APPLICATION OF DIGITAL FILTERING METHODS TO STATE AND PARAMETER ESTIMATION IN PROCESS PLANT.

A thesis submitted for the degree of
Doctor of Philosophy
by
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November 1974.

Summary.

The application of on-line state variable and parameter estimation for chemical processes, with particular reference to a pilot plant scale double effect evaporator, has been investigated.

The investigation has shown the requirement of some adaptive modification to the recursive Kalman Filter to be necessary. This adaptive modification prevents the occurrence of bias and divergence of the estimates of the state of the system, when investigating poorly understood chemical processes.

A mathematical model of the double effect evaporator is derived along with heat transfer correlations that are suitable for implementation within the Kalman Filter.

Finally a computer package is developed, which incorporates an adaptive filter, for on-line estimation of the state and parameters of a chemical process. The computer package is shown to operate successfully in real time on the double effect evaporator.

ACKNOWLEDGEMENTS.

The author wishes to express his gratitude to the following:-

Professor G.V. Jeffreys

For providing facilities for the work to be carried out in his department.

Dr. B. Gay

For his supervision of this project, his many useful suggestions especially in the preparation of the computer software and his constructive comments on the preparation of this thesis.

S.G. Payne.

For his constructive comments on all aspects of this thesis.

Messrs. M. Lea and D. Bleby.

For their help in maintaining the electronic equipment associated with the project.

University of Aston in Birmingham and the Science Research Council.

For their financial support.

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CHAPTER ONE.

Chapter 1. Introduction.

In any decision making process a knowledge is required of the state of the system under study. Within the chemical industry the complexity of the processes has resulted in a greater use of computers to aid the engineer in the estimation of the state of the system and in the decision making process. This is particularly so for modern control schemes where the engineer has two sources of information on which to base his estimate of the state of the physical process, measurements from and a mathematical description of the physical process. Both are subject to error.

This area of state and parameter estimation has been the subject of much research for many years, gaining greater impetus following the publication of the classical Kalman Filter,(1.1).

The classical Kalman Filter has been widely applied in many diverse fields, in particular the aerospace industry. Its use within the field of chemical processes has been very limited. This limitation can in some part be attributed to a lack of knowledge of the process under consideration. Chemical process yield complicated mathematical models which are generally non-linear and of a high order and as such are incompatible with the requirements of real time estimation using the classical Kalman Filter.

The aim of this thesis is to show how modifications to the classical Kalman Filter can remove some of the previous limitations to its use. Particular reference is made to real time estimation of the state and parameters of a pilot plant scale double effect evaporator whose dynamic characteristics are poorly understood.

The thesis is divided into the following main areas,

(i) A review of the relevant literature concerning the development of estimation theory and in particular the problems associated with real time estimation for chemical processes. Within the literature review a short appraisal is included of the relevant heat transfer research to show the difficulties involved in (a) accurately describing the dynamics of heat exchange equipment, and (b) the prediction of heat transfer coefficients.

(ii) A description of the equipment used for this research.

(iii) An analysis of the double effect evaporator for both steady state and dynamic operation. The analysis is utilised in the development of a dynamic model of the evaporator in a form that is suitable for implementation within the Kalman Filter.

(iv) An analysis of the behaviour of the Kalman Filter when ill-defined mathematical models are used to describe the physical process. The analysis is developed to include filter modifications that have been shown to be capable of dealing with the problems encountered with ill definition of the mathematical model.

(v) Finally the results of the previous sections are brought together in a computer package to produce real time estimates of the state of the double effect evaporator and the associated parameters.

CHAPTER TWO.

Chapter 2. Literature Survey.

2.1 Estimation Theory.

2.1.1 Introduction.

An important task facing any engineer involved in the design or performance of a physical system is how to use information from this system in order to make decisions. In order to make decisions the engineer requires to know the best estimate of the state of the system under study. The task is complicated by three main factors; (i) The information obtained from the system is often corrupted with noise caused by the components of the measuring device. (ii) The system itself may be subject to random disturbances so that the state of the system itself may be random. (iii) The measurements from the system may be too few at a given time to infer the values of the state even if the measurements were accurate.

2.1.2 Historical Development.

The problem of determining the state of a system from noisy measurements is called estimation or filtering and in one form or another has been the subject of man's attention for over one hundred years. Possibly the earliest attempt at a solution to the problem was proposed by Gauss (2.1) in 1809 in his attempts at determining the orbital elements of a celestial body from available data. His method has come to be known as the "Method of Least Squares" and forms the basis for much of the subsequent work in the field of estimation. The method of least squares is a deterministic approach to the problem of minimising errors and basically attempts to pass the solution of a physical model, as closely as possible, through the observations. It has the distinct disadvantage of requiring all observations to be available before any minimisation can take place and thus the computational requirements involved in solution can become prohibitive as observations increase. One attempt to alleviate this problem partially was proposed by Swerling (2.2) who using batch processing of data devised a recursive least squares filter for estimation. An excellent review of the aspects of this approach to estimation theory and its applications has been presented by Deutsch (2.3).

Apart from the previously stated computation problem posed by this approach to the estimation problem it also has the severe practical disadvantage of being purely a smoothing procedure. That is it in no way makes use of known statistics of the system under consideration in order to produce a more accurate estimate of the state of the system. Theoretically this could be accomplished satisfactorily if the correct weighting matrix for the data could be computed for the system under consideration. Both Deutsch and Swerling accept that this can rarely be accomplished in practical application.

Use of the known system statistics has been termed the probabilistic approach to the problem by researchers in the field of estimation. The initial development of the work of estimation theory using this approach can be credited to the original papers by Wiener (2.4) and Kolmogorov (2.5, 2.6). These works, although containing complex mathematical treatments, offered for the first time an analytical synthesis technique which could be used for the seperation of a desired signal in an enviroment of undesired noise. The technique derived is based upon frequency domain analysis and is basically reduced to the solution of a complex integral equation (the Wiener-Hopf equation). Using this frequency domain technique Wiener solved the estimation problem for a class of linear, stationary problems. These problems in the engineering sense can be classified as " trivial " and the more useful cases of non-linear and non-stationary systems remained essentially unsolved although various modifications to the Weiner-Kolmogorov theory have been proposed for these cases. Deutsch (2.3) has shown the modifications in detail and concludes that in the final analysis the assumptions that are required in the solution of the Weiner-Hopf integral for complex systems make the theory a dubious tool for estimation.

2.1.3 Kalman Filtering Theory.

The Weiner-Hopf theory has served both as an end in itself and as a starting point for related theories designed to avoid the problems encountered in the solution of the Weiner-Hopf integral. The general linear non-stationary filtering and estimation problem was essentially solved by what is now regarded as the classical method due to Kalman (2.7), Kalman and Bucy (2.8) and Kalman (2.9) who by substitution of an equivalent differential equation managed to remove the inherent difficulties in the solution of the Weiner-Hopf integral. The theory of Kalman using this approach has the practical advantage that the differential equation technique has the property that the optimum filter can be synthesised in a sequential fashion and, thus, is often readily implemented.

The Kalman-Bucy theory recognises the inherent difficulties in attempting to solve the Weiner-Hopf integral directly and the desirability of converting this integral equation into a non-linear differential equation. It is this non-linear differential equation which on solution yields the covariance matrix of the minimum filtering error which contains all the necessary information for the design of the optimum filter.

The Kalman-Bucy method can be characterised by the following five relations :-

(i) The differential equation governing the error of the best linear estimate.

(ii) The differential equation governing the optimum filter, which is excited by the observed signals and generates the best linear estimate of the message.

(iii) The time varying gains of the optimal filter expressed in terms of the error variances.

(iv) The non-linear differential equation governing the covariance matrix of the errors of the best linear estimate.

(v) The formula for prediction.

A continuous time linear dynamic system can be described either by a differential equation formulation or by a linear difference equation. For the purpose of this thesis a system characterised only by difference equations will be considered.

The linear estimation theory due to Kalman and Bucy,(and hereafter referred to as the Kalman Filter), is composed of a group of matrix recursion relations. The simplicity of these relations make them particularly amenable to implementation on a digital computer. A detailed derivation of these relations will not be presented here and the reader is referred to the original work by Kalman (2.7) and generalisations by Jazwinski (2.10) and Sorenson (2.11) for fuller details.

The discrete Kalman Filter equations specify an optimal estimate of the state of a linear, time varying, dynamic system observed sequentially in the presence of additive white gaussian noise. The estimate obtained at each time is the maximum likelihood estimate conditioned on all observations up to that time. The vector difference equation

$$X_{k+1} = A_k . X_k + w_k \qquad \text{-----------} \ (2.1)$$

describes such a system where k denotes a particular instant of time and A_k is the state transition matrix at k. The n components of X_k are the states of the system and w_k is a zero-mean, white gaussian noise process that represents input disturbances to the system. At each interval of time, m observations represented by the vector Y_k are obtained from the system that are linearly related to the state and which are corrupted by additive noise by the equation;

$$Y_k = H_k . X_k + V_k \quad \text{-------------} \; (2.2)$$

where H_k is a known (m x n) dimensional observation matrix and V_k is a zero-mean, white gaussian noise process assumed to be independent of w_k. The respective covariances of w_k and V_k are Q_k and R_k.

It is furthur assumed that an a priori prediction $X_{0/-1}$ has been made with error covariance $P_{0/-1}$.

The linear Kalman Filter determines the estimate of the state and minimises the quantity, J, as follows:

$$J = \frac{1}{2} . (\bar{X}_k - X_{k/k})^T . P_{k/k}^{-1} . (\bar{X}_k - X_{k/k}) + \frac{1}{2} \sum_{j=0}^{k-1}$$

$$((Y_{j+1} - H_{j+1} . X_{j+1/j})^T . R_{j+1}^{-1} . (Y_{j+1} - H_{j+1} . X_{j+1/j})) \quad \text{-------------} \; (2.3)$$

where $\bar{X}_k$ is the true state of the system. Superscript T denotes transpose and superscript -1 denotes matrix inversion.

The estimation procedure may be written as a set of prediction and estimation equations as follows;

PREDICTION

$$X_{k/k-1} = A_{k-1} . X_{k-1/k-1} \quad \text{------------} \; (2.4)$$

$$P_{k/k-1} = A_{k-1} . P_{k-1/k-1} . A_{k-1}^T + Q_{k-1} \quad \text{-------------} \; (2.5)$$

These equations describe the behaviour of the state and its covariance at time k based on observations through time k-1.

ESTIMATION

$$W_k = P_{k/k-1} . H_k^T . (H_k . P_{k/k-1} . H_k^T + R_k)^{-1} \quad \text{---------} \; (2.6)$$

$$X_{k/k} = X_{k/k-1} + W_k . (Y_k - H_k . X_{k/k-1}) \quad \text{---------} \; (2.7)$$

$$P_{k/k} = (I - W_k . H_k) . P_{k/k-1} \quad \text{----------} \; (2.8)$$

where W_k is the gain matrix of dimension (n x m).

The a priori prediction and corresponding error covariance are used as initial conditions for the above recursive equations.

Kalman (2.7) introduced the dual concepts of observability and controllability as a part of his general filtering theory. A system is said to be controllable if every state variable of the system can be affected by the input vector to the system.

The more important concept to the field of filtering theory is that of observability. A system is said to be observable if all of the state variables can be derived from the measurement vector of the system either directly or indirectly. If one of the state variables of the system cannot affect the measurement vector then the system is unobservable.

It can be shown that if insufficient measurements or the " incorrect measurements " are available from the system such that it is unobservable then the estimates produced by the filter will not be optimal.

Following the original work by Kalman the main theoretical contributions in linear filtering theory have been based upon generalising Kalman's earlier work. Contributions have been made by Cox (2.12), Kushner (2.13) and Friedland and Bernstein (2.14) in extending the theory to allow for correlation between the system and measurement noise, and the problem of coloured (time-correlated) noise has been partially solved by Kalman (2.9).

2.1.4 Extension to Non-Linear Systems.

The discussion of the preceding section has been based upon a mathematical model described by a first-order system of linear differential equations, the output of the system being provided by quantities that are linearly related to the state variables. This can be regarded as a linear gaussian problem for which the theory of Kalman provides an optimal filter. In the real world, no such problem exists however, and the dynamic system for a particular problem is frequently found to be described by a series of $n^{th.}$ order non-linear differential equations. The $n^{th.}$ order derivatives offer no theoretical problems as they can be rewritten as n-1st. order differential equations. However the problem of treating the non-linearities of the system poses considerable theoretical and practical problems if an optimal solution is required.

An exact optimal solution to the non-linear estimation problem can be obtained theoretically using general recursion relations describing the evolution of the a posteriori density functions in terms of a-priori distributions and the measurement data. This a posteriori density function of the state conditioned on the measurement data contains all the available information that can be used in the development of estimation for stochastic dynamic systems with noisy measurements. Alspach (2.15) states that it is seldom possible to express the a posteriori density function in a closed form that can be used to generate specific estimation policies and therefore some approximation has to be made to use this approach in a practical situation.

Two such specific techniques have been presented in the literature over the past three years. The first due to Bucy and Senne (2.16) is based upon a specific rotating variable density grid, numerical integration technique and the second by Alspach and Sorenson (2.17) is based upon the approximation of certain densities by a sum of gaussian like densities with positive weighting coefficients. Alspach (2.15) and Jazwinski (2.10) in discussions of these above policies both concluded that they are excessively expensive in computation requirements during implementation on a practical basis. This point is given even greater credence in the light of work carried out on the extensions of Kalman's original theory to the non-linear problem.

The initial attempts at extending Kalman's theory to the non-linear problem were based upon providing a linear approximation to the non-linear system and measurement equations, (see Sorenson (2.11) for details). These linearisations were based upon the first term of a Taylor Series expansion around the most recent estimate of the state and they were then suitable for use within the Kalman Filter, (equations 2.4 to 2.8). This approach has come to be known as the extended Kalman Filter. When the non-linearities of a system are such that the linearisations previously described become inappropriate in terms of accurately describing the system then the extended Kalman Filter can cause severe discrepancies between the estimates produced from the filter and the true state. In this event, there are essentially two types of filters proposed to overcome this problem. The most complicated of the two types takes into account second or higher order terms in the Taylor Series expansion for the linearisation. These filters are usually refered to as second order filters. In cases were the extended Kalman Filter has failed due to severe non-linearities the second order filter has shown considerable improvement, (see for example 2.14, 2.18 and 2.19). However the computational problems arising from the requirement to compute the higher order moments can often outweigh the improvement of the accuracy of the estimates from the filter. This is especially true in real time applications, as shown by Jazwinski (2.10), where there is limited time available between successive cycles of the filter.

The second possibility is to relinearise at each stage about the new estimate obtained, thus obtaining a first iterated estimate. If the residual is not satisfactory after one iteration another linearisation is performed. Such filters are called iterated filters. These iterators have been reported as extremely effective in solving non-linear problems by Wishner et al. (2.20), Denham and Pines (2.21) and Leung and

Padmanabhan (2.22).

Several papers have been presented in an attempt to clarify the individual requirements of the various methods proposed for solving the non-linear estimation problem and in particular to determine when a truely optimal filter is worth while or necessary and under what conditions is some version of the modified Kalman Filter adequate. These papers (2.10, 2.15, 2.23, 2.24 and 2.48) compare by simulation as many as fourteen different filters. The conclusions are generally vague in that the choice of filter is very much system dependent. For systems with only slight non-linearities the extra computational requirements of the more complicated methods may be unjustified in terms of the increased accuracy obtained whereas for complex non-linear systems the simpler methods may break down completely.

2.1.5 Applications of Kalman Filtering.

Following the publication of Kalman's original work the aerospace industry was the first to take advantage of the filter with applications in the field of celestial navigation by Smith, Schmidt and colleagues (2.25, 2.26 and 2.27). Since this time the theory has been applied in many fields as diverse as Agricultural Pest Control (2.28), Traffic Surveillance and Control (2.29) and Stock Market Forcasting (2.30).

The Chemical Industry has been much slower in its use of the Kalman Theory than the aerospace industry. The reasons for this delay are numerous but possibly the major one is that chemical processes yield complicated dynamic models which are usually distributed parameter, non-linear, stochastic and of relatively high order. To overcome this problem early researchers tended to use simulated experiments, using an identical mathematical model in the filter equations as that used to obtain the " pseudo-measurements ". This, as will be discussed later, can cause some of the more difficult problems of real-time implementation to be overlooked but never the less these early publications provided solutions to many practical and theoretical problems and showed the possibilities of the theory for on-line applications.

Sargent and co-workers (2.31, 2.32 and 2.33) besides demonstrating the use of the filter equations within a closed cycle control loop, have shown the effect of the initial apriori estimate $X_{0/-1}$ and its co-variance $P_{0/-1}$ upon the speed of responce of the filter and the accuracy of later estimates. Their general conclusions in the choice of the initial value of $P_{0/-1}$ have since been verified by other workers, see for example Yoshimura and Soeda (2.34). Further contributions have also been made by Sargent et al. in dealing with the problem of instrument bias, drift and scatter of readings.

Wells (2.35) demonstrated the use of the filter equations for estimating state variables and parameters in a highly non-linear chemical process. His computation times indicated that for a physical system of similar dimension the Kalman Filter could be implemented in real time. Some of his conclusions regarding the use of poor models within the filter equations have since been demonstrated by the author and other workers (see for example Jazwinski (2.10)) to be without foundation. This point will be discussed in detail in a later section.

Coggan, Noton and co-workers (2.36, 2.37, 2.38 and 2.39) have had considerable success in applying the filter equations in a control loop and demonstrating the possible use of the algorithm in real time using timed computer experiments. Developments to include the effects of strong non-linearities, inaccurate measurements and variable transport lags were also demonstrated successfully.

Seinfeld and co-workers (2.40, 2.41, and 2.42) have made major practical and theoretical contributions in the field of parameter estimation using the filter algorithm and also in attempting to define theoretically an analysis of the errors of the estimates of these parameters. Systems studied using this technique include catalytic chemical reactors and kinetic reaction systems.

On-line implementations within the field of chemical engineering have been very few in number and probably the most significant have been presented by Payne (2.43), Hamilton et al. (2.44) and Payne and Gay (2.45). These works have highlighted the many difficulties that are encountered during on-line implementation, many of which have been overlooked by workers carrying out research using simulated results. The most notable points arising from the works above are the times required by the filter algorithm for large systems and the assumptions required by these workers in order to make their systems operate within the limits of the mmeasurement intervals imposed by their equipment. Hamilton et al., for example, used precomputation of the weighting matrix, W_k , prior to the start of the filtering in order to reduce the computational burden during his experiments. Payne reduced the order of his system considerably and fed measured inputs directly into his transition matrix, A_k , in order to bring about meaningful real-time implementation.

2.1.6 Practical Difficulties of Implementation of the Kalman Filter.

During the early simulation experiments carried out using the Kalman Filter several problem areas were encountered by the investigators. One of these problems was the requirement of high precision in the filter computations and specifically in the computation of the estimation error covariance matrix, $P_{k/k}$. This matrix is susceptible to computation error, (round off), as its elements decrease in magnitude after many sets of data have been processed. These errors can cause $P_{k/k}$ to lose its property of non-negative definiteness and make the diagonal elements of $P_{k/k}$, which represent variances, negative and hence meaningless. Besides the use of double precision arithmetic, two methods have been proposed in the literature for overcoming this problem. The first uses an alternative derivation, (see Sorenson (2.11)), for $P_{k/k}$ to that given by Equ. 2.8

$$\text{i.e.} \quad P_{k/k} = (I - W_k . H_k) . P_{k/k-1} \qquad \text{----------} (2.8)$$

becomes

$$P_{k/k} = (I - W_k . H_k) . P^T_{k/k-1} . (I - W_k . H_k)^T + W_k . R_k . W^T_k \qquad \text{----------} (2.9)$$

Manipulation reduces equation 2.9 to equation 2.8 but because of its symmetry positive-definiteness is guaranteed. The second method uses the square root of $P_{k/k}$ rather than the value of $P_{k/k}$ itself. Again positive definiteness is guaranteed. Recursions for the square root of $P_{k/k}$ have been developed by Bellantoni and Dodge (2.46) and Andrews (2.47).

A further problem concerning computation accuracy as well as computation time and storage arises when a large number of measurement sources are available. This arises due to the requirement to invert an m x m dimensional matrix, where m is equal to the number of measurements, from equation 2.6 during the computation of the weighting matrix W_k.

$$\text{i.e.} \quad W_k = P_{k/k-1} . H^T_k . (H_k . P_{k/k-1} . H^T_k + R_k)^{-1} \qquad \text{-----} (2.6)$$

Providing that the measurements are uncorrelated then one method proposed, and successfully demonstrated, to overcome this problem has been presented by Singer and Sea (2.49) and Sorenson (2.11). The method involves the processing of measurements individually and circumvents the requirement of inversion. Singer and Sea report a 30% reduction in computation times for the algorithm in practical applications of the Kalman Filter.

Possibly the most disturbing problem that has arisen during experiments with the Kalman Filter is that of divergence or drift of the estimates produced by the filter away from the true state. Alspach (2.15) has stated that the problem arises from three possible sources;

(i) Excessive non-linearities within the system under study.

(ii) Incorrect system statistics.

(iii) A poor mathematical description of the system.

The first point has already been discussed under the section dealing with non-linear filtering.

The problem of incorrect system statistics can be broken down into two main areas, the incorrect choice of the initial conditions and their error covariances, i.e. $X_{0/-1}$ and $P_{0/-1}$, and the incorrect choice of the system input and measurement noise covariances, Q_k and R_k. Work in the area of incorrect choice of initial conditions (2.31, 2.50, 2.51, 2.52 and 2.53) has shown that divergence of the estimates will only occur, providing the system model is correct, if the initial value of $X_{0/-1}$ is incorrect and no allowance is made for the fact in the selection of values in $P_{0/-1}$. That is if too much confidence is given to the initial conditions that are in error the filter algorithm converges too rapidly for the measurements to be used in correcting the values of the state. The general conclusions of the works quoted above is that provided the initial values alloted to $P_{0/-1}$ are large enough the system will converge to the true state. The disadvantage in this approach is that the time for convergence to the true state may be large and the error covariances of the estimates produced during this period are unreliable.

Within the area of incorrect process and measurement noise statistics, applied to chemical processes, the problem reduces to that of incorrect values of the input noise disturbance to the system, as the measurement noise statistics should be readily evaluated for the type of instruments involved. Divergence occurs when the values of Q_k are too small, resulting in a false low value of $P_{k/k-1}$ and hence W_k. This means that insufficient weight is placed upon new measurement data coming into the system. Mehra (2.54) and Graupe and Krause (2.55) have been concerned with computation of the matrices Q and R from measurement data prior to filtering. The work has been directed towards single output systems only due to the theoretical complexity of the problem. Graupe and Krause have shown practical results for their methods but accept the immense problems involved in extending the method to multi-output systems. Heffes (2.56), Nishimura (2.57) and Fitzgerald (2.58) have attempted to incorporate the errors in the Q matrix into the filter algorithm by modification of the $P_{k/k}$ relationship. Although promising on a theoretical basis no practical results have appeared to date to show the feasability of these procedures. The problem is still at present unsolved for practical implementation but providing the model is accurate and the measurement noise low then a high level of Q will suffice to give accurate estimates. The question that must be asked is " What is a sufficiently high level of Q to stop filter divergence? " Up to the present time researchers have used trial and error experiments on simulated data to determine this value of Q.

Probably the most common cause of filter divergence in chemical systems is a poor mathematical description or model of the process. As has been previously stated chemical systems are notoriously difficult to model accurately. The problem is compounded by the form of the model required for implementation within the Kalman Filter. With incorrect models the divergence is caused by the filter learning " the wrong state too well" when it operates over many data. The problem is particularly acute when the noise inputs to the system and the measurement noise are very low, for then the filter is capable of learning the wrong state very well.

The linear filtering theory of Kalman assumes that system dynamics are completely known and are precisely modeled in the filter. Clearly this is never true in practice and therefore more detailed models of the system are unlikely to offer a guarantee to accurately predict the dynamics of the system.

Initial attempts at a solution to the problem of filter divergence caused by a poor model centred around the use of the matrix of input noise covariances, Q. It was stated by researchers, (see for example Schlee et al. (2.59)), that inaccuracies in the mathematical model could be accounted for by increasing the value of the Q matrix, i.e. the addition of"fictitious noise". This they justified by the fact that the difference between the true and estimated state could be due to unknown disturbances upon the inputs to the system if the model was correct. The method has the advantage that the addition of this constant fictitious noise stops the convergence of the error covariances of the predictions and thus forces the filter to take into account the measurements at all time levels. The method has two obvious disadvantages, the first is in the selection of this constant fictitious noise and the second lies in the fact that the fictitious noise addition is a constant value and if it is to account for model error then this error itself must be assumed constant. An assumption that cannot be justified in all cases. Jazwinski (2.10) in a discussion of this technique notes that for some inaccurate systems this method will be adequate in giving good estimates, (see for example Schlee et al. (2.59)). However the theoretical justification is such that fictitious noise addition may not always be effective in the prevention of divergence.

Jazwinski himself, (2.60, 2.61) attempts to overcome the two disadvantages above by adaptively computing, on line, the " correct " value of Q to give consistency between the residuals of the predictions and measurements and the system statistics. The adaptive filter provides feedback from the residuals, in real time, in terms of system noise input levels. These degrade the estimation error covariance matrix, increase the filter gain, and thus open the filter to incoming data.

Because of the theoretical complexities involved in such an operation Jazwinski makes assumptions about the form of the matrix Q , i.e.

$$Q_k = q_k . I \qquad \text{------------- (2.10)}$$

where q_k is a scalar adaptively calculated and I is the identity matrix. This assumption makes the method somewhat limited in its applications. The method also requires a noise coefficient to be modeled, (the distribution of the noise among the components has to be specified a priori), and this can be a difficult if not impossible task to accomplish.

Kalman's originally derived filter makes use of all data available from the system, from time zero onwards, in order to estimate the state at any time. If the model used within the filter is inaccurate then data projected through this model over long time spans are obviously of little value. This fact has been used by researchers in an attempt to overcome the problem of filter divergence. The method proposed degrades old information, or equivalently, overweights the more recent information. This has the direct effect of increasing the error covariance matrix of the estimates. Weighting is accomplished by the use of an exponential time factor. Papers in this area, (Anderson (2.62) and Jazwinski (2.10)), have shown the effect of the exponential filter during simulated experiments and its ability to cope with, if not totally remove, the divergence problem inherent with inaccurately modelled systems. The main disadvantage of the method is in choosing the exponential time factor, i.e. the number of past measurements that are to be used for providing the estimate of the state.

A furthur method adopting the same principle as the exponential filter is the " moving-average " or " moving-window " filter, (see Lee (2.63) and Jazwinski (2.64)). In this method a poor model is presumed to be applicable only over a limited time span and it is projections outside of this time span that lead to model errors. On this assumption can be based the notion of only using data from within this time span within the filter for estimation. The problem previously stated for the exponential filter of finding the number of measurements to base the estimates on is even more acute with this method.

Schmidt (2.65) adopted the use of new parameters within the system to account for the uncertainty that exists within the poor model. These new parameters then being estimated along with the remaining states of the system through the Kalman Filter. The problems are twofold, firstly there may not be enough measurements available to carry out the filtering procedure, i.e. the system may become unobservable, and secondly the computational burden imposed by increasing the size of the state vector by the addition of these parameters may be intolerable. Friedland (2.66) and Lin and Sage (2.67) have proposed improved methods for estimating these parameters, which at the same time reduce the computation load. Friedland uses a technique of augmenting the state vector and Lin and Sage a technique of invariant inbedding. Both methods have been shown to reduce the computational burden but with the large number of variables associated with a chemical process the aim must be to reduce rather than increase the state variables and parameters required for estimation.

As has been discussed previously filter divergence can arise if the non-linearities of the system are too great for linearisation to be effective. This is analogous to the problem of an initial poor model, (linear), and the solution proposed by such authors as Leung and Padmanabhan (2.22) can be applicable. Their method involves smoothing the trajectory back one measurement and relinearising the non-linear model to obtain an improved prediction. In the case of a linear model the relinearisation is not carried out and only the reprediction is required. If the residuals are not within the statistical limits of the system the step is repeated, using a recursive relationship, until convergence to within the statistical limits occurs. As there is no non-linear model to relinearise problems of divergence can arise with the recursive algorithm itself, thus limiting possible applications of the method.

Apart from the method of Jazwinski (2.60), none of the previously discussed methods for dealing with filter divergence make use of the system statistics in order to improve the estimation of the states of the system when an inaccurate model is applied in the filter equations. These statistics offer not only an indication that divergence is occuring but also the extent of the inaccuracy of the predictions fom the poor model. Srizananda (2.68) has suggested an approach based upon these statistics for the conrol of divergence. He defines an innovation process IN as;

$$IN_k = Y_k - H_k.X_{k/k-1} \quad \text{-----------} (2.11)$$

which is a non-stationary gaussian white noise process with variance ($H_k.P_{k/k-1}.H_k^T + R_k$). He states that it would be expected that ($IN_k^T.IN_k$) would be less than three times the trace of this variance ($H_k.P_{k/k-1}.H_k^T + R_k$) with more than 90% probability. If this is not the case then divergence can be suspected. In his proposed scheme Srizananda states that when divergence is suspected the filter gain is frozen at its current value. This has the effect of increasing $P_{k/k-1}$ because on updating it is in fact incremented by the factor Q_k after allowing for the effect of the transition matrix. This process is allowed to continue until ($IN_k^T.IN_k$) is less than the trace of ($H_k.P_{k/k-1}.H_k^T + R_k$), when the gain is defrozen. If no process noise is present, i.e. Q_k is equal to zero, the filter would remain frozen and thus keep the error within bounds. Srizananda in no way attempts to go further than merely stopping the divergence. He does however offer a very simple technique which removes some of the more serious damages involved in Kalman Filtering in the absence of absolute knowledge of the system under consideration.

Coggan and Wilson (2.69) state that inaccurate models lead to divergence or bias of the estimates produced by the filter and that this is particularly so in chemical processes. They derive a method for detecting and eliminating bias which uses as a starting point a similar method as that proposed by Srizananda (2.68). They define the matrix S_k,

$$S_k = (H_k . P_{k/k-1} . H_k^T + R_k) \quad \text{---------} (2.12)$$

to be the expected covariances of the differences between the predicted and measured values of the measured variables.

A similar matrix can be obtained directly from the data thus;

$$Z_{k+1} = a . Z_k + (1 - a) . z_{k+1} . z_{k+1}^T \quad \text{-------} (2.13)$$

where $$z_{k+1} = H_k . X_{k+1/k} - Y_{k+1} - b_{k+1} \quad \text{---------} (2.14)$$

and $$b_{k+1} = a . b_k + (1 - a) . (H_k . X_{k+1/k} - Y_{k+1}) \quad \text{----} (2.15)$$

An exponential filter is used in preference to an aggregated sample filter because Z_k and b_k are " dynamic " statistics.

If the measurements have errors with zero mean, b_k gives the filtered mean error and if an element of b_k is consistently positive or negative this implies biased predictions. Coggan and Wilson incorporate this development into the Kalman Filter by the following procedure after the relevant matrix computations have been carried out;

(i) Element Z_{ii} replaces element S_{ii} if Z_{ii} is greater than S_{ii}.

(ii) Compute the matrix v_k where

$$v_k = H_k^T.(S_k - R_k).H_k - H_k^T.H_k.P_{k/k-1}.H_k^T.H_k + P_{k/k-1} \qquad \text{---------} (2.16)$$

(iii) Element v_{ii} replaces element P_{ii} if v_{ii} is greater than P_{ii}.

(iv) Elements of the bias vector b_k are subtracted from corresponding elements of $X_{k/k-1}$ to give bias free predictions of the measured variables.

Results produced by Coggan and Wilson have demonstrated the ability of the procedure to deal with model bias and divergence of the filter. The procedure has its drawbacks in cases where parameters are required to be estimated along with state variables. In this case the bias vector, b_k, can not be used to produce a bias free state as this deviation is the driving force required to drive the parameters to their " true " values. A further limitation is that the method can in no way take into account deviations of the unmeasured variables, although correction of the measured variables will go some way to limiting the bias element of these variables on estimation.

Two recent developments in the area of adaptive filtering have been proposed by Jazwinski (2.70) and Kilbride-Newman (2.71). Jazwinski essentially combines the methods proposed in reference(2.66) and reference (2.60). He proposes using a low frequency random forcing function to represent the model error. The estimator tracks this random forcing function, as well as the system state, thus adapting to any observable model or enviromental variations. The model for the random forcing function is a polynomial with random, time-varying, coefficients which allows adaption to almost any model or system variation. This is in direct contrast to the parametric structure proposed by Friedland (2.66) which can often lead to the identification of the wrong parameters, since any parametric representation is a finite one.

Jazwinski models his system thus;

$$X_{k+1/k} = A_k.X_{k/k} + G_k.u_k \quad \text{--------} \ (\ 2.16\ )$$

where u_k represents the low frequency random forcing function and G_k represents the matrix of noise correlation.

The vector u_k is incorporated into an augmented state vector for estimation within the Kalman Filter.

The disadvantages of the proposed method are that, as in (2.60), the matrix G_k has to be specified a priori, and this assumes a knowledge of the system which is in itself contradictory. The other disadvantage lies in the extra computation required. The extended Kalman Filter consists of five matrix recursive equations (equations 2.4 to 2.8) whereas the method of Jazwinski increases this to eighteen matrix recursive equations. Even counting for the fact that some of the relations are partitioned to discard the statistics of the forcing functions the increase in computation load is significant.

Kilbride-Newman (2.71) uses a similar model formulation to that of equation 2.16. The differences in his procedure are (a) the method of computation of the vector u_k and, (b) the matrix G_k becomes a noise incidence matrix and is itself adaptively estimated so that no a priori knowledge of the system is required, apart from the inaccurate model and the system statistics. The method uses an exponential filter on the mean and covariances of the residuals to estimate the mean, u_k, and the covariances of the fictitious inputs, Q_k. This is similar to the approach adopted by Coggan and Wilson (2.67) but has the advantage that it can also be used for estimating parameters of the system. This is due to the fact that the mean of the fictitious disturbances, u_k, is not updated at each time interval and therefore the mean of the fictitious inputs is only conditioned on the error remaining due to the poor model.

The disadvantage of the method is in the computation of the optimum G_k matrix. If the system is of large dimension, then because the G_k matrix is updated every N time increments, it may take a considerable time to reach the optimum. During this time, of reaching the optimum, there may be some doubt about the accuracy of the estimates produced and divergence could still possibly occur. A further disadvantage lies in choosing the optimum value of N. To date experiments continue to improve these points regarding the mechanics of implementation.

2.2 Heat Transfer Survey.

2.2.1 Introduction.

Heat transfer equipment, in its many diverse forms, is an integral part of practically all chemical and industrial processes. Accordingly, a large amount of research effort has been expended in the study of its dynamic and steady state characteristics for use within the area of equipment and control system design. Developments in the area of power generation from nuclear reactors and desalination processes have provided extra incentive for this field of research.

Because of the nature of the experimental equipment under study in this thesis consideration must be given to previous research carried out not only with evaporator systems but also heat exchangers of the shell and tube variety, in particular to researchers who have used for experimental purposes two phase mixtures for one of the heat transfer media.

2.2.2 Characteristics of Steady State Behaviour.

Over the last decade a large body of experimental data and associated theoretical treatment on two phase, vapour-liquid flow in relation to heat exchange equipment has appeared in the literature. The majority of this work has been concerned with correlations and predictions of various aspects of the design of heat exchange equipment, in particular the prediction of individual heat transfer coefficients. From these individual heat transfer coefficients an overall heat transfer coefficient for the equipment under study can then be computed. Examples of this type of work are to be found in publications by Kay and London (2.72), Kern (2.73), McAdams (2.74) and Collier (2.75). The results published for computing heat transfer coefficients are usually of a complicated form, being given as a function of design geometry, flow dynamics, physical properties etc.. Starczewski (2.76) in a recent publication provides experimental evidence to show the change of heat transfer coefficent with position in the heat transfer equipment, adding yet a further complication to an already difficult calculation.

Evaporator studies have received much attention for a large number of years, the earliest publication appearing in 1899 with Kestners original patent application, (2.77), for a climbing film evaporator. The first quantitative data was published by Brooks and Badger (2.78) in 1937. They produced a correlation for predicting heat transfer coefficients from their experimental results for a water/steam system. The correlation was of the form;

$$\frac{U.V^{0.27}}{M^{n}} = f(\triangle T_{av.}) \quad \text{---------}(2.17)$$

where U equals the overall heat transfer coefficient in Btu/hr.ft^{2}.^{0}F

M and V are the liquid feed and vapourisation rates respectively in lb./hr.

$\triangle T_{av.}$ is the average temperature difference driving force in the boiling section of the evaporator in ^{o}F.

and n is a function of $\triangle T_{av.}$

The function $f(\triangle T_{av.})$ is obtained graphically.

The results obtained from the above equation were unrealistic for two reasons; (i) The authors divided the evaporator into a preboiling and boiling zone which they identified by means of a temperature profile. This division is not necessarily true as boiling has been found to occur in the lower region by Stroebe et al. (2.79).

(ii) The temperatures required for the correlation were obtained using centrally located thermocouples in the tubes. These temperatures are not normally obtainable and do not take into account the radial temperature profile.

Stroebe et al. (2.79) themselves produced a correlation for predicting the heat transfer coefficent of the form;

$$h_b = \frac{7.8 \times 10^6 \times V^{.1}}{(N_{Pr})^{.3} \times \sigma^2 \times (\triangle T_L)^{.13}} \quad \text{-----------} \ (2.18)$$

where V equals the specific volume of vapour in $ft^3/lb.$,

N_{Pr} equals the dimensionless Prandtl Number,

σ equals the surface tension in dynes/cm.,

$\triangle T_L$ equals the difference between the average tube wall temperature and the average liquid temperature in $^oF.$,

and h_b equals the film heat transfer coefficient for the boiling material in Btu/hr.ft.^{2} ^oF.

They overcame the problems previously stated by feeding liquid in a boiling condition to the tubes. The correlation has the advantage of taking the physical properties of the liquid into account in the tubes of the evaporator. The main disadvantage of the correlation is that it fails to recognise the importance of the liquid feed rate in calculating the heat transfer coefficient. This variable has been shown to be highly significant by several workers, e.g. Gupta and Holland (2.80), Coulson and Mehta (2.81) and Starczewski (2.76).

Gupta and Holland (2.80) proposed a correlation for predicting heat transfer coefficients for water systems of the form;

$$q/A = \psi . M^{0.6} + 90.3 \times (T_b - T_i) . C_p \quad \text{--------} \ (2.19)$$

where q/A equals the heat flux in Btu/hr.^oF,

M equals the liquid feed rate in lbs./hr.,

T_i equals the temperature of the feed in $^oF.$,

T_b equals the boiling temperature in $^oF.$,

C_p equals the heat capacity per unit mass in Btu/ lb.$^oF.$,

and ψ equals a graphically read function of the temperature driving force.

Although no account is taken of the physical properties of the feed stream the correlation was also found to accurately predict heat transfer coefficients for other physical systems.

When the feed enters at its boiling point equation 2.19 reduces to;

$$q/A = \psi M^{0.6} \qquad \text{------------} \; (2.20)$$

and thus

$$U_b = \frac{\psi M^{0.6}}{\triangle T} \qquad \text{------------} \; (2.21)$$

Equation 2.21 was found to predict U_b, the overall boiling heat transfer (Btu./ hr.ft.^{2} ^oF.), to an accuracy given by a standard deviation of 2.85%.

Duckler et al. (2.82) and Beveridge et al. (2.83) have written mathemematical models for evaporation systems within flow-sheeting computer programs. They conclude in their works that heat transfer correlations of the type discussed above are of little value in accurate design studies for the following reasons; (a) The correlations are very much equipment and system dependent. (b) The correlations are not of sufficiently high accuracy. (c) Some of the parameters required in the correlation are difficult if not impossible to precompute for design purposes. Beveridge et al. (2.83), in their work, divide the evaporator tubes into six distinct regions for heat transfer. Each region requires an accurate prediction of the film side heat transfer coefficient to be computed. For example in the region defined as sub-cooled boiling the authors use a correlation derived by Bergles and Rohenson (2.84) and in the region defined as nucleate boiling the correlation derived by Chen (2.85). Not only does the model have to account for these different correlations in different regimes but also the point of transition from one regime to the next.

The general inaccuracies of the first type of correlations discussed, along with their system dependence, and the complexities of the approach suggested by Beveridge et al., make all the steady state correlations either difficult or dubious for use in dynamic modelling exercises.

2.2.3 Characteristics of Dynamic Behaviour.

The study of the dynamics of heat exchange equipment has recieved considerable attention over the past thirty years. Because of the many diverse types of equipment and the different forms of disturbances that the equipment can undergo the number of papers in the area is considerable.

The models for transient behaviour of heat exchange equipment can be broken down into two main types;

(i) Frequency response analysis,

(ii) Models based upon the physical laws governing the process.

The frequency response method consists of measuring the response to a known disturbance to the system and then fitting a transfer function to this output response. Using the displaced cosine pulse function technique Lees and Hougen (2.86) evaluated the dynamics of a tube and shell heat exchanger and Cohen and Johnson (2.87) contributed the dynamic analysis of a concentric tube unit. This technique is very limited in that only one output can be tested, i.e. single output / single input and the output required must be available in a measured form. The technique is therefore of very little value in model building for complex processes.

Models based upon the physical laws governing the process have in general been written for use within control systems and control system design. The models are very similar in approach, the difference in the publications lies in the type of disturbance applied to the system and the assumptions made in order to gain a solution of the model and hence the output response.

The model for a heat exchanger based upon the physical laws governing the process requires the solution of a set of partial differential equations, with the outlet temperature as the dependent variable and the independent variables being time and position along the exchanger tubes.

Early publications in this field by Mozley (2.88), Rizika (2.89) and Takkahashi (2.90) were limited in their solution due to a lack at this time of digital computers of high speed and accuracy. In order to gain any form of solution the partial differential equations produced by an analysis of the exchanger required unrealistic assumptions, e.g. constant physical properties and heat transfer coefficients, as well as the conversion of the model from a distributed to a lumped parameter form. Comparison of these results with experimental data proved unsatisfactory especially for large system disturbances. A further disadvantage of the model was that due to the assumption of well mixed fluids existing on each side of the exchanger tubes the model gives identical results for both co-current and counter-current exchangers.

Stermole and Larson (2.91) produced a very complicated distributed parameter model which included besides the main flow streams the effects of the heat capacities of the exchanger walls and tubes. The model has also been used and extended for results published by Privett and Ferrell (2.92) and Imeada et al. (2.93). The model obtained is extremely complicated and for its use relationships for the heat transfer coefficients require specification. The authors assume that the Dittus-Boelter correlations, which they prove apply at steady state, can also be used in the transient state. In two different solutions of the model the heat transfer coefficients are assumed to be functions of (a) the average bulk temperature and flow rate and (b) a function of flow rate only. The resulting models were solved using Laplace transformations and only the first which used a heat transfer coefficient of average bulk temperature and flow rate proved satisfactory. Attempts to simplify the model further using linearisation by perturbation techniques proved unsuccessful. Stainthorp and Axon (2.94) used a similar model formulation as that above for a steam heated exchanger, with variable tube passes allowed for in the model. As the system was steam heated some of the restrictive assumptions applied by the other workers could now be used with justification and the results produced by the authors verify this point.

Korol'kov (2.95) and (2.96) attempted to show the non-applicability of lumped parameter models to heat exchanger dynamics. He uses a complicated partial differential equation model as a standard reference to compare the results from both lumped parameter models and models based on assumptions for solution of the standard model. These models he shows to be inadequate due to the difference in output response with the standard model. In view of the assumptions made by the author in order to gain a reference solution it is thought that some experimental verification of the model should have been made in order to give greater credence to the conclusions drawn. Finlay and Smith (2.97) use a similar technique to that of Korol'kov but do in fact verify their standard reference model with experimental data prior to comparison. They also show when the simplified models can be applicable and the relative accuracy of the results produced.

Koppel (2.98) attempts to remove some of the inaccuracies caused by linearisation of the partial differential equations by substitution of a temperature normalised variable for the temperature prior to linearisation and solution by Laplace transformation methods. The advantage is that the normalised equation is no longer very dependent upon small variations in the ratio of heat exchange to heat capacity and hence the heat transfer coefficient. Koppel showed the advantage of this approach by comparison with experimental data. For small variations or disturbances the approach showed an improvement on previously mentioned techniques but for larger disturbances the model predictions proved inaccurate.

Myers et al. (2.99) realises the inaccuracies that are caused by transforming the distributed parameter model to a lumped form. Knowing the initial and final temperature distributions in the axial direction of the heat exchanger they assume that this will also exhibit itself during the transient period. They then use this assumption to simplify thedistributed parameter model and obtain a transient solution. With evaporators and condensers the assumption is more justified as the temperature of one of the fluids remains constant and the results produced by the authors verify this point. The results for heat exchangers depend to a great extent upon the wall capacity of the exchanger under examination. If the capacitance is large the model gives accurate results but for small capacitance the model predictions are inaccurate.

Dorri (2.100) in a theoretical treatment of an evaporator reduced the set of partial differential equations to a set of ordinary differential equations by the use of Hermitian polynomials to approximate the dependence of temperature upon axial position. The resulting equations are then easily solved using an analogue computer. The results produced although mathematically sound are not verified by the author with experimental data.

Schoenberg (2.101) in a theoretical and experimental study of a single tube condenser concluded that predicted responses from a mathematical model of this type of process were very sensitive to the heat transfer coefficients and the temperature drop across the tube and shell. His mathematical model was based upon approximating the fundamental dynamic phenomena rather than attempting a rigorous solution of the partial differential equations governing the condenser.

The model consists of eight ordinary non-linear differential equations and includes such assumptions as constant overall heat transfer coefficient based upon the average temperature of the condensing fluid at initial and final steady state. The model is linearised for small perturbations and solved by the the Laplace transform method. As the disturbances to the system are small the linearisations and assumption of constant heat transfer coefficient are valid.

Schoenberg's results show that in the initial stages of the transient regime the model accurately predicts the experimental results but at later stages the error begins to increase and exert what can be classified as bias. The author attributes this discrepancy to a time lag in the vapour-liquid interface which he fails to account for in his mathematical model.

2.2.4 Dynamics of Evaporator Systems.

Research carried out into the dynamics of evaporator systems has been primarily concerned with the prediction of outlet concentration of a required product from the evaporator system under study. Because of the nature of the equipment under study heat transfer dynamics are secondary factors in this work. The reasons for this are;

(i) The time constants associated with the dynamics of the heat transfer processes are very much smaller than those associated with the dynamics of the concentration processes.

(ii) The pressure and hence temperature in most evaporation equipment is controlled.

These reasons make valid the assumptions that the dynamics of the heat transfer processes can be ignored and that any change can be considered as a step change.

Zavorka et al. (2.102) have derived a mathematical model for multiple effect evaporation systems used in the sugar industry. The model using the assumption discussed above regarding the temperature dynamics was used in the design of control systems for the equipment. Burdett and Holland (2.103) derived a mathematical model for a seventeen effect system for desalination processes. The model, again using the assumption discussed above, contained 380 non-linear equations in 380 unknowns. The authors show experimental results to demonstrate the accuracy of the model over large time spans and for large process disturbances.

The most complete work in this area has been presented by workers from the Department of Chemical and Petroleum Engineering, University of Alberta, Canada. Workers in this department (2.104, 2.105, 2.106, 2.107 and 2.44) have researched into the dynamics of a pilot plant double effect evaporator. The initial publication by André (2.104) was concerned with the modeling of the evaporator and reduction of the model to an order suitable for on-line implementation. The work has developed through control system design (2.105), on-line parameter and state variable identification (2.44) to finally computer control (2.107).

CHAPTER THREE.

Chapter 3. Equipment Description.

3.1 Introduction.

On-line estimation requires the linking of the physical system under study to the computer so that measurement data can be obtained and processed as required.

The physical process studied in this thesis was a double effect evaporator using a water / steam system. The evaporator was linked by use of an MPD 200 Data Logging system to a Honeywell H316 Computer. The evaporator process was situated approximately one hundred feet away from the computer with the analogue signals generated by the process instruments being transmitted via cable.

A schematic representation of the system is shown in Figure 3.1.

3.2 Double Effect Evaporator.

3.2.1 Description of the Evaporator.

The evaporator process consists of two stages, a climbing film first stage and a forced circulation second stage. The system operates under an applied vacuum. A schematic diagram of the evaporator is shown in Figure 3.2 with Figures 3.3 and 3.4 showing front and rear views of the evaporator system.

The liquid feed to the system is by gravity from a header tank, situated some twenty feet above the process, to the tube side of the preheater. The liquid is heated before passing to the tube side of the first effect. Steam is passed to the shell side of the first effect resulting in boiling of the tube contents. A two phase mixture leaves the first effect tubes and passes to a cyclone for separation. The liquid phase passes on to the second effect and the vapour passes firstly to the preheater shell and secondly to the second effect shell where in both cases a proportion of the vapour condenses. The liquid from the cyclone enters the second effect separator.

FIGURE 3.1 SCHEMATIC REPRESENTATION OF THE EXPERIMENTAL SYSTEM.

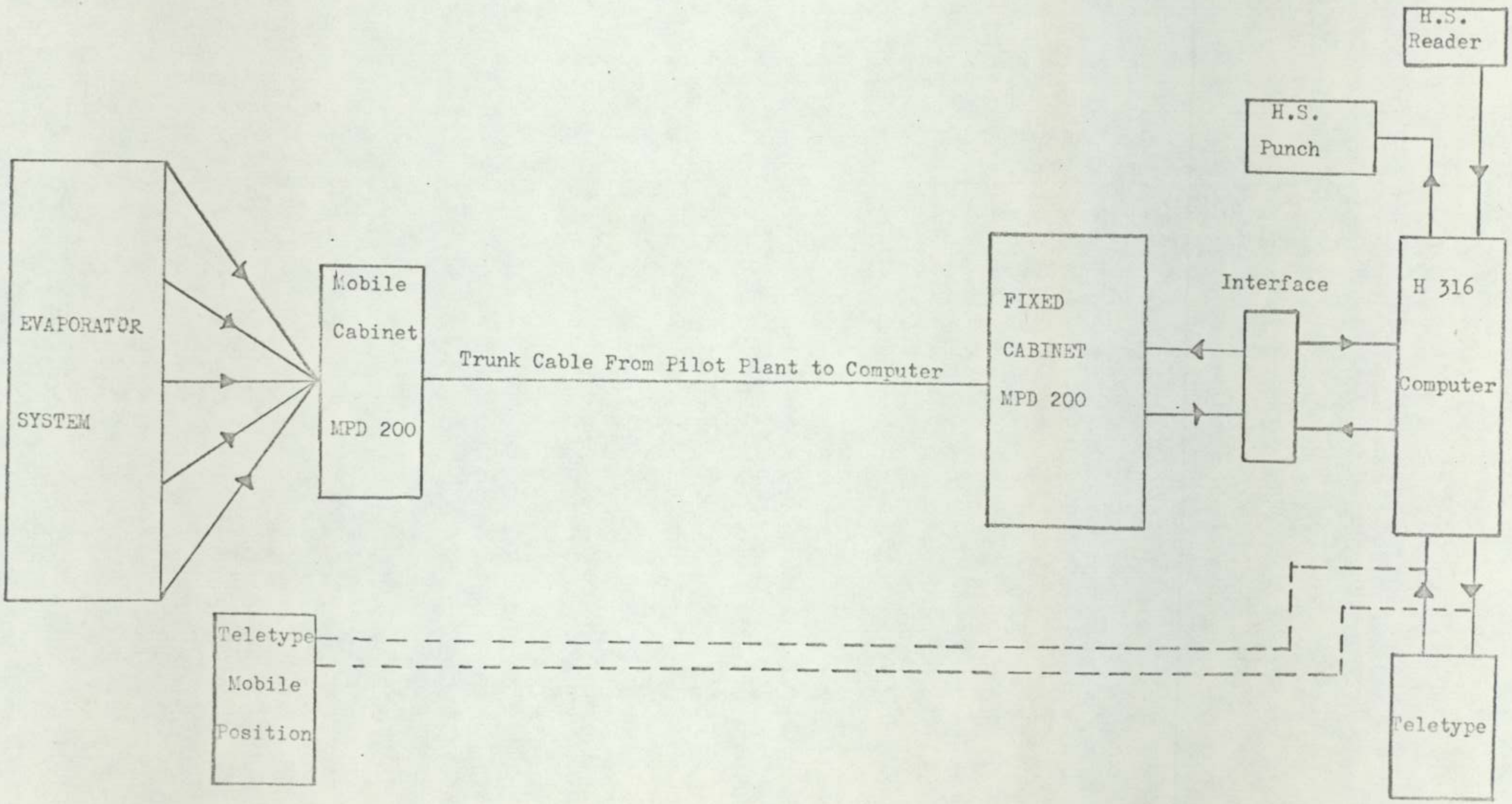


FIGURE 3.2 DOUBLE EFFECT EVAPORATOR.

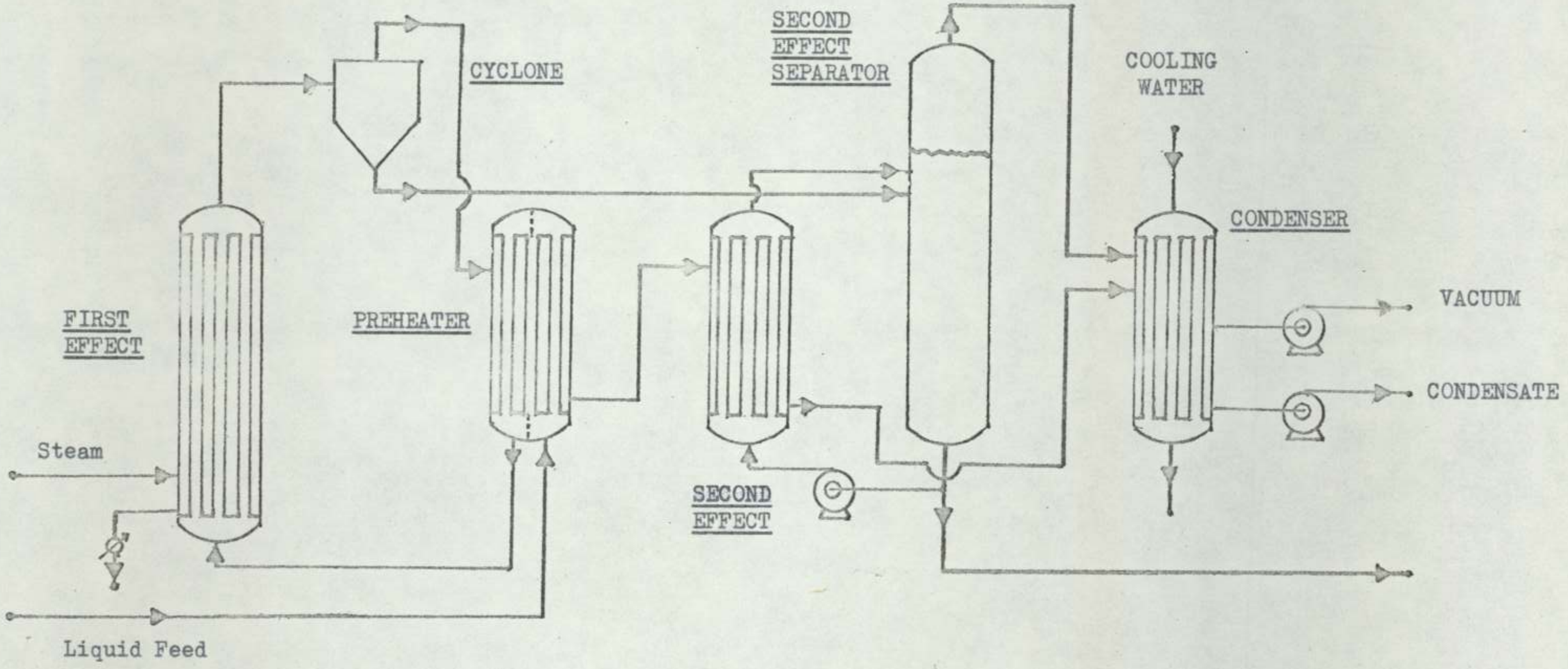
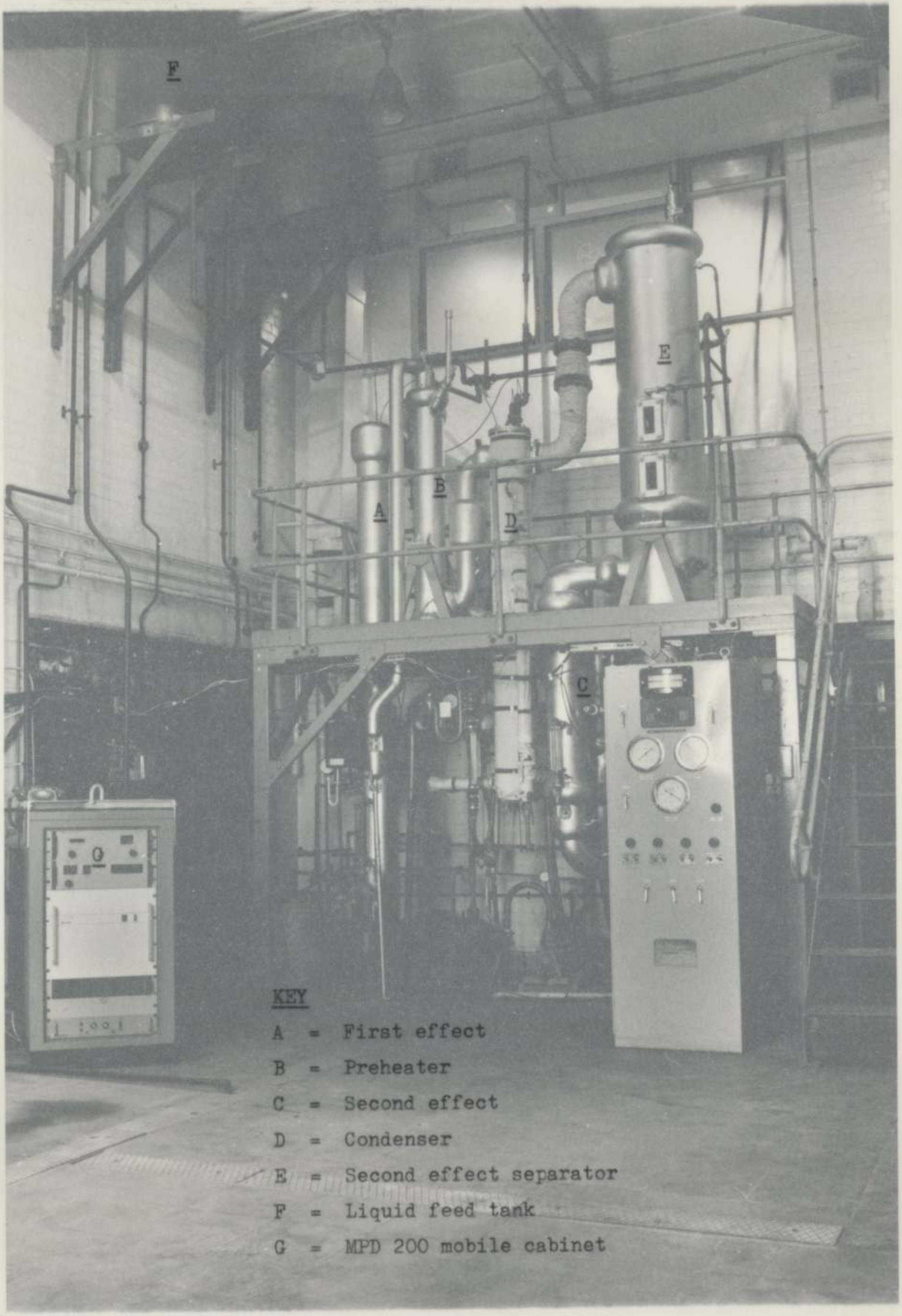


FIGURE 3.3 DOUBLE EFFECT EVAPORATOR.



