors might be better and therefore these were calculated and plotted for comparison, particularly between the 1967 valve data when some of the valves were known to be malfunctioning and 1970 data when this type of information was not available. The plots of the standard deviations are given in Figs. 8.15 to 8.23.

The study of instrument signals from industrial installations has always been of interest throughout this project. Programmes were initiated for obtaining these but not all the expected data were obtained. Signals from gas pressure, flow, pressure and temperature measuring devices were obtained at the late stage of this work. The signals were for the normal instrument behaviour. The standard deviations of the signals were calculated and have been plotted in Figs. 8.24 to 8.27.

The data for all the plotted figures are given in the appendix tables A21 to A31, for the gas pressure, flow, pressure and temperature measuring instrument data, only the standard deviations have been given.

The computer plots shown are for the 1970 valve data. The errors were generally within the 0.8% band, see Figs. 8.7 to 8.14. The errors were larger for CVL valves than for the others, see Figs. 8.7 and 8.8.

Errors arose from both excursions of valve demand while valve position remained constant and vice versa but these errors were not sustained. The correlation between the plots of valve position and valve demand, error and delta was not very good. The typical complete plots of these four variables shown in Figs. 8.7 to 8.10 bring this point out very well. The correlation between error and valve demand change-rate was low and almost arbitrary. Figs. 8.7 to 8.10 generally bring out this point but Figs. 8.7 and 8.9 particularly show it well. There was a finite error even when change in valve demand was zero. This appeared to be due to variation of the valve position signal. Again Figs. 8.7 and 8.9 show this very well.

Rapid excursions of valve demand may arise as a result of derivative action. Rapid excursions of valve position may arise from the equipment measuring valve position, or, possibly, from that sending the signal to the valve. In any event, a simple detection of error between valve demand and valve position did not seem good enough. The standard deviation was expected to be better as it is an average parameter and is more likely to show up persistent and significant errors after a change in valve demand.

The standard deviation plots for the 1970 valve data, Figs. 8.15 to 8.18 show some consistency in low values. The plots for the top cooling and draw valves show values well below the 1.0% margin. Valve one of the CVL, Fig. 8.15, shows some high values. These may be significant and indicative of an off-normal condition. The states of the 1970 valves is not known but the standard deviation values of this particular valve in that series are much higher than the others.

The 1967 valves were known to be generally sluggish with zero errors. The degree of severity of these faults are not known but the standard deviation plots of these valves, Figs. 8.19 to 8.23 are much higher, and were consistently so, than the 1970 values. The bottom cooling valve, Fig. 8.23, must have been particularly bad.

On the basis of these plots, the standard deviation characteristics of the valve signals do show different characteristics which could be indicative of an off-normal condition. On this basis, high values of the standard deviation above a tolerance limit could be indicative of development or existence of an off-normal condition. This can form the basis of a computer based algorithm that will use the standard deviation technique for malfunction detection.

Valves were set to give 2 and 98% full travel for 0 - 100% valve demand. Many of the 1967 faulty valves gave for 0 valve demand zeros in the region of 5 to 37%. So they would not shut off. If they had been working 50% open say, this might not have been detected.

A check on zero and full range error is clearly desirable as there could be real trouble if a valve will not shut off completely in an emergency.

The plots of the standard deviations of the gas pressure, flow, pressure and temperature measurements showed interesting characteristics. The different measurement signals showed consistency in the levels and behaviours of their standard deviations, see Figs. 8.24 to 8.27. The temperature measurement signals, Fig. 8.7 for instance, showed consistently low and steady values whereas the flow measurements on the other hand showed higher values. The interesting point is that despite these variations, the same type instrument measurements showed similar and consistent characteristics. This brings out the relevance of the intrinsic characteristics of a particular measurement or instrument in setting a basis for off-normal behaviour detection. These would vary and the computer can either learn these or such information would have to be fed in a priori. It would have been more interesting to have obtained the corresponding instrument signals for off-normal conditions.

8.3. DISCUSSION OF THE CASE STUDIES OF INSTRUMENT MALFUNCTION DETECTION

The different instruments studied offered both different signals and malfunction detection approaches. The specific techniques tested promised effectivness and versatility of application.

The standard deviation of the signal mean error proved adequate for thermocouple malfunction detection. The technique promises wide applications but for instruments such as the differential pressure transmitter, the power spectral analysis promised a more superior approach.

The control valve differed from the differential pressure transmitter and the thermocouple because it is not a measuring instrument. Because the valve demands and valve positions tend to make single point excursions, stickiness tests on the basis of error between valve demand and valve position are unlikely to be sufficient, at least, if based on the absolute value of error or standard deviation of error alone. What might be better is something which detects persistent error over a short period as this is likely to be a better guide. It seems likely that the sampling and control interval for stickiness tests will affect the sort of tests required. It is clear that more work is required with shorter sampling intervals than were used in the data obtained and analysed in this work.

An algorithm that can detect error and unsatisfactory response to valve demand could be more effective for detection of control valve stickiness. Knowledge of control valve dynamics - the movement of control valves in practice — would be relevant to the detection of unsatisfactory response to valve demand. Other possible algorithms to detect stickiness and blockage could include 'stroking' the valve, or comparison with flowmeters.

Techniques that will be based on spectral analysis of signals, promise both a powerful computer based and display type malfunction detection technique. The results of the differential pressure transmitter analysis are very encouraging and promise versatility in the use of this technique. More work needs to be done in this direction, particularly in developing an on-line algorithm based on the technique and exhaustively testing it.

The thermocouple malfunction detection algorithm proved effective for the laboratory simulations. Data were expected from an industrial installation which uses many thermocouples and in which thermocouple failure is frequent. It was hoped to test the algorithm on them but the data are not yet available. It was hoped that the stage might have been reached in this project when the algorithm could have been tried on an industrial installation. The time did not permit this but this would be an interesting next step with the algorithm, and another test for its effectiveness.

Generally, the different instruments, because of their varying intrinsic characteristics, bring out the relevance of these considerations for the malfunction detection of different instruments. The central ideas put forward in Chapter 5 offer a wide scope for direct application and adaptation to particular requirements.

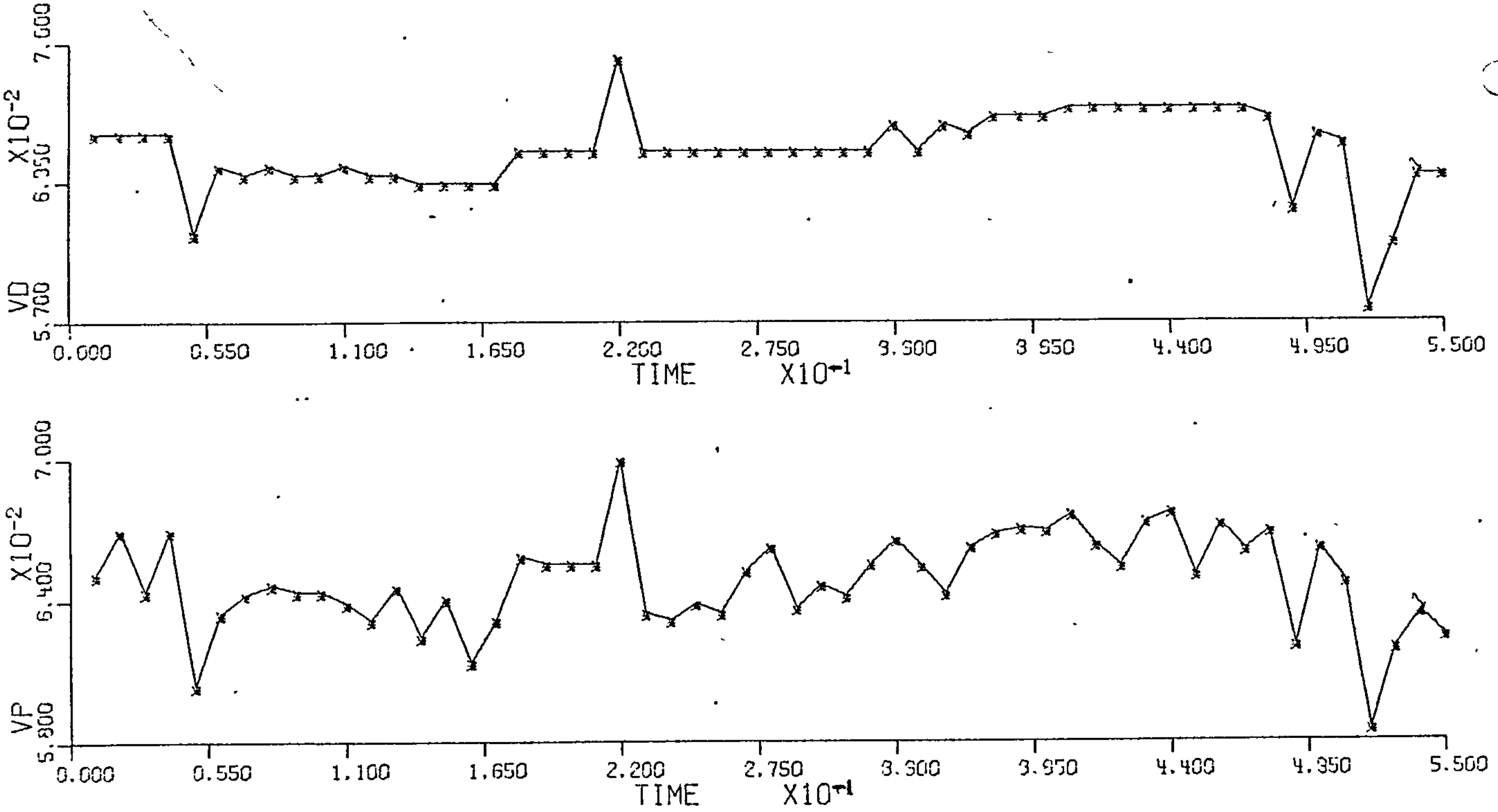


Fig. 8.7. Typical 1970 valve data plot - Top cooling valve (1)

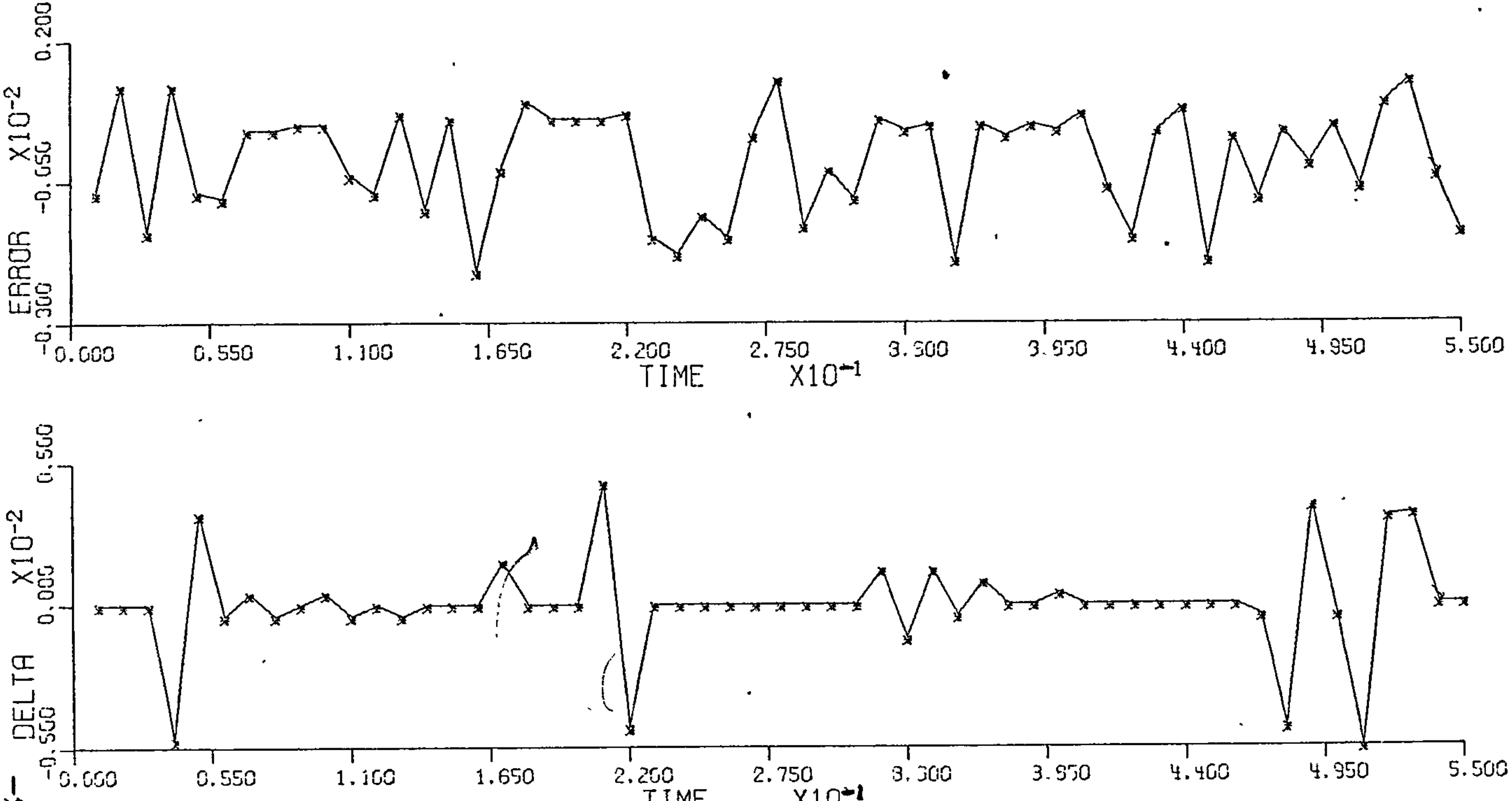


Fig. 8.7. (cont'd) Typical 1970 valve data plot - Top cooling valve (1)

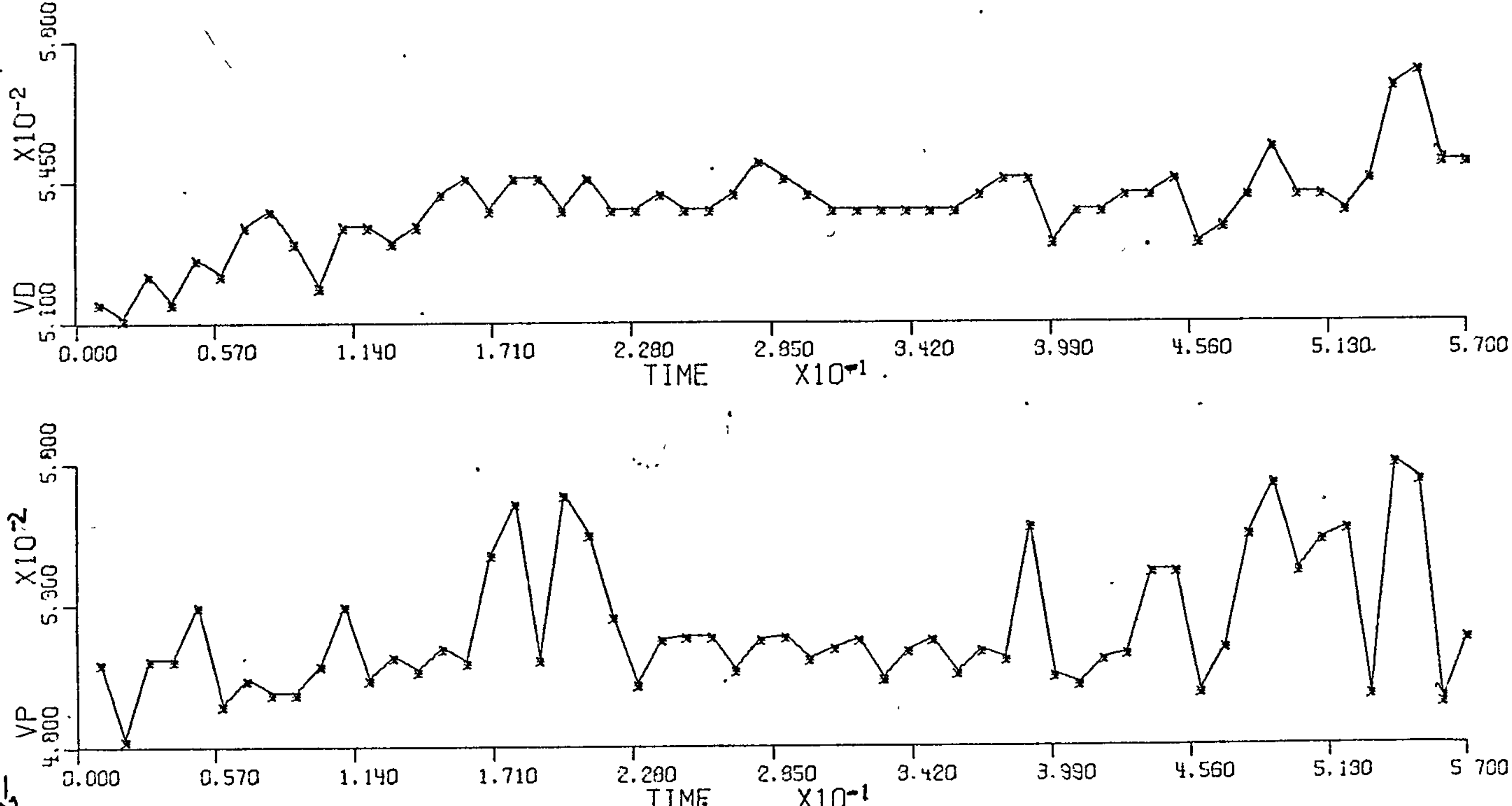


Fig. 8.8. Typical 1970 valve data plot - CVL valve (1)

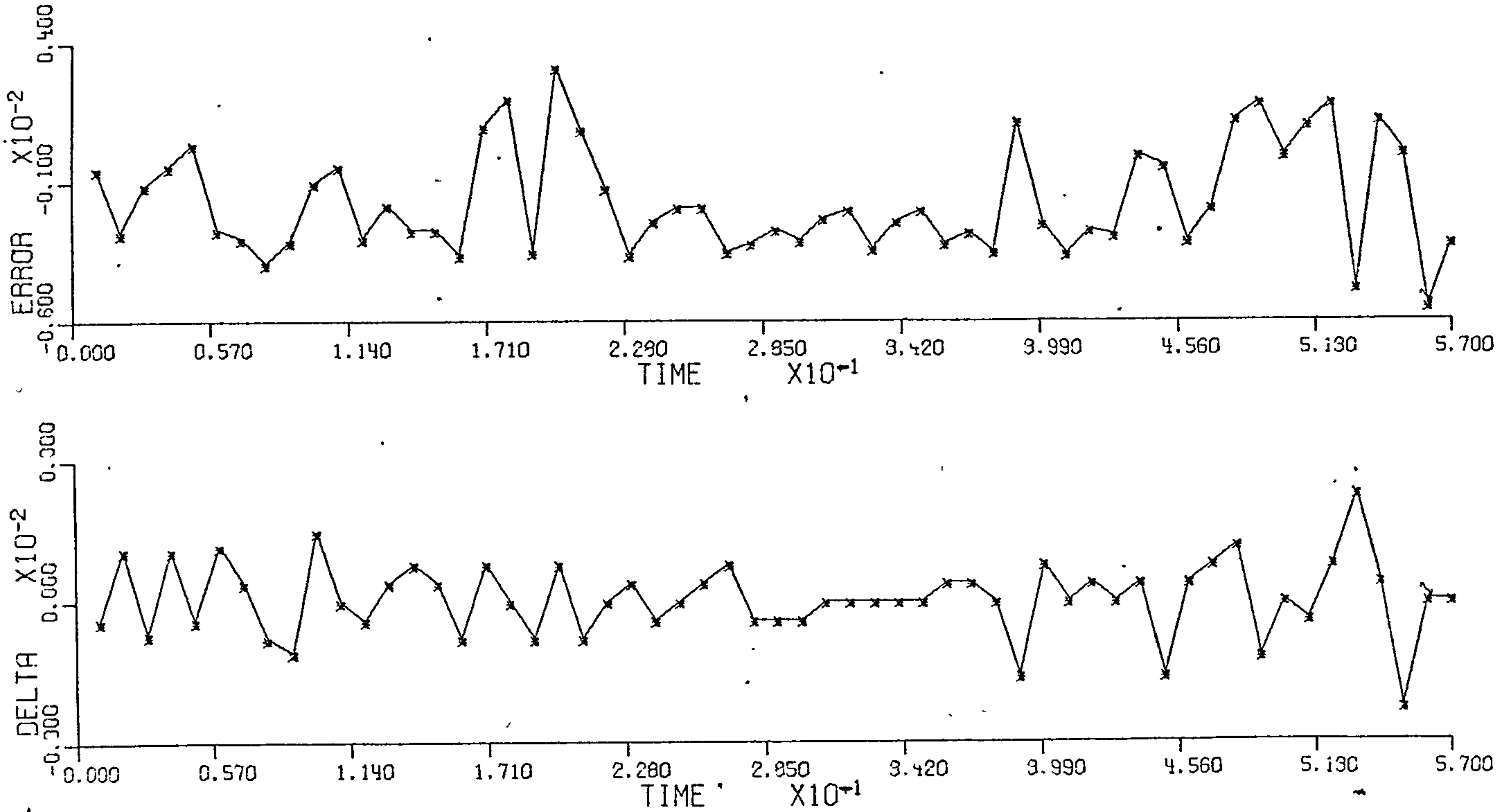


Fig. 8.8. (cont'd) Typical 1970 valve data plot - CVL valve (1)

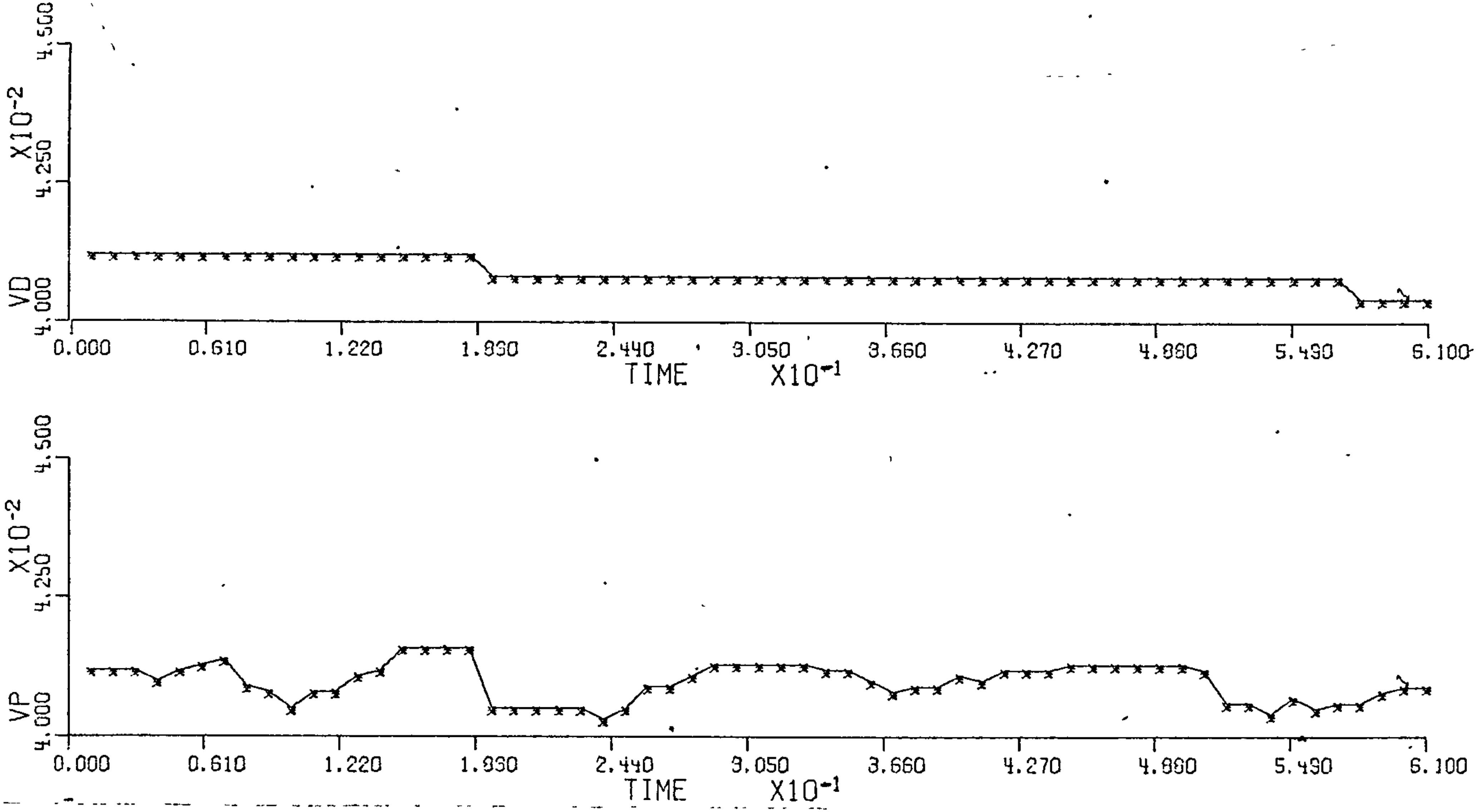


Fig. 8.9. Typical 1970 valve data plot - Bottom cooling valve (1)

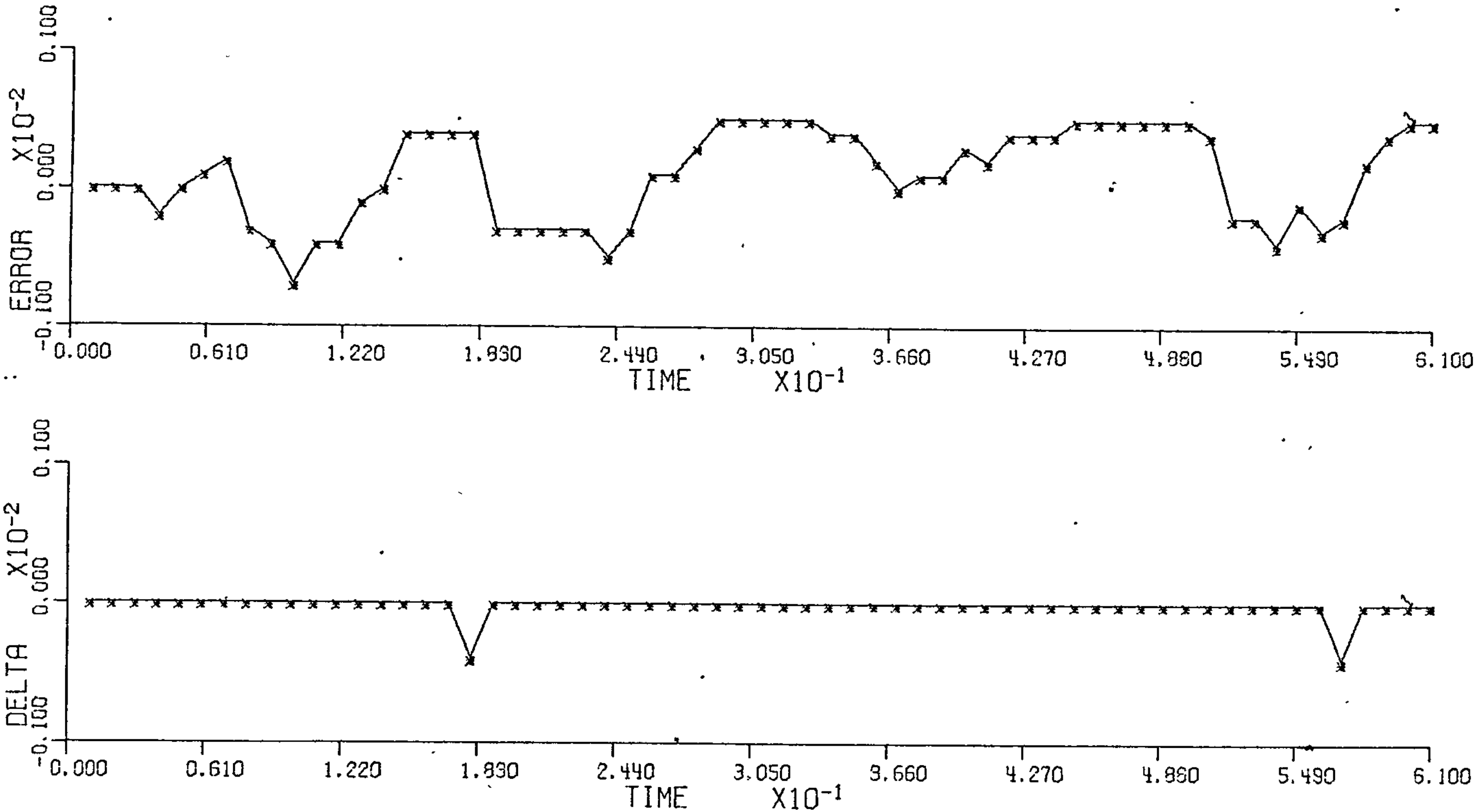


Fig. 8.9. (cont'd) Typical 1970 valve data plot - Bottom cooling valve (1)

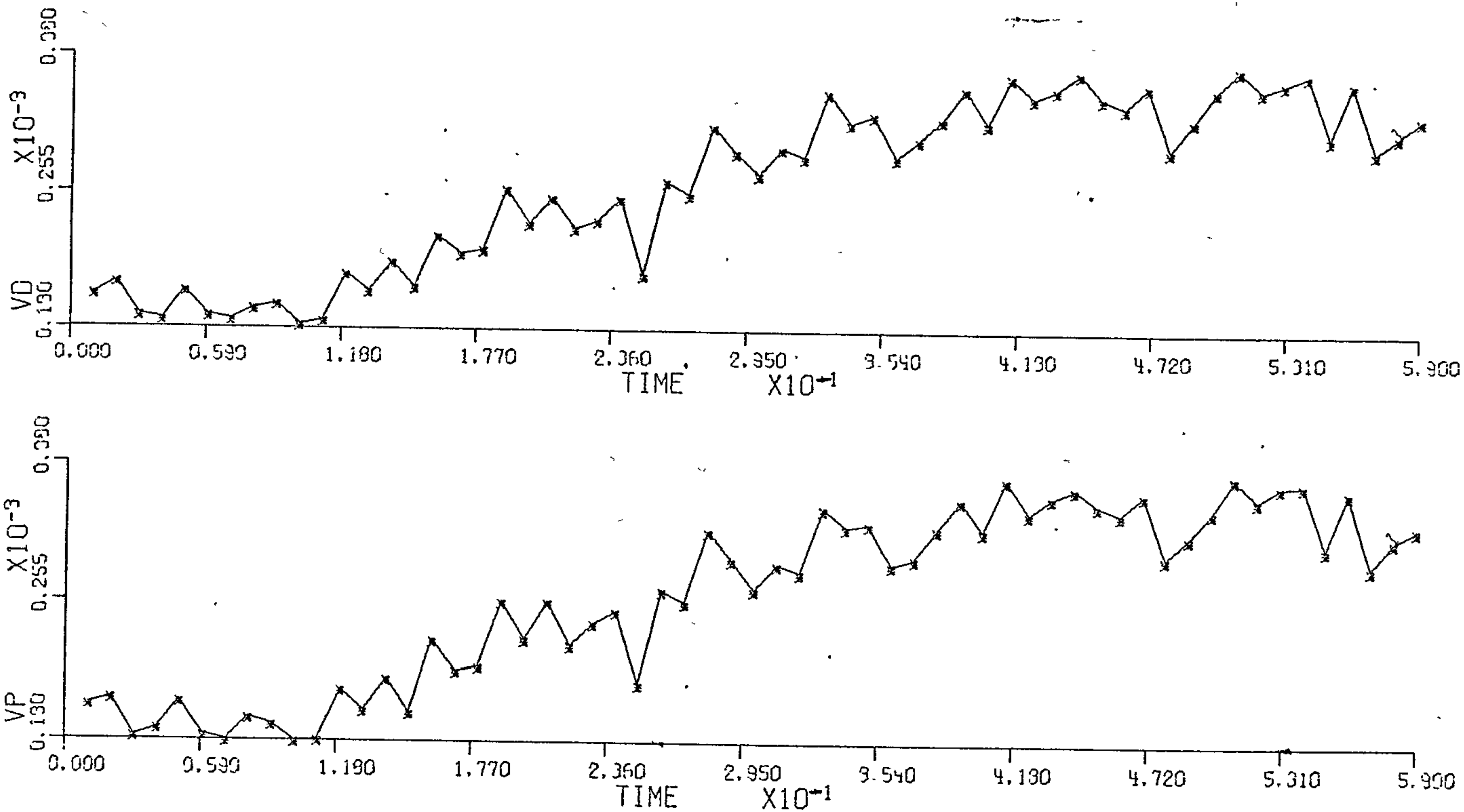


Fig. 8.10. Typical 1970 valve data plot - Draw valve (2)

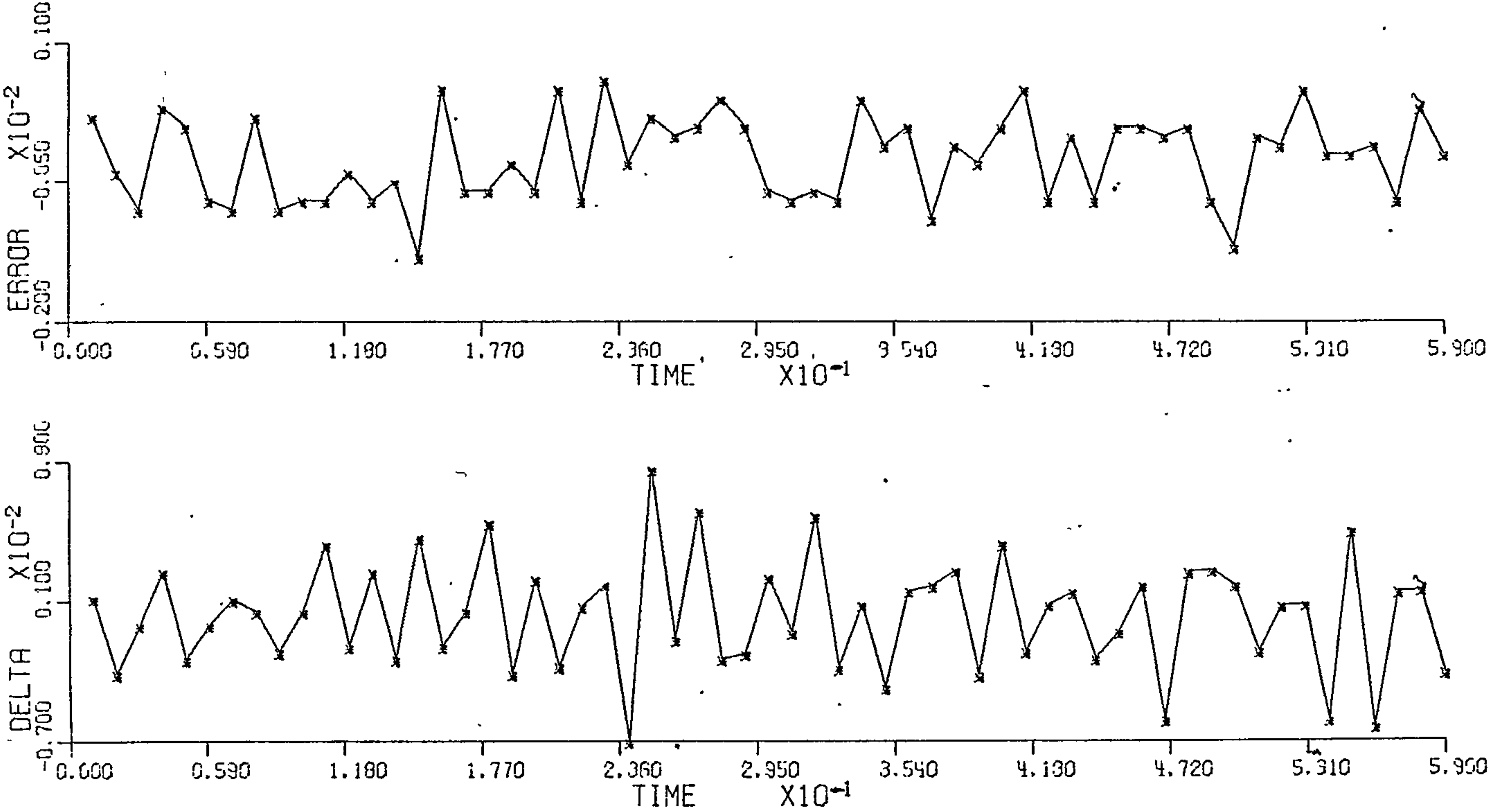


Fig. 8.10. (cont'd) Typical 1970 valve plot - Draw valve (2)

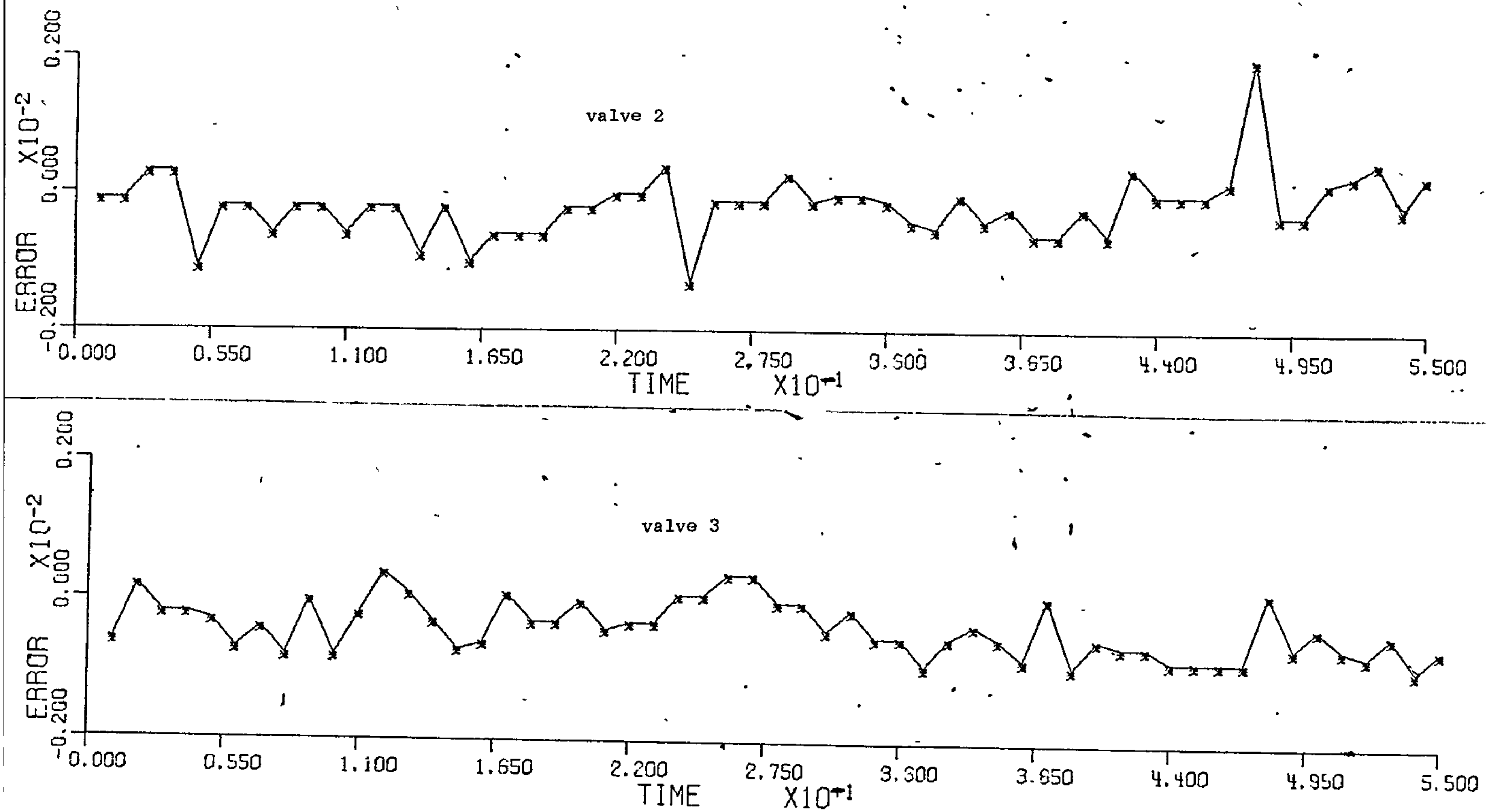


Fig. 8.11. Error plots of 1970 top cooling valves (2) and (3)

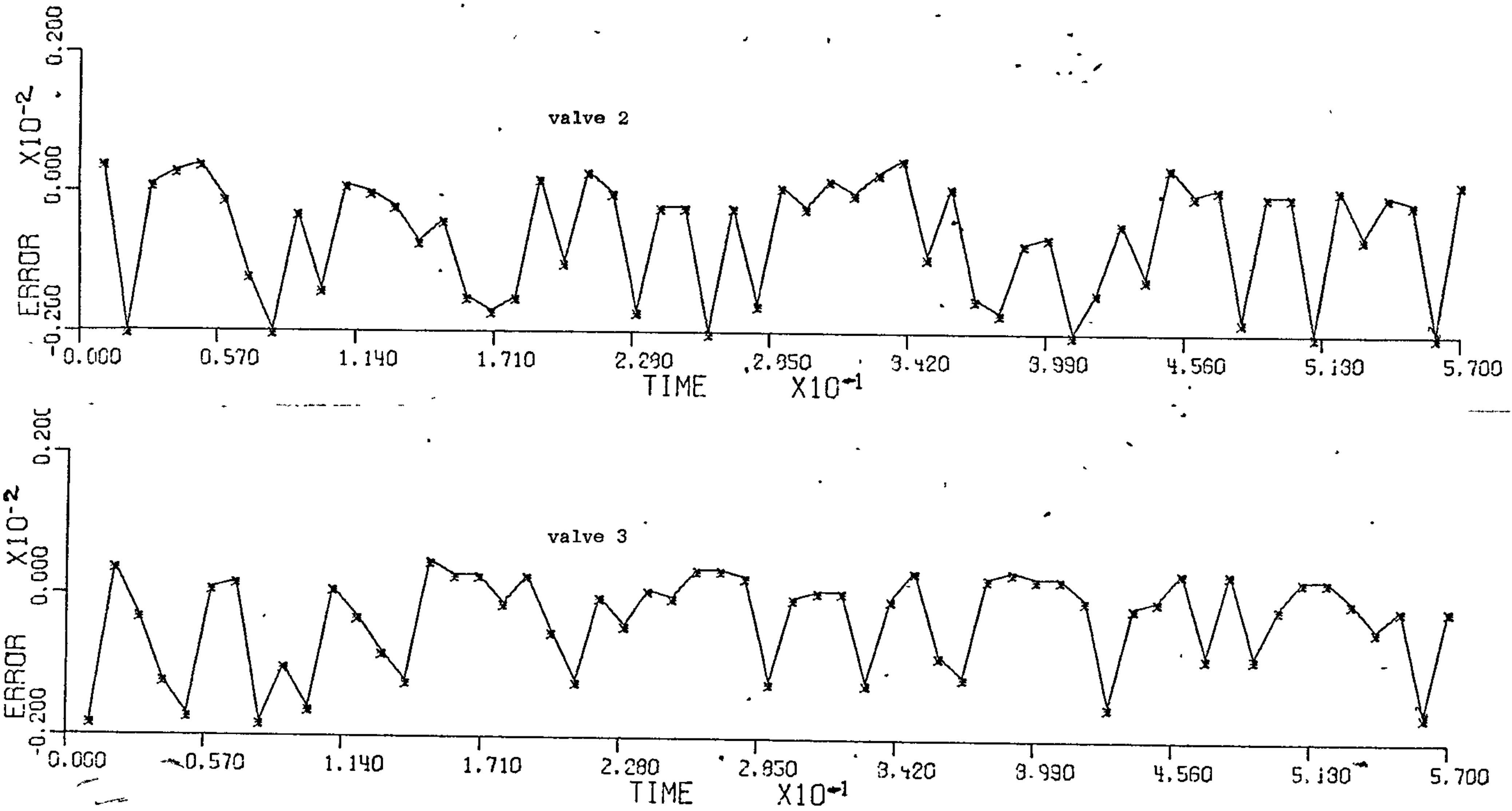


Fig. 8.12. Error plots of 1970 CVL valves (2) and (3)

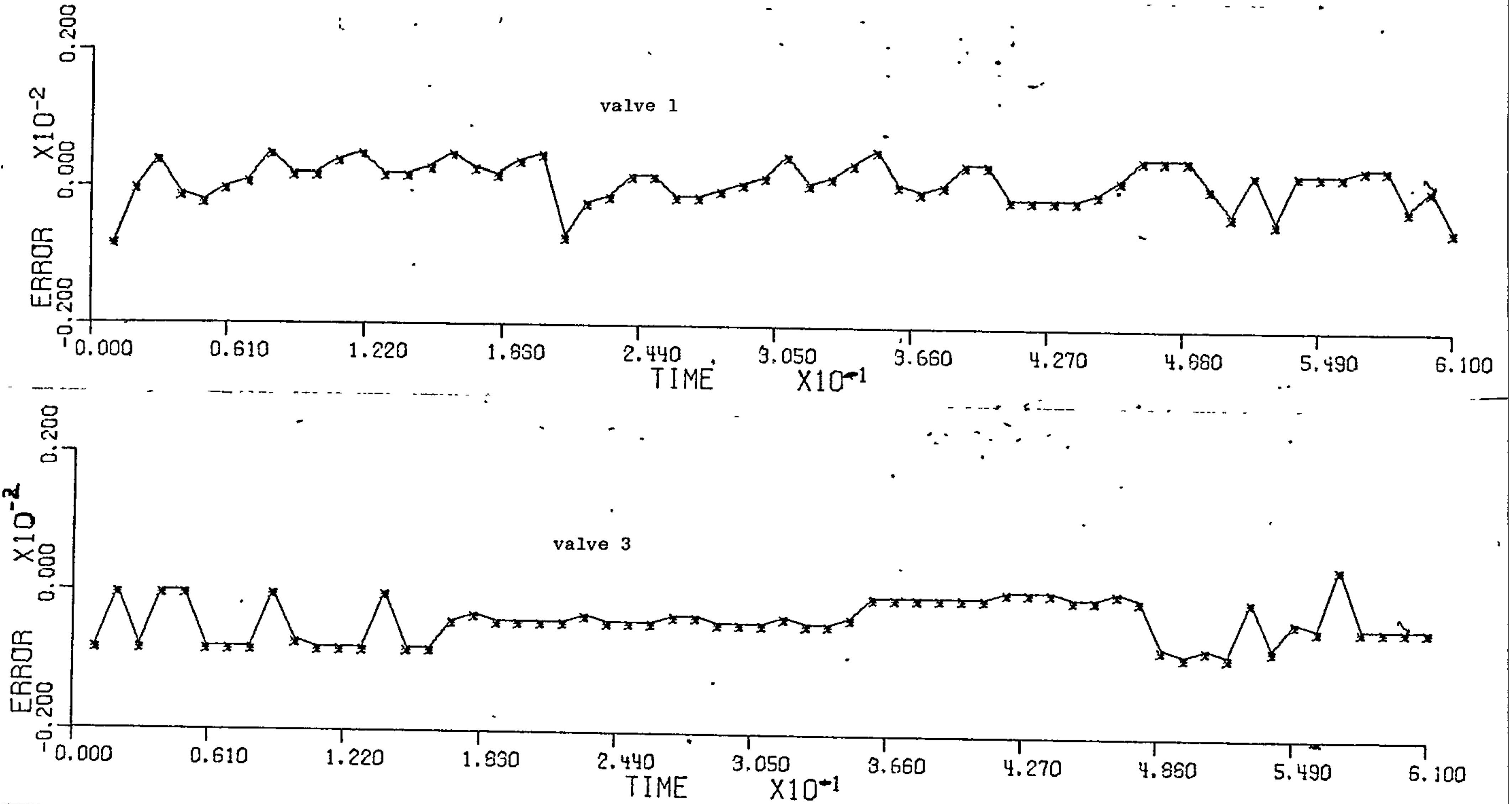


Fig. 8.13. Error plots for 1970 Bottom cooling valves (1) and (3)

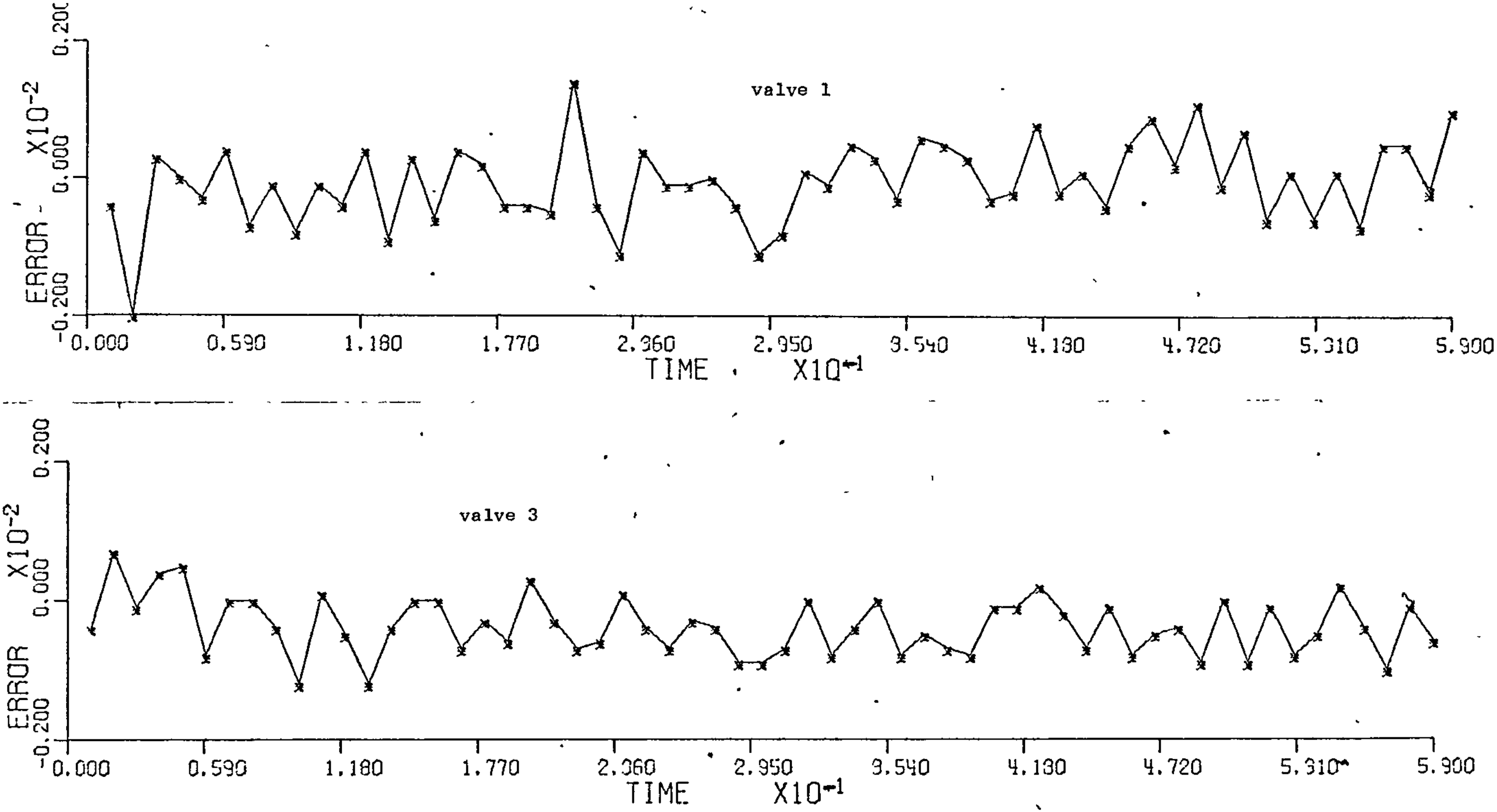


Fig. 8.14. Error plots for 1970 Draw valves (1) and (2)

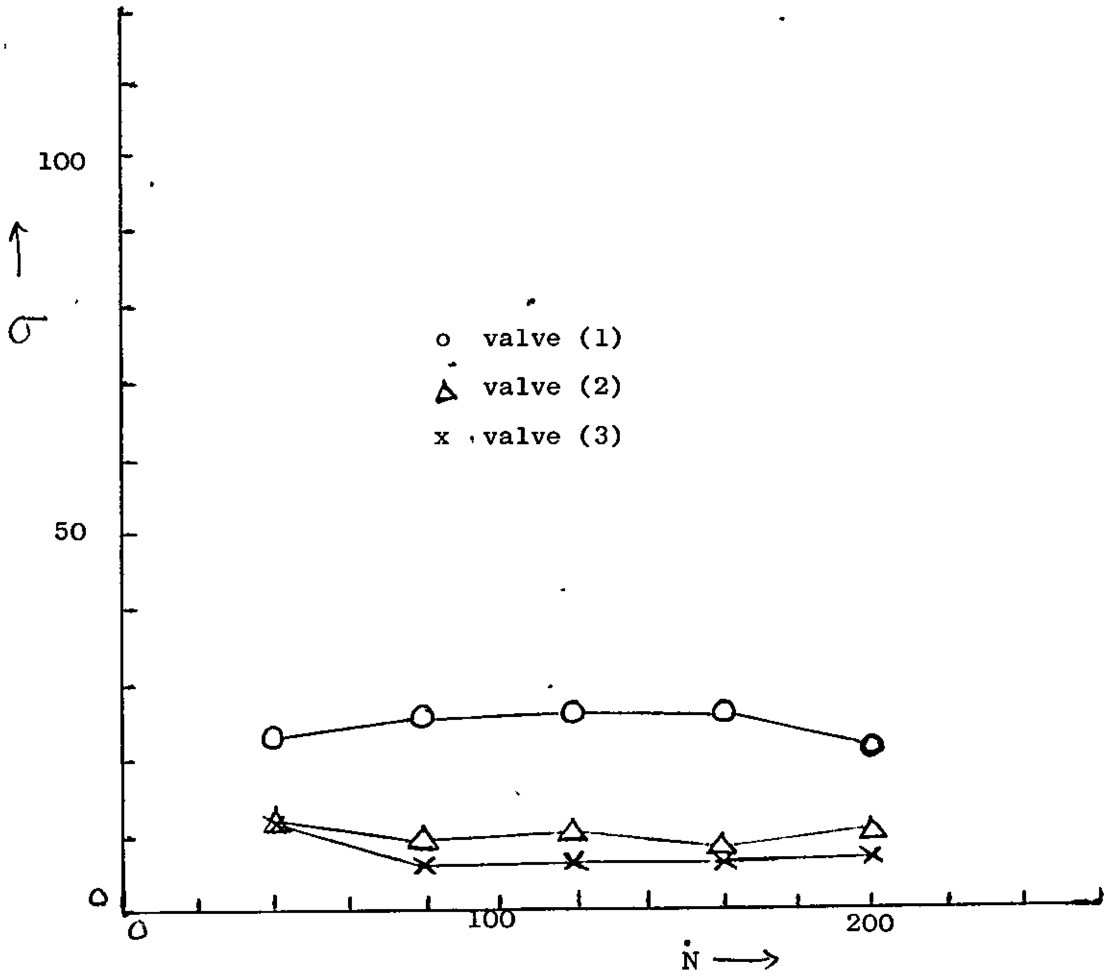


Fig. 8.15 1970 CVL valve data standard deviations of errors

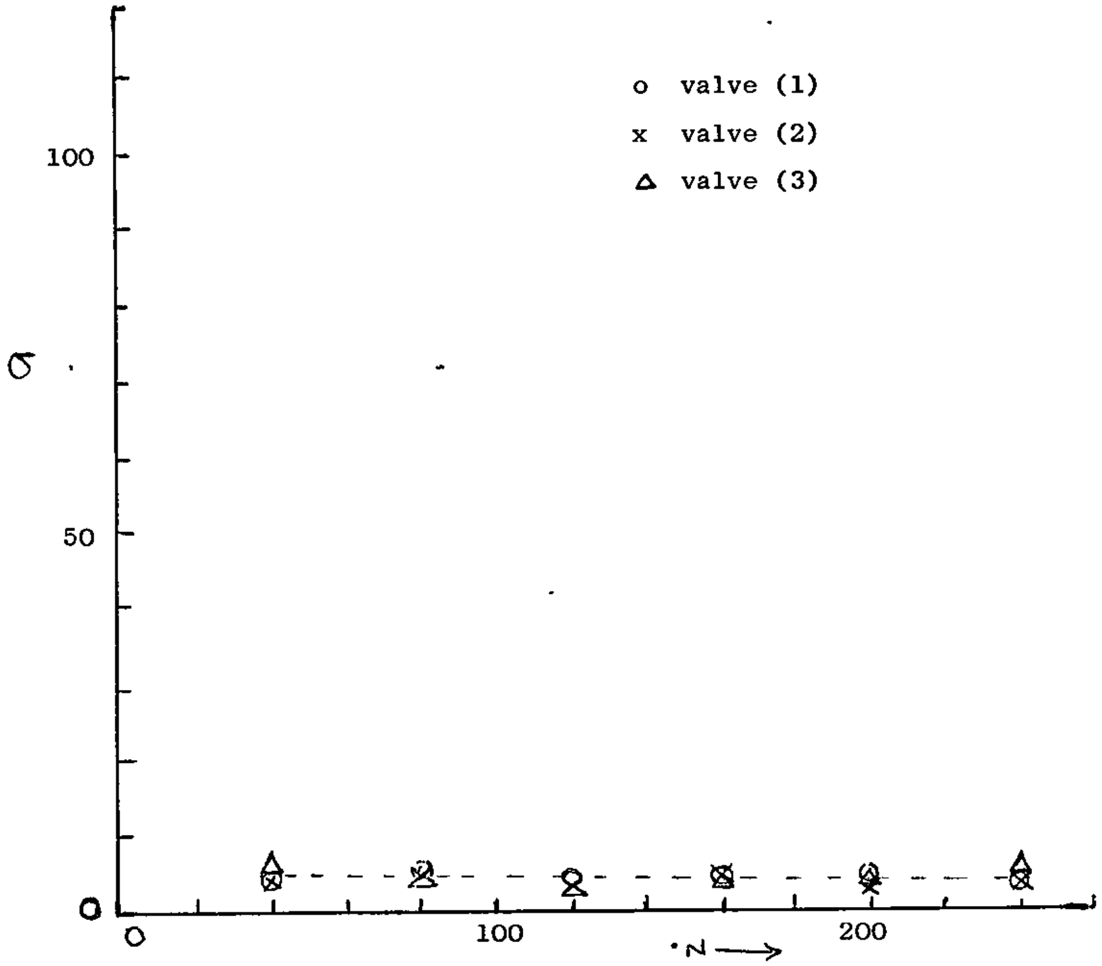


Fig. 8.16 1970 draw valve data standard deviation of errors

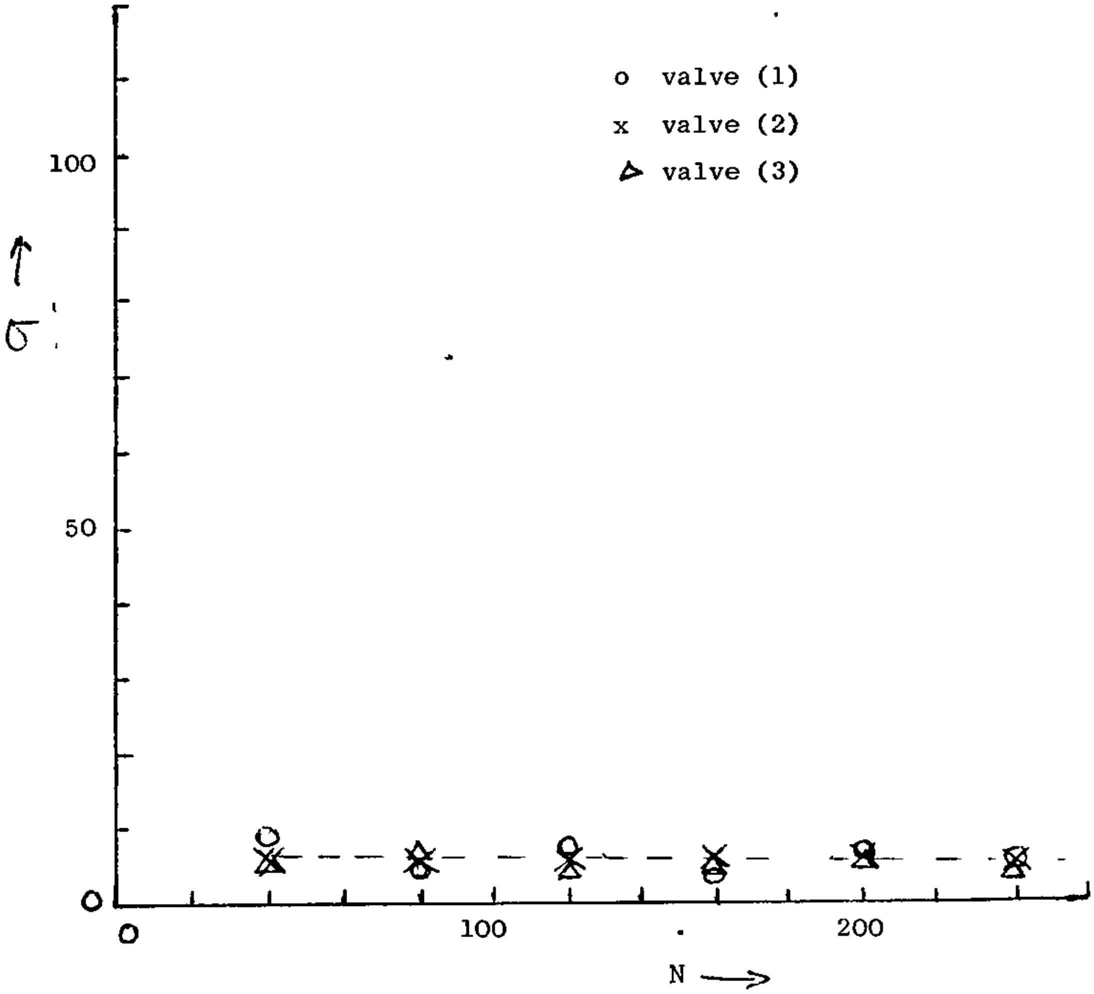


Fig. 8.17 1970 Top cooling valve data standard deviation of error

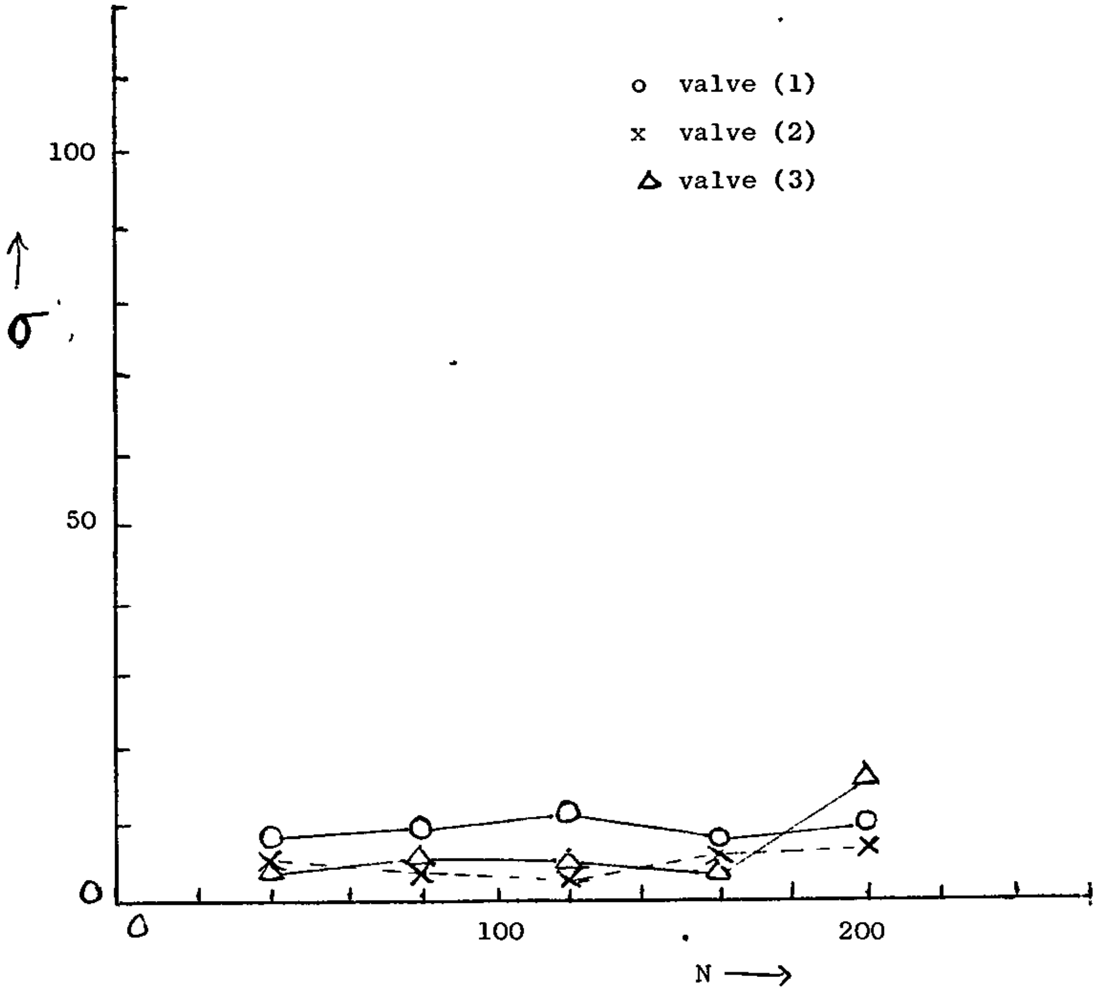


Fig. 8.18 1970 Bottom cooling valve data standard deviation of error

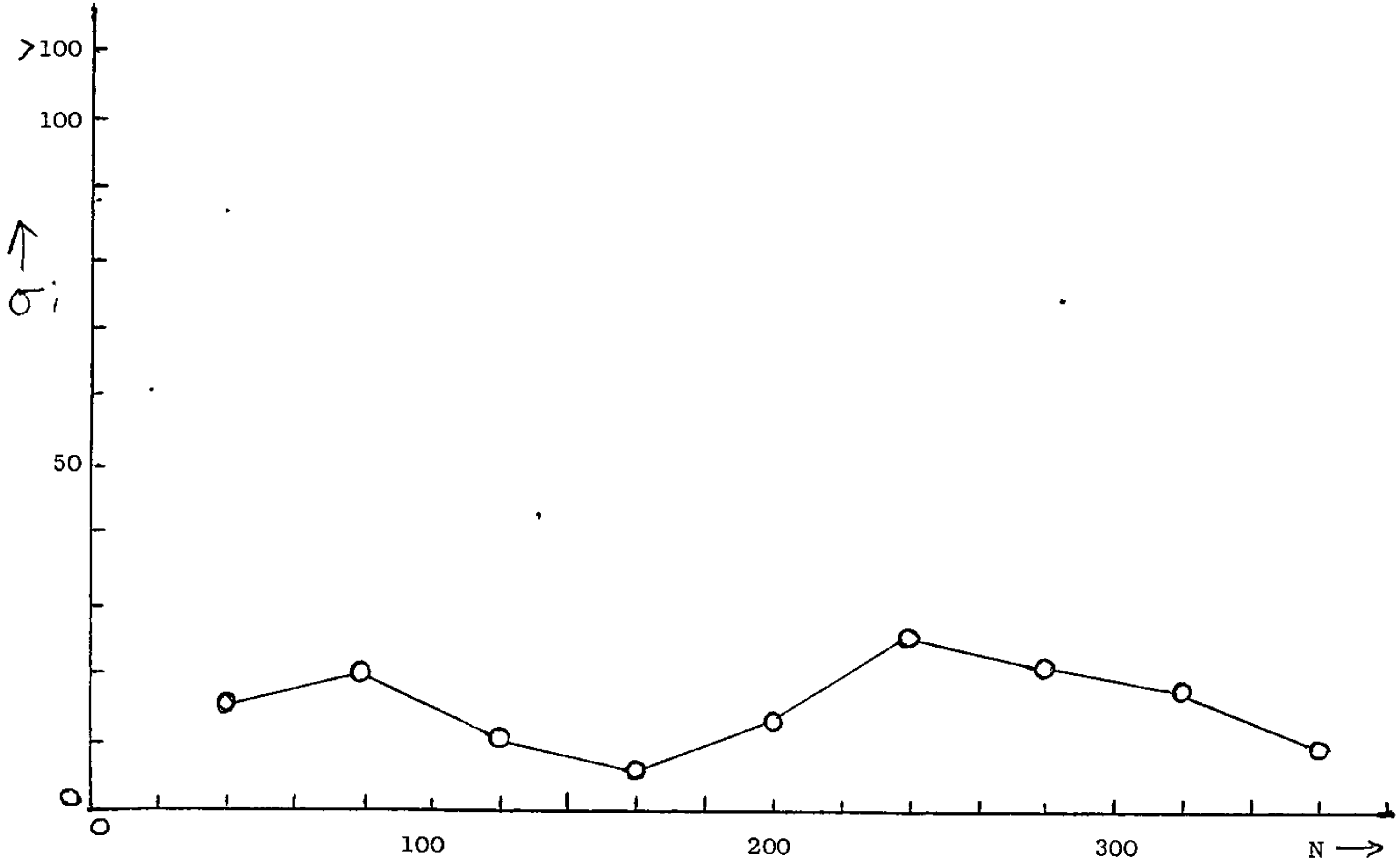


Fig. 8.19 1967 Bottom cooling valve data standard deviation of error (known zero error only)

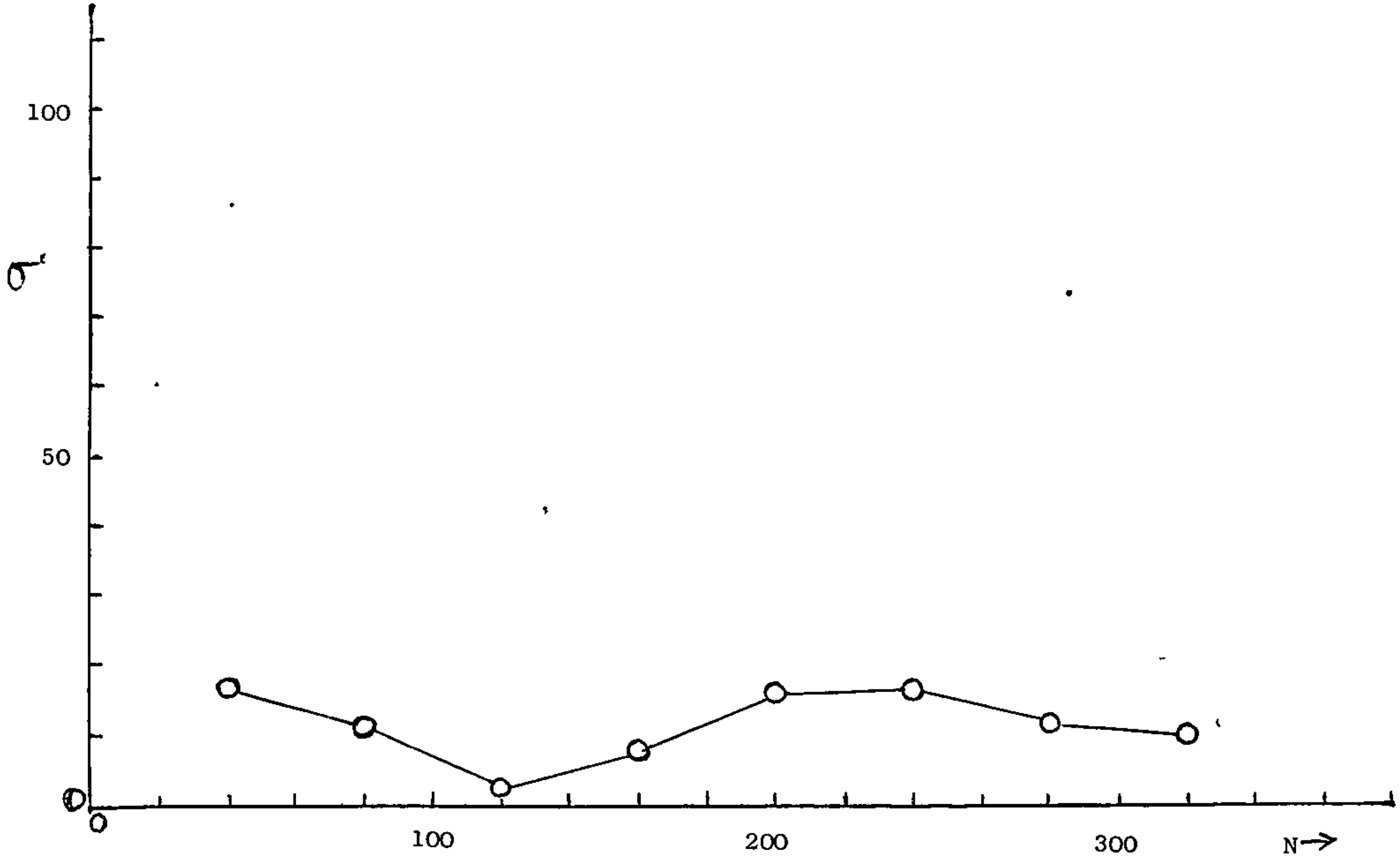


Fig. 8.20 1967 Top cooling valve data standard deviation of error (known sluggish and zero error)

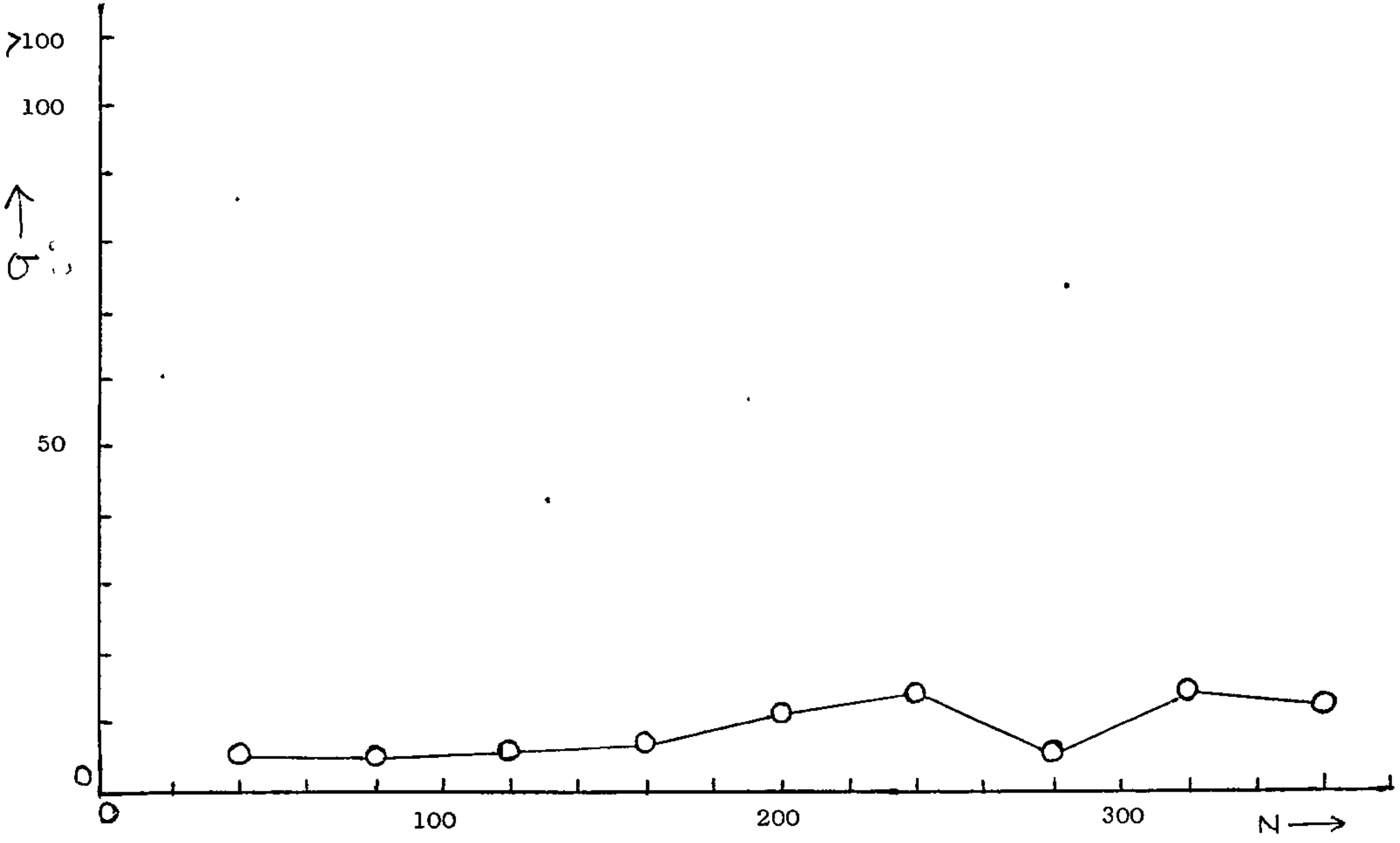


Fig. 8.21 1967 Top cooling valve data standard deviation of error (known sluggish and zero error)

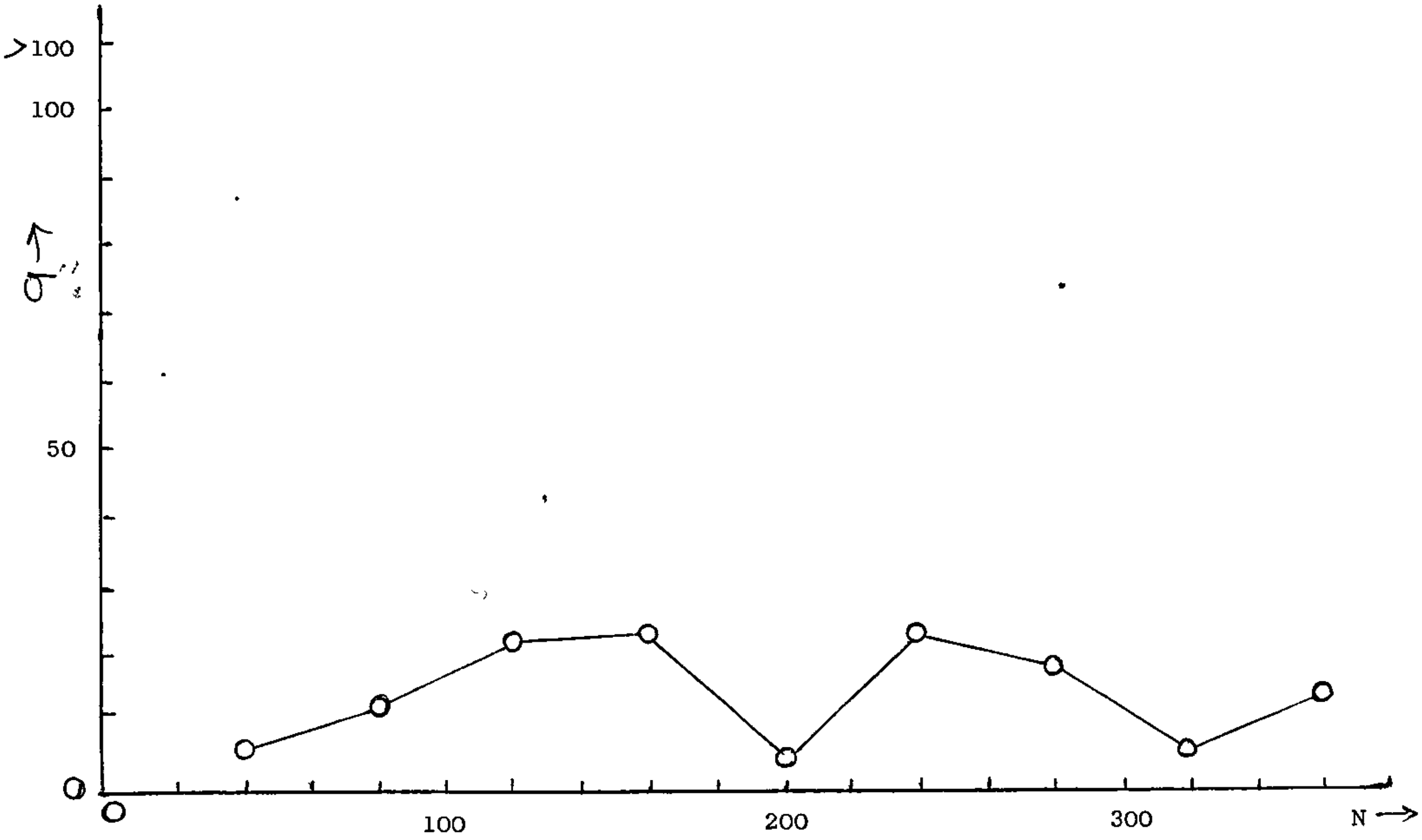


Fig. 8.22 1967 Bottom cooling valve data standard deviation of error (known sluggish and zero error)

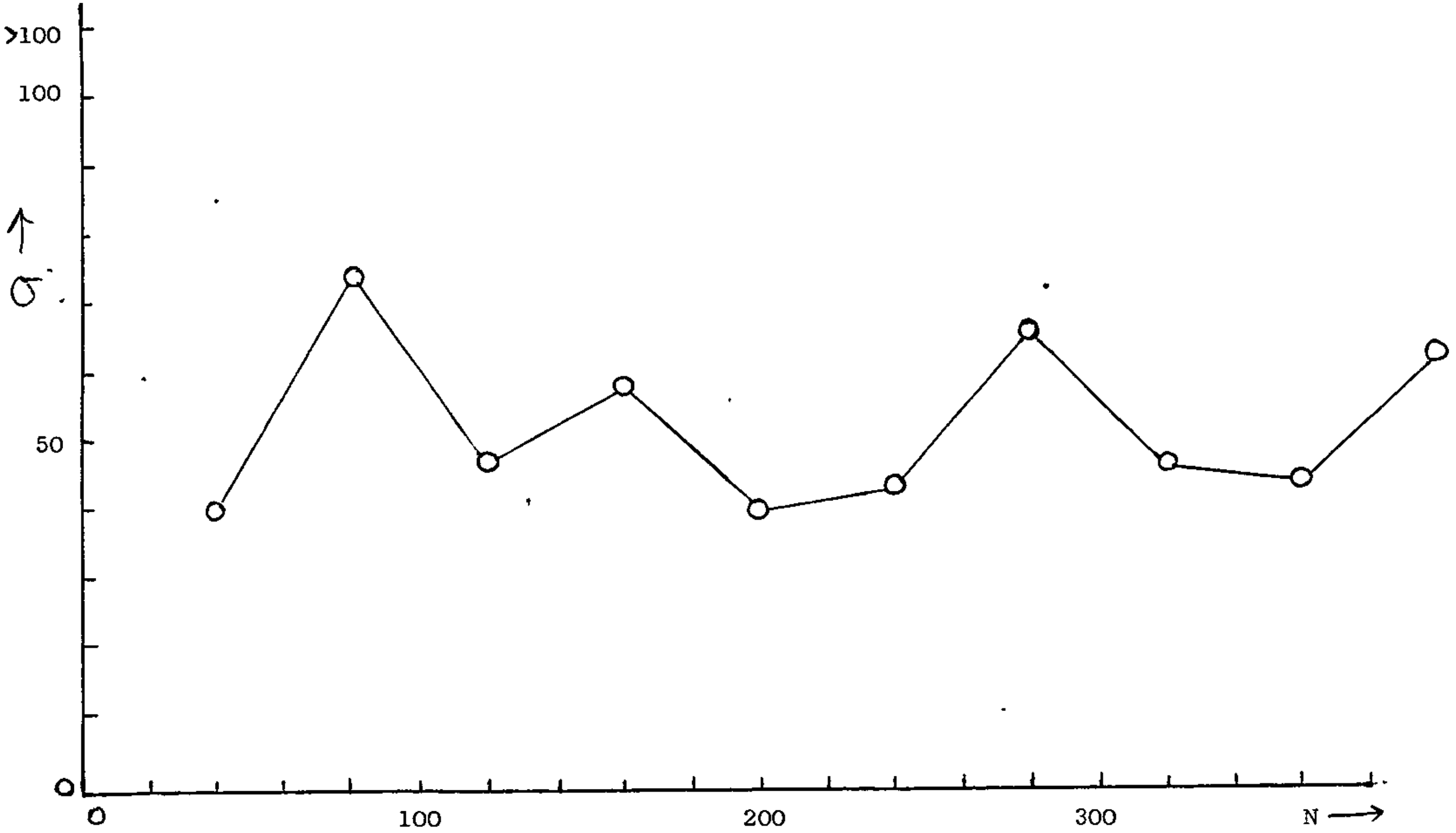


Fig. 8.23 1967 Bottom cooling valve data standard deviation of error (known sluggish and zero error)