KEY

A = First effect

B = Preheater

C = Second effect

D = Condenser

E = Second effect separator

F = Liquid feed tank

G = MPD 200 mobile cabinet

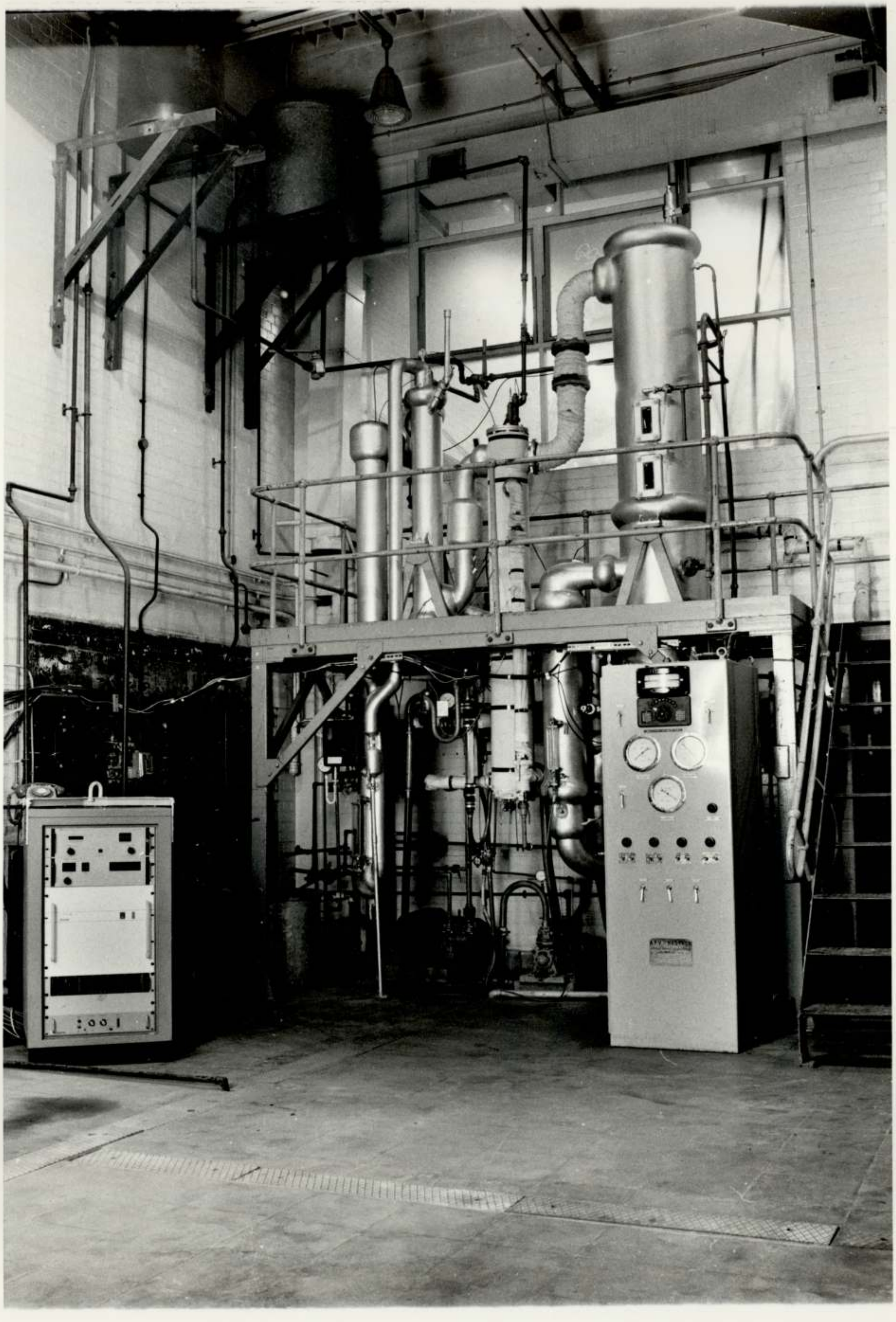
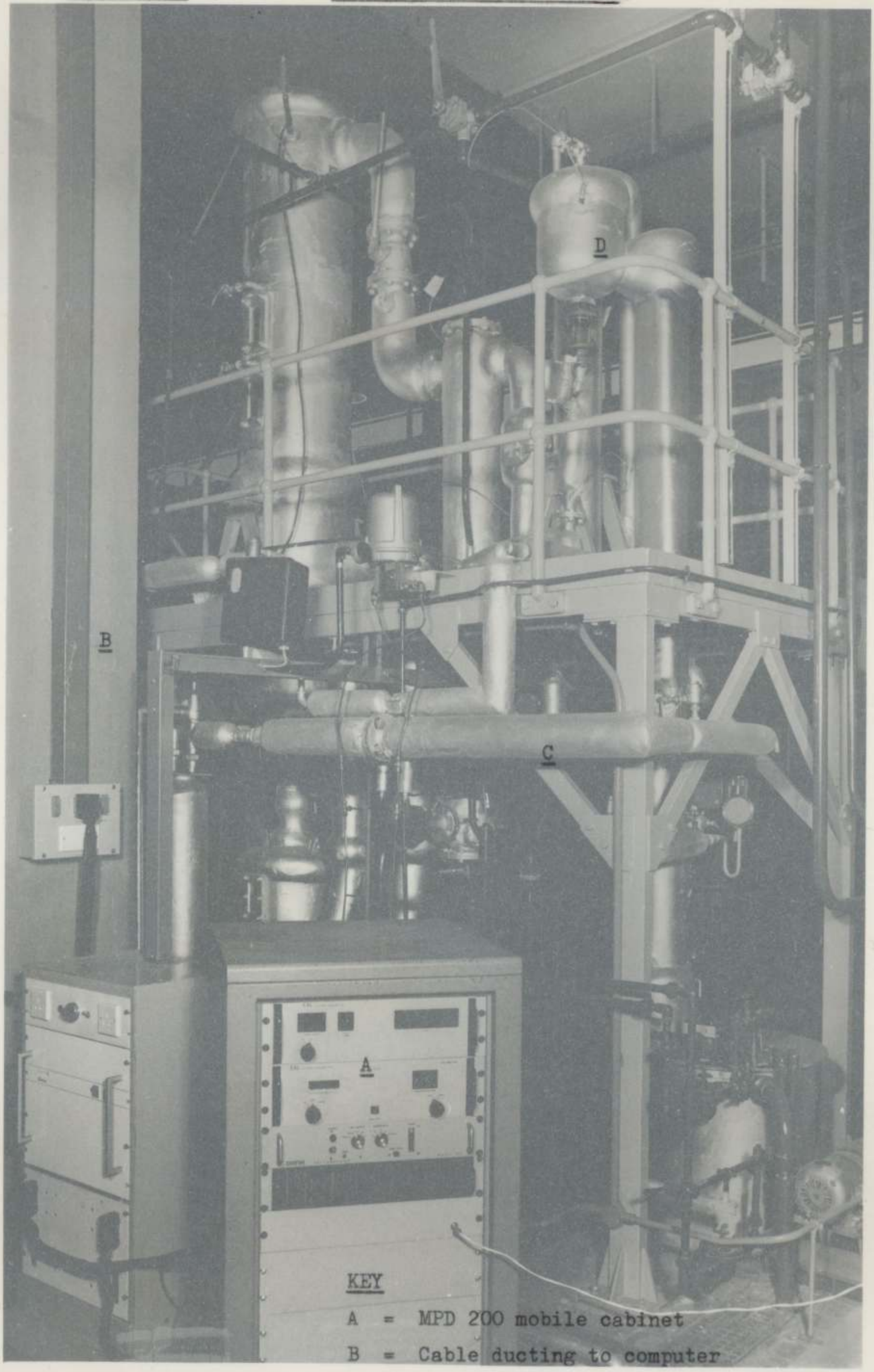


FIGURE 3.4 DOUBLE EFFECT EVAPORATOR.



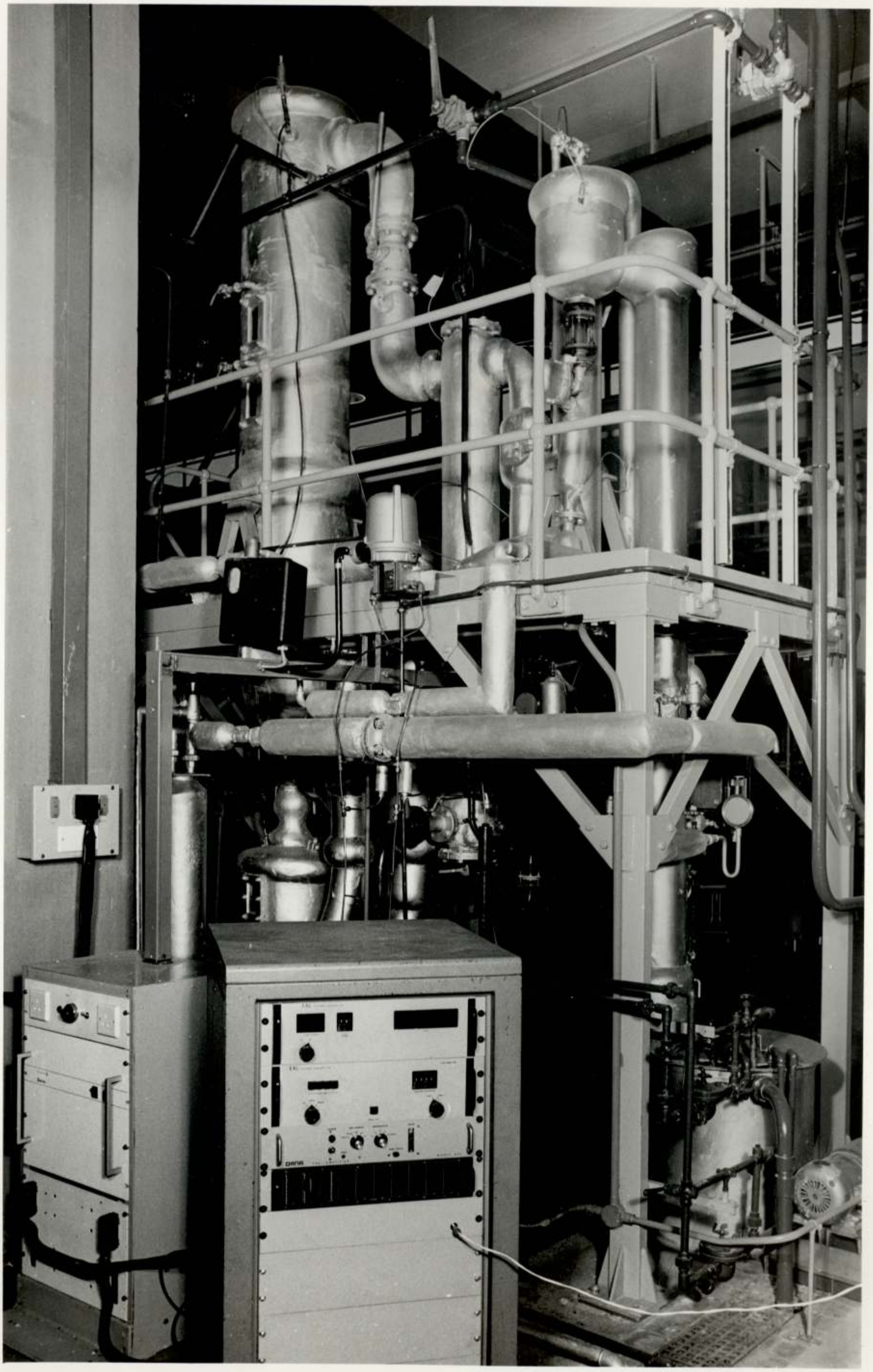
KEY

A = MPD 200 mobile cabinet

B = Cable ducting to computer

C = Steam feed to first effect

D = Cyclone separator


DANA

The second effect acts as an external calandria to the second effect separator with liquid being force circulated by means of a centrifugal pump through the tubes of the second effect. Vaporisation of some of the contents of the second effect separator occurs with the vapour passing into the condenser to-gether with the two phase mixture from the second effect shell. Condensation of all of the vapour entering the shell occurs with the heat being removed from the system via cooling water circulating in the condenser tubes. The condensate from the condenser shell is removed by means of a positive displacement pump acting through a vapour trap. Vacuum is applied to the system through the shell of the second effect.

The physical dimensions of the system heat exchangers and materials of construction are listed in Table 3.1.

3.2.2 Operating Procedure.

When starting up the evaporator the following procedure is adopted;

(i) The liquid feed header tank is filled with water.

(ii) Cooling water to the condenser tubes and pumps is turned on.

(iii) A level of approximately 50% is established in the second effect separator using the specially installed lines direct from the liquid feed header tank.

(iv) Liquid feed from the header tank to the preheater tubes is established at the required level. This flow is to fill the tubes of the preheater and the first effect.

(v) The condensate pump is started and primed prior to starting the vacuum pump.

(vi) When a satisfactory vacuum has been established within the evaporator system the second effect circulating pump is started.

(vii) Steam is established at the required level to the first effect shell. The various vapour traps in the condensate line from the

Table 3.1 Physical Dimensions of the Evaporator System Heat Exchangers.

	Preheater	First Effect	Second Effect	Condenser
Exchanger Type	2:2	1:1	1:1	1:1
No. of tubes	4	4	7	6
Material of tubes	Copper	Copper	Copper	Copper
Tube length (cm.)	141.6	259.0	106.5	219.7
O.D. tube (cm.)	2.22	2.22	2.86	2.87
Wall thickness (cm.)	.165	.32	.32	.33
Mass Tubes (grm.)	4910.2	8192.2	8922.2	14949.6
Int. Vol. Tubes (cm^3)	1593.3	2918.5	3946.8	6613.1
Shell length (cm.)	139.7	259.0	106.5	219.7
Wall thickness (cm.)	.34	.476	.681	.476
I.D. Shell (cm.)	10.16	10.16	15.24	15.57
Vol. of Shell (cm.)	7779.0	16938.4	15100.4	41765.4
Mass of Shell (gm.)	22303.8	36442.7	13452.1	37606.9
Material of Shell	Mild Steel	Mild Steel	Mild Steel	Mild Steel
Heat transfer area (cm^2)	3955.5	7237.6	7063.2	11834.1

first effect shell are opened to bleed the air pockets from the steam system.

(viii) During the start up period constant checks are made to ensure that a satisfactory vacuum is being maintained within the system.

On closing down the evaporator system the following procedure is adopted;

(i) Steam is shut off to the first effect and the shell is allowed to drain.

(ii) The second effect circulating pump and the vacuum pump are closed down and air is allowed to enter the system at the vacuum pump suction point to allow the evaporator system to return to atmospheric pressure.

(iii) Liquid feed from the header tank to the preheater tubes is closed off.

(iv) The second effect separator is drained.

(v) The condensate pump is closed down when the condenser shell is emptied of liquid.

(vi) The cooling water to the pumps and condenser tubes is closed down.

During operation a check has to be made at regular intervals of the level in the second effect separator. This is due to the fact that there is no liquid take off from the separator and at particular operating conditions the separator level will rise. The liquid feed tank is refilled at regular intervals during the experiment.

3.3 MPD 200 Data Logging System.

The MPD 200 Data Logging System presents data from the physical system to the computer and its position within the equipment scheme is shown in Figure 3.1. The MPD 200 system comprises the following main items;

(i) Mobile Cabinet.

(ii) Fixed Cabinet.

(iii) Interface between the fixed cabinet and the H316 computer.

The mobile cabinet is situated beside the evaporator (see Figures 3.2 and 3.3) and is connected to the fixed cabinet by cable. The fixed cabinet is situated in the computer suite and is connected via the interface to the H316 computer.

3.3.1 Mobile Cabinet.

Electrical analogue signals from the instruments of the evaporator system are fed directly into the rear of the mobile cabinet.

The main items of hardware associated with the mobile cabinet are;

(i) A scan identification data switch which allows manual entry of data to the computer when analogue signals are not available from required instruments.

(ii) Sense switches which are linked directly to the sense switches of the H316 computer and are used for program control.

(iii) A Digital Visual Display which allows the user to display the required analogue signal of a particular instrument.

(iv) A Channel Selector and Amplifier. The channel selector unit receives a signal from the fixed cabinet indicating the instrument reading required by the computer. The channel selector connects the instrument to a high gain amplifier. The gain of this amplifier is either set manually, for each instrument, by means of a patch panel or else via the computer. In this research the gain was set manually, the gain being such that the output analogue signal from the amplifier was in the range -10 to 0 volts. This output signal is transmitted back to the fixed cabinet by banks of reed relays along trunk cabling.

3.3.2 Fixed Cabinet.

The main items of hardware associated with the fixed cabinet are;

(i) A clock which provides the time in hours, minutes, seconds and tenths of seconds with the hours and minutes displayed on a digital display. The clock has two modes of operation, either twenty-four hours repeating or thirty hours. The time can be read by the computer, if required, in two halves. The first part being the hours and minutes and the second half being the seconds and tenths of seconds.

(ii) A Reed Relay Scanner by which the appropriate reed relays are selected to connect the required instrument output to the amplifier in the mobile cabinet. The current channel being scanned is shown on a digital display.

(iii) An Analogue to Digital Converter which takes the input analogue signal from the amplifier in the range -10 to 0 volts and converts this to its digital equivalent in two forms. The first being the actual digital decimal value which is displayed on the fixed cabinet panel and the second being the binary coded decimal form which is presented to the computer.

(iv) A Differential Buffer which eliminates the difference in the ground voltage which may occur between the fixed and mobile cabinets.

(v) A Buffer Multiplexer which accepts the input command from the H316 computer and decodes the instruction for the data logging system. When the data is collected it is placed in the buffer for transmission back to the computer.

3.3.3 Interface.

The interface between the computer and the MPD 200 Data logger was constructed in the Electronic Workshop in the University of Aston to make compatible; (a) the logic levels, (i.e. the MPD 200 uses a negative voltage for its logic signal and the computer uses a positive voltage.), and (b) the difference in operating speeds, (i.e.

the MPD 200 receives demands for signals from the computer at a speed in excess of that at which it can operate. The interface slows down the speed of these demands.)

3.4 Computer Hardware.

3.4.1 Honeywell H316 Computer.

The Honeywell H316 Computer and its peripherals are shown in Figure 5.3. The following data and information has been abstracted from the Honeywell reference manual (3.1).

The Honeywell H316 Computer is designed for both batch scientific applications and real-time on-line data processing and control. The broad variety of applications both on and off-line includes data reduction, process control, simulation and batch scientific computation.

The computer is a solid-state, 16-bit binary word, general purpose computer with an internally stored program, a 1.6 μs. memory cycle time and a memory expandable from 4 to 16K. The machine has a fully parallel organisation and both indexing and multi-level indirect addressing capabilities. Standard features include a repertoir of 72 commands, an input / output (I / O) bus structure, standard teletype I / O equipment, and a full line of options and optional peripheral devices designed with plug-in modularity.

The overall characteristics of the Honeywell H316 Computer are given in Table 3.4.

The H316 computer uses the DAP-16 symbolic assembly program language for translation of source programs to machine code. The source program languages available to the user are BASIC-16, the Honeywell version of BASIC, and / or FORTRAN.

3.4.2 Peripheral Equipment.

Three items of hardware are used in conjunction with the Honeywell H316 Computer for on-line data acquisition

FIGURE 3.5

COMPUTER HARDWARE AND PERIPHERALS.

A

E

B

C

D

KEY

A = Honeywell H316 Computer
B = High speed punch
C = High speed paper tape reader
D = ASR teletype
E = MPD 200 fixed cabinet

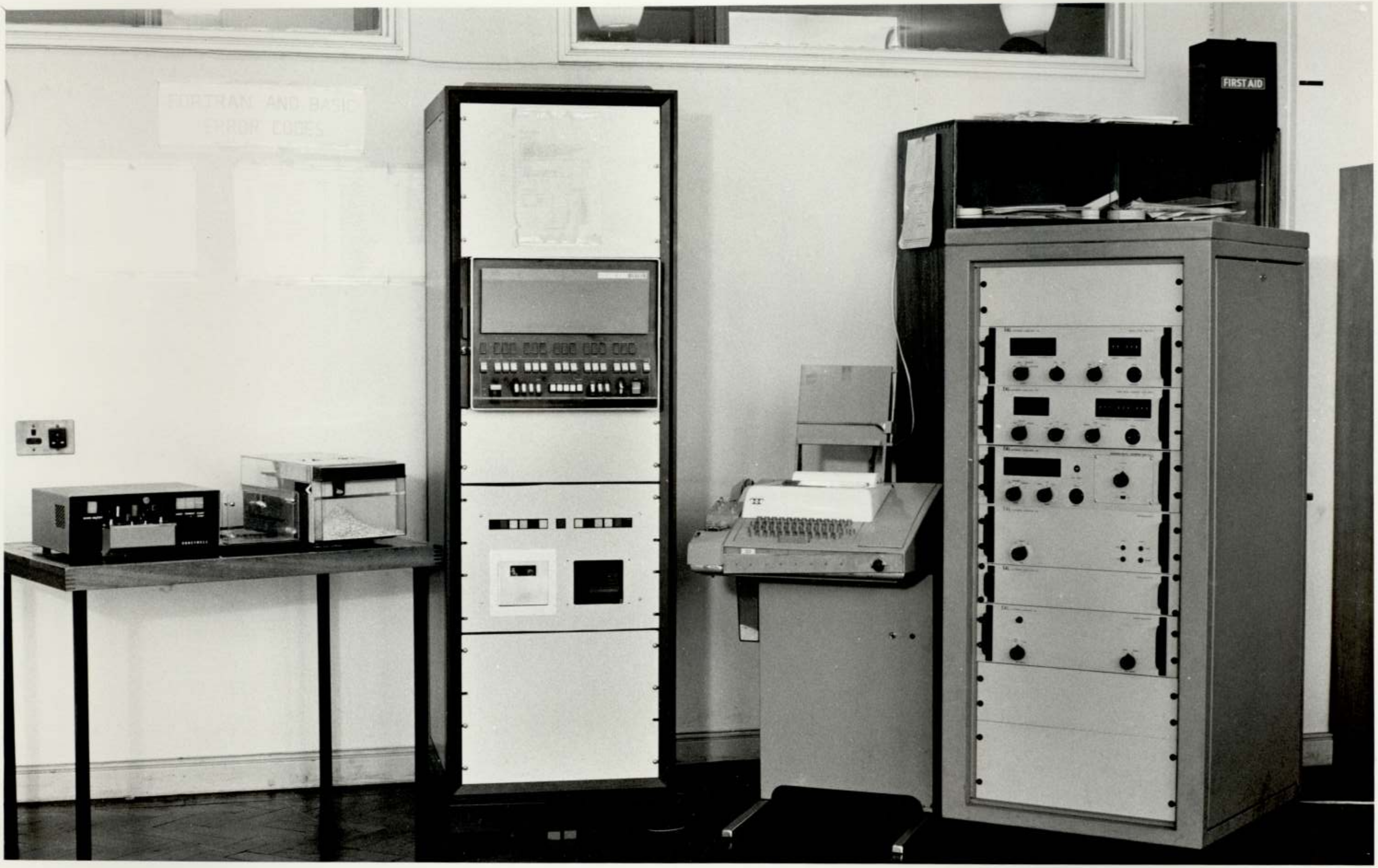

FORTRAN AND BASIC
ERROR CODES
FIRST AID

Table 3.4 Honeywell H316 Leading Particulars.

Primary power	475 watts, 5.5 ampers at 115 vac ±10% at 60 ± 2 Hz.
Type	Parallel binary, solid state
Addressing	Single address with indexing and indirect addressing.
Word length.	16 bits (single precision). 31 bits (double precision).
Machine code	Two's complement.
Circuitry	Intergrated.
Signal levels	Active: 0 volts Passive: +6 volts
Memory type	Coincident-current ferrite core.
Memory size	16K
Memory cycle time	1.6 µs.
Instruction complement	72 instructions.
Speed, Add	3.2 µs.
Subtract	3.2 µs.
Multiply	8.8 µs.
Divide	17.6 µs.
Standard memory protect.	Designed to protect memory data in event primary power fails.
Standard interrupt	Single standard interrupt line.
Input / Output modes	Single word transfer Single word transfer with priority interrupts Data multiplex channel.

Table 3.4 Continued.

Standard I / 0 lines.	10- bit address bus- (4 function code and 6 device address.) 16- bit imput bus. 16- bit output bus, priority interrupt external control and sense lines.
Standard teletype.	Read paper tape at 10cps. Punch paper tape at 10cps. Print at 10cps. Keyboard input. Off-line paper tape preparation, reproduction and listing.
Enviroment	Room ambient for computer less I / 0 devices: 0 to 45°C.
Cooling	Filtered forced air.

a high speed paper tape reader, a high speed paper tape punch and a portable teletype.

The high speed paper tape reader operating at 200 characters per second, is used for entering programs and data into the computer.

The high speed paper tape punch, operating at 75 characters per second, is used for output of programs and in particular the output of data during on-line runs.

The portable teletype, operating at 10 characters per second, is used for entering data in small amounts, for entering small programs into the computer, on-line program corrections and in particular, because of its mobility, used in conjunction with the sense switches on the MPD 200 mobile cabinet for controlling the data acquisition from the evaporator system.

3.5 Computational Aspects of Data Acquisition.

3.5.1 Introduction.

Data from the double effect evaporator is collected via the MPD 200 Data Logging system which is itself controlled by the programed Honeywell H316 computer. The computer program controlling the data collection is written in BASIC in conjunction with the Baseline compiler.

Programming is carried out at four distinct levels;

(i) Basic level for interaction,

(ii) High level (FORTRAN)

(iii) Intermediate level (DAP-16)

(iv) Low level (DAP-16)

Levels 2,3 and 4 are incorporated in the form of subroutines, accessed via the CALL statement in the users BASIC program.

3.5.2 The Baseline Compiler.

A detailed description of the Baseline compiler is given by Payne (3.2) and its use for on-line data acquisation described in (3.3). Baseline is a version of the BASIC-16 compiler which includes subroutines for on-line data acquisition and processing from experiments using the MPD 200 data logging system. The compiler offers the user the following facilities:-

(i) To read the data value on a MPD 200 channel.

(ii) To read the time on the MPD 200 clock.

(iii) To read a data value from the scan identification data switches on the MPD 200 mobile cabinet.

(iv) To test the sense switch settings on the H316 computer or the mobile cabinet.

(v) To scan the MPD 200 data channels at predetermined time intervals using the interrupt facility of the H316 computer.

(vi) To process the data by a BASIC program using all standard BASIC instructions.

Each of these facilities is accessed within a normal BASIC program by use of subroutine call statements as follows:-

(1) The statement CALL(1,N,V,F) causes MPD 200 channel number N to be read and the variable V to be set equal to the current data value on this channel. V will be a four digit value with the decimal point placed at the right hand end of the number (i.e. $0 \leqslant V \leqslant 9999$). The users program must take care of any scaling or conversion factors. The flag F will be set to 1 if N is out of range of the channels of the MPD 200.

(2) The statement CALL(2,H) causes the variable H to be set equal to the current hours and minutes reading of the MPD 200 clock. H will be a four digit value (i.e. $0 \leqslant H \leqslant 2359$) in which the two left most digits represent the hours and the two right most digits represent the minutes, e.g. 1020 represents 10 hours and 20 minutes.

(3) The statement CALL(3,S) causes the variable S to be set equal to the current seconds reading of the MPD 200 clock. S will be a four digit value (i.e. $0 \le S \le 5990$) in which the two left most digits represents seconds, the third digit represents tenths of seconds and the fourth digit is always zero, e.g. 4350 represents 43.5 seconds.

(4) The statement CALL(4,D) causes the variable D to be set equal to the current setting of the scan identification data switches on the MPD 200 mobile cabinet. D will be a four digit value (i.e. $0 \le D \le 9999$)

(5) The statement CALL(5,0) causes the H316 computer clock to stop. This statement is used in association with subroutine 7 when the interrupt facility is being used.

(6) The statement CALL(6,T,X) causes the sense switches on the H316 computer or the MPD 200 mobile cabinet to be tested. If sense switch number T is set, X is set to 2, otherwise X is set to 1.

(7) The statement CALL(7,I,N1,N2,R,A(1),F) causes channels N1 to N2 to be scanned R times and the average to be stored in A(N1) to A(N2). This sequence will be repeated every I seconds ($I \le 655$) through the interrupt facilities of the computer. I.E. the computation in progress will be suspended and resumed after the scans have been carried out. If I = 0 only the first R scans take place and there is no subsequent interrupt. The flag F is set equal to 1 on each exit from the subroutine.

The Baseline compiler can be used for data acquisition in either the non-interrupt or interrupt mode. In the non-interrupt mode subroutine 1 is the principal subroutine and may be used, for instance, in a FOR ----- NEXT loop to read a set of data channels.

e.g.

```
 5 FOR I = 1,10
10 CALL( 1,I,V(I),F )
15 NEXT I
```

Alternatively subroutine 7 may be used with I = 0. Subroutine 2 &

3 may be used to time programs, to initiate scans at predetermined times etc.. Subroutine 4 may be used to input data values not available as analogue inputs or to input a value for program control, e.g.

```
5 CALL(4,D)
10 IF D = 1 THEN GO TO 100
```

Subroutine 6 may also be used for program control via the sense switches.

In the interrupt mode subroutine 7 is the principal subroutine that is used. Once the subroutine has been called in the users program it will automatically be called again every I seconds with the same arguments as the initial call until either subroutine 5 is called or the BASIC compiler returns to the command mode. Subroutine 7 is usually called explicitly only once but may be called again (with different arguments, for instance) provided subroutine 5 is called first. Subroutine 5 inhibits interrupt and is used as above or to stop interrupt during lengthy computation,. input / output of data etc.. It should be noted that the program being executed is suspended on interrupt and resumed after the interrupt has been serviced. Consequently the users program should contain a loop which will " waste " time while waiting for the next interrupt.

3.6 Instrumentation.

3.6.1 Instrument Description.

Four types of instruments are used in conjunction with the MPD 200 Data Logger for supplying analogue values to the computer. These instruments are;

(i) Thermocouples of the Ni/Al, Ni/Cr type (10)

(ii) Differential Pressure cells of the variable inductance type (2)

(iii) Variable inductance flowmeters (2)

(iv) Pressure transducers of the variable resistance type.(1)

Each instrument is connected to a channel of the mobile cabinet. The channels and their corresponding instruments are shown in Table 3.6.1.

The cooling water flowrate is measured using a variable area rotameter. Data from this instrument is entered into the computer manually.

A schematic diagram showing the positions of each of the instruments is shown in Figure 3.6.

3.6.2 Instrument Calibration.

All instruments were calibrated in an on-line situation to take account of the noise and errors introduced through the data logging system, computer and analogue transmission lines. The baseline compiler was used to collect and average analogue signals from a particular instrument corresponding to a known variable. All instruments were assumed to have a linear correlation of the form;

$$Y = A + BX \qquad \text{---------} \; (3.1)$$

where Y = the value of the variable that the instrument reads.

X = the analogue signal generated by the instrument

and A and B are constants.

The individual values of A & B along with the correlation coefficients for each of the instruments are given in Table 3.6.2.

3.6.2.1 Thermocouples.

Data was available from the manufacturer of the thermocouples corresponding to the values of A & B in equation 3.1. This data was checked using a portable electronic thermocouple having an accuracy of $\pm\ 0.1^{\circ}C$.

3.6.2.2 Differential Pressure Cells.

The D.P. Cell used for measuring the steam flow is used in conjunction with an orifice plate. The pressure drop across the orifice plate was measured using a mercury manometer along with the corresponding analogue signal generated by the D.P.

Table 3.6.1 Channel Identification.

Channel No.	Instrument type.	Instrument function.
15	Pressure Transducer	Vapour Pressure, Second Effect Shell.
16	Flowmeter	Liquid flow to preheater tubes
17	Flowmeter	Liquid flow exit cyclone.
18	D.P. Cell	Head in second effect separator.
19	D.P. Cell	Steam flow to first effect.
20	Thermocouple	Temp. Cooling water into condenser.
21	"	Temp. Cooling water exit condenser.
22	"	Temp. liquid into preheater.
23	"	Temp. liquid exit preheater.
24	"	Temp. into second effect tube
25	"	Temp. exit second effect tube
26	"	Temp. liquid exit cyclone
27	"	Temp. liquid exit condenser shell.
28	"	Temp. fluid exit preheater shell.
29	"	Temp. vapour exit cyclone.

FIGURE 3.6 INSTRUMENTATION ON THE DOUBLE EFFECT EVAPORATOR.

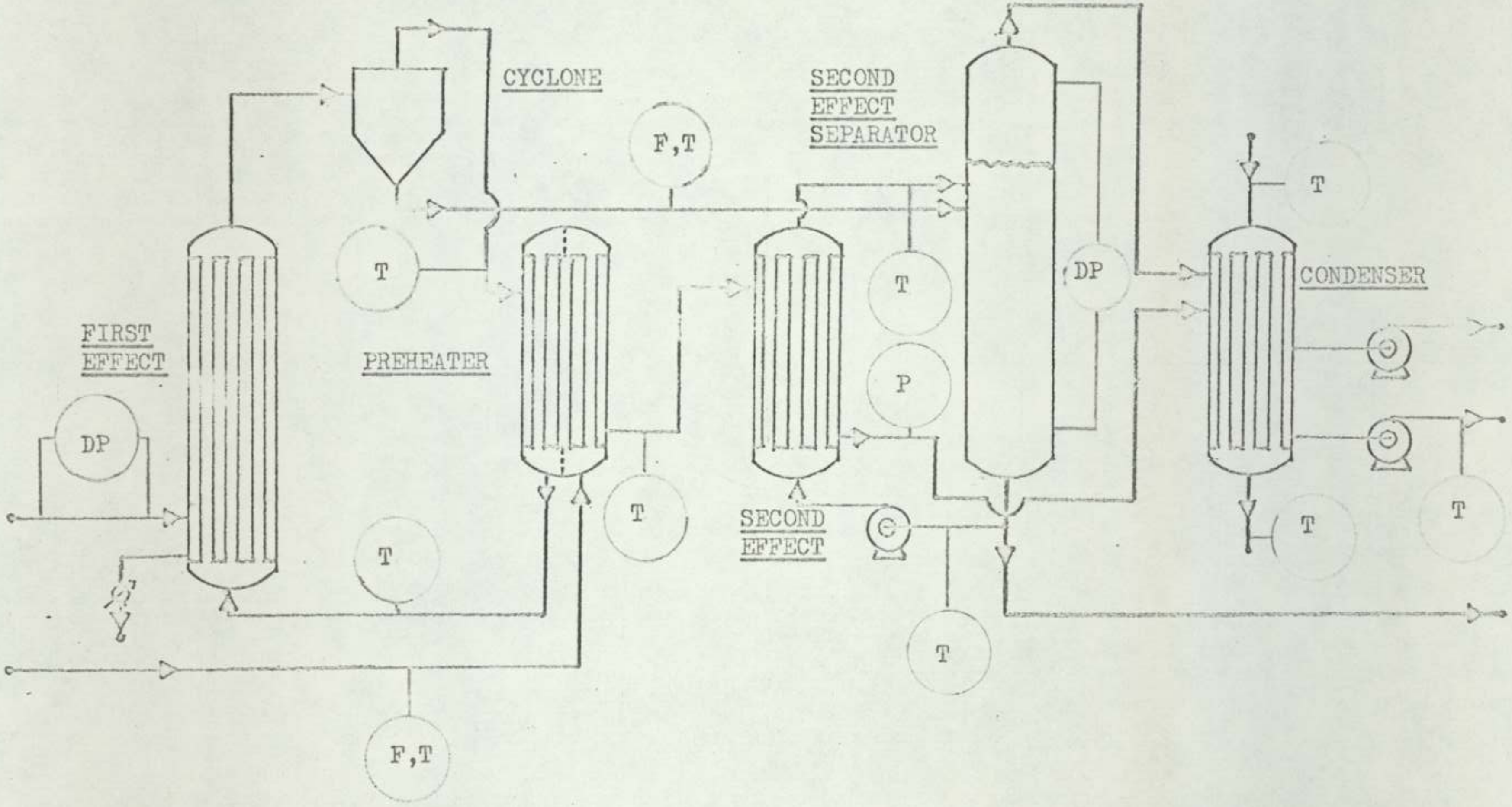


Table 3.6.2 Instrument Calibrations.

Channel No.	Intercept.	Gradient	Correlation Coefficient.
15	-59.0324	-.05214	0.9994876
16	-16.2798	-.00644646	0.9955125
17	3.02299	-.00577411	0.9885055
18	-165.352	-.0416595	0.9994429
19	1.26556	-.00243361	0.9770261
20	0.0	-.025	0.9998424
21	0.0	-.025	0.9998424
22	0.0	-.025	0.9998424
23	0.0	-.025	0.9998424
24	0.0	-.025	0.9998424
25	0.0	-.025	0.9998424
26	0.0	-.025	0.9998424
27	0.0	-.025	0.9998424
28	0.0	-.025	0.9998424
29	0.0	-.025	0.9998424

Cell. The pressure drop across the orifice plate was then used to calculate a theoretical steam flow rate which was correlated against the analogue signals. The correlation was checked by running the evaporator at steady state for a period of time and comparing the predicted steam flows from the correlation with the amount of condensate leaving the first effect shell.

The D.P. Cell used for measuring the height in the second effect separator was calibrated by correlating the analogue signals generated from the instrument against known heights of liquid in the separator.

3.6.2.3 Pressure Transducers.

The pressure transducers were calibrated by correlating the analogue signals generated by the instruments against the pressure drop across a mercury manometer when one of the manometer limbs was connected to the same point of the evaporator system as the pressure transducer.

3.6.2.4 Flowmeters.

The flowmeter measuring the liquid flow rate into the preheater was calibrated by breaking the flow line after the instrument and measuring the liquid flow rate by collection and weighing. This rate was then correlated against the analogue signal generated by the instrument.

This correlation was then used to correlate the flowmeter measuring the liquid flow rate exit the cyclone. The system was operated without steam flowing into the first effect shell. As a result all liquid entering the preheater tubes also left the cyclone along the liquid exit line. The two flowmeters therefore registered analogue signals for an identical flow rate.

CHAPTER FOUR.

Chapter 4. Steady State Analysis of the Evaporator.

4.1 Introduction.

The reasons that steady state analysis are required for the double effect evaporator are as follows;

(i) An analysis of the measurement statistics under operating conditions is required for use within the Kalman Filter.

(ii) An attempt to quantify the heat losses that exist within the system must be made.

(iii) An attempt must be made to quantify the noise on the inputs to the system

(iv) An equation describing the overall heat transfer coefficient for each of the four items of heat exchange equipment must be obtained.

The fourth reason is of particular importance. As has been discussed previously in the literature survey the predicted transient response of outlet temperatures from heat exchange equipment is highly susceptible to changes in the heat transfer coefficient. Methods reviewed in the literature for predicting and correlating heat transfer coefficients were found to be of little value for the following reasons;

(i) The simpler methods were either too inaccurate or else contained parameters that were difficult to obtain directly from the system.

(ii) The more complicated methods were such that real-time computation of the heat transfer coefficients would have been very difficult for the dynamic situation.

It was decided therefore to produce a multiple non-linear correlation relating the overall heat transfer coefficient to the flow and temperature variables of each unit.

Within the evaporator system there is in fact never a situation of true steady state. This is due to the fluctuating level in the second effect separator and the disturbances upon the inputs into the system. Because of the requirement for the steady state analysis it is therefore assumed that even though the level in the second effect separator is changing and the inputs to the system are being disturbed all other variables will remain constant once thermal equilibrium is reached within the evaporator. Examination of the standard deviations of the analogue signals, collected every thirty seconds over a five minute time interval, from the temperature measuring instruments shows the validity of the assumption.

4.2 Mathematical Model.

A schematic diagram of the double effect evaporator along with the stream identification numbers is shown in Figure 4.1. Table 4.1 shows the stream identification numbers, their connections and the phase of the stream present.

The following subscripted variables are used within the model, where the subscript denotes the stream number.

M = liquid flow rate in g / sec.

V = vapour flow rate in g / sec.

T = temperature in ^{o}C.

E = the specific enthalpy of the vapour in J / g.

(where $E = 1.6742 \times T + 2500.8$ (see reference 4.4) ---- (4.0))

The following unsubscripted variables are used in the model;

Cl = the specific heat of the liquid, assumed constant at 4.1868 J / g.^{o}C.

and S4 = the accumulation in the second effect separator in g / sec.

The following assumptions are made;

(i) The specific heat of the liquid in the system is constant and not a function of temperature.

(ii) There is no loss of mass from the system.

(iii) The steam entering the first effect is at a controlled

FIGURE 4.1 DOUBLE EFFECT EVAPORATOR.

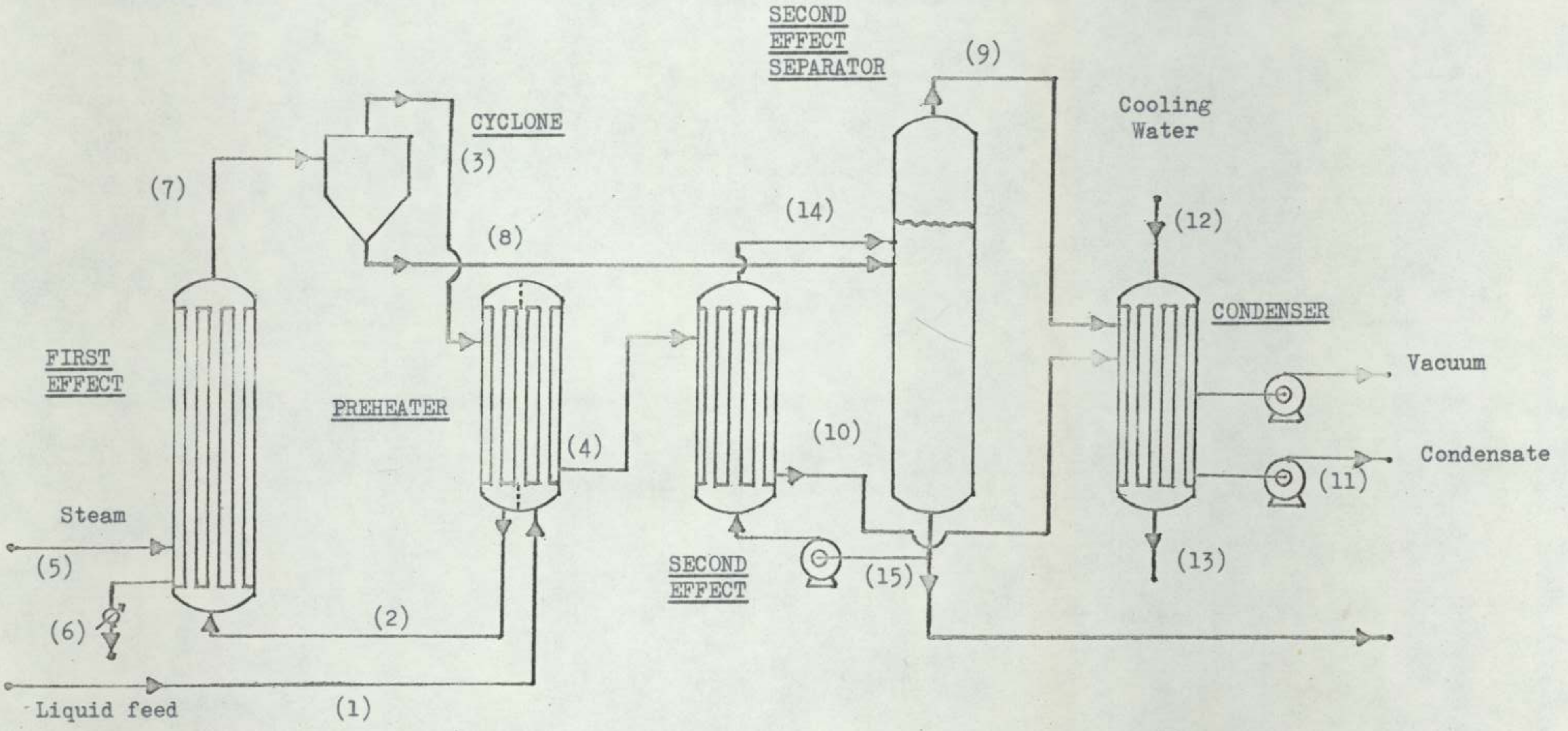


Table 4.1 STREAM IDENTIFICATION.

STREAM	FROM	TO	PHASE
1	-	Preheater Tubes	Liquid
2	Preheater Tubes	First Effect Tubes	"
3	Cyclone	Preheater Shell	Vapour
4	Preheater Shell	Second Effect Shell	Vapour + Liquid
5	-	First Effect Shell	Vapour
6	First Effect Shell	-	Liquid
7	First Effect Tubes	Cyclone	Vapour + Liquid
8	Cyclone	Second Effect Separator	Liquid
9	Second Effect Separator	Condenser Shell	Vapour
10	Second Effect Shell	Condenser Shell	Vapour + Liquid
11	Condenser Shell	-	Liquid
12	-	Condenser Tubes	Liquid
13	Condenser Tubes	-	Liquid
14	Second Effect Tubes	Second Effect Separator	Liquid
15	Second Effect Separator	Second Effect Tubes	Liquid

fixed pressure corresponding to a temperature of 122 °C. The heat transfered from this steam is by condensation alone and all of the steam entering the first effect shell is condensed.

(iv) The cyclone is 100% effective.

Using the assumptions listed above and the nomenclature previously stated the following heat and mass balances can be constructed.

Mass balance over the preheater.

Tubes: $$M(1) = M(2) \tag{4.1}$$

Shell: $$V(3) = V(4) + M(4) \tag{4.2}$$

Heat balance over the preheater.

$$C1.M(1).T(1) + V(3).E(3) = V(4).E(4) + M(4).T(4).C1 + M(2).T(2).C1 \tag{4.3}$$

Mass balance over the first effect.

Tubes: $$M(2) = V(7) + M(7) \tag{4.4}$$

Shell: $$V(5) = M(6) \tag{4.5}$$

Heat balance over the first effect.

$$M(2).T(2).C1 + V(5).E(5) = M(6).T(6).C1 + M(7).T(7).C1 \quad V(7).E(7) \tag{4.6}$$

Mass balance over the cyclone.

$$V(7) + M(7) = V(3) + M(8) \tag{4.7}$$

and using assumption number 4 then;

$$V(7) = V(3) \tag{4.8}$$

and $$M(7) = M(8) \quad \text{--------------} \; (4.9)$$

<u>Mass balance over the second effect.</u>

Tubes: $$M(14) = M(15) \quad \text{---------------} \; (4.10)$$

Shell $$M(4) + V(4) = M(10) + V(10) \quad \text{-----} \; (4.11)$$

<u>Heat balance over the second effect.</u>

$$M(4).T(4).C1 + V(4).E(4) + M(15).T(15).C1 = M(14).T(14).C1 + V(10).E(10) + M(10).T(10).C1 \quad \text{-------------} \; (4.12)$$

<u>Mass balance over the condenser.</u>

Tubes: $$M(12) = M(13) \quad \text{---------} \; (4.13)$$

Shell $$M(11) = V(9) + V(10) + M(10) \quad \text{----} \; (4.14)$$

<u>Heat balance over the condenser.</u>

$$M(12).C1.T(12) + V(9).E(9) + V(10).E(10) + M(10).C1.T(10) = M(11).C1.T(11) + M(13).C1.T(13) \quad \text{------} \; (4.15)$$

<u>Mass balance over the second effect separator.</u>

$$M(8) + M(14) - V(9) - M(15) = S4 \quad \text{---------} \; (4.16)$$

<u>Heat balance over the second effect separator.</u>

$$M(14).T(14).C1 + M(8).T(8).C1 - V(9).E(9) - M(15).T(15).C1 = S4.T(15).C1 \quad \text{----------} \; (4.17)$$

<u>Mass balance over the Evaporator system.</u>

$$M(1) + M(12) + V(5) - M(13) - M(6) - M(11) = S4 \quad \text{----------------} \; (4.18)$$

which by use of equations 4.5 and 4.13 reduces to;

$$M(1) - M(11) = S4 \qquad \text{--------------} \; (4.19)$$

Heat balance over the evaporator system.

$$M(1).T(1).C1 + M(12).T(12).C1 + V(5).E(5) - M(13).T(13).C1$$
$$- M(6).T(6).C1 - M(11).T(11).C1 - S4.T(9).C1$$
$$= \text{HEAT LOSS} \qquad \text{--------------} \; (\ 4.20\ )$$

From the steady state model above the twenty equations reduce to nineteen independent equations containing thirty-four unknown variables. From the evaporator system fifteen direct measurements are available and two indirect measurements. This leaves a redundancy within either the model equations or the measurement system and thus offers several approaches to a solution.

The solution of the model for the purpose of this thesis is as follows;

From the evaporator system the following measurements are available directly to the computer as analogue signals via the MPD 200 Data logging system: M(1), M(8), V(5), T(1), T(2), T(3), T(4), T(8), T(10), T(11), T(12), T(13), T(14), T(15) and S4.

The cooling water flow rate and the condensate flowrate can be measured on the evaporator system and entered into the computer via the portable teletype.

Assuming that the above measured variables are accurate the following variables require calculation using the equations of the model; M(2) M(4), M(6), M(7), M(10), M(11), M(13), M(14), M(15), V(3), V(4), V(7), V(9), V(10), T(5), T(6), T(7) and T(9).

From equation 4.1 then,

$$M(2) = M(1) \qquad \text{------------} \; (\ 4.21\ )$$

Combining equations 4.21, 4.4, 4.8 and 4.9 then,

$$V(3) = M(1) - M(8) \quad \text{-------------} \ (4.22)$$

Equations 4.2 and 4.3 now contain only two unknowns and therefore by direct substitution,

$$M(4) = \frac{C1.M(1).T(1) + V(3).E(3) - C1.M(2).T(2) - V(3).E(3)}{T(4).C1 - E(4)} \quad \text{------------} \ (4.23)$$

and $$V(4) = V(3) - M(4) \quad \text{------------} \ (4.24)$$

From equations 4.8 and 4.9 then,

$$M(7) = M(8) \quad \text{------------} \ (4.25)$$

and $$V(7) = V(3) \quad \text{------------} \ (4.26)$$

From assumption 3 then,

$$M(6) = V(5) \quad \text{------------} \ (4.27)$$

$$T(5) = 122^{\circ}C. \quad \text{---------} \ (4.28)$$

and $$T(6) = 100^{\circ}C. \quad \text{---------} \ (4.29)$$

Assuming that the stream temperature into the cyclone is equal to the stream temperature leaving the cyclone then,

$$T(7) = \frac{T(8) + T(3)}{2} \quad \text{----------} \ (4.30)$$

At this point there are several methods of continuing the solution of the steady state equations. One approach is to continue in the step wise manner as above.

e.g. From equation 4.19 then,

$$M(11) = M(1) - S4 \quad \text{-----------} \; (4.31)$$

and combining equations 4.14 and 4.11 then,

$$V(9) = M(11) - M(4) - V(4) \quad \text{--------} \; (4.32)$$

etc.

This is the approach adopted by Payne (4.1), and allthough the simplest method for implementation it is thought not to be of the required accuracy for the following reasons;

(i) The first step in the solution of the heat and mass balances around the second effect and the condenser uses the measurement of S4. This value was found to be subject to large errors especially at high steam rates when boiling in the second effect separator makes an accurate estimate of the head in the vessel at any instant of time very difficult.

(ii) A step wise procedure does not allow for heat losses that may be occuring from the system.

The following method of solution is therefore proposed. During the experiment an accurate reading of cooling water flow rate, M(12), and condensate flow rate, M(11), are taken. After the analogue signals from all of the remaining instruments have been collected and averaged by the computer these values are then input as data via the portable teletype.

T(9) is assumed to be equal to the bulk liquid temperature in the second effect separator.

$$\text{i.e.} \qquad T(9) = T(15) \quad \text{-----------} \; (4.33)$$

There are now six unknown variables remaining and six equations for solution. The unknown variables are; V(9), V(10), M(10), M(11), M(15), and S4.

The six equations to be solved are as follows;

From equation 4.14,

$$V(9) + V(10) + M(10) - M(11) = 0 \quad \text{------} \; (\, 4.34 \,)$$

From equation 4.15,

$$V(9).E(9) + V(10).E(10) + M(10).T(10).C1 - M(11).T(11).C1$$
$$= M(12).C1.(\, T(13) - T(12) \,) \quad \text{--------} \; (\, 4.35 \,)$$

From equation 4.11,

$$M(10) + V(10) = M(4) + V(4) \quad \text{---------} \; (\, 4.36 \,)$$

From equation 4.12,

$$V(10).E(10) + M(10).T(10).C1 + M(15).C1.(\, T(14) - T(15) \,)$$
$$= V(4).E(4) + M(4).T(4).C1 \quad \text{--------} \; (\, 4.37 \,)$$

From equation 4.16,

$$S4 + V(9) = M(8) \quad \text{-----------} \; (\, 4.38 \,)$$

From equation 4.17,

$$M(15).C1.(\, T(14) - T(15) \,) - V(9).E(9) - S4.T(15).C1$$
$$= -M(8).T(8):C1 \quad \text{-----------} \; (\, 4.39 \,)$$

The right hand side of equations 4.34 to 4.39 contain only known variables, i.e. either measured or previously calculated.

The variable M(11), the condensate flow rate, is included as an unknown in the L.H.S. of the above equations in order to allow an estimate of the heat losses from this section of the plant to be made. This is accomplished by solving equations 4.34 to 4.39 by matrix inversion with the measured value of the cooling water flow rate included in the R.H.S. of the above equations. On solution of the equations a comparison is made between the calculated and measured values of M(11), the condensate flow rate. Any difference between the two values is assumed to be due to unaccounted for heat losses. If the difference between the two values is in excess of the convergence limit set by the programmer then the cooling water flow rate is incremented by a factor corresponding to the discrepancy between the calculated and measured values of M(11). The solution of equations 4.34 to 4.39 is then repeated until the convergence criteria is met. At this point the difference between the calculated and measured values of the heat content leaving the condenser in the cooling water stream is taken to represent the heat losses from this section of the evaporator system, i.e. from the second effect, condenser and the second effect separator.

The heat loss from the first effect and preheater is taken to be the difference between the heat content of the measured and calculated steam flow rates, V(5). The calculated steam flow rate is obtained from equation 4.6 as follows;

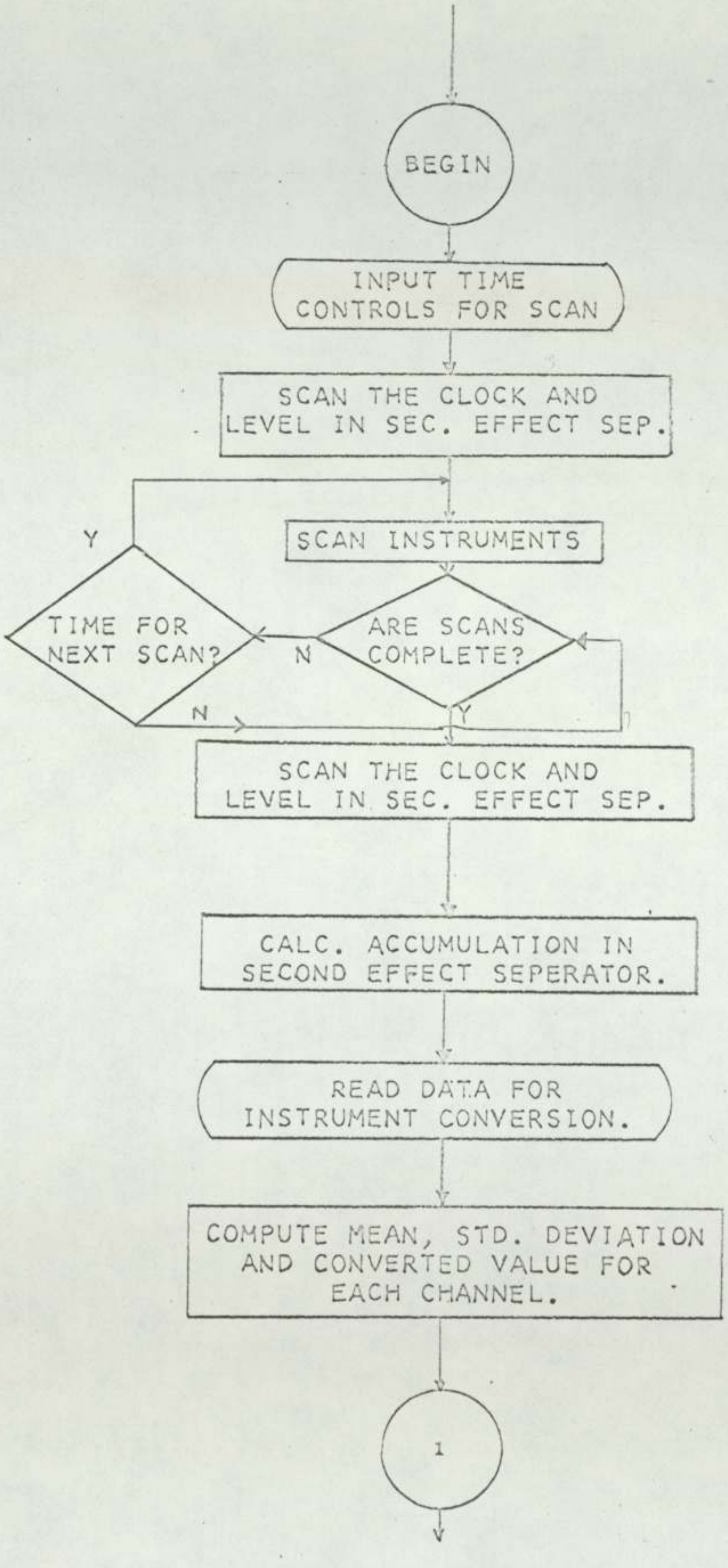
$$V(5) = \frac{M(7).T(7).C1 + V(7).E(7) - M(2).T(2).C1}{E(5) - T(6).C1} \qquad \text{----------------- (4.40)}$$

4.3 Steady State Computer Program and Experiment Description.

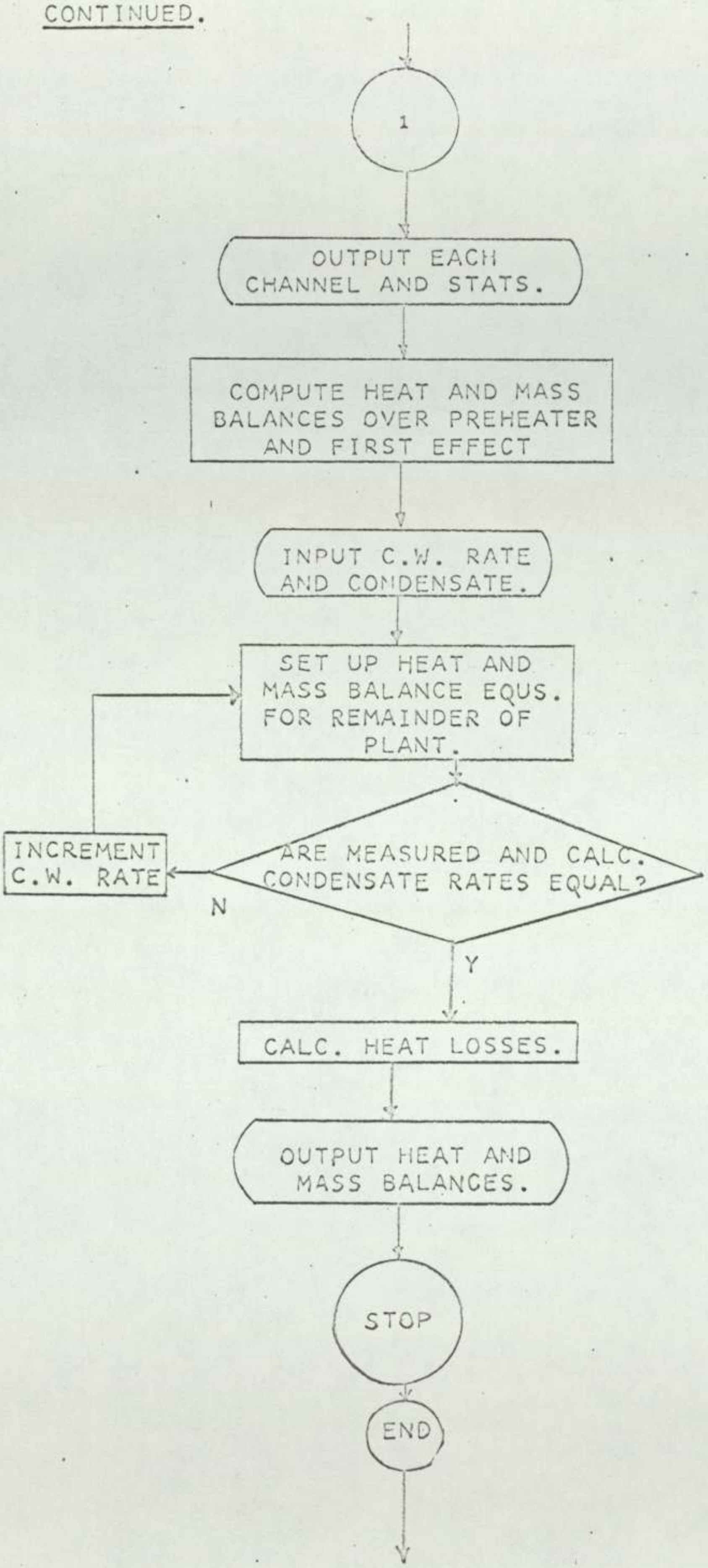
Following the setting up of the equipment as discussed in Chapter three the system is allowed to come to " steady-state " for a period of time of not less than twenty minutes. After this time the program for controlling the acquisition of data and solving the mass and heat balance equations of section 4.2 is set in operation. This computer program is listed in Appendix 1 and a flow diagram for the program is given in Figure 4.2.

To commence data acquisition both the total time of the steady

FIG.4.2 FLOW CHART FOR STEADY STATE COMPUTER PROGRAM.



CONTINUED.


1
OUTPUT EACH CHANNEL AND STATS.
COMPUTE HEAT AND MASS BALANCES OVER PREHEATER AND FIRST EFFECT
INPUT C.W. RATE AND CONDENSATE.
SET UP HEAT AND MASS BALANCE EQUS. FOR REMAINDER OF PLANT.
ARE MEASURED AND CALC. CONDENSATE RATES EQUAL?
N
INCREMENT C.W. RATE
Y
CALC. HEAT LOSSES.
OUTPUT HEAT AND MASS BALANCES.
STOP
END

state run and the interval between samples is entered as data via the portable teletype. Once entered the experiment begins.

The computer first scans the MPD 200 clock and also the level in the second effect separator. The two values collected are used at a later stage for the calculation of the accumulation that takes place during the experiment in the second effect separator. Once these values have been stored by the computer the sequential scanning of the instruments on the evaporator system begins. After each complete scan has taken place the computer enters a time wasting loop which ensures that none of the later calculations can be computed until all of the required data has been collected.

During this scanning period accurate measurements of both the cooling water flow rate and the condensate flowrate are taken. The cooling water flowrate is measured using a calibrated rotameter and the condensate flowrate by collection and measurement over a known time interval. A minimum of three values of each measurement is taken and the average value used in subsequent calculations.

At the completion of the scanning period the time of the MPD 200 clock and the level in the second effect separator are again scanned. The accumulation in the second effect separator is then computed.

The computer next reads the conversion factors for each instrument which convert the analogue signal to the required measurement units. This data is stored within the main computer program. The scans of each instrument collected over the experiment are then averaged, the standard deviation of the mean is computed, the mean is converted to its correct units and finally all three values for each channel are output onto the portable teletype. At this point the validity of the steady state assumption is checked. The thermocouples situated within the evaporator system are of a high accuracy and therefore if the standard deviations associated with these instruments are high the system is considered not to have been at " steady-state " and the run is aborted. The abortion is carried out manually by use of the sense switches on the MPD 200 mobile cabinet. If the run is aborted the system is allowed further time to reach " steady state " and the experiment repeated.

If the standard deviations are acceptable the measured values of the cooling water flowrate and the condensate flowrate are entered via the portable teletype. The computer then calculates the heat and mass balances over the evaporator system and the results are output onto the portable teletype. Finally the heat losses from the system are computed and output onto the teletype. A typical print out for a steady state experiment is shown in Figure 4.3.

The input variables to the evaporator system are then reset and after " steady state " conditions have been attained the experimental procedure is repeated.

4.4 Results.

Based upon the mathematical model and its solution as described in the previous two sections a total of 47 experiments were conducted to analyse the steady state behaviour of the double effect evaporator.

The results of these experiments are shown for each individual heat transfer unit of the system in Tables 4.2A to 4.2D in Appendix 2.

The nomenclature and units used in the tables is as follows;

U = the overall heat transfer coefficient in J / sec. cm^2. ^oC.

T = temperature in ^oC.

M = liquid flow rate in G / sec.

V = vapour flow rate in G / sec.

subscripts; C = condenser

P = preheater

FE = first effect

```
          J.COLEBY STEADY STATE LOGGING PROGRAM
SAMPLING INTERVAL (SECS) !30

TOTAL RUN TIME (MINS.)!5


START TIME  1125
FINISH TIME  1130



CHANNEL.      ANALOGUE.          STD.DEV.   CONVERTED VAL.

  12           -229.253           1.41145     97.9479
  13           2893.72          69.728       250.205
  14          -3383.91            2.82843      4.49826
  15          -1657.32            2.12132     13.3788
  16          -6708               2.82843     29.5693
  17          -5101.37          105.333       12.9273
  18          -5124.67            3.4641       2.74355
  19          -9772.6            55.2311       1
  20           -501.541            .984251    12.5385
  21           -859.4             2.82843     21.485
  22           -761.908           3.24037     19.0477
  23          -1309.23            2           45.2308
  24          -1417.67            4.3589      35.4417
  25          -1508.2             4.12311     37.58
  26          -2126.87            1.73205     53.1719
  27           -976.95            3           24.4237
  28          -2167.07            3           54.1769
  29          -2156.2             4.12311     53.985


C.W.RATE/STEAM/CONDENSATE!833.333,18.6,29.2


STREAM          LIQ.(G/S.)   VAP(G/S.)     TEMP.(DEG.C)   ENTHALPY(J/S)

   1              29.5693      0             19.0477      2358.12
   2              29.5693      0             45.2308      5599.6
   3               0          16.642         53.985       .431201E 05
   4               1.374      15.268         54.1769      .398737E 05
   5               0          19.087        122           .516312E 05
   6              19.087       0            100           7991.33
   7              12.9273     16.642         53.5384      .45998E 05
   8              12.9273      0             53.1719      2377.87
   9               0          12.5458        35.4417      .32119E 05
  10              13.6974      2.94487       51.6416      .105387E 05
  11              29.1881      0             24.4237      2984.7
  12            1060.29        0             12.5385      .556611E 05
  13            1060.29        0             21.485       .953763E 05
  14            3272.49        0             37.58        .514893E 06
  15            3272.49        0             35.4417      .485595E 06

             MEASURED ACCM.      -1.06374  G/S.
             CALC. ACCM.          .381445  G/S.
MEASURED VALUES
---------------

STEAM    18.6
C.W.RATE  833.333
CONDENSATE    29.2


 CALC. VALUES
 ------------

STEAM    19.087
C.W.RATE  1060.29
CONDENSATE    29.1881

     TOTAL HEAT LOSS  8500.97 J/S
HEAT LOSS/LB. STEAM    16.4648
  HEAT LOSS FROM PLANT    8.69787 %
```

SE = second effect

numbered subscripts refer to streams within the system as described in Table 4.1.

The overall heat transfer coefficients for each item of heat transfer equipment were calculated from the equation,

$$q = U.a.\Delta T \qquad \text{------------} \ (4.41)$$

and thus

$$U = \frac{q}{a.\Delta T} \qquad \text{-------------} \ (4.42)$$

where a = the area available for heat transfer in cm^2.

q = the amount of heat transfered in unit time in J / sec.

and ΔT = the log mean temperature driving force in ^{o}C.

For the condenser calculations in which there are two inlet streams into the shell, i.e. streams 9 and 10, an inlet temperature is required for the calculation of ΔT.

This inlet temperature is assumed to be a weighted average based upon the heat contents of the streams in question, i.e. temperature into condenser shell,

$$= \frac{T(9).C(9) + T(10).C(10)}{C(9) + C(10)} \qquad \text{------} \ (4.43)$$

where C = the heat content of the stream in J / sec.

4.4.1 Heat Transfer Coefficient Correlations.

All of the measured and calculated variables, obtained for each heat transfer unit by the experimental procedures previously defined, were classified as independent variables in the initial attempt at obtaining accurate correlations for the heat transfer coefficients.

Examination of these initial correlations determined which, if any, of the independent variables could be removed from the correlation analysis. This removal of variables was based upon, (i) the individual regression coefficients, (ii) the partial correlation coefficients and (iii) the " Student's T-test ".

The number of independent variables in each unit correlation was reduced until subsequent reductions caused a lowering of the multiple correlation coefficient.

Using the method quoted by Davies (4.2) for multiple non-linear regression analysis the results shown in Tables 4.2A to 4.2D were used to produce the following correlations.

The nomenclature is as previously defined.

Preheater.

$$U_P = \frac{5.8749 \times 10^{-3} \times M(1)^a \times T(2)^b}{V(3)^c \times T(1)^d \times T(3)^e} \quad \text{-------} \; (4.44)$$

where $a = 0.946622$ $b = 4.06841$

$c = 0.0678808$ $d = 0.603357$

and $e = 3.65735$

The above correlation gave a multiple correlation coefficient of 0.990889.

First Effect.

$$U_{FE} = 4.18596 \times 10^{-4} \times M(2)^a \times V(7)^b \times T(2)^c \times T(7)^d \quad \text{-------------} \; (4.45)$$

where $a = 0.0287992$ $b = 0.958777$

$c = 0.194165$ and $d = 0.504994$

The above correlation gave a multiple correlation coefficient of 0.999676.

Second Effect.

$$U_{SE} = \frac{3.9574 \times T(14)^a \times V(4)^b \times M(10)^c}{V(10)^d \times T(4)^e \times T(10)^f} \quad \text{-------} \; (4.46)$$

where $a = 3.21051$ $b = 0.568398$

$c = 0.494838$ $d = 0.115259$

$e = 2.40123$ and $f = 1.89576$

The above correlation gave a multiple correlation coefficient of 0.980299.

Condenser.

$$U_C = \frac{5.3554 \times 10^{-5} \times M(12)^a \times T(13)^b \times M(10)^c}{T(12)^d \times T(9)^e \times T(11)^f} \quad \text{-----} \; (4.47)$$

where $a = 1.07948$ $b = 2.56339$

$c = 0.251088$ $d = 0.360554$

$e = 1.48368$ and $f = 1.05817$

The above correlation gave a multiple correlation coefficient of 0.932653.

The correlations produced above show a steady decline in accuracy through the units of the evaporator system. This is due to the fact that the heat losses from the system were found in practice to be mainly concentrated around the second effect and the condenser. As the heat losses from this section of the plant have all been accounted for in the cooling water flow rate in the condenser this unit as would be expected shows the lowest degree of accuracy. Examination of Tables 4.3A to 4.3D in Appendix 2, showing the predicted values versus the observed experimental heat transfer coefficients and the relative error, shows that the vast majority of results are within an accuracy of ∓ 10% for the heat transfer units of the system.

Examination of the coefficients associated with the independent variables in the correlations for the heat transfer coefficients shows some extremely low values. For example the correlation for the heat transfer coefficient in the first effect contains the variable M(2) to the power 0.0287992. In the majority of correlations it would be expected that this type of term could be removed from the correlation with little loss of accuracy. However because of the relative magnitude of these terms this was not found to be the case. Attempts to produce a new correlation without including these variables produced correlations of lower accuracy as shown by a reduction in the value of the multiple correlation coefficient. For example removal of this term discussed above from the correlation reduces the multiple correlation coefficient from 0.999676 to 0.66676.

The correlations produced by the regression analysis show the clear dependence of the heat transfer coefficients upon the temperatures of the unit, in particular the outlet temperatures on both shell and tube side. As has been discussed previously in the literature survey the solution of a dynamic model for heat exchange equipment involves assumptions based upon for example the dependence of the heat transfer coefficient upon the variables of the equipment involved. The fact that the heat transfer coefficient was found to be temperature dependent verifies the point made by Privett and Ferrel (4.3) that assuming the heat transfer coefficient to be a function of flow rates only leads to gross inaccuracies on solution and that a temperature term must be included in the heat transfer coefficient correlation.

4.4.2 Heat Losses From the Evaporator System.

Using the steady state model and computer program described in sections 4.2 and 4.3 the heat losses from the evaporator system were computed for all of the " steady state " experiments. Because of a lack of sufficient measurements of important variables within the system, the heat losses associated with each of the individual units could not be computed, and no method could be devised to proportion the total heat loss between them.

Examination of Table 4.4 in Appendix 2 shows the total heat loss and the percentage heat loss in terms of the total heat input to the system. These results show no obvious trends and attempts to correlate the heat loss with the main process flows and temperatures proved unsuccessful. Table 4.4 shows also one attempt at such a correlation where the heat loss has been expressed as a ratio of the total heat content of the steam flow to the first effect.

The average percentage heat loss from the evaporator system was found to be 8.5%. Because of the magnitude of this heat loss, and the fact that it can not be defined either empirically or theoretically, it will obviously cause errors in any dynamic simulation of the evaporator system.

4.4.3 Instrument Statistics.

The data provided by the instrument manufacturers gives the relative accuracy of each instrument over the range of operation. However this does not take into account the error introduced by the data acquisition system, especially the noise generated by interference on the analogue transmission lines and through the mechanical nature of the MPD 200 Data Logging system. In the initial calibration of the instruments some of these effects have been accounted for as discussed in section 3.5. The effects of noise caused by the data logging system when scanning many channels in rapid succession under operating conditions, can not be accounted for during calibration for all instruments, i.e. flow measuring instruments and pressure transducers.

To overcome this problem the results from the " steady-state " experiments were used. The mean of the analogue signals is taken to be the "true value", and the noise, or error, to be represented by the calculated standard deviation of the mean. As has been discussed previously " steady-state " is ensured by examination of the standard deviations corresponding to the thermocouples, as these instruments could be examined on-line as discussed above. The experimental results were used to calculate a weighted mean standard deviation for each channel. Using the calibrations for the instruments discussed in section 3.5 these analogue values were transformed to the units of the measuring device for use in Kalman Filtering experiments. These results are given in Table 4.5, the meaurement units for each channel are those described in section 3.5.

CHAPTER FIVE.

Chapter 5. Dynamic Analysis of the Double Effect Evaporator.

5.1 Introduction.

A dynamic analysis of the double effect evaporator that is to be used for implementation within the Kalman Filter must take into account the following points previously highlighted in the literature survey;

(i) The model must be of a form that is compatible with the Kalman Filter equations, i.e. the dynamic model, of the double effect evaporator, must be a set of ordinary differential equations. This is in direct contrast to previous research carried out into heat exchanger dynamics, (see section 2.2.3), where the dynamics of heat exchange equipment have been described by a set of partial differential equations.

(ii) The dynamic model must be readily implemented on a digital computer and be of an order and form that makes solution in real-time feasible bearing in mind the limits of the computation and ancillary equipment available. This point is regarded as being of particular importance in the light of conclusions drawn by Payne (5.1) and Hamilton et al. (5.2) in their works dealing with on-line implementation of the Kalman Filter for chemical processes. These works highlight the problem of estimation in real time for chemical processes and the requirement of reducing the computational burden to a minimum.

(iii) The model must take into account the measurements that are available, from the double effect evaporator, directly as analogue signals to the MPD 200 Data Logger, i.e. the model must be observable. Although further measurements could be made available, from the double effect evaporator, any increase in their number would have the effect of,

(a) increasing the computation time involved in their processing within the Kalman Filter.

(b) increasing the time required for data acquisition via the data logging equipment.

Both of these points are in contradiction to the aims of the modeling exercise as described in (ii) above.

5.2 Experimental Observations.

Prior to the development of a dynamic model, describing the behaviour of the double effect evaporator, certain quantitative approximations were made. These approximations were based upon an examination of the transient data obtained from the evaporator following a disturbance upon the system inputs. These approximations are;

(i) That the vapour dynamics associated with the shell of the second effect, the shell of the preheater and the tubes of the first effect could be considered identical, i.e.

$$\frac{dT(3)}{dt} = \frac{dT(4)}{dt} = \frac{dT(10)}{dt} \quad \text{--------} \ (5.1)$$

The reason for this condition is that the temperatures above are all associated with the same vapour space with the vacuum pump taking suction from the second effect shell. The temperature differences between the vapour units are due to the pressure drops occuring in the interconnecting pipework.

Figures 5.1A and 5.1B show two typical sets of experimental data to verify this approximation.

(ii) That the temperature dynamics associated with the tubes of the second effect, (inlet and outlet temperatures), could be considered identical, i.e.

$$\frac{dT(14)}{dt} = \frac{dT(15)}{dt} \quad \text{---------} \ (5.2)$$

Figures 5.2A and 5.2B show two typical sets of experimental data

FIGURE 5.1A. VAPOUR TEMPERATURE PROFILES. DYNAMIC EXPERIMENT No. 1.

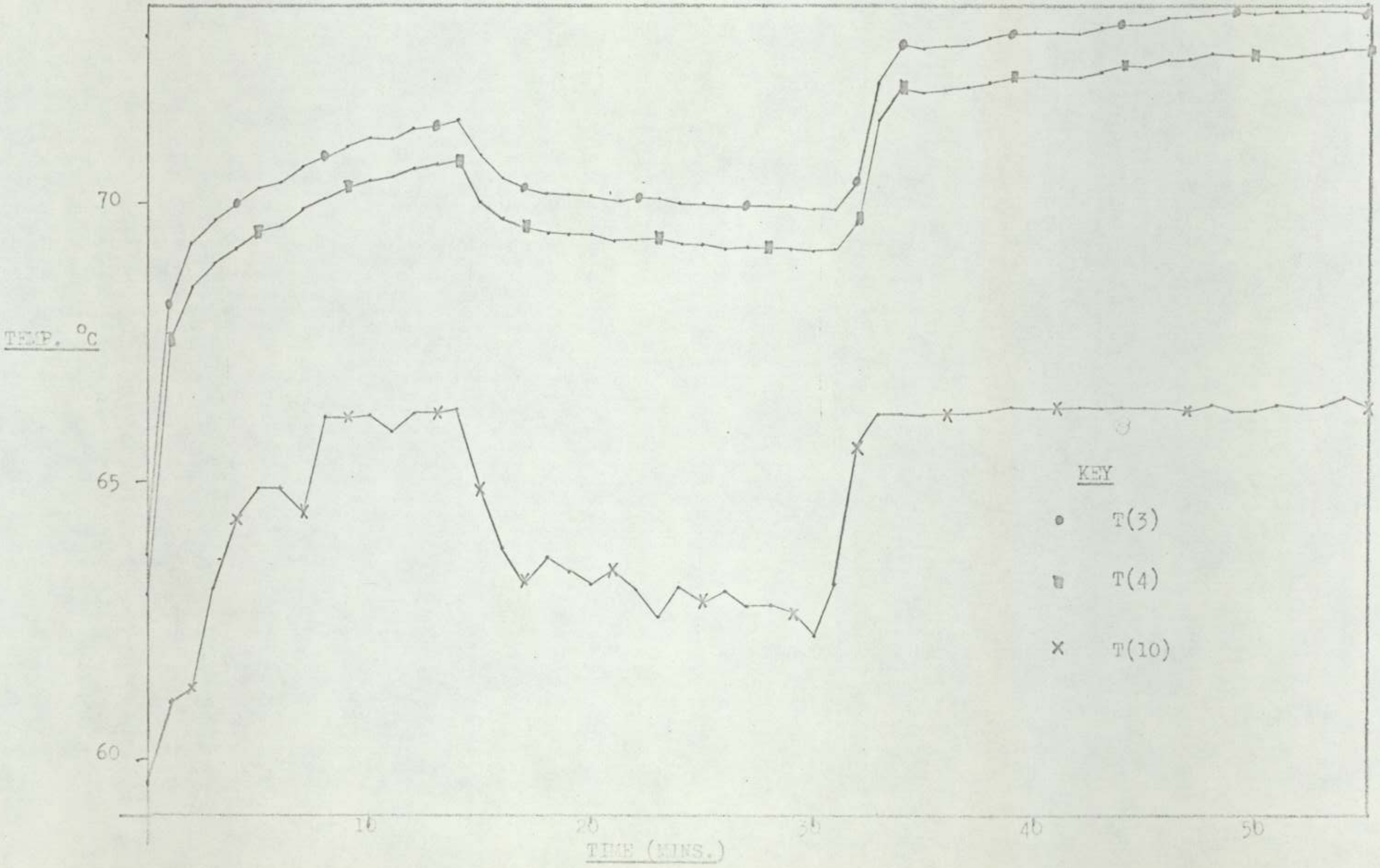


FIGURE 5.1B VAPOUR TEMPERATURE PROFILES . DYNAMIC EXPERIMENT No. 2

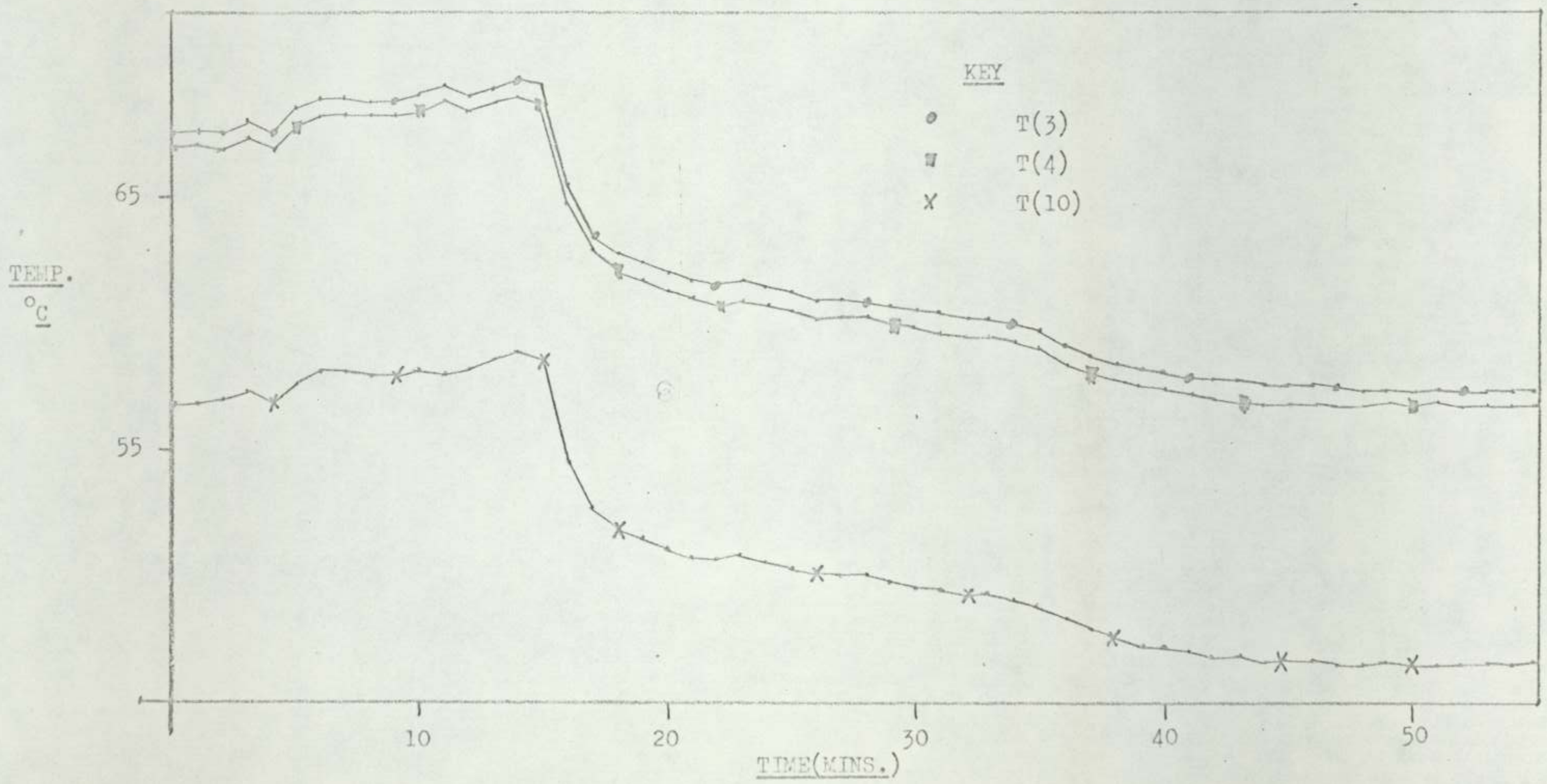


FIGURE 5.2A LIQUID TEMPERATURE PROFILES - SECOND EFFECT TUBES. DYNAMIC EXPERIMENT No. 1.

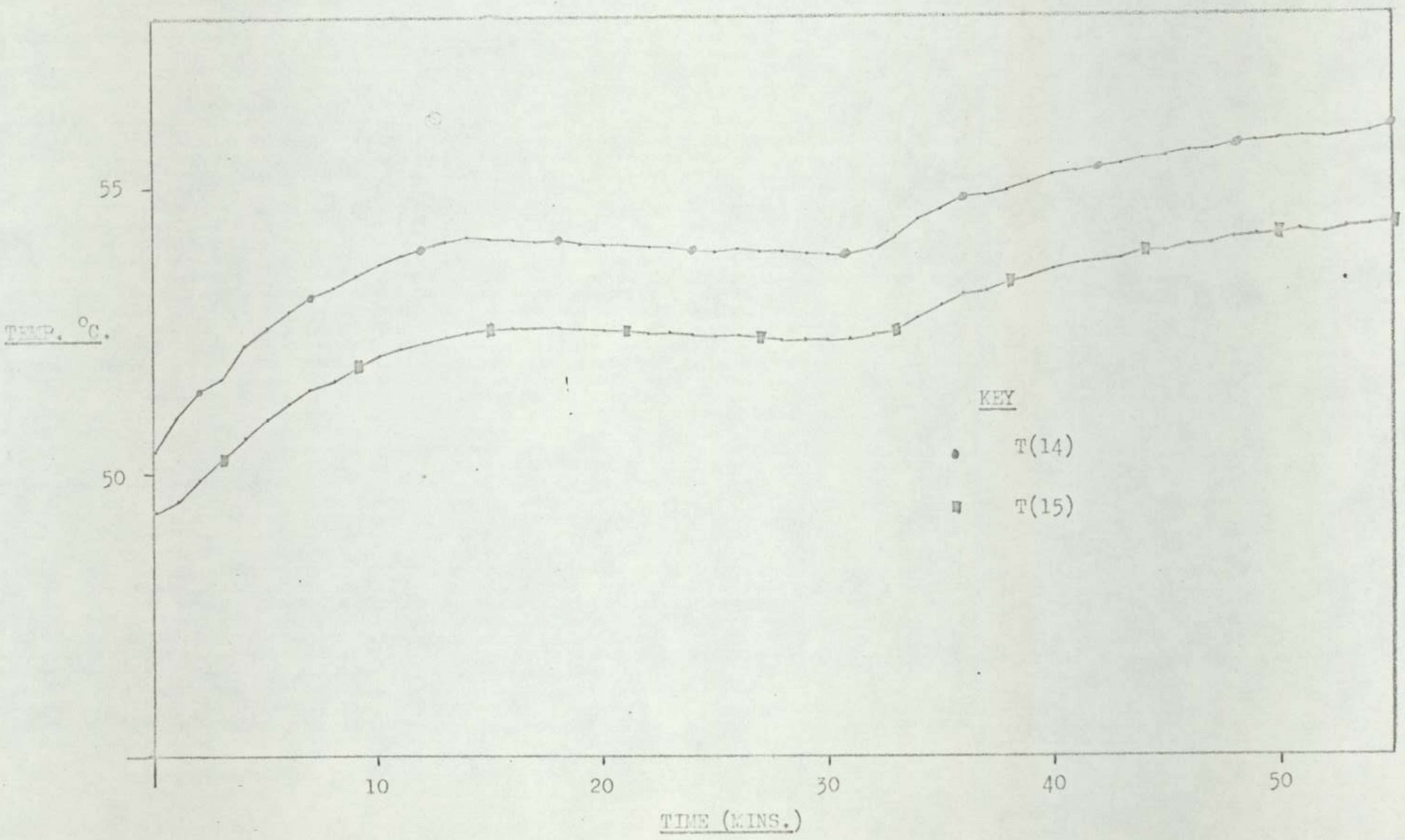
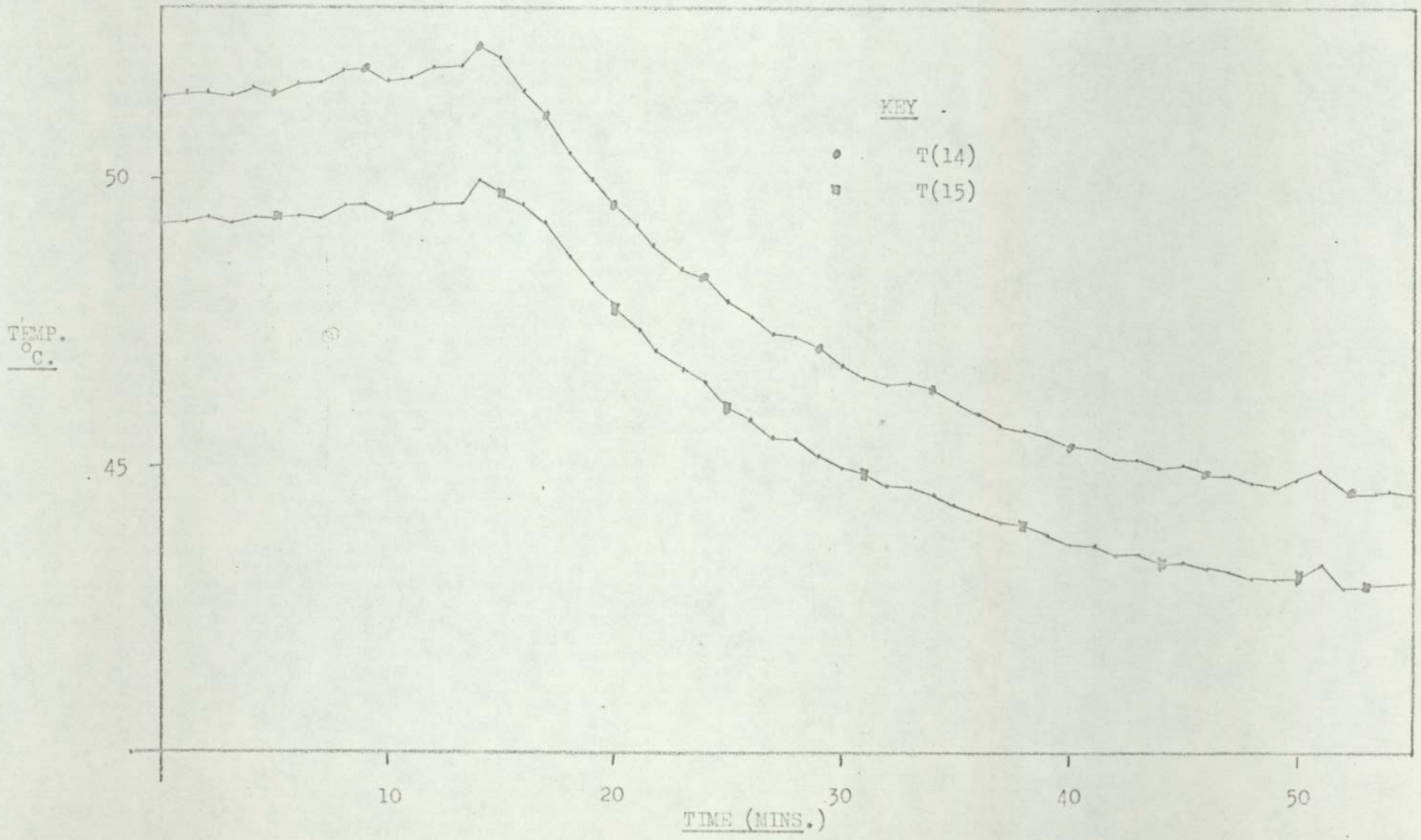


FIGURE 5.2B. LIQUID TEMPERATURE PROFILES - SECOND EFFECT TUBES. DYNAMIC EXPERIMENT No. 2



to verify this approximation

5.3 Dynamic Model Development.

In order to obtain mathematical relationships for the remaining variables and parameters of the double effect evaporator, within the aims specified in the introduction, certain assumptions are required. The assumptions are;

(i) The vapour is in equilibrium with the liquid in all two phase mixtures existing within the double effect evaporator.

(ii) The tubes and shell of each of the four heat exchange units of the evaporator are assumed to be well mixed. The temperature of these well mixed systems being equal to the outlet temperature. This assumption allows a dynamic equation to be derived that is both simple and in a lumped parameter form.

(iii) The heat losses from the double effect evaporator are assumed to be constant.

(iv) The cyclone separator is assumed to be an extension of the first effect tubes. This assumption allows the temperatures of liquid and vapour to be taken as equal and also ignores any contribution that the cyclone may make to the dynamics of the evaporator system.

(v) The tubes of each heat exchange unit are assumed to be at a temperature equal to that of their contents. A similar assumption is made regarding the shell of the condenser.

(vi) The vapour dynamics within the double effect evaporator are assumed to be described by steady state equations. Previous research in the field of heat transfer dynamics, (see for example André (5.3), Payne (5.1) and Zavorka et al. (5.4)), has shown that the time constants associated with vapour dynamics are of small enough magnitude for the dynamics to be approximated by steady state equations with little loss in accuracy.

(vii) The heat given up by the contents of the shells, of the heat exchange units, is assumed to be by condensation alone when considering the dynamics of the shell side liquid flow rates.

(viii) All physical properties associated with the evaporator are assumed to be constant unless otherwise specified.

By use of these assumptions and approximations the following mathematical model is obtained;

Energy balance on preheater tubes.

$$\text{Heat in} = M(1).Cl.T(1) + U_P.A_P.(T(4) - T(2)) \quad \text{--------} \; (5.3)$$

$$\text{Heat out} = M(1).Cl.T(2) \quad \text{---------} \; (5.4)$$

$$\text{Accumulation} = \frac{dT(2)}{dt}.(V_{PT}.\rho.Cl + M_{PT}.C_T) \quad \text{-------} \; (5.5)$$

Combing equations 5.3 to 5.5 then,

$$\frac{dT(2)}{dt} = \frac{M(1).Cl.(T(1) - T(2)) + U_P.A_P.(T(4) - T(2))}{(V_{PT}.\rho.Cl + M_{PT}.C_T)} \quad \text{-----------------} \; (5.6)$$

where V = the volume of the tubes

M = the mass of the tubes

C_T = the specific heat of the tube walls

the subscript PT referes to the preheater tubes.

Energy balance on preheater shell.

From assumption (vii) the rate of heat lost on the shell side of the preheater, at any instant of time , to the contents of the tube can be expressed as;

$$M(4).\lambda \quad \text{---------} \; (5.7)$$

where λ = the latent heat of vaporisation.

Equation 5.7 is equivalent, discounting heat losses to the atmosphere, to the rate of heat gained by the preheater tube contents,i.e.

$$M(1).Cl.(\,T(2) - T(1)\,) \quad \text{----------} \; (\,5.8\,)$$

Thus combining equations 5.7 and 5.8 then;

$$M(4).\lambda = M(1).Cl.(\,T(2) - T(1)\,) \quad \text{-------} \; (\,5.9\,)$$

In order to obtain a differential equation describing the behaviour of M(4) the following approximation is used, previously adopted by Wells (5.5). The R.H.S. of equation 5.9 contains only one variable i.e. T(2). Therefore;

$$\frac{dM(4)}{dT(2)} = \frac{M(1).Cl}{\lambda} \quad \text{-----------} \; (\,5.10\,)$$

Expansion of equation 5.10 by the chain rule gives the relationship,

$$\frac{dM(4)}{dt} = \frac{M(1).Cl}{\lambda}.\frac{dT(2)}{dt} \quad \text{--------} \; (\,5.11\,)$$

and using assumption (vi) then,

$$V(4) = V(3) - M(4) \quad \text{---------} \; (\,5.12\,)$$

Energy balance on the first effect tubes.

$$\text{Heat in} = M(1).Cl.T(2) + U_{FE}.A_{FE}.(\,T_S - T(3)\,) \quad \text{-----} \; (\,5.13\,)$$

$$\text{Heat out} = V(3).E(3) + M(8).Cl.T(3) \quad \text{---------} \; (\,5.14\,)$$

$$\text{Accumulation} = \frac{dT(3)}{dt}.(\,V_{FET}.\rho_{FE}.C_{FE} + M_{FET}.C_T\,) \quad \text{-----} \; (\,5.15\,)$$

Combining equations 5.13 to 5.15 then,

$$\frac{dT(3)}{dt} = \frac{M(1).Cl.T(2) + U_{FE}.A_{FE}.(T_S - T(3)) - V(3).E(3) - M(8).Cl.T(3)}{(\,V_{FET}.\rho_{FE}.C_{FE} + M_{FET}.C_T\,)}$$

$$\text{---------------------} \; (\,5.16\,)$$

where T_S = steam condensing temperature

ρ_{FE} = density of the tube contents

C_{FE} = the specific heat of the tube contents

subscript FET refers to the first effect tubes.

Using assumptions (vi) and (vii) then the heat lost by the steam condensing in the first effect shell·to the contents of the tubes can be expressed as;

$$V(5).\lambda \qquad \text{---------} \; (5.17)$$

This amount of heat will (a) raise the temperature of the liquid entering the tubes from T(2) to T(3) and (b) vaporise the quantity V(3). Therefore;

$$V(3) = \frac{V(5).\lambda - M(1).Cl.(T(3) - T(2))}{\lambda} \qquad \text{-----} \; (5.18)$$

and using assumption (vi) then,

$$M(8) = M(1) - V(3) \qquad \text{--------} \; (5.19)$$

Energy balance on the second effect tubes.

$$\text{Heat in} = M(15).Cl.T(15) + U_{SE}.A_{SE}.(T(10) - T(14)) \quad \text{----} \; (5.20)$$

$$\text{Heat out} = M(15).Cl.T(15) \qquad \text{----------} \; (5.21)$$

$$\text{Accumulation} = \frac{dT(14)}{dt}.(V_{SET}.Cl.\rho + M_{SET}.C_T) \qquad \text{---------} \; (5.22)$$

Combining equations 5.20 to 5.22 then,

$$\frac{dT(14)}{dt} = \frac{M(15).Cl.(T(15) - T(14)) + U_{SE}.A_{SE}.(T(10) - T(14))}{(V_{SET}.\rho.Cl + M_{SET}.C_T)}$$

$$\text{---------------} \; (5.23)$$

where subscript SET refers to the second effect tubes.

Adopting a similar approach to describe the behaviour of M(10) as that for M(4) , (see equation 5.9), then an instantaneous heat balance over the second effect gives,

$$(M(10) - M(4)).\lambda = M(14).Cl.(T(14) - T(15)) \quad \text{------- (5.24)}$$

again the heat lost from the second effect shell is assumed to be zero. From equation 5.24 then,

$$M(10) = \frac{M(14).Cl.(T(14) - T(15))}{\lambda} + M(4) \quad \text{----------- (5.25)}$$

and by a chain rule expansion then,

$$\frac{dM(10)}{dt} = \frac{dM(4)}{dt} + \frac{M(14).Cl}{\lambda} . \frac{dT(14)}{dt} - \frac{M(14).Cl}{\lambda} . \frac{dT(15)}{dt} \quad \text{------------ (5.26)}$$

and by use of assumption (vi) then

$$V(10) = M(4) + V(4) - M(10) \quad \text{-------- (5.27)}$$

Energy balance on condenser tubes.

$$\text{Heat in} = M(12).Cl.T(12) + U_C.A_C.(T(11) - T(13)) \quad \text{---------- (5.28)}$$

$$\text{Heat out} = M(12).Cl.T(13) \quad \text{---------- (5.29)}$$

$$\text{Accumulation} = \frac{dT(13)}{dt} . (V_{CT}.\rho.Cl + M_{CT}.C_T) \quad \text{-------- (5.30)}$$

Combining equations 5.28 to 5.30 then,

$$\frac{dT(13)}{dt} = \frac{M(12).Cl.(T(12) - T(13)) + U_C.A_C.(T(11) - T(13))}{(V_{CT}.\rho.Cl + M_{CT}.C_T)} \quad \text{---------------- (5.31)}$$

where subscript CT refers to the condenser tubes.

Energy balance on second effect shell.

$$\text{Heat in} = V(9).E(9) + V(10).E(10) + M(10).Cl.T(10) \text{ ------ } (5.32)$$

$$\text{Heat out} = M(11).Cl.T(11) + U_C.A_C.(T(13) - T(11)) \text{ ---- } (5.33)$$

$$\text{Accumulation} = \frac{dT(11)}{dt}.(V_{CS}.\rho_S.C_S + M_{SC}.C_{SS}) \text{ --------- } (5.34)$$

Combining equations 5.32 to 5.34 then,

$$\frac{dT(11)}{dt} = \frac{V(9).E(9) + V(10).E(10) + (M(10).T(10) - M(11).T(11)).Cl}{(V_{CS}.\rho_S.C_S + M_{SC}.C_{SS})}$$

$$- \frac{U_C.A_C.(T(11) - T(13))}{(V_{CS}.\rho_S.C_S + M_{SC}.C_{SS})} \text{ ---------- } (5.35)$$

where C_{SS} = the specific heat of the shell

and subscript CS refers to the condenser shell.

Mass balance on second effect separator.

$$\text{Mass in} = M(15) + M(8) \text{ ---------- } (5.36)$$

$$\text{Mass out} = M(15) + V(9) \text{ ----------- } (5.37)$$

$$\text{Accumulation} = \frac{dH}{dt}.A_{SEP}.\rho \text{ --------- } (5.38)$$

Combining equations 5.36 to 5.38 then,

$$\frac{dH}{dt} = \frac{M(8) - V(9)}{A_{SEP}.\rho} \text{ -------- } (5.39)$$

where A_{SEP} = the cross sectional area of the second effect separator.

H = the height in the second effect separator

The difference in vapour pressure between the inlet streams to the separator and the contents of the separator is assumed to account for the vaporisation of the quantity V(9). By use of assumption (vi) then,

$$V(9) = \frac{\dot{M}(15).Cl.(\,T(14)-T(15)\,) + M(8).Cl.(\,T(3)-T(15)\,)}{\lambda} \qquad \text{----------}\ (\,5.40\,)$$

The heat transfer coefficient correlations derived in chapter 4, (see equations 4.44 to 4.47), from a steady state analysis of the double effect evaporator, are assumed to apply when the system is in a transient state. The equations for the heat transfer coefficients within the model are therefore;

$$U_P = f(\,T(1), M(1), V(3), T(3)\,) \qquad \text{---------}\ (\,5.41\,)$$

$$U_{FE} = f(\,M(1), V(3), T(3), T(2)\,) \qquad \text{----------}\ (\,5.42\,)$$

$$U_{SE} = f(\,T(14), V(4), M(10), V(10), T(4), T(10)\,) \qquad \text{-------}\ (\,5.43\,)$$

$$U_C = f(\,T(13), M(12), M(10), T(12), T(9), T(11)\,) \qquad \text{-------}\ (\,5.44\,)$$

5.4 Experimental Details.

In order to (i) Test the validity of the model described above and (ii) obtain the required inputs to the model equations for its solution, transient data from the double effect evaporator were collected using the BASELINE compiler and the MPD 200 Data Logging system described in Chapter 3. A further requirement for the simulation is a set of initial conditions.

The evaporator was set up and run for steady state analysis as described in Chapter 4. A steady state experiment was completed, this provided the required initial conditions for later simulations. A disturbance was introduced into the physical system via the steam flow and/or the liquid feed to the preheater. Data from the double effect evaporator instruments were collected every minute over a sixty minute period and output onto paper tape for later processing. This data was to (a) provide the required inputs to the model and (b) provide a check on the accuracy of the model predictions where appropriate, during simulation experiments.

Simulation of the differential equations described previously was carried out using the Honeywell H316 computer and the ASP compiler, (see reference 5.6 for details). The ASP compiler is a set of FORTRAN subroutines that can be accessed through a BASIC program to integrate a set of ordinary differential equations and control the various facets of data transfer. The ASP compiler offers the user the choise of integration methods, (modified Euler or 4th. order Runge-Kutta). The modified Euler technique was chosen, for simulation of the differential equations, due to its ease of implementation and also its lower processing time requirements given equal step lengths for integration. This choice was based upon the original aims of the model and its implementation as discussed in the introduction.

5.5 Results and Discussion.

At steady state the derivative terms associated with the mathematical model must be equal to zero. A loss term is calculated for each differential equation to ensure that this is in fact the case. The loss terms account for errors in the model and also heat losses from the evaporator to the atmosphere.

The model previously described and including the loss terms was simulated using the ASP compiler. The steady state analysis carried out prior to the introduction of the disturbance was used to generate the initial conditions and also to calculate the loss terms. The inputs to the model were read directly into the mathematical model from the prepared data tape.

On simulation a problem arises due to the complex interrelationships that exist between T(2) and T(3). When a positive disturbance is applied in the model to the liquid feed rate, M(1), equations 5.6 and 5.16 predict a continuous negative derivative. Simulation experiments predict a continual decrease in the magnitude of T(2) and T(3) and within the period of experimentation, steady state was never again achieved within the model following this type of disturbance.

The equations 5.6 and 5.16, i.e.

$$\frac{dT(2)}{dt} = \frac{M(1).Cl.(\ T(1) - T(2)\ ) + U_P.A_P.(\ T(4) - T(2)) - L(1)}{(V_{PT}.\rho.Cl \ + \ M_{PT}.C_T\ )} \qquad \text{----------- (5.6)}$$

(where L(1) is the loss term associated with the above differential equation.)

and

$$\frac{dT(3)}{dt} = \frac{M(1).Cl.T(2) + U_{FE}.A_{FE}.(\ T_S - T(3)) - V(3).E(3)}{(\ V_{FET}.\rho_{FE}.C_{FE} \ + \ M_{FET}.C_T\ )} - \frac{M(8).Cl.T(3) \ - \ L(2)}{(V_{FET}.\rho_{FE}.C_{FE} + M_{FET}.C_T\ )} \qquad \text{------- (5.16)}$$

(where L(2) is the loss term associated with the above differential equation,)

reveal the source of the inaccuracy. From equation 5.6 the term M(1).Cl.(T(1) - T(2)) is negative so that at steady state if M(1) is increased the derivative becomes negative and T(2) decreases. Substitution of these values of T(2) and M(1) into equation 5.16 produces a negative derivative. The increase in M(1) produces a corresponding increase in M(8) and the decrease in T(2) therefore produces a negative value of the derivative and a decrease in T(3). This drop in T(3) causes a corresponding drop in T(4) as seen through equation 5.1. Examination of equation 5.6 shows that if T(4) decreases, and all other variables remain constant, then the temperature driving force for heat transfer, decreases also. The effect is a reduction in T(2) once again. This process continues with T(2) and T(3) reducing at each cycle of the integration. An example of this behaviour for the predicted responses of T(2) and T(3), after this type of disturbance has occured, is shown in Figures 5.3A and 5.3B.

The problem is compounded by the mathematical relationship between M(4) and T(2) within the mathematical model,i.e.

$$\frac{dM(4)}{dt} = \frac{M(1).C1}{\lambda} . \frac{dT(2)}{dt} \quad \text{---------} \; (5.11)$$

As M(4) was found experimentally to have relatively low values (approximately 1.0 grm./sec.), it can be seen that with continuous negative values of $\frac{dT(2)}{dt}$, substituted into equation 5.11 , the predicted value of M(4) becomes negative. In the context of the double effect evaporator the negative values of M(4) are meaningless.

The errors within the mathematical model assumptions that give rise to this behaviour are those concerning well mixed fluids on both shell and tube side of the heat exchange units. The assumption of well mixed fluids ensures that any change in fluid flow rate has a greater effect within the model equations than is to be expected from an examination of the measurement data. In practice flow rate disturbances produced only small changes in outlet temperatures from the tubes and shells of the heat exchangers and steady state was re-established within a period of five minutes following the disturbance.

No method could be found,within the aims originally stipulated for the mathematical model, that would produce a more accurate and hence stable response for the temperatures T(2) and T(3).

Because of the complex interactions that exist between the mathematical equations describing the evaporator, errors in the prediction of T(2) and T(3) have obvious repercussions with all other variables

FIGURE 5.3A

TEMPERATURE EX PREHEATER TUBES.

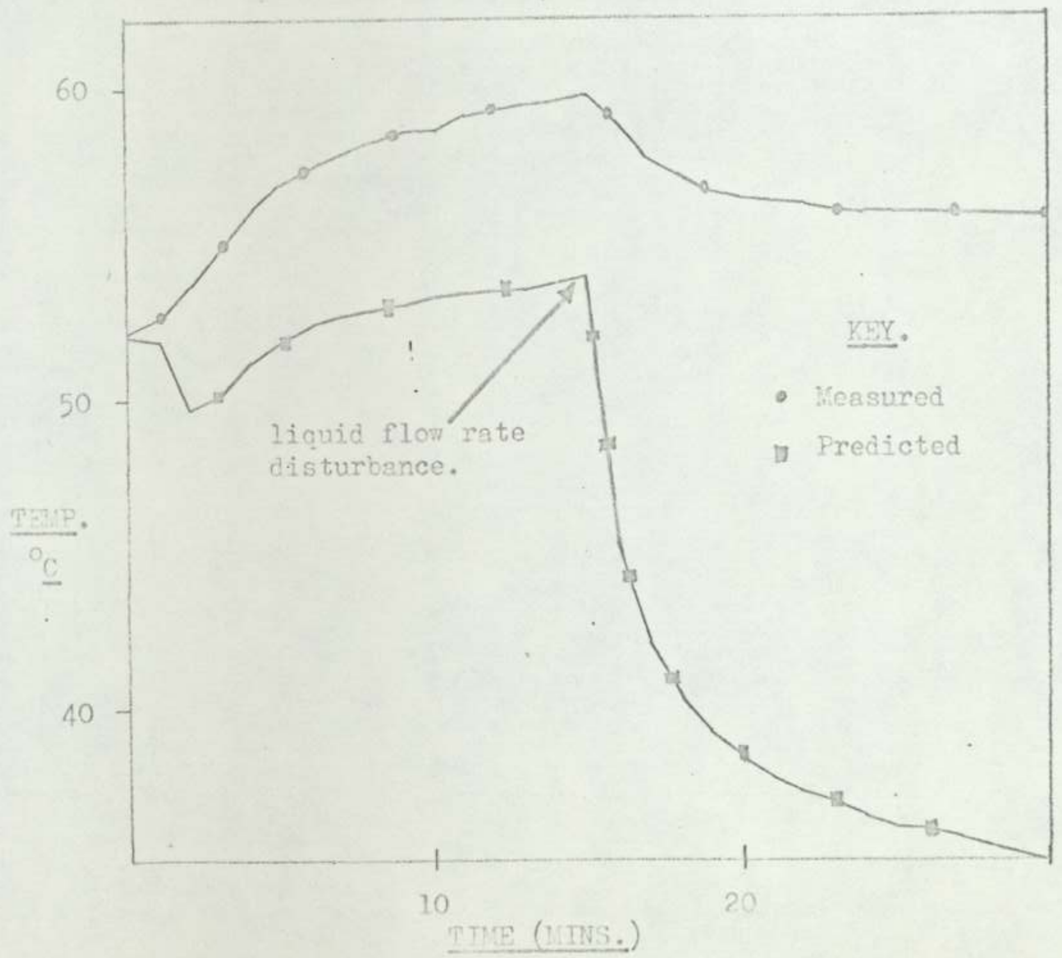
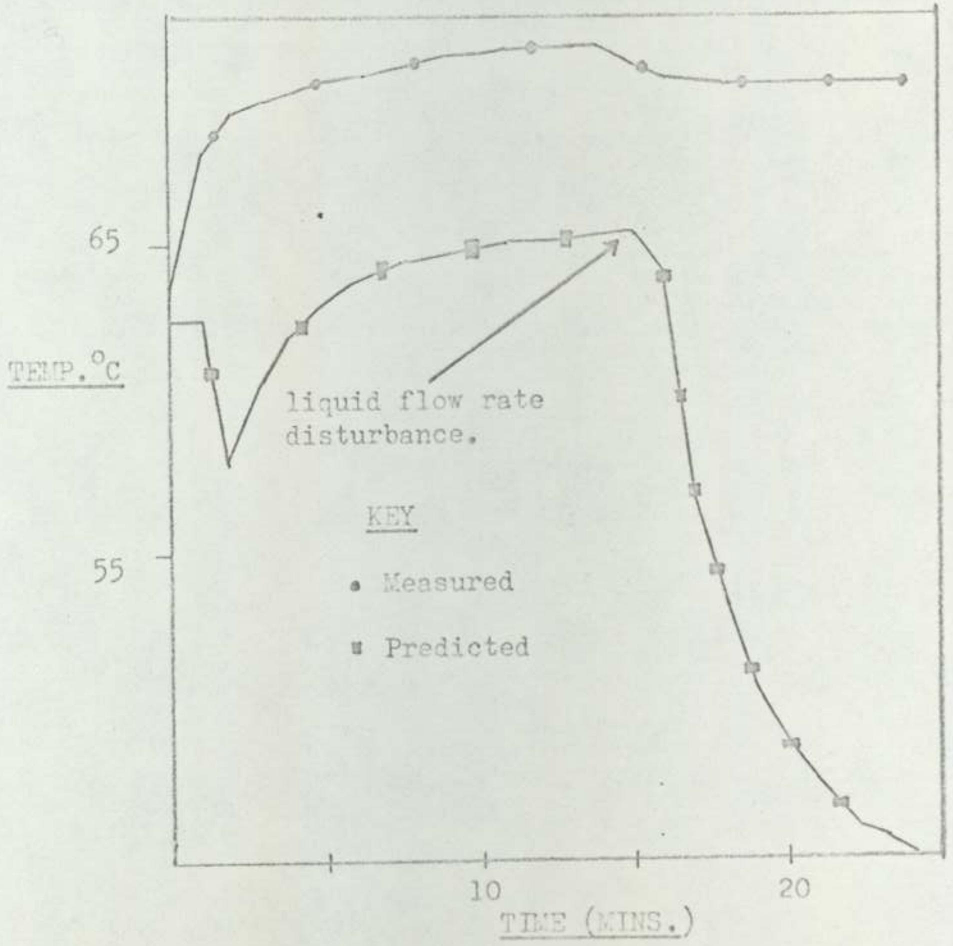


FIGURE 5.3B.

TEMPERATURE EX FIRST EFFECT TUBES.



predicted from the model. Some method must be found to accurately predict T(2) and T(3).

Examination of the instrument calibration data associated with T(3), from chapters 3 and 4, shows the high degree of accuracy of readings from the instrument. It was decided therefore to incorporate the measured values of T(3) into the model, directly as inputs. This modification allows equation 5.16 to be removed from the mathematical model with a corresponding reduction in computation times associated with the simulation of the model.

The inaccuracies in the model, remaining at this stage of the development, can once again be attributed to the assumption of well mixed fluids on the tube and shell side of the heat exchanger units. The well mixed assumption offers an approximation to the true state in only the broadest sense. In the literature survey the point has already been made that the correct mathematical description of the temperature dynamics of a heat exchanger is a system of distributed parameter equations. As an ordinary differential equation model is required within the filter algorithm then the well mixed assumption must remain in some form. An empirical constant is therefore suggested which when operating on the time constants associated with the mass flow rate terms, contained in each equation, will reduce the effect of flow rate changes and thus increase the accuracy of the predicted responses from the model.

For example equation 5.6,

$$\frac{dT(2)}{dt} = \frac{M(1).C1.(\ T(1) - T(2)) + U_P.A_P.(\ T(4) - T(2)) - L(1)}{(\ M_{PT}.C_T \ + \ V_{PT}.\rho.C1\ )}$$

-------- (5.6)

becomes,

$$\frac{dT(2)}{dt} = \frac{M(1).C1.(\ T(1) - T(2)\ )}{N.(\ M_{PT}.C_T + V_{PT}.\rho.C1\ )} + \frac{U_P.A_P.(\ T(4) - T(2)\ ) - L(1)}{(\ M_{PT}.C_T + V_{PT}.\rho.C1\ )}$$

--------------(5.45)

The constant N must be determined for each of the differential equations of the model associated with temperature dynamics. To determine this constant the simulation of the model was carried out with changing values of N, for each equation, in an attempt to match up model predictions with measurement data from the evaporator. Because of the interaction between the equations the value of N must be determined independently for each equation. During these simulation experiments if the value of N was too low then the model predictions were (i) too vigorous for mass flow rate changes and (ii) relatively constant for steam flow rate changes , i.e. temperature driving force changes. If the value was too high then the predictions from the model were (i) the opposite to those measured for flow rate changes and (ii) too vigorous for steam flow rate changes.

The simulation experiments, to determine the value of N for equation 5.45, are shown for a particular measured dynamic response in Figure 5.4.

Similar experiments were carried out for the remaining differential equations of the model.

Incorporating the assumptions and empirical developments, described above, into the derived mathematical model gives the following steady-state, parameter and dynamic equations along with the required inputs to describe the double effect evaporator.

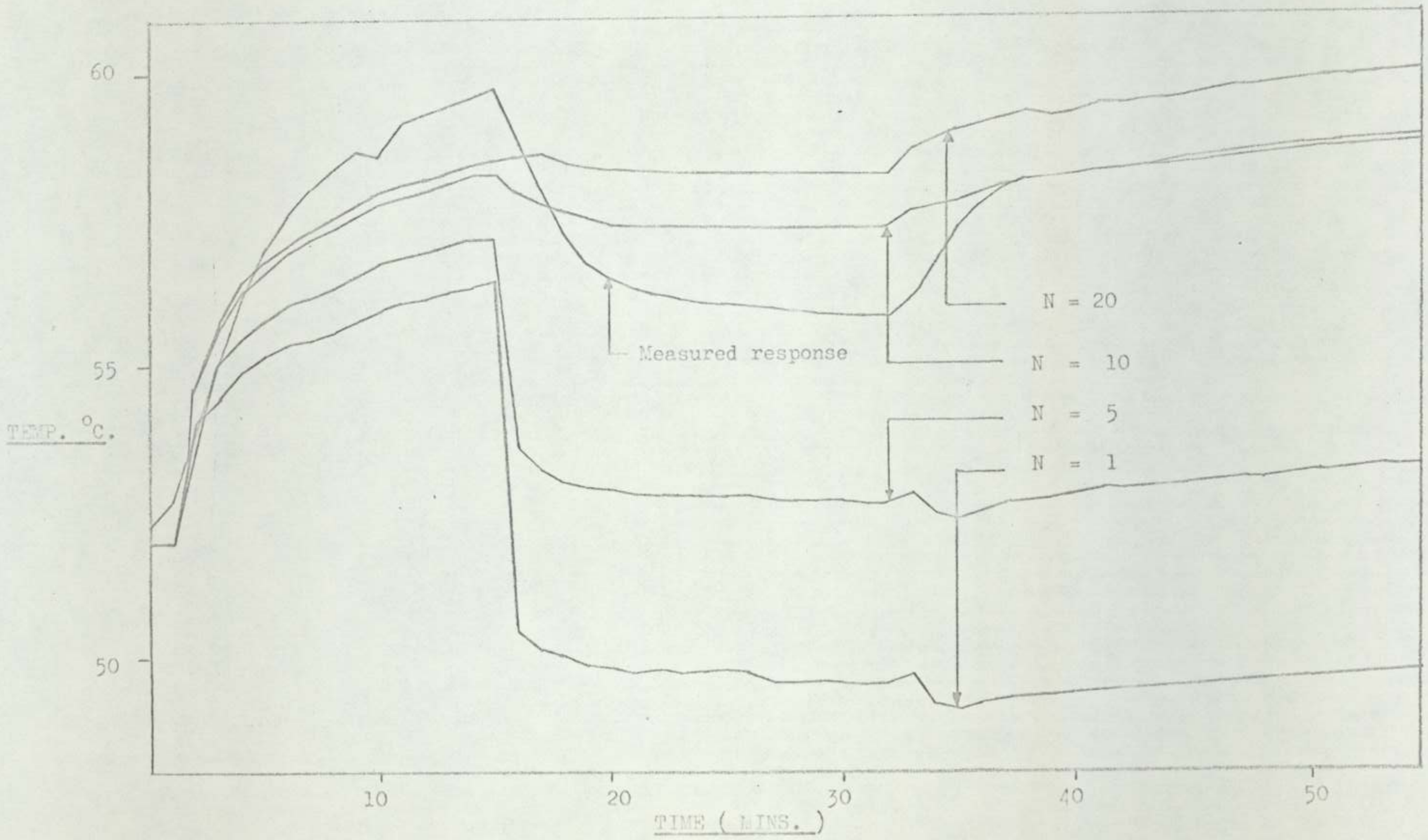
Inputs to the model; T(1), T(3), T(12), M(1), M(12) and V(5).

Differential equations;

$$\frac{dT(2)}{dt} = \frac{M(1).Cl.(\ T(1) - T(2)\ )}{10.(\ M_{PT}.C_{T} + V_{PT}.\rho.Cl\ )} + \frac{U_{P}.A_{P}.(\ T(4) - T(2)\ ) - L(1)}{(\ M_{PT}.C_{T} + V_{PT}.\rho.Cl\ )} \text{ ------------------ } (\ 5.46\ )$$

$$\frac{dM(4)}{dt} = \frac{M(1).Cl}{\lambda} . \frac{dT(2)}{dt} - L(2) \text{ --------- } (\ 5.47\ )$$

FIGURE 5.4. SIMULATION EXPERIMENTS TO DETERMINE THE EMPIRICAL CONSTANT ASSOCIATED WITH T(2).



$$\frac{dT(14)}{dt} = \frac{U_{SE}.A_{SE}.(\,T(10) - T(14)\,) - L(3)}{(\,V_{SET}.\rho.Cl + M_{SET}.C_T\,)} + \frac{M(14).Cl.(\,T(15) - T(14))}{10.(\,V_{SET}.\rho.Cl + M_{SET}.C_T)} \quad \text{---------- (5.48)}$$

$$\frac{dM(10)}{dt} = \frac{M(1).Cl}{\lambda} . \frac{dT(2)}{dt} - L(4) \quad \text{----------- (5.49)}$$

$$\frac{dT(13)}{dt} = \frac{M(12).Cl.(\,T(12) - T(13)\,) + U_C.A_C.(\,T(11) - T(13)\,) - L(5)}{(\,V_{CT}.\rho.Cl + M_{CT}.C_T\,)} \quad \text{----------- (5.50)}$$

$$\frac{dT(11)}{dt} = \frac{V(9).E(9) + V(10).E(10) + M(10).Cl.T(10) - M(11).Cl.T(11)}{(\,M_{CS}.C_{SS} + V_{CS}.\rho.Cl\,)} - \frac{U_C.A_C.(\,T(11) - T(13)\,) - L(6)}{(\,M_{CS}.C_{SS} + V_{CS}.\rho.Cl\,)} \quad \text{------ (5.51)}$$

$$\frac{dH}{dt} = \frac{M(8) - V(9)}{A_{SEP}.\rho} \quad \text{--------------- (5.52)}$$

Steady State equations:

$$V(3) = \frac{V(5).\lambda - M(1).Cl.(\,T(3) - T(2)\,)}{\lambda} \quad \text{----------- (5.53)}$$

$$V(9) = \frac{M(14).Cl.(\,T(14) - T(15)\,) + M(8).Cl.(\,T(3) - T(15)\,)}{\lambda} \quad \text{---------- (5.54)}$$

$$V(4) = V(3) - M(4) \quad \text{---------- (5.55)}$$

$$M(8) = M(1) - V(3) \quad \text{---------- (5.56)}$$

$$V(10) = M(1) - M(8) - M(10) \quad \text{--------- (5.57)}$$

$$M(11) = V(9) + M(10) + V(10) \quad \text{-----------} \quad (5.58)$$

$$T(4)_{k+1} = T(4)_k + (T(3)_{k+1} - T(3)_k) \quad \text{-------} \quad (5.59)$$

$$T(10)_{k+1} = T(10)_k + (T(3)_{k+1} - T(3)_k) \quad \text{------} \quad (5.60)$$

$$T(15)_{k+1} = T(15)_k + (T(14)_{k+1} - T(14)_k) \quad \text{------} \quad (5.61)$$

Parameter equations;

$$U_P = f(T(1), M(1), T(3), V(3)) \quad \text{---------} \quad (5.62)$$

$$U_{FE} = f(T(2), M(1), V(3), T(3)) \quad \text{---------} \quad (5.63)$$

$$U_{SE} = f(V(4), M(10), V(10), T(4), T(10)) \quad \text{-------} \quad (5.64)$$

$$U_C = f(M(12), T(13), M(10), T(12), T(15), T(11)) \quad \text{-------} \quad (5.65)$$

A simulation of the mathematical model described by equations 5.46 to 5.65 , for a typical experiment carried out on the double effect evaporator, is shown in Figures 5.5A to 5.5Z in Appendix 3. All variables and parameters are shown, with the measured response where appropriate. A listing of the computer program used to carry out the simulation experiments is shown in Appendix 1, the flow diagram is shown in Figure 5.6.

From the simulated results the following points arise for discussion;

(i) The assumption of constant temperature drop across the shell of the preheater and the shell of the second effect is not applicable in every instance. This is because the temperature drop is proportional to the pressure drop, which is itself flowrate dependent. Any change in vapour flow rate during an experiment will change the temperature drop, and thus cause errors in the model predictions. The error is greatest for the second effect shell, as the vapour flow rates in this unit are approximately fifty percent lower, and any absolute error in the pressure drop

Figure 5.6 Computer Program Flow Diagram For Simulation of Dynamic Model.