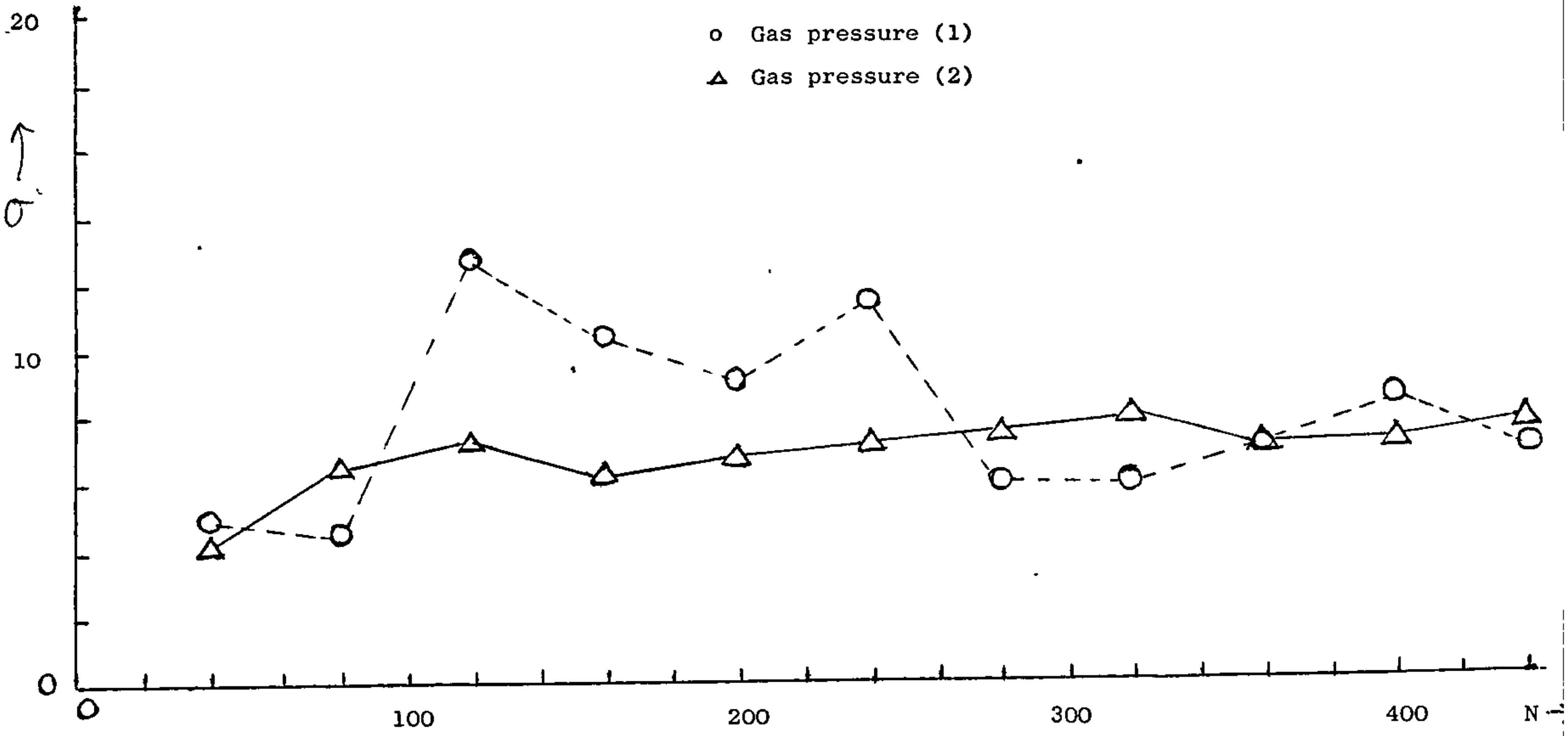


Fig. 8.24 Standard deviation of Gas pressure signal measurements

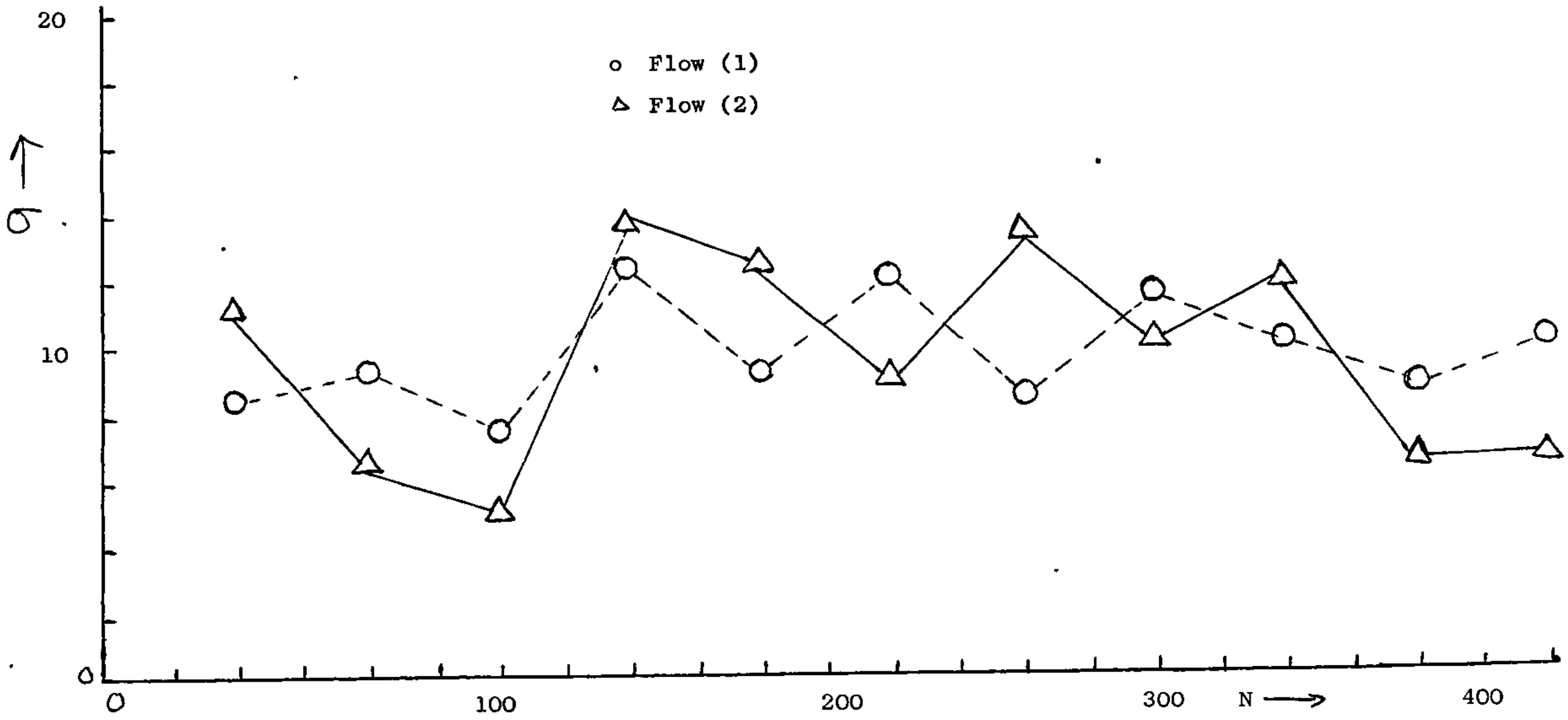


Fig. 8.25 Standard deviation of flow signal measurements

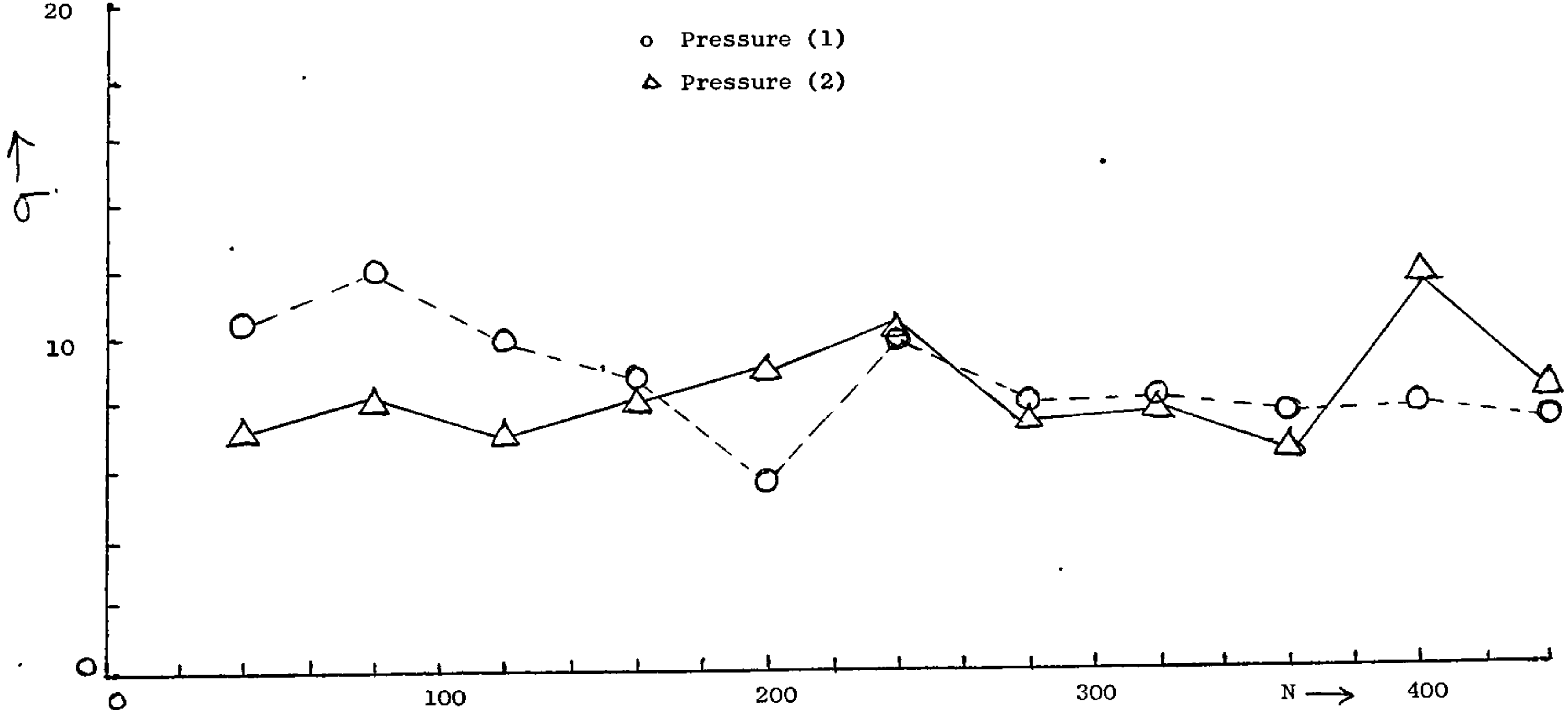


Fig. 8.26 Standard deviation of pressure signal measurements

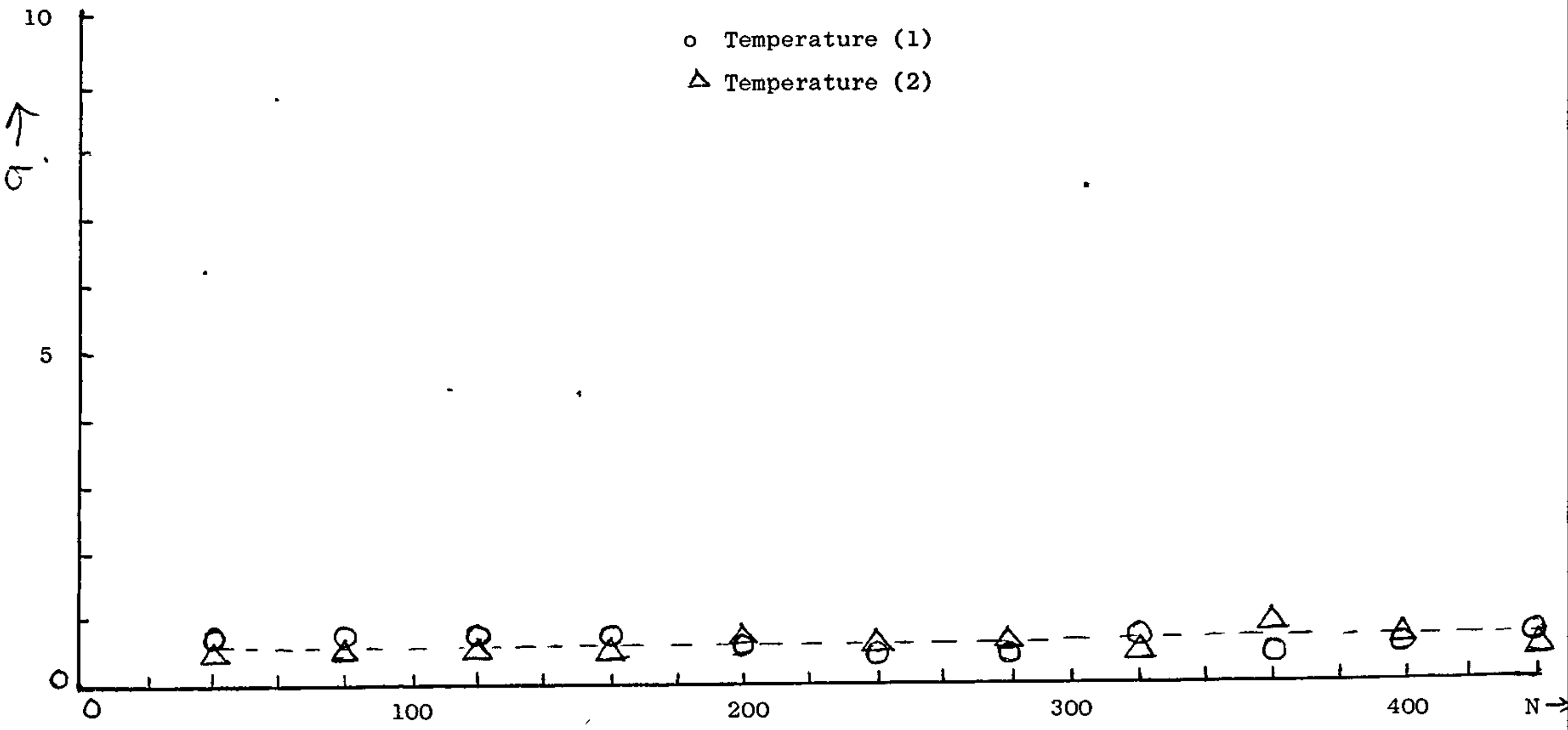


Fig. 8.27 Standard deviation of temperature signal measurements

9. AN INDUSTRIAL EXAMPLE

9. AN INDUSTRIAL EXAMPLE

The project has a strong industrial bias. The stage of direct industrial application and use of the malfunction detection techniques has always been envisaged. It was hoped that some of the algorithms could have been tried on-line on actual working industrial installations. Work was initiated on this line but the stage of trying out the algorithms was not reached in the present work. However, towards the end of this work, an interesting industrial situation that could have been ideal for an industrial testing of the algorithms arose. At this stage there was not enough time to do more than examine the problem . A probing of the problem was carried out and a possible line of approach to its solution is presented here.

9.1 The industrial problem

The process is an industrial batch polymerisation process. The temperature measurements and control are critical in the different cycles of the process. The process is not automated at present but will soon be.

The present arrangement uses two temperature measuring instruments in the same sheath - a resistance thermometer and a mercury in steel thermometer, to indicate the batch temperature. This is the critical temperature measurement.

The output of the resistance thermometer is logged by a data logger and the output of the mercury in glass thermometer is a chart recorder trace. The resistance thermometer has shown a high degree of unreliability, hitherto, and the mercury in steel thermometer has been much more reliable. With the present arrangement, the malfunctioning of the resistance thermometer is not known until after the batch process run is completed and the printout of the resistance thermometer is compared with the usually more reliable and accurate chart recording of the mercury in steel thermometer. This arrangement will not be satisfactory when the process is automated and the control actions will be based on the temperature measurement signals.

The company is in the process of installing an on-line process control digital computer to automate and control the process. It is desired to eliminate the mercury in steel thermometer and use the resistance thermometer only. This, of course, requires more reliable instrument signals from the resistance thermometer. It is not only desirable that the instrument signal be reliable but because of the importance of the temperature measurement, it will be desirable that any off-normal condition be detected immediately and to avoid poor plant availability, that approximate substitute estimate of the measurements be used in the circumstances of unreliable instrument signals.

This would be the right stage to plan and build these provisions into the computer.

9.2 The process characteristics

The batch process characteristics are well known. Briefly, it is a multi-stage batch process in which each stage involves heating the batch to a desired temperature and maintaining it at that temperature for a desired time. The heating is done by an oil jacket round the reactor. Apart from the measurements of the batch temperature, the heating oil temperatures at the inlet and outlet are also measured. The environmental conditions for their measurement are less severe than those for the measurement of the batch temperature.

A typical two stage reaction would look like Fig. 9.1. Known disturbances are sometimes introduced.

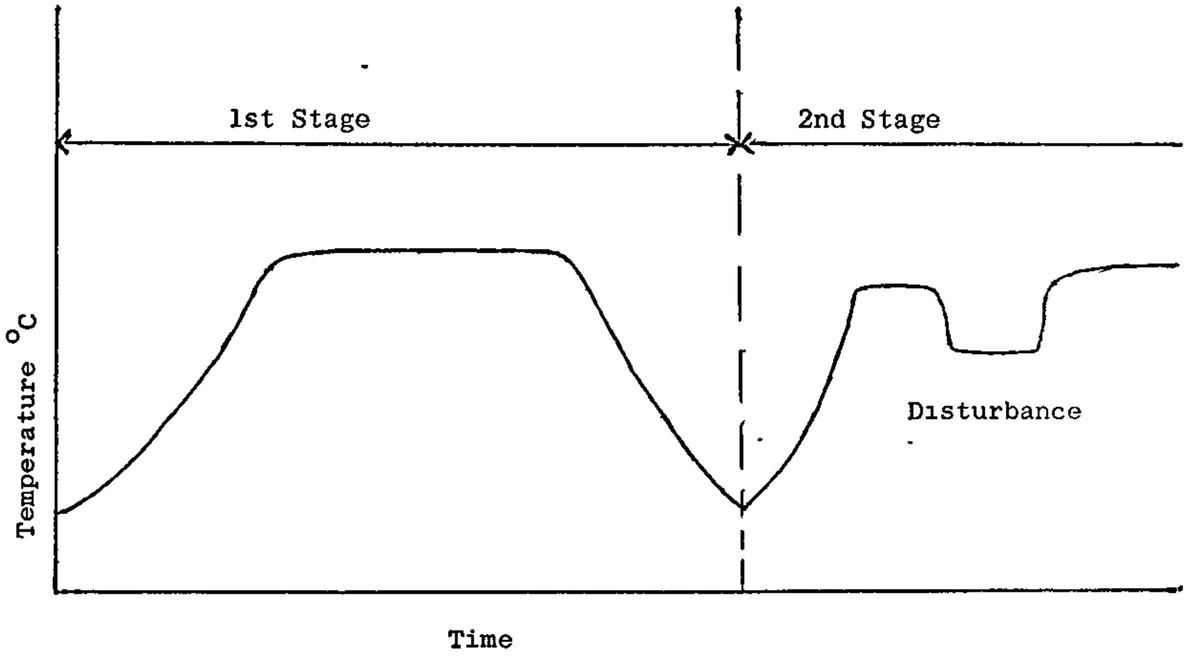


Fig. 9.1 Typical temperature characteristics of a two stage reaction

9.3 An approach to the problem

The first step in approaching the problem was to obtain data for normal functioning of the instruments and for off-normal conditions of the instruments also.

The resistance thermometer loggings were obtained and the corresponding mercury in steel thermometer readings were extracted from the chart recorder traces. All the data are given in the appendix tables A 32 to A 35. Most of the loggings were printed out at ten minute intervals. The readings are in degrees centigrade.

Fig. 9.2 is a plot of normal behaviour of the two instruments. It shows the degree of agreement of the readings to be expected normally. The closeness of the readings would be expected as the two instruments are placed in the same well.

Figs. 9.3 to 9.5 show the different forms of off-normal behaviour of the resistance thermometer signal. The temperature response was different from what it should be in all cases. Figs. 9.3 and 9.5 bring this out very well. Fig. 9.4 suggests that other than responding improperly, the bad instrument signals show excessive noisiness.

A study of these plots suggests that the problem could be amenable to the ideas generally discussed in Chapter 5. Most appropriate of all, is the use of the known process temperature characteristics as a forcing function for routine checking of the instrument behaviour. The temperature response at the start of a stage; the time to reach the reaction temperature; the temperature behaviour at the steady state and such characteristics should offer an effective means of detecting the on-set of off-normal behaviour. Fig. 9.4 suggests that the problem could also be amenable to the standard deviation approach - for instance, the standard deviation of the signal error.

Instrument signal data at shorter logging intervals could have been of interest but unfortunately these were not available and could not be obtained in the time that was available. A study of these shorter logging interval data could suggest the best approach and other possible approaches.

Detection of an off-normal condition in this case is only the beginning, even though a very important one, of any improvement of instrument signal reliability and plant availability. It is also necessary that some substitute action for the measured variable be taken on detection of unreliability in the instrument readings.

Approximate estimates of the batch temperatures, it would appear, could be got from a heat and mass balance calculation using such knowledge as the inlet and outlet temperatures of the heating oils which are usually reliably known.

The routine checks and calculations involved are very well suited to the process control computer and should provide added functions which it can perform and which should help to justify and make fuller the use of it.

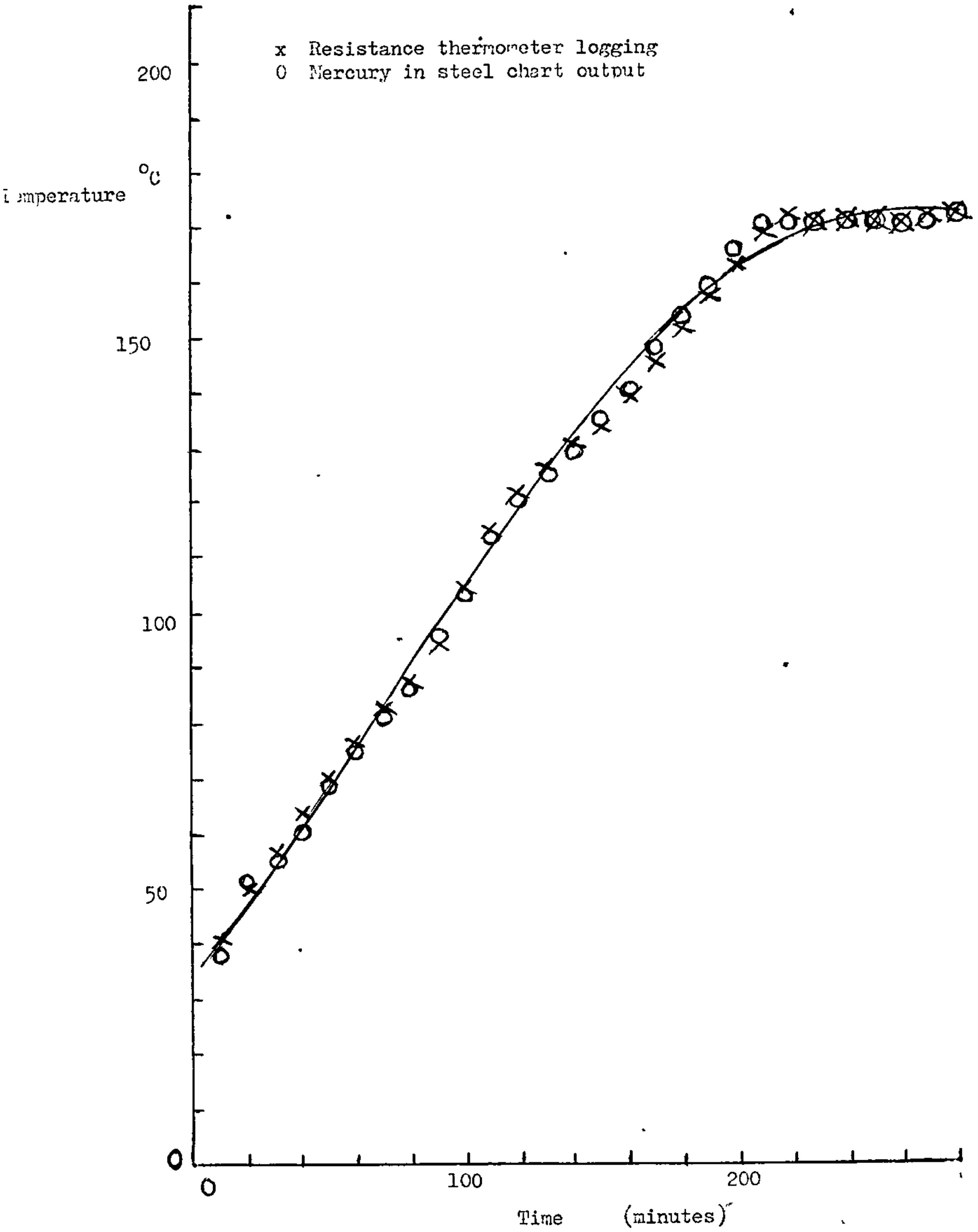


Fig 9.2 Normal behaviour of instruments

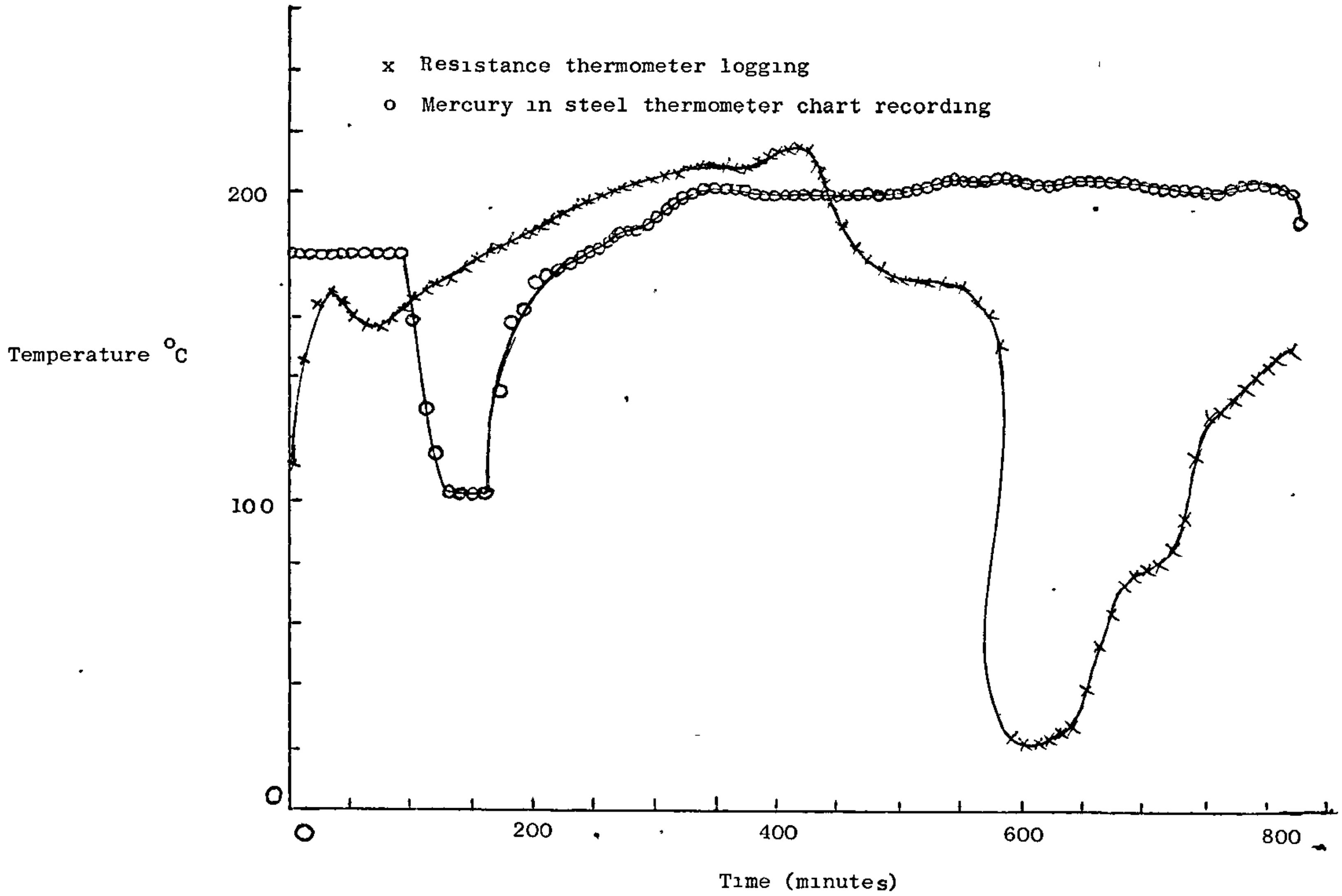


Fig. 9.3 Malfunction of resistance thermometer

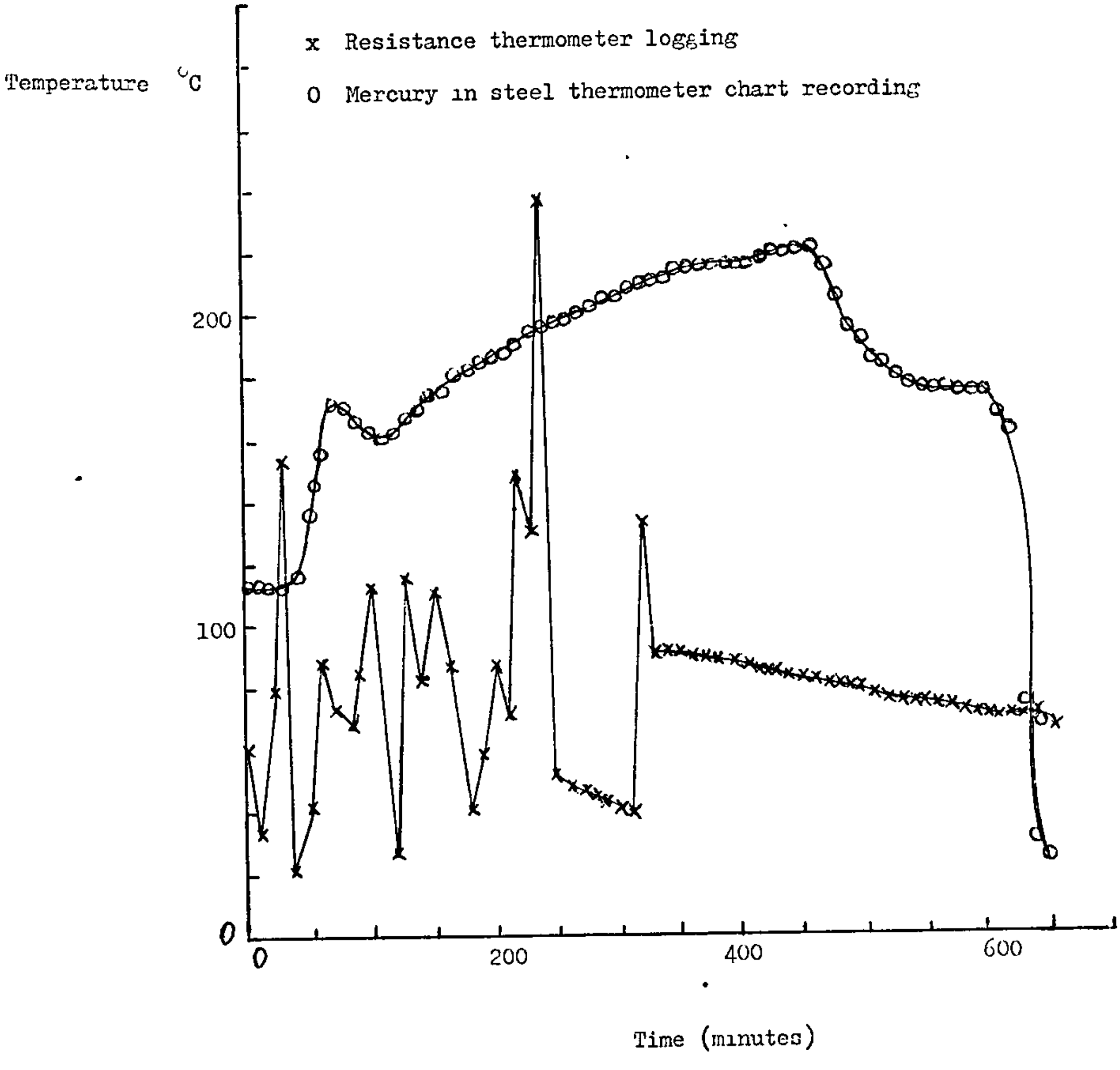


Fig 9.4 Resistance thermometer malfunction

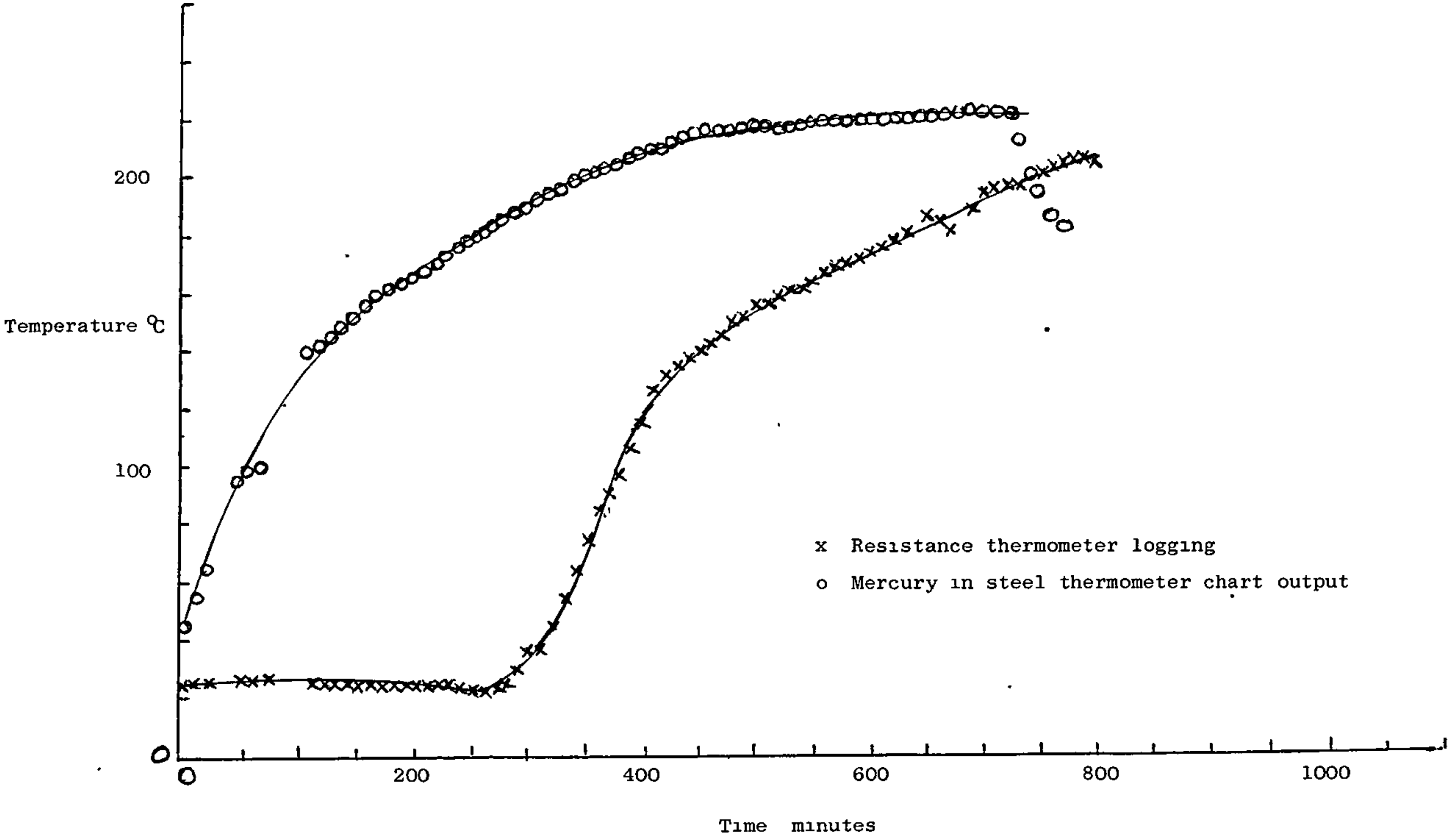


Fig. 9.5 Resistance thermometer malfunction

10. DISCUSSION

10. DISCUSSION

10.1 Review of Work

The complete program of work is industrially biased. It is a large program and because of its various unexplored aspects, there was a danger of pursuing too many different subjects at the same time. It was not easy narrowing down this work.

The review of computers and operators in industrial control, helped to reduce and define this project as instrument malfunction detection. Even though a lot of the work on the functions currently performed by the operator and computer is background work, on reflection, it helps bring out the relevance and importance of malfunction detection for automatic control of process plants.

One of the major experimental results achieved in this project is the result of the industrial survey of instrument reliability. There is a need for data on instrument reliabilities in their working environments. There is a glaring absence of this in the open literature. More information could have been obtained from the survey with an improvement on the existing data collecting systems in the different works studied. Despite the lack of some desirable information on the log tickets of two out of the three works the survey still yielded useful information.

Most valuable of the information from the survey is considered to be the operator comments obtained from one of the works. These threw light on instrument failure and their modes and behaviour during and at failure. Information on the reliability of the instruments, particularly the influence of environment, is invaluable for meeting future engineering requirements and for planning instrument maintenance.

The principles and techniques of instrument malfunction detection discussed promise very wide, direct or adapted applications in industry.

The use of display techniques should optimise man-machine interplay for malfunction detection. The continuing developments in display techniques augurs very well for this. The illustrations cited in this work show how effective the selection of the right display parameter(s) can be for malfunction detection.

The two main techniques (standard deviation and spectral analysis) tested in this work promise both effectiveness and versatility in application. The quality and superiority of the standard deviation algorithm lies in the fact that it is an average paramerer and also has the ability, based on the use of a running mean, to damp out spurious spikes and cope with normal drifts in the measured variable. The potential of the technique lies in its application to such situations.

The work based on spectral analysis techniques, did not reach the same stage as the use of standard deviation technique. What has been done in the project is effectively a feasibility study of its practical usefulness for malfunction detection. The results of the analysis of the differential pressure transmitter signals are very encouraging and suggest that effective algorithms for malfunction detection can be based on this technique. The display of the line spectra should be a very effective display method of malfunction detection for the operator. A lot more work clearly needs to be done in further development of this technique for use in industry. The emphasis placed on developing and exhaustively testing an algorithm based on the technique.

The case studies of different instrument signals bring out the relevance of considerations of the intrinsic characteristics of a particular instrument signal to the malfunction detection approach to be adopted for it.

The routine tasks of the techniques discussed and tested are very well suited to process control computers. It is an added function the computer can readily take on. In this way, fuller use can be made of its potentials, and it can contribute to the upgrading of the performance of its own instruments and to the plant system as a whole.

Even though the emphasis in the project has been on the detection of the malfunction of instruments, the malfunction of plant items such as pumps and compressors are important as well.

The detection of an off-normal situation should lead to action. The use of substitute measurements or changing of control organisation in such an event have been discussed. Some examples have been given and these show how fruitful an area for exploration and development this field is.

The detection of malfunction will only be the beginning of any maintenance or repair procedure. An actuation of diagnosis and location of the failure should provide information that will offer hope of getting more precise reliability data. Some such implications of malfunction detection have been discussed and it has always been envisaged that malfunction detection will be an initiation of the development of such implications.