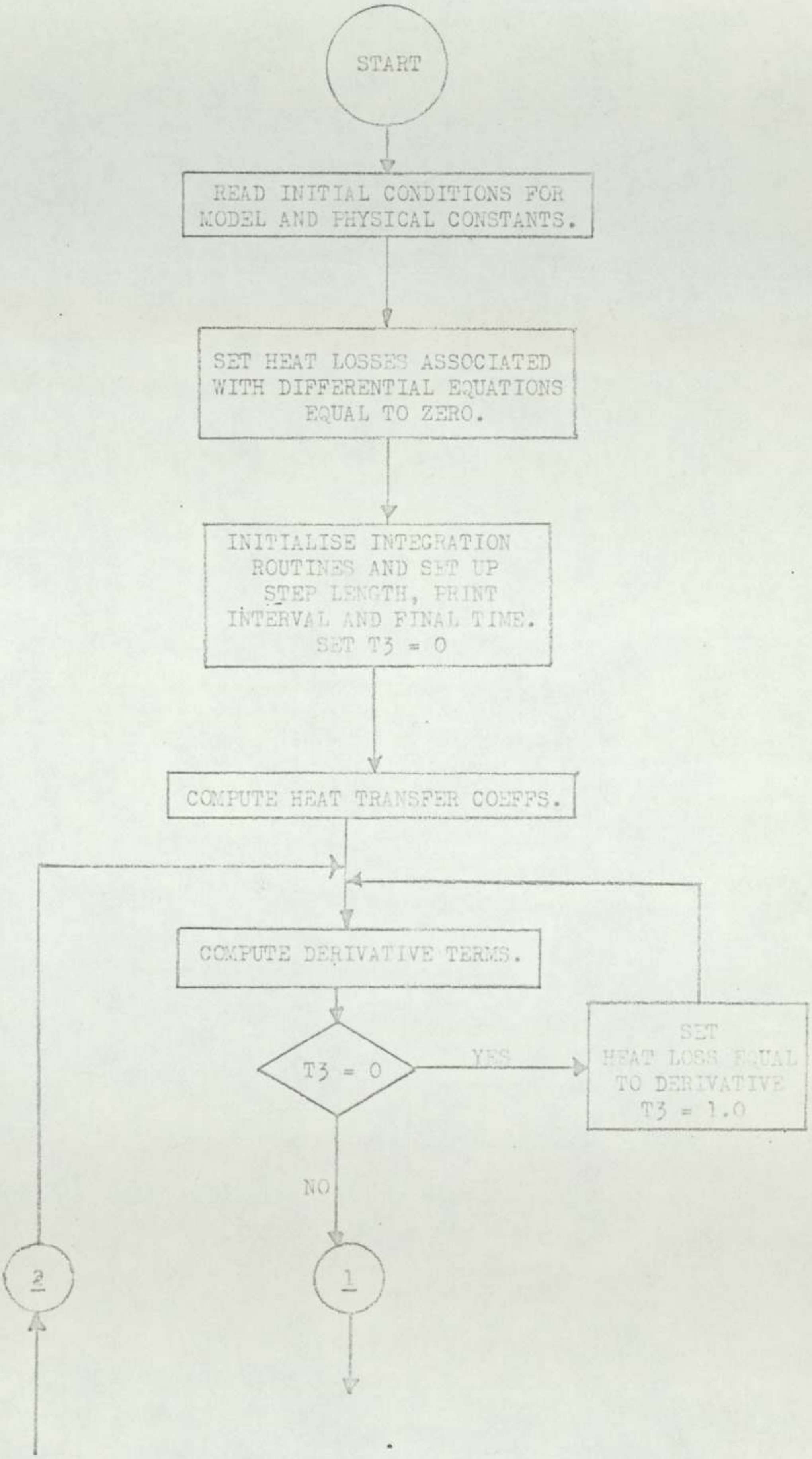
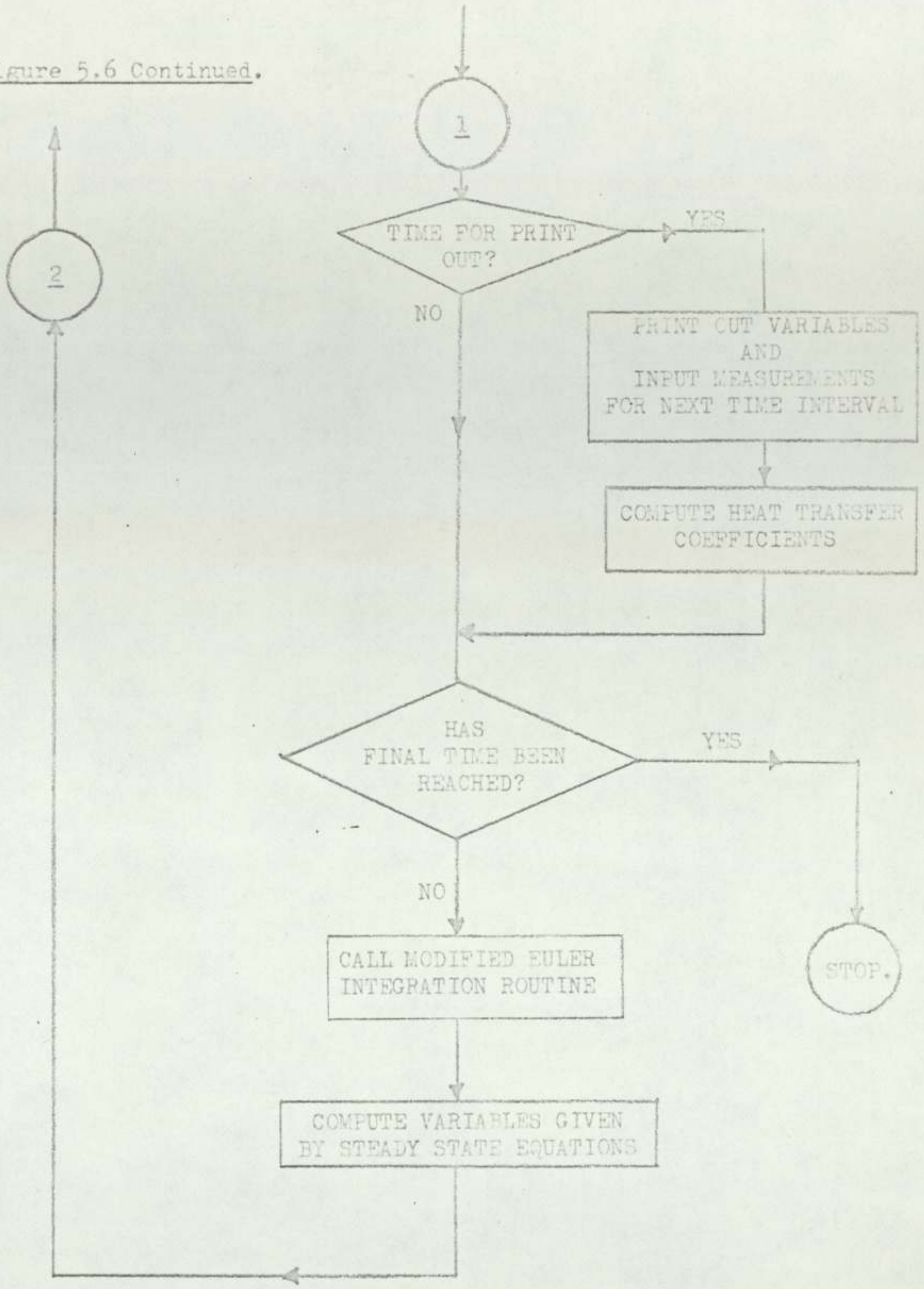


Figure 5.6 Continued.



will have its most noticeable repercussions at this point.

(ii) The oscillations in the measured response of M(8), as shown in Figure 5.5I, can be accounted for by the action of a liquid/vapour trap situated in the liquid exit line of the cyclone. This effect can not be incorporated into the model.

(iii) Some of the predicted responses, for example M(8) in figure 5.5I, are shown as step changes when a disturbance occurs to the system. During this period there exists a discrepancy between the predicted and measured responses. This is due to two reasons, the first being the assumption that the dynamics of some of the variables can be approximated by steady state equations and secondly the fact that time lags associated with the double effect evaporator have not been incorporated into the model.

(iv) Examination of the predicted and measured responses for the temperature of the liquid leaving the cyclone shows a sharp deviation between the two following a disturbance to the system, (see Figure 5.5C),. The assumption has been made within the model that the vapour and liquid are in equilibrium and that there is no heat loss over the cyclone. An analysis of the steady state data,(see Chapter 4), shows that these assumptions would appear valid. However following a disturbance to the system the fluid leaving the first effect tubes would appear not to be in equilibrium. The result is that on entering the cyclone further vaporisation occurs due to the drop in pressure across the cyclone entrance, with the latent heat of vaporisation being removed from the liquid stream.

(v) The derivation of the dynamic equation describing the height in the second effect separator involves no assumption that can not be justified, i.e. that there is no loss of mass from the separator. Any errors in its prediction therefore must occur through errors in the values of M(8) and/or V(9) substituted into the dynamic equation 5.52. Examination of Figures 5.5I and 5.5J for dynamic experiment No. 1 show that the errors in the prediction of H can not be accounted for by the errors associated with the prediction of M(8) alone. There must therefore be errors in the prediction of V(9). Any errors in the prediction of V(9) will also have repercussions in the prediction of both T(11) and T(13) as seen through equations 5.50 and 5.51. This accounts partly for the discrepancy in the predictions of these variables as seen through Figures 5.5E and 5.5F. The vaporisation rate, V(9), is dependent upon the vacuum pump characteristics, the vapour rate from the second effect shell and the vapour temperatures. In other dynamic experiments carried out, especially at high steam rates, equation 5.54 was found to produce accurate estimates of V(9) as seen through comparisons of the measured and predicted values of H and M(8). A typical example of this is shown in Figures 5.7A and 5.7B, (the predicted and measured values of H for dynamic experiments 1 and 2.), and also Figure 5.8, (the measured and predicted values of M(8) for dynamic experiment 2). In order to produce accurate predictions of V(9) under all conditions an accurate description of the vacuum pump characteristics is required. No simple method could be found to describe the behaviour of the vacuum pump.

5.6 Integration Interval for model simulation.

To keep the computation process time optimal it is desirable to make the integration step length, for the solution of the differential equations of the mathematical model, as large as possible. It is accepted however that an increase in integration step length will cause a corresponding increase in the error in the predictions from the integration routine. It is desirable that some compromise be reached between the two extremes of accuracy and computation times.

From an examination of Appendix 3 it can be seen that the largest transient response is obtained from the simulation when a disturbance occurs to the steam flow rate to the first effect shell. The differential equation showing the largest response to this disturbance was the temperature T(2). For a typical experimental data set, the model was simulated

FIGURE 5.7A.

Height in Second Effect Separator.

Dynamic Experiment No. 1.

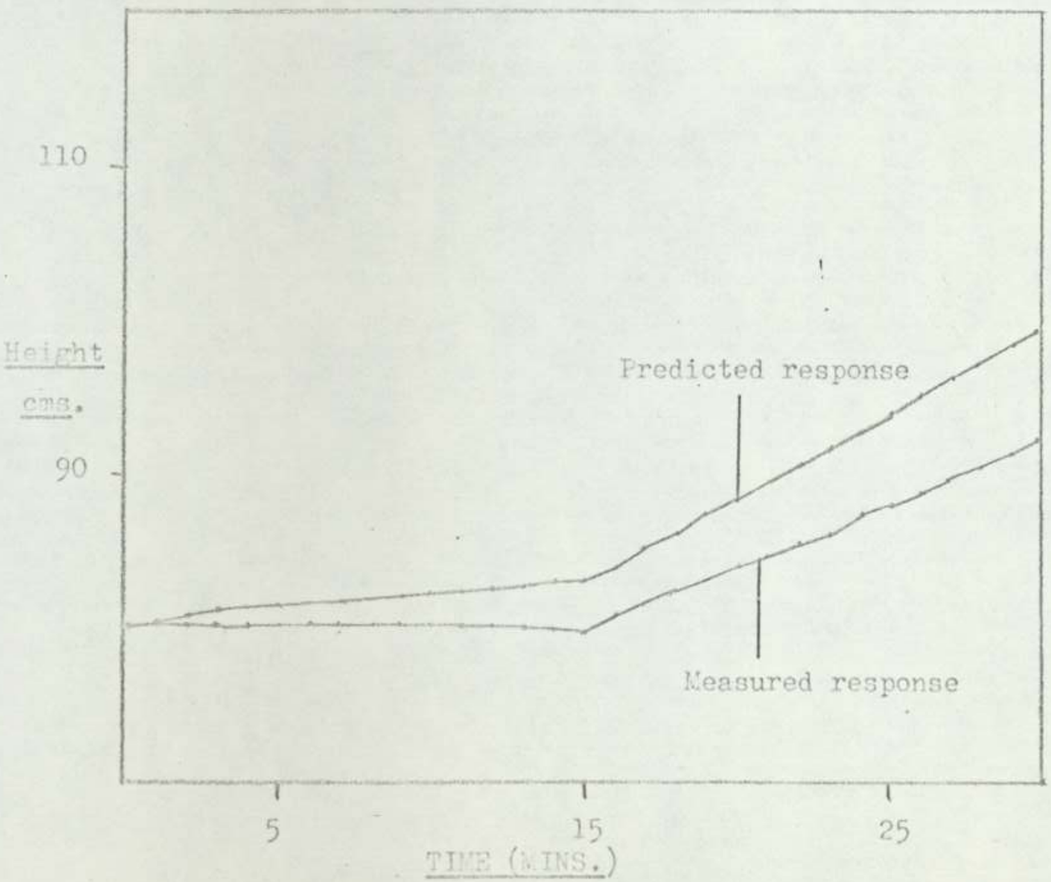


FIGURE 5.7B.

Height in Second Effect Separator.

Dynamic Experiment No. 2

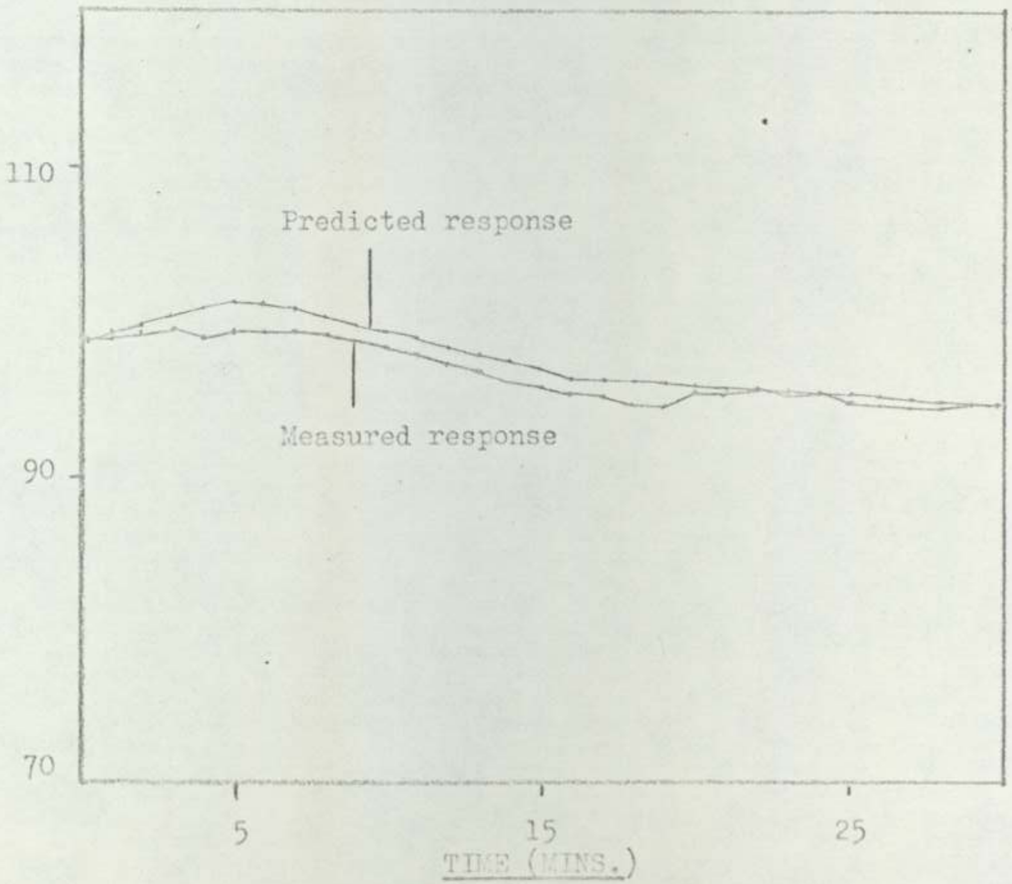
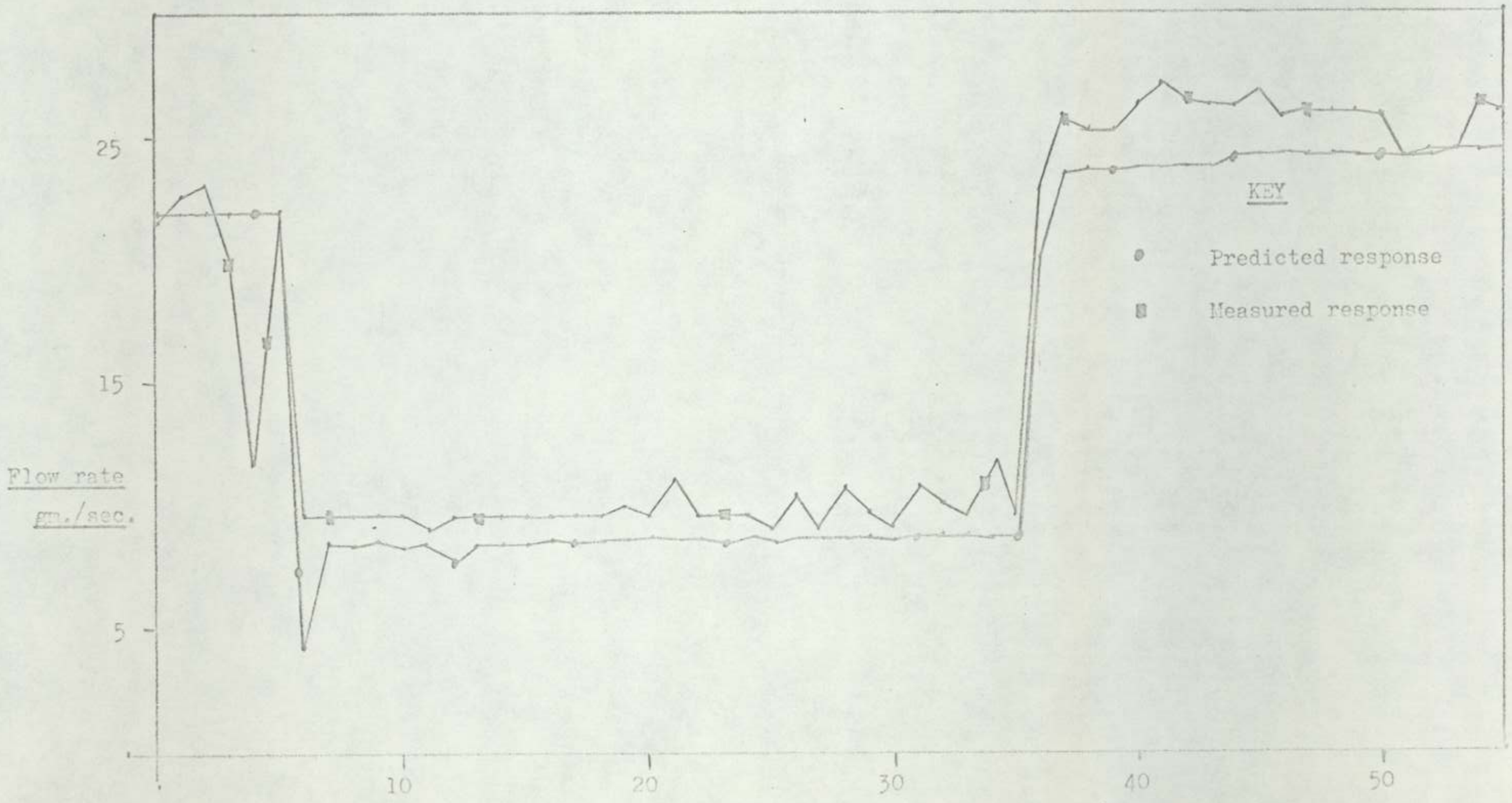


FIGURE 5.8. LIQUID FLOW RATE EX CYCLONE. DYNAMIC EXPERIMENT No. 2.



using varying step lengths within the integration routines. A step length of 0.01 seconds was used as the standard on which to base the accuracy or otherwise of more meaningful step lengths, i.e. those offering solution in real-time or better. Step lengths compatible with the measurement data interval were used for comparison.

Following a steam flow rate disturbance to the evaporator it was found from an examination of the measurement data that the rate of change of the variables of the mathematical model reached a maximum after five minutes. This was therefore chosen as the comparison point. At this point of the integration of the mathematical model the computer program was stopped and the value of the temperature $T(2)$ noted. These values are shown in Table 5.1. It was decided that any "inaccuracy", or difference, in excess of 0.1°C., for the variable $T(2)$, against the standard would be unacceptable. Based upon this criteria an integration step length of twelve seconds was chosen for use in model simulation experiments.

Table 5.1 Comparison of Step length within the Integration routine.

INTEGRATION STEP LENGTH(SECS.)	VALUE OF T(2) AFTER FIVE MINUTES (°C).
0.01	48.5137
1.00	48.5196
2.00	48.5237
3.00	48.5346
4.00	48.5454
5.00	48.5561
6.00	48.5668
7.50	48.5827
10.00	48.6090
12.00	48.6298
15.00	48.6933
20.00	49.9500
30.00	52.6321

CHAPTER SIX.

Chapter 6. The Kalman Filter and Model Error.

6.1 Introduction.

A comparison of the simulated and measured values, from the double effect evaporator dynamic model and plant shown in Chapter 5, highlights the difficulty of accurately predicting plant responses for a given plant disturbance.

Several authors, for example Wells (6.1) and Sorenson (6.2) have suggested that the Kalman Filter is capable of dealing with slight model inaccuracies. Jazwinski (6.3), on the other hand, states that an "erroneous" model will lead to divergence, of the estimates produced from the filter, away from the true state of the physical system. This he states is especially the case when the filter operates over many data, for then the filter is capable of learning the "wrong" state too well. As the operation time of the filter increases so the error covariances of the predictions, and hence the gain matrix, becomes numerically small. Subsequent observations therefore have little or no effect upon the filter and the estimates produced show a continual divergence from the "true" state. As the two stated viewpoints above have been verified by their respective authors, there is an obvious problem to be overcome in the definition of the term "slight model inaccuracies". This definition could not be achieved by the author or any previous researchers in this field. An examination of the simulation experiments carried out in Chapter 5 would suggest however that the dynamic model of the double effect evaporator should be placed in the "erroneous group" cited by Jazwinski. That this is in fact the case is demonstrated in a later section, (see Chapter 7).

In order that any estimation exercise, carried out with reference to the double effect evaporator, should produce meaningful results, the inaccuracy of the dynamic model developed in Chapter 5 must be recognised and acted upon. Several alternatives exist to compensate for this inaccurate model of which the two most obvious are (i) a more accurate dynamic model of the double effect evaporator should be developed and/or (ii) one of the previously discussed, (see section 2.1.6), extensions to the Kalman Filter algorithm should be adopted that would improve the estimates produced from the filter when using a model that has been recognised as inaccurate. In the context of the double effect evaporator, model improvement alone would not appear to be the solution, as any extensions to the model that would improve the agreement between measurements and predictions would still offer no guarantee of accuracy as regards those variables and parameters that can not be measured. Obviously model improvements must go some way towards providing the solution to the divergence problem. Any improvement in the knowledge of the dynamics, of the system under study, must give a corresponding improvement in the actions of the filter algorithm when predictions and measurements are not compatible. However due to the reasons highlighted and discussed in Chapter 5, extensions to the model to improve the accuracy overall are not thought to be feasible.

The more practical proposal is to incorporate within the Kalman Filter algorithm some extension that will control and if possible eliminate the divergence of the estimates produced by the filter when using an inaccurate model.

6.2 The Prevention of Divergence.

In the literature review, (see section 2.1.6), an account has been given of the methods that have been proposed for the solution of the divergence problem. It is desirable to find one such method that will (a) be compatible with the computer hardware available in terms of processing time and core requirements and (b) offer implementation without the requirement of extensive system testing.

The second point is important with regard to implementation of estimation to modern chemical processes. It may not be possible or convenient to cause disturbances to the system so that transient data can be collected for off-line experiments.

Of the many theoretical and empirical methods that have been proposed for the solution of the divergence problem some can be discarded immediately as they are incompatible with the practical aims of the estimation exercise with reference to the double effect evaporator. Examples of this incompatability are to be found in the methods proposed by Lin and Sage (6.4) and Friedland (6.5). These authors in separate publications have recognised the ability of the Kalman Filter to accurately estimate parameters associated with the dynamic model of the physical system under investigation. They therefore incorporate into each prediction equation a parameter to account for the errors that may exist within that equation. This approach has been shown to be feasible, providing the condition of observability is met, for simulated experiments. The inclusion of these parameters however has the practical effect of doubling the size of the state vector and its associated matrices and thus placing an intolerable burden upon computer core requirements and computer processing times.

To study the effects of these proposed modifications to the Kalman Filter, of those methods that offered practical compatibility, two test models were proposed for simulation and filtering experiments. The first model represented a heat exchanger with associated chemical reaction and the second model a co-current heat exchanger. Both models deliberately avoid the use of non-linearities for mathematical description, as the non-linearities themselves have been shown to be the cause of some cases of filter divergence, (see for example Yoshimura (6.6) and Alspach (6.7)). To gain a "true" state and an "inaccurate" model for each of the test systems the dynamic equations were simulated to represent different numbers of C.S.T.R.'s.

Model Number 1. This model represents a heat exchanger in which an exothermic chemical reaction takes place. Heat exchange occurs from the shell to the tube contents with the shell contents being at a constant temperature. The chemical reaction is first order. The equations describing the transient behaviour are:-

$$\frac{dT_{N+1}}{dt} = \frac{U.A}{VT.\rho.C_p} . \left(T_s - \left(\frac{T_{N+1} + T_N}{2} \right) \right) + \frac{M}{VT.\rho} . (T_N - T_{N+1}) + \frac{\triangle H.k.C_{N+1}}{VT.\rho.C_p} \quad \text{---------} \; (6.1)$$

and $$\frac{dC_{N+1}}{dt} = \frac{M}{VT.\rho} . (C_N - C_{N+1}) - k.C_{N+1} \quad \text{------} \; (6.2)$$

where C = concentration, T = temperature

VT = volume of the tubes, k = reaction rate constant

U = heat transfer coefficient, M = mass flow rate (tube)

A = area for heat transfer, ρ = density

C_p = specific heat, T_s = Temperature of shell

$\triangle$H = enthalpy change for reaction,

subscripts N + 1 refers to the exit of the C.S.T.R.

N refers to the inlet to a C.S.T.R.

Model Number 2. This model represents a co-current heat exchanger. The heat transfer coefficient and the physical properties are taken as constant. The temperature driving force between the shell and the tube is taken to be the arithmetic average. The equations describing the transient behaviour are:-

$$\frac{dTS_{N+1}}{dt} = \frac{MS}{VS.\rho} .(TS_N - TS_{N+1}) - \frac{U.A}{2.C_p.VS.\rho} . (TS_{N+1} + TS_N) - (T_{N+1} + T_N)) \quad \text{-----------} \; (6.3)$$

$$\frac{dT_{N+1}}{dt} = \frac{MT}{VS.\rho} . (T_N - T_{N+1}) + \frac{U.A}{2.C_p.VT.\rho} . ((TS_{N+1} + TS_N) - (T_{N+1} + T_N)) \qquad \text{-----------} (6.4)$$

where MT = tube flow rate

MS = shell flow rate

VS = volume of shell.

The values of the constants used in Model Nos. 1 and 2 along with the initial conditions of the variables are shown in Table 6.1.

In both of these models the simulation of the equations was carried out for cases when N was set equal to three and one. The case when N was equal to three provided the "true" state for later comparisons of the estimates produced from the filtering experiments. When N was set equal to one provides the model that was used within the filter equations. Figures 6.1A and B and 6.2A and B show typical results of these simulations for models 1 and 2 respectively when a flow disturbance was applied to the equations. For all filtering experiments the final tube exit temperature from the model equations was taken as measured. The measurements were obtained from results of the simulation of the "true state" with added random noise of known statistics.

6.3 Results and Discussion.

As a preliminary experiment the "inaccurate" models were applied in the Kalman Filter algorithm. The noise statistics for both the measurements and equation inputs were correctly defined. The results of these experiments are shown in Figures 6.3A and B and 6.4A and B. The divergence of the estimates produced by the filter can clearly be observed, particularly so for the unmeasured variables of each model. This acute divergence of the unmeasured variables is due to the fact that in the early stages of the filtering experiments the predictions of all variables are slightly inaccurate.

Table 6.1

Model no. 1

Variable.	Value.	Units.
U	450	J/ M^2.°C.sec.
C (in)	0.8	mass fraction
T (in)	50	°C.
VT	π.10	M^3
k	125	sec^{-1}
A	π.10	M^2
ρ	62.4	grms/M^3
C_P	1.98	J/grm.°C
TS	132	°C
△H	-2500	J
M	13500	grms/sec.
C(out)	.606	mass fraction
T(out)	66.94	°C.

Model no. 2

Variable.	Value.	Units.
MS	900	grms/sec.
MT	500	grms/sec.
VS	10	M^3
VT	15	M^3
C_P	1.98	J/grm.°C.
TS(in)	90	°C.
TS(out)	70.26	°C.
T(in)	54.9	°C.
T(out)	70	°C.
ρ	62.4	grm/M^3
A	7	M^2
U	125	J/M^2.°C.sec.

Figure 6.1A Temperature exit tubes.

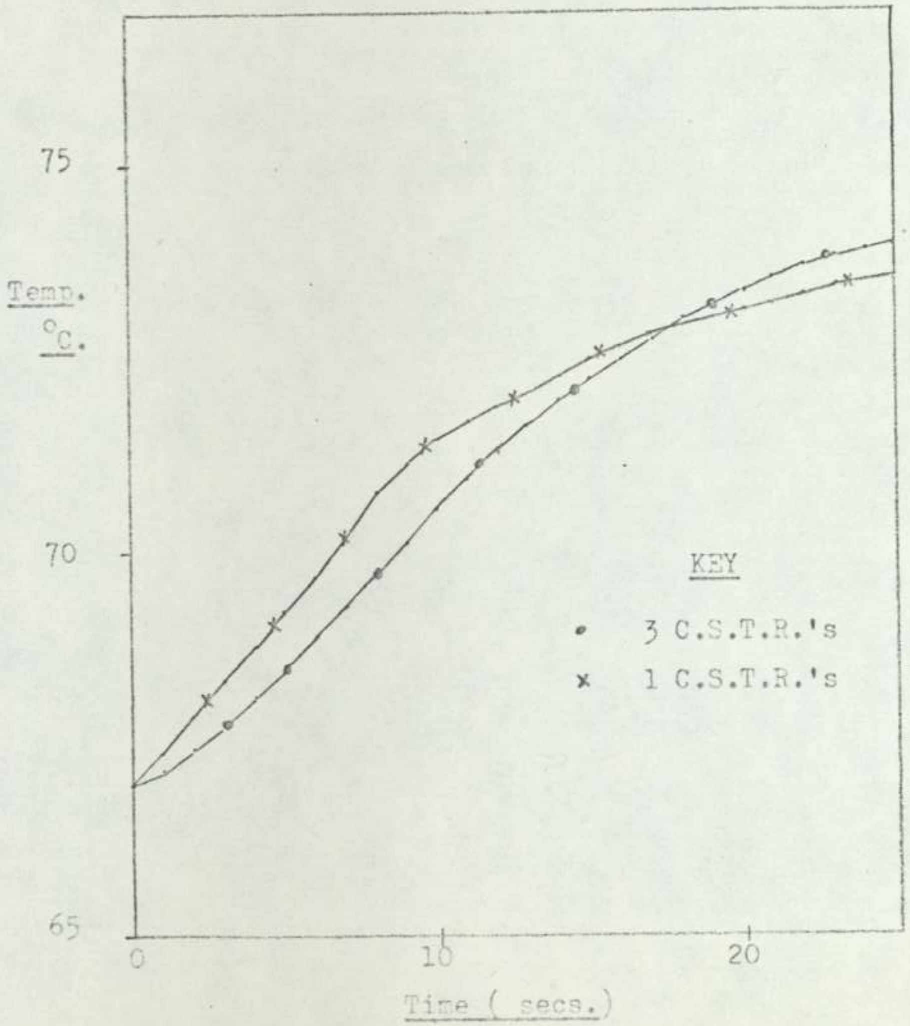


Figure 6.1B Concentration exit tubes.

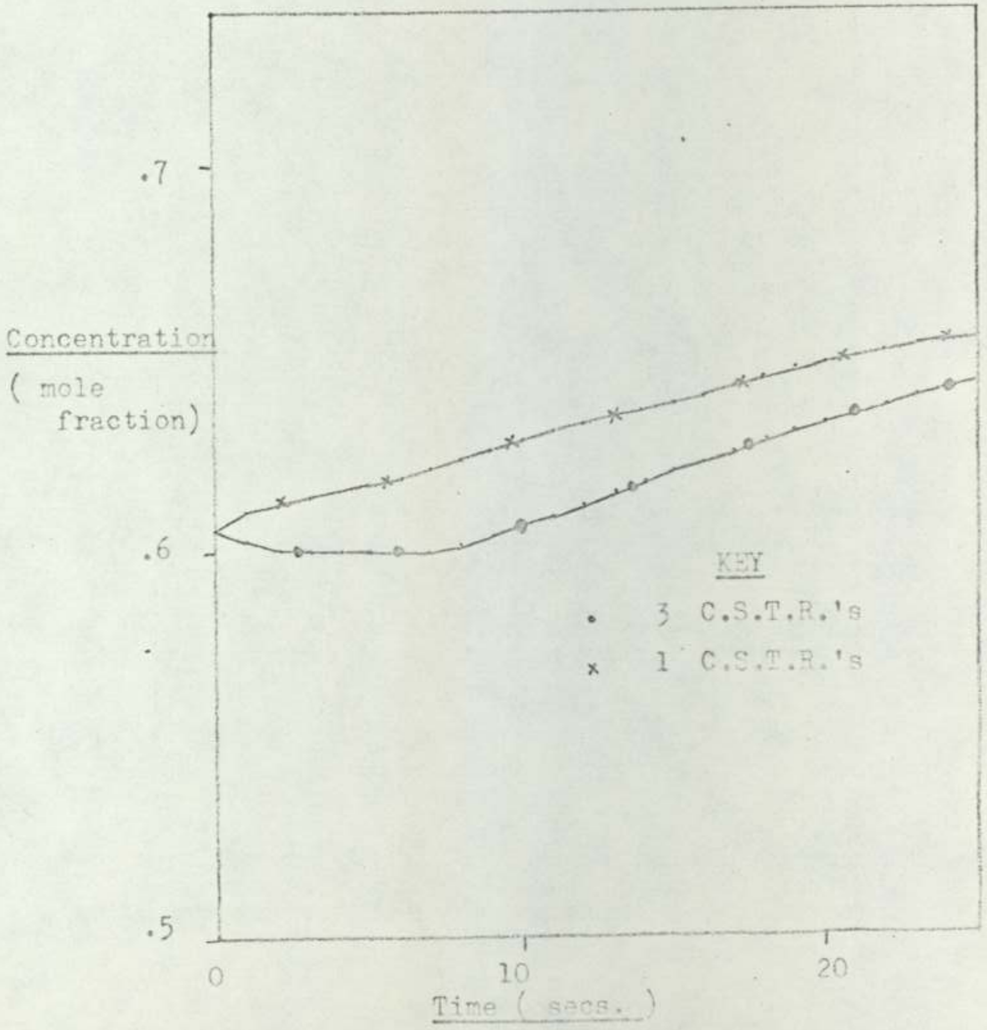


Figure 6.2A Tube exit temperature.

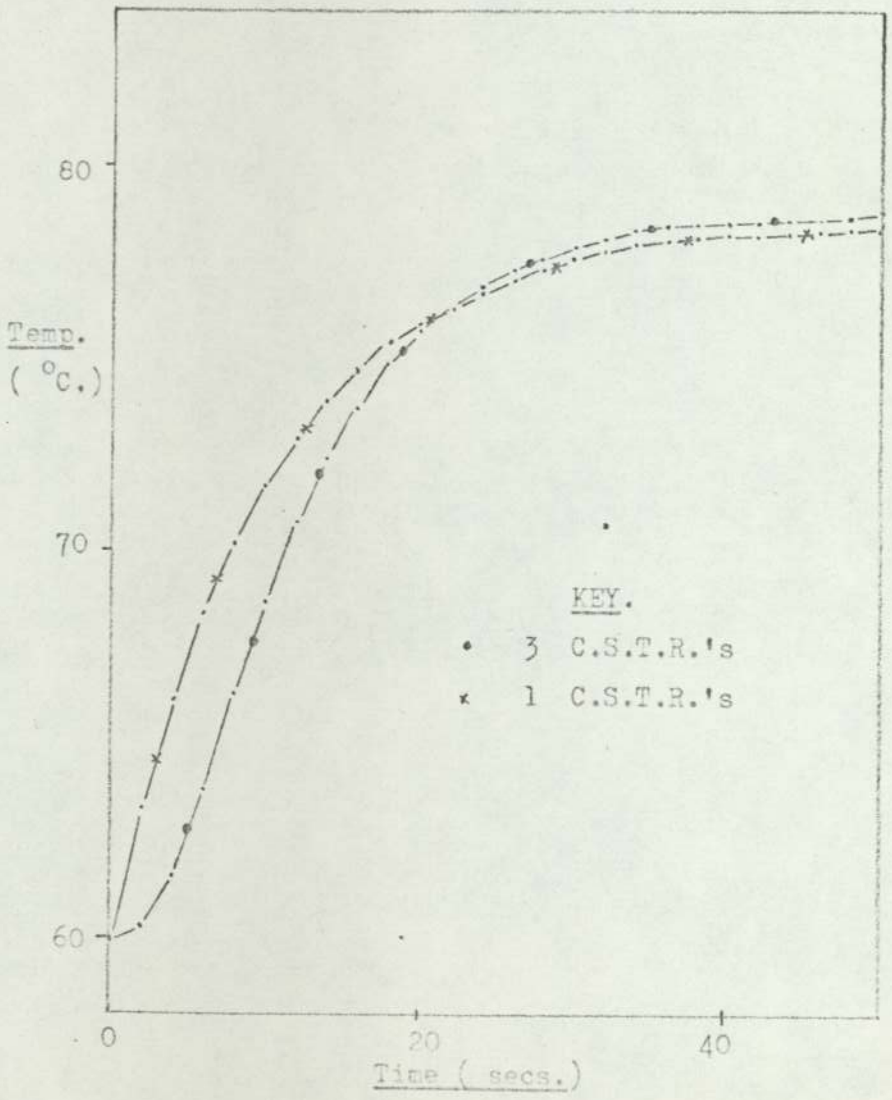


Figure 6.2B Shell exit temperature.

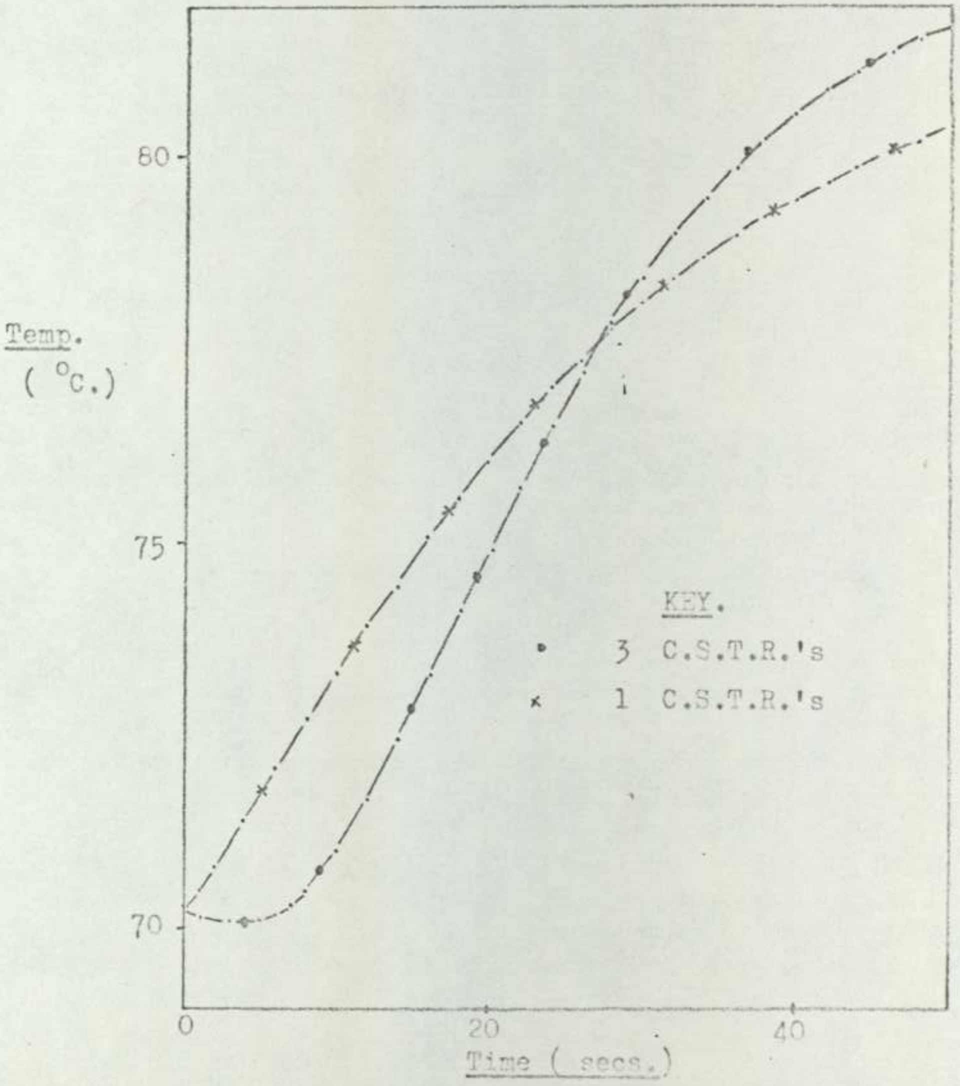


Figure 6.3A. Temperature exit tubes.

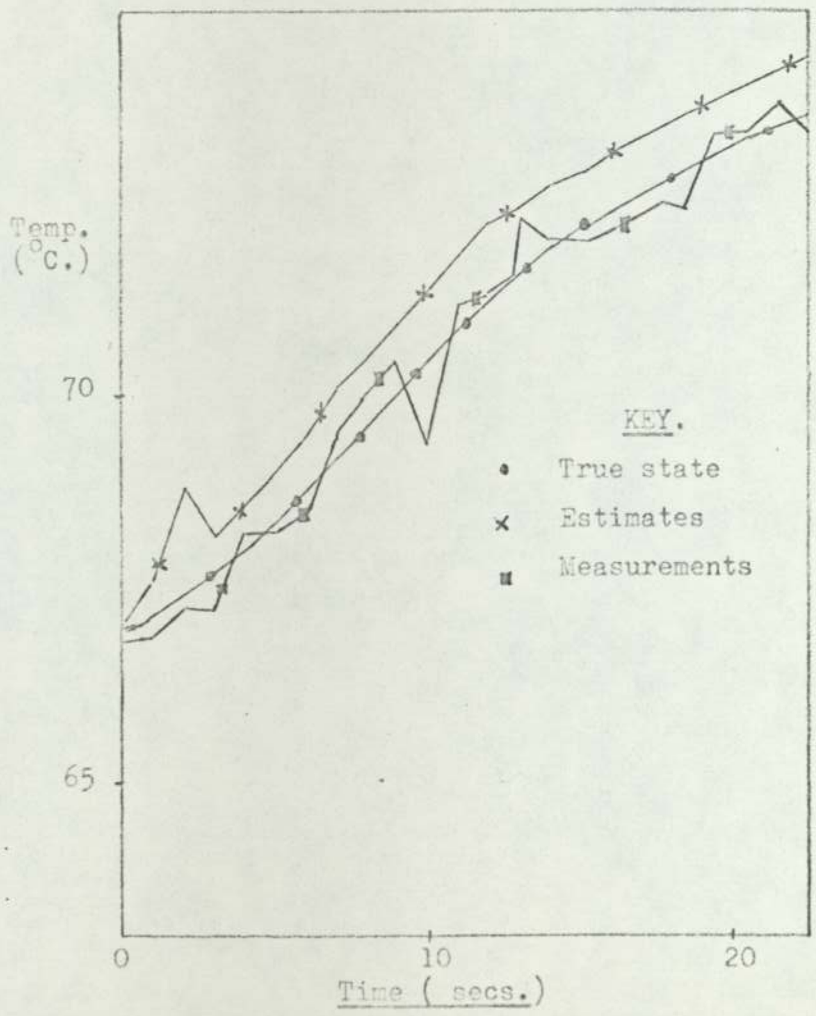
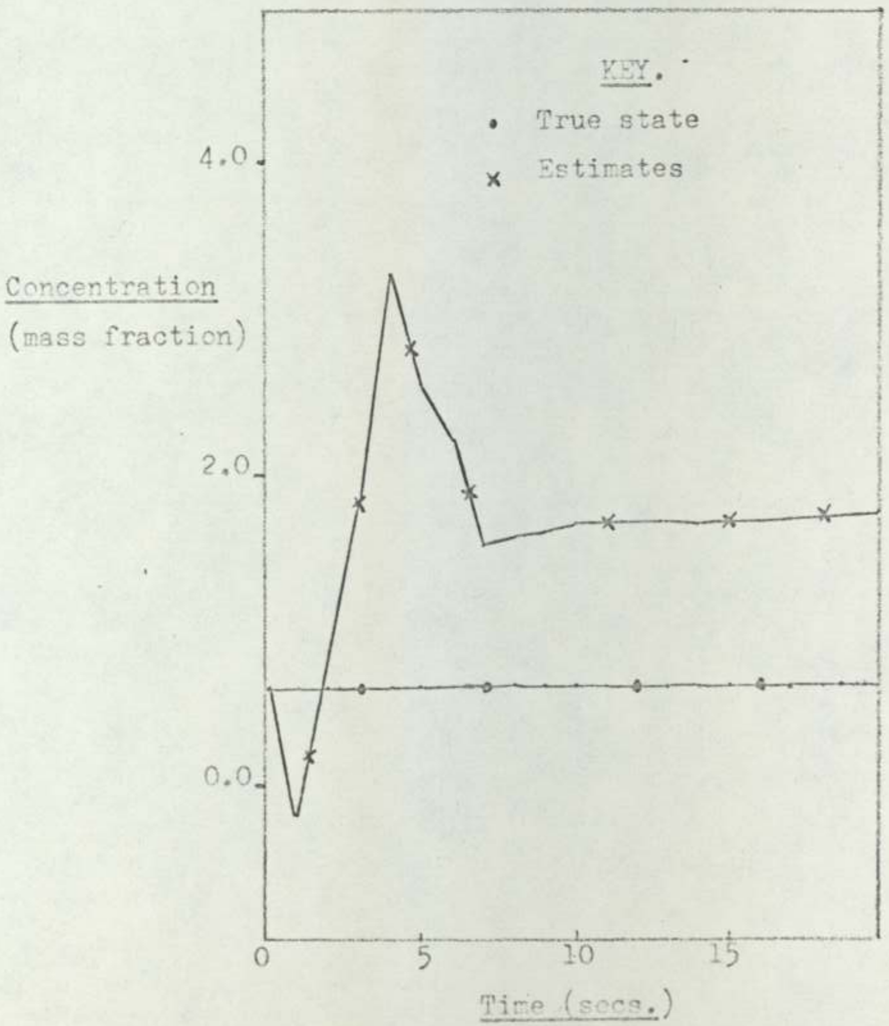


Figure 6.3B. Concentration exit tubes.



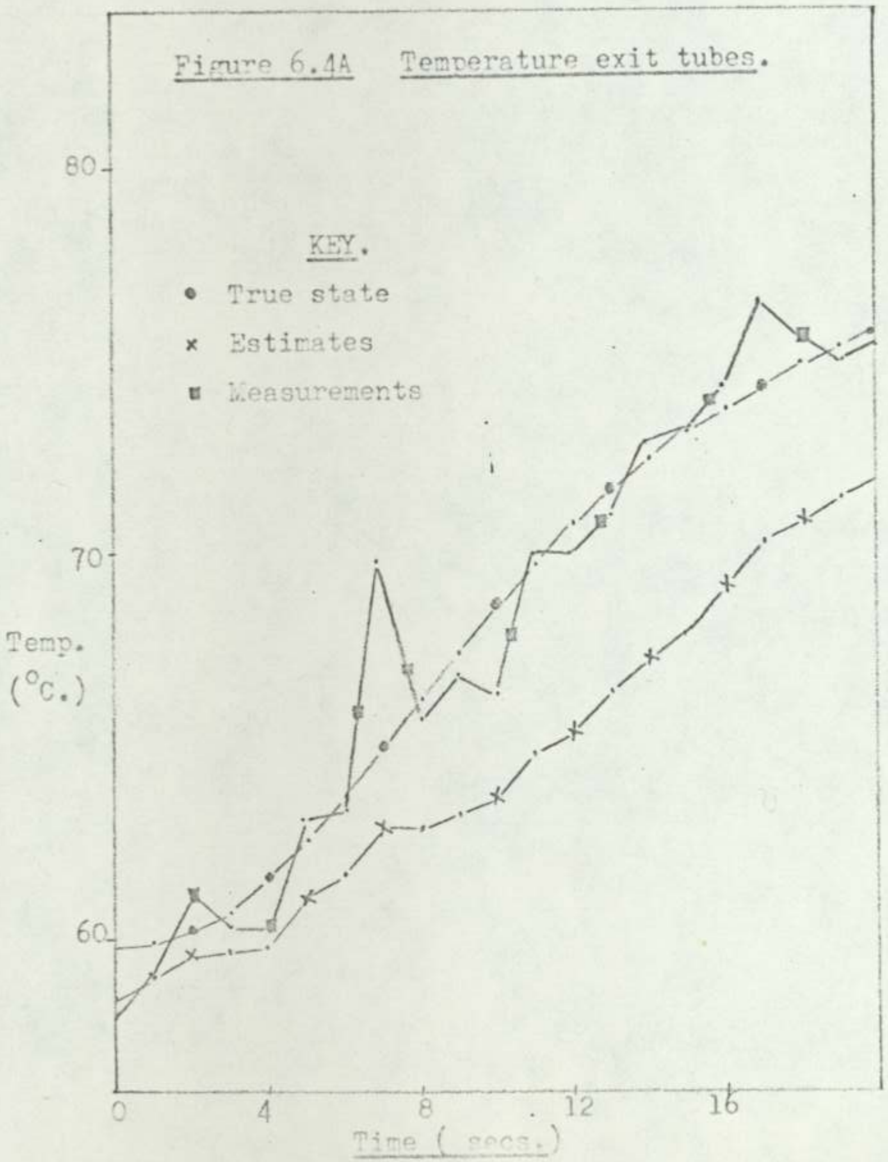


Figure 6.4A Temperature exit tubes.

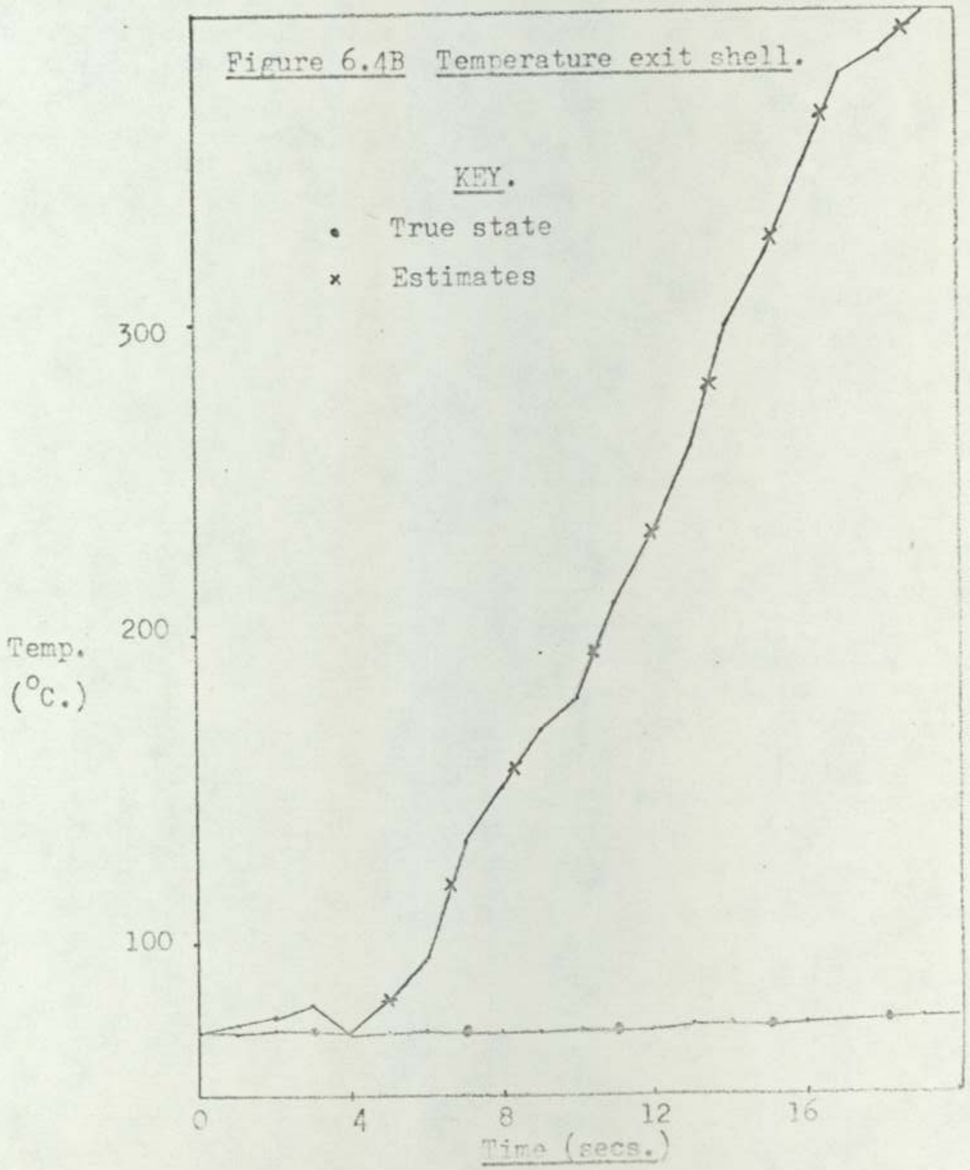


Figure 6.4B Temperature exit shell.

The measurements that come into the filter allow these predictions to be updated. This updating however is done on the basis of the poor model within the filter algorithm. This causes the unmeasured variables to be driven to values that would have given the "correct" values of the measured variables after taking into account the measurement statistics. As the experiment time increases so the filter statistics converge, the filter takes less notice of the new information that comes into the algorithm via the measurements and bases its estimates more and more on the predictions from the poor model.

6.3.1 Input noise statistics.

Early attempts at a solution to the problem of filter divergence centred around the use of the matrix of input noise covariances, Q, (see for example Schlee et al. (6.8)). These researchers stated that inaccuracies occuring in the mathematical model predictions could be compensated for by increasing the numerical values of the Q matrix. This increase in the Q matrix they called "fictitious noise". The justification for this approach was that any difference that existed between a predicted and measured output could be accounted for by a lack of knowledge of the inputs to the system. The method has the obvious advantage that increasing Q stops the convergence of the error covariances of the predictions $P_{k/k-1}$ beyond a certain point, (dependant upon the numerical value of the Q matrix), and through $P_{k/k-1}$ to the gain matrix. The overall result is that the filter must take into account the new information presented by the measurements at all time levels and the divergence of the estimates is controlled if not eliminated. The disadvantages of this approach are (i) the choise of the numerical value of the fictitious noise, and (ii) if the method is to account for error in the model then an examination of the results shown in Figures 6.1A and B and 6.2A and B indicates that the error is not a constant factor. The value of Q therefore should more accurately be classified as a variable that itself is recalculated at each time interval.

Experiments carried out to determine the "best" value of Q showed the necessity for off-line trials due to its system dependence. Various numerical values were used to describe the "fictitious noise" and examples of this for Model no. 2 are shown in Figure 6.5A and B. If the value of the fictitious noise was too low the system diverged as with the ordinary filter and too high a value meant that the filter followed the measurements exactly, using the model to change the unmeasured variables as described previously. Even the "best" value of this fictitious noise, found experimentally, produced estimates from the filter that were both inaccurate and contained an inherent bias.

For systems having large measurement noise a problem of oscillation was found for the unmeasured variables. The large values of Q required to control the divergence caused the measured variables to follow these inaccurate measurements exactly. This in turn causes the unmeasured variables to fluctuate wildly as the filter attempts to match the measurements and the predictions of the measured variables.

6.3.2 The exponential filter.

Several researchers, (see for example Anderson (6.9)), have suggested the use of an exponential filter to overcome the divergence problem caused through a poor model description. An exponential filter has the effect of overweighting the most recent information made available to the filter algorithm in the form of measurements. The practical significance of this approach is that the error covariances of the predictions and hence the gain matrix are not allowed to converge.

The exponential time constant associated with this method is taken to represent the approximate time span over which the poor model will accurately represent the system under consideration. If this time constant is too low the method reduces to that of a filter with a large addition of

Figure 6.5A Temperature exit tubes.

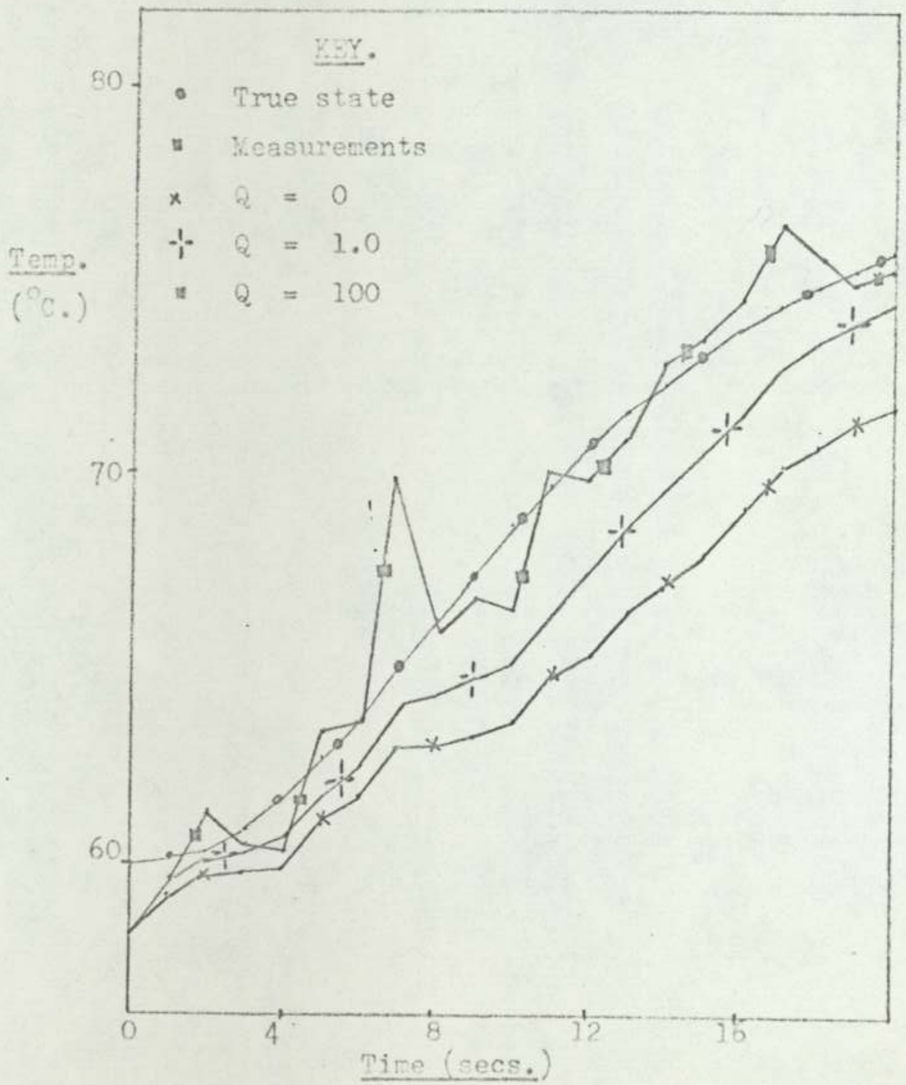
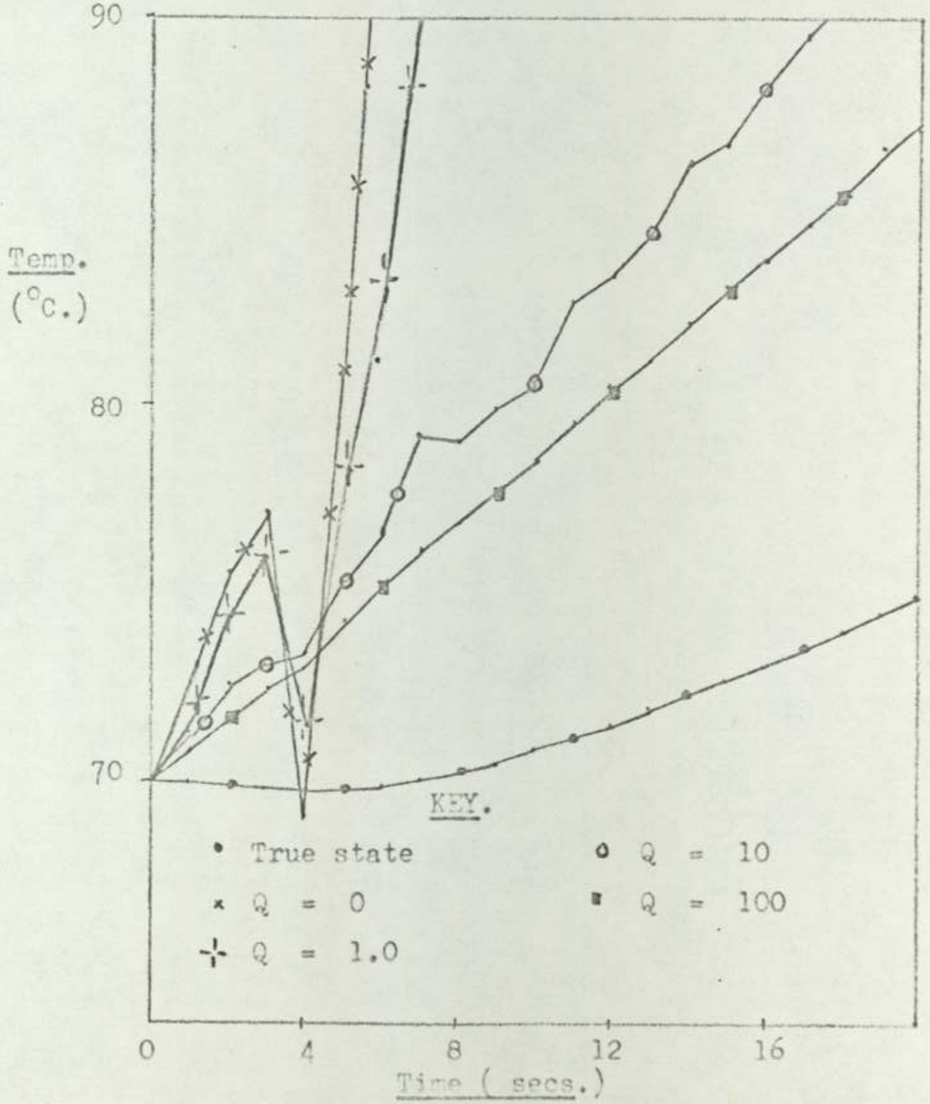


Figure 6.5B Temperature exit shell.



fictitious noise. Too high a value reduces the method to an ordinary Kalman Filter.

Experiments carried out using this approach for both models 1 and 2 indicated that a time constant of four produced the most accurate estimates from the filter. This time constant agrees with values produced by Kilbride-Newman (6.10) and Coggan and Wilson (6.11) which would suggest that the exponential filter is not system dependent. The results of the filtering experiments using this time constant are shown in Figures 6.6A and B and 6.7A and B along with the "best" values of the fictitious noise experiments.for comparison.

6.3.3 The method of Sriyananda.

Sriyananda (6.12) offers an excellent method for the control of divergence. The method recognises the fact that the covariances of the differences between the measured and predicted values of the measured variables produced by the filter, i.e.

$$H.P_{k/k-1}.H^T + R$$

can be verified from the measurements themselves. Define the matrix IN as,

$$IN = (Y_k - H.X_{k/k-1}) \text{ --------- } (6.5)$$

then $IN^T IN$ should be less than 3 times the trace of $(H.P_{k/k-1}.H^T + R)$ with 90% probability. If this is not the case then divergence can be suspected.

If divergence is suspected the filter gain is frozen at its current value, i.e. it is not updated. This ensures that the error covariance matrix $P_{k/k-1}$, is then limited to incrementing by the factor Q at each time interval, (after accounting for the effects of the transition matrix.) This process continues until $IN^T IN$ becomes less than the trace

Figure 6.6A Temperature exit tubes.

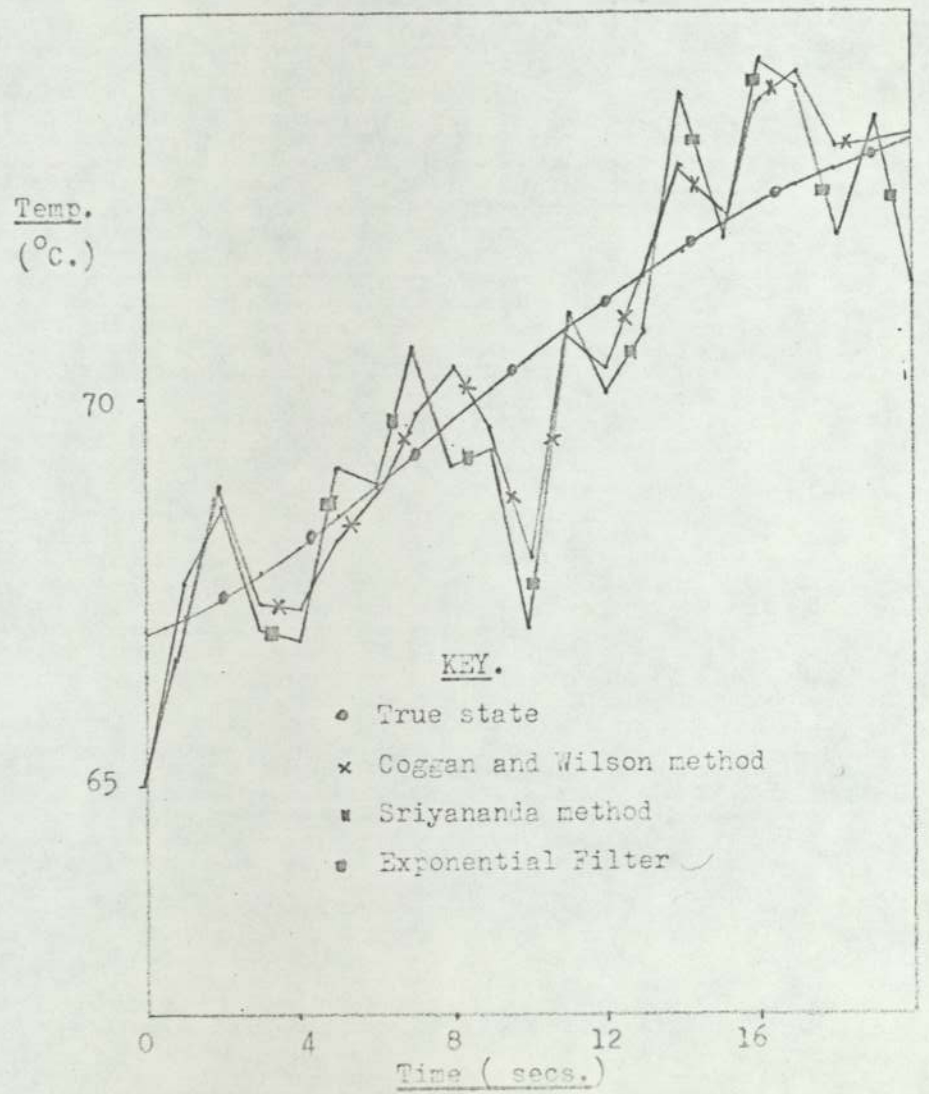


Figure 6.6B Concentration exit tubes.

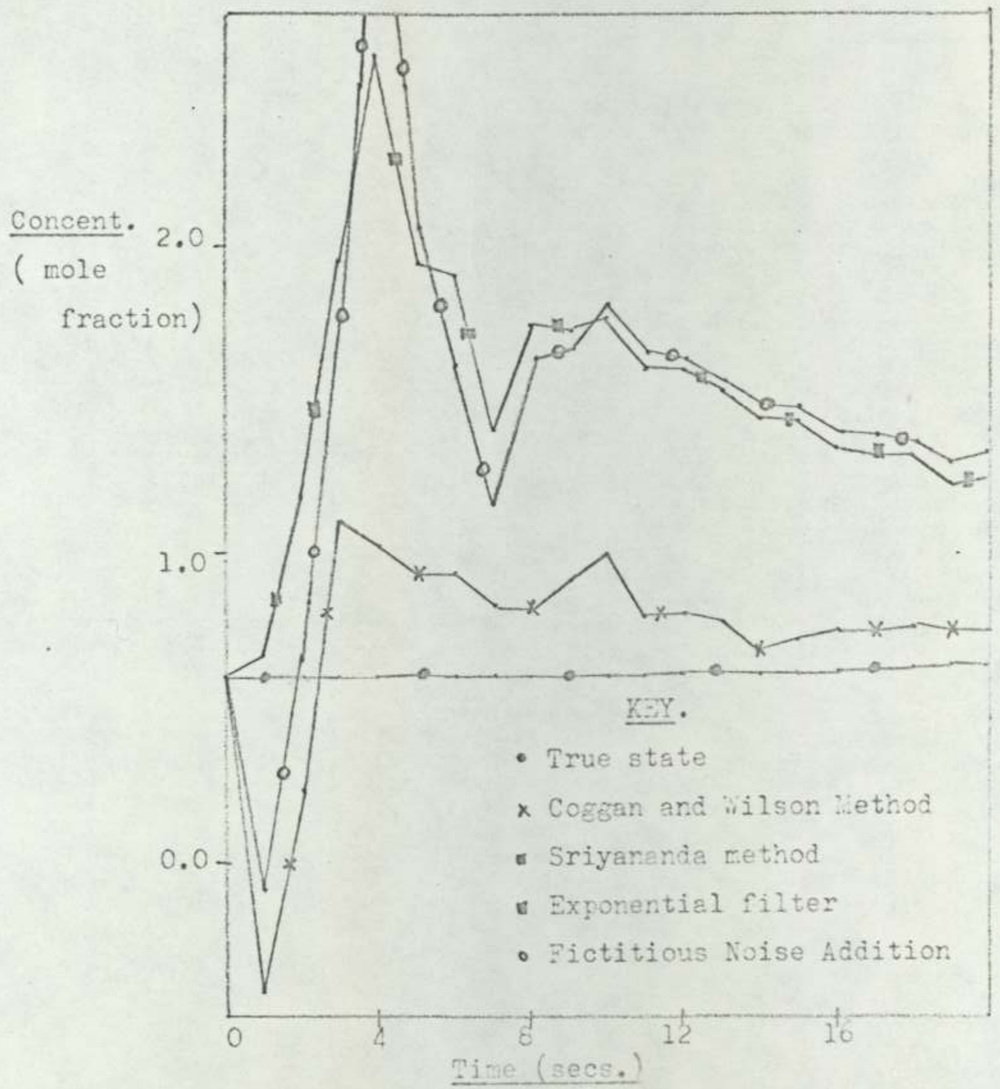


Figure 6.7A Temperature exit tubes.

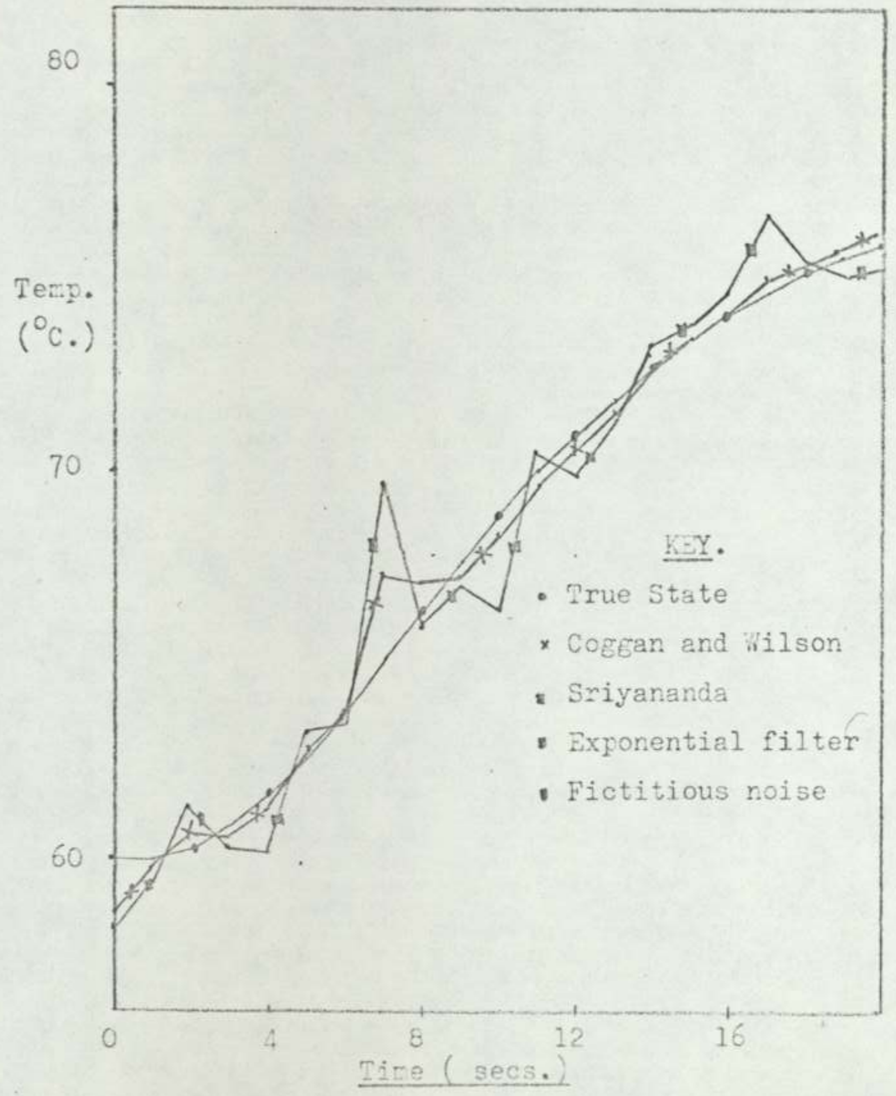
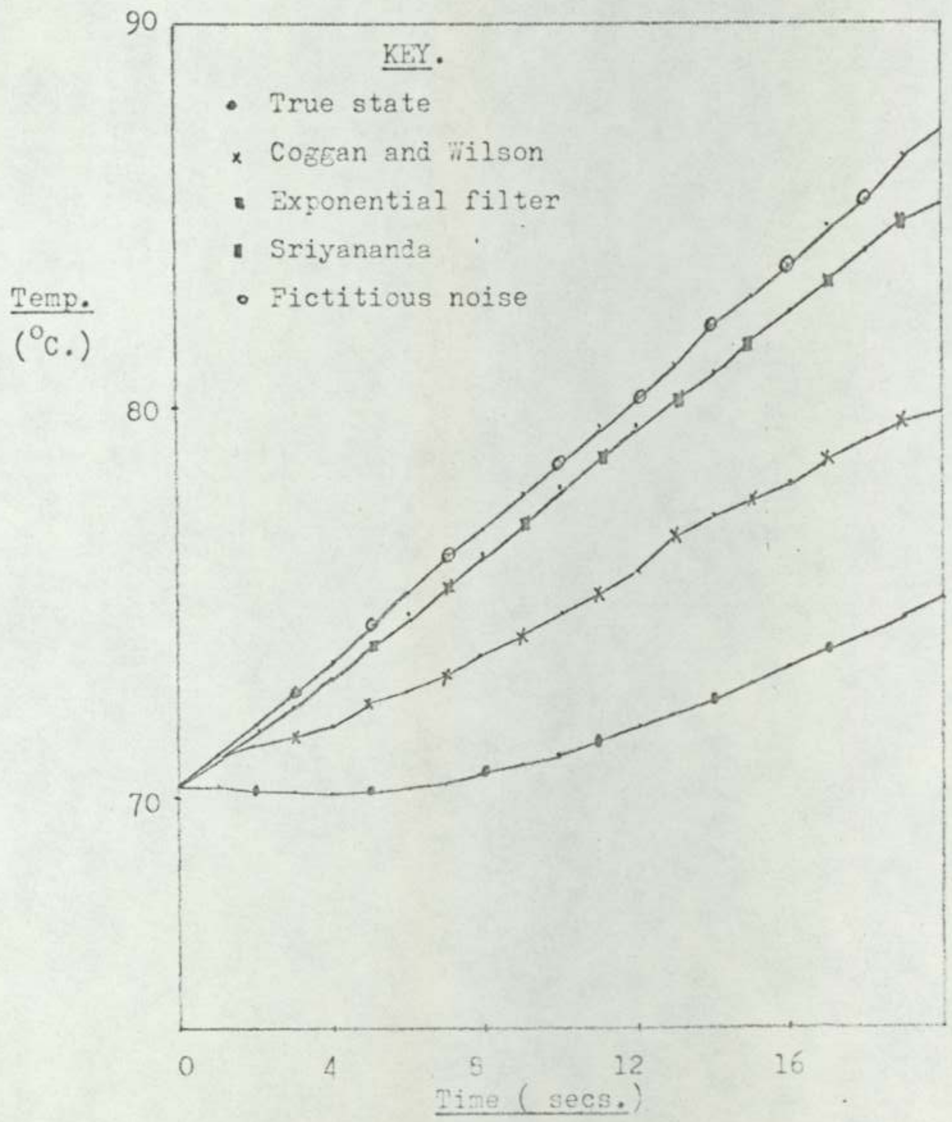


Figure 6.7B Temperature exit shell



of ($H.P_{k/k-1}.H^T + R$), at this point the filter is defrozen. As $P_{k/k-1}$ would be large at this point, the filter gain would increase, thus exhibiting some of the features of the exponential filter.

The method was used for both Models no. 1 and 2 and produced estimates that were as accurate as the "best" of the previous two methods without the requirement of pre-tuning experiments. It has the obvious advantages that it is not system dependent and even more important if the model is accurate it will not operate unless unmeasured disturbances occur. In this case the filter would loosen and realign upon the new trajectory of the system output vector.

Once divergence is suspected, using this approach, nothing further is done with the information available, concerning the extent of the divergence. The method in no way attempts to remove the divergence which results in a continuation of inaccurate predictions and estimates, (see Figures 6.6A and B and 6.7A and B.)

6.3.4 The method of Coggan and Wilson.

Coggan and Wilson (6.11) take the general process described in the previous section a step further and make use of the calculations required in the recognition of divergence. These calculations are extended to calculate a bias term associated with each of the measured variables. The method of Coggan and Wilson can be described generally as follows:-

(i) A matrix corresponding to $P_{k/k-1}$ is computed from the difference that exists between the measurements from the process and the predictions from the mathematical model. In all further calculations the largest of the two values is used.

(ii) A bias vector is computed based upon the statistics of the differences that exist between the measurements and the predictions.

(iii) The bias vector is subtracted from the original prediction vector to obtain bias free predictions of the measured variables.

As can be seen from Figures 6.6A and B and 6.7A and B, this method was the most successful of those examined for dealing with the divergence problem caused by model error. Because of the ability to recompute the correct matrix of error covariances of the predictions, associated with the measured variables, $P_{k/k-1}$, the filter can be started without an accurate knowledge of the initial values of the error covariances of the initial conditions, $P_{0/-1}$, and the error covariances of the input noise Q. The point has already been discussed in Chapter 4 regarding the difficulties associated with gaining an accurate estimate of the Q matrix.

The method does have the following disadvantages;

(i) All of the errors are assumed to lie in the predictions of the measured variables and no attempt is made to relate a proportion of the detected error to the unmeasured variables. Accurate estimates of the measured variables however go some way towards producing more accurate predictions overall from the mathematical model.

(ii) During parameter estimation the bias vector that is computed can no longer be used to produce bias free predictions. It is this bias term that acts as the driving force for the estimation of the parameters. With a poor model therefore the result is to drive the parameters to values that are consistent with the measurements and the "poor" model rather than the "true" state.

Experiments carried out using this method produced the most accurate estimates from the filter for model no. 1 and 2. The unmeasured variables were estimated to a high degree of accuracy but still offered scope for improvement due to their inherent bias. The results quoted by Coggan and Wilson showed a much higher degree of accuracy for unmeasured variables. This was due in some part to the criteria that was placed upon any mathematical model that was to represent the system under consideration by the authors. Their models had equal total capacitance, equal transfer or conversion in unit time and equal steady state boundary values as the physical system. These conditions imply a complete knowledge of the physical system under consideration, which is itself contradictory, and in a practical situation may not be readily implemented.

6.4 Conclusions.

In any modelling exercise associated with a chemical process there will always be some doubt about the accuracy of one or more of the predictions associated with the dynamic model. It is reasonable to suppose that such a model would on implementation within the Kalman Filter give rise to a problem of filter divergence to a greater or lesser extent. This being the case it is recommended that some method to control filter divergence should always be incorporated within the filter algorithm. The method proposed by Coggan and Wilson is recommended as being the most appropriate for the control of filter divergence in terms of its computational requirements and accuracy of estimates produced. A further consideration in its choise is that the statistics associated with the measured variables, i.e. $P_{k/k-1}$ and $P_{k/k}$, are accurate and offer therefore the required information for the starting point of a control algorithm.

The method of Sriyananda also offers an excellent approach to the control of filter divergence due to its ease of implementation and its non system dependence. In practical situations where problems of computer storage and processing times arise its use could be justified.

The exponential filter and fictitious noise addition have been shown to have only very limited practical application due to their system dependence and their inability to control the divergence problem.

The statistics of the filter produced by these two methods are "user" dependent in that they are functions of the exponential time constant or input noise matrix value respectively, which are set by the programmer. Because of this fact the statistics produced by the filter are of little value. Further more after a short operating period the filter statistics associated with these two methods reach a point of equilibrium, (dependent upon the value of the exponential time constant or input noise matrix), and may not be capable of "loosening" up when further disturbances occur to the system. This is not a criticism that can be levelled at the methods of Coggan and Wilson and Sriyananda, both of which adequately recomputed the statistics of the filter when a disturbance was detected.

CHAPTER SEVEN.

Chapter 7. On-line Kalman Filtering.

7.1 Introduction.

The aim of this chapter is to bring to-gether the results of the earlier sections in order to produce a filter algorithm that will generate accurate estimates of the state of the double effect evaporator. The filter must be capable of operating in conjunction with the hardware available and in real time.

The mathematical model of the double effect evaporator, (equations 5.46 to 5.65), was divided into sections to reduce the computation burden associated with the prediction and estimation of each of the 16 variables and parameters. That is only a proportion of the variables were estimated from the filter, the remainder because of their steady state relationships could be estimated outside of the filtering process. For this reason the following variables were estimated using the filtering process:- T(2), T(13), T(11),H, T(14), M(8), T(10), M(4) and M(10), with the first seven of these variables being available to the filter in the form of measurements.

7.2 Computer Program Development.

The ease of carrying out program modifications and error corrections when using the BASIC language makes its use highly desirable from a programming viewpoint. The FORTRAN language however offers the user much faster processing times and therefore some compromise between the two must be achieved for real time implementation.

In the development of an overall system for on-line filtering two further points require consideration. The first is the core available, for user programs and calculations, within the Honeywell H316. The Honeywell H316 computer offers the user a core of approximately 15000 octal locations for subroutines written in either DAP-16 or FORTRAN that are to be accessed from the users BASIC program. The second point is the base sector locations available for cross sector referencing. Within the Honeywell H316 computer the core is broken down into sectors, each of 1000 octal locations. If a subroutine crosses from one sector to another the appropriate reference points must be stored. Only 62 octal locations are available for this referencing within the base sector. Subroutines should be, as far as is possible, therefore of a size that allows their storage to be completed with a minimum of sector crossings.

On-line filtering requirements can be broken down into the following main areas; (i) The Kalman Filter algorithm and

(ii) Data acquisition from the double effect evaporator.

7.2.1 The Kalman Filter Algorithm.

The computer program for Kalman filtering requires the implementation of the algorithm described by equations 2.4 to 2.8 along with the modifications proposed by Coggan and Wilson (7.1), i.e. equations 2.12 to 2.16, for dealing with model errors. Examination of these equations shows the many matrix calculations that are required, including a large matrix inversion, (equation 2.6). It was decided that if real time implementation was to be at all feasible this section of the computer package would require to be written in the FORTRAN language.

Within the filtering algorithm measurements from the physical system are required. In order that off-line filtering experiments could also be accomplished the required programming for data acquisition was not incorporated into the Kalman Filter program. When data was required by the filter it was decided that the program should be returned to the BASIC level. Here the appropriate data could be entered into the computer from the required source and then returned to the FORTRAN level for processing. The change from one data source to another is obviously easily impemented using the interactive facilities of the BASIC language.

In order to reduce the cross sector referencing required the filter algorithm was divided into two sections. The first section being the prediction section, i.e. the solution of the mathematical model of the double effect evaporator, (equations 5.46 to 5.61), which was included in a separate subroutine, subroutine PREDIC. The remaining computation of the algorithm was carried out in subroutine KALMAN. Linking these two subroutines and the BASIC level is subroutine DATA.

7.2.1.1 Subroutine PREDIC.

A listing of this program is included in Appendix 1 and its position within the overall computation scheme is shown in Figure 7.1.

Subroutine PREDIC solves the mathematical model of the double effect evaporator, (equations 5.46 to 5.61). In the preceeding section the poor performance of the Coggan and Wilson algorithm, when dealing with poor models that also require parameter estimation, has been highlighted. For this reason the estimation of the heat transfer coefficients by the Kalman Filter was not attempted. The heat transfer coefficients were assumed constant over the prediction interval and updated, based upon the estimates from the filter, by use of equations 5.62 to 5.65 at each cycle of the computer program.

As in the simulation experiments of Chapter 5 the solution of the mathematical model of the double effect evaporator was accomplished by use of the modified Euler integration method. The step length for integration was set at the BASIC level.

The following variables are predicted from the mathematical model, for transfer to subroutine KALMAN, in the order T(2), T(13), T(11), H, T(14), M(4), T(10) and M(8), which optimises the vector manipulation required.

The subroutine obtains the values of the gradients, required for

FIGURE 7.1 Flow Diagram for On-line Filtering Program.

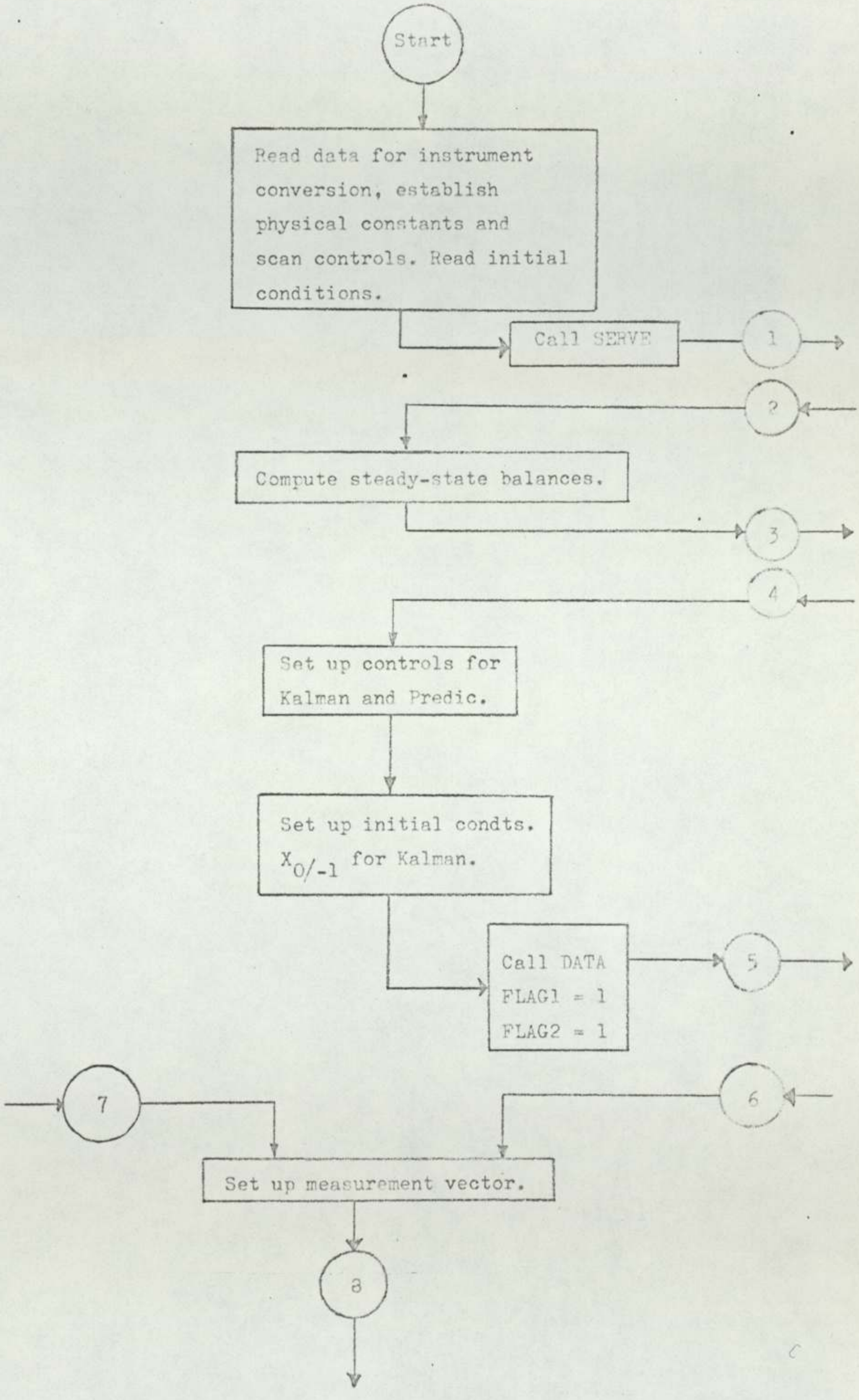


FIGURE 7.1 Continued.

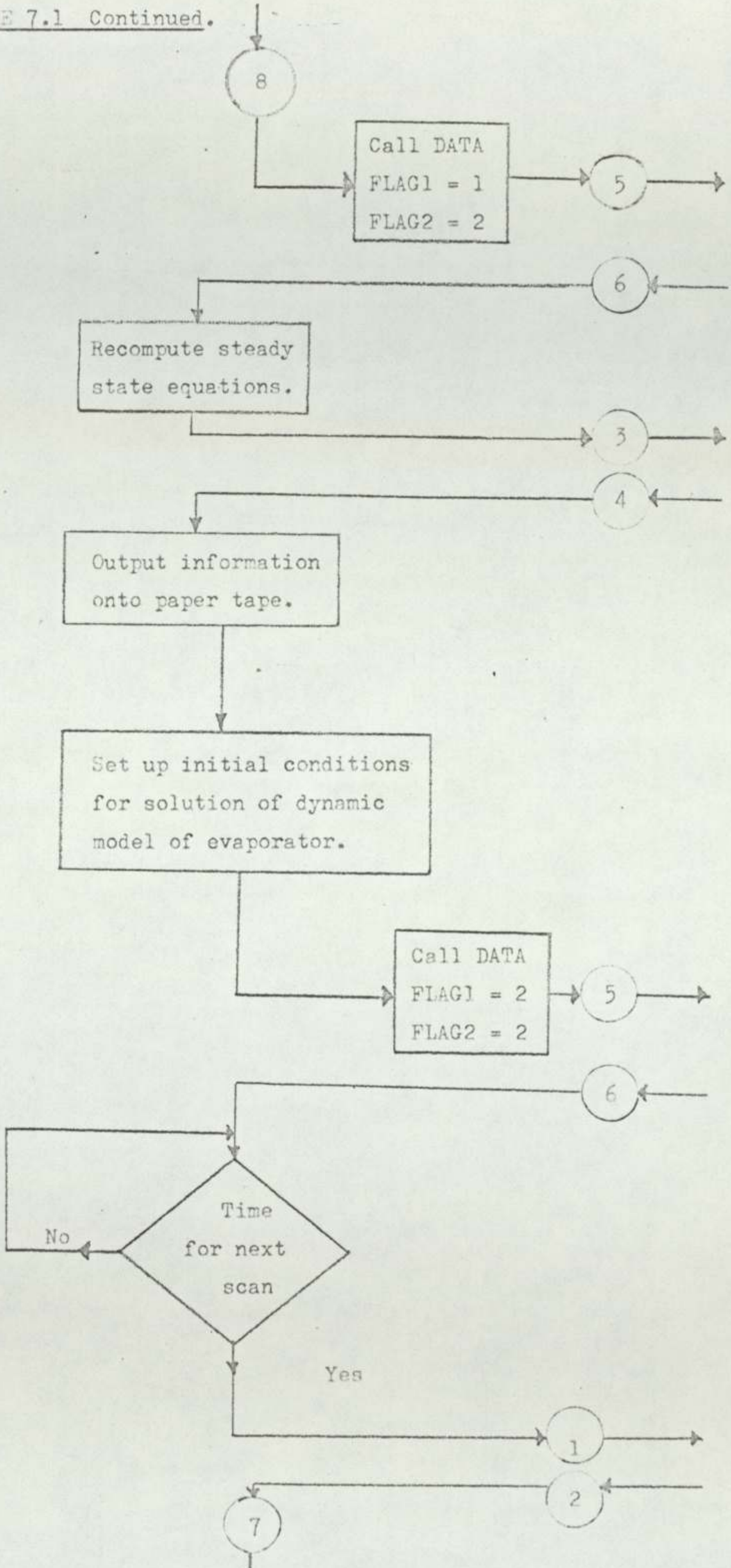


FIGURE 7.1 Continued.

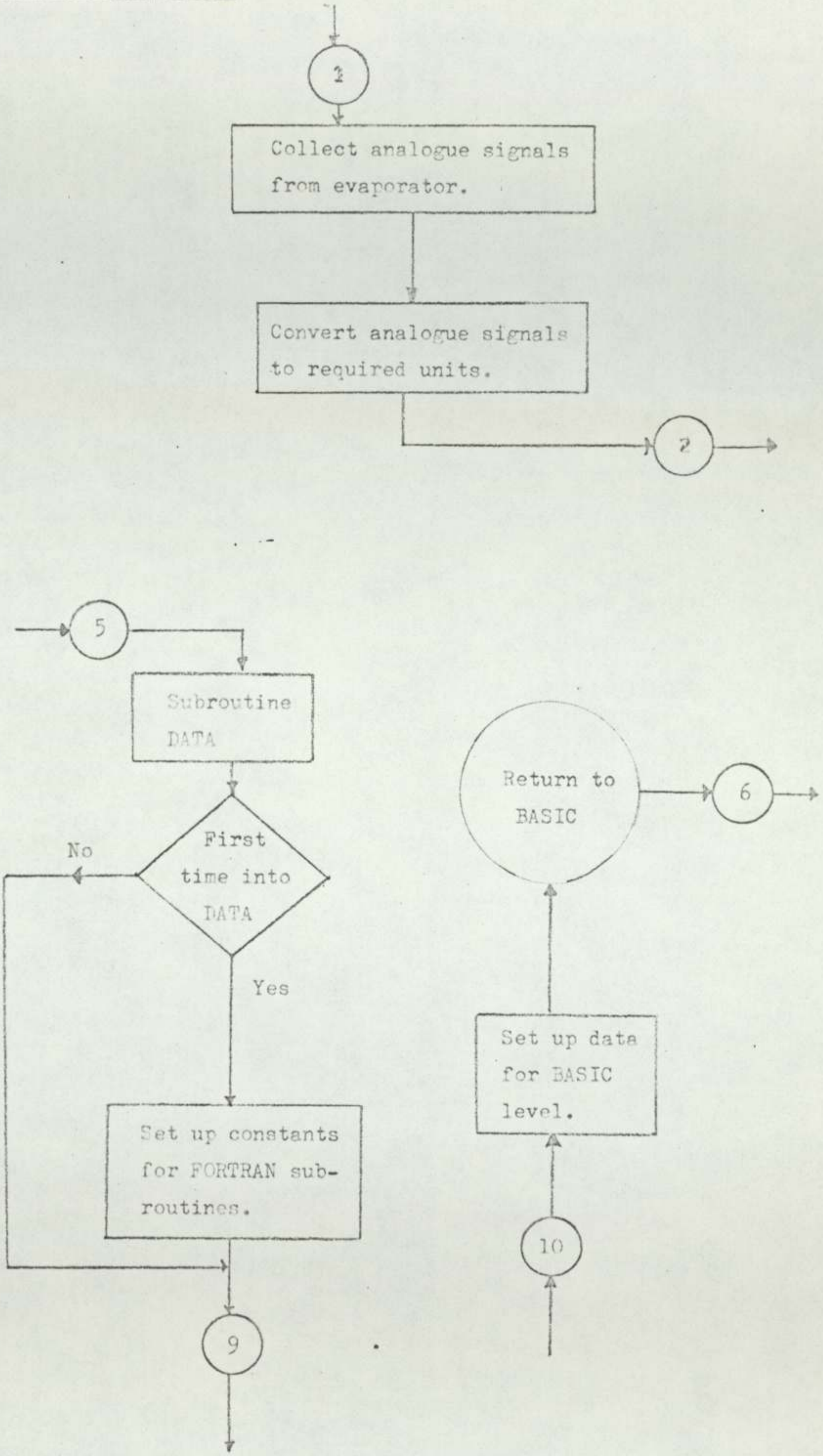


FIGURE 7.1 Continued.

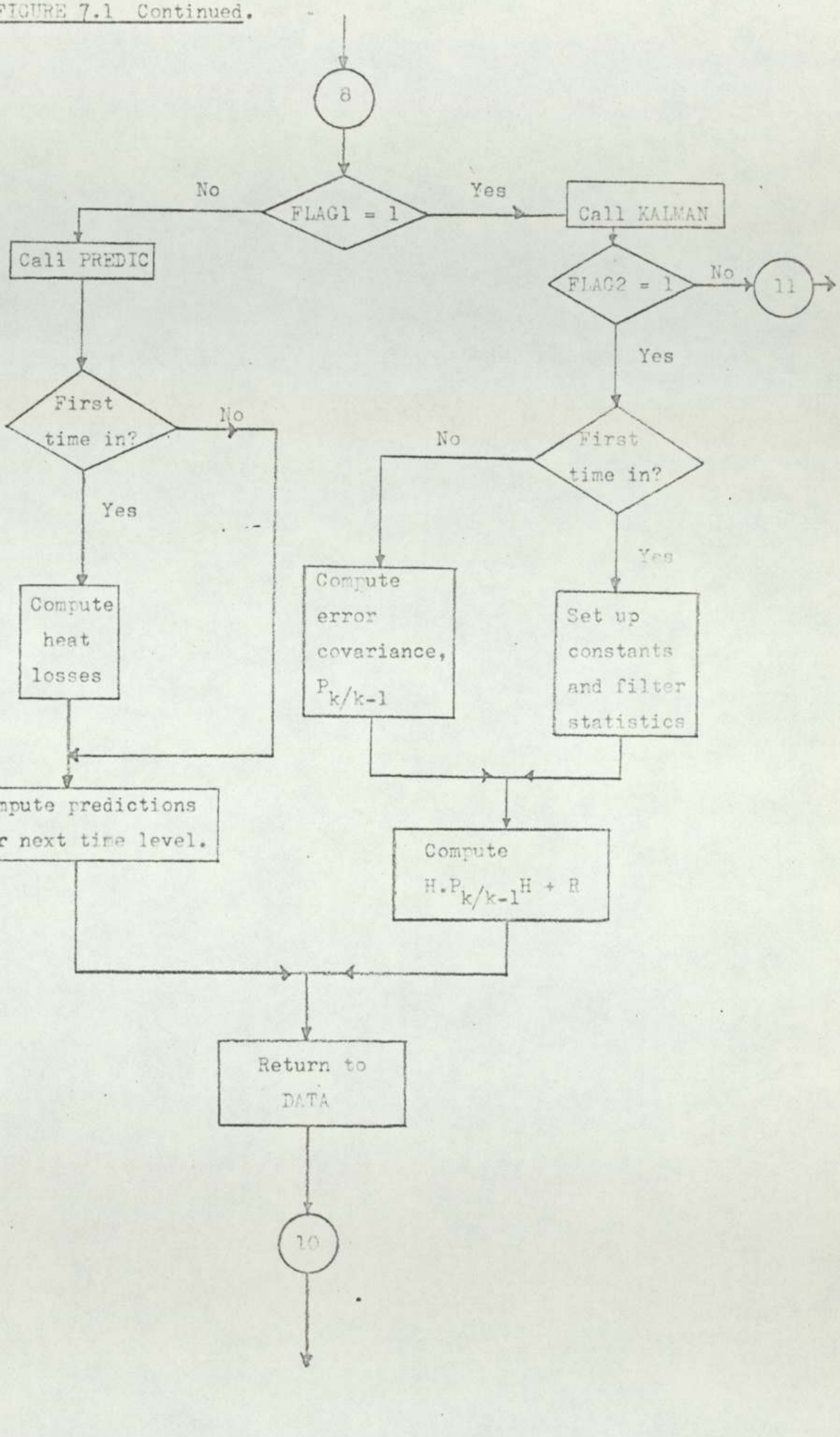
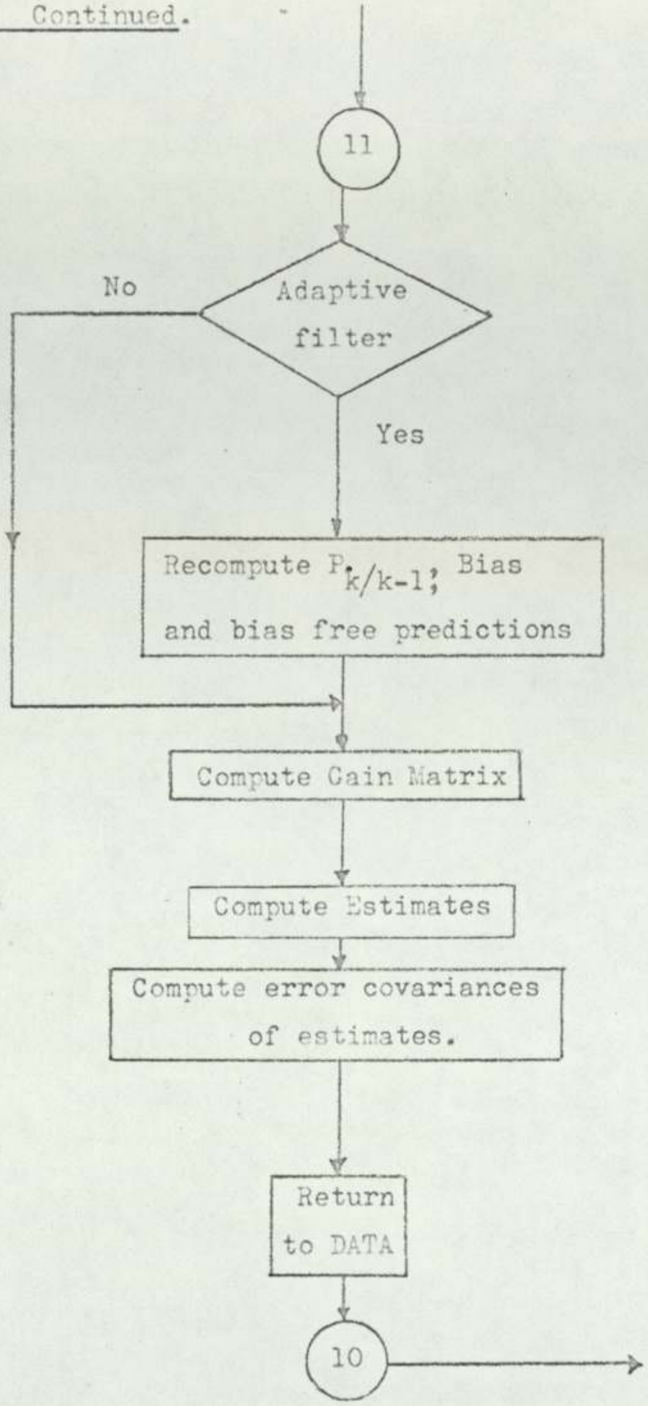
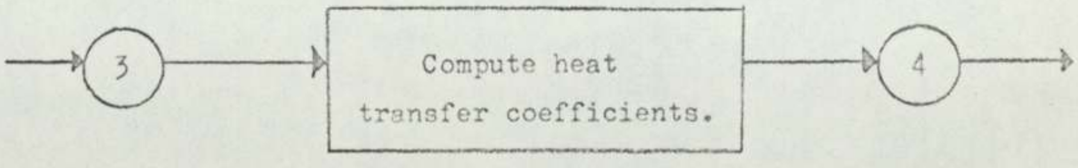


FIGURE 7.1 Continued.





the integration method, of the differential equations associated with the above variables, by use of subroutine GRAD. Subroutine GRAD takes the value of the state vector and substitutes this into the differential equations. The gradient vector is returned to PREDIC.

On entering subroutine PREDIC for the first time the system is assumed to be at steady state. The derivative values should therefore be zero and a loss term for each differential equation is computed to ensure this.

7.2.1.2 Subroutine KALMAN.

The remaining section of the Kalman Filter algorithm is carried out within this subroutine, a listing of which appears in Appendix 1. Its position within the computer scheme is shown in Figure 7.1.

Predictions from subroutine PREDIC in the order T(2), T(13), T(11) , T(10), H, M(8), T(14), M(4) and M(10) along with the first seven of these variables as measurements are used within the subroutine to obtain estimates. In order that off-line tests could be carried out, to show the effects of the dynamic model of the evaporator within the extended Kalman Filter and also the adaptive method of Coggan and Wilson, both methods were programmed into this subroutine. Due to their similarity, i.e. the adaptive filter is merely an extension of the Kalman Filter, this could be easily accomplished. The choise of the method is dependent upon the value of a flag set at the BASIC level. The initial values of the filter statistics can be set in a similar manner, if so required, for off-line experiments.

Due to the non-linearity of the dynamic model of the evaporator a transition matrix can not be computed directly. The approximation quoted by Coggan and Noton (7.2), Wells (7.3) and Sorenson (7.4) has therefore been adopted. If the non-linear model is expressed as,

$$X_{k+1} = f_k(X_k) \qquad \text{---------} (7.1)$$

then the element $A_{i,j}$, of the transition matrix, can be approximated by,

$$A_{i,j} \hat{=} \frac{\partial f_i}{\partial x_j} \qquad \text{---------} \; (7.2)$$

for computation of the error statistics within the filter algorithm.

Even allowing for the removal of the prediction section of the algorithm, the remaining section in subroutine KALMAN requires approximately 10 octal sectors of storage when compiled. The resulting cross sector references were far in excess of the storage available within the base sector.

To overcome this problem use was made of the Fortran Translator, (7.5). The translator produces the relevant assembler language, DAP-16, instructions to carry out each FORTRAN statement as well as allowing the user to insert DAP-16 instructions into the FORTRAN program. These DAP-16 instructions are recognised by the translator, by the insertion of the character "A" in column 1 of the relevant statement.

Using this technique the pseudo-operation "SET BASE" can be implemented. That is part of the machine core within the users program can be utilised for cross sector referencing. For example,

```
    120 CONTINUE
A       SETB,*+1
A       JMP,*+46
A       BSS,45
    121 CONTINUE
```

might appear within the users program. The translator would produce a set of DAP-16 instructions for the FORTRAN statement `120 CONTINUE`, the following 3 instructions would be recognised as DAP-16 instructions and entered as such. The instruction `A      SETB,*+1` being a pseudo operation requires no machine instruction. The other two DAP-16 instructions each produce an identical instruction, with the correct addresses, in the translator output. The instruction A JMP,*+46 causes the machine to jump over the next 45 memory locations, i.e. that core that is required for cross sector referencing. The A BSS,45 instruction saves 45 memory locations for cross sector referencing. The number of locations employed in this manner must be sufficient to ensure that there is sufficient core available for cross sector referencing within that sector and also that the final DAP-16 instruction, associated with a FORTRAN statement, coincides with the end of the core sector. The A JMP,*+46 instruction will therefore be the first instruction of a particular core sector and similar instructions will appear at each sector start used within the subroutine.

The translated version of the FORTRAN plus DAP-16 instructions is then processed to produce a machine code version using the DAP-16 assembler.

7.2.1.3 Subroutine DATA

This subroutine controls the passage of information between the BASIC and FORTRAN levels. A program listing is shown in Appendix 1 and its position within the computation scheme shown in Figure 7.1.

The users BASIC program enters DATA each time calculations from sections of the filtering algorithm are required, i.e. prediction or estimation. This is accomplished in the BASIC program by use of the CALL statement, i.e.

```
CALL(2,A6,M(1),T(1),V(1),U(1),K,B(1),C(1),D(1),A(1),G(1),E(1),F(1))
```

where A6 is a flag that ensures that constants are only computed at the initial entry.

M, T, V are the liquid flow rates, temperatures and vapour flow rates of the physical process respectively.

U is the vector of heat transfer coefficients.

K is a flag to determine which subroutine is called from DATA

B is the control vector for PREDIC.

D is the vector of predictions computed by PREDIC.

C is the vector of initial conditions required for solution of the dynic model in PREDIC.

A is the control vector for KALMAN.

G is the vector of estimates produced by KALMAN.

E is the vector of predictions transferred to KALMAN.

F is the measurement vector for KALMAN.

When DATA is entered all common blocks are established. The remaining subroutines, KALMAN, PREDIC and GRAD, receive their data from the common blocks. Once the common blocks are established a flag, K, indicates the required subroutine to be accessed. After the subroutine accessed has completed its calculations it returns to DATA which transfers the required information back to the BASIC level.

7.2.2 Data Acquisition from the Double Effect Evaporator.

In chapter 3 a description of the BASELINE compiler was given. This compiler, produced by Payne (7.6), offers all of the required subroutines for data acquisition. Parts of this compiler, along with modifications produced by Thornhill (7.7), were therefore adopted for on-line filtering. Data acquisition subroutines are accessed from the BASIC level via the CALL statement, i.e.

```
CALL(1,Z4,N1,N2,E8,R(0,0),Z6,Z7,Z8)
```

where Z4 = time interval (secs.) between scans.

N1 = initial channel to be scanned.

N2 = final channel to be scanned.

E8 = ensemble number.

R = the matrix in which the average values of the analogue signals are stored for each instrument.

Z6 = number of scans that the computer has completed at any instant of time.

Z7 = number of scans required by the user.

Z8 = a scanning error flag.

7.2.3 The Interactive System.

The programs described in the previous two sections along with the BASIC compiler are loaded into the computer to produce an interactive system for on-line filtering. The subroutines, written in either DAP-16 or FORTRAN, occupy fixed positions within the computer core. The loading order of these subroutines must be such that the minimum of cross sector referencing is required. Standard FORTRAN subroutines required for such operations as addition, subtraction etc. are obtained from a standard FORTRAN library tape. Subroutine KALMAN, because it contains its own core for cross sector referencing, must be the final subroutine to be loaded into the core. Details of the loading procedure are given in the Honeywell H316 operating manual (7.8).

Figure 7.2 shows the memory map of the core when all of the subroutines have been loaded.

The following subroutines are associated with data acquisition, details of which are given by Payne (7.6) and Thornhill (7.7);
SERV ,GOGET, SCAN, BCDBIN, BINBCD, INT, ENAB, [illegible] and REST.

The following subroutines are associated with the Kalman Filter and have been described in section 7.2.1;
DATA, KALMAN, PREDIC and GRAD.

The following are FORTRAN library subroutines; EXP, FLOAT, IDINT, IFIX, M\$11X, M\$11, M\$22X, M\$22, D\$22X, D\$22, C\$12, C\$21, S\$22, A\$22, N\$22, REAL, L\$22, H\$22, F\$ER, F\$HT, F\$AT, ARG\$, AC1, AC2, AC3, AC4, AC5 and SUB\$.

Along with these subroutines an input/output modification is patched into the computer manually, (see Payne (7.6) for details), from

Figure 7.2 Memory Map of Core for On-line Filtering System.

*LOW	21300
*START	21777
*HIGH	36670
*NAMES	12355
*COMN	37337
*BASE	32033
*BASE	33035
*BASE	34031
*BASE	35032
*BASE	36014
*BASE	00763
EXP	21300
BCDBIN	21742
DATA	22000
SERV	23060
INT	23540
SCAN	23646
FLOAT	23700
IDINT	23710
IFIX	23710
M$11X	23720
M$11	23720
M$22X	24000
M$22	24000
D$22X	24161
D$22	24161
C$12	24420
C$21	24452
S$22	24504
A$22	24512
N$22	24734
REAL	24746
L$22	24746
H$22	24756
F$ER	24774
F$HT	25004
F$AT	25042

Figure 7.2 Continued.

ARGS	25124
AC1	25144
AC2	25145
AC3	25146
AC4	25147
AC5	25150
PREDIC	25152
GRAD	26000
BINBCD	26464
SUBS	26536
ENAB	26656
SAVE	26674
REST	26710
GOGET	26720
KALMAN	31745
BLK7	37337
BLK6	37373
BLK5	37451
BLK4	37564
BLK3	37726
BLK2	37762
BLK1	37770

LC

octal locations 21200 onwards. This enables data to be output from the computer to the paper tape punch, rather than the ASR teletype, and eliminates some of the restrictions on data output during real time implementation. Manual patches are also made of the starting locations of those subroutines that are to be accessed from the users BASIC program, in a dedicated area of the base sector.

7.2.4 Computer Program for On-line Filtering.

The BASIC program written for on-line filtering makes use of the interactive system described in section 7.2.3, to carry out the computations of the Kalman Filter algorithm and to collect data at the correct instant of time. A listing of the BASIC program is shown in Appendix 1 and its position within the computer scheme shown in Figure 7.1.

The operation of the BASIC program is as follows;

(i) The data required for the operation of the on-line filter is established, i.e. physical constants, initial conditions of the process variables, conversion factors for instrument calibrations and the controls for data acquisition.

(ii) The data acquisition time controls are started and the first instrument readings collected.

(iii) The initial conditions of the variables and the measurements are rationalised.

(iv) The heat transfer coefficients are calculated in a BASIC subroutine.

(v) The controls for subroutine KALMAN and PREDIC are established.

(vi) Subroutine DATA is entered and constants and common blocks are established.

(vii) Subroutine KALMAN is entered and the constants and filter statistics are established before returning to the BASIC level.

(viii) The measurement vector is established, the program returns to KALMAN where the estimates of the state are computed, control is then returned to the BASIC level.

(ix) Variables calculated from steady state equations, (equations 5.53 to 5.61) are recomputed based upon the estimates from the filter.

(x) Heat transfer coefficients are updated for the next time interval.

(xi) The required information is output onto paper tape.

(xii) The estimate vector is transferred to PREDIC where the predictions for the next time level are computed. Control returns to BASIC.

(xiii) The predictions are transferred to KALMAN and the error covariances of these predictions are computed. When measurements are required the control passes back to the BASIC level.

(xiv) A time wasting loop is entered until the time for the next measurement sampling is due.

(xv) The data acquisition subroutine is entered. On returning to the BASIC level the analogue conversions of the instrument signals are made.

(xvi) Continue with (viii).

Within the filtering program no provision has been made for the computation of the initial conditions. This is due to the lack of core available once the above program has been loaded. It is however not thought to be a serious omission as these calculations are only required at the very start of the filtering process. To overcome this omission the initial conditions are computed using the steady state analysis program described in chapter 4. The initial conditions are output onto paper tape and are used as input data to the filtering program described above.

7.3 Results and Discussion.

7.3.1 Off-line Experiments.

To study the effects of the dynamic model, described in chapter 5 by equations 5.46 to 5.61, upon the estimates from an extended Kalman Filter algorithm, several experiments were carried out using measurement data previously obtained from the double effect evaporator.

In section 4.4.3 an analysis of the instrument statistics,for the measurements of the inputs, shows the small amount of noise associated with these analogue signals. However no method could be found to describe the effects of this small amount of noise upon the system outputs. In the context of the Kalman Filter and its application to the double effect evaporator, it can be assumed that the input noise matrix, Q, will be low. This is because (i) all of the plant inputs apart from the cooling water flow rate, are available to the computer and as such are fed directly into the dynamic model. The effects of any noise upon the inputs are therefore partially accounted for within the predictions.

(ii) at the start of the filtering process the differential equations associated with the dynamic model are driven to numerical values of zero. This in some part accounts for heat losses etc. which can be classified as negative disturbances upon the evaporator.

Using previously obtained measurement data, from the double effect evaporator, experiments were carried out with the constant value of the diagonal elements of the Q matrix varying from 0.0 to 1000. A comparison experiment was also carried out using the adaptive filter quoted by Coggan and Wilson with a zero Q matrix.

In all of the experiments the initial value of the error covariance matrix of the predictions was set to 1000. The point has already been made in the literature survey, (see section 2.1), that the value of $P_{0/-1}$ has an effect only upon the speed of response of the filter, if its value is high, and has no effect upon the accuracy of the estimates produced. The measurement statistics were all assumed equal and set to a value in excess of the maximum figure produced in section 4.4.3. This step has also been discussed in the literature survey and shown to produce little loss of accuracy. Its use allows the filter a greater freedom when updating predictions and its practical effect is,

(i) to allow only one rather than seven values to be transferred between the BASIC and the FORTRAN levels.

and (ii) reduce the storage requirements at the FORTRAN level as with only one value the matrix of measurement statistics is no longer required.

From the results produced during these experiments the following points arise for discussion:-

(i) Using low values for the input noise statistics, (i.e. values numerically less than 10), results were produced that showed either inherent bias or in more serious cases severe divergence. Examples of this are shown in Figures 7.3A to 7.3H and Tables 7.1A to 7.1M in Appendix 4. This fact justifies the statement made in chapter 6, that the dynamic model of the evaporator, exhibits the divergence qualities cited by Jazwinski (7.9).

(ii) In all cases the use of the adaptive filter produced estimates that were highly accurate, as defined by their consistency with plant measurements and operating conditions.

(iii) Examination of Figures 7.3A to 7.3H, Tables 7.1A to 7.1M and results produced from the dynamic simulation of the evaporator model, (see Appendix 3), indicated that not only was the fictitious noise addition system dependent but also that it was equation dependent. If the differential equation, associated with a particular variable, predicted an accurate transient response then the value of the fictitious noise required to produce accurate estimates from the filter was low, (see Figures 7.3D and 7.3F). If the differential equation was

Figure 7.3A Estimates of T(2) from Filter.

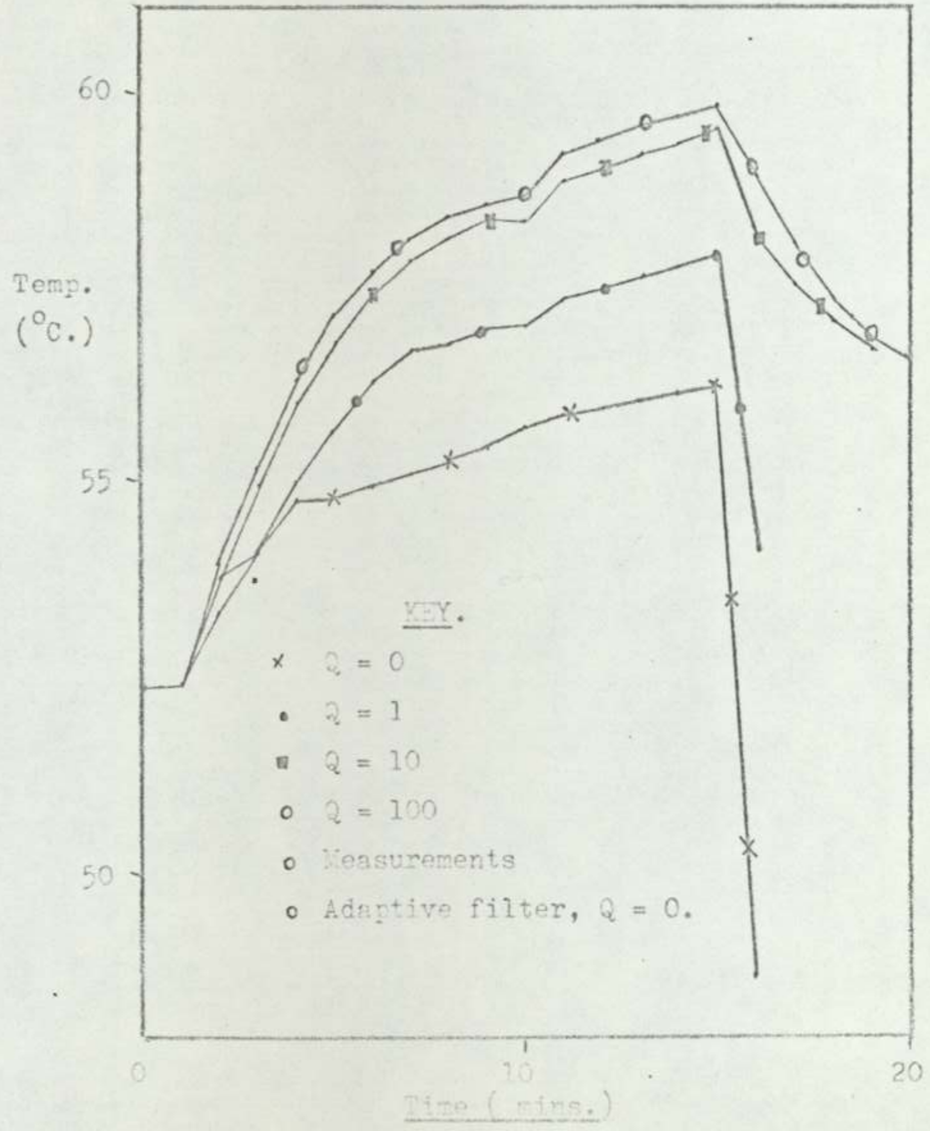


Figure 7.3B Estimates of T(11) from filter.