10.2 Suggestions for further work

Generally, different aspects of this work need further development. Some suggestions have been made in the main text. Various suggestions put forward add up to a very large program of work but the following may be high lighted.

(a) Collection of reliability data in some more precisely defined instruments and environments. This will involve initiating new data collecting systems or improving existing systems to offer more useful information.

(b) Detailed study and analysis of malfunction detection done by the operator.

(c) Study of data from on-line computers' instruments going into the failed mode.

(d) Application of malfunction detection algorithms on on-line computers.

(e) Use of advanced filter algorithms of the type based on the work of Wiener and Kalman to detect instrument malfunctions.

ACKNOWLEDGEMENTS

The author is indebted to Dr. F.P. Lees for his supervision of this work and for his invaluable suggestions and sustained interest in the success of this project. He wishes to thank Professor D.C. Freshwater for his interest and encouragement. The entire staff of the Process Dynamics and Control Group showed a healthy interest in the project for which the author is grateful.

There were illuminating discussions with many of the staff of the Electrical Engineering Department, especially Dr. M.H. Ackroyd on time series analysis. The work on industrial survey of the reliability of instruments received the collaboration of Dr. F.P. Lees and Mr. G.F. Engel for which the author is grateful. The technicians, especially the Chief Technician, always showed willingness to help. M. Morris helped with obtaining the computer plots of the industrial data. The author is grateful for all this kindness.

Without the offer of a grant from the Department of Chemical Engineering and the University, this work would not have been carried out. The author is grateful for this grant.

The patient job of typing this thesis has been done by Miss Everline Johnson.

REFERENCES

1. F.P. LEES "The Evaluation and Organisation of New On-line Computer Control Projects in the Chemical Industry" J. of Birmingham Univ. Chem. Eng. Soc. Vol. 19, No. 3, 1968.

2. P.W. GALLIER "Surveying process digital control" 1965 IEEE International Convention RC pt. 6.Vol. 13 pp. 2-9.

3. A.H. HIX "Status of Process Control Computers in the Chemical Industry" Proc. IEEE, Vol. 58 Jan 1970.

4. MCMILLAN,, J. Control, 10, 512 1966.

5. ROQUEMORE, K.G. AND EDDEY, E.E., Chem. Eng. Prog., 57 (9).

6. KAY, P.C.M., Industrial Electronics, 4, 50, 1966.

7. BARTH, J. AND MAARLEVELD, A. The Application of Automation in the Process Industries, p.23 Inst. Chem. Eng. 1967.

8. BOX,, G.E.P. AND JENKINS,, G.M., Application of Mathematical Models in Chemical Engng., Research and Production , p. 61, Inst. Chem. Eng. 1965

9. KOPPEL, H.H. "Direct Digital Control" Automation Oct. 1969 pp. 77

10. WEEKS, L.W. "Magic memory solves raw mix problems" Rock Prod., Vol. 63, April 1960.

11. KAISER, V.A. AND SCHIOYA, Y. "Computer controls two kilns at Japanese cement plant", Rock Prod., Vol. 67, Feb. 1964.

12. TRAUFFER, W.E. "New Computer control concept adapted to Penn-Dixies Peloskey wet process plant", Putt and Quarry, Vol. 58 Dec. 1965.

13. "Closing the Loop at North Western States", Vol. 58 May 1966.

14. WEEKS, L.W. "Control of Kiln operations with a digital computer", Mining Congr. J., June 1964.

15. BAY T et al "Dynamic control of the cement process with a digital computer system", IEEE Trans. Industry and General Applications, Vol. 19A-4 pp. 294-303, May-June 1968.

16. KAISER, V.A. "A scheme for dynamic control of a cement kiln" Proc. 4th Annual Cement Industry Operations Seminar, Chicago, Illi. Dec. 1968.

17. JOHNSON R.L. AND LYLE J. "Installations of a computer for kiln control (a method)," Minerals Process, Vol. 6 Aug. 1965.

18. - "The year ahead" Rock and Prod. Vol. 69, pp. 70-71, Jan 1966.

19. TRAUFFER W.E. "Computer, other changes at Dundee's Michigan plant", Pitt and Quarry, Vol. 59, July 1966.

20. HIGHAM J.D. "Computer control at Dalen Portland Cement - fabrick", Pitt and Quarry, Vol. 61, Aug. 1968.

21. "Cement Plant will use direct digital control", Control Engng., Vol. 13 p. 24, July 1966.

22. -"First DDC system in cement goes on-line", I.S.A. J., Vol. 13, p. 16, Dec. 1966.

23. WONG K.W. et al., "Computer control of the Clarksville cement plant by State space design method", Proc. IEEE Cement Industry Tech. Cmf. St. Louis, Mo., May 1968.

24. KIHLSTEDT P.G. "Der Zusammenhang Zivischen Kornverteilung und spezifischer Oberflache bei der Zerkleinerung", Zenaent - Kalk - Gips, Vol. 16, No. 2 1963.

25. TRAUFFER W.E. "Whitehall succesfully applies full digital control, Pitt and Quarry, Vol. 59, pp 127-140 July 1966.

26. HURLBUT M.R. et al "Applications of digital computer control to the cement manufacturing process" Presented at the Internatl. Seminar on Autom. Control in line, Cement and Connected Industries, Brussels, Belgium, Sept. 1968.

27. HOLMES J.A. "A contribution to the study of communication – a modified form of Kick's law" Trans. Inst. of Chem. Engnrs. Vol. 35, 1957.

28. KUONG J.F. "Nomograph finds cyclone particle size" Hydrocarbon Process, Vol. 46, March 1967.

29. ROSE H.E. "A mathematical analysis of the internal dynamics of the ball mill on the basis of probability theory" Trans. Inst. of Chem. Engrs. Vol. 35 1957.

30. BOND F.C., "The third theory of communition". AIME Soc. Minining Engnrs Vol. 193, May 1952.

31. BARTON A.D. et al, "Commissioning and Operation of a Direct Digital Control Computer on a cement Plant".

32. BREWSTER D.B., AND BJERRING A.K., "Computer Control in Pulp and Paper 1961-1969" Proc. IEEE, Vol. 58 No. 1 Jan. 1970.

33. FOX E.C. "Computer control of the continuous digester at the Gulf States Paper Corporation", Southern Pulp Paper Manuf. Vol. 27, No. 2, Feb. 10, 1964.

34. FOX E.C., "Control Strategy", TAPPI, Vol. 49, 5, p. 87A. May 1966

35. HOAG D.S. "Analog computer control of a Kamyr digester" TAPPI, Vol. 47, pp. 734-741 Dec. 1964.

36. HOAG D.S. "Computer Control of a Kamyr Digester", presented at the 2nd Ann. Workshop on the Use of Digital Computers in Process Control, Louisiana State University, Baton Rouge, La. March 1967.

37. SANGREGORIO G. AND ALSHOLM O., "Integrated computer control of a paper machine - process control", Billeruds/ IBM Private Symposium, June 1966.

38. ASTROM K.J. "Computer Control of a paper machine - application of linear stochastic control theory", IBM J. Res. and Develop., Vol. 11 No. 4, pp. 389-405, July 1967.

39. ASTROM K.J., "Computer problems in paper making", presented at the IBM scientific computing symp. N.Y., Oct. 1964.

40. PETTERSON B., "Optimal production schemes co-ordinating sub-process in a complex integrated pulp and paper mill" presented at the ISA/CPPA Symp. on pulp and paper process control, Vancouver, Canada, April 1969.

41. MARTENSSON E., "Integrated computer control of a paper machine - production planning", presented at the Billeruds/IBM Private Symp. June 1966.

42. EKSTROM A AND HEMPEL A., "Integrated computer control of a paper machine - the production supervising system" Ibid.

43. ASTROM K.J. AND BOHLIN T., "Integrated computer control of a paper machine - new methods for control strategy design in operation" Ibid.

44. ASTROM K.J. AND TVEIT O., "Integrated computer control of a paper machine – quality control" Ibid.

45. EKSTROM A. "Integrated computer control of a paper machine - systems summary" Ibid.

46. BILLERUDS A.B. AND I.B.M.WORLD TRADE CORP. "Computer plays sophisticated role at a Swedish Mill", Pulp and Paper Magazine of Canada, Vol. 67, pp. 100-103, Oct. 1966.

47. EKSTROM A.AND SENGREGORIO G., "Automating the control loops on a Swedish Kraft paper machine", Pulp and Paper, p.30, April 3, 1967.

48. ALSHOLM O., "Computer control at Billerud", presented at the ISA/CPPA Symp. on Pulp and paper process control, Vancouver, Canada, April 1969.

49. ALSHOLM O. "Integrating process computers into production operations", Pulp and Paper Internatl. Vol. 73, pp. 43-47, Feb. 1969.

50. SIDEBOTTOM A.W. and OUGHTON K.D., "Computer Control at Wolvercote paper mill", Paper Technol. Vol. 6 no. 4 pp. 335, 1965.

51. LARKING J.H. "Are computers for paper makers?" Norsk. Skogind., Vol. 20 no. 6 pp. 218-223, 1966.

52. BENNETT J.A. "Computer Controlled paper making at Grove Mill Paper Company", The Paper Maker, May 1968.

53. CLOSE D.G., "Computer Control of the LD/AC steel making process" I.Ch. E. Symp. series No. 24 (1967: Inst. Chem. Engnrs.)

54. TESCHNER H.G., "Controlling Data Flow in a steel mill" Cont. Engng. April 1968 p. 76.

55. HESS W.T. et al "The Little Gipsy Story" Electrical world, May 1962.

56. SKLANSKY J. "Learning Systems for automatic control" IEEE International Convention Proc. part 6, March 1965.

57. BRISTOL D.R., "Computer Controlled Hot Rolling of Steel", 19th Annual ISA Conf. Proc., Vol. 19, 1964.

58. THOMSON J.W. et al, Trans. Soc. Instr. Tech 19, 19, 1967.

58. - "Digital Mini-Computers on the British Market" Automation Sept. 1969 pp. 18-21.

59. FREAR D. "The Industrial applications of small computers,, Automation. Sept. 1969 p. 9.

60. - "Small Control Computers" Equity Research Associates, July 31, 1969.

61. MERCER J.R., "Reliability of solenoid valves" Conference on Safety and Failure of Components, University of Sussex, Sept. 3-5, 1969, Inst. Mech. Engnrs. (London).

62. HENSLEY G. "Safety assessment - A method for determining the performance of alarm and shut down systems for chemical plants" Trans. Inst. Meas. and Cont. 1968, 1 , T72.

63. LOW T.A.W. and SANDLE P.J., "Analysis of reliability data from operational control equipment," in Reliability in Electronics, Inst. Elec. Engnrs. (London) 1969, p. 178.

64 I.S.A. MANAGEMENT COMMITTEE, MAINTENANCE DIVISION, "Standard Instrument Rating," (draft) Inst. Soc. of America 1970.

65. BAZOVSKY I., "Reliability Theory and Practice" Prentice Hull, 1961.

66. MYERS R.H. et al, "Reliability Engineering for Electronic Systems," John Wiley 1964.

67. BRITISH STANDARDS INSTITUTION (BS 4200: Part 2: 1967) and I.E.C. (International) definitions.

68. LENK J. "ABC's of Thermocouples," W.Foulsham and Co. Ltd., Slough, England, 1968.

69. CHOROFAS D., "Statistical Processes and Reliability Engineering", 1960 (Princeton: van Nostrand Co. Inc.)

70. SANDLER G., "System Reliability Engineering", 1963 (Englewood Cliffs: Prentice - Hall Inc.).

71. LLOYD D.R. and LIPOW M. "Reliability: Management, Methods and Mathematics", 1962 (Englewood Cliffs: Prentice - Hall Inc.).

72. PIERUSCHKA E. "Principles of Reliability", 1963 (Englewood Cliffs: Prentice - Hall Inc.)

73. COX D.R. "Renewal Theory", 1962 (New York: John Wiley & Sons Inc).

74. CALABRO S.R. "Reliability Principles and Practice", 1962 (New York: McGraw - Hill Book Co.).

75. ZELEN M. "Statistical Theory of Reliability", 1963 (University of Winsconsin Press).

76. VON ALVEN W.H. (Ed.) "Reliability Engineering", 1963 (Englewood Cliffs: Prentice - Hall Inc.)

77. BARLOW R. and PROSCHAN F. "Mathematical Theory of Reliability". 1965 (New York: John Wiley & Sons Inc.).

78. ROBERTS N.H. "Mathematical Methods in Reliability Engineering" 1964 (New York: McGraw - Hill Book Co.).

79. MYERS R.H. et al "Reliability Engineering for Electronic Systems", 1964 (New York: John Wiley & Sons Inc.).

80. POLOVKO A.M. "Fundamentals of Reliability Theory", 1968 (New York: Academic Press Inc.).

81. HAVILAND R.P. "Reliability Engineering and long life Design", 1964 (Princeton: Van Nostrand Co. Inc.).

82. GOLDMAN A. and SLATTERY T. "Maintainability: A major element of system effectiveness", 1964 (New York: John Wiley & Sons Inc.).

83. IRESON W.G. (Ed) "Reliability Handbook", 1968 (New York: McGraw - Hill Book Co.).

84. SCHOOMAN M.L. "Probabilistic Reliability: An Engineering Approach", 1968 (New York: McGraw - Hill Books Co.).

85. HAJEK and DUPAC V. "Probability in Science and Engineering", 1967 (New York: Academic Press).

86. BLANCHARD B.S. and LOWERY E.E. "Maintainability Principles and Practice", 1969 (New York: McGraw - Hill Book Co.).

87. GNEDENKO B.V. et al "Mathematical Methods of Reliability Theory", 1969 (New York: Academic Press Inc.)

88. RUDD D.F. and WATSON C.C. "Strategy of Process Design" 1968 (New York: John Wiley and Sons Inc.).

89. WEISMAN J. "Engineering Design Optimisation under conditions of risk", 1968 Ph.D Thesis, University of Pittsburg.

90. RUDD D.F. Ind. Engng. Chem. Fund. 1962 <u>1</u>, 138

91. WILLIAMS H.L. and RUSSELL B.H. "The application of NASA reliability techniques to the Chemical Industry" paper presented to third joint meeting of the A.I. Ch. E and Puerto Rican I.Ch.E., San Juan, Puerto Rico, May 17-20, 1970.

92. TUCKER W. and CLIVE W.E., "Plant Reliability and its impact on large plant design and economics". Ibid.

93. CORNETT C.L. and JONES J.L. "Reliability revisited" Ibid.

94. PAN J.J., "Reliability Engineering and the Process Plant Industry", 1970, M.Sc. Thesis, Loughborough University of Technology.

95. BUFFAM B.A. et al. "Reliability Engineering – A Rational Technique for Minimising Loss" Inst. of Mech. Engnrs. Conference on Maintenance in the Process Industries, Durham 24th–25th March 1971.

96. BARLOW R.E. and HUNTER L.C. ."Optimum Preventive Maintenance Policies", Operations Research, Vol. 8, No. 1 Jan–Feb. 1960, pp. 90-100.

97. CROOKES P.C.I., "Replacement Strategies", Operational Research Quarterly, Vol. 14, No. 2, June 1963. pp. 167-185.

98. GLASSER G.J. "Planned Replacement. Some Theory and its Applications", Journal of Quality Technology, Vol. 1, No. 2, April 1969, pp. 110-119.

99. FRESHWATER D.C. and BUFFAM B.A. "Reliability and Maintenance in Process Plants". Paper Presented at the Instn. of Chem. Engnrs. Symposum, New Castle, July 1971.

100. NARESKY J.J., Proc. Sixth Reliability and Maintainability Conference, S A.E., A.S.M.E., and A.I. A.A. 1967, p. 113.

101. GREEN A.E. and BOURNE A.J. U.K.A. E.A. Report No. AHSB(S) R117, parts 1-3, 1966.

102. EAMES A.R. U.K.A.E.A. Report No. AHSB(S) R138, 1967.

103. BADGER F.W. Symposium on Stop Equipment Failures Analytically, The American Inst. of Chem. Engnrs. 68th National Meeting, 6th Petrochemical and Refining Exposition, Houston, Texas Feb. 28 – March 4, 1971.

104. JONES F.G. "Prevention of Catastrophic Failure of Reciprocating Compressors" paper No. 47C. Ibid.

105. BETRAM J.B. et al "Acoustic Emission – A powerful new tool for the Petroleum Industry" paper No. 47d, Ibid.

106. GRANT J. "An economic design method for computer supervision of large plant"(draft). Paper to be presented at Symposium on "On-Line Computer Methods Relevant to Chemical Engineering" Nottingham, BCS/I.Chem. E. Sept. 1971.

107. HOYTE D.W. "The Checking and calibration of process instruments on the plant with a digital computer" I.E.E.E. On-line measurement techniques 1968.

108. TATIEVSKII A.B. "Allowance for gradual failures in calculations of the reliability of electrical measuring instruments" Reliability of Electrical Measuring Instruments (In Russian) On Tipribor, Moscow (1967).

109. RAIVERSON S.M. "Theory of instrument reliability testing on the basis of Poisson distribution" Problems of the Reliability of Radio Electronic Equipment (edited by I.I. Morozona) (in Russian) Izd. Sov. Radio, Moscow (1959.)

110. ARUTYUNOV V.O. et al "Reliability in Measures and Instruments – General problem and specific aspects of reliability in measuring devices". Measurement techniques No. 3 March 1969.

111. ROLLINS T.J. and MARTIN T.D. "An analysis of Instrument functions to produce efficient calibration systems" Instruments and control (1966) pp 165-174.

112. ROLLINS T.J. and MARTIN T.D. "The assured performance calibration (APC) program", pp 463-473) Nineteenth Annual Convention Transactions, ASQC, 1965.

113. WELBOURNE D. "Alarm analysis and display at Wylfa Nuclear power station" Proc. IEE Vol. 115, No. 11 Nov. 1968.

114. PATTERSON D. "Application of a computerised alarm - analysis system to a nuclear power station" Proc. IEE Vol. 115, No. 12 Dec. 1968.

115. BOWEN H.M. "The Imp in the System" The Human Operator in complex systems. Edited by Singleton W.T. et al., Taylor Francis Ltd., London 1967.

116. HUGO WOLFF, Introductory paper, Symposium on Data Reduction, Communication and Presentation. Inst. Meas. and Control, Univ. of Sussex, March 22-25, 1971.

117. KOPPEL L. "Introduction to Control Theory," pp 453-461. Prentice - Hall, Inc. (1968).

118. LEE Y.W., "Statistical Theory of Communication", Wiley, New York 1960, Chap.12.

119. LANGE H.F.H., " Correlation Techniques"(P.B. Johns Transl) Van Nostrand, Princeton, 1967.

120. GENTLEMAN W.M. and SANDE G. "Fast Fourier transforms - for fun and profit", 1966 Fall joint computer conference AFIPS Proc. Vol. 29 Washington DC: Spartan, 1966 pp. 563-578.

121. BOGGERT B.P. et al "The frequency analysis of time series for echoes: Cepstrum, pseudo autocovariance, cross-cepstrum and saphe-cracking", Time series analysis, Murray Rosenblatt, ed. New York: Wiley 1963, pp 201-243.

122. TUKEY J.W., "An introduction to the calculations of numerical spectrum analysis, "in spectral analysis of time series, Bernard Harris, ed. New York: Wiley, 1967 pp 25-46.

123. GOLD B. and RADER C.M., "Digital Processing of Signals." New York: McGraw - Hill 1969.

124. BINGHAM C. et al., "Modern techniques of power spectrum estimation", IEEE Trans. Audio and Electroacoustics, Vol. AU-15, pp 56-66, June 1967.

125. BLACKMAN R.B. and TUKEY J.W., "The Measurement of Power Spectra." New York: Dover, 1958.

126. NOLL A.M. "Short-time spectrum and 'cepstrum' techniques for vocal - pitch detection," J. Acoust. Soc. Am., Vol. 36, pp 296-302, 1964.

127. OPPENHEIM A.V. et al. "Nonlinear fittering of multiplied and convolved signals "Proc. IEEE Vol. 56, pp. 1264-1291, Aug. 1968 (Reprinted in IEEE Trans. Audio and Electroacoustics, vol. AU-16, pp 437-465, Sept. 1968).

128. PARZEN E., "Statistical spectral analysis (single channel case) in 1968", Tech Rep. 11, ONR Contract Nonr - 225 (80) (NR-042-234), Stanford University, Dept. of Statistics, Stanford, Calif. June 10, 1968.

129. Richards, P.I. "Computing reliable power spectra", IEEE spectrum, vol. 4, pp 83-90, Jan 1967.

130. TUKEY J.W. "An introduction to the measurement of spectra" in probability and statistics, Ulf. Grenander, ed. New York: Wiley 1959, pp. 300-330.

131. WELCH P.D. "A direct digital method of power spectrum estimation", IBM J. Res. Develop., vol. 5, pp. 141-156, 1961.

132. WELCH P.D., "The use of the fast Fourier transform for the estimation of power spectra: a method based on time averaging over short, modified periodograms", IEEE Trans. Audio and Electroacoustics, vol. AU-15, pp. 70-73. June 1967.

133. GOLD B., and RADER C.M., "Digital Processing of Signals", McGrew-Hill, 1969.

134. STOCKHAM T.G. Jr. "Highspeed Convolution and Correlation", 1966 Spring Joint Computer Conference, AFIPS Proc. 28: 229-233 (1966).

135. BERGLAND G.D., "The fast fourier transform recursive equations for arbitrary length records", Math. Comput., Vol. 21, pp 236-238, April 1967.

136. BERGLAND G.D. "A fast fourier transform algorithm using base 8 iterations", Math. Comput., vol. 22, pp. 275-279, Apr. 1968.

137. BERGLAND G.D., "A fast fourier transform algorithm for real-valued series", Commun. Assoc. Comput. Mach. vol. 11, pp 703-710, Oct. 1968.

138. BERGLAND G.D., and WILSON D.E., "An FFT algorithm for a global, highly parallel processor", IEEE Trans. Audio and Electro-acoustics, vol. AU-17, June 1969.

139. BLUESTEIN L.I., "A linear filtering approach to the computation of the discrete fourier transform", 1968 NEREM Record, pp 218-219.

140. BRENNER N.M., "Three Fortran programs that perform the Cooley-Tukey Fourier transform", Tech.Note 1967-2, Lincoln Laboratory, M.I.T., Lexington, Mass., July 1967.

141. COOLEY J.W. and TUKEY J.W., "An algorithm for the machine calculation of complex Fourier series", Math. Comput., vol. 19, pp.297-301, Apr. 1965.

142. COOLEY J.W., "Harmonic analysis complex Fourier series," SHARE Doc. 3425, Feb. 7, 1966.

143. COOLEY J.W., "Complex finite Fourier transform subroutine", SHARE Doc. 3465, Sept. 8, 1966.

144. DANIELSON G.C. and LANCZOS C. "Some improvements in practical Fourier analysis and their application to X-ray scattering from liquids," J. Franklin Inst., vol. 233, pp 365-380, 435-452.

145. GOOD I.J., "The interaction algorithm and practical Fourier series," J. Roy. Statist. Soc., Vol. 20, series B, pp 361-372, 1958; addendum , vol. 22, pp 372-375, 1960.

146. PEASE M.C., "An adoption of the fast Fourier transform for parallel processing", J. Assoc. Comput. Mach., vol. 15, pp 252-264, Apr. 1968.

147. RADER C.M., "Discrete Fourier transforms when the number of data samples is prime", Proc. IEEE, vol. 56, pp. 1107-1108 June 1968.

148. SANDE G., "Arbitrary radix one-dimensional fast Fourier transform subroutines", University of Chicago, Ill., 1968.

149. SINGLETON R.C., "On computing the fast Fourier transform", Commum. Assoc. Comput Mach., vol. 10, pp 647-654.

150. SINGLETON R.C., "Algorithm 338, Algol procedure for the fast Fourier transform", Commum. Assoc. Comput. Mach., vol. 11, pp 647-654, Nov. 1968.

151. SINGLETON R.C., "Algorithm 339, an Algol procedure for the fast Fourier transform with arbitrary factors", Commum. Assoc. Comput. Mach., vol. 11, pp 776-779, Nov. 1968.

152. SINGLETON R.C. "Algorithm 345, an Algol convolution procedure based on the fast Fourier transform", Commum. Assoc. Comput. Mach, vol. 12, Mar. 1969.

153. YAUNE R. "An economical method for calculating the discrete Fourier transform", 1968 Fall Joint Computer Conf., IFIPS Proc., vol. 33. Washington D.C. Spartan Books, pp 115-125.

154. BERGLAND G.D., "Fast Fourier transform hardware implementations - a survey", IEEE Trans. Audio and Electroacoustics, vol. AU-17, June 1969.

155. ROBINSON E.A., "Multichannel Time Series Analysis", Holden-Day 1967.

156. BOGNER R.E., and CONSTANTINIDES A., "Introduction to Digital Filtering", Wiley (to be published).

157. CONSTANTINIDES A., "Synthesis of Chebyshev Digital Filters". Electronic Letters, vol. 3, No. 3, March 1967, pp 124-126.

158. CONSTANTINIDES A., "Elliptic Digital Filters" Ibid, vol. 3, No. 6, June 1967, pp 255-256.

159. SEEBECK T.J., Konigl. Akad. Wiss., Berlin 265 (1822-1823).

160. DIKE P.H., "Thermoelectric Thermometry"(Leeds and Northrup Company, Philadelphia, Pensylvania 1958) 3rd. ed.

161. ROESER W.F., "Temperature, Its Measurement and Control in Science and Industry" (Reinhold Publishing Corporation, New York 1941), p. 180.

162. BRIDGMAN P.W., "Thermodynamics of Electrical Phenomena in Metals" (The Macmillan Company, New York, 1934) p. 39.

163. MOTT W.F. and JONES H., "The Theory of the Properties of Metals and Alloys" (Clarendon Press, Oxford, 1936) p.308.

164. CRUSSARD C., "Report of a Conference on Strength of Solids" (The Physical Society, London, 1948) p. 119.

165. MILLER J.T., "Instrument Practice" May 1960, Jan. 1964.

166. B.S. 1041: Part 4: 1966.

167. COXON W., "Temperature, Measurement and Control", London, Heywood and Co. Ltd. (1960).

168. FINCH D.I., "General Principles of Thermoelectric Thermometry" Leeds and Northup, North Wales Pa., seen in "Temperature, its Measurement and Control in Science and Industry" (Reinhold Publishing Corporation, New York 1962) p. 3.

169. I.S.A. (Instrument Society of America, Pittsburgh, Pensylvania) "Recommended Practice for Thermocouples and Extension wires" I.S.A. – RP 1.1 - 7 (July 1959).

170. MILLER J.T., "Instrument Practice," Jan. 1964.

171. SHULZE A., "Metallic materials for thermocouples". J. Inst. Fuel, vol. 12 (1939) p. 541.

172. KUTZ M., "Temperature Control," John Wiley and Sons Inc. (1968).

173. SANDERS V.D., "Review of high-temperature immersion thermal sensing devices for in-flight engine control", Rev. Sci. Instr. 29, 217 (1958).

174. KUETHER F.W., "Uniqueness of Thermal e.m.f.'s measured in Molybdenum, Rhenium, Tungsten, Iron and Copper". High-Temperature Thermometry Semenar, Oak Ridge National Laboratory, Oct. 1-2, 1959, TID 7586 (pt 1). p. 23.

175. LACHMAN J.C. and KUETHER F.W., "Stability of Rhenium/tungsten thermocouples in hydrogen atmospheres" I.S.A. Journal 7, 67 (1960).

176. LACHMAN J.C. and KUETHER F.W. "How reliable are the two new high-temperature thermocouples in vacuum?", I.S.A. Journal 7, 66, (1960).

177. LACHMAN J.C. and McGURTY J.A. "Thermocouples for 5,000°F using Rhenium alloys", presented at the Electrochemical Society Symposium on Rhenium, Chicago, Illinois, May 4, 1960.

178. THEILKE N.R. and SHEPARD R.L. "High - Temperature Thermocouples Based on Carbon and its Modification" High Temperature Thermometry Seminar, Oak Ridge National Laboratory, Oct. 1-2, 1959, TID - 75 86 (Pt. 1.).

179. UBBELHODE A.R., BLACKMAN L.C.F. and DUNDES P.H., "A graphite/graphite thermocouple for high temperatures" Chemistry and Industry 595 (May 9, 1959).

180. BIDWELL C.C., "Thermojunctions of carbon and graphite" Phys. Rev. Ser. 3, 38, 450 (1914).

181. WATSON H.L. and ABRAMS H., "Thermoelectric measurements of temperatures above 1500°C", Trans. Am. Electrochem. Soc. 54, 19 (1928).

182. FILTERER G.R., "A new thermocouple for the determination of temperatures up to at least 1800°C" Trans. Am. Inst. Mining Met. Engnrs. 105, 290 (1933).

183. SHEPARD R.L. and WESTBROOK R.D. and PATTIN H.S. "A high-temperature boron - graphite - graphite thermocouple". Bull. Am. Phys. Soc. 1. Ser. 11 No. 3, G.A.4 (1956).

184. B.S. 1041: 1943.

185. CALDWELL F.R. "Thermocouple Materials" Temperature, Its Measurement and Control in Science and Industry vol. 3 (1962) pp 81-134.

186. ZYSK E.D. "Platinum Metal Thermocouples" Ibid pp 135-156.

187. BENNETT E.H. "Noble Metal Thermocouples" Johnson and Matthey and Co. Ltd. (1961).

188. MORTLOCK A.J., J. Sci. Instr. 35, 283 (1958).

189. SOURDILLON A. and ROLET, Metallurgist, 1928, 4 pp 109-110.

190. HUTTER C., Korrosion (Supple to Chem. Apparatus). 1929, 4 pp 49 – 50; (1930) 5, pp 5-6.

191. HOUGEN O.A. and MILLER B.L., Chem. Met. Eng. 1923, 29, pp 662-663.

192. GAT J.D., Chem. Met. Eng. 1923, 29, p 806.

193. CHAUSSAIN M. Proc. Inst. Brit. Foundrymen 1951, 44, pp 60-77.

194. CROOKS W. Proc. Roy. Soc. (London) A86, 461 (1912).

195. McQUILLAN M.K., J. Sci. Instr. 31, 329-331 (1949).

196. BRENNER B. "Temperature, Its Measurement and Control in Science and Industry (Reinhold Publishing Corporation, New York 1941) Vol. 1 pp 1267-1271.

197. HOMEWARD C.F. "Temperature, Its Measurement and Control in Science and Industry"(Reinhold Publishing Corporation New York 1941 Vol. pp 1272-1279).

198. JEWEL R.C. and KNOWLES E.G., J. Sci. Instr. 28, 353 (1951).

199. SVEC H.J. AECU 1804 (1952).

200. Quaterly Report, "High Temperature Properties and Alloying Behaviour of the Refractory Platinum Group" Oct. 1 to Dec. 31, 1959, Contract No. Nonr 2547 (00), N.R. 039-067, Office of Naval Research.

201. POWELL A.R., Platinum Metals Rev. 2, No. 3 (1958).

202. NEVILLE R.P. Am. Electrochem. Soc. (1923).

203. KOSTOWSKI, Proceedings of the International Symposium on High Temperature Technology (McGraw-Hill Book Company Inc., New York, 1960).

204. DAHL A.I., "The Stability of Base Metal Thermocouples in Air from 800 to 2200°F" Temperature, Its Measurement and Control in Science and Industry (Reinhold Publishing Corporation, New York, 1941) p. 1238.

205. McELROY D.L., "Progress Report 1, Thermocouple research report for the period No. 1 1956 to Oct. 31 1957" ORNL – 2467.

206. POTTS J.F. and McELROY D.L., "Thermocouple Research to 1000° C Final report No. 1, 1957 through June 30 1959" ORNL – 2773, UC – 37 – Instruments, TID – 4500 (15th ed).

207. FENTON A.W., Proc. I.F.E. vol. 116, No. 7 pp (1277 – 1285).

208. ROESER W.F. and DAHL A.L., "Reference tables for iron v constantan and copper v constantan thermocouples." J. Research Natl. Bur. Standard 20, 337. (1938), RP1080.

209. NEAVERSON A.G., Rolls Royce Ltd. Derby (Private Communication).

210. – High Temperature Thermometry Seminar, Oct. 1959, Oak Ridge National Laboratory, TID – 7586 (Pt. 1).

211. ARBITER W., Nuclear Development Corporation of America.

212. WEAVING A.H. Proceedings of the Symposium of some developments in Techniques for Temperature measurement. Communications. London 26th April 1962. Published by the Inst. Mech. Engnrs. pp 91–93.

213. CLARK R.D. National Engineering Laboratory, East Kilbride, Glasgow (Private Communication).

214. - Instructions for Taylor fixed range differential pressure transmitter. Taylor Instrument Companies IB - 23205 (GB) issue 3.

215. HOLZBOCK W. "Instruments for Measurement and Control" Reinhold Publishing Corp., New York, 1955 pp 350-351.

216. FINNERAN J.A. et al "Start up performance of large ammonia plants", Chem. Eng. Prog. Vol. 64, No. 8 Aug. 1968 . pp 191-194.

217. HOLROYD R. "Ultra large single stream chemical plants: their advantages and disadvantages", Chem. and Ind., Aug. 5, 1967, pp 1310-1315.

218. LANDAN R. "The Chemical Plant", Reinhold Publishing Corp., New York, N.Y., 1966.

219. GILLILAND G.J. "Planned replacement: some theory and its applications" Journal of Quality Tech., Vol. 1, No. 2, April 1969, pp 110-119.

220. ONGE G.H. "Power system reliability in petroleum and petrochemical plants" Procs., 7th reliability and maintainability conference, SAE, ASME and AIAA, 1968 pp 133-147.

221. VACCARO D.J. "Reliability of power and control systems in a chemical plant" paper (preprint 28D) presented at the symposium on Loss Prevention in Process Industries - part IV of 64th National Meeting of A.I. Ch. E., New Orleans, La., March 16-20, 1969.

222. GOLDMAN S.F. and SARGENT R.W.H. "Applications of linear estimation theory to chemical processes A feasibility study", paper presented to Inst. Chem. Eng. Symposium London, 1969.

223. CLEMENTSON A.T. "Statistical determination of plant yields" British Chem. Engng. Vol. 8, No. 8, August 1963, pp 564-565.

224. BECK M.S., KHANDURI S.C and MEHTA R.G., "Control valve hysteresis can be reduced by dither" Instrument practice, Sept. 1968 pp 773 - 775.

225. THOMPSON A. "Operating experience with direct digital control" The Chemical Engineer, May 1965 pp 96 - 101.

APPENDIX 1

Differential pressure transmitter data and spectral analysis results.

The data in Tables A5 to A6 are the actual voltage output from the computer.

The units of power P_w are volts^2/hertz.

The units of Standard deviation calculations of table A4 are volts.

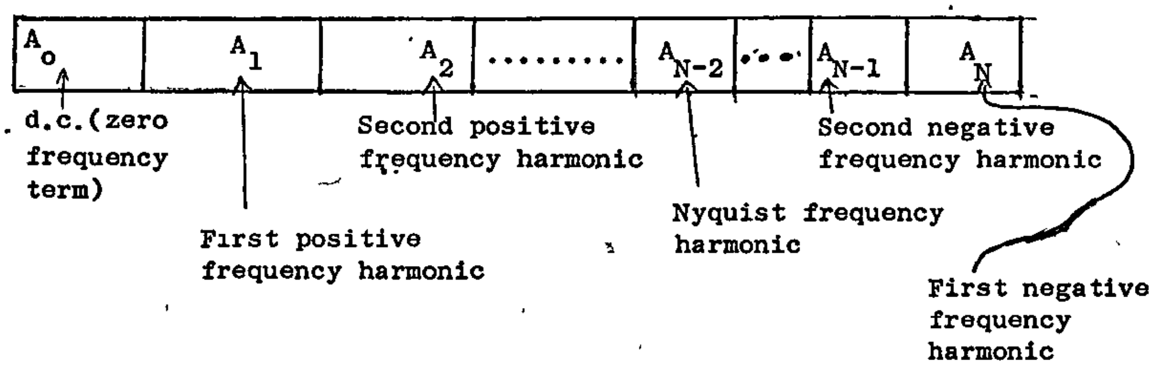
For tables A5 and A6, the first reading of each column of readings is the time interval and the second is the voltage output from the computer. The amplification of the signals from the fast pressure to current transducer was 300.

The Fortran program used for the FFT calculations, reads a sequence of N complex numbers $x_o, x_1, \ldots, x_{N-1}$ and computes the discrete Fourier transform (DFT) given by

$$A_k = \sum_{l=0}^{N-1} W^{kl} x_l , \quad K=0,\ 1,\ \ldots,\ N-1$$

where $W = e^{-j2\pi/N}$

If the X_k are the N samples of a periodic signal (sampled at the Nyquist rate, or above) then the A_k, computed using the DFT, are the Fourier coefficients of the corresponding exponential series.



If the X_l are real, the A_k display real-even, imaginary - odd symmetry about zero frequency.

Limitation N must be an integer power of 2.

Data are in free format; the real part of a complex number followed by its imaginary part.

A1 Contd.

Table A.1 (a) Power Spectra Estimations Corresponding to Table 8.3 (a)

Power X10^{+9}

Fractions of highest detectable frequency in $\frac{1}{8}$th	Corresponding number in table 8.3 (a)					
	1	2	3	4	5	6
0	677. 9	322. 43	832. 06	257. 67	992. 34	1725. 4
1	3685. 8	1161. 2	1763. 4	1418. 1	1968. 9	2138. 7
2	3297. 9	3247. 3	1994. 0	2513. 4	1557. 0	474. 42
3	340. 34	419. 37	1962. 7	1719. 4	553. 01	959. 32
4	17.729	90.752	42.487	83.483	46.332	92.559
5	11.681	45.761	62.578	194. 73	33.524	44.505
6	49.377	134. 86	3.3575	30.294	9.4383	165. 50
7	56.056	28.957	282. 77	75.367	14.569	25.304
8	18.906	33.994	74.508	88.087	16.826	93.789

Table A.1 (b) Power Spectra Estimates Corresponding to Table 8.3 (b)

Power X 10^{+9}

Fractions of highest detectable frequency in $\frac{1}{8}$th	Corresponding number in table 8.3 (b)					
	1	2	3	4	5	6
0	34.136	13. 024	31.401	16.341	16. 344	70.972
1	18.369	54. 930	46.310	94.040	24. 775	33.333
2	79.033	37. 253	36.680	30.728	45. 508	38.479
3	10.067	49. 878	46.680	18.948	26. 275	71.631
4	50.409	7.8125	19.531	28.203	72. 249	21.133
5	24.590	58. 269	20.279	12.427	54. 964	38.715
6	14.951	43. 955	36.953	57.659	15. 704	49.772
7	88.711	42. 276	18.879	26.524	40. 737	14.463
8	86.289	56. 406	30.625	15.625	4.7266	7.208

TABLES A.2(a) and A.2(b) Power spectra estimates corresponding to tables 8.4(a) and 8.4(b)

Power $X10^{+9}$

Fraction of highest detectable frequency in $\frac{1}{8}$th	Corresponding number in table 8.4(a)			Corresponding number in table 8.4(b)		
	1	2	3	1	2	3
0	428.53	293.20	570.89	49.519	38.175	23.434
1	588.76	3441.5	102.22	18.076	47.493	50.464
2	416.71	3666.4	258.86	24.904	15.417	59.936
3	58.686	1333.7	3.9703	39.273	2.0251	8.870
4	23.11	150.99	8.9087	23.127	11.182	4.883
5	27.882	6.8501	31.486	18.321	16.499	13.018
6	14.590	222.19	22.9044	50.063	45.579	16.626
7	5.240	52.932	26.843	13.581	39.257	1.4761
8	47.852	13.369	1.5259	63.282	43.838	0.976

TABLES A.3(a) and A.3(b) Power spectra estimates corresponding to tables 8.5(a) and 8.5(b)

Power x 10^{+9}

Fraction of highest detectable frequency in $\frac{1}{8}$th	Corresponding number in table 8.5(a)			Corresponding number in table 8.5(b)		
	32	64	128	32	64	128
0	257.67	992.30	1036.4	83.071	37.306	10.967
1	1418.1	1968.9	2136.1	20.658	76.698	56.863
2	2513.4	1557.0	1204.5	13.860	30.122	20.139
3	1719.4	997.05	2127.5	29.727	52.232	29.710
4	83.483	200.88	56.762	20.444	48.174	35.733
5	194.73	117.90	74.280	22.571	23.951	27.903
6	30.294	44.561	40.279	24.215	48.459	33.589
7	75.367	54.369	23.760	24.674	24.604	13.197
8	88.087	95.506	60.178	17.227	9.3808	11.585

Table A.4 Standard deviation for the normal Instrument signal and Impulse lines frozen.

Sample Number	Normal Signal	Impulse lines Frozen
32	0.0022	0.0005
64	0.0013	0.0005
96	0.0017	0.0010
128	0.0021	0.0006
160	0.0014	0.0005
192	0.0018	0.0006
224	0.0014	0.0006
256	0.0016	0.0008
288	0.0018	0.0005
320	0.0021	0.0007
352	0.0016	0.0006
384	0.0019	0.0011
416	0.0014	0.0004
448	0.0021	0.0006
480	0.0022	0.0006
512	0.0014	0.0011
544	0.0011	0.0007
576	0.0015	0.0007
608	0.0024	0.0007
640	0.0015	0.0007
672	0.0018	0.0007
704	0.0015	0.0006
736	0.0017	0.0006
768	0.0009	0.0005
800	0.0011	0.0008
832	0.0012	0.0008
864	0.0019	0.0005
896	0.0012	0.0005
928	0.0020	0.0008

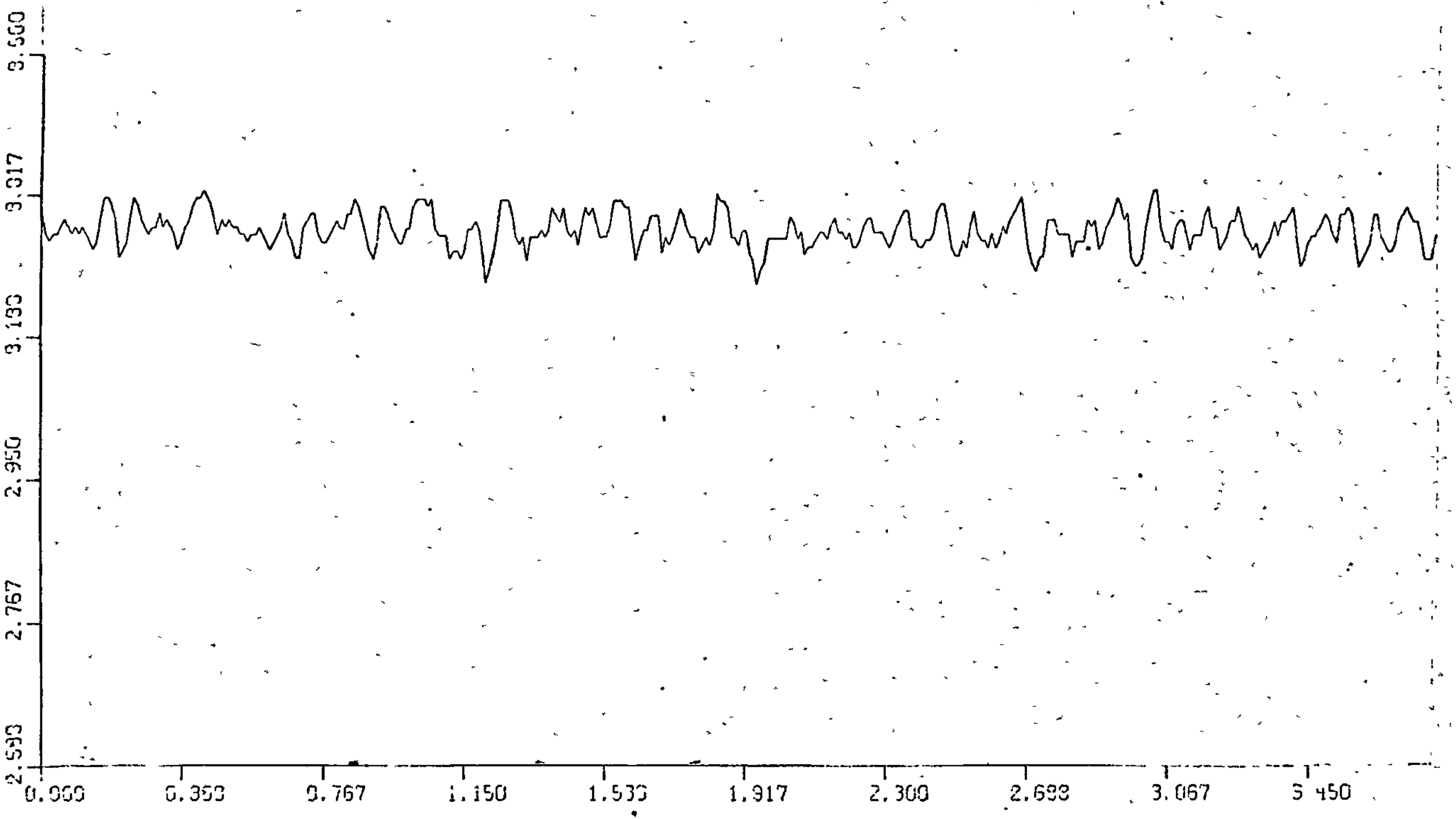


Fig. A.1. Computer plot of normal differential pressure signal

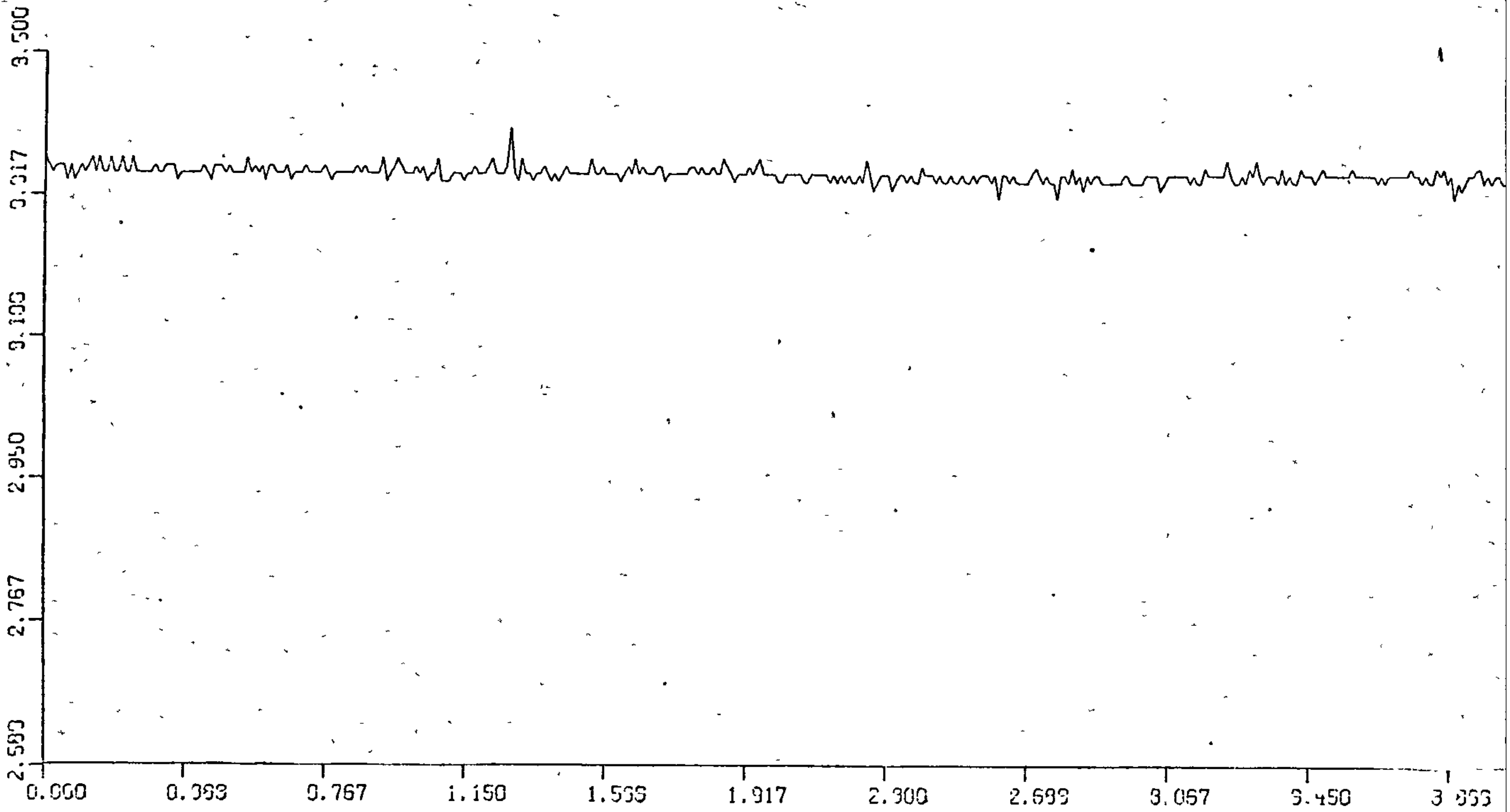


Fig. A.2. Computer plot of frozen impulse line logging

TABLE A.5. Logged Data for normal differential transmitter signal pressure

0	0.3364	1	0.3354	2	0.3345	3	0.3354
4	0.3354	5	0.3354	6	0.3335	7	0.3354
8	0.3335	9	0.3345	10	0.3354	11	0.3345
12	0.3354	13	0.3364	14	0.3345	15	0.3364
16	0.3345	17	0.3345	18	0.3364	19	0.3345
20	0.3345	21	0.3364	22	0.3345	23	0.3345
24	0.3364	25	0.3345	26	0.3345	27	0.3345
28	0.3345	29	0.3345	30	0.3354	31	0.3345
32	0.3345	33	0.3354	34	0.3354	35	0.3354
36	0.3335	37	0.3345	38	0.3345	39	0.3345
40	0.3345	41	0.3345	42	0.3345	43	0.3354
44	0.3345	45	0.3335	46	0.3354	47	0.3354
48	0.3354	49	0.3345	50	0.3354	51	0.3345
52	0.3345	53	0.3345	54	0.3345	55	0.3364
56	0.3345	57	0.3354	58	0.3345	59	0.3354
60	0.3335	61	0.3354	62	0.3354	63	0.3345
64	0.3345	65	0.3345	66	0.3354	67	0.3335
68	0.3345	69	0.3345	70	0.3345	71	0.3354
72	0.3345	73	0.3345	74	0.3345	75	0.3345
76	0.3354	77	0.3345	78	0.3335	79	0.3345
80	0.3345	81	0.3345	82	0.3345	83	0.3345
84	0.3345	85	0.3354	86	0.3345	87	0.3354
88	0.3345	89	0.3345	90	0.3345		
91	0.3345	92	0.3364	93	0.3335	94	0.3345
95	0.3354	96	0.3364	97	0.3354	98	0.3345
99	0.3345	100	0.3345	101	0.3354	102	0.3345
103	0.3354	104	0.3335	105	0.3345	106	0.3345
107	0.3364	108	0.3335	109	0.3335	110	0.3335
111	0.3345	112	0.3345	113	0.3345	114	0.3335
115	0.3345	116	0.3345	117	0.3354	118	0.3345
119	0.3345	120	0.3345	121	0.3354	122	0.3364
123	0.3345	124	0.3345	125	0.3345	126	0.3354
127	0.3403	128	0.3345	129	0.3335	130	0.3364
131	0.3345	132	0.3345	133	0.3335	134	0.3345
135	0.3345	136	0.3354	137	0.3345	138	0.3335
139	0.3345	140	0.3335	141	0.3345	142	0.3354
143	0.3345	144	0.3345	145	0.3345	146	0.3345
147	0.3345	148	0.3345	149	0.3364	150	0.3345
151	0.3345	152	0.3354	153	0.3345	154	0.3345
155	0.3345	156	0.3345	157	0.3335	158	0.3345
159	0.3354	160	0.3345	161	0.3364	162	0.3345
163	0.3354	164	0.3345	165	0.3345	166	0.3345
167	0.3354	168	0.3354	169	0.3335	170	0.3345
171	0.3345	172	0.3345	173	0.3345	174	0.3345
175	0.3345	176	0.3354	177	0.3354	178	0.3345
179	0.3354	180	0.3345	181	0.3345		
182	0.3354	183	0.3345	184	0.3345	185	0.3364
186	0.3354	187	0.3345	188	0.3335	189	0.3345
190	0.3345	191	0.3345	192	0.3354	193	0.3345
194	0.3354	195	0.3364	196	0.3345	197	0.3345
198	0.3345	199	0.3345	200	0.3335	201	0.3335
202	0.3345	203	0.3345	204	0.3345	205	0.3345
206	0.3345	207	0.3335	208	0.3335	209	0.3345
210	0.3345	211	0.3345	212	0.3345	213	0.3345
214	0.3335	215	0.3345	216	0.3335	217	0.3345
218	0.3335	219	0.3345	220	0.3335	221	0.3335

TABLE A.5. (cont'd) Logged Data for normal differential transmitter signal pressure

222	0.3345	223	0.3335	224	0.3364	225	0.3345
226	0.3325	227	0.3335	228	0.3345	229	0.3345
230	0.3345	231	0.3325	232	0.3335	233	0.3345
234	0.3345	235	0.3335	236	0.3345	237	0.3335
238	0.3335	239	0.3354	240	0.3345	241	0.3345
242	0.3345	243	0.3335	244	0.3345	245	0.3335
246	0.3335	247	0.3345	248	0.3335	249	0.3335
250	0.3345	251	0.3335	252	0.3335	253	0.3345
254	0.3335	255	0.3345	256	0.3345	257	0.3345
258	0.3335	259	0.3345	260	0.3315	261	0.3345
262	0.3345	263	0.3335	264	0.3345	265	0.3335
266	0.3335	267	0.3335	268	0.3335	269	0.3345
270	0.3354	271	0.3345	272	0.3335	273	0.3345
274	0.3335	275	0.3335	276	0.3315	277	0.3345
278	0.3345	279	0.3335	280	0.3354	281	0.3335
282	0.3345	283	0.3325	284	0.3345	285	0.3335
286	0.3345	287	0.3345	288	0.3335	289	0.3335
290	0.3335	291	0.3335	292	0.3335	293	0.3335
294	0.3345	295	0.3345	296	0.3335	297	0.3335
298	0.3335	299	0.3335	300	0.3345	301	0.3345
302	0.3345	303	0.3345	304	0.3325	305	0.3335
306	0.3345	307	0.3345	308	0.3345	309	0.3345
310	0.3345	311	0.3345	312	0.3335	313	0.3345
314	0.3335	315	0.3335	316	0.3354	317	0.3345
318	0.3345	319	0.3345	320	0.3345	321	0.3345
322	0.3364	323	0.3345	324	0.3335	325	0.3335
326	0.3345	327	0.3335	328	0.3354	329	0.3345
330	0.3364	331	0.3345	332	0.3335	333	0.3345
334	0.3345	335	0.3345	336	0.3335	337	0.3354
338	0.3335	339	0.3345	340	0.3335	341	0.3335
342	0.3354	343	0.3345	344	0.3345	345	0.3345
346	0.3335	347	0.3345	348	0.3354	349	0.3345
350	0.3345	351	0.3345	352	0.3345	353	0.3345
354	0.3345	355	0.3345	356	0.3354	357	0.3345
358	0.3345	359	0.3345	360	0.3345		
361	0.3345	362	0.3345	363	0.3335	364	0.3345
365	0.3335	366	0.3345	367	0.3345	368	0.3345
369	0.3345	370	0.3345	371	0.3345	372	0.3354
373	0.3345	374	0.3345	375	0.3335	376	0*3345
377	0.3335	378	0.3335	379	0.3354	380	0.3345
381	0.3354	382	0.3335	383	0.3345	384	0.3315
385	0.3335	386	0.3325	387	0.3335	388	0.3345
389	0.3345	390	0.3354	391	0.3354	392	0.3335
393	0.3345	394	0.3335	395	0.3345	396	0.3345
397	0.3335	398	0.3335	399	0.3354	400	0.3345
401	0.3335	402	0.3403	403	0.3345	404	0.3345
405	0.3364	406	0.3345	407	0.3354	408	0.3335
409	0.3345	410	0.3354	411	0.3345	412	0.3345
413	0.3345	414	0.3354	415	0.3345	416	0.3335
417	0.3345	418	0.3345	419	0.3354	420	0.3335
421	0.3345	422	0.3345	423	0.3345	424	0.3345
425	0.3345	426	0.3345	427	0.3335	428	0.3335
429	0.3345	430	0.3345	431	0.3335	432	0.3345
433	0.3335	434	0.3345	435	0.3354	436	0.3354
437	0.3345	438	0.3345	439	0.3345	440	0.3345
441	0.3345	442	0.3345	443	0.3345	444	0.3354

TABLE A.5. (cont'd) Logged Data for normal differential transmitter signal pressure

445	0.3345	446	0.3345	447	0.3345	448	0.3345
449	0.3354	450	0.3345	451	0.3354		
452	0.3345	453	0.3345	454	0.3345	455	0.3354
456	0.3335	457	0.3345	458	0.3354	459	0.3345
460	0.3354	461	0.3364	462	0.3364	463	0.3335
464	0.3364	465	0.3345	466	0.3354	467	0.3345
468	0.3345	469	0.3345	470	0.3364	471	0.3345
472	0.3354	473	0.3345	474	0.3364	475	0.3345
476	0.3364	477	0.3345	478	0.3345	479	0.3345
480	0.3364	481	0.3345	482	0.3335	483	0.3364
484	0.3354	485	0.3354	486	0.3345	487	0.3345
488	0.3364	489	0.3345	490	0.3335	491	0.3364
492	0.3345	493	0.3345	494	0.3354	495	0.3354
496	0.3354	497	0.3354	498	0.3354	499	0.3345
500	0.3345	501	0.3345	502	0.3345	503	0.3345
504	0.3345	505	0.3345	506	0.3345	507	0.3345
508	0.3345	509	0.3354	510	0.3345	511	0.3345
512	0.3345	513	0.3345	514	0.3335	515	0.3345
516	0.3364	517	0.3335	518	0.3345	519	0.3345
520	0.3335	521	0.3354	522	0.3345	523	0.3335
524	0.3335	525	0.3345	526	0.3335	527	0.3335
528	0.3335	529	0.3354	530	0.3345	531	0.3345
532	0.3345	533	0.3335	534	0.3345	535	0.3325
536	0.3345	537	0.3335	538	0.3345	539	0.3345
540	0.3345	541	0.3345	542	0.3345	543	0.3335
544	0.3345	545	0.3345	546	0.3345	547	0.3354
548	0.3335	549	0.3315	550	0.3325	551	0.3345
552	0.3345	553	0.3403	554	0.3345	555	0.3335
556	0.3345	557	0.3345	558	0.3345	559	0.3335
560	0.3335	561	0.3335	562	0.3345	563	0.3325
564	0.3345	565	0.3345	566	0.3335	567	0.3345
568	0.3345	569	0.3345	570	0.3335	571	0.3345
572	0.3345	573	0.3335	574	0.3325	575	0.3345
576	0.3335	577	0.3364	578	0.3345	579	0.3354
580	0.3335	581	0.3335	582	0.3335	583	0.3345
584	0.3345	585	0.3335	586	0.3364	587	0.3345
588	0.3345	589	0.3354	590	0.3345	591	0.3345
592	0.3325	593	0.3345	594	0.3335	595	0.3345
596	0.3335	597	0.3354	598	0.3354	599	0.3345
600	0.3345	601	0.3345	602	0.3354	603	0.3345
604	0.3345	605	0.3335	606	0.3335	607	0.3345
608	0.3345	609	0.3335	610	0.3345	611	0.3345
612	0.3345	613	0.3345	614	0.3345	615	0.3345
616	0.3335	617	0.3345	618	0.3345	619	0.3345
620	0.3345	621	0.3345	622	0.3345	623	0.3335
624	0.3345	625	0.3345	626	0.3335	627	0.3335
628	0.3335	629	0.3364	630	0.3345		
631	0.3345	632	0.3345	633	0.3345	634	0.3345
635	0.3335	636	0.3335	637	03345	638	0.3345
639	0.3364	640	0.3345	641	0.3345	642	0.3345
643	0.3335	644	0.3345	645	0.3335	646	0.3335
647	0.3345	648	0.3345	649	0.3345	650	0.3335
651	0.3345	652	0.3345	653	0.3345	654	0.3364
655	0.3345	656	0.3345	657	0.3345	658	0.3354
659	0.3345	660	0.3345	661	0.3345	662	0.3364
663	0.3345	664	0.3354	665	0.3315	666	0.3345

Logged Data for normal differential transmitter signal pressure

667	0.3345	668	0.3345	669	0.3354	670	0.3335
671	0.3335	672	0.3345	673	0.3345	674	.3354
675	0.3345	676	0.3345	677	0.3354	678	0.3345
679	0.3345	680	0.3345	681	0.3345	682	0.3345
683	0.3345	684	0.3335	685	0.3345	686	0.3345
687	0.3345	688	0.3335	689	0.3345	690	0.3345
691	0.3345	692	0.3345	693	0.3345	694	0.3345
695	0.3354	696	0.3364	697	0.3345	698	0.3335
699	0.3345	700	0.3345	701	0.3364	702	0.3345
703	0.3345	704	0.3345	705	0.3345	706	0.3345
707	0.3364	708	0.3345	709	0.3345	710	0.3345
711	0.3345	712	0.3354	713	0.3345	714	0.3335
715	0.3345	716	0.3345	717	0.3345	718	0.3335
719	0.3345	720	0.3354	721	0.3345		
722	0.3345	723	0.3335	724	0.3345	725	0.3335
726	0.3345	727	0.3345	728	0.3325	729	0.3345
730	0.3354	731	0.3345	732	0.3325	733	0.3364
734	0.3335	735	0.3354	736	0.3345	737	0.3345
738	0.3345	739	0.3345	740	0.3345	741	0.3345
742	0.3345	743	0.3364	744	0.3345	745	0.3345
746	0.3354	747	0.3345	748	0.3345	749	0.3345
750	0.3335	751	.3335	752	0.3345	753	0.3354
754	0.3345	755	0.3335	756	0.3335	757	0.3345
758	0.3364	759	0.3354	760	0.3345	761	0.3335
762	0.3335	763	0.3345	764	0.3315	765	0.3345
766	0.3354	767	0.3345	768	0.3335	769	0.3345
770	0.3345	771	0.3315	772	0.3345	773	0.3345
774	0.3345	775	0.3354	776	0.3335	777	0.3345
778	0.3345	779	0.3345	780	0.3345	781	0.3345
782	0.3354	783	0.3345	784	0.3364	785	0.3345
786	0.3354	787	0.3345	788	0.3345	789	0.3335
790	0.3364	791	0.3345	792	0.3335	793	0.3345
794	0.3335	795	0.3345	796	0.3345	797	0.3345
798	0.3345	799	0.3345	800	0.3354	801	0.3345
802	0.3345	803	0.3345	804	0.3345	805	0.3335
806	0.3345	807	0.3345	808	0.3354	809	0.3335
810	0.3335	811	0.3345	812	0.3345	813	0.3345
814	0.3345	815	0.3364	816	0.3345	817	0.3335
818	0.3345	819	0.3354	820	0.3335	821	0.3345
822	0.3335	823	0.3335	824	0.3354	825	0.3345
826	0.3345	827	0.3345	828	0.3345	829	0.3345
830	0.3354	831	0.3364	832	0.3345	833	0.3345
834	0.3354	835	0.3345	836	0.3335	837	0.3345
838	0.3335	839	0.3345	840	0.3345	841	0.3345
842	0.3345	843	0.3345	844	0.3345	845	0.3345
846	0.3345	847	0.3335	848	0.3335	849	0.3345
850	0.3345	851	0.3345	852	0.3335	853	0.3345
854	0.3335	855	0.3345	856	0.3335	857	0.3354
858	0.3345	859	0.3345	860	0.3335	861	0.3335
862	0.3364	863	0.3325	864	0.3335	865	0.3325
866	0.3345	867	0.3345	868	0.3345	869	0.3345
870	0.3345	871	0.3345	872	0.3335	873	0.3335
874	0.3345	875	0.3335	876	0.3345	877	0.3335
878	0.3335	879	0.3345	880	0.3325	881	0.3345
882	0.3335	883	0.3335	884	0.3345	885	0.3345
886	0.3345	887	0.3354	888	0.3345	889	0.3335

TABLE A.6. Logged data for frozen impulse line

0	0.3296	1	0.3267	2	0.3257	3	0.3267
4	0.3267	5	0.3276	6	0.3286	7	0.3276
8	0.3267	9	0.3276	10	0.3267	11	0.3276
12	0.3267	13	0.3257	14	0.3247	15	0.3257
16	0.3286	17	0.3315	18	0.3315	19	0.3306
20	0.3286	21	0.3237	22	0.3247	23	0.3257
24	0.3286	25	0.3315	26	0.3306	27	0.3286
28	0.3276	29	0.3267	30	0.3276	31	0.3276
32	0.3296	33	0.3276	34	0.3286	35	0.3276
36	0.3267	37	0.3247	38	0.3257	39	0.3276
40	0.3286	41	0.3306	42	0.3315	43	0.3315
44	0.3325	45	0.3315	46	0.3306	47	0.3286
48	0.3267	49	0.3286	50	0.3276	51	0.3286
52	0.3276	53	0.3276	54	0.3267	55	0.3267
56	0.3257	57	0.3267	58	0.3267	59	0.3276
60	0.3267	61	0.3257	62	0.3247	63	0.3257
64	0.3267	65	0.3276	66	0.3296	67	0.3267
68	0.3257	69	0.3237	70	0.3237	71	0.3276
72	0.3286	73	0.3296	74	0.3296	75	0.3267
76	0.3257	77	0.3257	78	0.3267	79	0.3276
80	0.3286	81	0.3276	82	0.3276	83	0.3296
84	0.3296	85	0.3315	86	0.3306	87	0.3286
88	0.3267	89	0.3247	90	0.3237		
91	0.3257	92	0.3306	93	0.3306	94	0.3296
95	0.3276	96	0.3267	97	0.3257	98	0.3257
99	0.3276	100	0.3276	101	0.3306	102	0.3315
103	0.3315	104	0.3315	105	0.3306	106	0.3315
107	0.3276	108	0.3267	109	0.3267	110	0.3267
111	0.3237	112	0.3247	113	0.3247	114	0.3237
115	0.3247	116	0.3276	117	0.3276	118	0.3286
119	0.3276	120	0.3247	121	0.3208	122	0.3228
123	0.3247	124	0.3276	125	0.3315	126	0.3315
127	0.3315	128	0.3296	129	0.3267	130	0.3257
131	0.3267	132	0.3237	133	0.3267	134	0.3267
135	0.3267	136	0.3276	137	0.3267	138	0.3276
139	0.3306	140	0.3296	141	0.3286	142	0.3306
143	0.3276	144	0.3267	145	0.3276	146	0.3257
147	0.3286	148	0.3306	149	0.3296	150	0.3306
151	0.3286	152	0.3267	153	0.3267	154	0.3267
155	0.3286	156	0.3315	157	0.3315	158	0.3315
159	0.3306	160	0.3306	161	0.3267	162	0.3237
163	0.3257	164	0.3276	165	0.3276	166	0.3296
167	0.3296	168	0.3296	169	0.3247	170	0.3267
171	0.3257	172	0.3267	173	0.3286	174	0.3306
175	0.3296	176	0.3276	177	0.3267	178	0.3267
179	0.3247	180	0.3257	181	0.3267		
182	0.3257	183	0.3276	184	0.3325	185	0.3315
186	0.3315	187	0.3306	188	0.3267	189	0.3267
190	0.3257	191	0.3276	192	0.3276	193	0.3247
194	0.3237	195	0.3208	196	0.3228	197	0.3237
198	0.3267	199	0.3267	200	0.3267	201	0.3267
202	0.3267	203	0.3267	204	0.3296	205	0.3286
206	0.3267	207	0.3276	208	0.3247	209	0.3257
210	0.3257	211	0.3267	212	0.3276	213	0.3276
214	0.3267	215	0.3286	216	0.3296	217	0.3276
218	0.3276	219	0.3267	220	0.3276	221	0.3257

TABLE A.6. (cont'd) Logged data for frozen impulse line

222	0.3257	223	0.3267	224	0.3286	225	0.3296
226	0.3296	227	0.3276	228	0.3276	229	0.3276
230	0.3267	231	0.3257	232	0.3267	233	0.3286
234	0.3296	235	0.3306	236	0.3306	237	0.3267
238	0.3267	239	0.3257	240	0.3257	241	0.3267
242	0.3267	243	0.3276	244	0.3306	245	0.3315
246	0.3315	247	0.3286	248	0.3257	249	0.3247
250	0.3247	251	0.3267	252	0.3257	253	0.3286
254	0.3306	255	0.3276	256	0.3267	257	0.3267
258	0.3257	259	0.3276	260	0.3257	261	0.3267
262	0.3286	263	0.3276	264	0.3296	265	0.3306
266	0.3315	267	0.3325	268	0.3296	269	0.3257
270	0.3237	271	0.3228	272	0.3247	273	0.3247
274	0.3296	275	0.3296	276	0.3296	277	0.3276
278	0.3276	279	0.3276	280	0.3276	281	0.3247
282	0.3267	283	0.3267	284	0.3267	285	0.3296
286	0.3286	287	0.3296	288	0.3257	289	0.3267
290	0.3286	291	0.3296	292	0.3306	293	0.3325
294	0.3315	295	0.3296	296	0.3306	297	0.3247
298	0.3237	299	0.3237	300	0.3247	301	0.3286
302	0.3315	303	0.3335	304	0.3335	305	0.3286
306	0.3267	307	0.3267	308	0.3257	309	0.3286
310	0.3296	311	0.3296	312	0.3276	313	0.3257
314	0.3276	315	0.3276	316	0.3276	317	0.3306
318	0.3315	319	0.3286	320	0.3286	321	0.3257
322	0.3267	323	0.3276	324	0.3296	325	0.3296
326	0.3315	327	0.3296	328	0.3276	329	0.3267
330	0.3257	331	0.3267	332	0.3247	333	0.3257
334	0.3267	335	0.3276	336	0.3296	337	0.3276
338	0.3296	339	0.3296	340	0.3306	341	0.3315
342	0.3276	343	0.3237	344	0.3247	345	0.3267
346	0.3276	347	0.3276	348	0*3286	349	0.3296
350	0.3306	351	0.3296	352	0.3276	353	0.3267
354	0.3306	355	0.3306	356	0.3315	357	0.3306
358	0.3267	359	0.3237	360	0.3247		
361	0.3257	362	0.3267	363	0.3306	364	0.3306
365	0.3276	366	0.3267	367	0.3257	368	0.3257
369	0.3267	370	0.3296	371	0.3306	372	0.3315
373	0.3306	374	0.3296	375	0.3296	376	0.3276
377	0.3247	378	0.3247	379	0.3247	380	0.3276
381	0.3286	382	0.3296	383	0.3306	384	0.3296
385	0.3286	386	0.3257	387	0.3237	388	0.3237
389	0.3276	390	0.3306	391	0.3315	392	0.3306
393	0.3267	394	0.3286	395	0.3276	396	0.3276
397	0.3296	398	0.3306	399	0.3286	400	0.3296
401	0.3296	402	0.3276	403	0.3276	404	0.3286
405	0.3286	406	0.3296	407	0.3296	408	0.3276
409	0.3276	410	0.3276	411	0.3257	412	0.3276
413	0.3286	414	0.3276	415	0.3267	416	0.3276
417	0.3276	418	0.3267	419	0.3257	420	0.3257
421	0.3267	422	0.3267	423	0.3286	424	0.3306
425	0.3296	426	0.3286	427	0.3267	428	0.3267
429	0.3286	430	0.3306	431	0.3325	432	0.3315
433	0.3286	434	0.3267	435	0.3208	436	0.3237
437	0.3257	438	0.3286	439	0.3315	440	0.3335
441	0.3315	442	0.3306	443	0.3257	444	0.3247

TABLE A.6. (cont'd) Logged data for frozen impulse line

445	0.3257	446	0.3267	447	0.3267	448	0.3267
449	0.3286	450	0.3286	451	0.3306		
452	0.3296	453	0.3257	454	0.3247	455	0.3237
456	0.3247	457	0.3237	458	0.3276	459	0.3286
460	0.3315	461	0.3306	462	0.3296	463	0.3267
464	0.3257	465	0.3257	466	0.3267	467	0.3286
468	0.3286	469	0.3306	470	0.3306	471	0.3306
472	0.3296	473	0.3286	474	0.3257	475	0.3228
476	0.3228	477	0.3257	478	0.3296	479	0.3325
480	0.3335	481	0.3315	482	0.3296	483	0.3267
484	0.3267	485	0.3267	486	0.3276	487	0.3286
488	0.3296	489	0.3286	490	0.3276	491	0.3267
492	0.3276	493	0.3276	494	0.3276	495	0.3286
496	0.3296	497	0.3306	498	0.3286	499	0.3257
500	0.3257	501	0.3286	502	0.3315	503	0.3325
504	0.3315	505	0.3315	506	0.3306	507	0.3276
508	0.3276	509	0.3286	510	0.3286	511	0.3286
512	0.3276	513	0.3276	514	0.3286	515	0.3296
516	0.3296	517	0.3276	518	0.3276	519	0.3286
520	0.3276	521	0.3276	522	0.3267	523	0.3267
524	0.3286	525	0.3296	526	0.3296	527	0.3276
528	0.3276	529	0.3267	530	0.3276	531	0.3306
532	0.3315	533	0.3315	534	0.3306	535	0.3276
536	0.3276	537	0.3257	538	0.3267	539	0.3286
540	0.3286	541	0.3276	542	0.3276	543	0.3286
544	0.3276	545	0.3276	546	0.3315	547	0.3306
548	0.3306	549	0.3276	550	0.3276	551	0.3286
552	0.3296	553	0.3276	554	0.3267	555	0.3237
556	0.3247	557	0.3276	558	0.3286	559	0.3286
560	0.3286	561	0.3296	562	0.3276	563	0.3296
564	0.3296	565	0.3296	566	0.3286	567	0.3276
568	0.3276	569	0.3257	570	0.3257	571	0.3267
572	0.3296	573	0.3315	574	0.3325	575	0.3306
576	0.3267	577	0.3257	578	0.3257	579	0.3276
580	0.3286	581	0.3315	582	0.3296	583	0.3296
584	0.3276	585	0.3257	586	0.3257	587	0.3276
588	0.3306	589	0.3345	590	0.3345	591	0.3306
592	0.3276	593	0.3247	594	0.3218	595	0.3247
596	0.3276	597	0.3315	598	0.3315	599	0.3325
600	0.3296	601	0.3267	602	0.3257	603	0.3257
604	0.3276	605	0.3306	606	0.3306	607	0.3325
608	0.3286	609	0.3286	610	0.3257	611	0.3267
612	0.3296	613	0.3306	614	0.3306	615	0.3296
616	0.3267	617	0.3267	618	0.3247	619	0.3276
620	0.3276	621	0.3267	622	0.3276	623	0.3276
624	0.3276	625	0.3306	626	0.3267	627	0.3267
628	0.3267	629	0.3267	630	0.3286		
631	0.3286	632	0.3306	633	0.3276	634	0.3276
635	0.3257	636	0.3237	637	0.3247	638	0.3257
639	0.3286	640	0.3296	641	0.3296	642	0.3306
643	0.3276	644	0.3276	645	0.3286	646	0.3267
647	0.3257	648	0.3267	649	0.3267	650	0.3286
651	0.3315	652	0.3306	653	0.3296	654	0.3267
655	0.3267	656	0.3276	657	0.3276	658	0.3267
659	0.3276	660	0.3286	661	0.3286	662	0.3325
663	0.3335	664	0.3335	665	0.3315	666	0.3286

TABLE A.6. (cont'd) Logged data for frozen impulse line

667	0.3267	668	0.3267	669	0.3267	670	0.3306
671	0.3325	672	0.3335	673	0.3315	674	0.3286
675	0.3267	676	0.3267	677	0.3276	678	0.3286
679	0.3276	680	0.3267	681	0.3276	682	0.3257
683	0.3286	684	0.3296	685	0.3306	686	0.3315
687	0.3315	688	0.3286	689	0.3286	690	0.3267
691	0.3257	692	0.3267	693	0.3286	694	0.3296
695	0.3296	696	0.3296	697	0.3286	698	0.3296
699	0.3296	700	0.3306	701	0.3325	702	0.3306
703	0.3276	704	0.3247	705	0.3228	706	0.3247
707	0.3267	708	0.3306	709	0.3335	710	0.3315
711	0.3315	712	0.3286	713	0.3276	714	0.3286
715	0.3276	716	0.3257	717	0.3257	718	0.3257
719	0.3267	720	0.3276	721	0.3286		
722	0.3306	723	0.3296	724	0.3306	725	0.3306
726	0.3296	727	0.3306	728	0.3296	729	0.3286
730	0.3267	731	0.3267	732	0.3267	733	0.3267
734	0.3267	735	0.3276	736	0.3257	737	0.3276
738	0.3286	739	0.3267	740	0.3276	741	0.3276
742	0.3276	743	0.3276	744	0.3306	745	0.3286
746	0.3276	747	0.3257	748	0.3267	749	0.3286
750	0.3267	751	0.3267	752	0.3276	753	0.3267
754	0.3286	755	0.3276	756	0.3276	757	0.3257
758	0.3257	759	0.3257	760	0.3276	761	0.3276
762	0.3276	763	0.3276	764	0.3276	765	0.3276
766	0.3276	767	0.3296	768	0.3286	769	0.3267
770	0.3267	771	0.3267	772	0.3276	773	0.3276
774	0.3276	775	0.3276	776	0.3286	777	0.3276
778	0.3306	779	0.3306	780	0.3296	781	0.3286
782	0.3267	783	0.3257	784	0.3257	785	0.3257
786	0.3276	787	0.3267	788	0.3296	789	0.3296
790	0.3296	791	0.3286	792	0.3286	793	0.3276
794	0.3276	795	0.3267	796	0.3276	797	0.3286
798	0.3276	799	0.3257	800	0.3276	801	0.3276
802	0.3286	803	0.3296	804	0.3306	805	0.3315
806	0.3306	807	0.3296	808	0.3296	809	0.3267
810	0.3276	811	0.3296	812	0.3296	813	0.3286
814	0.3276	815	0.3286	816	0.3296	817	0.3296
818	0.3267	819	0.3286	820	0.3267	821	0.3296
822	0.3267	823	0.3247	824	0.3228	825	0.3257
826	0.3257	827	0.3267	828	0.3267	829	0.3267
830	0.3257	831	0.3267	832	0.3257	833	0.3276
834	0.3296	835	0.3306	836	0.3296	837	0.3276
838	0.3276	839	0.3267	840	0.3267	841	0.3276
842	0.3306	843	0.3315	844	0.3315	845	0.3296
846	0.3267	847	0.3247	848	0.3237	849	0.3267
850	0.3286	851	0.3315	852	0.3315	853	0.3306
854	0.3306	855	0.3276	856	0.3257	857	0.3267
858	0.3237	859	0.3247	860	0.3247	861	0.3276
862	0.3296	863	0.3286	864	0.3276	865	0.3267
866	0.3257	867	0.3267	868	0.3267	869	0.3267
870	0.3296	871	0.3306	872	0.3306	873	0.3296
874	0.3257	875	0.3267	876	0.3276	877	0.3306
878	0.3296	879	0.3296	880	0.3276	881	0.3276
882	0.3276	883	0.3267	884	0.3286	885	0.3286
886	0.3276	887	0.3276	888	0.3286	889	0.3286

Fortran coded program for the Fast Fourier Transform analysis

```
      MASTER FFT
      COMPLEX A(1024)
      DIMENSION AMOD(1024),PW(1024)
C  THIS PROGRAM COMPUTES THE DISCRETE
C  FOURIER TRANSFORM (DFT) OR THE INVERSE
C  DISCRETE FOURIER TRANSFORM (IDFT) OF A
C  SEQUENCE OF COMPLEX NUMBERS USING THE
C  FAST FOURIER TRANSFORM METHOD.
C  THE DFT IS GIVEN BY
C
C               N-1
C   A(K) =  SUM  X(K)*W**KL, K=0,1,...,N-1
C               L=0
C
C  THE IDFT IS GIVEN BY
C
C               N-1
C  X(L)=1/N SUM A(K)*W**(-KL),L=0,1,...,N-1
C               K=0
C  N MUST BE AN ITEGER POWER OF 2
C  REFERENCE, IEEE TRANSACTIONS ON AUDIO AND
C   ELECTROACOUSTICS, VOL. AU-15, NO.2, JUNE
C   1967. (SPECIAL ISSUE ON THE FFT)
C
C***************************************
C
C  DATA IS IN FREE FORMAT AS FOLLOWS
C
C  DIR  (-1.0 FOR DFT, 1.0 FOR IDFT,
C         4.0 AFTER LAST PROBLEM TO STOP)
C  M     (BASE-2 LOG OF NUMBER OF DATA POINTS)
C  A(0) A(1) ... A(N-1) (DATA POINTS)
  1   READ(1,100)DIR
  100 FORMAT(F0.0)
      IF(DIR.GT.2.0)STOP
      IF(DIR.LT.0.0)WRITE(2,101)
  101 FORMAT(17H1DIRECT TRANSFORM)
      IF(DIR.GT.0.0)WRITE(2,102)
  102 FORMAT(18H1INVERSE TRANSFORM)
      READ(1,10)N
  10  FORMAT(I0)
      NP = 2**N
      DO 9 II=1,25
      WRITE(2,2)NP
  2   FORMAT(17H0NUMBER OF POINTS,I5)
      READ(3,3)(A(I),I=1,NP)
  3   FORMAT(2048F0.0)
178  IS THIS LARGE A REPEAT COUNT INTENDED AT ABOUT COL 16, LINE 0060 ?

      DO 4 I =1,NP
  4   WRITE(2,5)I,A(I)
  5   FORMAT(13H INPUT SAMPLE,I5,2(1PE14.4))
        CALL NLOGN(N,A,NP,DIR)
  7   FORMAT(1H ,I5,4(1PE14.4))
      DO 6 I=1,NP
      A(I )=A(I)/ NP
      XY=REAL(A(I))
      XZ=AIMAG(A(I))
      PW(I)=XY*XY+XZ*XZ
      AMOD(I)=SQRT(XY*XY+XZ*XZ)
  6   WRITE(2,7)I,A(I),AMOD(I),PW(I)
      K=62
```

```
        9 CONTINUE
          GO TO 1
          END

GMENT, LENGTH   243, NAME  FFT        - COMMENTS
```

```
      SUBROUTINE NLOGN (N,X,LX,DIR)
C
C     COMPUTES D.F.T. OF X(LX) BY F.F.T. METHOD.
C     DIR:   -1.0   DIRECT TRANSFORM
C            +1.0   INVERSE TRANSFORM
C     IN MAIN PROGRAM N MUST BE SET TO LOG2(LX).
C     J.S.S.  16/3/71
C
      COMPLEX X,WK,HOLD,Q
      DIMENSION M(20),X(LX)
      FLX=FLOAT(LX)
      VA=DIR*6.2831853070/FLX
      K=2**(N-1)
      DO 1 I=1,N
      M(I)=K
    1 K=K/2
      DO 4 L=1,N
      NBLOCK=2**(L-1)
      LBLOCK=LX/NBLOCK
      LBHALF=LBLOCK/2
      K=0
      DO 4 IBLOCK=1,NBLOCK
      FK=FLOAT(K)
      V=VA*FK
      WK=CMPLX(COS(V),SIN(V))
      ISTART=LBLOCK*(IBLOCK-1)
      DO 2 I=1,LBHALF
      J=ISTART+I
      JH=J+LBHALF
      HOLD=X(J)
      Q=X(JH)*WK
      X(JH)=HOLD-Q
    2 X(J)=HOLD+Q
      DO 3 I=2,N
      IF(K.LT.M(I)) GO TO 4
    3 K=K-M(I)
    4 K=K+M(I)
      K=0
      DO 7 J=1,LX
      IF(K.LT.J) GO TO 5
      HOLD=X(J)
      X(J)=X(K+1)
      X(K+1)=HOLD
    5 DO 6 I=1,N
      IF(K.LT.M(I)) GO TO 7
    6 K=K-M(I)
    7 K=K+M(I)
      IF(DIR.LT.0.0) RETURN
      HOLD=CMPLX(FLX,0.0)
      DO 8 I=1,LX
    8 X(I)=X(I)/HOLD
      RETURN
      END

EGMENT, LENGTH   446, NAME  NLOGN
```

APPENDIX 2

Thermocouple data for the figures given in the main text Chapter 7. Enough data are given in each case to show the trend demonstrated in the figures in the main text.