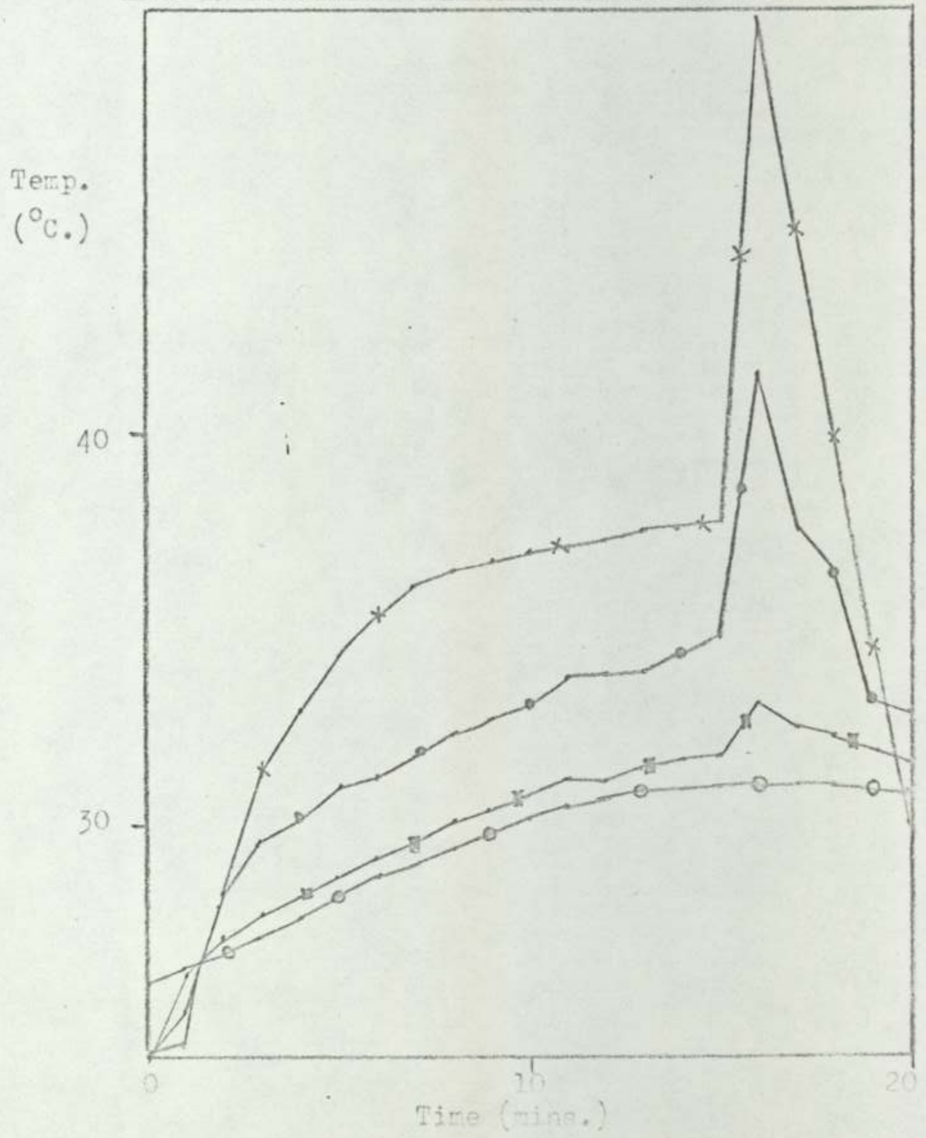


Figure 7.3C Estimates of T(13) from filter.

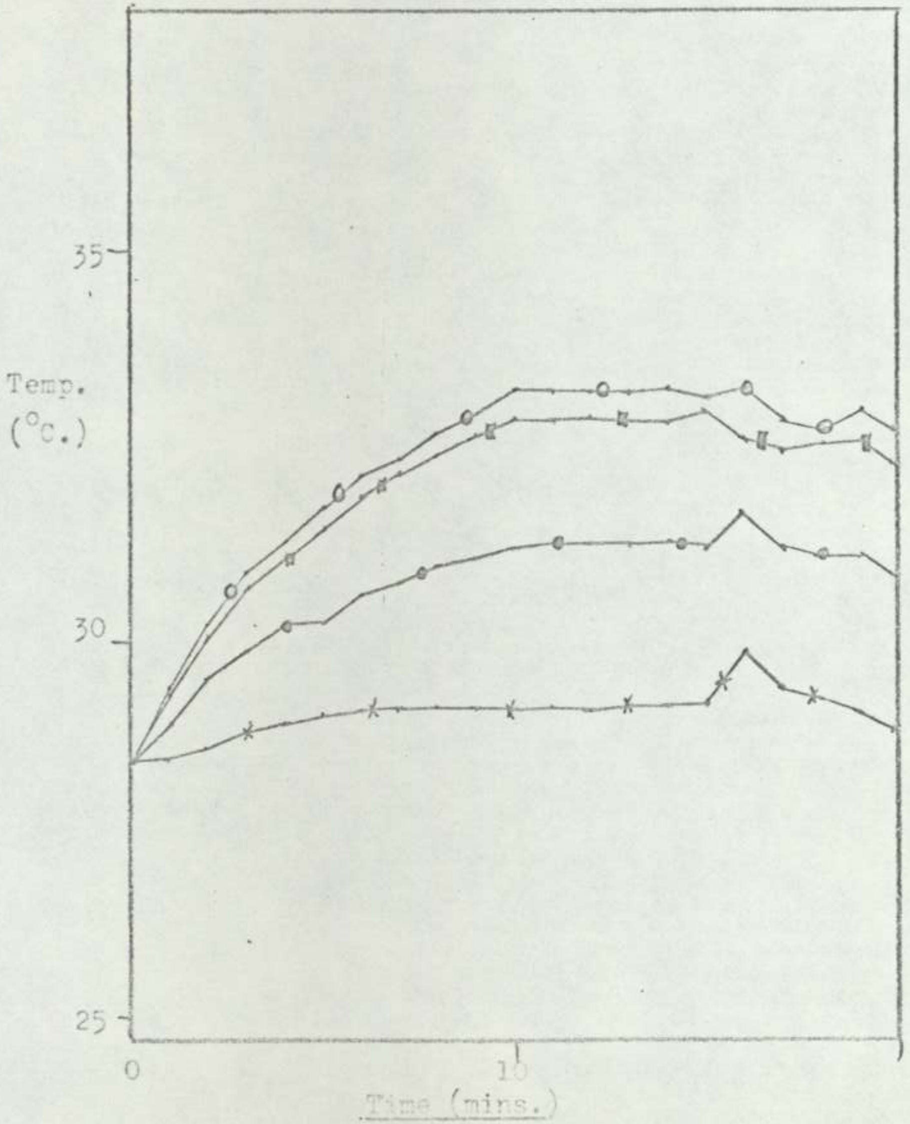


Figure 7.3D Estimates of T(14) from filter.

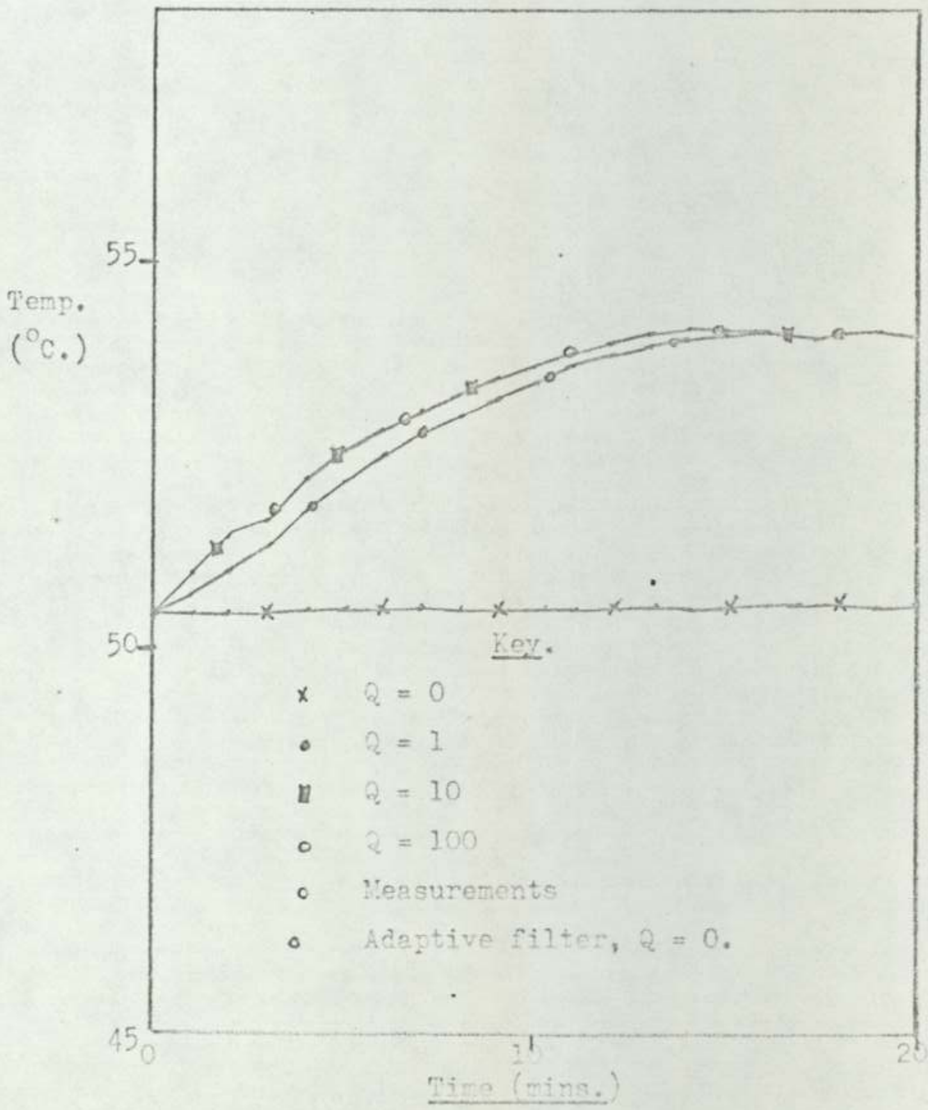


Figure 7.3E. Estimates of M(8) from filter.

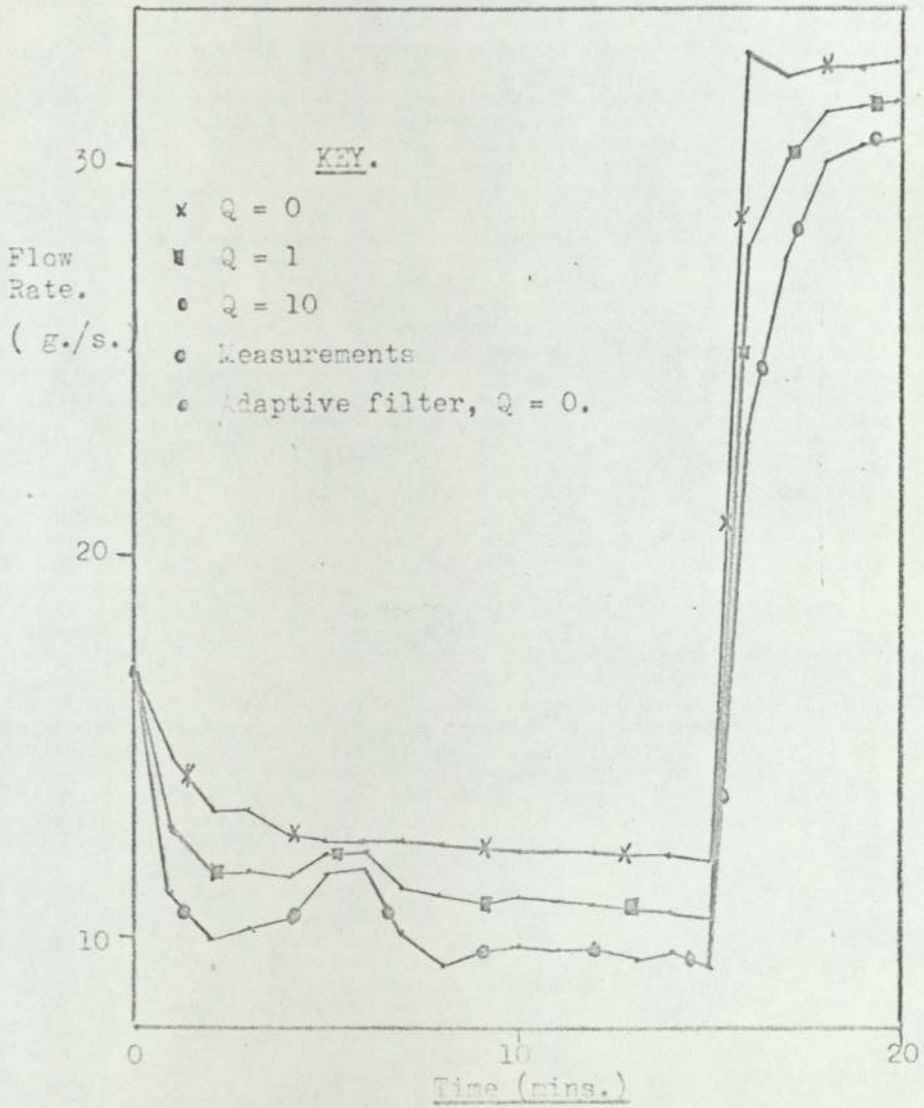


Figure 7.3F Estimates of H from filter.

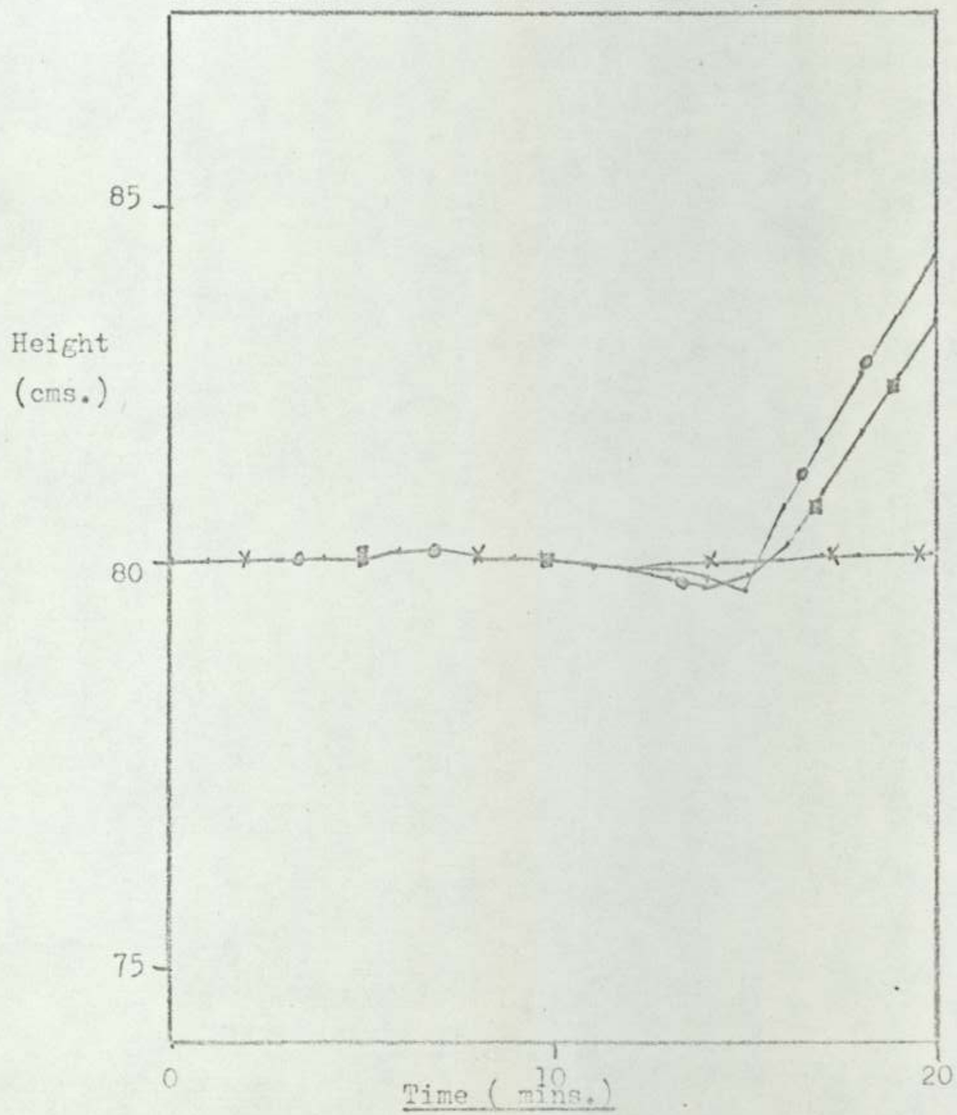


Figure 7.3H Predictions of U(2) from filter.

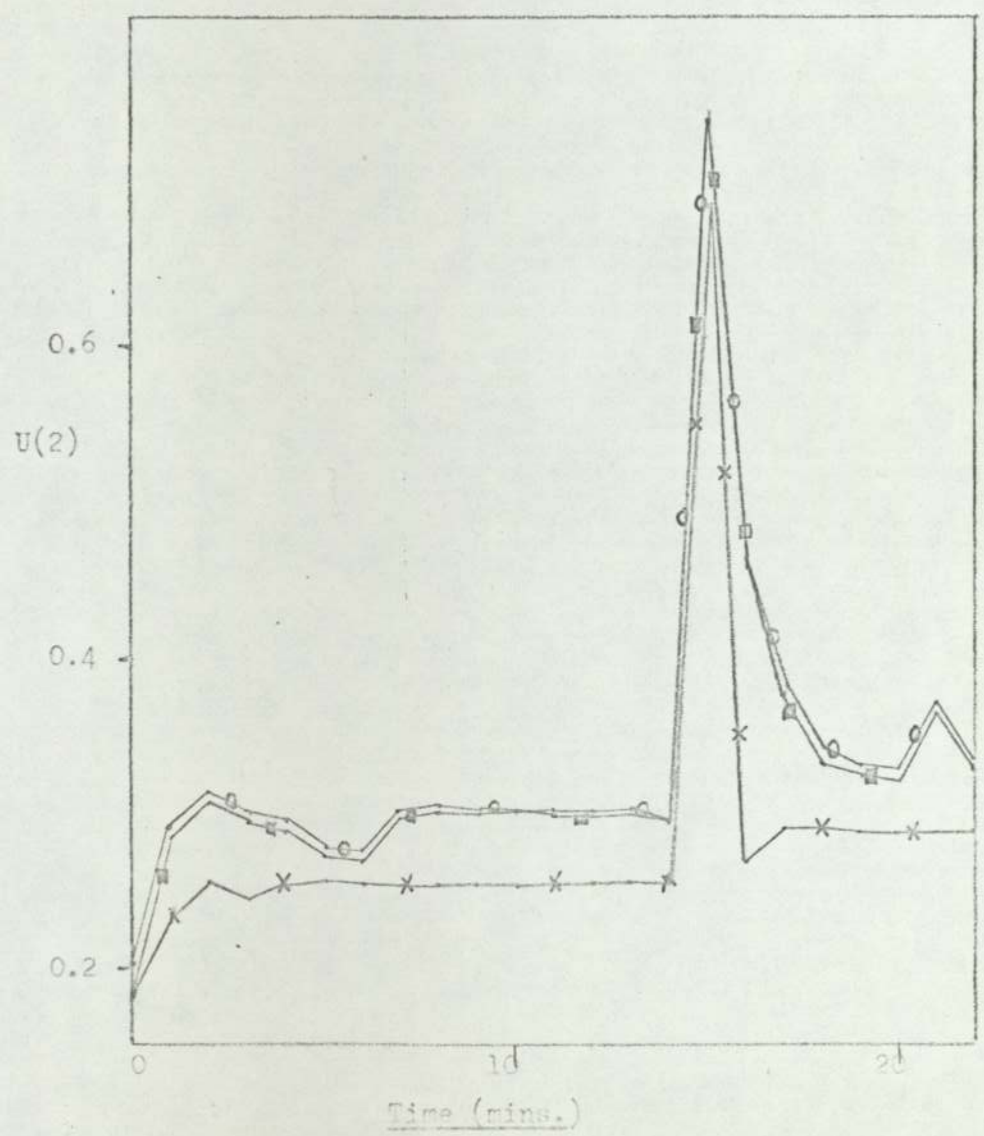
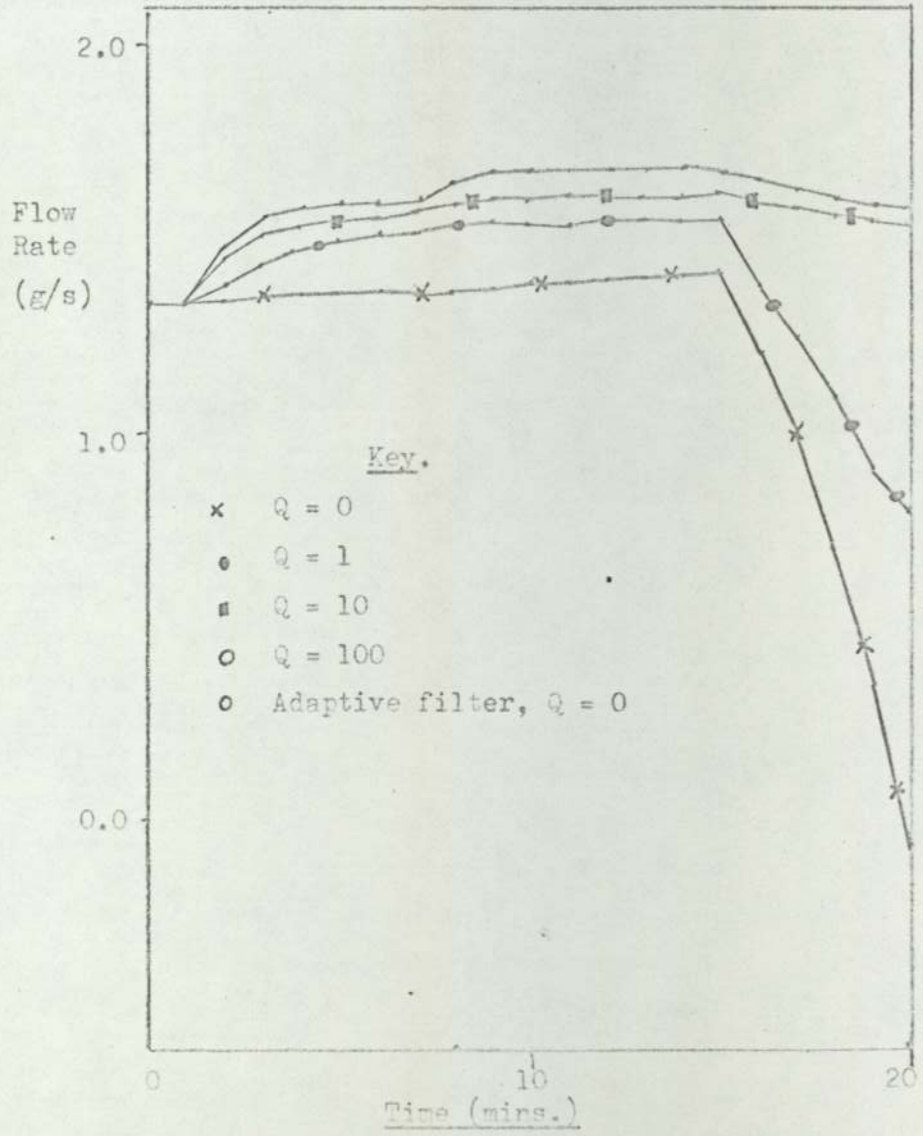


Figure 7.3G Estimates of M(4) from filter.



not representative of the system response then much higher fictitious noise values were required, (see Figures 7.3A and 7.3B).

(iv) Due to the form of the double effect evaporator dynamic model, described in chapter 5, i.e. equations 5.46 to 5.61, the problems discussed in chapter 6 relating to unmeasured variables, do not occur. This is due to the off-diagonal terms of the transition matrix. In the case of the double effect evaporator there are no links to relate the unmeasured variables with any errors in the predictions of the measured variables. That is the unmeasured variables are functions of the measured variables and not vice versa.

Due to this fact the measured variables are very much dependent upon their initial conditions and the values of those variables with which they are associated. In the use of either the extended Kalman Filter with high fictitious noise or the adaptive filter of Coggan and Wilson the point has been made, in chapter 6, that no attempt is made by these methods to proportion part of the detected error to the unmeasured variables. It becomes essential therefore to ensure that the dynamic equations describing the unmeasured variables and the values associated with their calculation should be as accurate as is possible to achieve.

7.3.2 On-line Filtering.

The previous section, 7.3.1, has shown, (i) the ability of the adaptive filter, produced by Coggan and Wilson, to produce accurate estimates of the double effect evaporator even when containing an inaccurate model of the physical process.

(ii) the ability of the filter to operate without any knowledge of the input noise matrix, Q, which has been shown previously to be very difficult to describe.

(iii) its non system dependence as compared to the use of fictitious noise addition.

In order to carry out on-line filtering experiments it is essential that the timing interval of the measurement cycle is correct. The subroutine contolling the data acquisition must not be called before all of the required pre-computation has been completed. To ensure that the measurement interval is correct the following timing experiments were carried out.

(i) The time for the Honeywell H316 computer to complete a full cycle of the extended Kalman Filter was 6.2 secs.. This figure was for a system containing nine variables and seven measurements. Increasing the computation to include the modifications of Coggan and Wilson produced a processing time of 8.5 seconds. The vast majority of this time was taken up by the computation associated with KALMAN. Because of the very short time , the computation associated with PREDIC required, no accurate breakdown of the overall figure was possible.

(ii) The output of the required data, as shown in the computer listing for on-line filtering, required 20.1 seconds. Obviously not all of this information would be required in a practical estimation exercise once the development work was complete and therefore this time offers scope for improvement.

(iii) The ensemble number, associated with data acquisition, is one of the variables that the programmer can utilise to ensure that the measurement interval is correct. Table 7.2 shows the operation time for subroutine SERV with varying values of the ensemble number.

From an examination of these figures it can be seen that with an ensemble of 20 the whole package would operate within a cycle time of 60 seconds. This measurement cycle time would seem a reasonable proposal in the light of the speed of response of the physical process. However it

Table 7.2 Processing times for subroutine SERV with ensemble number.

Ensemble.	Time (secs.)
2	3.8
5	8.0
7	11.6
10	16.5
12	19.1
15	23.7
20	30.8

------ooOoo------

does not take into account either the extra computation that is required during the first cycle of the program or any possible control algorithm that may be incorporated at a later stage. For this reason an ensemble of seven was chosen for on-line filtering experiments. This figure leaves approximately ten seconds of processing time available for any further computation that may be required.

Using these timing figures and similar statistical values as quoted in section 7.3.1, on-line filtering experiments were carried out using the adaptive filter of Coggan and Wilson. During these experiments , which were started following a steady state experiment, disturbances applied to both steam and liquid flow rates were investigated.

These experiments were conducted for periods of up to two hours during which time the disturbances were applied. The filter produced estimates of the state of the system every minute along with predictions of the system parameters. Typical results for these on-line experiments are shown in Tables 7.3A to 7.3M in Appendix 4.

The results produced during these on-line experiments were consistent with the system measurements and operating conditions at all time levels, (see Tables 7.3A to 7.3M.)

Examination of these tables shows the corrective action applied by the adaptive filter when serious discrepancy arises between the prediction and measurement of a variable. An example of this is shown in the estimation of the variable T(11), see Table 7.3C. The model consistently predicts inaccurate values of T(11) following a system disturbance. The adaptive filter accurately realigns this value to produce an estimate that is consistent with the measurement statistics.

The results of the On-line filtering experiments verified the conclusions of the earlier off-line experiments, (see section 7.3.1). These conclusions were:-

(i) The ability of the adaptive filter to be instigated without the requirement of pre-tuning experiments.

(ii) The ability of the adaptive filter to operate without a knowledge of the input noise matrix, Q.

(iii) The ability of the adaptive filter to respond to system disturbances no matter when they occur.

The results demonstrate the ability to accurately estimate the state of the physical process in real time using the interactive computer package described in section 7.2.3 and within the limits of the available hardware.

CHAPTER EIGHT.

Chapter 8. Conclusions and Recommendations for further work.

8.1 Conclusions.

Within this thesis it has been shown that when there is only a limited knowledge of the dynamic characteristics of a physical process that some adaptive modification should be incorporated into the estimation algorithm. When model inaccuracy arises the estimates, in particular of those variables that are not available as measurements, may exhibit bias and in extreme cases diverge from the true state. A number of approaches to the solution of this problem, proposed in the literature have been investigated and the most appropriate found to be the modifications developed by Coggan and Wilson (8.1). This adaptive modification has been shown to be capable of dealing with,

(i) uncertainty that may exist within the mathematical description of the process under investigation,

(ii) large unmeasured disturbances that may occur once the filter algorithm has reached a point of equilibrium, and

(iii) a total lack of knowledge regarding the input noise statistics.

A mathematical model of the double effect evaporator has been developed, along with correlations for the prediction of the heat transfer coefficients, in a form that is suitable for implementation within the Kalman Filter algorithm. The dynamic model, although offering considerable scope for improvement in accuracy, was tested off-line using the adaptive Kalman Filter and measurement data from the physical process. The estimates produced were consistent with the measurement data and the operating conditions. This model when incorporated into the extended Kalman Filter produced estimates that exhibited an inherent bias and in some cases estimates that were inconsistent with the operating conditions of the double effect evaporator.

This mathematical model of the double effect evaporator has been incorporated, along with the adaptive filter of Coggan and Wilson, into an interactive computer package for on-line estimation. Experiments carried out using this package showed that estimation of nine state variables and prediction of four parameters could be achieved within a filter cycle time of approximately fourty seconds. This cycle time was consistent with the time constants associated with the differential equations of the mathematical model. The estimates produced during on-line experiments were consistent with the measurement data and operating conditions of the physical process.

8.2 Recommendations for further work.

The following areas for further work are recommended,

(i) In the light of the conclusions drawn,in section 7.3.1, regarding the inability of the adaptive filter proposed by Coggan and Wilson, to proportion part of the detected prediction errors to the unmeasured variables, it is recommended that the modifications at present being developed by Kilbride-Newman (8.2), should be examined with reference to the double effect evaporator. If successful this would improve the confidence in the estimates of the unmeasured variables produced by the Kalman Filter and also aid in model improvements.

(ii) The feasibility of controlling the vapour dynamics of the double effect evaporator should be examined. If implemented this would allow the removal of the vapour pressure dynamics from the mathematical model. These dynamics have been shown to be extremely complex and in the context of the Kalman Filter and this thesis their description required unrealistic approximations. These approximations in some part account for the inaccuracies of the mathematical model used in this thesis. The controlled vapour space pressure would allow a reduction in the size of the mathematical model without in any way being detrimental to the evaporation process. The resulting savings in both computer core and processing times could then be utilised in the solution of more complex equations describing the unmeasured variables and parameters of the double effect evaporator.

BIBLIOGRAPHY.

References for Chapter 1.

1.1 Kalman, R.E., J. Basic Eng., Trans. ASME, 82D, pp 35-45, 1960

References for Chapter 2.

2.1 Gauss,K.F., " Theory of the Motion of the Heavenly Bodies Moving About the Sun in Conic Sections.", Dover, New York, 1963.

2.2 Swerling,P., J. Astronomical Sci., 6, pp 46-52, 1959.

2.3 Deutsch,R., " Estimation Theory.", Prentice-Hall, New Jersey, 1965.

2.4 Wiener,N., " The Extrapolation, Interpolation and Smoothing of Stationary Time Series.", John Wiley and Sons, Inc., New York, 1949.

2.5 Kolmogorov,A.N., " Interpolation and Extrapolation of Stationary Random Sequences.", Translated by W. Doyle and J. Selin, RM-3090-PR, The Rand Corp., U.S.A., 1962.

2.6 Kolmogorov,A.N., Bull. Acad. Sci. (U.S.S.R.), Ser. Math., 5, pp 3-14, 1941.

2.7 Kalman,R.E., J. Basic Eng., Trans. ASME, 82D, pp 33-45, 1960.

2.8 Kalman,R.E. and Bucy,R.S., J. Basic Eng., Trans. ASME, 83D, pp 95-108, 1961.

2.9 Kalman,R.E., Proc. 1st. Symp. Appl. Random Function Theory and Probability, (J.L. Boganoff and F. Kozin, eds.), Wiley, New York, 1963.

2.10 Jazwinski,A.H., " Stochastic Processes and Filtering Theory.", Academic Press, New York, 1970.

2.11 Sorenson,H.W., " Advances in Control Systems.", (ed. C.T. Leondres) 3, pp 219-292, 1966.

2.12 Cox,H., " Estimation of State Variables via Dynamic Programming.", Proc. 1964 Joint Automatic Control Conf., Stanford, U.S.A., pp 376-381, 1964.

2.13 Kushner,H.J., SIAM. J. Control, 2, pp 106-119, 1964.

2.14 Friedland,B. and Bernstein,I., J. Franklin Inst., 281, pp 455-480, 1966.

2.15 Alspach,D.L., " Some Comparisons of Optimal and Suboptimal Filters for Non-linear Estimation Problems.", Proc. 14th. Midwest Symp. on Circuit Theory, Denver, U.S.A., 1971.

2.16 Bucy,R.S. and Senne,K.D., " Realization of Optimum Discrete-Time, Non-linear Estimators.", Proc. of the Symp. on Non-linear Estimation Theory and its Applications, San Diego, U.S.A., 1970.

2.17 Alspach,D.L. and Sorenson,H.W., " Approximation of Density Functions by a Sum of Gaussians for Non-linear Bayssian Estimation.", Proc. of the Symp. on Non-linear Estimation Theory and its Applications, San Diego, U.S.A., 1970.

2.18 Kushner,H.J., IEEE Trans. Auto. Control, AC-12, pp 546-556, 1967

2.19 Athans,M., Wishner,R.P. and Bertolini,A., " Suboptimal State Estimation for Continuous-time Nonlinear Systems from Discrete Noisy Measurements.", Proc. 1968 Joint Automatic Control Conf., Ann Arbor, U.S.A., pp 364-382, 1968.

2.20 Wishner,R.P., Tabaczynski,J.A. and Athans,M., " On the Estimation of the State of Noisy Non-linear Multivariable Systems.", IFAC Symp. on Multivariable Control Systems, Dusseldorf, West Germany, 1968.

2.21 Denham,W.F. and Pines,S., AIAA J., 4, pp 1071-1076, 1966.

2.22 Leung,V.P. and Padmanabhan,L., The Chem. Engineering J., 5, pp 197-208, 1973.

2.23 Jazwinski,A.H., " Non-linear Filtering - Numerical Experiments.", NASA - Goddard Astrodynamics Conf., Maryland, U.S.A., April 1966.

2.24 Wishner,R.P., Lawson,R.F. and Athans,M., " Status of Radar Tracing Algorithms.", Proc. of Symp. on Non-linear Estimation Theory and its Applications, San Diego, U.S.A., 1970.

2.25 Smith,G.L., Schmidt,S.F. and McGee,L.A., " Application of Statistical Filter Theory to the Optimal Estimation of Position and Velocity on Board a Circumlunar Vehicle.", NASA - TR R - 135, 1962.

2.26 Smith,G.L., SIAM J. Control, 2, pp 19-32, 1964.

2.27 Schmidt,S.F., " State Space Techniques Applied to the Design of a Space Navigation System.", Proc. 1962 Joint Automatic Control Conf., U.S.A., pp 1-10, 1962.

2.28 Ford-Levine,C., " The Kalman - Bucy Filter and Dynamic Programing in Agricultural Pest Control.", Proc. 6th. Hawaii Int. Conf. on Systems Sci., Honolulu, Hawaii, Jan. 1973.

2.29 Szeto,M.W., Transp. Sci., 6, pp 419-439, 1972.

2.30 Wheelwright,S.W., Operation Res. Quarterly, 24, pp 55-64, 1973

2.31 Goldman,S.F. and Sargent,R.W.H., Chem. Engng. Sci., 26, pp 1535-1542, 1971.

2.32 Joffe,B.L. and Sargent,R.W.H., Trans. Instn. Chem. Engrs., 50, pp T270-T282, 1972.

2.33 Goldman,S.F., Ph.D. Thesis, University of London, 1969.

2.34 Yoshimura,T. and Soeda,T., " An Approach to the Divergence Prevention of the Extended Kalman Filter.", Proc. 3rd. Symp. on Non-linear Estimation Theory, San Diego, U.S.A., pp 282-285, 1972.

2.35 Wells,C.H., A.I.Ch.E.J., 17, pp 966-973, 1971.

2.36 Coggan,G.C. and Noton,A.R.M., Trans. Instn. Chem. Engrs., 48, pp T255-T264, 1970.

2.37 Noton,A.R.M. and Choquette,P., " Application of Modern Control Theory to the Operation of an Industrial Process.", Proc. IFAC / IFIP Conf. Symp., Toronto, Canada, 1968.

2.38 Coquette,P., Noton,A.R.M. and Watson,C.A.G., Proc. IEEE, 58, pp 10-16, 1970.

2.39 Coggan,G.C. and Wilson,J.A., Computer J., 14, pp 61-64, 1971.

2.40 Gavalas,G.R. and Seinfeld,J.H., Chem. Eng. Sci., 24, p 625, 1969.

2.41 Seinfeld,J.H., Gavalas,G.R. and Hwang,M., Ind. Eng. Chem. Fund., 8, p 257, 1969.

2.42 Hwang,M. and Seinfeld,J.H., A.I.Ch.E.J., 18, pp 90-93, 1972.

2.43 Payne,S.G. and Gay,B., " Development and Use of a High Level Language Compiler for Interactive Data Aquisition and Processing.", 1st. Annual Research Meeting of the Inst. of Chem. Engineers, London, U.K., April 1974.

2.44 Hamilton,J.C., Seborg,D.E. and Fisher,D.G., A.I.Ch.E.J., 19, pp 901-909, 1973.

2.45 Payne,S.G., Ph.D. Thesis, University of Aston in Birmingham, to be published.

2.46 Bellantoni,J.F. and Dodge,K.W., AIAA J., 5, pp 1309-1314, 1967.

2.47 Andrews,A., AIAA J., 6, pp 1165-1166, 1968.

2.48 Schwartz,L. and Stear,E.B., IEEE Trans. Auto. Control, AC-13, pp 83-86, 1968.

2.49 Singer,R.A. and Sea,R.G., IEEE Trans. Auto. Control, AC-16, pp 254-257, 1971.

2.50 Storey, B., M.Sc. Thesis, University of Aston in Birmingham, 1973.

2.51 Chaw Bing Chang, " The Initiation of the Kalman Filter with Uncertain Initial Conditions.", Proc. 6th. Hawaii Int. Conf. on Systems Sci., Honolulu, Hawaii, Jan. 1973.

2.52 Ryabova-Oreshkova,A.P., Eng. Cybern., 10, pp 177-180, 1972.

2.53 Krepyshev,G.P. and Pollack,Ya.A., Inf. Process. Lett., 1, 5, pp 211-215, 1972.

2.54 Mehra,R.K., IEEE Trans. Auto. Control, AC-16, pp 12-21, 1971.

2.55 Graupe,D. and Krause,D.J., " Sequential Regression Identification Procedure for Prediction and Non-linear Systems Parameters.", Proc. 14th. Midwest Symp. on Circuit Theory, Denver, U.S.A., 1971.

2.56 Heffes,H., IEEE Trans.Auto. Control, AC-11, pp 541-543, 1966.

2.57 Nishimura,T., IEEE Trans. Auto. Control, AC-11, pp197-204, 1966.

2.58 Fitzgerald,R.S., " Error Divergence in Optimal Filtering Problems.", 2nd. IFAC Symp. on Automatic Control in Space, Vienna, Austria, 1967

2.59 Schlee,F.H., Standish,C.J. and Toda,N.F., AIAA J., 5, pp 1114-1121, 1967.

2.60 Jazwinski,A.H., " Adaptive Filtering.", Proc. IFAC Symp. on Multivariable Control Systems, Dusseldorf, Germany, 2, pp 1-15, 1968.

2.61 Jazwinski,A.H., Automatica, 5, pp 475-485, 1969.

2.62 Anderson,B.D.O., Inf. Sciences, 5, pp 217-230, 1973.

2.63 Lee,R.C.K., " The Moving Window Approach to Problems of Estimation and Identification.", Aerospace Corp. Tech. Memo., ATM-65 (5540 - 10) - 18, 1965.

2.64 Jazwinski,A.H., IEEE Trans. Auto. Control, AC-13, pp 558-563, 1968.

2.65 Schmidt,S.F., " Computational Techniques in Kalman Filtering.", in " Theory and Applications of Kalman Filtering.", ed. C.T. Leondes, NATO - AGARD, 1970.

2.66 Friedland,B., IEEE Trans. Auto. Control, AC-14, pp 359-367, 1969.

2.67 Lin,J.L. and Sage,A.P., IEEE Trans. Syst., Man., Cybern., SMC-1, pp 314-324, 1971.

2.68 Sriyananda,H., Int. J. Control, 16, pp1101-1106, 1972.

2.69 Coggan,G.C. and Wilson,J.A., " Approximate Models and the Elimination of Bias in On-line Estimation of Industrial Processes.", Symp. on On-line Computer Methods Relevant to Chemical Engineers, Nottingham, U.K., Sept. 1971.

2.70 Jazwinski,A.H., Automatica, 10, pp 203-207, 1974.

2.71 Kilbride-Newman,R.F., Ph.D. Thesis, University of Aston in Birmingham, to be published.

2.72 Kay,W.M. and London,A.L., " Compact Heat Exchangers.", McGraw-Hill Book Co. Inc., New York, 1958.

2.73 Kern,D.Q., " Process Heat Transfer.", McGraw-Hill Book Co. Inc., New York, 1950.

2.74 McAdams,W.H., " Heat Transmission.", McGraw-Hill Book Co. Inc., New York, 1954.

2.75 Collier,J.G., " Convective Boiling and Condensation.", McGraw-Hill Book Co. (U.K.) Ltd., London, 1972.

2.76 Starczewski,J., Brit. Chem. Engng., 10, pp 523-531, Aug. 1965

2.77 British Patent 24, 024, 1899.

2.78 Brooks,C.H. and Badger,W.L., Trans. Am. Inst. Chem. Engrs., 33, pp 392, 1937.

2.79 Stroebe,G.W., Baker,E.M. and Badger,W.L., Trans. Am. Inst. Chem. Engrs., 35, pp 17-28, 1939.

2.80 Gupta,A.S. and Holland,F.A., The Canadian J. of Chem. Engng., 44, pp 77-81, April 1966.

2.81 Coulson,J.M. and Mehta,R.R., Trans. Inst. Chem. Engrs., 31, p 208, 1953.

2.82 Dukler,A.E., Hwang,C.J. and Lee,H.M., Desalination, 6, pp 25-56, 1969.

2.83 Beveridge,G.S.G., Stewart,G. and Rajeswaran,T., " Mathematical Model of a Multiple-Effect Evaporater.", I. Chem. E. Symp. Series No. 35, Inst. of Chem. Engrs., London, pp 3:28-3:39, 1972.

2.84 Bergles,A.E. and Rohsenow,W.N., Paper 63 - HT - 22, Presented at 6th. National Heat Transfer Conf., ASME - A.I.Ch.E., Boston, 1963.

2.85 Chen,J.C., Paper 63 - HT - 34, Presented at 6th. National Heat Transfer Conf., ASME - A.I.Ch.E., Boston, 1963.

2.86 Lees,S. and Hougen,J.O., Ind. and Eng. Chem., 48, N6, pp 1064-1068, 1956.

2.87 Cohen,W. and Johnson,E., Ind. and Eng. Chem., 48, N6, pp 1031-1034, 1956.

2.88 Mozley,J.M., Ind. and Eng. Chem., 48, N6, pp 1035-1041, 1956.

2.89 Rizika,J.N., Trans. A.S.M.E., 78, p 1407, 1956.

2.90 Takahashi,Y., " Automatic and Manual Control.", (ed. A. Tustin.), pp 235-248, Academic Press, New York, 1952.

2.91 Stermole,F.J. and Larson,M.A., A.I.Ch.E.J., 10, 5, pp 688-694, 1964.

2.92 Privett,W.J. and Ferrell,J.K., Chem. Eng. Progress Symp. Series, 62, (64), pp 200-208, 1966.

2.93 Imeada,M., Hoeda,S. and Sugiyama,S., Int. Chem. Engng., 10, 2, pp 303-309, April 1970.

2.94 Stainthorp,F.P. and Axon,A.G., Chem. Engng. Sci., 20, pp 107-119, 1965.

2.95 Korol'kov,B.P., Heat Transfer - Soviet Research, 1, 2, pp 85-96, March 1969.

2.96 Korol'kov,B.P., Heat Transfer - Soviet Research, 2, 3, pp 74-82, May 1970.

2.97 Finlay,I.C. and Smith,J., J. Mech. Engng. Sci., 9, 3, pp 211-217, June 1967.

2.98 Koppel,L.B., Ind. Eng. Chem. Fundamentals, 5, 3, pp 403-413, 1966.

2.99 Myers,G.E., Mitchell,J.W. and Norman,R.F., Trans. A.S.M.E.- J. of Heat Transfer, 89,1, pp 75-80, Feb. 1967.

2.100 Dorri,M.Kh., Heat Transfer - Soviet Research, 1, 2, pp 186-192, March 1969.

2.101 Schoenberg,A.A., " Mathematical Model with Experimental Verification for the Dynamic Behaviour of a Single-Tube Condenser.", NASA - TN - D - 3453, June 1966.

2.102 Zavorka,J., Sutek,L., Aguado,A. and Delgado,E., " Dynamics of Multiple - Effect Evaporaters in the Sugar Industry.", Identification in Auto. Control Systems, IFAC Symp., Prague, 1967.

2.103 Burdett,J.W. and Holland,C.D., A.I.Ch.E.J., 17, 5, pp 1080-1089, 1971.

2.104 Andre,H., Ph.D. Thesis, University of Alberta, 1966.

2.105 Ritter,R.A. and Andre,H., Canadian J. Chem. Eng., 48, pp 696-701, Dec. 1970.

2.106 Newell,R.B. and Fisher,D.G., Ind. Eng. Chem. Process Des. Develop., 11, 2, pp 213-221, 1972.

2.107 Fisher,D.G. and Jacobson,B.A., The Chem. Eng., 279, pp 552-558, Nov. 1973.

References for Chapter 3.

3.1 Honeywell Document No. 70130072 543, M-449

3.2 See reference 2.45

3.3 See reference 2.43

References for Chapter 4.

4.1 See reference 2.45

4.2 Davies,O.L., "Statistical Methods in Research and Production.", Hafner Publishing Co., New York, 1967.

4.3 See reference 2.92.

4.4 Richards,J.M., J. Phys. D : Appl. Phys., 4, pp L15-L18, 1971.

References for Chapter 5.

5.1 See reference 2.45

5.2 See reference 2.44

5.3 See reference 2.104

5.4 See reference 2.102

5.5 See reference 2.35

5.6 Gay,B. and Payne,S.G., The Computer J., 16, 2, pp 118-121, 1973

References for Chapter 6.

6.1 See reference 2.35

6.2 See reference 2.11

6.3 See reference 2.10

6.4 See reference 2.67

6.5 See reference 2.66

6.6 See reference 2.34

6.7 See reference 2.15

6.8 See reference 2.59

6.9 See reference 2.62

6.10 See reference 2.71

6.11 See reference 2.69

6.12 See reference 2.68

References for Chapter 7.

7.1 See reference 2.69

7.2 See reference 2.36

7.3 See reference 2.35

7.4 See reference 2.11

7.5 Honeywell FORTRAN Translator, Doc. No. 41286103126A

7.6 See reference 2.45

7.7 Thornhill,M.A.R., M.Sc. Thesis, University of Aston in Birmingham, 1974

7.8 See reference 3.1

7.9 See reference 2.10

References for Chapter 8.

8.1 See reference 2.69

8.2 See reference 2.71

Nomencalature.

Variables used in Heat transfer studies.

U = Overall heat transfer coefficient.

M = liquid feed rate.

V = vaporisation rate.

ΔT = Average temperature difference driving force.

h_b = film side heat transfer coefficient.

N_{Pr} = Prandtl Number.

σ = surface tension.

q = heat load.

T = temperature.

C_p = heat capacity

Ψ = f(Temperature driving force.)

Variables used in the studies of the Double Effect Evaporator.

M = Vector of liquid flow rates.

V = Vector of vapour flow rates.

T = vector of temperatures

E = vector of specific enthalpies.

t = time

ρ = density.

λ = latent heat.

ΔT = log mean temperature driving force.

$C1$ = specific heat of water.

$S4$ = accumulation in the second effect separator.

U = overall heat transfer coefficients.

q = Heat transferred in unit time.

A = area available for heat transfer.

C = heat content of stream.

Subscripts:-

C = condenser

SE = second effect

Nomenclature (Continued.)

FE = first effect.

P = preheater.

T = tube

S = shell

SEP = second effect separator.

N = inlet to a C.S.T.R.

Variables used in Kalman Filter studies.

X = state vector

A = transition matrix

w = Input disturbance vector to system

Y = measurement vector

H = Observation matrix.

V = noise vector associated with measurements.

Q = Covariance matrix of input noise.

R = Covariance matrix of measurement noise.

I = Identity matrix.

P = Covariance matrix of state vector.

W = Gain matrix.

IN = Innovation process based upon the differences between the measurements and predictions.

S = Expected covariances of the differences between the predicted and measured values of the measured variables.

Z = Measured covariances of the differences between the predicted and measured values of the measured variables.

b = Bias vector of measured variables.

z = Bias free vector of differences between measured and predicted values of variables.

v = Error covariance matrix of state vector based upon measurements.

Nomenclature (Continued.)

u = low frequency random forcing function vector.

G = Matrix of noise correlation.

J = Cost function to be minimised.

q = scalar quantity used in the adaptive computation of the Q matrix.

APPENDIX ONE.

COMPUTER PROGRAM LISTINGS.

Contents of Appendix 1.

Computer Program for Data Acquisiton and the solution of the Heat and Mass Balances.

Symbol Description.

N1 = Initial channel to be scanned.

N2 = Final channel to be scanned.

B1 = Measured cooling water rate.

B2 = Measured condensate flow rate.

B3 = Measured steam flow rate.

C1 = Specific heat of the liquid.

C3 = Calculated total heat loss.

C4 = Total heat entering the system per second.

C5 = Initial level measured in the second effect separator.

C6 = Final level measured in the second effect separator.

S2 = Calculated accumulation in the second effect separator.

S4 = Measured accumulation in the second effect separator.

S5 = Start time of the experiment.

S6 = Finish time of the experiment.

E8 = Ensemble to be averaged for each scan.

L9 = Vapour enthalpy calculated in subroutine from vapour temperature L8.

Z4 = Sampling interval.

Z5 = Experiment time duration.

Z6 = Number of samples to be taken for each instrument.

Z7 = Number of scans completed at any particular time.

The following symbols are used as counters; Z1, I, L, C8, J, K

The following flags are used to detect scanning errors; F1, Z8, J2

The following subscripted variables are used;

A = Matrix of stored analogue signals.

D = Gradient values for instruments, used for conversion of analogue signals to required units.

H = Intercept values for instruments, used for conversion of analogue signals to required units.

E = Vapour specific enthalpy for each flow stream.

G = Total enthalpy of each stream.

M = Liquid mass flow rate for each stream.

X = Vapour mass flow rate for each stream.

T = Temperature of each stream.

P = Mean of the analogue signals for each instrument.

Q = Standard deviation of mean analogue signal for each instrument.

R = Converted values of each instrument.

Y = Matrix used for the solution of equations 4.34 to 4.39.

```
5  PRINT "          J.COLEBY STEADY STATE LOGGING PROGRAM "
9 REM *****
10 REM INPUT TIME CONTROLS FOR SCAN *****
11 REM *****
15 PRINT " SAMPLING INTERVAL (SECS) ";: INPUT Z4
20  PRINT : PRINT " TOTAL RUN TIME (MINS.)";: INPUT Z5
25  Z6=Z5*60/Z4
30  PRINT : PRINT
35  CALL (2,Z7): PRINT "START TIME ";Z7
40  S5=Z7
44 REM *****
45 REM SET UP CHANNEL NUMBERS TO SCAN*****
46 REM *****
50  N1=15:N2=29:E8=12:Z7=0
55  DIM A(39,10)
59 REM *****
60 REM CALC. INITIAL LEVEL IN 2ND. EFFECT SEP. *****
61 REM *****
65  CALL (1,18,C8,F1)
70  C5=0: FOR I=1,200: CALL (1,18,C8,F1):C5=C5+C8
75  NEXT I:C5=C5/200
79 REM *****
80 REM COMMENCE SCAN *****
81 REM *****
85  CALL (7,Z4,N1,N2,E8,A(0,0),Z6,Z7,Z8)
90  IF Z8=2 THEN  PRINT "SCAN ERROR ": STOP
94 REM *****
95 REM TIME WASTING LOOP *****
96 REM *****
100  IF Z7>=Z6 THEN 120
105  CALL (6,2,J2): IF J=2 THEN STOP
110  GO TO 100
114 REM *****
115 REM CALC. FINAL LEVEL IN 2ND. EFFECT SEP. *****
116 REM *****
120  CALL (1,18,C8,F1): CALL (1,18,C8,F1)
125  C6=0: FOR I=1,200: CALL (1,18,C8,F1):C6=C6+C8
130  NEXT I:C6=C6/200
135  CALL (2,Z7): PRINT "FINISH TIME ";Z7
140  S6=Z7
145  CALL (5,0)
150  DIM D(15),H(15),P(15),Q(15),R(15)
154 REM *****
155 REM READ DATA FOR INSTRUMENT CONVERSION *****
156 REM *****
160  FOR I=1,5: READ H(I),D(I): NEXT I
165  DATA -59.0324,-.5214E-01
170  DATA -16.2798,-.644646E-02
175  DATA 3.02299,-.577411E-02
180  DATA -165.352,-.416595E-01
185  DATA 0,1
190  FOR I=6,15:H(I)=0:D(I)=-.25E-01: NEXT I
194 REM *****
195 REM CALC. VALS. OF VARIABLES + STATS. *****
196 REM *****
200  FOR I=1,15:P(I)=0:Q(I)=0
205  FOR J=1,Z6
210  P(I)=P(I)+A(I+14,J):Q(I)=Q(I)+A(I+14,J)↑2
215  NEXT J
220  P(I)=P(I)/Z6:Q(I)=Q(I)/Z6:Q(I)=SQR(ABS(P(I)↑2-Q(I)))
```

STEADY STATE LOGGING PROGRAM CONTINUED.

```
 225  R(I)=P(I)*D(I)+H(I)
 230  NEXT I
 234 REM *****
 235 REM OUTPUT THE VARIABLES + STATS. *****
 236 REM *****
 240  PRINT " CHANNEL.      ANALOGUE.";
 245  PRINT "       STD.DEV.     CONVERTED VAL."
 250  PRINT
 255  FOR I=1,15: PRINT I+14,P(I),Q(I),R(I): NEXT I
 259 REM *****
 260  REM SET UP MASS + HEAT BALANCE EQUS. *****
 261 REM *****
 265  DIM M(15),X(15),T(15),E(15),G(15)
 270  M(1)=R(2):M(8)=R(3):T(1)=R(8):T(2)=R(9):T(3)=R(15)
 275  T(4)=R(14):T(8)=R(12):T(9)=R(10)
 280  T(10)=R(1):T(11)=R(13):T(12)=R(6)
 285  T(13)=R(7):T(14)=R(11):T(15)=R(10)
 290  PRINT : PRINT
 294 REM *****
 295 REM INPUT UNMEASURED VARIABLES *****
 296 REM *****
 300  PRINT "C.W.RATE,CONDENSATE,STEAM";
 305  INPUT B1,B3,B2
 310  M(12)=B1
 315  C1=4.1868
 320  L8=T(9): GOSUB 1000
 325  E(9)=L9
 330  X(3)=M(1)-M(8)
 335  L8=T(3)
 340  GOSUB 1000
 345  E(3)=L9
 350  L8=T(4): GOSUB 1000
 355  E(4)=L9
 360  M(4)=(C1*M(1)*T(1)+X(3)*E(3)-C1*M(1)*T(2)-X(3)*E(4))
 365  M(4)=M(4)/(T(4)*C1-E(4))
 370  X(4)=X(3)-M(4)
 375  L8=122: GOSUB 1000
 380  F1=L9
 385  S1=(X(3)*E(3)+M(8)*C1*T(8)-M(1)*C1*T(2))/(F1-C1*100)
 390  E(5)=F1
 395  L8=T(10): GOSUB 1000
 400  E(10)=L9
 405  FOR I=1,6: FOR J=1,7:Y(I,J)=0: NEXT J: NEXT I
 410  Y(1,1)=1:Y(1,2)=1:Y(1,3)=1:Y(1,4)=-1
 415  Y(2,1)=E(9):Y(2,2)=E(10):Y(2,3)=C1*T(10)
 420  Y(2,4)=-T(11)*C1
 425  Y(2,7)=M(12)*C1*(T(13)-T(12))
 430  Y(3,2)=1:Y(3,3)=1:Y(3,7)=M(4)+X(4)
 435  Y(4,2)=-E(10):Y(4,3)=-T(10)*C1:Y(4,5)=-C1*(T(14)-T(15))
 440  Y(4,7)=-X(4)*E(4)-M(4)*C1*T(4)
 445  Y(5,1)=1:Y(5,6)=1:Y(5,7)=M(8)
 450  Y(6,1)=-E(9):Y(6,5)=C1*(T(14)-T(15)):Y(6,6)=-T(15)*C1
 455  Y(6,7)=-M(8)*C1*T(8)
 460  FOR I=1,6:Z1=Y(I,I): IF Z1=0 THEN 495
 465  FOR J=1,7:Y(I,J)=Y(I,J)/Z1: NEXT J
 470  FOR K=1,6: IF K=I THEN 485
 475  Z2=Y(K,I): FOR J=1,7:Y(K,J)=Y(K,J)-Z2*Y(I,J): NEXT J
```

STEADY STATE LOGGING PROGRAM CONTINUED.

```
480  NEXT K
485  NEXT I
490  GOTO 515
495  FOR L=I+1,6: IF Y(L,I)<>0 THEN 505
500  NEXT L: PRINT "NO GOOD ": STOP
505  FOR J=1,7:Z3=Y(L,J):Y(L,J)=Y(I,J):Y(I,J)=Z3: NEXT J
510  Z1=Y(I,I): GOTO 465
511 REM *****
512 REM CHECK CONVERGENCE OF COMPUTED VALS. *****
513 REM *****
515  IF ABS(Y(4,7)-B3)<.11E-02*B3 THEN530
520  M(12)=M(12)+(B3-Y(4,7))*T(11)/T(13)
525  GOTO 405
530  X(9)=Y(1,7):X(10)=Y(2,7):M(10)=Y(3,7):M(11)=Y(4,7)
535  M(15)=Y(5,7):S2=Y(6,7):M(14)=M(15)
540  M(2)=M(1):X(5)=S1:M(6)=S1:T(5)=122:T(6)=100
545  M(13)=M(12)
550  M(14)=M(15)
555  FOR I=1,15:G(I)=X(I)*E(I)+M(I)*T(I)*C1: NEXT I
560  M(7)=M(8):X(7)=X(3):G(7)=G(8)+G(3):T(7)=(T(3)+T(8))/2
564 REM *****
565 REM PRINT OUT THE HEAT + MASS BALANCES *****
566 REM *****
570  PRINT : PRINT : PRINT
575  PRINT : FOR I=1,15: PRINT I,M(I),X(I),T(I),G(I): NEXT I
580  S4=((C6-C5)*D(4)*3.147*.408↑2*1000)/((S6-S5)*240)
584 REM *****
585 REM  PRINT OUT UNMEASURED VARIABLES + CALC. VALS.*****
586 REM *****
590  PRINT : PRINT " ","MEASURED ACCM. ";S4
595  PRINT " ","CALC. ACCM.   ";S2
600  PRINT "MEASURED VALUES "
605  PRINT "---------------"
610  PRINT : PRINT "STEAM";B2
615  PRINT "C.W.RATE";B1
620  PRINT "CONDENSATE ";B3
625  PRINT : PRINT : PRINT " CALC. VALUES"
630  PRINT " ------------"
635  PRINT : PRINT "STEAM";X(5)
640  PRINT "C.W.RATE ";M(12)
645  PRINT "CONDENSATE ";M(11)
650  C3=(M(12)-B1)*C1*(T(13)-T(12))
654 REM *****
655 REM PRINT OUT HEAT LOSSES FROM PLANT *****
656 REM *****
660  PRINT : PRINT "      TOTAL HEAT LOSS ";C3;"J/S"
665  PRINT "HEAT LOSS/LB. STEAM";C3*100/G(5);"%"
670  C4=G(1)+G(5)+B1*C1*T(12)
675  PRINT " HEAT LOSS FROM PLANT";C3*100/C4;"%"
680  PRINT : PRINT : PRINT : PRINT
685 STOP
994 REM *****
995 REM SUBROUTINE TO CALC. ENTHALPY OF VAPOUR *****
996 REM *****
1000  L9=1.6742*L8+2500.8
1005  RETURN
```

Computer Program for the dynamic simulation of the mathematical model of the evaporator system.

Symbol Description.

T = Time

P1 = Measurement and Print Interval.

E = Total Simulation Run Time.

P = Density of two phase mixture.

C = Specific Enthalpy of two phase mixture.

A5 = Cross sectional area of Second Effect Separator.

C1 = Specific heat of water.

E2 = Specific Enthalpy of Vapour.

E1 = Latent heat of vaporisation

T1 = Specific heat of Vapour.

H = Height in Second Effect Separator.

N5 = Empirical Constant associated with the the heat capacity of the exchanger units.

H1 = Differential equation describing T(2).

H3 = " " " M(4).

H5 = " " " T(14).

H6 = " " " T(10).

H7 = " " " M(10).

H8 = " " " T(13).

H9 = " " " T(11).

F2 = " " " H.

D1 = Capacitance term associated with the shell of the preheater.

D2 = " " " " " " " " second effect.

D3 = " " " " " " " " condenser.

D6 = " " " " " tubes of the preheater.

D7 = " " " " " " " " second effect.

D8 = Capacitance term associated with the tubes of the condenser.

P2 = Density of Vapour.

B7 = $T(3)_{k+1} - T(3)_k$

B5 = $T(14)_{k+1} - T(14)_k$

The following variables are used with subscripts;

U = Heat transfer coefficent.

A = Area for heat transfer.

V = Volume of tubes of exchanger unit.

with the following subscripts;

1 = Preheater.

2 = First Effect.

3 = Second Effect.

4 = Condenser.

The following counters are used; I, J.

The following flags are used;

L1 = Flag to control finish of simulation.

L2 = Flag to control print out.

T3 = Flag to control the calculation of heat losses at start of simulation.

T5 = Flag to control print out from subroutine.

The following vectors are used;

M = Liquid flow rates.

V = Vapour flow rates.

T = Temparature.

L = Heat losses associated with differential equations.