The data in Tables A7 to A20 are the actual e.m.f. outputs of the thermocouples amplified by a factor of 100.

In each column of 3 readings, the first is the time, the second is the e.m.f. in millivolts x 100 and the third is the Standard deviation in millivolts x 100.

Astral coded program for thermocouple logging and on-line calculation of Standard deviation

```
#TITLE:"T/C LOGGING & ON-LINE STD-DEVIATION(4-CHANNELS)"
#WAIT

#DATA:THERMO NUMBER:ALPHA:ALPHACOMP:SAMPLE SIZE:SAMPLING TIME:COUNTER
#DATA:INTERVAL:DATA(4):READING:DUMP:ESTIMATE(2):ERROR:STD DEVIATION:SUM

#LOADAT:*10020
INT PROG
$GO TO:TIMER
$CUEWRITE:PRINTER
#LOADAT:*10110

START
$CHANGE WRITE TO:PRINTER
$TEXT:";:SET TAPE READER REVERSING SWITCH UP AND LOAD TAPE OF"
$TEXT:";:THERMOCOUPLE REQD -ALPHA-SAMPLE SIZE-AND SAMPLING TIME;:"
$CHANGE WRITE TO:PUNCH8
$CLEAR BUFFER
$PAUSE

$READINT:THERMO NUMBER
3 SBC 1
3 STO X2 /COPY FOR USE TO PICK OUT REQD THERMOCOUPLE
$READFL:ALPHA
$LOADFL:!+1F
$SUBFL:ALPHA
$STOFL:ALPHA COMP
$READINT:SAMPLE SIZE
$READINT:SAMPLING TIME
$CLEAR :SUM
$CLEAR:X1

MAKE LEADER
$BLANKS:300

LOG
0 STO INTERVAL
0 STO COUNTER
0 STO X5
READ SIGNAL
$ANALOG FRAC:*101
6 STO DATA
$ANALOGFRAC:*102
6 STO DATA+1
$ANALOGFRAC:*103
6 STO DATA+2
$ANALOGFRAC:*104
6 STO DATA+3
$FLOAT:DATA:+0:2
$STOFL:READING
$MPYFL:ALPHA
$STOFL:DUMP
$LOADFL:READING
$MPYFL:ALPHACOMP
$ADDFL:DUMP
$STOFL:ESTIMATE
```

```
ROUTINE
$ANALOGFRAC:*101
6 STO DATA
$ANALOGFRAC:*102
6 STO DATA+1
$ANALOGFRAC:*103
6 STO DATA+2
$ANALOGFRAC:*104
6 STO DATA+3
CALCULATE
$FLOAT:DATA:+0:2 /PICK REQD READING
$STOFL:READING
$MPYFL:ALPHA
$STOFL:DUMP
$LOADFL:ESTIMATE
$MPYFL:ALPHACOMP
$ADDFL:DUMP
$STOFL:ESTIMATE+1
FIND ERROR
$LOADFL:READING
$SUBFL:ESTIMATE
$STOFL:ERROR
$SQUAREFL:ERROR
$ADDFL:SUM
$STOFL:SUM
$LOADFL:ESTIMATE+1
$STOFL:ESTIMATE

6 LDX INTERVAL
6 SRA 23
6 DIV !+60
6 JZE PRINT TIME
$NEW LINE

PRINT TIME
$PRINT:INTERVAL:V60:+23
$PRINT:DATA:F24:+0
$PRINT:DATA+1:F24:+0
$PRINT:DATA+2:F24:+0
$PRINT:DATA+3:F24:+0

$PRINTFL:ERROR:F24

7 LDX HSW
7 SLC 1
7 JGE INCREASE INT
MAKE TAIL
$TEXT:";:L;:"

$BLANKS:20
$ERASES:20
$BLANKS:100
$PAUSE
$GO TO:MAKE LEADER

INCREASE INT
4 LDC 1
4 ADS INTERVAL

WAIT TILL INT
0 LDX *25
0 LDX *11
0 JZE V
```

```
TIMER
0 LDX *25
4 LDX COUNTER
4 ADC 1
4 STO COUNTER
4 SUB SAMPLING TIME
4 JNZ WAIT TILL INT
0 STO COUNTER

LFBR
1 ADC 1
1 STO X5
5 NEQ SAMPLE SIZE
5 JNZ ROUTINE

FIND DEVIATION
$FLOAT:SAMPLE SIZE:+23
$SUBFL:!+1F
$RDIVFL:!+1F
$MPYFL:SUM /FIND VARIANCE
$SQRTFX
$STOFL:STD DEVIATION
$PRINTFX:F24
$CLEAR:X1
$CLEAR:SUM
$CLEAR:X5
$GO TO :ROUTINE

#BREAK
#END
```

TABLE A.7. Data for Figs. 7.3. and 7.4.

0	0.5220	1	0.4937	
2	0.5034	3	0.5005	
4	0.5044	5	0.5073	
6	0.5044	7	0.5063	
8	0.5005	9	0.5005	0.0087
10	0.5005	11	0.5005	
12	0.5005	13	0.5005	
14	0.5005	15	0.5005	
16	0.4927	17	0.5005	
18	0.5054	19	0.5054	0.0040
20	0.5063	21	0.5005	
22	0.5063	23	0.5073	
24	0.5073	25	0.5073	
26	0.5083	27	0.5083	
28	0.5005	29	0.5005	0.0040
30	0.4917	31	0.5005	
32	0.5005	33	0.5005	
34	0.5005	35	0.5005	
36	0.5005	37	0.5073	
38	0.5073	39	0.5122	0.0058
40	0.5083	41	0.5112	
42	0.5083	43	0.5083	
44	0.5005	45	0.5005	
46	0.5005	47	0.5005	
48	0.5005	49	0.5132	0.0055
50	0.4927	51	0.5122	
52	0.5132	53	0.5132	
54	0.5093	55	0.5093	
56	0.5093	57	0.5093	
58	0.5103	59	0.5093	0.0065
60	0.5112	61	0.5161	
62	0.5142	63	0.5005	
64	0.5161	65	0.5161	
66	0.5171	67	0.5024	
68	0.5015	69	0.5181	0.0081
70	0.5024	71	0.5151	
72	0.5151	73	0.5151	
74	0.5151	75	0.5171	
76	0.5161	77	0.5171	
78	0.5171	79	0.5063	0.0055
80	0.5054	81	0.5063	
82	0.5034	83	0.5044	
84	0.5229	85	0.5239	
86	0.5220	87	0.5210	
88	0.5220	89	0.5210	0.0085
90	0.5190	91	0.5171	
92	0.5181	93	0.5239	
94	0.5190	95	0.5190	
96	0.5190	97	0.5190	
98	0.5190	99	0.5190	0.0020
100	0.5220	101	0.5200	
102	0.5190	103	0.5200	
104	0.5200	105	0.5259	
106	0.5239	107	0.5249	
108	0.5239	109	0.5249	0.0027
110	0.5073	111	0.5259	

TABLE A.7. (cont'd) Data for Figs. 7.3. and 7.4.

112	0.5259	113	0.5249	
113	0.5240	115	0.5239	
116	0.5210	117	0.5210	
118	0.5210	119	0.5210	0.0062
120	0.5229	121	0.5210	
122	0.5220	123	0.5249	
124	0.5259	125	0.5249	
126	0.5259	127	0.5259	
128	0.5259	129	0.5200	0.0025
130	0.5200	131	0.5190	
132	0.5200	133	0.5200	
134	0.5200	135	0.5190	
136	0.5210	137	0.5259	
138	0.5259	139	0.5259	0.0032
140	0.5073	141	0.5269	
142	0.5249	143	0.5249	
144	0.5249	145	0.5249	
146	0.5239	147	0.5259	
148	0.5239	149	0.5239	0.0062
150	0.5151	151	0.5259	
152	0.5239	153	0.5259	
154	0.5249	155	0.5259	
156	0.5200	157	0.5210	
158	0.5200	159	0.5200	0.0041
160	0.5220	161	0.5249	
162	0.5200	163	0.5210	
164	0.5210	165	0.5220	
166	0.5229	167	0.5220	
168	0.5220	169	0.5220	0.0015
170	0.5220	171	0.5210	
172	0.5210	173	0.5210	
174	0.5210	175	0.5210	
176	0.5210	177	0.5200	
178	0.5200	179	0.5200	0.0007
180	0.5200	181	0.5200	
182	0.5200	183	0.5190	
184	0.5190	185	0.5190	
186	0.5190	187	0.5190	
188	0.5190	189	0.5190	0.0006
190	0.5210	191	0.5190	
192	0.5181	193	0.5181	
194	0.5181	195	0.5181	
196	0.5181	197	0.5181	
198	0.5239	199	0.5181	0.0022
200	0.5200	201	0.5181	
202	0.5181	203	0.5190	
204	0.5181	205	0.5181	
206	0.5181	207	0.5181	
208	0.5181	209	0.5181	0.0008
210	0.5200	211	0.5181	
212	0.5181	213	0.5181	
214	0.5181	215	0.5220	
216	0.5220	217	0.5220	
218	0.5220	219	0.5200	0.0019
220	0.5005	221	0.5210	
222	0.5210	223	0.5210	

TABLE A.7. (cont'd) Data for Figs. 7.3 and 7.4.

224	0.5220	225	0.5220	
226	0.5220	227	0.5210	
228	0.5229	229	0.5229	0.0074
230	0.5044	231	0.5220	
232	0.5210	233	0.5220	
234	0.5210	235	0.5220	
236	0.5171	237	0.5171	
238	0.5171	239	0.5171	0.0064
240	0.5190	241	0.5181	
242	0.5181	243	0.5171	
244	0.5181	245	0.5181	
246	0.5181	247	0.5181	
248	0.5171	249	0.5200	0.0009
250	0.5112	251	0.5229	
252	0.5220	253	0.5229	
254	0.5210	255	0.5220	
256	0.5239	257	0.5229	
258	0.5229	259	0.5220	0.0039
260	0.5210	261	0.5239	
262	0.5190	263	0.5181	
264	0.5171	265	0.5220	
266	0.5171	267	0.5181	
268	0.5190	269	0.5181	0.0026
270	0.5210	271	0.5181	
272	0.5181	273	0.5181	
274	0.5181	275	0.5181	
276	0.5181	277	0.5229	
278	0.5181	279	0.5181	0.0019
280	0.5200	281	0.5181	
282	0.5171	283	0.5171	
284	0.5171	285	0.5171	
286	0.5171	287	0.5171	
288	0.5161	289	0.5161	0.0012
290	0.5190	291	0.5161	
292	0.5220	293	0.5161	
294	0.5171	295	0.5171	
296	0.5171	297	0.5181	
298	0.5171	299	0.5181	0.0020
300	0.5181	301	0.5181	
302	0.5181	303	0.5181	
304	0.5181	305	0.5171	
306	0.5181	307	0.5210	
308	0.5210	309	0.5220	0.0016
310	0.5142	311	0.5220	
312	0.5229	313	0.5220	
314	0.5210	315	0.5220	
316	0.5210	317	0.5210	
318	0.5220	319	0.5210	0.0027
320	0.5054	321	0.5210	
322	0.5210	323	0.5210	
324	0.5210	325	0.5210	
326	0.5210	327	0.5200	
328	0.5200	329	0.5200	0.0056
330	0.5024	331	0.5200	
332	0.5044	333	0.5034	
334	0.5200	335	0.5190	

TABLE A.7. (cont'd) Data for Figs. 7.3. and 7.4.

336	0.5190	337	0.5024	
338	0.5044	339	0.5210	0.0109
340	0.5015	341	0.5200	
342	0.5200	343	0.5200	
344	0.5200	345	0.5181	
346	0.5200	347	0.5034	
348	0.5024	349	0.5034	0.0092
350	0.5093	351	0.5044	
352	0.5034	353	0.5015	
354	0.5005	355	0.5005	
356	0.5005	357	0.5005	
358	0.5005	359	0.5005	0.0039
360	0.5972	361	0.5005	
362	0.5005	363	0.5005	
364	0.5005	365	0.5005	
366	0.5005	367	0.5005	
368	0.5005	369	0.5005	0.0343
370	0.4927	371	0.5005	
372	0.5005	373	0.5005	
374	0.4927	375	0.4888	
376	0.4614	377	0.4614	
378	0.4595	379	0.4575	0.0179
380	0.6597	381	0.4536	
382	0.4497	383	0.4507	
384	0.4468	385	0.4468	
386	0.4448	387	0.4468	
388	0.4429	389	0.4419	0.0719
390	0.4927	391	0.4438	
392	0.4390	393	0.4380	
394	0.4380	395	0.4341	
396	0.4253	397	0.4253	
398	0.4243	399	0.4233	0.0199
400	0.5620	401	0.5640	
402	0.5620	403	0.5620	
404	0.5610	405	0.5620	
406	0.5620	407	0.5620	
408	0.5610	409	0.5601	0.0664
410	0.5562	411	0.5571	
412	0.5562	413	0.5542	
414	0.5532	415	0.5532	
416	0.5532	417	0.5522	
418	0.5522	419	0.5513	0.0018
420	0.5532	421	0.5522	
422	0.5532	423	0.5532	
424	0.5532	425	0.5542	
426	0.5532	427	0.5522	
428	0.5522	429	0.3862	0.0555
430	0.5571	431	0.5542	
432	0.5552	433	0.5552	
434	0.5552	435	0.5552	
436	0.5552	437	0.5552	
438	0.5542	439	0.5532	0.0223
440	0.7505	441	0.5542	
442	0.5532	443	0.3687	
444	0.3560	445	0.3560	
446	0.3511	447	0.3560	

TABLE A.7. (cont'd) Data for Figs. 7.3. and 7.4.

448	0.3540	449	0.3530	0.1309
450	0.5015	451	0.3481	
452	0.3384	453	0.3413	
454	0.3442	455	0.3267	
456	0.3276	457	0.3286	
458	0.3286	459	0.3237	0.0549
460	0.3198	461	0.3179	
462	0.3237	463	0.3228	
464	0.3208	465	0.3198	
466	0.3198	467	0.3140	
468	0.3110	469	0.3120	0.0092
470	0.6479	471	0.3022	
472	0.3071	473	0.3003	
474	0.2944	475	0.3013	
476	0.2974	477	0.2983	
478	0.3003	479	0.2974	0.1211
480	0.3940	481	0.3013	
482	0.2866	483	0.2974	
484	0.2896	485	0.2905	
486	0.2983	487	0.2983	
488	0.2944	489	0.2905	0.0342
490	0.5815	491	0.2954	
492	0.2993	493	0.5815	
494	0.5806	495	0.5786	
496	0.5786	497	0.5767	
498	0.5757	499	0.6050	0.1577
500	0.6001	501	0.6362	
502	0.6362	503	0.6353	
504	0.6372	505	0.6343	
506	0.6401	507	0.6362	
508	0.6362	509	0.6353	0.0395
510	0.6470	511	0.6470	
512	0.6489	513	0.6450	
514	0.6479	515	0.6470	
516	0.6460	517	0.6460	
518	0.6479	519	0.6489	0.0083
520	0.6567	521	0.6538	
522	0.6538	523	0.6538	
524	0.6528	525	0.6548	
526	0.6548	527	0.6558	
528	0.6538	529	0.6548	0.0043
530	0.6646	531	0.6665	
532	0.6694	533	0.6714	
534	0.6772	535	-0.1597	
536	-0.1616	537	-0.1597	
538	-0.1558	539	-0.1597	0.4049
540	-0.1626	541	-0.1655	
542	-0.1733	543	-0.1685	
544	-0.1724	545	-0.0171	
546	0.0210	547	-0.1675	
548	0.6675	549	0.6665	0.33729
550	0.6694	551	0.6724	
552	0.6763	553	0.6802	
554	0.6880	555	-0.1675	
556	-0.1851	557	-0.1870	
558	-0.1870	559	-0.1899	0.4276

TABLE A.7 (cont'd) Data for Figs. 7.3. and 7.4.

560	0.3218	561	-0.1929	
562	-0.1851	563	-0.1890	
564	-0.1938	565	0.6704	
566	0.6724	567	0.6782	
568	0.6802	569	0.6821	0.4178
570	0.6860	571	0.6909	
572	0.6919	573	0.6958	
574	0.7036	575	0.7046	
576	-0.2104	577	-0.2124	
578	-0.2173	579	-0.2124	0.4299
580	-0.0024	581	-0.2192	
582	-0.2144	583	-0.2085	
584	-0.2192	585	-0.2104	
586	-0.2144	587	-0.2144	
588	-0.2153	589	-0.2173	0.1336
590	0.4829	591	-0.2124	
592	0.6812	593	0.6851	
594	0.6860	595	0.6870	
596	0.6880	597	0.6909	
598	0.6919	599	0.6938	0.4469
600	0.6987	601	0.7046	
602	-0.2222	603	-0.2192	
604	-0.2163	605	-0.2173	
606	-0.2173	607	-0.2144	
608	-0.2134	609	-0.2163	0.4381
610	-0.1646	611	-0.2163	
612	-0.2065	613	0.6880	
614	0.6899	615	0.6929	
616	0.6948	617	0.6997	
618	0.7046	619	0.7036	0.4326
620	0.7075	621	0.7075	
622	-0.2280	623	-0.2173	
624	-0.2183	625	-0.2261	
626	-0.2231	627	-0.2222	
628	-0.2251	629	-0.2251	0.4347
630	-0.2261	631	-0.2212	
632	-0.2222	633	-0.2300	
634	-0.2222	635	0.7065	
636	0.7065	637	0.7075	
638	0.7046	639	0.7085	0.4477
640	0.7114	641	0.7144	
642	0.7153	643	0.7153	
644	-0.2358	645	-0.2310	
646	-0.2368	647	-0.2300	
645	-0.2372	649	-0.2261	0.4479
650	-0.2261	651	-0.2300	
652	0.7075	653	0.7026	
654	0.7075	655	0.7114	
656	0.7114	657	0.7114	
658	-0.2358	659	-0.2397	0.5403
660	0.3999	661	-0.2378	
662	-0.2358	663	-0.2358	
664	-0.2261	665	0.7075	
666	0.7114	667	0.7183	
668	0.7134	669	-0.2397	0.5066
670	-0.1655	671	-0.2358	

TABLE A.7. (cont'd) Data for Figs. 7.3. and 7.4.

672	-0.2251	673	-0.2368	
674	-0.2300	675	0.7075	
676	0.7104	677	0.7065	
678	0.7144	679	0.7124	0.4680
680	0.7114	681	0.7114	
682	0.7114	683	0.7153	
684	0.7153	685	0.7192	
686	0.7163	687	0.7134	
688	-0.2456	689	-0.2466	0.4043
690	0.4097	691	-0.2495	
692	-0.2476	693	-0.2397	
694	-0.2476	695	-0.2495	
696	-0.2407	697	-0.0591	
698	-0.2495	699	-0.2437	0.2876
700	0.4038	701	-0.2427	
702	-0.2446	703	-0.2437	
704	-0.2495	705	-0.2495	
706	-0.0200	707	-0.2495	
708	-0.2495	709	-0.2534	0.2322
710	-0.1050	711	0.7212	
712	0.7310	713	0.7192	
714	0.7153	715	0.7173	
716	0.7153	717	0.7124	
718	0.7134	719	0.7144	0.4554
720	0.7114	721	0.7134	
722	0.7134	723	-0.0474	
724	-0.0356	725	-0.0435	
726	-0.0396	727	-0.0415	
728	-0.0278	729	-0.0396	0.3639
730	0.4800	731	-0.0630	
732	-0.0786	733	-0.0708	
734	-0.0366	735	-0.0415	
736	-0.0591	737	-0.0552	
738	0.7231	739	0.7212	0.3601
740	0.7212	741	0.7173	
742	0.7163	743	0.7192	
744	0.7163	745	0.7173	
746	0.7144	747	0.7144	
748	0.7183	749	0.7124	0.2096
750	0.4546	751	-0.0415	
752	-0.0767	753	-0.0649	
754	-0.0864	755	-0.0786	
756	-0.0796	757	-0.0669	
758	-0.0698	759	-0.0552	0.3601
760	-0.0786	761	-0.0903	
762	-0.0493	763	-0.0942	
764	-0.0737	765	-0.0903	
766	0.7261	767	0.7183	
768	0.7231	769	0.7192	0.3719
770	0.7212	771	0.7212	
772	0.7241	773	0.7231	
774	0.7241	775	0.7192	
776	0.7212	777	-0.0786	
778	-0.0864	779	-0.0630	0.3713
780	0.4214	781	-0.0884	
782	-0.0708	783	-0.0991	

TABLE A.8. Data for Fig. 7.5.

0	0.4380	1	0.4380	
2	0.4390	3	0.4380	
4	0.4409	5	0.4419	
6	0.4399	7	0.4419	
8	0.4429	9	0.4409	0.0018
10	0.4390	11	0.4390	
12	0.4399	13	0.4399	
14	0.4399	15	0.4409	
16	0.4409	17	0.4409	
18	0.4399	19	0.4399	0.0009
20	0.4409	21	0.4429	
22	0.4429	23	0.4429	
24	0.4429	25	0.4419	
26	0.4429	27	0.4419	
28	0.4399	29	0.4399	0.0015
30	0.4399	31	0.4399	
32	0.4399	33	0.4399	
34	0.4390	35	0.4390	
36	0.4390	37	0.4390	
38	0.4399	39	0.4429	0.0014
40	0.4409	41	0.4429	
42	0.4438	43	0.4448	
44	0.4448	45	0.4448	
46	0.4429	47	0.4438	
48	0.4429	49	0.4448	0.0019
50	0.4438	51	0.4438	
52	0.4448	53	0.4438	
54	0.4438	55	0.4458	
56	0.4448	57	0.4448	
58	0.4458	59	0.4448	0.0008
60	0.4419	61	0.4448	
62	0.4419	63	0.4419	
64	0.4419	65	0.4419	
66	0.4419	67	0.4419	
68	0.4409	69	0.4419	0.0016
70	0.4419	71	0.4438	
72	0.4429	73	0.4438	
74	0.4438	75	0.4438	
76	0.4429	77	0.4419	
78	0.4399	79	0.4438	0.0015
80	0.4409	81	0.4419	
82	0.4438	83	0.4429	
84	0.4438	85	0.4458	
86	0.4458	87	0.4458	
88	0.4458	89	0.4458	0.0017
90	0.4468	91	0.4468	
92	0.4438	93	0.4438	
94	0.4448	95	0.4438	
96	0.4448	97	0.4438	
98	0.4448	99	0.4438	0.0012
100	0.4438	101	0.4438	
102	0.4429	103	0.4458	
104	0.4468	105	0.4458	
106	0.4468	107	0.4468	
108	0.4487	109	0.4497	0.0020
110	0.4478	111	0.4478	

TABLE A.8 (cont'd) Data for Fig. 7.5.

112	0.4478	113	0.4478	
114	0.4478	115	0.4487	
116	0.4497	117	0.4487	
118	0.4497	119	0.4497	0.0009
120	0.4487	121	0.4517	
122	0.4517	123	0.4517	
124	0.4517	125	0.4526	
126	0.4526	127	0.4526	
128	0.4536	129	0.4536	0.0017
130	0.4507	131	0.4517	
132	0.4526	133	0.4526	
134	0.4526	135	0.4517	
136	0.4517	137	0.4517	
138	0.4556	139	0.4546	0.0016
140	0.4556	141	0.4565	
142	0.4565	143	0.4595	
144	0.4585	145	0.4595	
146	0.4585	147	0.4595	
148	0.4575	149	0.4585	0.0024
150	0.4585	151	0.4575	
152	0.4546	153	0.4546	
154	0.4536	155	0.4546	
156	0.4546	157	0.4546	
158	0.4546	159	0.4575	0.0020
160	0.4565	161	0.4575	
162	0.4585	163	0.4614	
164	0.4604	165	0.4614	
166	0.4614	167	0.4604	
168	0.4614	169	0.4614	0.0024
170	0.4614	171	0.4604	
172	0.4565	173	0.4575	
174	0.4575	175	0.4585	
176	0.4585	177	0.4585	
178	0.4585	179	0.4595	0.0017
180	0.4595	181	0.4585	
182	0.4604	183	0.4614	
184	0.4614	185	0.4604	
186	0.4604	187	0.4614	
188	0.4624	189	0.4644	0.0017
190	0.4634	191	0.4614	
192	0.4624	193	0.4634	
194	0.4634	195	0.4624	
196	0.4624	197	0.4644	
198	0.4653	199	0.4644	0.0013
200	0.4644	201	0.4644	
202	0.4663	203	0.4644	
204	0.4653	205	0.4644	
206	0.4653	207	0.4634	
208	0.4663	209	0.4653	0.0012
210	0.4624	211	0.4653	
212	0.4624	213	0.4624	
214	0.4624	215	0.4614	
216	0.4604	217	0.4614	
218	0.4614	219	0.4604	0.0018
220	0.4604	221	0.4604	
222	0.4595	223	0.4624	

TABLE A.9. Data for Fig. 7.6.

0	0.4556	1	0.4634	
2	0.4634	3	0.4644	
4	0.4644	5	0.4644	
6	0.4644	7	0.4692	
8	0.4673	9	0.4663	0.0053
10	0.4712	11	0.4663	
12	0.4653	13	0.4653	
14	0.4614	15	0.4634	
16	0.4634	17	0.4692	
18	0.4673	19	0.4692	0.0033
20	0.4673	21	0.4683	
22	0.4673	23	0.4692	
24	0.4702	25	0.4712	
26	0.4702	27	0.4702	
28	0.4692	29	0.4702	0.0016
30	0.4741	31	0.4692	
32	0.4692	33	0.4692	
34	0.4673	35	0.4673	
36	0.4692	37	0.4702	
38	0.4731	39	0.4702	0.0024
40	0.4702	41	0.4731	
42	0.4712	43	0.4722	
44	0.4702	45	0.4731	
46	0.4741	47	0.4741	
48	0.4702	49	0.4702	0.0020
50	0.4702	51	0.4731	
52	0.4692	53	0.4712	
54	0.4722	55	0.4731	
56	0.4722	57	0.4731	
58	0.4712	59	0.4751	0.0018
60	0.4761	61	0.4731	
62	0.4731	63	0.4722	
64	0.4731	65	0.4702	
66	0.4673	67	0.4692	
68	0.4683	69	0.4692	0.0025
70	0.4692	71	0.4692	
72	0.4702	73	0.4692	
74	0.4692	75	0.4702	
76	0.4741	77	0.4722	
78	0.4722	79	0.4731	0.0017
80	0.4771	81	0.4741	
82	0.4731	83	0.4692	
84	0.4692	85	0.4683	
86	0.4692	87	0.4692	
88	0.4692	89	0.4692	0.0028
90	0.4692	91	0.4673	
92	0.4712	93	0.4702	
94	0.4702	95	0.4692	
96	0.4702	97	0.4692	
98	0.4692	99	0.4692	0.0012
100	0.4692	101	0.4692	
102	0.4702	103	0.4692	
104	0.4692	105	0.4683	
106	0.4673	107	0.4692	
108	0.4673	109	0.4673	0.0010
110	0.4673	111	0.4702	

TABLE A.9. (cont'd) Data for Fig. 7.6.

112	0.4712	113	0.4702	
114	0.4712	115	0.4712	
116	0.4712	117	0.4702	
118	0.4702	119	0.4702	0.0015
120	0.4673	121	0.4692	
122	0.4692	123	0.4692	
124	0.4692	125	0.4673	
126	0.4692	127	0.4673	
128	0.4692	129	0.4692	0.0014
130	0.4673	131	0.4702	
132	0.4712	133	0.4692	
134	0.4712	135	0.4712	
136	0.4712	137	0.4731	
138	0.4722	139	0.4692	0.0018
140	0.4673	141	0.4712	
142	0.4692	143	0.4702	
144	0.4712	145	0.4702	
146	0.4741	147	0.4722	
148	0.4722	149	0.4722	0.0019
150	0.4722	151	0.4722	
152	0.4712	153	0.4771	
154	0.4790	155	0.4780	
156	0.4780	157	0.4810	
158	0.4829	159	0.4829	0.0042
160	0.5151	161	0.4849	
162	0.4849	163	0.4829	
164	0.4868	165	0.4810	
166	0.4800	167	0.4790	
168	0.4780	169	0.4839	0.0124
170	0.4731	171	0.4829	
172	0.4829	173	0.4810	
174	0.4810	175	0.4810	
176	0.4800	177	0.4800	
178	0.4839	179	0.4800	0.0035
180	0.4819	181	0.4849	
182	0.4839	183	0.4858	
184	0.4868	185	0.4888	
186	0.4917	187	0.4839	
188	0.5005	189	0.4849	0.0061
190	0.4224	191	0.4927	
192	0.4917	193	0.4956	
194	0.4800	195	0.4937	
196	0.5005	197	0.4897	
198	0.4800	199	0.4800	0.0252
200	0.4810	201	0.4819	
202	0.4800	203	0.4800	
204	0.4868	205	0.4849	
206	0.4839	207	0.4849	
208	0.4858	209	0.4849	0.0029
210	0.4819	211	0.4829	
212	0.4858	213	0.4849	
214	0.5005	215	0.5005	
216	0.4858	217	0.4878	
218	0.5005	219	0.4897	0.0080
220	0.4849	221	0.4858	
222	0.4868	223	0.4858	

TABLE A.9. (cont'd) Data for Fig. 7.6.

224	0.4849	225	0.4946	
226	0.5005	227	0.5005	
228	0.4829	229	0.4946	0.0073
230	0.6050	231	0.4849	
232	0.4849	233	0.4810	
234	0.4839	235	0.4810	
236	0.5005	237	0.4819	
238	0.4878	239	0.5005	0.0422
240	0.4438	241	0.5103	
242	0.5073	243	0.5005	
244	0.5005	245	0.5103	
246	0.5005	247	0.5005	
248	0.5093	249	0.5015	0.0212
250	0.6167	251	0.5073	
252	0.5005	253	0.5005	
254	0.5005	255	0.5435	
256	0.5005	257	0.5005	
258	0.5005	259	0.5005	0.0429
260	0.5005	261	0.5005	
262	0.5063	263	0.4937	
264	0.5063	265	0.4839	
266	0.5229	267	0.5005	
268	0.5005	269	0.5005	0.0116
270	0.5034	271	0.5005	
272	0.5005	273	0.5005	
274	0.5112	275	0.5005	
276	0.5190	277	0.5073	
278	0.5054	279	0.4956	0.0075
280	0.5044	281	0.5005	
282	0.5024	283	0.5103	
284	0.5093	285	0.5054	
286	0.5210	287	0.5015	
288	0.5171	289	0.5005	0.0079
290	0.6841	291	0.5073	
292	0.5063	293	0.5269	
294	0.5073	295	0.5054	
296	0.5278	297	0.5015	
298	0.5396	299	0.5269	0.0635
300	0.6733	301	0.5073	
302	0.5024	303	0.5044	
304	0.5024	305	0.5054	
306	0.5181	307	0.5229	
308	0.5073	309	0.5308	0.0574
310	0.5073	311	0.5063	
312	0.5044	313	0.5054	
314	0.5073	315	0.5093	
316	0.5112	317	0.5073	
318	0.5073	319	0.5005	0.0074
320	0.5054	321	0.5142	
322	0.5142	323	0.5132	
324	0.5063	325	0.5122	
326	0.5073	327	0.5151	
328	0.5229	329	0.5210	0.0064
330	0.7017	331	0.5132	
332	0.5122	333	0.5396	
334	0.5181	335	0.5073	

TABLE A.10 Sample data for Fig. 7.9.

P

0	0.2417	1	0.2417	
2	0.2417	3	0.2417	
4	0.2417	5	0.2417	
6	0.2427	7	0.2427	
8	0.2427	9	0.2427	0.0005
10	0.2397	11	0.2427	
12	0.2427	13	0.2427	
14	0.2417	15	0.2427	
16	0.2427	17	0.2427	
18	0.2427	19	0.2427	0.0010
20	0.2417	21	0.2407	
22	0.2427	23	0.2407	
24	0.2427	25	0.2417	
26	0.2427	27	0.2427	
28	0.2427	29	0.2427	0.0001
30	0.2427	31	0.2417	
32	0.2427	33	0.2427	
34	0.2417	35	0.2437	
36	0.2427	37	0.2427	
38	0.2427	39	0.2427	0.0006
40	0.2407	41	0.2427	
42	0.2427	43	0.2427	
44	0.2437	45	0.2407	
46	0.2407	47	0.2417	
48	0.2417	49	0.2417	0.0011
50	0.2417	51	0.2437	
52	0.2427	53	0.2417	
54	0.2437	55	0.2427	
56	0.2427	57	0.2427	
58	0.2417	59	0.2397	0.0012
60	0.2437	61	0.2417	
62	0.2427	63	0.2427	
64	0.2437	65	0.2407	
66	0.2437	67	0.2437	
68	0.2427	69	0.2427	0.0010
70	0.2427	71	0.2437	
72	0.2427	73	0.2417	
74	0.2427	75	0.2437	
76	0.2407	77	0.2407	
78	0.2417	79	0.2427	0.0011
80	0.2427	80	0.2427	
82	0.2427	83	0.2427	
84	0.2427	85	0.2437	
86	0.2437	87	0.2427	
88	0.2417	89	0.2437	0.0000
90	0.2417	91	0.2427	
92	0.2437	93	0.2417	
94	0.2427	95	0.2427	
96	0.2427	97	0.2427	
98	0.2427	99	0.2427	0.0006
100	0.2417	101	0.2397	
102	0.2427	103	0.2437	
104	0.2417	105	0.2427	
106	0.2427	107	0.2437	
108	0.2427	109	0.2446	0.0014
110	0.2437	111	0.2417	

TABLE A.10 (cont'd) Sample data for Fig. 7.9.

112	0.2437	113	0.2437	
104	0.2446	115	0.2437	
116	0.2437	117	0.2446	
118	0.2417	119	0.2417	0.0012
120	0.2427	121	0.2427	
122	0.2437	123	0.2437	
124	0.2417	125	0.2437	
126	0.2427	127	0.2427	
128	0.2427	129	0.2437	0.0007
130	0.2427	131	0.2417	
132	0.2427	133	0.2427	
134	0.2427	135	0.2427	
136	0.2417	137	0.2446	
138	0.2427	139	0.2437	0.0009
140	0.2417	141	0.2427	
142	0.2437	143	0.2427	
144	0.2437	145	0.2466	
146	0.2437	147	0.2437	
148	0.2437	149	0.2427	0.0014
150	0.2427	151	0.2427	
152	0.2427	153	0.2437	
154	0.2437	155	0.2427	
156	0.2446	157	0.2437	
158	0.2417	159	0.2427	0.0009
160	0.2427	161	0.2437	
162	0.2417	163	0.2427	
164	0.2417	165	0.2446	
166	0.2427	167	0.2437	
168	0.2446	169	0.2437	0.0011
170	0.2437	171	0.2437	
172	0.2446	173	0.2437	
174	0.2437	175	0.2446	
176	0.2437	177	0.2437	
178	0*2427	179	0.2446	0.0008
180	0.2446	181	0.2437	
182	0.2437	183	0.2427	
184	0.2427	185	0.2466	
186	0.2437	187	0.2427	
188	0.2437	189	0.2437	0.0012
190	0.2427	191	0.2427	
192	0.2427	193	0.2437	
194	0.2437	195	0.2437	
196	0.2437	197	0.2437	
198	0.2446	199	0.2446	0.0007
200	0.2427	201	0.2446	
202	0.2437	203	0.2446	
204	0.2446	205	0.2437	
206	0.2437	207	0.2427	
208	0.2446	209	0.2437	0.0000
210	0.2437	211	0.2466	
212	0.2437	213	0.2446	
214	0.2437	215	0.2456	
216	0.2437	217	0.2437	
218	0.2437	219	0.2446	0.0012
220	0.2437	221	0.2427	
222	0.2437	223	0.2437	

TABLE A.11. Sample data for Fig. 7.10.

0	0.2466	1	0.2466	
2	0.2466	3	0.2446	
4	0.2466	5	0.2476	
6	0.2466	7	0.2466	
8	0.2476	9	0.2466	0.0008
10	0.2466	11	0.2466	
12	0.2456	13	0.2446	
14	0.2456	15	0.2466	
16	0.2466	17	0.2446	
18	0.2476	19	0.2466	0.0011
20	0.2466	21	0.2466	
22	0.2466	23	0.2466	
24	0.2466	25	0.2466	
26	0.2466	27	0.2456	
28	0.2466	29	0.2456	0.0004
30	0.2456	31	0.2466	
32	0.2446	33	0.2466	
34	0.2466	35	0.2466	
36	0.2456	37	0.2456	
38	0.2476	39	0.2466	0.0009
40	0.2466	41	0.2466	
42	0.2466	43	0.2466	
44	0.2476	45	0.2466	
46	0.2466	47	0.2466	
48	0.2456	49	0.2456	0.0006
50	0.2456	51	0.2466	
52	0.2466	53	0.2466	
54	0.2466	55	0.2466	
56	0.2476	57	0.2456	
58	0.2466	59	0.2476	0.0007
60	0.2456	61	0.2466	
62	0.2466	63	0.2466	
64	0.2476	65	0.2466	
66	0.2456	67	0.2466	
68	0.2476	69	0.2466	0.0007
70	0.2456	71	0.2466	
72	0.2466	73	0.2456	
74	0.2466	75	0.2456	
76	0.2456	77	0.2466	
78	0.2466	79	0.2466	0.0006
80	0.2456	81	0.2456	
82	0.2446	83	0.2456	
84	0.2456	85	0.2466	
86	0.2476	87	0.2466	
88	0.2476	89	0.2476	0.0010
90	0.2466	91	0.2485	
92	0.2476	93	0.2485	
94	0.2485	95	0.2476	
96	0.2466	97	0.2466	
98	0.2466	99	0.2466	0.0011
100	0.2476	101	0.2485	
102	0.2466	103	0.2485	
104	0.2476	105	0.2476	
106	0.2485	107	0.2476	
108	0.2466	109	0.2485	0.0010
110	0.2476	111	0.2476	

TABLE A.12. Sample data for Fig. 7.11

0	0.2905	1	0.2905	
2	0.2905	3	0.2915	
4	0.2905	5	0.2905	
6	0.2896	7	0.2905	
8	0.2905	9	0.2896	0.0006
10	0.2896	11	0.2905	
12	0.2905	13	0.2905	
14	0.2915	15	0.2905	
16	0.2905	17	0.2896	
18	0.2896	19	0.2896	0.0007
20	0.2896	21	0.2905	
22	0.2905	23	0.2905	
24	0.2905	25	0.2905	
26	0.2886	27	0.2886	
28	0.2886	29	0.2896	0.0009
30	0.2896	31	0.2896	
32	0.2896	33	0.2896	
34	0.2896	35	0.2896	
36	0.2896	37	0.2896	
38	0.2905	39	0.2905	0.0004
40	0.2905	41	0.2905	
42	0.2905	43	0.2896	
44	0.2896	45	0.2896	
46	0.2896	47	0.2896	
48	0.2905	49	0.2896	0.0005
50	0.2886	51	0.2896	
52	0.2896	53	0.2905	
54	0.2905	55	0.2905	
56	0.2905	57	0.2905	
58	0.2896	59	0.2905	0.0007
60	0.2896	61	0.2896	
62	0.2896	63	0.2896	
64	0.2896	65	0.2905	
66	0.2905	67	0.2896	
68	0.2896	69	0.2905	0.0006
70	0.2905	71	0.2896	
72	0.2896	73	0.2905	
74	0.2896	75	0.2896	
76	0.2886	77	0.2886	
78	0.2896	79	0.2886	0.0007
80	0.2886	81	0.2886	
82	0.2886	83	0.2886	
84	0.2886	85	0.2886	
86	0.2896	87	0.2896	
88	0.2886	89	0.2896	0.0005
90	0.2896	91	0.2896	
92	0.2886	93	0.2886	
94	0.2886	95	0.2886	
96	0.2876	97	0.2886	
98	0.2876	99	0.2876	0.0007
100	0.2896	101	0.2896	
102	0.2905	103	0.2905	
104	0.2896	105	0.2905	
106	0.2905	107	0.2896	
108	0.2896	109	0.2905	0.0011
110	0.2915	111	0.2896	

TABLE A.12. (cont'd) Sample data for Fig. 7.11.