Y = Measurements from evaporator system.

```
1   REM*****
2   REM  SET UP SYSTEM CONSTANTS IN SUBROUTINE.
3   REM*****
4   GOSUB 2000
5   DIM M(15),V(15),T(15),Y(15)
6   DIM L(15)
7   REM*****
8   REM  INPUT PLANT MEASUREMENTS FOR TIME ZERO.
9   REM*****
10   REM*****
11   REM  READ INITIAL CONDITIONS FOR MODEL.
12   REM*****
14   FOR I=1,15
15   READ M(I),V(I),T(I)
17   INPUT Y(I)
20   NEXT I
21  REM*****
22   REM  RATIONALISE INITIAL CONDTS. AND PLANT DATA.
23  REM*****
24   GOTO 3945
26   REM*****
27   REM  INITIALISE THE INTEGRATION ROUTINES.
28   REM*****
29   CALL (1,T)
30   T5=1: GOSUB 2999
31   P1=60:E=55*60
32   GOTO 55
33   REM*****
34   REM  HEAT TRANSFER CORRELATIONS FOR MODEL.
35   REM*****
36   U1=.189958*(T(1)↑.115644)*(M(1)↑.254433)
37   U1=U1/(V(3)↑.915914)/(T(3)↑.496023E-01)
40   U2=.418596E-03*(M(1)↑.287992E-01)*(V(3)↑.958777)
41   U2=U2*(T(2)↑.194165)*(T(3)↑.504994)
45   U3=.696263E07*(3416.32↑.477818E-03)*(T(14)↑3.21051)
46   U3=U3*(V(4)↑.568395)*(M(10)↑.494838)
47   U3=U3/(V(10)↑.115259)/(T(4)↑2.40123)/(T(10)↑1.89546)
48   U3=U3*.565872E-06
50   U4=.110997E05*(M(12)↑1.07948)*(T(13)↑2.56339)
51   U4=U4*(M(10)↑.251088)/(T(12)↑.360554)/(T(15)↑1.48368)
52   U4=U4/(T(11)↑1.05817)
53   U4=U4*.482487E-07
54   GOTO 3105
55   I=4: GOSUB 1000
60   D1=7790*P*C+.223038E05*.45186
65   I=10: GOSUB 1000
70   D2=.151004E05*P*C+8922.21*.45186
75   D3=2812.8*C1+.369787E05*.45186
77   E2=E1-(C1-T1)*122
78   REM*****
79   REM  SET UP MODEL DIFFERENTIAL EQUATIONS.
80   REM*****
82   N5=10
84   D6=V1*C1+4910.2*.38494
86   H1=M(1)*T(1)*C1/D6/N5+A1*U1/D6*(T(4)-T(2))
87   H1=H1-M(1)*C1*T(2)/D6/N5-L(1)
95   H3=H1*M(1)*C1/E1
104   D7=V3*C1+8922.21*.38494
106   H5=A3*U3*T(10)/D7+M(14)*T(15)*C1/D7
107   H5=H5-(A3*U3+M(14)*C1)*T(14)/D7-L(5)
```

SIMULATION PROGRAM LISTING CONTINUED.

```
110  H6=M(4)*T(4)*C1/D2+V(4)*E1/D2+V(4)*T(4)*T1/D2
111  H6=H6-M(10)*T(10)*C1/D2-V(10)*E1/D2
112  H6=H6-V(10)*T(10)*T1/D2-U3*A3*T(10)/D2
113  H6=H6+U3*A3*T(14)/D2
114  H6=H6-L(6)
115  H7=H3
119  D8=V4*C1+.149496E05*.38494
121  H8=M(12)*T(12)*C1/D8+U4*A4*T(11)/D8
122  H8=H8-(M(12)*C1+U4*A4)*T(13)/D8-L(8)
125  H9=V(9)*E1/D3+T1*V(9)*T(15)/D3+V(10)*E1/D3
126  H9=H9+T1*T(10)*V(10)/D3+M(10)*T(10)*C1/D3
127  H9=H9-M(11)*T(11)*C1/D3+U4*A4*(T(13)-T(11))/D3
128  H9=H9-L(9)
135  F2=M(8)/A5-V(9)/A5
140  IF T3=0 THEN 500
141  REM*****
142  REM  SUBROUTINE CONTROLLING PRINT INTERVAL
143  REM  AND TOTAL RUN TIME.
144  REM*****
145  CALL (2,P1,E,L1,L2)
150  IF L2=1 THEN 190
155  IF T=0 THEN 185
156  REM*****
157  REM  INPUT MEASURED DATA FROM SYSTEM.
158  REM*****
160  FOR I=1,15
165  INPUT Y(I)
170  NEXT I
173  B7=T(3):T(3)=Y(15):B7=T(3)-B7
174  T(10)=T(10)+B7:T(4)=T(4)+B7
175  M(1)=Y(2):T(1)=Y(8):V(5)=-Y(5)
176  V(5)=1.26556+.243361E-02*V(5)
180  T(12)=Y(6):T5=1: GOSUB 2999
185  GOSUB 2999
190  IF L1=2 THEN  STOP
195  REM*****
196  REM  INTEGRATION OF INDEPENDANT VARIABLE.
197  REM*****
200  CALL (3,T,12,2)
202  REM*****
203  REM  INTEGRATION OF DEPENDANT VARIABLES.
204  REM*****
205  CALL (4,T(2),H1)
215  CALL (4,M(4),H3)
223  B5=T(14)
225  CALL (4,T(14),H5)
227  B5=T(14)-B5:T(15)=T(15)+B5
235  CALL (4,M(10),H7)
240  CALL (4,T(13),H8)
245  CALL (4,T(11),H9)
255  CALL (4,H,F2)
256  REM*****
257  REM  STEADY STATE EQUATIONS OF MODEL.
258  REM*****
260  V(3)=V(5)*(E1+122*T1-C1*100)/E2-M(1)*C1/E2*(T(3)-T(2))
262  V(3)=V(3)-L(11)
265  E2=E1-(C1-T1)*T(15)
267  V(9)=(M(14)*C1*(T(14)-T(15)))/E2
```

SIMULATION PROGRAM LISTING CONTINUED.

```
268  V(9)=V(9)+M(8)*C1*(T(3)-T(15))/E2
270  V(9)=V(9)-L(10)
272  V(4)=V(3)-M(4)
275 M(8)=M(1)-V(3)
280  V(10)=M(1)-M(8)-M(10)
285 M(11)=V(9)+M(10)+V(10)
290  GOTO 55
295  REM*****
296  REM  DATA FOR INITIAL CONDITIONS.
297  REM*****
300  DATA 27.9693,0,24.9888
305  DATA 27.9693,0,51.9164
310  DATA 0,10.8601,62.5604
315  DATA 1.33916,9.52091,61.8732
320  DATA 0,11.5432,122
325  DATA 1,1,1
330  DATA 1,1,1
335  DATA 17.1092,0,58.2864
340  DATA 0,7.12855,48.9461
345  DATA 8.2457,2.61426,59.7094
350  DATA 17.9887,0,24.6362
355  DATA 550,0,18.1062
360  DATA 550,0,27.4797
365  DATA 3872.73,0,49.9502
370  DATA 3872.73,0,48.9461
495  REM*****
496  REM  SET UP HEAT LOSSES FROM THE SYSTEM.
497  REM*****
500  L(1)=H1:L(3)=H3:L(5)=H5
503  L(2)=0
505  L(6)=H6:L(7)=H7:L(8)=H8:L(9)=H9
520  T3=1: GOTO 77
996  REM*****
997  REM  SUBROUTINE TO COMPUTE DENSITY AND
998  REM  SPECIFIC ENTHALPY OF 2 PHASE MIX.
999  REM*****
1000  P2=-.452405E-04+.247885E-05*T(I)
1005  P=(V(I)+M(I))/(V(I)/P2+M(I))
1010  C=V(I)/(V(I)+M(I))*(E1+T1*T(I))
1015  C=C+M(I)/(V(I)+M(I))*T1*T(I)
1020  RETURN
1995  REM*****
1996  REM  PHYSICAL CONSTANTS OF SYSTEM.
1997  REM*****
2000  C1=4.1868:E1=2500.8:T1=1.6742:M(14)=3416.32
2002  B7=0
2005  A1=3367.4:V1=1593.3
2010  A2=6160.2:V2=2918.5
2015  A3=6247:V3=3946.81
2020  A4=.104666E05:V4=6613.06
2025  A5=1297.2
2026  REM*****
2027  REM  SET HEAT LOSSES TO ZERO INITIALLY.
2028  REM*****
2030  FOR I=1,15
2035  L(I)=0
2040  NEXT I
```

SIMULATION PROGRAM LISTING CONTINUED.

```
2045  T3=0
2050  RETURN
2900  REM*****
2901  REM  SUBROUTINE FOR OUTPUT OF RESULTS.
2902  REM*****
2999  IF T5=1 THEN 3100
3000  FOR J=1,5: PRINT : NEXT J
3003  PRINT "TIME";T: PRINT : PRINT
3005  PRINT T(2),Y(9)
3015  PRINT T(3),Y(12)
3020  PRINT T(4),Y(14)
3025  PRINT T(10),Y(1)
3030  PRINT T(11),Y(13)
3035  PRINT T(13),Y(7)
3040  PRINT T(14),Y(11)
3045  PRINT T(15),Y(10)
3050  PRINT M(8),Y(3)
3055  PRINT H,Y(4)
3060  PRINT
3065  PRINT V(3)
3070  PRINT V(4),M(4)
3075  PRINT V(9)
3080  PRINT V(10),M(10)
3085  PRINT M(11)
3090  PRINT U1,U2,U3,U4
3092  PRINT M(1),V(5),T(12),T(1)
3093  PRINT Y(15)
3095  RETURN
3100  GOTO 36
3105  T5=0
3110  RETURN
3900  REM*****
3901  REM  SUBROUTINE TO RATIONALISE THE INITIAL
3902  REM  CONDITIONS AND MEASUREMENTS AT TIME ZERO.
3903  REM*****
3945  E2=E1-(C1-T1)*T(15)
3950  V(9)=(M(14)*C1*(T(14)-T(15)))/E2
3955  L(10)=B4-V(9)
3957  E2=E1-(C1-T1)*122
3960  V(3)=V(5)*(E1+122*T1-C1*100)/E2-M(1)*C1/E2*(T(3)-T(2))
3965  L(11)=B6-V(3)
3995  T(3)=Y(15)
3996  T(4)=Y(14):T(10)=Y(1)
4000  M(1)=Y(2):T(1)=Y(8):V(5)=-Y(5)
4005  V(5)=1.26556+.243361E-02*V(5)
4010  H=Y(4)
4015  V(3)=V(5)*(E1+122*T1-C1*100)/E2-M(1)*C1/E2*(T(3)-T(2))
4020  V(3)=V(3)-L(11)
4025  M(8)=M(1)-V(3)
4030  V(4)=V(3)-M(4)
4035  V(10)=M(1)-M(8)-M(10)
4040  GOTO 25
```

Computer program for On-line Kalman Filtering.

Symbol Description.

C1 = Specific heat of water

E1 = Latent heat of vaporisation

T1 = Specific heat of vapour

H = Head of liquid in second effect separator

B8 = Change in variable T(3) over time increment of filter

B4 = Constant associated with computation of variable V(9)

B9 = Constant associated with computation of variable V(3)

A3 = Constant associated with estimation of T(14)

A4 = Constant associated with estimation of T(15)

G4 = Constant associated with estimation of T(10)

E2 = Specific enthalpy of vapour

E8 = number of instrument scans to be averaged at each time interval

Z4 = Time interval between scans

N1 = Initial channel to be scanned

N2 = Final channel to be scanned

Z7 = Number of scans completed at any instant of time

Z6 = Number of scans to be carried out

Z8 = Scanning error flag

The variables I and K are used as counters

The following variables are used with subscripts:-

M = Liquid flow rates in streams

V = Vapour flow rates in streams

T = Temperatures in streams

Y = measurements from evaporator

U = Heat transfer coefficients for evaporator units

A = Controls for subroutine KALMAN, with vector positions;

1 = No. of variables to be estimated, 2 = No. of measurements

3 = Control flag to ensure initial statistics are set up on first entry.

4 = input noise statistics, 5 = error statistics for initial predictions

6 = instrument statistics, 7 = Flag to choose type of filter

8 = Flag to ensure that computer returns to correct point when measurements are available from the Basic level.

B = Control vector for subroutine PREDIC, with vector positions;

1 = No. of iterations of integration cycle for each entry to PREDIC

2 = Control flag to ensure that differential equations equal zero on initial entry.

3 = No. of differential equations, 4 = Step length of integration.

C = Initial conditons for solution of dynamic model in PREDIC.

D = Predictions obtained from dynamic model. Vector positions for C and D are as follows;

1 = T(2) 2 = T(13) 3 = T(11)

4 = H 5 = T(14) 6 = M(4)

7 = M(10) 8 = T(10) 9 = M(8)

E = Prediction vector for KALMAN. G = Estimate vector from KALMAN.

F = Measurement vector for KALMAN. Vector positions for E,G and F are;

1 = T(2) 2 = T(13) 3 = T(11)

4 = T(10) 5 = H 6 = M(8)

7 = T(14) 8 = M(4) 9 = M(10)

R = Matrix of instrument analogue signals from evaporator.

P = Intercept values of instruments for conversion of analogue signals.

H = Gradient values for instruments for conversion of analogue signals.

BASIC COMPUTER PROGRAM FOR ON-LINE FILTERING
****

```
1 REM*****
2 REM  SET UP CONSTANTS AND SCAN CONTROLS.
3 REM*****
4  C1=4.1868:E1=2500.8:T1=1.6742:E8=7:Z4=60:A6=1
5 N1=14:N2=29:Z7=0:Z6=10:GO TO 4050
6 DIM V(15),M(15),T(15),U(4),B(5),C(9),D(9),P(15)
7 DIM Y(15),A(10),G(9),E(9),F(9),R(39,1),H(15)
8 REM*****
9 REM  INPUT INITIAL CONDITIONS.
10 REM*****
11 FOR I=1,15
12  INPUT M(I),V(I),T(I)
14 NEXT I
16 REM*****
17 REM  START THE INSTRUMENT SCAN ROUTINES.
18 REM*****
20 GOSUB 4020
21 REM*****
22 REM  RATIONALISE INITIAL CONDITIONS
23 REM  AND INITIAL MEASUREMENTS.
24 REM*****
25 Y(3)=M(8)
27 B4=V(9):B9=V(3)
30  E2=E1-(C1-T1)*T(15)
35  V(9)=M(14)*C1*(T(14)-T(15))
37  V(9)=V(9)+M(8)*C1*(T(3)-T(15))
38  V(9)=V(9)/E2
40  B4=V(9)-B4
45  E2=E1-(C1-T1)*T(3)
50  V(3)=V(5)*(E1+122*T1-100*C1)
52  V(3)=V(3)-M(1)*C1*(T(3)-T(2)):V(3)=V(3)/E2
55  B9=V(3)-B9
60  T(3)=Y(15):T(4)=Y(14):T(10)=Y(1)
65  M(1)=Y(2):T(1)=Y(8):V(5)=Y(5)
75  H=Y(4)
80  V(3)=V(5)*(E1+122*T1-C1*100)
82  V(3)=V(3)-M(1)*C1*(T(3)-T(2))
83  V(3)=V(3)/E2
85  V(3)=V(3)-B9
90  M(8)=M(1)-V(3)
95  V(4)=V(3)-M(4)
100  V(10)=M(1)-M(8)-M(10)
101 REM*****
102 REM  COMPUTE HEAT TRANSFER COEFFICIENTS.
103 REM*****
105  GOSUB 2000
106 REM*****
107 REM  SET UP CONTROLS FOR SUBROUTINE KALMAN
108 REM*****
110  FOR I=1,10:A(I)=0: NEXT I
115  A(1)=9:A(2)=7:A(3)=2:A(5)=1000
117  A(4)=1
```

CONTINUED.

```
120  A(6)=2:A(8)=1
122  A(7)=2
123 REM*****
124 REM  SET UP CONTROLS FOR SUBROUTINE PREDIC.
125 REM*****
127  B(1)=5
130  B(2)=2:B(3)=7:B(4)=12
131 REM*****
132 REM  SET UP PREDICTIONS FOR INITIAL FILTER ENTRY.
133 REM*****
134  E(1)=T(2):E(2)=T(13):E(3)=T(11):E(7)=T(14)
135  E(4)=T(10):E(5)=H:E(6)=M(8):E(8)=M(4):E(9)=M(10)
138 REM*****
139 REM  ENTER KALMAN FOR FIRST TIME.
140 REM*****
141 GO SUB 215
142 GO TO 205
143 REM*****
144 REM  SET UP INITIAL CONDITIONS FOR SOLUTION
145 REM  OF THE DYNAMIC MODEL.
146 REM*****
147  C(1)=T(2):C(2)=T(13):C(3)=T(11):C(4)=H
148 C(5)=T(14):C(6)=M(4):C(7)=M(10):C(8)=T(10):C(9)=M(8)
150 REM*****
151 REM  ENTER PREDIC VIA DATA
152 REM*****
153  K=1
155 CALL(2,M(1),T(1),V(1),U(1),K,B(1),C(1),D(1),A(1),G(1)
   ,E(1),F(1))
156 REM*****
157 REM  COLLECT MEASUREMENTS FROM EVAPORATOR.
158 REM*****
160  GOSUB 4000
161 REM*****
162 REM  SET UP MODEL INPUTS FROM MEASUREMENTS.
163 REM*****
165  B8=T(3):T(3)=Y(15):B8=T(3)-B8
170  T(4)=T(4)+B8:T(10)=T(10)+B8
175  M(1)=Y(2):T(1)=Y(8):V(5)=Y(5)
185  D(8)=T(10)
186 REM*****
187 REM  SET UP PREDICTION VECTOR FOR KALMAN
188 REM  AND ENTER KALMAN VIA DATA
189 REM*****
190  FOR I=1,3:E(I)=D(I): NEXT I
192  E(4)=D(8):E(5)=D(4):E(6)=D(9)
194  E(7)=D(5):E(8)=D(6):E(9)=D(7)
196  GOSUB 215
```

CONTINUED.

```
198 REM*****
199 REM  RETURN FOR MEASUREMENTS FROM KALMAN.
200 REM  SET UP MEASUREMENT VECTOR FOR KALMAN
201 REM  AND RETURN VIA DATA.
202 REM*****
205  F(1)=Y(9):F(2)=Y(7):F(3)=Y(13):F(4)=Y(1)
207  F(5)=Y(4):F(6)=Y(3):F(7)=Y(11)
209  A3=T(14):A4=T(15)
211  GOSUB 215: G4=G(4):GO TO 220
212 REM*****
213 REM  CALL STATEMENT FOR FORTRAN SUBROUTINE DATA
214 REM*****
215 CALL(2,M(1),T(1),V(1),U(1),2,B(1),C(1),D(1),A(1),G(1)
  ,E(1),F(1))
216  RETURN
217 REM*****
218 REM  SET UP VARIABLES BASED ON ESTIMATES FROM FILTER
219 REM*****
220  T(2)=G(1):T(13)=G(2):T(11)=G(3):T(10)=G4
225  H=G(5):M(8)=G(6):T(14)=G(7):M(4)=G(8)
230  M(10)=G(9):A3=T(14)-A3:T(15)=A4+A3
231 REM*****
232 REM  COMPUTE STEADY STATE EQUATIONS BASED ON
233 REM  ESTIMATES OBTAINED FROM FILTER.
234 REM*****
240  V(3)=M(1)-M(8)
243  E2=E1-(C1-T1)*T(15)
245  V(9)=M(14)*C1*(T(14)-T(15))
247  V(9)=V(9)+M(8)*C1*(T(3)-T(15))
249  V(9)=V(9)/E2:V(9)=V(9)-B4
255  V(4)=V(3)-M(4)
260  V(10)=M(1)-M(8)-M(10)
262  M(11)=V(9)+V(10)+M(10)
264  T(8)=T(3)
265 REM*****
266 REM  COMPUTE HEAT TRANSFER COEFFICIENTS IN SUBROUTINE
267 REM*****
270  GOSUB 2000
271 REM*****
272 REM  OUTPUT REQUIRED INFORMATION ONTO PAPER TAPE.
273 REM*****
275  PRINT T(2),Y(9),D(1)
280  PRINT T(4),Y(14)
285  PRINT T(8),Y(12)
290  PRINT T(10),Y(1),D(8)
296  PRINT T(11),Y(13),D(3)
300  PRINT T(13),Y(7),D(2)
305  PRINT T(14),Y(11),D(5)
310  PRINT T(15),Y(10)
315  PRINT M(8),Y(3),D(9)
320  PRINT H,Y(4),D(4)
325  PRINT : PRINT : PRINT
```

CONTINUED.

```
330  PRINT V(3)
335  PRINT V(4),M(4),D(6)
340  PRINT V(9)
345  PRINT V(10),M(10),D(7)
350  PRINT M(11)
355  FOR I=1,4: PRINT U(I),: NEXT I: PRINT
360  PRINT : PRINT : PRINT
365  PRINT M(1),T(1),T(3),M(12),T(12)
370  PRINT : PRINT : PRINT : PRINT : PRINT
371 REM*****
372 REM  START NEXT CYCLE OF FILTERING PROCESS.
373 REM*****
375  GOTO 147
1990 REM*****
1991 REM  SUBROUTINE TO COMPUTE HEAT
1992 REM  TRANSFER COEFFICIENTS.
1993 REM*****
2000  U(1)=.189958*(T(1)↑.115644)*(M(1)↑.254433)
2005  U(1)=U(1)/(V(3)↑.915914)/(T(3)↑.496023E-01)
2010  U(2)=.418596E-03*(M(1)↑.287992)*(V(3)↑.958777)
2015  U(2)=U(2)*(T(2)↑.194165)*(T(3)↑.504994)
2020  U(3)=3.9574*(T(14)↑3.21051)*(V(4)↑.568398)
2025  U(3)=U(3)*(M(10)↑.494838)/(V(10)↑.115259)
2030  U(3)=U(3)/(T(4)↑2.40123)/(T(10)↑1.89576)
2035  U(4)=.53554E-04*(M(12)↑1.07948)*(T(13)↑2.56339)
2040  U(4)=U(4)*(M(10)↑.251088)/(T(12)↑.360554)
2045  U(4)=U(4)/(T(15)↑1.48368)/(T(11)↑1.05817)
2050  RETURN
3990 REM*****
3991 REM  SUBROUTINE TO COLLECT DATA FROM EVAPORATOR.
3992 REM*****
4000  IF Z7=0 THEN 4000
4010  GOTO 4025
4020  CALL (1,Z4,N1,N2,E8,R(0,0),Z6,Z7,Z8)
4025  Z7=0
4026 REM*****
4027 REM  CONVERT ANALOGUE SIGNALS.
4028 REM*****
4030  FOR I=1,15
4035  Y(I)=R(I+14,1)*H(I)+P(I)
4040  NEXT I
4045  RETURN
4046 REM*****
4047 REM  DATA FOR INSTRUMENT CONVERSIONS
4048 REM*****
4050  FOR I=1,5: READ P(I),H(I): NEXT I
4052  DATA -59.0324,-.5214E-01
4054  DATA -16.2798,-.644646E-02
4056  DATA 3.02299,-.577411E-02
4058  DATA -165.352,-.416595E-01
4060  DATA 1.26556,-.243361E-02
4065  FOR I=6,15:P(I)=0:H(I)=-.25E-01: NEXT I
4070  GOTO 6
```

Computer Program for the transfer of data from the BASIC to the FORTRAN level, (Subroutine DATA).

Symbol Description.

MTC = Mass of the condenser tubes

MTP = Mass of the tubes of the preheater

MSC = Mass of the shell of the condenser

MTSE = Mass of the tubes of the second effect

AP = Area for heat transfer in the preheater

AC = Area for heat transfer in the condenser

ASE = Area for heat transfer in the second effect

ASEP = Cross sectional area of the second effect separator

VTP = Volume of the tubes of the preheater

VTC = Volume of the tubes of the condenser

VSC = Volume of the shell of the condenser

VTSE = Volume of the tubes of the second effect

C1 = Specific heat of water

CS = Specific heat of steel

CT = Specific heat of copper

T1 = Specific heat of steam vapour

E1 = Latent heat of vaporisation

D1 = Capacitance term associated with the tubes of the preheater

D2 = Capacitance term associated with the tubes of the condenser

D3 = Capacitance term associated with the tubes of the second effect

D4 = Capacitance term associated with the shell of the condenser

I = Loop counter

A6 = L5 = Flag for setting up constants during first entry into DATA

A3 = L9 = Flag controlling the passage from BASIC to required FORTRAN subroutine

The following subscripted variables are used;

M = MA = Liquid flow rates in evaporator

T = TA = Temparatures in evaporator

V = VA = Vapour flow rates in evaporator

U = UA = Heat transfer coefficients in evaporator

X = XA = Estimates of the state of the system obtained from the Kalman Filter for transfer back to the BASIC level.

FLAGS = FLAGSA = Data and control flags for the Kalman Filter program passed from the BASIC level.

XPR = XPRA = Predictions of the state of the system passed from the BASIC level to the Kalman Filter program

Y = YA = Measurements from the evaporator passed to the Kalman Filter

FLAG = FLAGA = Data and control flags for the Solution of the dynamic model of the system passed from the BASIC level

X3 = X3A = Initial conditions at each time interval for the solution of the dynamic model (i.e. estimates from the Kalman Filter)

XO = XOA = Predictions from the dynamic model for use in the Kalman Filter.

IFIX = Fortran library routine for assigning an integer value to a real number

```
      SUBROUTINE DATA(A6,MA,TA,VA,UA,A3,FLAGA
     1,X3A,XAO,FLAGSA,XA,XPRA,YA)
C
C
C     THIS SUBROUTINE CONTROLS THE PASSAGE OF
C     DATA BETWEEN THE BASIC AND FORTRAN LEVELS.
C
C
      REAL MA,MTC,MTP,MSC,MTSE,M
      DIMENSION M(15),T(15),V(15),U(4),FLAGS(10)
     1,XPR(9),Y(9),X(9),FLAG(5),X3(9),XO(9)
     2,MA(15),TA(15),VA(15),UA(15),FLAGA(5)
     3,X3A(9),XAO(9),FLAGSA(10),XA(9),XPRA(9)
     4,YA(9)
      COMMON/BLK6/FLAG,X3,XO
      COMMON/BLK5/FLAGS,XPR,L7,Y,X
      COMMON/BLK4/M,T,V,U
      COMMON/BLK3/AP,VTP,MTP,CT,AC,VTC,MTC,
     1MSC,CS,VSC,ASEP,ASE,VTSE,MTSE
      COMMON/BLK2/C1,E1,T1
      COMMON/BLK1/D1,D2,D3,D4
C
C
C     SET UP VARIABLE VALUES IN FORTRAN FOR
C     USE IN COMMON BLOCKS.
C
C
      DO 150 I=1,15
      V(I)=VA(I)
      T(I)=TA(I)
      M(I)=MA(I)
  150 CONTINUE
      DO 151 I=1,4
      U(I)=UA(I)
  151 CONTINUE
      DO 152 I=1,5
      FLAG(I)=FLAGA(I)
  152 CONTINUE
      DO 153 I=1,9
      X(I)=XA(I)
      Y(I)=YA(I)
      XPR(I)=XPRA(I)
      X3(I)=X3A(I)
      XO(I)=XAO(I)
  153 CONTINUE
      DO 154 I=1,10
      FLAGS(I)=FLAGSA(I)
  154 CONTINUE
C
C
C     SET UP CONSTANT VALUES FOR FORTRAN
C     SUBROUTINES DURING FIRST ENTRY
C
C
      L5=IFIX(A6+.5)
      IF(L5.EQ.2) GO TO 100
```

```
C
C     SUBROUTINE DATA CONTINUED
C
      C1=4.1868
      AP=3367.4
      VTP=1593.3
      L7=IFIX(FLAGS(7)+.5)
      MTP=4910.2
      CT=.38494
      AC=10466.6
      VTC=6613.06
      MTC=14949.6
      MSC=36978.7
      CS=.45186
      VSC=2812.8
      T1=1.6742
      ASEP=1297.2
      ASE=6247.
      VTSE=3947.81
      MTSE=8922.21
      M(14)=3416.32
      E1=2500.8
      D1=VTP*C1+MTP*CT
      D2=VTC*C1+MTC*CT
      D3=10.*(VTSE*C1+MTSE*CT)
      D4=MSC*CS+VSC*C1
      A6=2.
C
C
C     CONTROL FOR ACCESSING REQUIRED FORTRAN
C     SUBROUTINE
C
C
  100 L9=IFIX(A3+.5)
      IF(L9.EQ.2) GO TO 200
      CALL PREDIC
      GO TO 300
  200 CALL KALMAN
C
C
C     SET UP DATA TO BE TRANSFERED BACK TO
C     BASIC LEVEL.
C
C
  300 DO 301 I=1,9
      XA(I)=X(I)
      XA0(I)=X0(I)
  301 CONTINUE
      FLAGA(2)=FLAG(2)
      FLAGSA(3)=FLAGS(3)
      FLAGSA(8)=FLAGS(8)
      TA(10)=T(10)
      RETURN
      END
$0
```

Computer Program for the Solution of the Dynamic Model of the Evaporator System for use in conjunction with the Kalman Filter, (Subroutine Predic).

Symbol Description.

Symbols of Common blocks BLK2, BLK4, BLK6 are as described for Subroutine DATA

FLAG(3) = N = Number of variables to be predicted from model

FLAG(1) = IT = Number of steps to be taken by integration routine

FLAG(2) = L3 = Flag ensuring that heat losses are only computed on first entry to the program

FLAG(4) = Step length of integration routine

LL2 = Flag controlling the modified Euler Integration routine

The counters I and J are used

The following subscripted variables are used;

HEAT = Heat loss associated with each differential equation

DX = The value of the gradient at the modified Euler point

OLDDX = The value of the gradient at the Euler point

```
      SUBROUTINE PREDIC
C
C
C     THIS SUBROUTINE PREDICTS THE VALUE OF
C     THE STATE VARIABLES FROM THE MATH.
C     MODEL DERIVED IN CHAPTER 5. ALL REQU.
C     DATA FOR THE MODEL IS OBTAINED FROM THE
C     COMMON BLOCKS. THE SUBROUTINE CALLS
C     GRAD TO COMPUTE THE GRADIENTS OF THE
C     DIFFERENTIAL EQUATIONS
C
C
      REAL M
      DIMENSION FLAG(5),U(4),M(15),V(15)
     1,T(15),X(9),HEAT(7),DX(7),XO(9),
     2OLDDX(7)
C
C
C     SET UP COMMON DATA BLOCKS.
C
C
      COMMON/BLK6/FLAG,X,XO
      COMMON/BLK2/C1,E1,T1
      COMMON/BLK7/HEAT,DX
      COMMON/BLK4/M,T,V,U
      N=IFIX(FLAG(3)+.5)
      IT=IFIX(FLAG(1)+.5)
      L3=IFIX(FLAG(2)+.5)
      DO 100 I=1,IT
      IF(L3.NE.2) GO TO 200
      LL2=1
      DO 201 J=1,N
      HEAT(J)=0.
  201 CONTINUE
C
C
C     COMPUTE HEAT LOSS TERM FOR EACH DIFFERENTIAL
C     EQUATION
C
C
      CALL GRAD(X)
      DO 202 J=1,N
      HEAT(J)=DX(J)
  202 CONTINUE
      FLAG(2)=1.
  200 HOLDT=T(15)
      CALL GRAD(X)
      DO 203 J=1,N
      XO(J)=X(J)+FLAG(4)*DX(J)
      OLDDX(J)=DX(J)
  203 CONTINUE
C
C
C     COMPUTE VALUES OF REMAINING VARIABLES
C     BASED ON THESE NEW PREDICTED VALUES OF
C     THE VARIABLES LINKED BY DIFFERENTIAL
C     EQUATIONS
C
C
```

```
C
C     SUBROUTINE PREDIC CONTINUED.
C

  205 XO(9)=M(1)-V(3)
      T(15)=HOLDT+XO(5)-X(5)
      V(3)=V(5)*(E1+122.*T1-C1*100.)
      V(3)=V(3)-M(1)*C1*(T(3)-XO(1))
      V(3)=V(3)/(E1+T1*T(3)-C1*T(3))
      V(9)=M(14)*C1*(XO(5)-T(15))
      V(9)=V(9)+XO(9)*C1*(T(3)-T(15))
       V(9)=V(9)/(E1+T1*T(15)-C1*T(15))
      V(4)=V(3)-XO(7)
      V(10)=M(1)-XO(9)-XO(7)
      M(11)=XO(7)+V(10)+V(9)
      IF(LL2.EQ.2) GO TO 210
      CALL GRAD(X)
      DO 204  J=1,N
      XO(J)=X(J)+FLAG(4)*(DX(J)+OLDDX(J))/2.
      X(J)=XO(J)
  204 CONTINUE
      LL2=2
      GO TO 205
  210 LL2=1
  100 CONTINUE
      RETURN
      END
$0
```

Computer Program for the Calculation of the Gradients of the Dynamic Model of the Evaporator system for use in conjunction with PREDIC, (Subroutine GRAD).

Symbol Description.

Symbols of Common blocks BLK1, BLK2, BLK3, BLK4 are as described for DATA

Symbols of Common block BLK7 are as described for PREDIC

D5 = Capacitance term associated with the tubes of the second effect

D4 = Capacitance term associated with the shell of the condenser

HOLD = the value of the derivative describing T(2)

The subscripted variable A is the value of the state at which the gradient is required.

```
      SUBROUTINE GRAD(A)
C
C
C     THIS SUBROUTINE COMPUTES THE GRADIENT
C     AT A GIVEN VALUE OF THE STATE VECTOR.
C
C
      REAL MTP,MTC,MSC,MTSE,M
      DIMENSION A(9),HEAT(7),DX(7),U(4)
     1,M(15),V(15),T(15)
C
C
C     SET UP COMMON DATA BLOCKS
C
C
      COMMON/BLK1/D1,D2,D5,D3
      COMMON/BLK2/C1,E1,T1
      COMMON/BLK3/AP,VTP,MTP,CT,AC,VTC,LTC,
     1MSC,CS,VSC,ASEP,ASE,VTSE,MTSE
      COMMON/BLK4/M,T,V,U
      COMMON/BLK7/HEAT,DX
C
C
C     DIFFERENTIAL EQUATIONS OF THE EVAPORATOR
C     DYNAMIC MODEL.
C
C
      DX(1)=M(1)*C1*(T(1)-A(1))/10./D1
      DX(1)=DX(1)+AP*U(1)*(T(3)-A(1))/D1
      DX(1)=DX(1)-HEAT(1)
      DX(2)=M(12)*C1*(T(12)-A(2))/D2
      DX(2)=DX(2)+U(4)*AC*(A(3)-A(2))/D2
      DX(2)=DX(2)-HEAT(2)
      DX(3)=V(9)*(E1+T1*T(15)-C1*T(15))
      DX(3)=DX(3)+V(10)*(E1+T1*A(8)-C1*A(8))
      DX(3)=DX(3)+A(7)*A(8)*C1-M(11)*C1*A(3)
      DX(3)=DX(3)-U(4)*AC*(A(3)-A(2))
      DX(3)=DX(3)/D3-HEAT(3)
      DX(4)=(A(9)-V(9))/ASEP-HEAT(4)
      HOLD=-(DX(1)+HEAT(1))
      DX(5)=ASE*U(3)*(A(8)-A(5))
      DX(5)=DX(5)+M(14)*C1*(T(15)-A(5))
      DX(5)=DX(5)/D5-HEAT(5)
      DX(6)=M(1)*C1*HOLD/E1-HEAT(6)
      DX(7)=M(1)*C1*HOLD/E1-HEAT(7)
      ADD=EXP(-2.)
      RETURN
      END
50
```

Computer Program for the Implementation of the Kalman Filter and Modifications proposed by Coggan and Wilson, (Subroutine KALMAN).

Symbol Description.

Statements in the program which contain the letter A in column 1 refer to Machine instructions described in Chapter 7

Symbols of Common blocks BLK1, BLK2, BLK3, BLK4, BLK5 are as described for DATA

I, J, K, L are used as loop counters

FLAGS(1) = N = Number of variables

FLAGS(2) = M = Number of measurements

FLAGS(3) = L3 = Ensures that the constant data is only computed on the initial entry to the subroutine

FLAGS(4) = Noise covariance to the system inputs

FLAGS(5) = Initial error covariance of the state predictions

FLAGS(6) = Noise covariance to the system measurements

FLAGS(7) = L7 = Flag controlling the type of filter required by the programmer, i.e. extended filter or tha adaptive filter of Coggan et al.

FLAGS(8) = L8 = Flag controlling point of re-entry to computation in filter when measurements are required

ALPHA = Exponential weighting factor

L4 = Flag ensuring that the initial value of the error covariance of the predictions is <u>not</u> calculated by the filter

I1 = counter equall to I + 1 in calculations

DIV, DIV2 and SWOP are holding variables used to store required values

The following subscripted variables are used;

MM = Liquid flow rates in evaporator

THY = Transition matrix approximation for a non-linear system

B = Bias vector for measured variables

P = Error covariance matrix of the predictions and estimates

HOLD and HOLD1 are two matricies used for storing intermediate matrix calculations

W = Gain matrix

VNEW = Error covariance matrix of the predictions based upon the measurement data

S = Covariance matrix of the difference between measured and predicted values of the predicted variables

H = Measurement incidence matrix

Z = Update of S based upon the bias predictions

```
      SUBROUTINE KALMAN
C
C
C     THIS SUBROUTINE USES THE THEORY OF R.E.KALMAN
C      AND MODIFICATIONS PROPOSED BY COGGAN AND
C      WILSONTO UPDATE AND IMPROVE PREDICTIONS
C      FROM A MATHEMATICAL MODEL BY USE OF KNOWN
C     SYSTEM STATISTICS AND MEASUREMENTS OBTAINED
C     FROM THE PHYSICAL SYSTEM.
C
C
C
C     SET UP FIRST SET BASE INSTRUCTION
C
C
A     NOP
      REAL MTP,MSC,MTC,MTSE,MM
      DIMENSION FLAGS(10),P(9,9),H(9,9)
     1 ,MM(15),THY(9,9),B(7)
     2 ,U(4),V(15),X(9),HOLD(9,9),S(9,9)
     3 ,ZSMALL(7),HOLD1(9,9),VNEW(9,9)
     4 ,XPR(9),W(9,9),Y(9),Z(7,7)
C
C
C     SET UP COMMON BLOCKS FOR DATA REQUIRED
C
C
      COMMON/BLK1/D1,D2,D3,D4
      COMMON/BLK2/C1,E1,TI
      COMMON/BLK3/AP,VTP,MTP,CT,AC,VTC,MTC,
     1 MSC,CS,VSC,ASEP,ASE,VTSE,MTSE
      COMMON/BLK4/MM,T,V,U
      COMMON/BLK5/FLAGS,XPR,Y,X
      ALPHA=EXP(-4.)
      L8=IFIX(FLAGS(8)+.5)
      IF(L8.EQ.2) GO TO 103
C
C
C     SET UP SECOND SET BASE INSTRUCTION
C
C
A     SETB,*+1
A     JMP,*+50
A     BSS,49
      L3=IFIX(FLAGS(3)+.5)
      IF(L3.EQ.1) GO TO 100
      N=IFIX(FLAGS(1)+.5)
      M=IFIX(FLAGS(2)+.5)
C
C
C     SET UP FILTER STATISTICS FOR TIME ZERO.
C
C
      DO 200 I=1,N
      DO 201 J=1,N
```

```
C
C      SUBROUTINE KALMAN CONTINUED.
C
       P(I,J)=0.
       H(I,J)=0.
   201 CONTINUE
       P(I,I)=FLAGS(5)
       H(I,I)=1.
   200 CONTINUE
       H(N,N)=0.
       DO 190 I=1,N
       DO 190 J=1,N
       THY(I,J)=0.
   190 CONTINUE
       THY(5,6)=1./ASEP
C
C
C       SET UP INITIAL ESTIMATES OF THE BIAS
C       AND RESIDUAL STATISTICS FOR ADAPTIVE
C       FILTER
C
C
       DO 192 I=1,M
       B(I)=0.
       DO 192 J=1,M
       Z(I,J)=0.
   192 CONTINUE
      L4=1
   100 FLAGS(3)=1.
       IF(L4.EQ.1) GO TO 101
C
C       NON CONSTANT TERMS IN TRANSITION MATRIX
C       COMPUTED EACH ENTRY TO FILTER
C
       THY(1,1)=(-MM(1)*C1/10.-AP*U(1))/D1
       THY(2,2)=(-MM(12)*C1-U(4)*AC)/D2
       THY(2,3)=U(4)*AC/D2
       THY(3,2)=U(4)*AC/D4
       THY(3,3)=(-MM(11)*C1-U(4)*AC)/D4
       THY(3,4)=(V(10)*TI+X(9)*C1)/D4
       THY(3,9)=X(4)*C1/D4
       THY(7,4)=ASE*U(3)/D3
       THY(7,7)=(-ASE*U(3)-MM(14)*C1)/D3
C
C
C      SET UP THIRD SET BASE INSTRUCTION
C
C
A      SETB,*+1
A      JMP,*+39
A      BSS,38
       THY(8,1)=MM(1)*C1*THY(1,1)/E1
```

```
C
C
C     SUBROUTINE KALMAN CONTINUED
C
C
      THY(9,1)=THY(8,1)
C
C
C     COMPUTE ERROR COVAR. OF PREDICTIONS
C
C
      DO 203 I=1,N
      DO 203 J=1,N
      HOLD(I,J)=0.
      DO 203 L=1,N
      HOLD(I,J)=HOLD(I,J)+THY(I,L)*P(L,J)
  203 CONTINUE
      DO 204 I=1,N
      DO 205 J=1,N
      P(I,J)=0.
      DO 205 K=1,N
      P(I,J)=P(I,J)+HOLD(I,K)*THY(J,K)
  205 CONTINUE
      P(I,I)=P(I,I)+FLAGS(4)
  204 CONTINUE
  101 L4=2
C
C
C     COMPUTE THE MATRIX OF COVAR. OF DIFFERENCE BETWEEN
C     LEASURED AND PREDICTED VALUES OF THE MEASURED
C     VARIABLES
C
C
      DO 206 I=1,M
      DO 206 J=1,N
      HOLD(I,J)=0.
      DO 206 K=1,N
      HOLD(I,J)=HOLD(I,J)+H(I,K)*P(K,J)
  206 CONTINUE
      DO 207 I=1,M
      DO 208 J=1,M
      S(I,J)=0.
      DO 208 K=1,N
      S(I,J)=S(I,J)+HOLD(I,K)*H(J,K)
  208 CONTINUE
      S(I,I)=S(I,I)+FLAGS(6)
  207 CONTINUE
      FLAGS(8)=2.
      RETURN
C
C
C     IF L7=1 THEN THE EXTENDED KALMAN FILTER HS USED,
C     IF L7.NE.1 THEN THE ADAPTIVE PROCEDURE PROPOSED
C     BY COGGAN AND WILSON IS USED,
C
C
```

```
C
C     SUBROUTINE KALMAN CONTINUED
C
  103 FLAGS(8)=1.
      IF(L7.EQ.1) GO TO 102
C
C
C     COMPUTE THE BIAS OF THE PREDICTIONS
C
C.
      DO 288 I=1,M
      B(I)=ALPHA*B(I)+(1.-ALPHA)*(XPR(I)-Y(I))
      ZSMALL(I)=XPR(I)-Y(I)-B(I)
  288 CONTINUE
      DO 209 I=1,M
      DO 209 J=1,M
      HOLD(I,J)=ZSMALL(I)*ZSMALL(J)
C
C
C     SET UP THE FOURTH SET BASE INSTRUCTION
C
C
A      SETB,*+1
A     JMP,*+48
A     BSS,47
      Z(I,J)=ALPHA*Z(I,J)+(1.-ALPHA)*HOLD(I,J)
  209 CONTINUE
      DO 210 I=1,M
      IF(Z(I,I).LE.S(I,I)) GO TO 210
      S(I,I)=Z(I,I)
  210 CONTINUE
      DO 211 I=1,N
      DO 211 J=1,M
      HOLD(I,J)=0.
      DO 211 K=1,M
      IF(I.NE.J) GO TO 300
      HOLD(I,J)=HOLD(I,J)+H(K,I)*(S(K,J)-FLAGS(6))
      GO TO 211
  300 HOLD(I,J)=HOLD(I,J)+H(K,I)*S(K,J)
  211 CONTINUE
      DO 212 I=1,N
      DO 212 J=1,N
      HOLD1(I,J)=0.
      DO 212 K=1,M
      HOLD1(I,J)=HOLD1(I,J)+HOLD(I,K)*H(K,J)
  212 CONTINUE
      DO 213 I=1,N
      DO 213 J=1,N
      HOLD(I,J)=0.
      DO 213 K=1,N
      HOLD(I,J)=HOLD(I,J)+H(I,K)*P(K,J)
  213 CONTINUE
      DO 214 I=1,N
```

```
C
C     SUBROUTINE KALMAN CONTINUED
C
      DO 214 J=1,N
      W(I,J)=0.
      DO 215 K=1,N
      W(I,J)=W(I,J)+HOLD(I,K)*H(K,J)
  215 CONTINUE
      W(I,J)=-W(I,J)+P(I,J)
      WNEW(I,J)=HOLD1(I,J)+W(I,J)
  214 CONTINUE
      DO 216 I=1,N
      IF(WNEW(I,I).LE.P(I,I)) GO TO 216
C
C
C     SET UP FIFTH SET BASE INSTRUCTION
C
C
A     SETB,*+1
A     JMP,*+42
A     BSS,41
      P(I,I)=WNEW(I,I)
  216 CONTINUE
C
C
C     COMPUTE BIAS FREE PREDICTIONS
C
C
      DO 301 I=1,M
      XPR(I)=XPR(I)-B(I)
  301 CONTINUE
C
C
C     COMPUTE THE GAIN MATRIX
C
C
  102 DO 218 I=1,M
      DO 219 J=1,M
      HOLD(I,J)=0.
  219 CONTINUE
      HOLD(I,I)=1.
  218 CONTINUE
      DO 220 I=1,M
  227 DIV=S(I,I)
      IF(DIV.EQ.0.) GO TO 222
      DO 221 J=1,M
      S(I,J)=S(I,J)/DIV
      HOLD(I,J)=HOLD(I,J)/DIV
  221 CONTINUE
      GO TO 223
  222 I1=I+1
      DO 224 L=I1,M
      IF(S(L,I).NE.0.) GO TO 225
  224 CONTINUE
```

```
C
C    SUBROUTINE KALMAN CONTINUED
C
      RETURN
  225 DO 226 J=1,M
      SWOP=S(I,J)
      S(I,J)=S(L,J)
      S(L,J)=SWOP
      SWOP=HOLD(I,J)
      HOLD(I,J)=HOLD(L,J)
      HOLD(L,J)=SWOP
  226 CONTINUE
      GO TO 227
  223 DO 228 K=1,M
      IF(K.EQ.I) GO TO 228
      DIV2=S(K,I)
      DO 229 J=1,M
      S(K,J)=S(K,J)-DIV2*S(I,J)
      HOLD(K,J)=HOLD(K,J)-DIV2*S(I,J)
  229 CONTINUE
  228 CONTINUE
  220 CONTINUE
      DO 271 I=1,M
      DO 271 J=1,M
      S(I,J)=HOLD(I,J)
  271 CONTINUE
      DO 230 I=1,N
      DO 230 J=1,M
      HOLD(I,J)=0.
      DO 230 K=1,N
      HOLD(I,J)=HOLD(I,J)+P(I,K)*H(J,K)
  230 CONTINUE
      DO 231 I=1,N
      DO 231 J=1,M
      W(I,J)=0.
       DO 231 K=1,M
C
C
C     FINAL SET BASE INSTRUCTION
C
C
A     SETB,*+1
A     JMP,*+40
A     BSS,39
      W(I,J)=W(I,J)+HOLD(I,K)*S(K,J)
  231 CONTINUE
C
C
C     COMPUTE THE ESTIMATES OF THE STATE VECTOR.
C
C
      DO 232 I=1,N
      HOLD(I,1)=0.
```

```
C
C     SUBROUTINE KALMAN CONTINUED
C
      DO 233 J=1,M
      HOLD(I,1)=HOLD(I,1)+W(I,J)*(Y(J)-XPR(J))
  233 CONTINUE
  232 CONTINUE
      DO 245 I=1,N
      X(I)=XPR(I)+HOLD(I,1)
  245 CONTINUE
C
C
C     COMPUTE THE ERROR COVAR. OF THE ESTIMATES.
C
C
      DO 234 I=1,N
      DO 235 J=1,N
      HOLD(I,J)=0.
      DO 236 K=1,M
      HOLD(I,J)=HOLD(I,J)+W(I,K)*H(K,J)
  236 CONTINUE
      HOLD(I,J)=-HOLD(I,J)
  235 CONTINUE
      HOLD(I,I)=1.+HOLD(I,I)
  234 CONTINUE
      DO 237 I=1,N
      DO 237 J=1,N
      HOLD1(I,J)=0.
      DO 237 K=1,N
      HOLD1(I,J)=HOLD1(I,J)+HOLD(I,K)*P(K,J)
  237 CONTINUE
      DO 238 I=1,N
      DO 238 J=1,N
      P(I,J)=HOLD1(I,J)
  238 CONTINUE
      RETURN
      END
S0
```

APPENDIX TWO.

TABLES OF RESULTS.

Tables 4.2A to 4.2D.

Experimental results for steady state analysis of evaporator system.

The following nomenclature and units are used within the tables.

U = overall heat transfer coefficient (J / sec. cm^{2}. $^{\circ}$C.)

M = liquid mass flow rate (g / sec.)

V = vapour mass flow rate (g / sec.)

T = temperature ($^{\circ}$C.)

the numbers in brackets refer to the stream identification as described in table 4.1.

The following subscripts are used within the tables.

P = preheater

FE = first effect

SE = second effect

C = condenser.

Table 4.2A

Steady State Analysis of the Preheater.

U_P	M(1)	V(3)	M(4)	T(1)	T(2)	T(3)	T(4)
0.527003E-01	27.3125	14.4225	1.1073	18.4700	41.6700	48.0700	47.4400
0.512604E-01	27.2484	13.4619	1.1824	16.6900	41.4100	48.4700	48.1800
0.479196E-01	27.0575	13.9374	1.1495	17.8200	41.9700	49.9300	48.8400
0.459279E-01	32.8932	8.8378	0.8368	21.0000	35.6900	43.1900	41.9200
0.447754E-01	31.3441	9.1945	0.7882	19.7900	34.3100	41.4400	40.4500
0.440605E-01	29.6027	16.5160	1.2629	19.1200	43.3800	54.0800	53.4300
0.508704E-01	29.5693	16.6420	1.3740	19.0400	45.2300	53.9100	54.1800
0.552789E-01	39.5522	10.1770	0.9859	19.9800	34.4000	41.7700	40.4600
0.609069E-01	38.2378	17.2176	1.8195	17.5000	44.3400	54.6200	54.7300
0.596859E-01	38.1500	17.6436	1.7755	17.6300	43.9000	54.2500	54.2800
0.441575E-01	22.0500	12.1285	0.8247	19.3700	41.4800	47.9200	44.4800
0.417013E-01	21.3779	10.9242	0.7483	17.2600	37.6700	43.5500	41.6900
0.658077E-01	39.0952	11.2481	1.1888	17.2600	34.8600	41.8200	40.2900
0.677949E-01	38.1806	9.6979	1.3340	16.1700	36.3800	43.3500	41.2800
0.666898E-01	38.7553	10.5101	1.2567	16.5100	35.2500	41.9400	40.4800
0.814264E-01	35.6400	15.8469	1.8080	19.7500	48.4000	53.8700	53.9500
0.880191E-01	35.5200	14.8077	1.7717	18.2200	46.4300	50.8500	51.1200
0.761866E-01	27.2073	13.6652	1.3136	18.7000	46.1400	49.3900	49.2500
0.750150E-01	27.0555	13.7843	1.3071	17.1300	44.6900	48.0900	47.6600
0.831342E-01	29.2106	17.6294	1.6953	17.9300	50.7200	54.4300	54.3700
0.558940E-01	33.2296	6.3673	0.9566	17.1100	33.7800	40.1100	38.3600
0.710087E-01	33.0311	15.9465	1.7247	16.7700	46.3300	52.7300	52.6300
0.683685E-01	32.8657	15.9998	1.8748	15.3900	47.6100	53.4300	53.3100
0.977434E-01	37.9295	13.7841	1.8986	16.1700	44.6300	48.7600	48.6000
0.969145E-01	37.7000	14.0400	1.9063	15.2200	44.0400	48.3100	47.8000
0.719169E-01	25.1340	15.0571	1.3843	17.9000	49.0200	52.4600	52.6000

Table 4.2A Continued.

U_P	M(1)	V(3)	M(4)	T(1)	T(2)	T(3)	T(4)
0.710510E-01	24.1693	14.5803	1.3704	17.8700	49.8400	53.1000	53.4400
0.684506E-01	25.2725	7.7773	0.9301	17.4100	38.6600	41.6100	40.3700
0.710076E-01	24.9756	7.5574	0.9062	17.4400	38.4200	41.0300	39.6400
0.575218E-01	30.5357	9.5144	1.0143	19.6900	39.2500	46.0300	41.6300
0.654515E-01	37.0920	11.0625	1.3493	18.0400	38.9200	45.9100	44.7700
0.685790E-01	37.0543	11.3336	1.3739	18.1300	39.2900	45.5000	45.3400
0.109858E 00	49.3917	15.7900	2.5812	16.1800	45.7000	51.5100	52.0100
0.877631E-01	49.6306	14.5996	2.3036	16.7200	42.9300	51.1000	51.6900
0.778475E-01	47.1195	17.1854	2.3501	15.8300	43.8500	53.7700	54.5100
0.764031E-01	47.1474	16.4591	2.3214	15.8400	43.5600	53.7100	54.3400
0.618437E-01	27.4004	19.4418	1.5820	15.8100	48.1600	56.4800	57.0500
0.626554E-01	27.2724	19.6661	1.6028	15.8800	48.8400	57.0300	57.4400
0.516973E-01	39.0853	14.6643	1.5755	13.7800	36.8200	49.2400	48.3900
0.495603E-01	39.8772	16.8392	1.7648	13.4500	36.6800	50.3200	49.6300
0.630701E-01	39.1230	18.8897	1.9106	13.7600	41.5400	52.0100	51.4100
0.463106E-01	29.1888	14.0222	1.3598	13.0800	39.4400	50.0600	48.6200
0.485195E-01	28.2573	17.3583	1.3462	13.2300	40.6200	50.2300	48.8800
0.448121E-01	26.7105	15.1894	1.0738	17.3800	40.3800	48.6100	48.0000
0.644016E-01	35.5468	15.4553	1.6126	19.9400	45.6600	53.5300	53.1600
0.576997E-01	34.7831	11.5088	1.1031	19.6500	37.6700	44.0100	44.5900
0.480181E-01	30.2951	15.5550	1.2153	21.8400	44.2900	52.6900	53.7400

Table 4.2B Steady State Analysis of the First Effect.

U_{FE}	M(2)	V(7)	V(5)	T(2)	T(7)
0.870153E-01	27.3125	14.4225	16.5235	41.6700	48.7000
0.815107E-01	27.2484	13.4619	15.6190	41.4100	49.0600
0.847665E-01	27.0575	13.9374	16.0569	41.9700	49.3500
0.498961E-01	32.8932	8.8378	10.5187	35.6900	42.4500
0.500493E-01	31.3441	9.1945	10.8549	34.3200	41.1200
0.104248E 00	29.6027	16.5160	18.9195	43.3800	52.8500
0.108198E 00	29.5693	16.6420	19.0870	45.2300	53.5400
0.566646E-01	39.5522	10.1770	12.1804	34.4000	41.1900
0.111523E 00	38.2378	17.2176	20.3663	44.3400	54.2100
0.113338E 00	38.1500	17.6346	20.7653	43.9000	53.7200
0.716381E-01	22.0466	12.1285	13.7363	41.4800	46.7300
0.612343E-01	21.3779	10.9242	12.4238	37.6700	42.7300
0.622989E-01	39.0952	11.2481	13.4700	34.8600	41.0900
0.551218E-01	38.1806	7.6979	11.9814	36.3800	42.7300
0.585290E-01	38.7553	10.5101	12.7515	35.2500	41.3100
0.103966E 00	35.6369	15.8469	18.5890	48.4000	53.4200
0.937123E-01	35.5247	14.8077	17.4850	46.4300	50.7700
0.848355E-01	27.2073	13.6652	15.7279	46.1400	49.2600
0.837481E-01	27.0555	13.7843	15.8699	44.6900	47.8300
0.117695E 00	29.2106	17.6294	20.1684	50.7200	54.1500
0.350592E-01	33.2296	6.3673	8.0141	33.7800	39.4100
0.101848E 00	33.0311	15.9465	18.6505	46.3300	52.0500
0.103609E 00	32.8657	15.9998	18.8084	47.6100	52.7500
0.871560E-01	37.9295	13.7841	16.5964	44.6300	48.6800
0.836434E-01	37.7014	14.0394	16.8781	44.0400	48.1100
0.971794E-01	25.1340	15.0571	17.1665	49.0200	51.7700

Table 4.2B Continued.

U_{FE}	M(2)	V(7)	V(5)	T(2)	T(7)
0.951875E-01	24.1693	14.5805	16.6326	49.8400	52.4300
0.434288E-01	25.2725	7.7773	9.2457	38.6600	41.2200
0.419930E-01	24.9756	7.5574	8.9871	38.4200	40.7700
0.546429E-01	30.5357	9.5145	11.2485	39.2500	44.0900
0.643549E-01	37.0920	11.0625	13.3421	38.9200	44.9300
0.658757E-01	37.0543	11.3336	13.6183	39.2900	44.7700
0.100944E 00	49.3917	15.7900	19.5579	45.7000	51.4000
0.923883E-01	49.6306	14.5996	18.2590	42.9400	50.9900
0.111789E 00	47.1195	17.1854	21.0695	43.8800	53.9000
0.106838E 00	47.1474	16.4591	20.2963	43.5600	53.6700
0.129017E 00	27.4004	19.4418	22.0728	48.1600	55.5800
0.131642E 00	27.2724	19.6661	22.3055	48.8400	56.0400
0.863165E-01	39.0853	14.6643	17.6255	36.8200	47.4700
0.101260E 00	39.8772	16.8392	20.0884	38.6800	49.2400
0.117041E 00	39.1230	18.8897	22.2778	41.5400	51.4100
0.839708E-01	29.1888	14.0222	16.4799	39.4400	48.9400
0.104212E 00	28.2573	17.3585	19.9037	40.6200	49.2500
0.898950E-01	26.7105	15.1894	17.2877	40.3800	47.6100
0.100419E 00	35.5468	15.4555	16.5188	45.6600	53.7000
0.662584E-01	34.7831	11.5085	12.4545	37.6700	44.2300
0.974469E-01	30.2951	15.5550	16.5081	44.2900	51.3700

Table 4.2C

Steady State Analysis of the Second Effect.

U_{SE}	M(15)	T(15)	T(14)	M(4)	V(4)	M(10)	V(10)	T(4)	T(10)
0.315797E 00	3269.750	34.2100	35.8900	1.1073	13.5151	10.7554	3.6667	47.4400	46.0300
0.319425E 00	3505.090	35.2200	36.8500	1.1824	12.2795	11.1981	2.2634	48.1800	47.8200
0.295595E 00	3265.850	35.6500	37.2800	1.1495	12.7879	10.4957	3.4417	48.8400	48.2100
0.214151E 00	3859.510	27.3400	28.4400	0.8368	8.0009	8.2835	0.5542	41.9200	40.6000
0.266281E 00	3453.160	30.0300	31.1000	0.7882	8.4062	7.2201	1.9746	40.4500	39.2800
0.243846E 00	3370.780	33.4200	35.5600	1.2630	15.2530	13.9073	2.6083	53.4300	50.2300
0.250051E 00	3272.490	35.4400	37.5800	1.3740	15.2680	13.6974	2.9449	54.1800	51.6400
0.360325E 00	3530.370	29.6900	30.7800	0.9859	9.1911	7.6323	2.5450	40.4600	34.8400
0.289656E 00	3380.750	36.0600	38.1600	1.8195	15.3982	14.2420	2.9757	54.7300	48.9100
0.267925E 00	2986.480	35.8500	37.8900	1.7755	15.8681	12.4310	5.2123	54.2800	49.9400
0.321579E 00	3040.690	32.6300	33.9700	0.8247	11.3037	7.8790	4.2492	44.4800	39.3800
0.298925E 00	3282.090	29.4300	30.6400	0.7483	10.1759	7.6037	3.3199	41.6900	36.4700
0.284332E 00	3190.550	28.5000	29.5500	1.1888	10.0593	6.9499	4.2985	40.2800	34.1300
0.373553E 00	4083.730	29.3400	30.4800	1.3340	8.3639	9.1931	0.5048	41.2800	35.3900
0.238215E 00	3572.480	28.8200	29.8700	1.2567	9.2534	7.8153	2.6949	40.4800	39.4100
0.308745E 00	3534.940	26.5000	38.4800	1.8080	14.0388	14.3954	1.4517	53.9500	51.4200
0.308268E 00	3393.480	35.9500	37.6900	1.7717	13.0360	12.1369	2.6709	51.1200	48.2400
0.284214E 00	3258.400	35.0700	36.6600	1.3136	12.5516	10.0426	3.2626	49.2500	46.9500
0.277787E 00	3359.880	34.1400	35.6300	1.3071	12.4772	10.0903	3.6936	47.6600	46.2900
0.292429E 00	3294.850	37.1000	39.0700	1.6951	15.9341	13.0733	4.5560	54.3700	51.4500
0.239748E 00	3857.270	28.5300	29.3100	0.9566	5.4107	6.1599	0.2073	38.3500	37.5000
0.286388E 00	3090.400	36.1700	38.1100	1.7247	14.2217	12.2388	3.7080	52.6300	49.6900
0.292607E 00	3131.540	37.4400	39.3400	1.8748	14.1249	12.3415	3.6584	53.5100	50.5700
0.340884E 00	3576.770	35.6000	37.1500	1.8986	11.8855	11.6197	2.1644	48.6000	46.0100
0.317138E 00	3421.370	34.7600	36.2600	1.9063	12.1351	10.8933	3.1457	47.8000	44.9900
0.328540E 00	3422.560	36.3600	38.3200	1.3843	13.6727	13.1800	1.8768	52.6000	49.5000

Table 4.2C Continued.