112	0.2896	113	0.2896	
114	0.2905	115	0.2915	
116	0.2896	117	0.2905	
118	0.2905	119	0.2915	0.0010
120	0.2896	121	0.2905	
122	0.2905	123	0.2905	
124	0.2896	125	0.2896	
126	0.2896	127	0.2886	
128	0.2896	129	0.2896	0.0007
130	0.2896	131	0.2896	
132	0.2896	133	0.2896	
134	0.2915	135	0.2905	
136	0.2905	137	0.2905	
138	0.2905	139	0.2896	0.0007
140	0.2896	141	0.2896	
142	0.2886	143	0.2896	
144	0.2886	145	0.2896	
146	0.2915	147	0.2886	
148	0.2886	149	0.2876	0.0012
150	0.2896	151	0.2905	
152	0.2896	153	0.2896	
154	0.2896	155	0.2896	
156	0.2896	157	0.2896	
158	0.2896	159	0.2896	0.0005
160	0.2896	161	0.2886	
162	0.2896	163	0.2905	
164	0.2896	165	0.2896	
166	0.2896	167	0.2905	
168	0.2896	169	0.2896	0.0006
170	0.2896	171	0.2886	
172	0.2886	173	0.2886	
174	0.2896	175	0.2886	
176	0.2896	177	0.2896	
178	0.2886	179	0.2896	0.0007
180	0.2886	181	0.2886	
182	0.2886	183	0.2896	
184	0.2896	185	0.2896	
186	0.2896	187	0.2896	
188	0.2896	189	0.2896	0.0005
190	0.2886	191	0.2886	
192	0.2896	193	0.2886	
194	0.2896	195	0.2896	
196	0.2896	197	0.2896	
198	0.2896	199	0.2905	0.0006
200	0.2896	201	0.2905	
202	0.2905	203	0.2896	
204	0.2896	205	0.2905	
206	0.2896	207	0.2896	
208	0.2896	209	0.2905	0.0006
210	0.2896	211	0.2896	
212	0.2886	213	0.2896	
214	0.2896	215	0.2896	
216	0.2896	217	0.2886	
218	0.2886	219	0.2886	0.0006
220	0.2896	327	0.2896	
328	0.2905	329	0.2915	0.0008

TABLE A.13. Sample data for Fig. 7 12

0	0.2925	1	0.2935	
2	0.2944	3	0.2935	
4	0.2925	5	0.2925	
6	0.2935	7	0.2944	
8	0.2925	9	0.2915	0.0010
10	0.2935	11	0.2935	
12	0.2935	13	0.2935	
14	0.2935	15	0.2944	
16	0.2935	17	0.2935	
18	0.2935	19	0.2935	0.0005
20	0.2935	21	0.2935	
22	0.2925	23	0.2935	
24	0.2935	25	0.2935	
26	0.2925	27	0.2935	
28	0.2944	29	0.2935	0.0006
30	0.2925	31	0.2935	
32	0.2935	33	0.2935	
34	0.2915	35	0.2925	
36	0.2935	37	0.2915	
38	0.2935	39	0.2925	0.0010
40	0.2915	41	0.2935	
42	0.2925	43	0.2935	
44	0.2935	45	0.2954	
46	0.2935	47	0.2915	
48	0.2925	49	0.2935	0.0013
50	0.2925	51	0.2925	
52	0.2925	53	0.2944	
54	0.2925	55	0.2915	
56	0.2915	57	0.2925	
58	0.2915	59	0.2915	0.0010
60	0.2905	61	0.2915	
62	0.2935	63	0.2905	
64	0.2915	65	0.2915	
66	0.2925	67	0.2915	
68	0.2915	69	0.2915	0.0010
70	0.2915	71	0.2905	
72	0.2935	73	0.2915	
74	0.2915	75	0.2915	
76	0.2915	77	0.2905	
78	0.2905	79	0.2925	0.0010
80	0.2905	81	0.2905	
82	0.2915	83	0.2905	
84	0.2915	85	0.2915	
86	0.2915	87	0.2915	
88	0.2905	89	0.2905	0.0006
90	0.2915	91	0.2925	
92	0.2915	93	0.2915	
94	0.2905	95	0.2915	
96	0.2915	97	0.2896	
98	0.2905	99	0.2896	0.0010
100	0.2915	101	0.2905	
102	0.2905	103	0.2915	
104	0.2925	105	0.2905	
106	0.2886	107	0.2896	
108	0.2915	109	0.2905	0.0012
110	0.2905	111	0.2915	

TABLE A.14. Sample data for Fig. 7.13

0	0.2954	1	0.2925	
2	0.2925	3	0.2915	
4	0.2915	5	0.2925	
6	0.2925	7	0.2915	
8	0.2915	9	0.2905	0.0013
10	0.2915	11	0.2925	
12	0.2935	13	0.2915	
14	0.2915	15	0.2925	
16	0.2925	17	0.2915	
18	0.2915	19	0.2915	0.0008
20	0.2905	21	0.2905	
22	0.2925	23	0.2915	
24	0.2915	25	0.2915	
26	0.2925	27	0.2915	
28	0.2935	29	0.2915	0.0010
30	0.2905	31	0.2915	
32	0.2915	33	0.2925	
34	0.2915	35	0.2905	
36	0.2915	37	0.2905	
38	0.2915	39	0.2915	0.0008
40	0.2915	41	0.2905	
42	0.2915	43	0.2905	
44	0.2915	45	0.2915	
46	0.2905	47	0.2905	
48	0.2915	49	0.2935	0.0010
50	0.2896	51	0.2905	
52	0.2915	53	0.2905	
54	0.2915	55	0.2915	
56	0.2915	57	0.2905	
58	0.2915	59	0.2915	0.0009
60	0.2905	61	0.2915	
62	0.2905	63	0.2915	
64	0.2905	65	0.2905	
66	0.2915	67	0.2905	
68	0.2905	69	0.2915	0.0006
70	0.2905	71	0.2915	
72	0.2905	73	0.2915	
74	0.2896	75	0.2915	
76	0.2896	77	0.2905	
78	0.2905	79	0.2886	0.0010
80	0.2896	81	0.2896	
82	0.2905	83	0.2905	
84	0.2896	85	0.2896	
86	0.2915	87	0.2896	
88	0.2886	89	0.2896	0.0009
90	0.2896	91	0.2896	
92	0.2886	93	0.2896	
94	0.2905	95	0.2896	
96	0.2896	97	0.2896	
98	0.2886	99	0.2905	0.0007
100	0.2886	101	0.2896	
102	0.2876	103	0.2886	
104	0.2896	105	0.2896	
106	0.2905	107	0.2896	
108	0.2886	109	0.2896	0.0010
110	0.2886	111	0.2896	

TABLE A.15. Sample data for Fig. 7.14.

0	0.2896	1	0.2896	
2	0.2896	3	0.2896	
4	0.2896	5	0.2886	
6	0.2905	7	0.2896	
8	0.2886	9	0.2876	0.0009
10	0.2876	11	0.2876	
12	0.2886	13	0.2876	
14	0.2886	15	0.2876	
16	0.2856	17	0.2866	
18	0.2876	19	0.2876	0.0011
20	0.2876	21	0.2866	
22	0.2886	23	0.2876	
24	0.2896	25	0.2896	
26	0.2896	27	0.2886	
28	0.2886	29	0.2896	0.0011
30	0.2886	31	0.2896	
32	0.2896	33	0.2886	
34	0.2876	35	0.2876	
36	0.2876	37	0.2876	
38	0.2876	39	0.2866	0.0009
40	0.2876	41	0.2866	
42	0.2886	43	0.2886	
44	0.2866	45	0.2876	
46	0.2866	47	0.2866	
48	0.2856	49	0.2856	0.0011
50	0.2866	51	0.2847	
52	0.2856	53	0.2856	
54	0.2856	55	0.2856	
56	0.2856	57	0.2847	
58	0.2847	59	0.2866	0.0009
60	0.2847	61	0.2837	
62	0.2856	63	0.2847	
64	0.2847	65	0.2847	
66	0.2847	67	0.2847	
68	0.2847	69	0.2856	0.0008
70	0.2866	71	0.2866	
72	0.2886	73	0.2886	
74	0.2876	75	0.2935	
76	0.2905	77	0.2896	
78	0.2905	79	0.2905	0.0027
80	0.2905	81	0.2896	
82	0.2905	83	0.2905	
84	0.2925	85	0.2925	
86	0.2925	87	0.2915	
88	0.2915	89	0.2935	0.0013
90	0.2925	91	0.2925	
92	0.2925	93	0.2915	
94	0.2905	95	0.2905	
96	0.2915	97	0.2896	
98	0.2905	99	0.2915	0.0010
100	0.2915	101	0.2915	
102	0.2915	103	0.2925	
104	0.2915	105	0.2935	
106	0.2925	107	0.2915	
108	0.2925	109	0.2935	0.0009
110	0.2915	111	0.2915	

TABLE A.16. Data for Fig.7.15

0	0.2495	1	0.2495	
2	0.2495	3	0.2495	
4	0.2495	5	0.2495	
6	0.2495	7	0.2495	
8	0.2495	9	0.2495	
10	0.2495	11	0.2495	
12	0.2495	13	0.2495	
14	0.2495	15	0.2495	
16	0.2495	17	0.2495	
18	0.2495	19	0.2495	
20	0.2495	21	0.2495	
22	0.2495	23	0.2495	
24	0.2495	25	0.2495	
26	0.2495	27	0.2495	
28	0.2495	29	0.2495	0.0000
30	0.2495	31	0.2495	
32	0.2495	33	0.2495	
34	0.2495	35	0.2495	
36	0.2495	37	0.2495	
38	0.2495	39	0.2495	
40	0.2495	41	0.2495	
42	0.2495	43	0.2495	
44	0.2495	45	0.2495	
46	0.2495	47	0.2495	
48	0.2495	49	0.2495	
50	0.2495	51	0.2495	
52	0.2495	53	0.2495	
54	0.2495	55	0.2495	
56	0.2495	57	0.2495	
58	0.2495	59	0.2495	0.0000
60	0.2495	61	0.2495	
62	0.2485	63	0.2495	
64	0.2495	65	0.2495	
66	0.2495	67	0.2495	
68	0.2495	69	0.2495	
70	0.2495	71	0.2495	
72	0.2495	73	0.2495	
74	0.2495	75	0.2495	
76	0.2495	77	0.2495	
78	0.2495	79	0.2495	
80	0.2495	81	0.2495	
82	0.2485	83	0.2495	
84	0.2495	85	0.2495	
86	0.2495	87	0.2495	
88	0.2495	89	0.2495	0.0003
90	0.2485	91	0.2495	
92	0.2495	93	0.2485	
94	0.2495	95	0.2495	
96	0.2495	97	0.2495	
98	0.2495	99	0.2495	
100	0.2495	101	0.2495	
102	0.2495	103	0.2495	
104	0.2495	105	0.2495	
106	0.2495	107	0.2495	
108	0.2495	109	0.2485	
110	0.2495	111	0.2495	

TABLE A.16. (cont'd) Data for Fig. 7.15

112	0.2495	113	0.2495	
114	0.2495	115	0.2495	
116	0.2495	117	0.2485	
118	0.2495	119	0.2495	0.0004
120	0.2485	121	0.2495	
122	0.2495	123	0.2495	
124	0.2495	125	0.2495	
126	0.2495	127	0.2495	
128	0.2495	129	0.2495	
130	0.2495	131	0.2495	
132	0.2495	133	0.2495	
134	0.2495	135	0.2495	
136	0.2495	137	0.2485	
138	0.2495	139	0.2495	
140	0.2495	141	0.2495	
142	0.2495	143	0.2495	
144	0.2495	145	0.2495	
146	0.2495	147	0.2495	
148	0.2495	149	0.2495	0.0003
150	0.2495	151	0.2524	
152	0.2495	153	0.2495	
154	0.2495	155	0.2495	
156	0.2495	157	0.2495	
158	0.2495	159	0.2495	
160	0.2495	161	0.2495	
162	0.2495	163	0.2495	
164	0.2495	165	0.2495	
166	0.2495	167	0.2495	
168	0.2495	169	0.2495	
170	0.2495	171	0.2495	
172	0.2505	173	0.2495	
174	0.2495	175	0.2495	
176	0.2495	177	0.2495	
178	0.2495	179	0.2495	0.0006
180	0.2495	181	0.2495	
182	0.2495	183	0.2495	
184	0.2495	185	0.2495	
186	0.2495	187	0.2495	
188	0.2495	189	0.2495	
190	0.2495	191	0.2495	
192	0.2495	193	0.2495	
194	0.2495	195	0.2495	
196	0.2495	197	0.2495	
198	0.2495	199	0.2495	
200	0.2495	201	0.2495	
202	0.2495	203	0.2495	
204	0.2495	205	0.2495	
206	0.2495	207	0.2495	
208	0.2495	209	0.2495	0.0000
210	0.2495	211	0.2495	
212	0.2495	213	0.2495	
214	0.2495	215	0.2495	
216	0.2495	217	0.2495	
218	0.2495	219	0.2495	
220	0.2495	221	0.2495	
222	0.2495	223	0.2495	

TABLE A.17. Data for Fig. 7.16.

0	0.2876	1	0.2886	
2	0.2876	3	0.2886	
4	0.2896	5	0.2876	
6	0.2896	7	0.2915	
8	0.2925	9	0.2925	
10	0.2925	11	0.2915	
12	0.2935	13	0.2915	
14	0.2905	15	0.2925	
16	0.2915	17	0.2896	
18	0.2925	19	0.2896	
20	0.2905	21	0.2896	
22	0.2905	23	0.2905	
24	0.2915	25	0.2915	
26	0.2915	27	0.2896	
28	0.2905	29	0.2896	
30	0.2905	31	0.2915	
32	0.2925	33	0.2925	
34	0.2935	35	0.2944	
36	0.2935	37	0.2944	
38	0.2925	39	0.2935	
40	0.2925	41	0.2915	
42	0.2935	43	0.2935	
44	0.2915	45	0.2925	
46	0.2935	47	0.2905	
48	0.2915	49	0.2915	
50	0.2915	51	0.2905	
52	0.2896	53	0.2896	
54	0.2896	55	0.2886	
56	0.2896	57	0.2896	
58	0.2876	59	0.2876	0.0014
60	0.2896	61	0.2886	
62	0.2876	63	0.2876	
64	0.2896	65	0.2886	
66	0.2876	67	0.2876	
68	0.2866	69	0.2866	
70	0.2876	71	0.2876	
72	0.2856	73	0.2866	
74	0.2856	75	0.2856	
76	0.2866	77	0.2837	
78	0.2847	79	0.2876	
80	0.2866	81	0.2886	
82	0.2876	83	0.2866	
84	0.2876	85	0.2896	
86	0.2896	87	0.2915	
88	0.2905	89	0.2896	
90	0.2905	91	0.2915	
92	0.2915	93	0.2915	
94	0.2915	95	0.2905	
96	0.2915	97	0.2905	
98	0.2905	99	0.2915	
100	0.2905	101	0.2905	
102	0.2886	103	0.2896	
104	0.2876	105	0.2876	
106	0.2905	107	0.2866	
108	0.2876	109	0.2886	
110	0.2886	111	0.2886	

TABLE A.17. (cont'd) Data for Fig. 7.16.

112	0.2896	113	0.2876	
114	0.2896	115	0.2896	
116	0.2886	117	0.2886	
118	0.2886	119	0.2896	0.0013
120	0.2896	121	0.2886	
122	0.2866	123	0.2856	
124	0.2876	125	0.2866	
126	0.2866	127	0.2856	
128	0.2866	129	0.2876	
130	0.2876	131	0.2896	
132	0.2886	133	0.2886	
134	0.2876	135	0.2876	
136	0.2896	137	0.2886	
138	0.2876	139	0.2876	
140	0.2856	141	0.2876	
142	0.2866	143	0.2856	
144	0.2856	145	0.2847	
146	0.2866	147	0.2847	
148	0.2856	149	0.2837	
150	0.2856	151	0.2847	
152	0.2856	153	0.2847	
154	0.2847	155	0.2856	
156	0.2847	157	0.2847	
158	0.2866	159	0.2866	
160	0.2847	161	0.2866	
162	0.2856	163	0.2876	
164	0.2847	165	0.2847	
166	0.2856	167	0.2847	
168	0.2866	169	0.2876	
170	0.2866	171	0.2876	
172	0.2876	173	0.2896	
174	0.2896	175	0.2896	
176	0.2905	177	0.2905	
178	0.2896	179	0.2905	0.0013
180	0.2935	181	0.2905	
182	0.2915	183	0.2905	
184	0.2915	185	0.2915	
186	0.2905	187	0.2905	
188	0.2915	189	0.2905	
190	0.2905	191	0.2896	
192	0.2896	193	0.2876	
194	0.2886	195	0.2886	
196	0.2886	197	0.2896	
198	0.2886	199	0.2896	
200	0.2896	201	0.2896	
202	0.2866	203	0.2886	
204	0.2886	205	0.2876	
206	0.2876	207	0.2896	
208	0.2896	209	0.2896	
210	0.2896	211	0.2886	
212	0.2896	213	0.2905	
214	0.2896	215	0.2886	
216	0.2896	217	0.2896	
218	0.2896	219	0.2896	
220	0.2896	221	0.2905	
222	0.2905	223	0.2876	

TABLE A.18. Sample data for Fig. 7.17

0	0.2495	1	0.2495
2	0.2495	3	0.2495
4	0.2485	5	0.2495
6	0.2495	7	0.2495
8	0.2495	9	0.2495
10	0.2485	11	0.2495
12	0.2495	13	0.2495
14	0.2495	15	0.2495
16	0.2495	17	0.2495
18	0.2495	19	0.2495
20	0.2495	21	0.2495
22	0.2495	23	0.2485
24	0.2495	25	0.2495
26	0.2495	27	0.2485
28	0.2495	29	0.2485
30	0.2495	31	0.2485
32	0.2495	33	0.2495
34	0.2495	35	0.2495
36	0.2495	37	0.2495
38	0.2495	39	0.2495
40	0.2495	41	0.2495
42	0.2495	43	0.2495
44	0.2495	45	0.2495
46	0.2495	47	0.2495
48	0.2495	49	0.2495
50	0.2495	51	0.2495
52	0.2495	53	0.2495
54	0.2495	55	0.2495
56	0.2495	57	0.2495
58	0.2495	59	0.2495
60	0.2495	61	0.2495
62	0.2495	63	0.2495
64	0.2495	65	0.2495
66	0.2495	67	0.2495
68	0.2495	69	0.2495
70	0.2495	71	0.2495
72	0.2495	73	0.2485
74	0.2495	75	0.2495
76	0.2485	77	0.2495
78	0.2495	79	0.2495
80	0.2495	81	0.2495
82	0.2495	83	0.2495
84	0.2495	85	0.2495
86	0.2495	87	0.2495
88	0.2495	89	0.2495
90	0.2495	91	0.2495
92	0.2495	93	0.2495
94	0.2495	95	0.2495
96	0.2495	97	0.2495
98	0.2495	99	0.2495
100	0.2485	101	0.2495
102	0.2495	103	0.2495
104	0.2495	105	0.2495
106	0.2495	107	0.2495
108	0.2495	109	0.2495
110	0.2495	111	0.2495

TABLE A.18. (cont'd) Sample data for fig. 7.17

112	0.2495	113	0.2495	
114	0.2495	115	0.2495	
116	0.2495	117	0.2495	
118	0.2495	119	0.2495	0.0003
120	0.2495	121	0.2495	
122	0.2495	123	0.2495	
124	0.2495	125	0.2495	
126	0.2495	127	0.2495	
128	0.2495	129	0.2495	
130	0.2495	131	0.2495	
132	0.2495	133	0.2495	
134	0.2495	135	0.2495	
136	0.2495	137	0.2495	
138	0.2495	139	0.2495	
140	0.2495	141	0.2495	
142	0.2495	143	0.2495	
144	0.2495	145	0.2495	
146	0.2495	147	0.2495	
148	0.2495	149	0.2495	
150	0.2495	151	0.2495	
152	0.2495	153	0.2495	
154	0.2495	155	0.2495	
156	0.2495	157	0.2495	
158	0.2495	159	0.2495	
160	0.2495	161	0.2495	
162	0.2495	163	0.2476	
164	0.2495	165	0.2485	
166	0.2495	167	0.2495	
168	0.2495	169	0.2476	
170	0.2495	171	0.2495	
172	0.2495	173	0.2495	
174	0.2495	175	0.2495	
176	0.2495	177	0.2495	
178	0.2495	179	0.2495	
180	0.2495	181	0.2495	
182	0.2495	183	0.2485	
184	0.2495	185	0.2495	
186	0.2495	187	0.2495	
188	0.2495	189	0.2495	
190	0.2495	191	0.2495	
192	0.2495	193	0.2495	
194	0.2495	195	0.2495	
196	0.2495	197	0.2495	
198	0.2495	199	0.2495	
200	0.2495	201	0.2495	
202	0.2485	203	0.2485	
204	0.2495	205	0.2485	
206	0.2495	207	0.2495	
208	0.2485	209	0.2495	
210	0.2495	211	0.2495	
212	0.2495	213	0.2495	
214	0.2485	215	0.2495	
216	0.2485	217	0.2476	
218	0.2495	219	0.2485	
220	0.2485	221	0.2485	
222	0.2466	223	0.2485	

TABLE A.19. Sample data for Fig. 7. 19.

0	0.1060	1	0.1030	
2	0.1030	3	0.1030	
4	0.1030	5	0.1030	
6	0.1040	7	0.1030	
8	0.1030	9	0.1030	
10	0.1030	11	0.1030	
12	0.1030	13	0.1030	
14	0.1040	15	0.1030	
16	0.1040	17	0.1040	
18	0.1030	19	0.1030	0.0013
20	0.1030	21	0.1030	
22	0.1030	23	0.1040	
24	0.1030	25	0.1030	
26	0.1030	27	0.1030	
28	0.1030	29	0.1030	
30	0.1040	31	0.1030	
32	0.1030	33	0.1030	
34	0.1030	35	0.1030	
36	0.1030	37	0.1030	
38	0.1030	39	0.1030	0.0003
40	0.1050	41	0.1040	
42	0.1030	43	0.1030	
44	0.1030	45	0.1030	
46	0.1030	47	0.1040	
48	0.1030	49	0.1030	
50	0.1030	51	0.1030	
52	0.1030	53	0.1030	
54	0.1030	55	0.1030	
56	0.1030	57	0.1030	
58	0.1030	59	0.1030	0.0006
60	0.1040	61	0.1030	
62	0.1030	63	0.1030	
64	0.1030	65	0.1030	
66	0.1030	67	0.1030	
68	0.1030	69	0.1030	
70	0.1030	71	0.1030	
72	0.1030	73	0.1030	
74	0.1030	75	0.1030	
76	0.1030	77	0.1030	
78	0.1030	79	0.1030	0.0002
80	0.1030	81	0.1030	
82	0.1030	83	0.1030	
84	0.1030	85	0.1040	
86	0.1030	87	0.1030	
88	0.1030	89	0.1030	
90	0.1040	91	0.1030	
92	0.1030	93	0.1030	
94	0.1206	95	0.9995	
96	0.9995	97	0.9995	
98	0.9995	99	0.9995	0.3006
100	0.9995	101	0.9995	
102	0.9995	103	0.9995	
104	0.9995	105	0.9995	
106	0.9995	107	0.9995	
108	0.9995	109	0.9995	
110	0.9995	111	0.9995	

TABLE A.19. (cont'd) Sample data for Fig. 7.19.

112	0.9995	113	0.9995	
114	0.9995	115	0.9995	
116	0.9995	117	0.9995	
118	0.9995	119	0.9995	0.0734
120	0.9995	121	0.2388	
122	0.9995	123	0.9995	
124	0.1245	125	0.1040	
126	0.1040	127	0.1030	
128	0.1040	129	0.1040	
130	0.1040	131	0.1030	
132	0.1030	133	0.1030	
134	0.1030	135	0.1040	
136	0.1040	137	0.1030	
138	0.1040	139	0.1021	0.3275
140	0.1021	141	0.1030	
142	0.1030	143	0.1030	
144	0.1030	145	0.1030	
146	0.1040	147	0.1030	
148	0.1030	149	0.1030	
150	0.1030	151	0.1030	
152	0.1030	153	0.1030	
154	0.1030	155	0.1030	
156	0.1030	157	0.1030	
158	0.1030	159	0.1040	0.0029
160	0.1040	161	0.1030	
162	0.1040	163	0.1030	
164	0.1030	165	0.1030	
166	0.1030	167	0.1030	
168	0.1040	169	0.1030	
170	0.1040	171	0.1030	
172	0.1030	173	0.1040	
174	0.1030	175	0.1030	
176	0.1040	177	0.1030	
178	0.1030	179	0.1030	0.0005
180	0.1060	181	0.1030	
182	0.1030	183	0.1030	
184	0.1030	185	0.1030	
186	0.1030	187	0.1030	
188	0.1030	189	0.1030	
190	0.1040	191	0.1030	
192	0.1030	193	0.1040	
194	0.1030	195	0.1030	
196	0.1030	197	0.1030	
198	0.1030	199	0.1040	0.0008
200	0.1030	201	0.1040	
202	0.1030	203	0.1030	
204	0.1030	205	0.1030	
206	0.1030	207	0.1021	
208	0.1040	209	0.1040	
210	0.1030	211	0.1030	
212	0.1030	213	0.1030	
214	0.1030	215	0.1030	
216	0.1030	217	0.1030	
218	0.1030	219	0.1040	0.0005
220	0.1030	221	0.1030	
222	0.1030	223	0.1030	

TABLE A.19. (cont'd) <u>Sample data for Fig. 7.19</u>

224	0·1030	225	0·1030	
226	0·1030	227	0·1030	
228	0·1030	229	0·1030	
230	0·1030	231	0·1030	
232	0·1030	233	0·1030	
234	0·1030	235	0·1030	
236	0·1040	237	0·1030	
238	0·1030	239	0·1040	0·0003
240	0·1050	241	0·1030	
242	0·1030	243	0·1030	
244	0·1030	245	0·1040	
246	0·9995	247	0·9995	
248	0·9995	249	0·9995	
250	0·9995	251	0·9995	
252	0·9995	253	0·9995	
254	0·9995	255	0·9995	
256	0·9995	257	0·9995	
258	0·9995	259	0·9995	0·3107
260	0·9995	261	0·9995	
262	0·9995	263	0·9995	
264	0·9995	265	0·9995	
266	0·9995	267	0·9995	
268	0·9995	269	0·9995	
270	0·9995	271	0·9995	
272	0·9995	273	0·9995	
274	0·9995	275	0·9995	
276	0·9995	277	0·9995	
278	0·9995	279	0·9995	0·0055
280	0·9995	281	0·1060	
282	0·1040	283	0·9995	
284	0·9995	285	0·2427	
286	0·1040	287	0·1099	
288	0·1030	289	0·1030	
290	0·1382	291	0·1040	
292	0·9995	293	0·1567	
294	0·1040	295	0·1030	
296	0·1030	297	0·1030	
298	0·1030	299	0·1030	0·4124
300	0·1040	301	0·1030	
302	0·1030	303	0·1040	
304	0·1040	305	0·1040	
306	0·1030	307	0·1030	
308	0·1030	309	0·1030	
310	0·1030	311	0·1030	
312	0·1030	313	0·1040	
314	0·1040	315	0·1030	
316	0·1030	317	0·1040	
318	0·1030	319	0·1030	0·0147
320	0·1030	321	0·1040	
322	0·1030	323	0·1030	
324	0·1040	325	0·1030	
326	0·1030	327	0·1040	
328	0·1030	329	0·1030	
330	0·1040	331	0·1030	
332	0·1030	333	0·1030	
334	0·1030	335	0·1040	

TABLE A.20. <u>Data for Fig. 7.20</u>.

0	0.0972	1	0.0972	
2	0.0972	3	0.0972	
4	0.0972	5	0.0972	
6	0.0972	7	0.0972	
8	0.0972	9	0.0981	
10	0.0972	11	0.0981	
12	0.0972	13	0.0972	
14	0.0981	15	0.0972	
16	0.0972	17	0.0972	
18	0.0972	19	0.0972	0.0004
20	0.0972	21	0.0972	
22	0.0972	23	0.0972	
24	0.0981	25	0.0981	
26	0.0972	27	0.0981	
28	0.0972	29	0.0972	
30	0.0972	31	0.0972	
32	0.0981	33	0.0972	
34	0.0981	35	0.0972	
36	0.0981	37	0.0972	
38	0.0493	39	0.0229	0.0181
40	0.0190	41	0.0239	
42	0.0269	43	0.0298	
44	0.0308	45	0.0308	
46	0.0298	47	0.0308	
48	0.0308	49	0.0337	
50	0.0366	51	0.0376	
52	0.0386	53	0.0386	
54	0.0396	55	0.0415	
56	0.0425	57	0.0435	
58	0.0405	59	0.0405	0.0157
60	0.0425	61	0.0435	
62	0.0435	63	0.0444	
64	0.0444	65	0.0454	
66	0.0425	67	0.0425	
68	0.0435	69	0.0435	
70	0.0435	71	0.0435	
72	0.0444	73	0.0444	
74	0.0435	75	0.0425	
76	0.0435	77	0.0425	
78	0.0435	79	0.0435	0.0014
80	0.0435	81	0.0435	
82	0.0435	83	0.0425	
84	0.0425	85	0.0425	
86	0.0435	87	0.0435	
88	0.0435	89	0.0444	
90	0.0454	91	0.0435	
92	0.0425	93	0.0435	
94	0.0435	95	0.0435	
96	0.0444	97	0.0444	
98	0.0454	99	0.0454	0.0009
100	0.0444	101	0.0435	
102	0.0444	103	0.0444	
104	0.0444	105	0.0444	
106	0.0454	107	0.0454	
108	0.0464	109	0.0464	
110	0.0444	111	0.0444	

TABLE A.20 (cont'd) Data for Fig. 7.20.

112	0.0454	113	0.0444	
114	0.0444	115	0.0454	
116	0.0454	117	0.0454	
118	0.0454	119	0.0464	0.0008
120	0.0444	121	0.0464	
122	0.0454	123	0.0444	
124	0.0444	125	0.0464	
126	0.0464	127	0.0464	
128	0.0483	129	0.0474	
130	0.0464	131	0.0474	
132	0.0474	133	0.0474	
134	0.0474	135	0.0474	
136	0.0474	137	0.0474	
138	0.0474	139	0.0474	0.0009
140	0.0474	141	0.0474	
142	0.0483	143	0.0474	
144	0.0483	145	0.0483	
146	0.0493	147	0.0493	
148	0.0493	149	0.0483	
150	0.0493	151	0.0493	
152	0.0493	153	0.0493	
154	0.0493	155	0.0503	
156	0.0503	157	0.0513	
158	0.0522	159	0.0513	0.0009
160	0.0532	161	0.0513	
162	0.0513	163	0.0522	
164	0.0513	165	0.0513	
166	0.0522	167	0.0522	
168	0.0532	169	0.0532	
170	0.0542	171	0.0542	
172	0.0542	173	0.0542	
174	0.0542	175	0.0542	
176	0.0532	177	0.0552	
178	0.0552	179	0.0552	0.0011
180	0.0552	181	0.0552	
182	0.0562	183	0.0562	
184	0.0571	185	0.0562	
186	0.0571	187	0.0562	
188	0.0562	189	0.0562	
190	0.0571	191	0.0581	
192	0.0581	193	0.0581	
194	0.0581	195	0.0581	
196	0.0591	197	0.0591	
198	0.0591	199	0.0601	0.0010
200	0.0610	201	0.0610	
202	0.0610	203	0.0601	
204	0.0601	205	0.0601	
206	0.0610	207	0.0610	
208	0.0610	209	0.0620	
210	0.0620	211	0.0620	
212	0.0620	213	0.0620	
214	0.0620	215	0.0620	
216	0.0620	217	0.0640	
218	0.0649	219	0.0649	0.0012
220	0.0649	221	0.0659	
222	0.0659	223	0.0659	

TABLE A.20. (cont'd) Data for Fig. 7.20.

224	0.0659	225	0.0620	
226	-0.0552	227	-0.0581	
228	-0.1060	229	-0.0962	
230	-0.4106	231	-0.4302	
232	-0.4331	233	-0.4282	
234	-0.4146	235	-0.4009	
236	-0.3940	237	-0.3774	
238	-0.3638	239	-0.3491	0.1396
240	-0.3452	241	-0.3335	
242	-0.3276	243	-0.3237	
244	-0.3130	245	-0.3101	
246	-0.3022	247	-0.3003	
248	-0.2964	249	-0.2974	
250	-0.2915	251	-0.2905	
252	-0.2866	253	-0.2827	
254	-0.2827	255	-0.2700	
256	-0.2749	257	-0.2749	
258	-0.2739	259	-0.2729	0.0181
260	-0.2603	261	-0.2681	
262	-0.2642	263	-0.2622	
264	-0.2622	265	-0.2622	
266	-0.2495	267	-0.2563	
268	-0.2583	269	-0.2495	
270	-0.2534	271	-0.2515	
272	-0.2524	273	-0.2534	
274	-0.2554	275	-0.2485	
276	-0.2524	277	-0.2495	
278	-0.2495	279	-0.2466	0.0073
280	-0.2466	281	-0.2476	
282	-0.2466	283	-0.2368	
284	-0.2397	285	-0.2417	
286	-0.2427	287	-0.2319	
288	-0.2358	289	-0.2437	
290	-0.2397	291	-0.2397	
292	-0.2476	293	-0.2407	
294	-0.2407	295	-0.2339	
296	-0.2407	297	-0.2319	
298	-0.2329	299	-0.2300	0.0056
300	-0.2231	301	-0.2349	
302	-0.2368	303	-0.2310	
304	-0.2231	305	-0.2280	
306	-0.2368	307	-0.2368	
308	-0.2280	309	-0.2222	
310	-0.2222	311	-0.2261	
312	-0.2339	313	-0.2202	
314	-0.2163	315	-0.2095	
316	-0.2114	317	-0.2271	
318	-0.2378	319	-0.2349	0.0090
320	-0.2261	321	-0.2095	
322	-0.1938	323	-0.1772	
324	-0.1636	325	-0.1636	
326	-0.1743	327	-0.1948	
328	-0.2329	329	-0.2983	
330	-0.6597	331	-0.4712	
332	-0.2944	333	-0.1724	
334	-0.0425	335	-0.0396	

TABLE A.21. (a)

1967 Valve data standard deviation of error

Bottom cooling valve (Zero error only)	Top cooling valve (Sluggish and zero error)	Top cooling valve (Sluggish and zero error)	Bottom cooling valve (Sluggish and zero error)	Bottom cooling valve (Sluggish and zero error)
15.5242	16.0640	5.3526	6.6671	39.4014
20.5647	11.0409	5.2488	12.2781	74.6602
11.0454	2.1331	6.1401	21.7910	47.6719
6.2729	11.7968	6.3600	23.6030	58.8853
13.1416	7.4700	11.4434	4.8010	39.7529
25.2339	16.7092	13.9768	23.0413	43.7885
20.9929	16.4089	5.5046	18.1797	62.6489
17.6453	12.1346	14.0089	5.3898	46.5644
9.3274	10.3851	12.0209	13.8906	44.3892
				63.0405
				68.4922
				42.5049

APPENDIX 3

Industrial control valves data and Standard deviations for Measuring instruments data.

For Tables A22 to A30, the first column represents the valve demand, the second column represents the valve position, the third represents the error between the valve and the valve position and the fourth column represents the change in valve demand. All the values are in parts per 1000.

TABLE A. 21(b) 1970 Valve data standard deviations of error

Top cooling valve number		
1	2	3
2.8810	3.4496	6.0745
3.3912	3.7914	6.1401
3.4929	2.6268	3.7283
3.4929	3.4059	2.5691
4.4944	2.8983	3.4205
3.1464	3.1305	5.0990

CVL valve number		
1	2	3
9.1707	5.6921	5.7533
4.8477	6.7082	5.3759
7.4297	4.2072	5.8907
3.5777	4.9396	5.7620
6.0498	5.6480	4.9498
5.2631	3.8210	5.8052

Bottom cooling valve number		
1	2	3
8.5322	4.3930	5.0000
9.2358	5.8395	3.6606
11.5586	4.4944	2.8983
7.9120	3.6606	5.8052
9.0554	16.9912	6.3404

Draw valve number		
1	2	3
22.7444	12.0499	12.1121
25.8457	9.5552	5.4406
25.9963	10.4880	5.8822
26.1975	8.4794	6.1725
21.7578	10.4737	6.2928

TABLE A.22 1967 Valve data for Fig. 8.19 Bottom cooling valve with zero error

647	644	-3	0	632	629	-3	-4
644	637	-7	3	632	629	-3	0
640	637	-3	4	636	630	-6	-4
640	637	-3	0	628	629	1	8
640	641	1	0	632	632	0	-4
640	643	3	0	628	630	2	4
644	642	-2	-4	632	624	-8	-4
636	641	5	8	632	624	-8	0
647	635	-12	-11	624	624	0	8
640	639	-1	7	624	626	2	0
647	637	-10	-7	636	626	-10	-12
683	641	-42	-36	624	626	2	12
647	643	-4	36	628	617	-11	-4
647	640	-7	0	632	620	-12	-4
647	681	34	0	620	626	6	12
647	639	-8	0	624	623	-1	-4
644	680	36	3	620	623	3	4
647	650	3	-3	620	623	3	0
651	642	-9	-4	628	624	-4	-8
647	642	-5	4	620	623	3	8
647	643	-4	0	620	608	-12	0
651	647	-4	-4	616	623	7	4
647	650	3	4	616	616	0	0
647	644	-3	0	620	617	-3	-4
644	645	1	3	620	616	-4	0
647	647	0	-3	617	617	0	3
647	600	-47	0	616	614	-2	1
644	638	-6	3	616	613	-3	0
644	600	-44	0	612	615	3	4
683	638	-45	-39	616	616	0	-4
651	639	-12	32	624	655	31	-8
647	640	-7	4	620	612	-8	4
647	642	-5	0	612	615	3	8
651	633	-18	-4	620	619	-1	-8
647	644	-3	4	624	626	2	-4
644	644	0	3	628	612	-16	-4
604	644	40	40	628	621	-7	0
644	645	1	-40	624	624	0	4
644	651	7	0	628	620	-8	-4
647	647	0	-3	663	620	-43	-35
647	645	-2	0	628	626	-2	35
651	635	-16	-4	632	625	-7	-4
647	646	-1	4	632	627	-5	0
683	639	-44	-36	632	623	-9	0
644	641	-3	39	628	623	-5	4
644	642	-2	0	620	624	4	8
644	647	3	0	628	623	-5	-8
644	636	-8	0	620	623	3	8
640	634	-6	4	624	573	-51	-4
632	633	1	8	624	624	0	0
632	635	3	0	624	622	-2	0
636	635	-1	-4	624	623	-1	0
632	639	7	4	628	624	-4	-4
632	631	-1	0	628	625	-3	0
632	634	2	0	663	621	-42	-35
628	629	1	4	628	624	-4	35
				632	662	30	-4

TABLE A.22. (cont'd) 1967 Valve data for Fig. 8.19 Bottom cooling with zero error

593	664	71	39
632	630	-2	-39
636	627	-9	-4
640	631	-9	-4
640	635	-5	0
640	639	-1	0
679	633	-46	-39
644	641	-3	35
679	641	-38	-35
644	631	-13	35
640	634	-6	4
636	639	3	4
647	641	-6	-11
644	644	0	3
670	639	-31	-26
644	598	-46	26
640	643	3	4
640	639	-1	0
640	641	1	0
644	642	-2	-4
640	639	-1	4
604	594	-10	36
632	626	-6	-28
636	630	-6	-4
593	631	38	43
632	631	-1	-39
636	587	-49	-4
593	630	37	43
632	626	-6	-39
632	625	-7	0
628	627	-1	4
632	624	-8	-4
636	664	28	-4
636	630	-6	0
636	627	-9	0
632	627	-5	4
632	585	-47	0
632	627	-5	0
636	673	37	-4
644	635	-9	-8
636	635	-1	8
640	635	-5	-4
640	634	-6	0
640	635	-5	0
636	637	1	4
636	639	3	0
640	639	-1	-4
636	628	-8	4
640	635	-5	-4
636	635	-1	4
640	635	-5	-4
644	638	-6	-4
640	641	1	4
644	640	-4	-4
644	640	-4	0
679	641	-38	-35
647	647	0	32

644	648	4	3
651	644	-7	-7
644	644	0	7
647	644	-3	-3
644	645	1	3
647	648	1	-3
651	651	0	-4
655	653	-2	-4
651	647	-4	4
651	647	-4	0
655	647	-8	-4
659	647	-12	-4

TABLE A.23. **1967 Valve data for Fig. 8.20. Sluggish top cooling with zero error**

335	285	-50	0
304	268	-36	31
265	268	3	39
265	267	2	0
269	270	1	-4
269	261	-8	0
265	269	4	4
269	268	-1	-4
269	266	-3	0
269	299	30	0
269	270	1	0
261	261	0	8
265	266	1	-4
261	266	5	4
261	265	4	0
257	261	4	4
265	262	-3	-8
265	267	2	0
265	265	0	0
261	244	-17	4
253	256	3	8
253	261	8	0
253	256	3	0
253	254	1	0
253	254	1	0
253	255	2	0
261	258	-3	-8
261	254	-7	0
296	259	-37	-35
261	258	-3	35
261	266	5	0
265	266	1	-4
261	267	6	4
269	298	29	-8
269	269	0	0
269	269	0	0
269	269	0	0
269	270	1	0
269	272	3	0
269	270	1	0
269	270	1	0
269	272	3	0
269	272	3	0
269	270	1	0
269	270	1	0
269	272	3	0
265	266	1	4
265	266	1	0
269	269	0	-4
265	269	4	4
269	270	1	-4
261	263	2	8
261	266	5	0
261	262	1	0
265	266	1	-4
265	266	1	0
269	266	-3	-4

269	269	0	0
272	272	0	-3
272	273	1	0
272	303	31	0
272	273	1	0
280	276	-4	-8
272	274	2	8
272	273	1	0
269	273	4	3
269	272	3	0
269	257	-12	0
269	265	-4	0
269	270	1	0
269	265	-4	0
269	269	0	0
269	270	1	0
265	269	4	4
269	266	-3	-4
265	270	5	4
265	270	5	0
269	269	0	-4
272	273	1	-3
233	272	39	39
265	264	-1	-32
269	267	-2	-4
269	270	1	0
269	273	4	0
269	270	1	0
269	273	4	0
269	270	1	0
269	269	0	0
269	270	1	0
272	270	-2	-3
272	273	1	0
272	273	1	0
272	274	2	0
315	319	4	-43
288	299	11	27
288	289	1	0
288	318	30	0
296	299	3	-8
296	299	3	0
296	299	3	0
296	299	3	0
296	299	3	0
296	295	-1	0
300	299	-1	-4
300	303	3	0
300	299	-1	0
300	303	3	0
300	307	7	0
304	307	3	-4
304	303	-1	0
300	303	3	4
296	298	2	4
288	259	-29	8
253	291	38	35

TABLE A.23 (cont'd) 1967 Valve data for Fig. 8.20. Sluggish top cooling valve with zero error

249	277	28	4
284	273	-11	-35
245	269	24	39
241	276	35	4
280	261	-19	-39
269	280	11	11
272	273	1	-3
276	273	-3	-4
280	270	-10	-4
280	274	-6	0
280	284	4	0
315	284	-31	-35
284	285	1	31
284	288	4	0
323	320	-3	-39
331	289	-42	-8
331	295	-36	0
296	303	7	35
300	332	32	-4
304	303	-1	-4
304	307	3	0
304	307	3	0
308	307	-1	-4
304	311	7	4
304	307	3	0
304	299	-5	0
257	255	-2	47
288	284	-4	-31
284	254	-30	4
284	277	-7	0
284	276	-8	0
284	288	4	0
288	291	3	-4
288	289	1	0
288	291	3	0
288	320	32	0
288	295	7	0
296	289	-7	-8
296	319	23	0
296	306	10	0
304	295	-9	-8
296	299	3	8
304	307	3	-8
308	307	-1	-4
304	303	-1	4
304	309	5	0
308	311	3	-4
308	311	3	0
308	303	-5	0
308	307	-1	0
304	311	7	4
304	310	6	0
308	295	-13	-4
304	307	3	4
265	307	42	39
296	294	-2	-31
296	299	3	0

296	298	2	0
296	298	2	0
292	288	-4	4
296	299	3	-4
292	294	2	4
292	295	3	0
292	295	3	0
292	295	3	0
292	295	3	0
292	295	3	0
292	295	3	0
257	285	28	35
292	288	-4	-35
292	291	-1	0
292	295	3	0
292	269	-23	0
292	295	3	0
292	295	3	0
288	288	0	4
292	291	-1	-4
288	289	1	4
296	291	-5	-8
292	294	2	4
292	295	3	0

TABLE A.24. 1967 Valve data for Fig. 8.21. Sluggish top cooling valve with zero error

431	436	5	0
431	436	5	0
435	440	5	-4
431	434	3	4
431	437	6	0
431	436	5	0
431	436	5	0
431	436	5	0
431	436	5	0
435	440	5	-4
435	440	5	0
435	440	5	0
435	440	5	0
431	440	9	4
435	440	5	-4
435	439	4	0
431	440	9	4
435	440	5	-4
431	428	-3	4
427	431	4	4
427	439	12	0
427	428	1	0
431	429	-2	-4
427	436	9	4
423	427	4	4
431	436	5	-8
431	428	-3	0
431	436	5	0
438	440	2	-7
435	440	5	3
438	440	2	-3
438	444	6	0
438	444	6	0
438	441	3	0
438	442	4	0
438	440	2	0
438	444	6	0
438	444	6	0
442	444	2	-4
442	448	6	0
442	449	7	0
442	448	6	0
442	445	3	0
442	444	2	0
438	448	10	4
438	442	4	0
438	444	6	0
442	448	6	-4
438	448	10	4
438	445	7	0
438	444	6	0
438	445	7	0
442	448	6	-4
438	440	2	4
438	445	7	0
438	444	6	0
438	444	6	0
438	444	6	0
442	448	6	-4
442	443	1	0
442	449	7	0
442	448	6	0
446	448	2	-4
442	447	5	4
442	452	10	0
442	448	6	0
442	448	6	0
442	448	6	0
442	440	-2	0
442	448	6	0
442	448	6	0
442	447	5	0
442	447	5	0
442	448	6	0
438	443	5	4
435	444	9	3
399	396	-3	36
438	442	4	-39
431	444	13	7
435	440	5	-4
438	440	2	-3
438	440	2	0
438	444	6	0
442	436	-6	-4
438	447	9	4
438	442	4	0
438	445	7	0
442	444	2	-4
442	450	8	0
442	448	6	0
442	448	6	0
446	445	-1	-4
446	452	6	0
446	490	44	0
446	452	6	0
446	452	6	0
450	440	-10	-4
450	456	6	0
450	456	6	0
450	456	6	0
450	456	6	0
450	456	6	0
446	456	10	4
450	453	3	-4
450	448	-2	0
450	448	-2	0
446	448	2	4
450	448	-2	-4
446	448	2	4
450	448	-2	-4
454	456	2	-4
454	459	5	0
454	452	-2	0
450	454	4	4

TABLE A.24. (cont'd) 1967 Valve data for Fig. 8.21. Sluggish top cooling valve with zero error

450	456	6	0
446	456	10	4
450	456	6	-4
450	408	-42	0
446	452	6	4
411	452	41	35
442	451	9	-31
450	452	2	-8
450	455	5	0
450	453	3	0
454	452	-2	-4
454	458	4	0
450	456	6	4
454	456	2	-4
454	459	5	0
454	459	5	0
454	459	5	0
454	448	-6	0
454	448	-6	0
454	453	-1	0
454	465	11	0
458	462	4	-4
454	457	3	4
450	454	4	4
450	459	9	0
450	456	6	0
450	452	2	0
450	451	1	0
450	456	6	0
450	456	6	0
446	409	-37	4
442	448	6	4
446	452	6	-4
446	452	6	0
442	451	9	4
442	445	3	0
407	449	42	35
438	448	10	-31
446	452	6	-8
440	452	12	6
446	452	6	-6
442	450	8	4
446	454	8	-4
446	452	6	0
442	448	6	4
446	447	1	-4
446	451	5	0
446	448	2	0
446	452	6	0
450	452	2	-4
446	449	3	4
442	448	6	4
446	448	2	-4
442	447	5	-4
442	448	6	0
438	445	7	4
438	440	2	0
442	441	-1	-4
438	448	10	4
442	394	-48	-4
438	442	4	4
438	448	10	0
438	442	4	0
435	444	9	3
438	444	6	-3
438	440	2	0
438	445	7	0
435	440	5	3
438	441	3	-3
442	448	6	-4
435	444	9	7
431	440	9	4
435	444	9	-4
438	444	6	-3
438	442	4	0
438	443	5	0
438	443	5	0
438	444	6	0
435	444	9	3
435	440	5	0

TABLE A.25. **1967 Valve data for Fig. 8.22. Sluggish bottom cooling valve with zero error**

821	820	-1	0
825	833	8	-4
856	866	10	-31
860	860	0	-4
860	870	10	0
817	815	-2	43
849	858	9	-32
849	858	9	0
849	849	0	0
849	848	-1	0
853	859	6	-4
853	848	-5	0
853	866	13	0
853	864	11	0
856	858	2	-3
856	861	5	0
856	860	4	0
856	860	4	0
856	862	6	0
860	863	3	-4
860	870	10	0
860	868	8	0
860	870	10	0
860	870	10	0
864	866	2	-4
864	865	1	0
864	864	0	0
864	864	0	0
868	864	-4	-4
868	877	9	0
868	874	6	0
868	870	2	0
868	870	2	0
872	878	6	-4
872	872	0	0
872	882	10	0
876	874	-2	-4
837	885	48	39
876	882	6	-39
872	877	5	4
872	877	5	0
876	877	1	-4
872	874	2	4
872	874	2	0
872	841	-31	0
864	877	13	8
786	874	88	78
864	865	1	-78
864	870	6	0
864	874	10	0
864	874	10	0
864	866	2	0
864	866	2	0
864	872	8	0
864	874	10	0
864	870	6	0
864	866	2	0
864	870	6	0
864	874	10	0
864	866	2	0
864	806	-58	0
860	819	-41	4
817	864	47	43
817	866	49	0
892	861	-31	-75
817	819	2	75
860	864	4	-43
845	848	3	15
845	853	8	0
845	849	4	0
845	853	8	0
841	847	6	4
841	845	4	0
841	842	1	0
841	838	-3	0
837	844	7	4
837	846	9	0
837	846	9	0
837	845	8	0
833	837	4	4
837	845	8	-4
833	837	4	4
833	834	1	0
833	835	2	0
833	834	1	0
829	833	4	-4
829	832	3	0
829	832	3	0
829	832	3	0
825	827	2	4
825	833	8	0
825	833	8	0
821	826	5	4
821	823	2	0
821	824	3	0
821	823	2	0
821	829	8	0
817	824	7	4
817	820	3	0
817	823	6	0
829	815	-14	-12
813	819	6	16
813	816	3	0
825	825	0	-12
825	828	3	0
825	825	0	0
825	782	-43	0
829	829	0	-4
825	831	6	4
860	782	-78	-35
821	824	3	39
825	828	3	-4
813	836	23	12
810	811	1	3

TABLE A.25. (cont'd) 1967 Valve data for Fig. 8.22. Sluggish bottom cooling valve with zero error

810	811	1	0
810	812	2	0
774	816	42	36
806	815	9	-32
806	806	0	0
806	807	1	0
806	806	0	0
806	811	5	0
802	806	4	4
802	815	13	0
813	781	-32	-11
813	815	2	0
770	820	50	43
813	811	-2	-43
813	856	43	0
806	820	14	7
810	816	6	-4
810	810	0	0
810	814	4	0
810	817	7	0
813	815	2	-3
845	820	-25	-32
813	815	2	32
813	815	2	0
813	815	2	0
810	819	9	3
813	815	2	-3
813	816	3	0
813	815	2	0
813	815	2	0
813	815	2	0
810	822	12	3
813	822	9	-3
813	816	3	0
813	817	4	0
813	816	3	0
813	816	3	0
813	815	2	0
813	811	-2	0
810	816	6	3
810	815	5	0
810	817	7	0
813	822	9	-3
813	816	3	0
813	821	8	0
813	817	4	0
813	818	5	0
813	816	3	0
813	817	4	0
810	815	5	3
813	816	3	-3
813	815	2	0
810	807	-3	3
806	814	8	4
806	807	1	0
806	812	6	0
810	811	1	-4
806	811	5	4
810	807	-3	-4
841	838	-3	-31
806	811	5	35
806	817	11	0
806	761	-45	0
806	807	1	0
810	848	38	-4
806	807	1	4
802	761	-41	4
790	811	21	12
802	808	6	-12
802	806	4	0
759	791	32	43
798	792	-6	-39
790	793	3	8
786	789	3	4
782	798	16	4
786	795	9	-4
782	795	13	4
782	790	8	0
778	789	11	4
782	791	9	-4
778	788	10	4
778	784	6	0
778	788	10	0

TABLE A.26 1967 Valve data for Fig. 8 23. Sluggish bottom cooling valve with zero error

497	550	53	0
450	501	51	47
493	548	55	-43
442	480	38	51
474	479	5	-32
524	557	33	-50
520	487	-33	4
478	483	5	42
524	503	-21	-46
493	504	11	31
446	508	62	47
524	495	-29	-78
493	536	43	31
493	527	34	0
497	499	2	-4
493	502	9	4
493	536	43	0
520	456	-64	-27
446	514	68	74
489	495	6	-43
524	492	-32	-35
395	478	83	129
470	510	40	-75
552	458	-94	-82
520	534	14	32
474	480	6	46
446	537	91	28
427	423	-4	19
454	464	10	-27
466	465	-1	-12
466	522	56	0
466	510	44	0
552	553	1	-86
466	445	-21	86
548	472	-76	-82
485	527	42	63
517	441	-76	-32
485	530	45	32
368	596	228	117
384	492	108	-16
524	536	12	-140
552	565	13	-28
599	600	1	-47
485	615	130	114
591	526	-65	-106
606	612	6	-15
563	564	1	43
618	623	5	-55
657	632	-25	-39
634	646	12	23
642	691	49	-8
595	687	92	47
681	697	16	-86
606	703	97	75
642	651	9	-36
696	694	-2	-54
669	672	3	27
575	585	10	94
704	741	37	-129
708	741	33	-4
591	608	17	117
673	683	10	-82
665	647	-18	8
716	719	3	-51
688	694	6	28
595	643	48	93
751	643	-108	-156
634	643	9	117
712	717	5	-78
720	656	-64	-8
673	670	-3	47
767	733	-34	-94
540	749	209	227
700	704	4	-160
700	709	9	0
704	711	7	-4
708	709	1	-4
712	722	10	-4
696	624	-72	16
653	665	12	43
747	785	38	-94
513	596	83	234
603	588	-15	-90
634	615	-19	-31
630	635	5	4
536	577	41	94
595	573	-22	-59
638	594	-44	-43
591	602	11	47
634	645	11	-43
603	688	85	31
599	608	9	4
548	582	34	51
638	643	5	-90
513	543	30	125
587	644	57	-74
571	543	-28	16
610	543	-67	-39
560	571	11	50
571	588	17	-11
571	576	5	0
520	530	10	51
563	643	80	-43
560	609	49	3
571	583	12	-11
552	561	9	19
563	600	37	-11
560	565	5	3
591	510	-81	-31
513	561	48	78
540	545	5	-27
462	518	56	78
532	541	9	-70
532	541	9	0

TABLE A.26. (cont'd) 1967 Valve data for Fig. 8.23. Sluggish bottom cooling valve with zero error

579	620	41	-47
497	550	53	82
528	531	3	-31
571	527	-44	-43
489	584	95	82
532	543	11	-43
513	462	-51	19
513	623	110	0
435	483	48	78
431	623	192	4
583	578	-5	-152
427	522	95	156
579	608	29	-152
450	454	4	129
478	459	-19	-28
520	483	-37	-42
470	479	9	50
517	538	21	-47
481	553	72	36
520	521	1	-39
478	526	48	42
478	483	5	0
474	482	8	4
474	481	7	0
470	479	9	4
435	504	69	35
431	465	34	4
517	489	-28	-86
517	495	-22	0
474	501	27	43
395	479	84	79
513	536	23	-118
466	481	15	47
466	474	8	0
462	467	5	4
509	510	1	-47
478	488	10	31
466	472	6	12
474	479	5	-8
470	504	34	4
423	471	48	47
403	394	-9	20
435	441	6	-32
431	453	22	4
462	625	163	-31
544	583	39	-82
513	516	3	31
435	487	52	78
388	449	61	47
290	384	94	98
438	441	3	-148
485	519	34	-47
454	487	33	31
454	453	-1	0
536	540	4	-82
474	534	60	62
505	432	-73	-31
474	499	25	31
474	481	7	0
454	461	7	20
450	424	-26	4
532	494	-38	-82
501	506	5	31
384	483	99	117
454	464	10	-70
501	514	13	-47
509	527	18	-8
470	492	22	39
345	480	135	125
345	521	176	0
501	459	-42	-156
466	495	29	35
466	479	13	0
501	428	-73	-35
423	499	76	78
552	573	21	-129
474	482	8	78
474	483	9	0
474	483	9	0
474	483	9	0
392	481	89	82
454	430	-24	-62
501	459	-42	-47
423	488	65	78
505	523	18	-82
501	495	-6	4
470	475	5	31
474	472	-2	-4
474	481	7	0
474	481	7	0
388	480	92	86
376	420	44	12
435	413	-22	-59
532	606	74	-97
458	496	38	74
419	506	87	39
501	506	5	-82
384	479	95	117
450	454	4	-66
458	424	-34	-8
458	583	125	0
579	420	-159	-121
560	529	-31	19
560	448	-112	0
489	546	57	71
497	518	21	-8
540	527	-13	-43
493	508	15	47
505	502	-3	-12
509	550	41	-4
505	523	18	4
509	530	21	-4
513	572	59	-4

TABLE A.26. (cont'd) 1967 Valve data for Fig. 8.23. Sluggish bottom cooling valve with zero error

517	525	8	-4
513	517	4	4
517	529	12	-4
517	527	10	0
435	499	64	82
466	471	5	-31
505	501	-4	-39
509	503	-6	-4
548	561	13	-39
466	534	68	82
544	510	-34	-78
548	554	6	-4
388	527	139	160
501	526	25	-113
579	578	-1	-78
552	561	9	27
505	495	-10	47

TABLE A.27. 1970 Top cooling valves data

VALVE NUMBER 1 224			
658	651	-7	0
658	670	12	0
658	644	-14	0
658	670	12	-47
611	604	-7	32
643	635	-8	-4
639	643	4	4
643	647	4	-4
639	644	5	0
639	644	5	4
643	639	-4	-4
639	632	-7	0
639	646	7	-4
635	625	-10	0
635	641	6	0
635	614	-21	0
635	632	-3	15
650	659	9	0
650	656	6	0
650	656	6	0
650	656	6	43
693	700	7	-43
650	635	-15	0
650	632	-18	0
650	639	-11	0
650	635	-15	0
650	653	3	0
650	663	13	0
650	637	-13	0
650	647	-3	0
650	642	-8	0
650	656	6	12
662	666	4	-12
650	655	5	12
662	643	-19	-4
658	663	5	8
666	669	3	0
666	671	5	0
666	670	4	4
670	677	7	0
670	664	-6	0
670	655	-15	0
670	674	4	0
670	678	8	0
670	651	-19	0
670	673	3	0
670	662	-8	-4
666	670	4	-43
623	621	-2	35
658	663	5	-4
654	648	-6	-78
576	585	9	31
607	620	13	32
639	635	-4	0
639	625	-14	0
639	643	4	-639

VALVE NUMBER 2 224			
492	491	-1	0
492	491	-1	-4
488	491	3	0
488	491	3	74
562	551	-11	-74
488	486	-2	0
488	486	-2	4
492	486	-6	-4
488	486	-2	0
488	486	-2	4
492	486	-6	-4
488	486	-2	-140
348	346	-2	62
410	401	-9	63
473	471	-2	15
488	478	-10	0
488	482	-6	0
488	482	-6	0
488	482	-6	-4
484	482	-2	0
484	482	-2	75
559	559	0	-59
500	500	0	0
500	504	4	-12
488	475	-13	12
500	499	-1	0
500	499	-1	0
500	499	-1	66
566	569	3	-58
508	507	-1	0
508	508	0	0
508	508	0	0
508	507	-1	4
512	508	-4	0
512	507	-5	-4
508	508	0	4
512	508	-4	0
512	510	-2	4
516	510	-6	0
516	510	-6	-4
512	510	-2	4
516	510	-6	-4
512	516	4	4
516	516	0	0
516	516	0	0
516	516	0	-12
504	506	2	-141
363	416	53	63
426	423	-3	62
488	485	-3	-4
484	486	2	0
484	487	3	-4
480	485	5	8
488	486	-2	-8
480	483	3	0
480	483	3	-480

VALVE NUMBER 3 224			
623	617	-6	-8
615	617	2	4
619	617	-2	0
619	617	-2	4
623	620	-3	4
627	620	-7	4
631	627	-4	4
635	627	-8	-4
631	631	0	8
639	631	-8	7
646	644	-2	-3
643	647	4	3
646	647	1	4
650	647	-3	4
654	647	-7	0
654	648	-6	4
658	659	1	4
662	659	-3	0
662	659	-3	0
662	662	0	-43
619	615	-4	43
662	659	-3	-8
654	651	-3	4
658	659	1	0
658	659	1	4
662	666	4	0
662	666	4	4
666	666	0	0
666	666	0	4
670	666	-4	0
670	669	-1	4
674	669	-5	0
674	669	-5	4
678	669	-9	-32
646	641	-5	0
646	643	-3	51
697	692	-5	4
701	693	-8	35
736	737	1	-27
709	700	-9	4
713	708	-5	4
717	711	-6	0
717	711	-6	4
721	713	-8	8
729	721	-8	0
729	721	-8	0
729	721	-8	0
729	731	2	-75
654	648	-6	71
725	722	-3	-4
721	715	-6	-32
689	682	-7	32
721	717	-4	-75
646	637	-9	36
682	676	-6	31
713	708	-5	-713

'TABLE A.28. 1970 CVL Valves data

VALVE NUMBER 1 232			
515	510	-5	-4
511	483	-28	11
522	511	-11	-7
515	511	-4	11
526	530	4	-4
522	495	-27	12
534	504	-30	4
538	499	-39	-8
530	499	-31	-11
519	509	-10	15
534	530	-4	0
534	504	-30	-4
530	512	-18	4
534	507	-27	8
542	515	-27	4
546	510	-36	-8
538	548	10	8
546	566	20	0
546	511	-35	-8
538	569	31	8
546	555	9	-8
538	526	-12	0
538	502	-36	4
542	518	-24	-4
538	519	-19	0
538	519	-19	4
542	507	-35	8
550	518	-32	-4
546	519	-27	-4
542	511	-31	-4
538	515	-23	0
538	518	-20	0
538	504	-34	0
538	514	-24	0
538	518	-20	0
538	506	-32	4
542	514	-28	4
546	511	-35	0
546	558	12	-16
530	505	-25	8
538	502	-36	0
538	511	-27	4
542	513	-29	0
542	542	0	4
546	542	-4	-16
530	499	-31	4
534	515	-19	8
542	555	13	12
554	573	19	-12
542	542	0	0
542	553	11	-4
538	557	19	8
546	498	-48	23
569	582	13	4
573	574	1	-23
550	495	-55	0
550	518	-32	0
550	522	-28	-550

VALVE NUMBER 2 232			
620	624	4	16
636	614	-22	-8
628	629	1	-4
624	627	3	-4
620	624	4	4
624	623	-1	8
632	620	-12	-8
624	600	-24	8
632	629	-3	0
632	618	-14	4
636	637	1	-4
632	632	0	0
632	630	-2	4
636	629	-7	8
644	640	-4	15
659	644	-15	-15
644	627	-17	3
647	632	-15	-3
644	646	2	3
647	637	-10	-3
644	647	3	7
651	651	0	8
659	642	-17	-4
655	653	-2	-8
647	645	-2	0
647	624	-23	4
651	649	-2	4
655	639	-16	-4
651	652	1	8
659	657	-2	-12
647	649	2	12
659	659	0	-4
655	658	3	-15
640	645	5	0
640	631	-9	7
647	648	1	0
647	632	-15	-3
644	627	-17	11
655	648	-7	-11
644	638	-6	-4
640	620	-20	0
640	626	-14	0
640	636	-4	-4
636	624	-12	8
644	648	4	-16
628	628	0	8
636	637	1	8
644	626	-18	0
644	644	0	-4
640	640	0	-24
616	588	-28	16
632	633	1	23
655	649	-6	0
655	655	0	-4
651	650	-1	12
663	638	-25	-16
647	649	2	8
655	647	-8	-655

VALVE NUMBER 3 232			
534	516	-18	0
534	538	4	8
542	539	-3	-8
534	522	-12	0
534	517	-17	0
534	535	1	12
546	548	2	4
550	532	-18	-8
542	532	-10	8
550	534	-16	4
554	555	1	4
558	555	-3	-4
554	546	-8	8
562	550	-12	-4
558	563	5	7
565	568	3	-7
558	561	3	4
562	561	-1	-4
558	561	3	4
562	557	-5	3
565	553	-12	4
569	569	0	-4
565	561	-4	4
569	570	1	0
569	569	0	-7
562	566	4	7
569	573	4	4
573	576	3	-8
565	553	-12	4
569	569	0	-11
558	559	1	35
593	594	1	-20
573	561	-12	-8
565	565	0	0
565	569	4	0
565	557	-8	8
573	562	-11	-11
562	565	3	7
569	573	4	0
569	572	3	-7
562	565	3	7
569	569	0	4
573	558	-15	-11
562	561	-1	3
565	565	0	0
565	569	4	-11
554	546	-8	15
569	573	4	-4
565	557	-8	-11
554	553	-1	-12
542	545	3	8
550	553	3	31
581	581	0	16
597	593	-4	-16
581	580	-1	-8
573	557	-16	0
573	572	-1	-4
569	561	-8	-569

TABLE A.29. 1970 Bottom cooling valves data

VALVE NUMBER 1			
248			
412	412	0	0
412	412	0	0
412	412	0	0
412	410	-2	0
412	412	0	0
412	413	1	0
412	414	2	0
412	409	-3	0
412	408	-4	0
412	405	-7	0
412	408	-4	0
412	408	-4	0
412	411	-1	0
412	412	0	0
412	416	4	0
412	416	4	0
412	416	4	0
412	416	4	-4
408	405	-3	0
408	405	-3	0
408	405	-3	0
408	405	-3	0
408	405	-3	0
408	403	-5	0
408	405	-3	0
408	409	1	0
408	409	1	0
408	411	3	0
408	413	5	0
408	413	5	0
408	413	5	0
408	413	5	0
408	413	5	0
408	412	4	0
408	412	4	0
408	410	2	0
408	408	0	0
408	409	1	0
408	409	1	0
408	411	3	0
408	410	2	0
408	412	4	0
408	412	4	0
408	412	4	0
408	413	5	0
408	413	5	0
408	413	5	0
408	413	5	0
408	413	5	0
408	413	5	0
408	412	4	0
408	406	-2	0
408	406	-2	0
408	404	-4	0
408	407	-1	0
408	405	-3	0
408	406	-2	-4
404	406	2	0
404	408	4	0
404	409	5	0
404	409	5	0
404	397	-7	-404

VALVE NUMBER 2			
248			
373	365	-8	35
408	408	0	0
408	412	4	0
408	407	-1	0
408	406	-2	0
408	408	0	0
408	409	1	0
408	413	5	0
408	410	2	0
408	410	2	0
408	412	4	0
408	413	5	0
408	410	2	0
408	410	2	0
408	411	3	0
408	413	5	0
408	411	3	0
408	410	2	0
408	412	4	0
408	413	5	4
412	405	-7	-4
408	406	-2	0
408	407	-1	-8
400	402	2	0
400	402	2	4
404	403	-1	0
404	403	-1	0
404	404	0	0
404	405	1	0
404	406	2	0
404	409	5	0
404	405	1	0
404	406	2	0
404	408	4	0
404	410	6	0
404	405	1	0
404	404	0	0
404	405	1	0
404	408	4	0
404	408	4	0
404	403	-1	0
404	403	-1	0
404	403	-1	0
404	403	-1	0
404	404	0	0
404	406	2	0
404	409	5	0
404	409	5	-4
400	405	5	-4
396	397	1	4
400	397	-3	-7
393	396	3	7
400	396	-4	-7
393	396	3	0
393	396	3	0
393	396	3	0
393	397	4	0
393	397	4	0
393	391	-2	-4
389	390	1	7
396	391	-5	0
396	390	-6	-396

404

VALVE NUMBER 3			
248			
420	412	-8	-8
412	412	0	8
420	412	-8	-8
412	412	0	0
412	412	0	8
420	412	-8	0
420	412	-8	0
420	412	-8	-8
412	412	0	8
420	413	-7	0
420	412	-8	0
420	412	-8	0
420	412	-8	-8
412	412	0	8
420	412	-8	0
420	412	-8	-4
416	412	-4	0
416	413	-3	0
416	412	-4	0
416	412	-4	0
416	412	-4	0
416	412	-4	0
416	413	-3	0
416	412	-4	0
416	412	-4	0
416	412	-4	0
416	413	-3	0
416	413	-3	0
416	412	-4	0
416	412	-4	0
416	412	-4	0
416	413	-3	0
416	412	-4	0
416	412	-4	0
416	413	-3	-4
412	412	0	0
412	412	0	0
412	412	0	0
412	412	0	0
412	412	0	0
412	412	0	0
412	413	1	0
412	413	1	0
412	413	1	0
412	412	0	0
412	412	0	0
412	413	1	0
412	412	0	0
412	405	-7	0
412	404	-8	0
412	405	-7	0
412	404	-8	-8
404	404	0	8
412	405	-7	-4
408	405	-3	0
408	404	-4	-8
400	405	5	8
408	404	-4	0
408	404	-4	0
408	404	-4	0
408	404	-4	0
408	404	-4	-408

VALVE NUMBER 1 240				VALVE NUMBER 2 240				VALVE NUMBER 3 240			
99	95	-4	-24	161	163	2	12	81	77	-4	0
75	49	-26	12	173	169	-4	-31	81	88	7	-23
87	90	3	27	142	134	-8	-4	58	57	-1	15
114	114	0	-8	138	141	3	27	73	77	4	0
106	103	-3	12	165	166	1	-23	73	78	5	0
118	122	4	-4	142	135	-7	-4	73	65	-8	43
114	107	-7	-8	138	130	-8	11	116	116	0	-35
106	105	-1	4	149	151	2	4	81	81	0	4
110	102	-8	4	153	145	-8	-19	85	81	-4	31
114	113	-1	39	134	127	-7	4	116	104	-12	0
153	149	-4	-47	138	131	-7	43	116	117	1	-19
106	110	4	-3	181	177	-4	-16	97	92	-5	7
103	94	-9	-4	165	158	-7	27	104	92	-12	40
99	102	3	-36	192	187	-5	-23	144	140	-4	0
63	57	-6	86	169	156	-13	47	144	144	0	-28
149	153	4	-15	216	221	5	-16	116	116	0	39
134	136	2	-28	200	194	-6	4	155	148	-7	-8
106	102	-4	8	204	198	-6	55	147	144	-3	-11
114	110	-4	31	259	256	-3	-31	136	130	-6	-4
145	140	-5	4	228	222	-6	23	132	135	3	8
149	163	14	-39	251	256	5	-27	140	137	-3	-32
110	106	-4	8	224	217	-7	7	108	101	-7	12
118	107	-11	20	231	237	6	20	120	114	-6	-12
138	142	4	-16	251	248	-3	-70	108	109	1	32
122	121	-1	-8	181	183	2	86	140	136	-4	19
114	113	-1	4	267	267	0	-12	159	152	-7	8
118	118	0	8	255	256	1	62	167	164	-3	-8
126	122	-4	4	317	321	4	-23	159	155	-4	20
130	119	-11	8	294	295	1	-20	179	170	-9	-4
138	130	-8	-39	274	268	-6	24	175	166	-9	-4
99	100	1	39	298	291	-7	-8	171	164	-7	23
138	137	-1	27	290	284	-6	59	194	194	0	8
165	170	5	-16	349	342	-7	-28	202	194	-8	-4
149	152	3	20	321	325	4	8	198	194	-4	0
169	166	-3	23	329	328	-1	-39	198	198	0	0
192	198	6	-27	290	291	1	16	198	190	-8	16
165	170	5	20	306	297	-9	19	214	209	-5	-16
185	188	3	27	325	324	-1	28	198	191	-7	4
212	209	-3	-12	353	350	-3	-32	202	194	-8	8
200	198	-2	-12	321	322	1	43	210	209	-1	0
188	196	8	0	364	369	5	-19	210	209	-1	-4
188	186	-2	-15	345	338	-7	8	206	208	2	0
173	174	1	12	353	353	0	15	206	204	-2	27
185	181	-4	3	368	361	-7	-23	233	226	-7	-19
188	193	5	-3	345	346	1	-8	214	213	-1	8
185	194	9	7	337	338	1	19	222	214	-8	0
192	194	2	24	356	356	0	-58	222	217	-5	-32
216	227	11	-63	298	299	1	27	190	186	-4	28
153	152	-1	4	325	318	-7	28	218	209	-9	27
157	164	7	-4	353	341	-12	19	245	245	0	-35
153	147	-6	35	372	372	0	-19	210	201	-9	-8
188	189	1	4	353	352	-1	7	202	201	-1	-8
192	186	-6	-7	360	365	5	8	194	186	-8	4
185	186	1	0	368	366	-2	-58	198	193	-5	4
185	178	-7	-20	310	308	-2	50	202	204	2	-8
165	170	5	16	360	359	-1	-62	194	190	-4	-11
181	186	5	27	298	291	-7	15	183	173	-10	-12
208	206	-2	-12	313	316	3	16	171	170	-1	-12
196	206	10	-43	329	327	-2	-31	159	153	-6	-12
153	153	0	-153	298	291	-7	-298	147	144	-3	-147

TABLE A.31. Measurement Instrument signal data standard deviations

Temperature	
1	2
0.6928	0.5477
0.7348	0.5099
0.7483	0.5292
0.7211	0.5292
0.6633	0.7348
0.4000	0.6481
0.4243	0.6928
0.6481	0.5099
0.4472	0.9274
0.6000	0.6633
0.7746	0.5099
0.7746	0.6325

Flow	
1	2
8.4829	11.3868
9.3209	6.5666
7.4377	4.9880
12.2915	13.7273
9.0266	12.4668
11.9950	8.9933
8.3798	13.4260
11.4149	10.0965
10.0010	11.8364
8.5790	6.2657
10.1341	6.4761
7.4391	9.6685

Pressure	
1	2
10.5109	7.2194
12.6235	8.1793
9.5676	6.9914
8.7761	8.1780
5.6125	9.0266
10.0430	10.2235
8.0299	7.6967
8.0212	7.9019
7.7278	6.7409
8.1179	12.0731
7.7291	8.4994
12.5292	10.7406

Gas pressure	
1	2
4.2450	4.9437
6.4777	4.5475
7.1916	12.7914
6.3859	10.4307
6.8279	8.9833
7.2291	11.5569
7.7614	6.1401
7.9031	6.1693
7.0753	6.4715
7.3946	8.5697
7.8230	7.1456
6.6182	4.5056

APPENDIX 4

Data for Industrial example.

Table A.32. Normal instruments behaviour data for Fig. 9.2

Time Mins.	Resistance thermometer logging °C	Mercury in steel thermometer reading °C
0	40	37.5
10	49.4	50.0
20	56.8	55.0
30	63.5	60.0
40	69.8	69.0
50	75.6	75.0
60	81.5	80.0
70	87	86.5
80	93.3	95.0
90	104.1	102.5
100	114.7	113
110	121.1	120
120	125.6	125
130	129.8	129
140	133.6	135
150	137.9	140
160	144.5	147.5
170	151	153
180	156.8	159
190	162.2	165
200	167.9	169.0
210	171	170.5
220	170.2	170.0
230	170.2	170.0
240	170.5	170.0
250	170.5	170.0
260	171.3	171.0
270	172.1	171.5
280	171.7	171.5
290	171.3	171.5
300	171.5	171.5

Table A: 33 Resistance thermometer malfunction data for Fig. 9.3

Time Mins.	Resistance thermometer logging °C	Mercury in steel thermometer reading °C	Time Mins	Resistance thermometer logging °C	Mercury in steel thermometer reading °C
0	115.9	180.0	250	198.4	183.5
10	145.4	180.0	260	199.9	187.0
20	163.2	180.0	270	201.4	188.5
30	167.5	180.0	280	202.8	190.5
40	163.3	180.0	290	204.1	193.0
50	159.6	180.0	300	205.3	195.0
60	157.3	180.0	310	206.8	198.0
70	157.0	180.0	320	208.6	200.0
80	159.9	180.0	330	209.3	201.5
90	163.1	160.0	340	207.8	202.5
100	166.3	130.0	350	208.2	202.5
110	169.6	115.0	360	208.8	201.5
120	172.3	102.5	370	210.2	200.5
130	174.6	102.0	380	212.4	200.0
140	176.9	102.0	390	214.3	200.0
150	179.1	102.0	400	214.7	200.0
160	181.3	135.0	410	215.8	200.0
170	183.4	157.5	420	216.7	200.0
180	185.0	162.0	430	206.4	200.0
190	187.3	171.5	440	197.4	200.0
200	189.0	173.5	450	190.0	200.0
210	191.0	175.0	460	183.4	200.0
220	193.0	177.5	470	178.6	200.0
230	195.0	179.5	480	177.6	201.5
240	197.1	182.0	490	173.3	202.0

Table A.33 Resistance thermometer malfunction data for Fig. 9.3 (continued)

Time Mins.	Resistance thermometer logging °C	Mercury in steel thermometer reading °C
500	172.3	202.5
510	171.7	204.0
520	171.2	205.0
530	171.1	205.0
540	170.4	205.0
550	169.2	205.0
560	164.7	205.0
570	160.4	205.0
580	151.1	204.0
590	24.5	203.5
600	22.5	203.0
610	23.5	204.0
620	24.2	205.0
630	25.9	205.0
640	27.5	205.0
650	39.9	205.0
660	53.7	205.0
670	64.1	205.0
680	73.4	205.0
690	77.7	204.0
700	78.5	203.0
710	79.4	202.5
720	84.6	202.0
730	95.6	201.0
740	115.9	201.0
750	128.1	200.5
760	129.8	203.0
770	133.6	203.5
780	137.5	204.0
790	141.5	202.5
800	144.9	202.5
810	148.4	201.0
820	151.7	191.0

Table A. 34 Resistance thermometer malfunction data for Fig. 9.4

Time Mins.	Resistance thermometer logging °C	Mercury in steel thermometer reading °C	Time Mins.	Resistance thermometer logging °C	Mercury in steel thermometer reading °C
0	60.5	113.0	250	51.2	197.0
10	33.7	112.5	260	48.9	198.0
20	77.9	112.0	270	46.7	200.0
30	151.9	111.0	280	44.5	203.0
40	20.8	115.0	290	42.6	205.0
50	40.5	135.0	300	40.8	206.0
60	87.0	155.0	310	39.3	208.0
70	71.8	171.0	320	132.0	209.0
80	68.4	170.0	330	89.6	210.0
90	84.9	165.0	340	91.1	212.0
100	111.9	162.0	350	90.9	214.0
110	74.0	160.0	360	90.2	215.0
120	26.6	162.5	370	89.7	215.0
130	114.8	167.0	380	88.8	215.0
140	81.2	170.0	390	87.7	215.0
150	111.6	174.0	400	86.7	215.0
160	86.4	176.0	410	85.7	215.0
170	81.0	180.0	420	84.7	215.0
180	40.2	182.0	430	84.7	218.0
190	58.3	184.0	440	83.5	220.0
200	87.1	186.0	450	82.5	220.0
210	70.9	187.5	460	82.0	221.0
220	148.4	190.0	470	80.8	222.0
230	129.6	193.0	480	80.3	215.0
240	257.5	195.0	490	79.2	205.0

Table A.34 Resistance thermometer malfunction data for Fig. 9.4 (continued)

Time Mins.	Resistance thermometer logging °C	Mercury in steel thermometer reading °C
500	78.4	195.0
510	77.6	192.0
520	76.8	185.0
530	75.9	184.0
540	75.1	180.0
550	74.5	177.0
560	73.7	176.0
570	72.9	176.0
580	72.2	176.0
590	70.9	175.0
600	70.8	175.0
610	70.1	175.0
620	69.5	167.0
630	68.7	162.5
640	68.1	75.0
650	67.3	30.0
660	66.9	25.0

Table A.35 Resistance thermometer malfunction data for Fig. 9.5

Time Mins.	Resistance thermometer logging °C	Mercury in steel thermometer reading °C	Time Mins.	Resistance thermometer logging °C	Mercury in steel thermometer reading °C
0	24.4	45.0	270	24.4	183.0
10	25.4	55.0	280	24.9	185.0
20	25.8	65.0	290	29.9	188.0
48	26.6	95.0	300	36.0	190.0
55	26.6	98.0	310	36.8	192.0
70	26.9	100.0	320	45.2	195.0
80	-	-	330	54.1	196.0
90	-	-	340	63.7	198.0
100	-	-	350	74.5	199.5
110	25.8	140.0	360	84.7	201.0
120	24.7	142.0	370	91.5	203.0
130	24.4	145.0	380	97.1	205.0
140	24.3	149.0	390	106.0	206.0
150	24.3	152.0	400	116.5	207.0
160	24.4	156.0	410	126.0	210.0
170	24.5	160.0	420	131.0	210.0
180	24.7	162.0	430	134.8	212.0
190	24.9	163.0	440	137.7	214.0
200	25.0	165.0	450	140.5	215.0
210	25.02	168.0	460	143.2	217.0
220	25.3	170.0	470	146.4	217.5
230	25.8	173.0	480	150.2	217.5
240	25.5	176.0	490	153.4	217.5
250	24.1	179.0	500	156.4	217.5
260	24.1	181.0	510	156.8	217.5

Table A. 35 Resistance thermometer malfunction data for Fig. 9.5 (continued)

Time Mins.	Resistance thermometer logging °C	Mercury in steel thermometer reading °C
520	159.0	217.5
530	161.0	217.5
540	160.6	218.0
550	164.1	219.0
560	167.2	220.0
570	170.3	220.0
580	170.1	220.0
590	172.4	220.0
600	173.9	220.0
610	176.3	220.0
620	178.3	220.0
630	180.1	220.0
640	182.5	221.0
650	185.3	221.0
660	184.7	221.0
670	181.5	222.0
680	180.8	222.5
690	188.0	222.5
700	194.0	222.5
710	195.7	223.0
720	197.2	223.0
730	198.4	223.0
740	200.2	223.0
750	201.7	212.0
760	203.0	203.0
770	204.7	195.0
780	206.4	186.0
790	206.9	183.0