U_{SE}	M(15)	T(15)	T(14)	M(4)	V(4)	M(10)	V(10)	T(4)	T(10)
0.314398E 00	3204.040	37.1700	39.1700	1.3704	13.2098	12.6352	1.9451	53.4400	50.2500
0.341577E 00	3753.820	32.6300	33.5300	0.9301	6.8472	6.8051	0.9730	40.3700	37.3500
0.424306E 00	3814.040	32.1500	33.0900	0.9062	6.6513	7.1171	0.4405	39.6400	37.0000
0.277435E 00	3400.240	31.3400	32.4500	1.0142	8.5001	7.5548	1.9598	41.6200	40.3100
0.257294E 00	3918.410	31.7900	33.0400	1.3493	9.7133	9.9566	1.1061	44.7700	45.6500
0.231071E 00	3901.390	31.9300	33.1900	1.3759	9.9598	10.0616	1.2719	45.3500	48.5600
0.263362E 00	3231.440	36.2800	38.0100	2.5812	13.2088	12.4419	3.3480	52.0100	50.7800
0.327257E 00	3746.230	36.2000	37.8700	2.5036	12.2960	13.2797	1.3201	51.6900	48.0900
0.318066E 00	3654.530	37.7100	39.6300	2.5501	14.8353	14.6780	2.5068	54.5100	52.3100
0.322224E 00	3851.800	37.5500	39.4100	2.5214	14.1378	14.9453	1.5138	54.5400	52.4000
0.260087E 00	3094.390	39.0600	41.1300	1.5820	17.8599	12.8954	6.5465	57.0500	56.0600
0.274654E 00	2981.930	39.4800	41.5800	1.6028	18.0635	12.6574	7.0085	57.4400	54.2400
0.204725E 00	3007.940	30.2600	32.0100	1.5755	13.0889	10.8177	3.8465	48.3900	48.3000
0.221129E 00	2816.120	32.2100	33.9900	1.7648	15.0744	10.5832	6.2599	49.6200	47.1200
0.245538E 00	2959.970	33.6100	35.5800	1.9106	16.9791	12.1601	6.7296	51.4100	49.6200
0.300676E 00	3882.600	31.5500	33.3200	1.5598	12.6824	13.3831	0.6392	48.6200	46.8600
0.224781E 00	2842.940	31.7300	33.5400	1.5462	16.0121	10.3751	6.9828	48.8800	47.1100
0.231402E 00	2948.490	32.5700	34.1900	1.0758	14.1156	9.4124	5.7773	48.0000	46.3300
0.313646E 00	3484.090	39.0500	40.7000	1.6126	13.8426	11.7336	3.7217	55.1600	51.1600
0.234630E 00	3797.760	33.5800	34.6200	1.1051	10.4057	8.0466	3.4623	44.5900	46.2600
0.239089E 00	3869.240	36.3200	37.7000	1.2155	14.3396	10.5931	4.9618	53.7400	50.2800

Table 4.2D

Steady State Analysis of the Condenser.

U_C	M(12)	T(12)	T(13)	M(10)	V(9+10)	M(11)	T(9)	T(10)	T(11)
0.237347E 00	866.667	13.4200	20.1400	10.7754	13.5504	24.3057	34.2100	46.0300	23.3900
0.232974E 00	866.667	13.4400	19.7300	11.1981	12.4935	23.6915	35.2200	47.8200	22.4000
0.228237E 00	866.667	13.1500	19.7700	10.4957	12.9943	23.4897	35.6500	48.2200	22.4700
0.361016E 00	833.333	13.8900	18.2800	8.2835	8.5030	16.7866	27.3400	40.6000	16.5800
0.221573E 00	833.333	12.9800	17.5000	7.2201	8.7656	15.9853	30.0300	39.2800	18.6600
0.309619E 00	833.333	12.8200	20.9200	13.9073	15.4859	29.3927	33.4200	50.2300	21.8300
0.257930E 00	833.333	12.5400	21.4900	13.6974	15.4907	29.1881	35.4400	51.6400	24.4200
0.292178E 00	900.000	11.8800	16.5500	7.6323	9.7545	17.3868	26.6900	34.8400	15.7900
0.249451E 00	900.000	11.6500	20.8000	14.2420	15.9594	30.2019	36.0600	48.9100	24.7700
0.241137E 00	900.000	10.5800	20.0300	12.4310	16.3907	28.8215	35.8500	49.9400	23.6800
0.206598E 00	833.333	12.7000	19.7800	7.8790	11.5228	19.4020	32.6300	39.3800	24.0600
0.239113E 00	833.333	12.4100	17.5400	7.6037	10.3942	17.9980	29.4300	36.4900	19.7800
0.232184E 00	833.333	12.3200	17.1600	6.9499	10.6501	17.5996	28.5000	34.1300	19.2900
0.230107E 00	833.333	12.1600	17.7300	9.1931	8.9886	18.1816	29.3700	35.3900	19.2800
0.220239E 00	833.333	11.8900	16.6400	7.8153	9.7686	17.5837	28.8200	39.4100	19.0200
0.259641E 00	771.000	14.3600	23.6600	14.3954	14.1824	28.5779	36.5000	51.4200	26.1300
0.239653E 00	771.000	14.4900	23.3300	12.1369	13.4676	25.6047	35.9500	48.2400	26.2300
0.230972E 00	771.000	14.5400	22.6800	10.4026	12.5945	22.9972	35.0700	46.9500	25.2800
0.239404E 00	771.000	14.4600	22.0500	10.0903	12.6902	22.7808	34.1400	46.2900	24.4800
0.259378E 00	771.000	14.4100	23.8300	13.0733	16.1422	29.2156	37.1000	51.4500	26.8800
0.183280E 00	736.667	12.9700	16.8300	6.1599	5.8372	11.9974	28.5300	37.5000	17.4100
0.248923E 00	736.667	12.3700	22.1800	12.2388	14.5636	26.8022	36.1700	49.6900	23.4700
0.238923E 00	736.667	12.2600	22.0400	12.3415	14.4501	26.7915	37.4400	50.5700	23.3300
0.240922E 00	736.667	12.7000	21.3100	11.6197	12.3549	23.9744	35.6000	46.0100	21.9000
0.251082E 00	736.667	12.7200	20.8400	10.8933	12.6101	23.5037	34.7600	44.9900	21.2900
0.253609E 00	825.000	12.0700	20.7800	13.1800	13.8054	26.9853	36.3600	49.5000	21.3800

Table 4.2D Continued.

U_C	M(12)	T(12)	T(13)	M(10)	V(9+10)	M(11)	T(9)	T(10)	T(11)
0.246432E 00	825.000	12.4400	20.7800	12.6552	13.3364	25.9716	37.1700	50.2500	21.4400
0.202012E 00	825.000	12.4700	16.5400	6.8051	7.0862	13.8914	32.6300	57.3300	16.0800
0.211384E 00	825.000	12.4200	17.0200	7.1171	6.8880	14.0052	32.1500	57.0000	15.8100
0.253951E 00	801.667	15.2500	21.0300	7.5548	8.8416	16.3964	31.3400	40.3100	20.5400
0.228688E 00	753.333	14.0000	20.5800	9.9566	10.1294	20.0860	31.7900	45.6500	22.4700
0.221159E 00	753.333	13.8300	20.6100	10.0616	10.3185	20.3802	31.9300	48.5600	22.7300
0.230941E 00	753.333	13.7900	22.5000	12.4419	13.9520	26.3941	36.2800	50.7800	25.6600
0.237790E 00	753.333	13.7900	22.2200	13.2797	13.0985	26.3784	36.2000	48.0800	25.0100
0.241300E 00	753.333	12.5300	23.6600	14.6780	15.5288	30.2071	37.7100	52.3100	26.7400
0.240779E 00	753.333	12.9400	23.0300	14.9453	14.8268	29.7722	37.5500	52.4000	26.2000
0.272975E 00	753.333	13.8100	23.4900	12.8954	17.8903	30.7857	39.0600	56.0600	21.6300
0.232424E 00	753.333	13.2300	23.5600	12.6574	18.1476	30.8051	39.4800	54.2400	26.7900
0.322076E 00	800.000	12.2200	19.4100	10.8177	13.5675	24.3853	30.2600	48.3100	18.0400
0.281040E 00	800.000	12.3700	20.5800	10.5832	15.6070	26.1902	32.2100	47.1300	22.1200
0.270775E 00	800.000	12.1500	21.4200	12.1601	17.4386	29.5987	33.6100	49.6200	24.8400
0.261944E 00	800.000	11.7300	19.9500	13.3851	12.9370	26.3201	31.5500	46.8600	22.6000
0.267933E 00	800.000	11.7600	20.0800	10.3751	16.2033	26.5785	31.7300	47.1200	22.9600
0.273495E 00	766.667	12.6400	20.6300	9.4124	14.2950	23.7072	32.5700	46.3300	21.2600
0.247905E 00	687.500	18.1300	28.9000	11.7336	14.2562	25.9894	39.0500	51.1600	31.7600
0.239471E 00	687.500	18.3600	25.5500	8.0466	10.7369	18.7838	33.5800	46.2600	27.4400
0.312368E 00	786.667	18.9800	26.7700	10.5951	14.5966	25.1897	36.2300	50.2800	27.3100

Tables 4.3A to 4.3D.

Comparison of experimental heat transfer coefficients with those predicted using the correlations discussed in chapter four.

The following nomenclature and units are used within the tables.

U = overall heat transfer coefficient (J / sec.cm^2.^{o}C.)

Table 4.3A PRE-HEATER.

```
U OBSERVED      U CALCULATED    U OBS-U CALC      % DEVIATION


0.527003E-01    0.531823E-01   -0.481998E-03     0.914601E 00
0.512604E-01    0.535719E-01   -0.231151E-02     0.450935E 01
0.479196E-01    0.483584E-01   -0.438796E-03     0.915692E 00
0.459279E-01    0.479211E-01   -0.199323E-02     0.433990E 01
0.447754E-01    0.469241E-01   -0.214868E-02     0.479880E 01
0.440605E-01    0.425549E-01    0.150559E-02     0.341710E 01
0.508704E-01    0.510362E-01   -0.165792E-03     0.325911E 00
0.552789E-01    0.566209E-01   -0.134199E-02     0.242768E 01
0.609069E-01    0.599807E-01    0.926172E-03     0.152064E 01
0.596859E-01    0.586493E-01    0.103658E-02     0.173672E 01
0.441575E-01    0.424926E-01    0.166485E-02     0.377027E 01
0.417013E-01    0.428325E-01   -0.113121E-02     0.271266E 01
0.658077E-01    0.637824E-01    0.202527E-02     0.307756E 01
0.677949E-01    0.682935E-01   -0.498631E-03     0.735500E 00
0.666898E-01    0.675613E-01   -0.871493E-03     0.130679E 01
0.814264E-01    0.788270E-01    0.259948E-02     0.319243E 01
0.880191E-01    0.864762E-01    0.154289E-02     0.175291E 01
0.761866E-01    0.722700E-01    0.391654E-02     0.514072E 01
0.750150E-01    0.733621E-01    0.165294E-02     0.220348E 01
0.831342E-01    0.800783E-01    0.305588E-02     0.367584E 01
0.558940E-01    0.586664E-01   -0.277243E-02     0.496016E 01
0.710087E-01    0.732921E-01   -0.228348E-02     0.321578E 01
0.683685E-01    0.817192E-01   -0.133507E-01     0.195276E 02
0.977434E-01    0.986482E-01   -0.904846E-03     0.925737E 00
0.969145E-01    0.995829E-01   -0.266845E-02     0.275341E 01
0.719169E-01    0.701094E-01    0.180754E-02     0.251338E 01
```

Table 4.3A CONT.

U OBSERVED	U CALCULATED	U OBS-U CALC	% DEVIATION
0.710510E-01	0.693569E-01	0.169414E-02	0.238439E 01
0.684506E-01	0.668930E-01	0.155761E-02	0.227553E 01
0.710076E-01	0.678537E-01	0.315389E-02	0.444162E 01
0.575218E-01	0.538310E-01	0.369086E-02	0.641644E 01
0.654515E-01	0.657198E-01	-0.268211E-03	0.409786E 00
0.685790E-01	0.701667E-01	-0.158765E-02	0.231506E 01
0.109858E 00	0.112756E 00	-0.289803E-02	0.263799E 01
0.877631E-01	0.891992E-01	-0.143610E-02	0.163634E 01
0.778475E-01	0.784965E-01	-0.648947E-03	0.833613E 00
0.764031E-01	0.769652E-01	-0.562029E-03	0.735609E 00
0.618437E-01	0.571555E-01	0.468823E-02	0.758076E 01
0.626554E-01	0.579373E-01	0.471819E-02	0.753037E 01
0.516973E-01	0.491545E-01	0.254277E-02	0.491857E 01
0.495603E-01	0.457616E-01	0.379870E-02	0.766480E 01
0.630701E-01	0.646141E-01	-0.154401E-02	0.244809E 01
0.463106E-01	0.480988E-01	-0.178814E-02	0.386118E 01
0.485195E-01	0.508382E-01	-0.231872E-02	0.477894E 01
0.448121E-01	0.454718E-01	-0.659692E-03	0.147213E 01
0.644016E-01	0.632799E-01	0.112168E-02	0.174169E 01
0.576997E-01	0.599371E-01	-0.223746E-02	0.387777E 01
0.480181E-01	0.482487E-01	-0.230542E-03	0.480114E 00

Table 4.3B FIRST EFFECT.

```
U OBSERVED       U CALCULATED    U OBS-U CALC     % DEVIATION


0.870153E-01     0.873324E-01    -0.317154E-03    0.364481E 00
0.815107E-01     0.819470E-01    -0.436372E-03    0.535355E 00
0.847665E-01     0.851775E-01    -0.410971E-03    0.484827E 00
0.498961E-01     0.497032E-01     0.192974E-03    0.386751E 00
0.500493E-01     0.503470E-01    -0.297719E-03    0.594852E 00
0.104248E 00     0.104700E 00    -0.452027E-03    0.433607E 00
0.108198E 00     0.107020E 00     0.117846E-02    0.108917E 01
0.566646E-01     0.559405E-01     0.724075E-03    0.127783E 01
0.111523E 00     0.111658E 00    -0.135320E-03    0.121338E 00
0.113338E 00     0.113499E 00    -0.161035E-03    0.142083E 00
0.716381E-01     0.719321E-01    -0.294015E-03    0.410417E 00
0.612343E-01     0.609875E-01     0.246805E-03    0.403050E 00
0.622989E-01     0.616362E-01     0.662676E-03    0.106370E 01
0.551218E-01     0.549511E-01     0.170739E-03    0.309749E 00
0.585290E-01     0.580202E-01     0.508838E-03    0.869378E 00
0.103966E 00     0.103905E 00     0.610506E-04    0.587218E-01
0.937123E-01     0.941218E-01    -0.409481E-03    0.436955E 00
0.848355E-01     0.850687E-01    -0.233171E-03    0.274850E 00
0.837481E-01     0.839768E-01    -0.228713E-03    0.273097E 00
0.117695E 00     0.116268E 00     0.142717E-02    0.121261E 01
0.350592E-01     0.345984E-01     0.460746E-03    0.131419E 01
0.101848E 00     0.102073E 00    -0.225352E-03    0.221264E 00
0.103609E 00     0.103625E 00    -0.159509E-04    0.153952E-01
0.871560E-01     0.855320E-01     0.162598E-02    0.186330E 01
0.836434E-01     0.862957E-01    -0.265234E-02    0.317101E 01
0.971794E-01     0.966436E-01     0.535715E-03    0.551264E 00
```

Table 4.3B

CONT.

U OBSERVED	U CALCULATED	U OBS-U CALC	% DEVIATION
0.951875E-01	0.945067E-01	0.680885E-03	0.715309E 00
0.434288E-01	0.436670E-01	-0.238255E-03	0.548611E 00
0.419930E-01	0.421823E-01	-0.189270E-03	0.450718E 00
0.546429E-01	0.552711E-01	-0.628280E-03	0.114979E 01
0.643549E-01	0.647344E-01	-0.379584E-03	0.589830E 00
0.658757E-01	0.662551E-01	-0.379465E-03	0.576032E 00
0.100944E 00	0.101374E 00	-0.429579E-03	0.425561E 00
0.923883E-01	0.925416E-01	-0.153336E-03	0.165969E 00
0.111789E 00	0.111580E 00	0.209421E-03	0.187336E 00
0.106838E 00	0.106674E 00	0.164654E-03	0.154115E 00
0.129017E 00	0.127866E 00	0.115086E-02	0.892026E 00
0.131642E 00	0.130155E 00	0.148673E-02	0.112938E 01
0.863165E-01	0.864042E-01	-0.877248E-04	0.101632E 00
0.101260E 00	0.101521E 00	-0.260544E-03	0.257301E 00
0.117041E 00	0.117392E 00	-0.351142E-03	0.300018E 00
0.839708E-01	0.844745E-01	-0.503689E-03	0.599838E 00
0.104212E 00	0.104487E 00	-0.274555E-03	0.263457E 00
0.898950E-01	0.901265E-01	-0.231481E-03	0.257502E 00
0.100419E 00	0.100558E 00	-0.138986E-03	0.138406E 00
0.662584E-01	0.661584E-01	0.999401E-04	0.150834E 00
0.974469E-01	0.979031E-01	-0.456205E-03	0.468157E 00

Table 4.3C SECOND EFFECT.

U OBSERVED	U CALCULATED	U OBS-U CALC	% DEVIATION
0.315797E 00	0.313631E 00	0.216663E-02	0.686084E 00
0.319425E 00	0.315150E 00	0.427551E-02	0.133850E 01
0.295595E 00	0.294386E 00	0.120889E-02	0.408971E 00
0.214151E 00	0.207553E 00	0.659790E-02	0.308096E 01
0.266281E 00	0.266244E 00	0.367738E-04	0.138101E-01
0.243846E 00	0.247443E 00	-0.359769E-02	0.147540E 01
0.250051E 00	0.265506E 00	-0.154549E-01	0.618070E 01
0.360325E 00	0.339334E 00	0.209910E-01	0.582558E 01
0.289656E 00	0.308728E 00	-0.190721E-01	0.658437E 01
0.267925E 00	0.263776E 00	0.414805E-02	0.154822E 01
0.321579E 00	0.316745E 00	0.483430E-02	0.150330E 01
0.298925E 00	0.292377E 00	0.654766E-02	0.219040E 01
0.284332E 00	0.295980E 00	-0.116483E-01	0.409673E 01
0.373553E 00	0.380947E 00	-0.739391E-02	0.197935E 01
0.238215E 00	0.245861E 00	-0.764603E-02	0.320972E 01
0.308745E 00	0.309321E 00	-0.575918E-03	0.186535E 00
0.308268E 00	0.305309E 00	0.295919E-02	0.959938E 00
0.284214E 00	0.277486E 00	0.672772E-02	0.236713E 01
0.277787E 00	0.279702E 00	-0.191562E-02	0.689600E 00
0.292429E 00	0.285990E 00	0.643866E-02	0.220179E 01
0.239748E 00	0.254896E 00	-0.151476E-01	0.631815E 01
0.286388E 00	0.283332E 00	0.305632E-02	0.106720E 01
0.292607E 00	0.292164E 00	0.443194E-03	0.151464E 00
0.340884E 00	0.342510E 00	-0.162615E-02	0.477038E 00
0.317138E 00	0.322940E 00	-0.580158E-02	0.182935E 01
0.328540E 00	0.319166E 00	0.937373E-02	0.285315E 01

Table 4.3C.

```
                      CONT.
U OBSERVED        U CALCULATED     U OBS-U CALC     % DEVIATION


0.314398E 00      0.306426E 00      0.797205E-02    0.253565E 01
0.341577E 00      0.351763E 00     -0.101857E-01    0.298197E 01
0.424306E 00      0.394741E 00      0.295647E-01    0.696777E 01
0.277435E 00      0.279470E 00     -0.203566E-02    0.733744E 00
0.257294E 00      0.259342E 00     -0.204820E-02    0.796052E 00
0.231071E 00      0.227927E 00      0.314389E-02    0.136057E 01
0.263362E 00      0.271359E 00     -0.799690E-02    0.303646E 01
0.327257E 00      0.333113E 00     -0.585549E-02    0.178926E 01
0.318066E 00      0.314076E 00      0.399046E-02    0.125460E 01
0.322224E 00      0.322377E 00     -0.152601E-03    0.473586E-01
0.260087E 00      0.259555E 00      0.531178E-03    0.204231E 00
0.274654E 00      0.278510E 00     -0.385635E-02    0.140408E 01
0.204725E 00      0.186717E 00      0.180077E-01    0.879606E 01
0.221129E 00      0.226369E 00     -0.524018E-02    0.236974E 01
0.245538E 00      0.248114E 00     -0.257588E-02    0.104908E 01
0.300676E 00      0.298482E 00      0.219422E-02    0.729763E 00
0.224781E 00      0.227635E 00     -0.285444E-02    0.126988E 01
0.231402E 00      0.236669E 00     -0.526668E-02    0.227599E 01
0.313646E 00      0.311625E 00      0.202081E-02    0.644296E 00
0.234630E 00      0.243432E 00     -0.880178E-02    0.375134E 01
0.239089E 00      0.230251E 00      0.883885E-02    0.369688E 01
```

Table 4.3D CONDENSER.

U OBSERVED	U CALCULATED	U OBS-U CALC	% DEVIATION
0.237347E 00	0.234812E 00	0.253529E-02	0.106818E 01
0.232974E 00	0.225378E 00	0.759604E-02	0.326046E 01
0.228237E 00	0.219920E 00	0.831638E-02	0.364375E 01
0.361016E 00	0.325813E 00	0.352027E-01	0.975101E 01
0.221573E 00	0.221446E 00	0.126530E-03	0.571053E-01
0.309619E 00	0.299498E 00	0.101215E-01	0.326901E 01
0.257930E 00	0.262289E 00	-0.435899E-02	0.168999E 01
0.292178E 00	0.310352E 00	-0.181742E-01	0.622024E 01
0.249451E 00	0.260972E 00	-0.115215E-01	0.461875E 01
0.241137E 00	0.250784E 00	-0.964644E-02	0.400039E 01
0.206598E 00	0.210979E 00	-0.438129E-02	0.212069E 01
0.239113E 00	0.222179E 00	0.169335E-01	0.708182E 01
0.232184E 00	0.221755E 00	0.104291E-01	0.449175E 01
0.230107E 00	0.248694E 00	-0.185865E-01	0.807731E 01
0.220239E 00	0.213432E 00	0.680659E-02	0.309055E 01
0.259641E 00	0.265175E 00	-0.553362E-02	0.213125E 01
0.239653E 00	0.248830E 00	-0.917727E-02	0.382940E 01
0.230972E 00	0.239891E 00	-0.891878E-02	0.386141E 01
0.239404E 00	0.238940E 00	0.464012E-03	0.193820E 00
0.259378E 00	0.249426E 00	0.995134E-02	0.383662E 01
0.183280E 00	0.195745E 00	-0.124642E-01	0.680064E 01
0.248923E 00	0.246103E 00	0.282036E-02	0.113303E 01
0.238923E 00	0.232750E 00	0.617231E-02	0.258339E 01
0.240922E 00	0.239243E 00	0.167872E-02	0.696788E 00
0.251082E 00	0.237189E 00	0.138931E-01	0.553329E 01
0.253609E 00	0.264870E 00	-0.112613E-01	0.444042E 01

Table 4.3D.

CONT.

U OBSERVED	U CALCULATED	U OBS-U CALC	% DEVIATION
0.246432E 00	0.250159E 00	-0.372718E-02	0.151246E 01
0.202012E 00	0.196087E 00	0.592542E-02	0.293320E 01
0.211384E 00	0.222405E 00	-0.110215E-01	0.521396E 01
0.253951E 00	0.275261E 00	-0.213101E-01	0.839143E 01
0.228688E 00	0.239634E 00	-0.109455E-01	0.478621E 01
0.221159E 00	0.237743E 00	-0.165837E-01	0.749854E 01
0.230941E 00	0.228758E 00	0.218304E-02	0.945283E 00
0.237790E 00	0.232143E 00	0.564720E-02	0.237487E 01
0.241300E 00	0.253812E 00	-0.125116E-01	0.518509E 01
0.240779E 00	0.241829E 00	-0.104989E-02	0.436041E 00
0.272975E 00	0.276651E 00	-0.367611E-02	0.134669E 01
0.232424E 00	0.221166E 00	0.112578E-01	0.484363E 01
0.322076E 00	0.320332E 00	0.174487E-02	0.541755E 00
0.281040E 00	0.270720E 00	0.103201E-01	0.367210E 01
0.270775E 00	0.259598E 00	0.111768E-01	0.412772E 01
0.261944E 00	0.272457E 00	-0.105129E-01	0.401340E 01
0.267933E 00	0.253186E 00	0.147472E-01	0.550405E 01
0.273495E 00	0.257138E 00	0.163568E-01	0.598064E 01
0.247905E 00	0.251493E 00	-0.358828E-02	0.144744E 01
0.239471E 00	0.242489E 00	-0.301786E-02	0.126022E 01
0.312368E 00	0.300476E 00	0.118918E-01	0.380697E 01

TABLE 4.4
STEADY STATE HEAT LOSSES FROM PLANT

RUN NO.	HEAT LOSS J/SEC.	% HEAT LOSS FROM PLANT	% HEAT LOSS PER LB. STEAM
1	.100502E 05	10.5227	22.4851
2	9213.51	9.91433	21.807
3	9209.67	9.88578	21.2035
4	6578.92	8.24393	23.1217
5	6528.72	8.45338	22.2344
6	.116624E 05	11.8666	22.7877
7	8500.97	8.69787	16.4648
8	7283.45	8.98908	22.1055
9	6230.05	6.1205	11.3084
10	6199.23	6.27203	11.0363
11	4150.19	4.98438	11.1692
12	8315.74	10.6012	24.744
13	9876.19	12.0065	27.1049
14	3395.41	4.3858	10.4763
15	8250.32	10.4899	23.9184
16	6933.73	6.9635	13.7891
17	5666.46	5.85446	11.9804
18	5638.42	6.1552	13.2529
19	7660.91	8.36932	17.8456
20	.10618E 05	10.2817	19.4622
21	3068.54	4.78921	14.1547
22	7049.26	7.75315	13.9726
23	6934.78	7.63758	13.6303
24	5164.16	5.96055	11.5042
25	7225.62	8.27896	15.8262
26	5644.65	6.27044	12.1557
27	5738.35	6.39265	12.7541
28	4178.92	5.97862	16.7089
29	1902.46	2.75584	7.82563
30	3085.85	3.66756	10.1416
31	5159.95	6.2134	14.2971
32	5088.17	6.11146	13.8122
33	8155.77	8.17619	15.4158
34	6906.21	7.16772	13.9826
35	4616.32	4.63269	8.09964
36	.151651E 05	14.4316	25.3987
37	6204.14	6.3124	11.3659
38	.135716E 05	13.0663	22.4929
39	.110145E 05	12.1217	23.102
40	.122014E 05	12.4464	22.4536
41	.131466E 05	12.7393	21.8156
42	5654.71	6.61576	12.6847
43	.132015E 05	13.9264	24.52
44	.107358E 05	12.0255	22.9572
45	4697.81	4.70578	10.5133
46	6237.11	6.97601	18.5131
47	.112129E 05	25.11	10.1978

TABLE 4.5

WEIGHTED STD. DEVIATIONS OF INSTRUMENTS

CHANNEL NO.	WGHT. MEAN STD. DEV.	CONVERTED VALUE
15	20.5662	.514155
16	19.3827	.12495
17	113.088	.652982
18	5.17949	.215775
19	44.2466	.107679
20	10.2098	.255245
21	4.4759	.111898
22	2.868	.717E-01
23	6.77844	.169461
24	4.99044	.124761
25	5.09102	.127276
26	5.86961	.14674
27	6.83178	.170794
28	6.04002	.151001
29	7.17602	.1794

APPENDIX THREE.

DYNAMIC RESPONSES FROM THE EVAPORATOR MATHEMATICAL MODEL.

FIGURE 5.5A. Temperature (T(2)), exit Preheater Tubes.

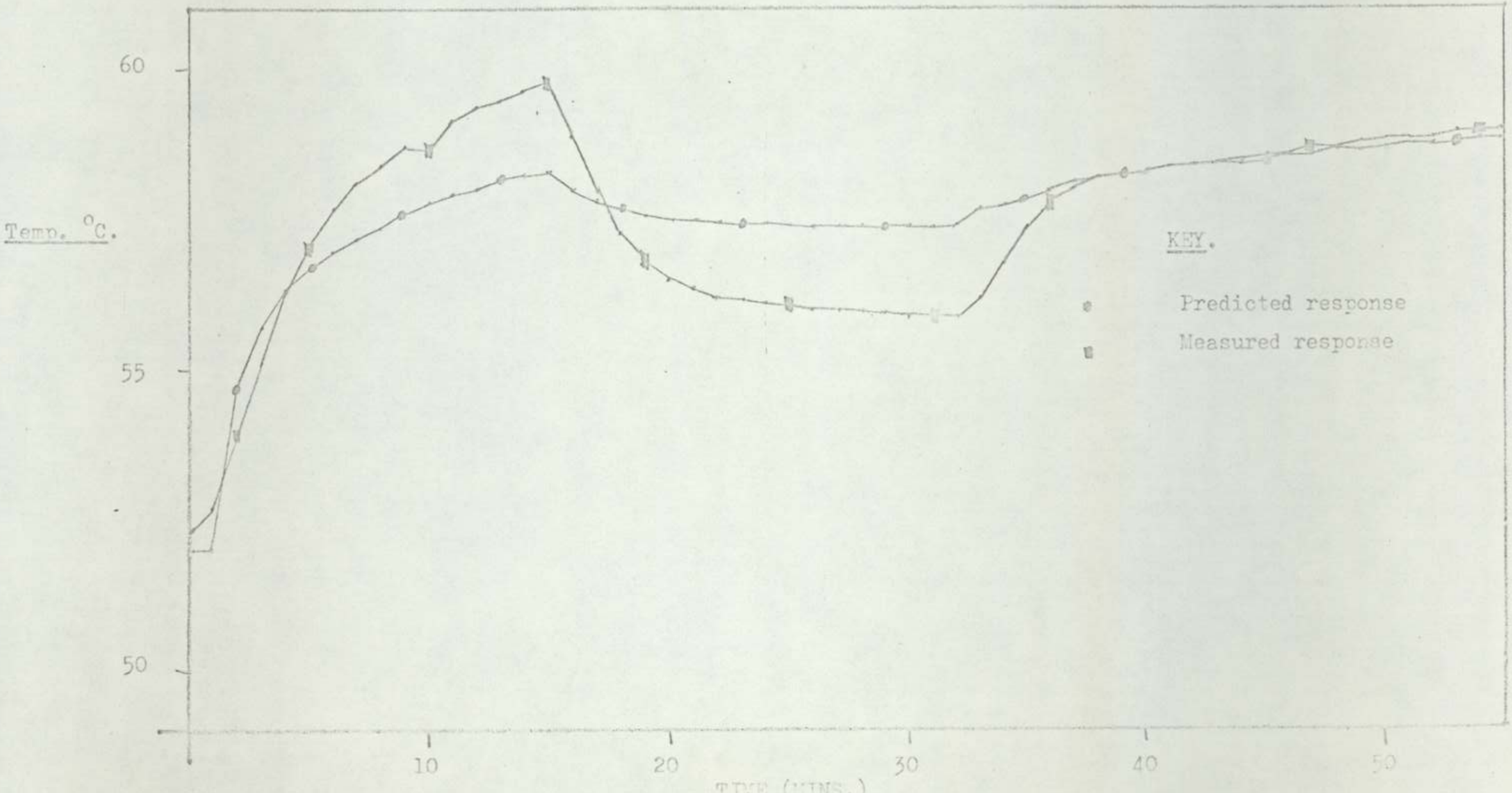


FIGURE 5.5B. Temperature (T(4)), exit Preheater shell.

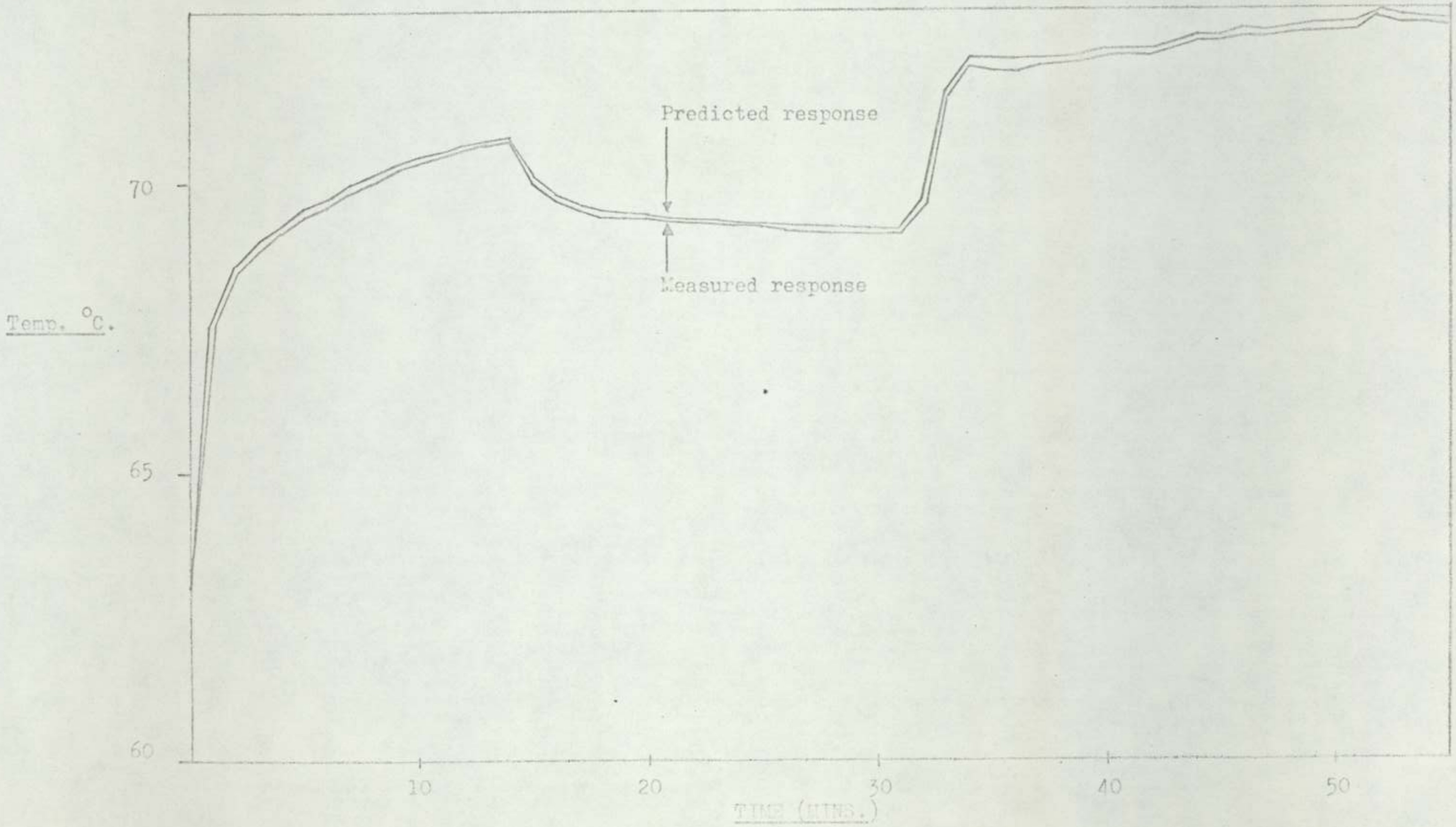


FIGURE 5.5C Temperature (T(8)), liquid exit cyclone.

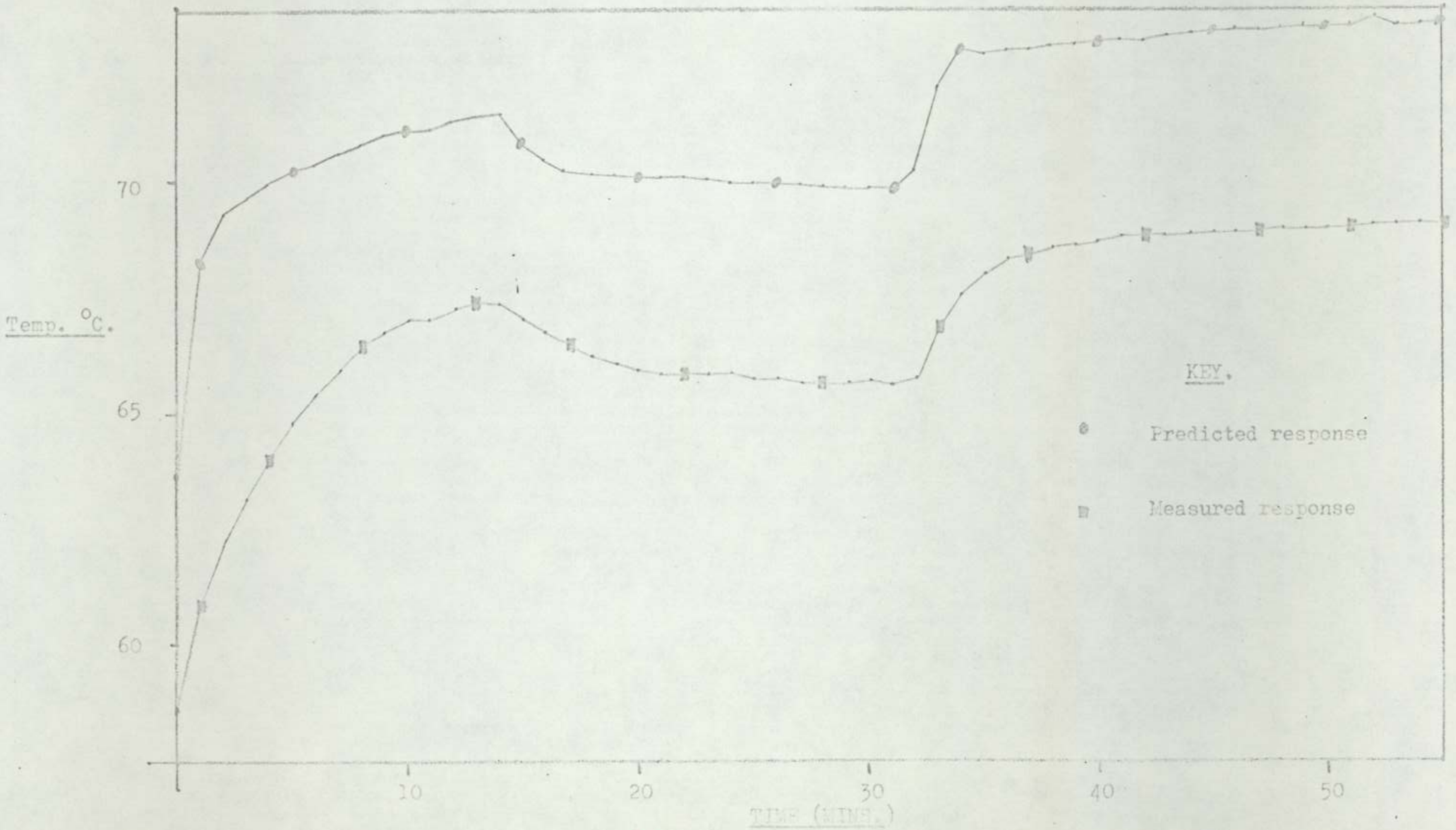


FIGURE 5.5D.

Temperature (T(10)), exit second effect shell.

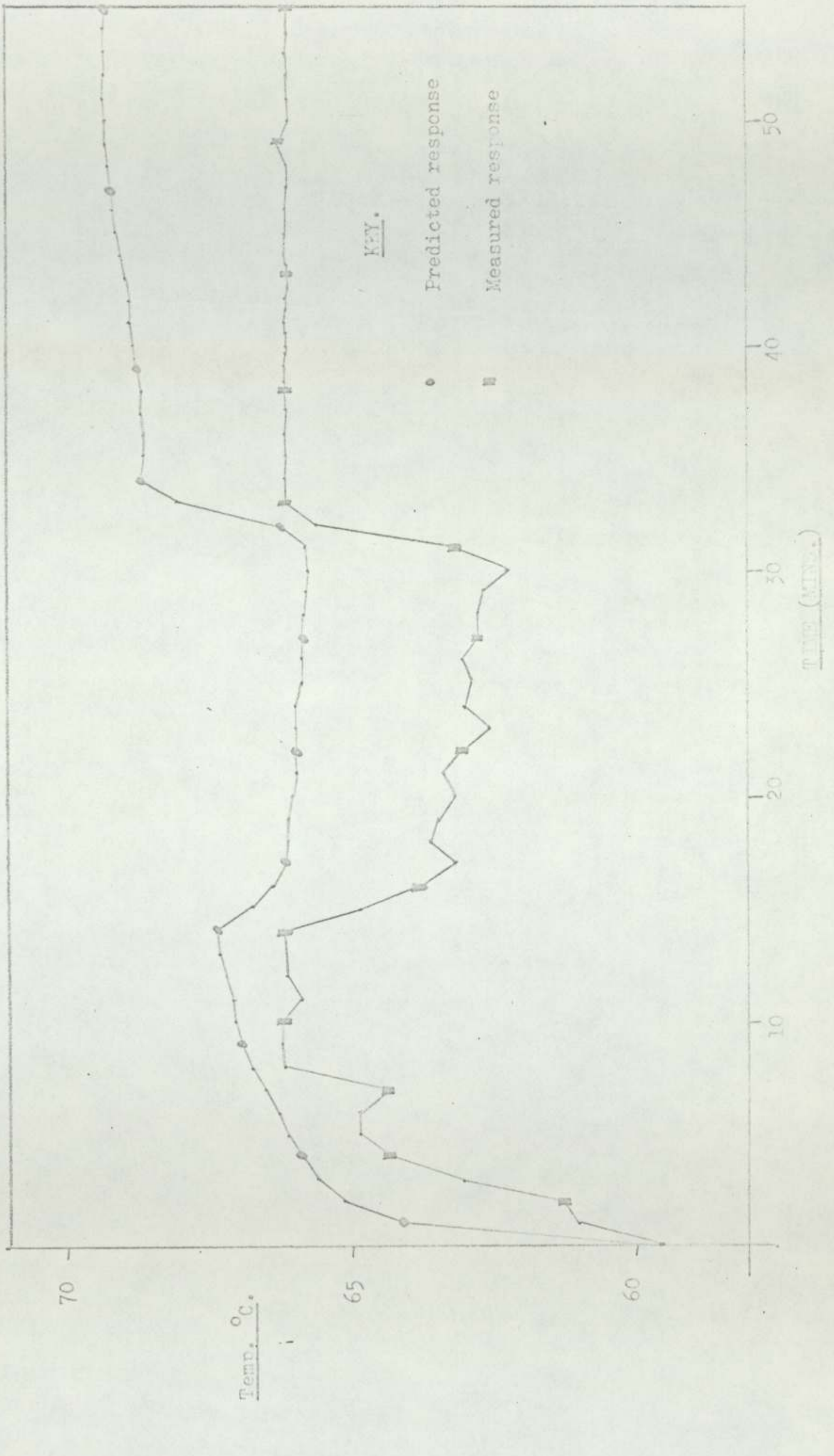


FIGURE 5.5E. Temperature (T(11)), exit condenser shell.

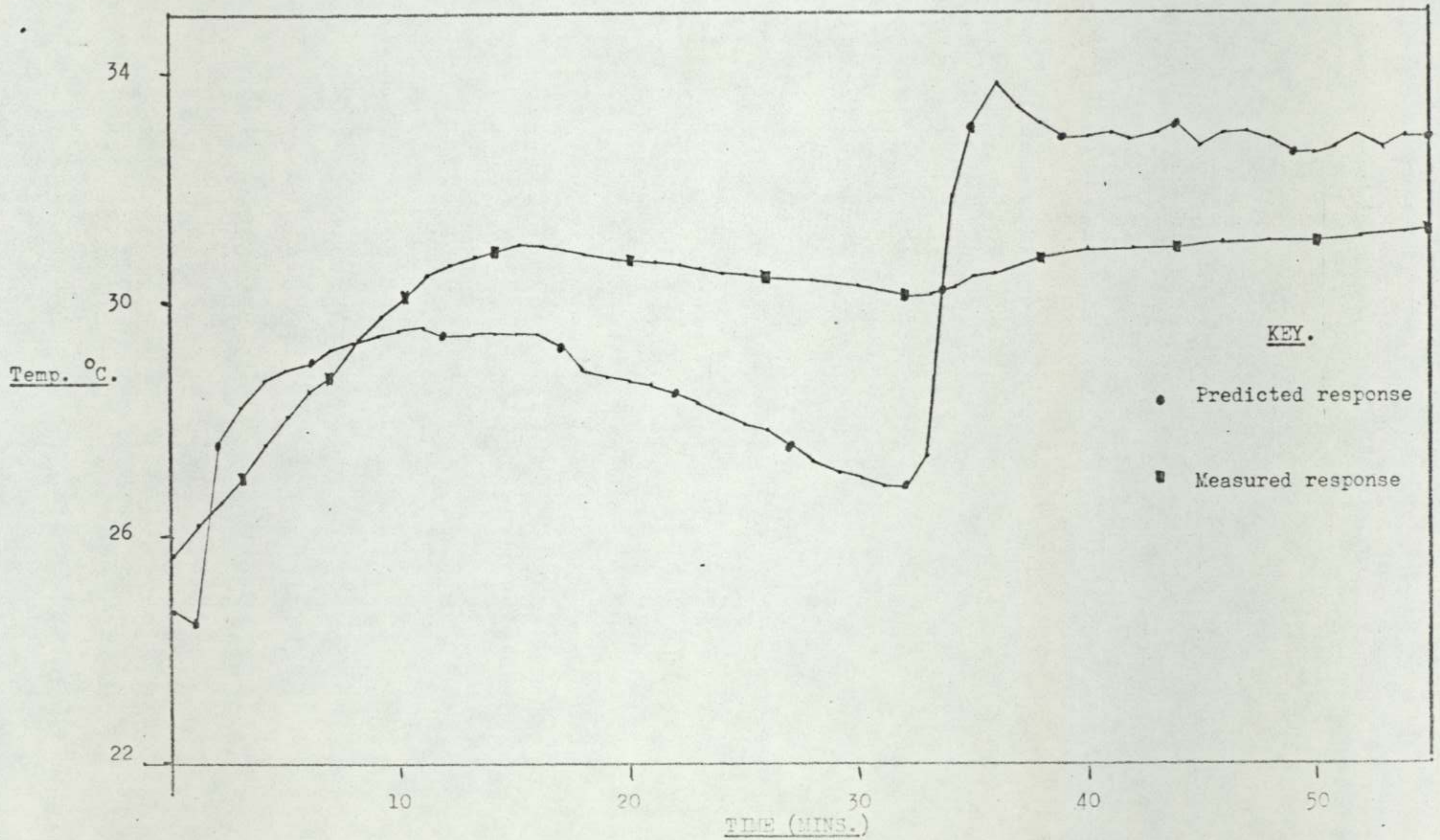


FIGURE 5.5F. Temperature (T(13)), cooling water exit condenser tubes.

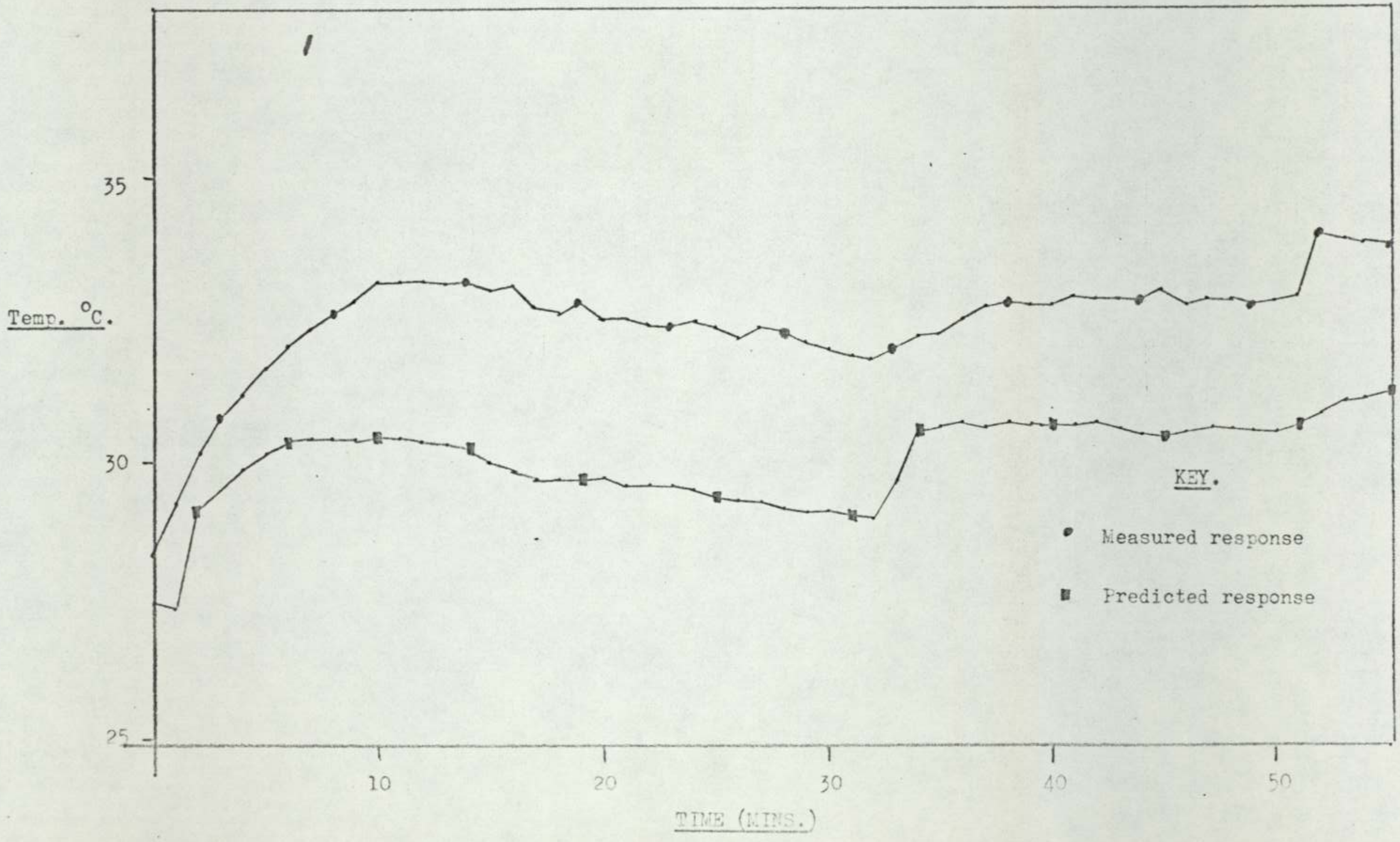


FIGURE 5.5G. Temperature (T(14)), liquid exit second effect tubes.

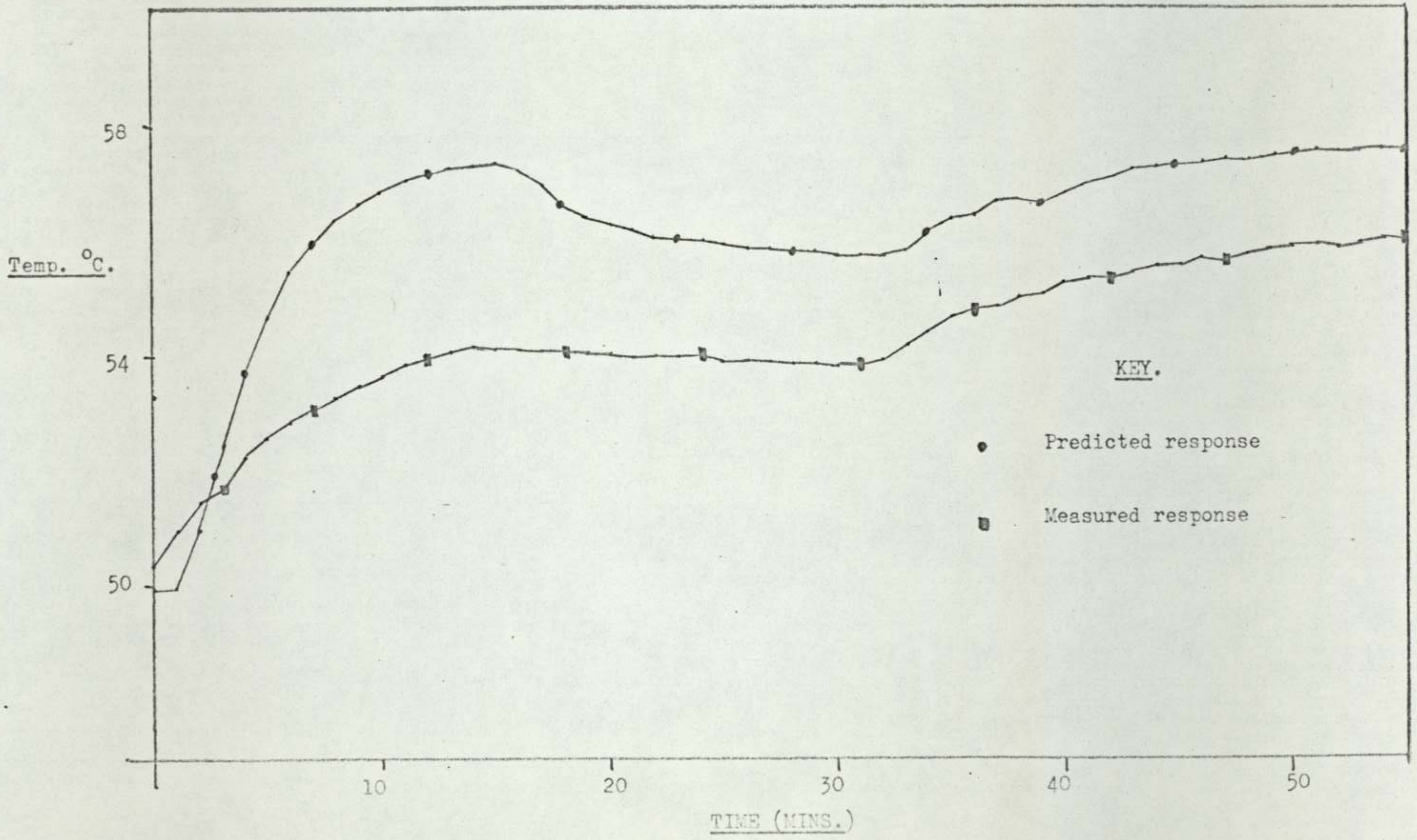


FIGURE 5.5H. Temperature (T(15)), liquid in second effect separator.

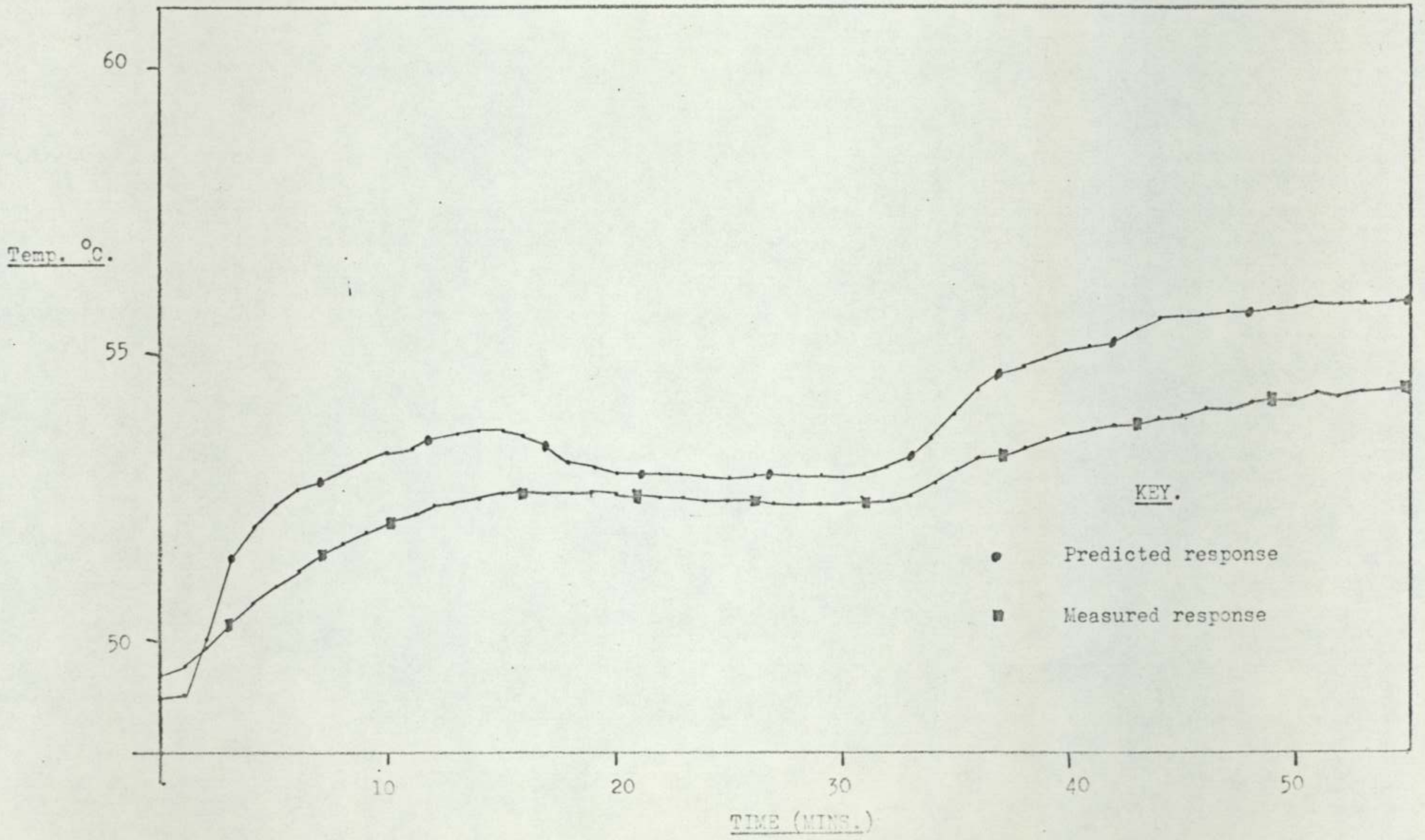


FIGURE 5.51. Liquid mass flow rate (M(8)), exit cyclone.

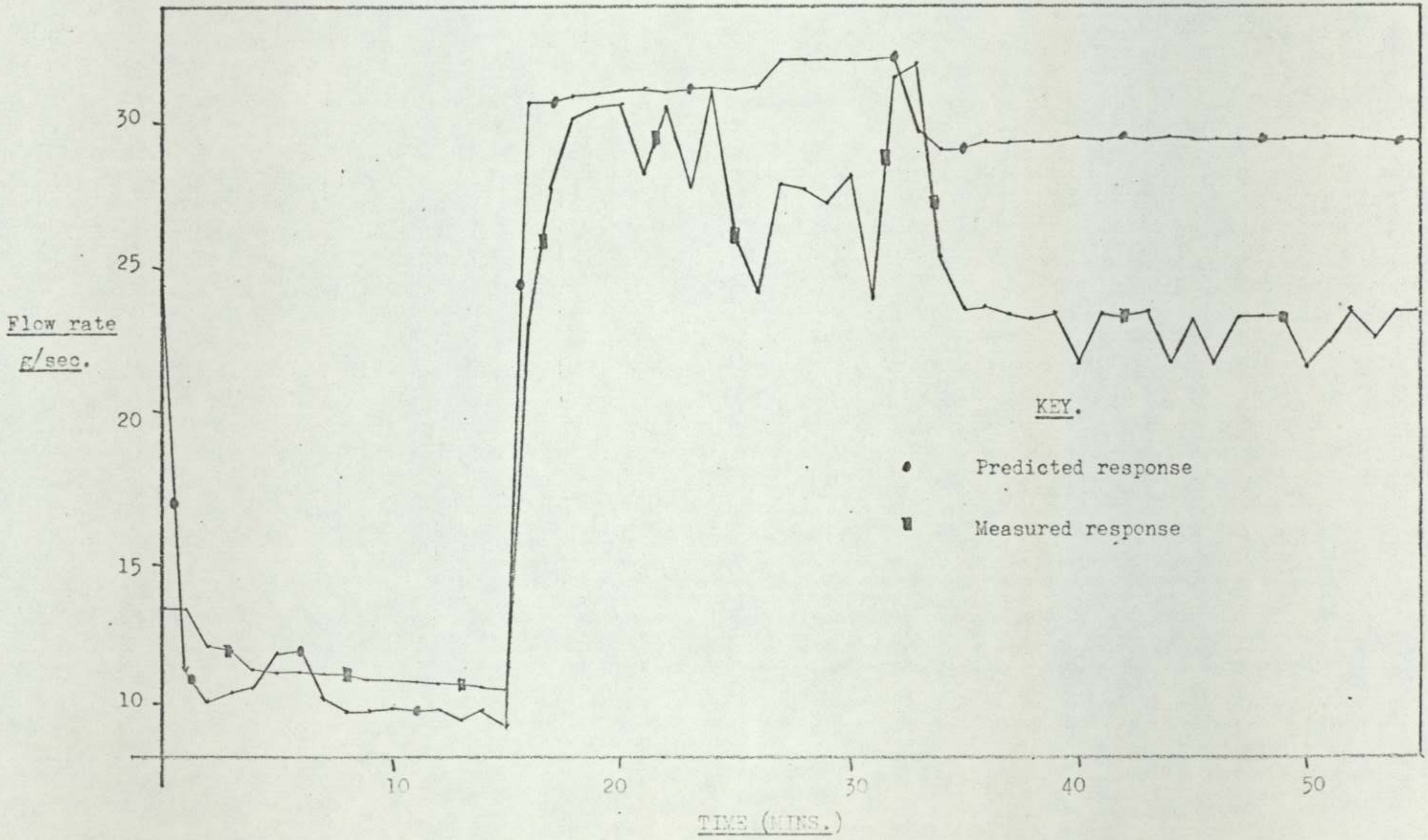


FIGURE 5.5J. Height in Second Effect Separator, (H).

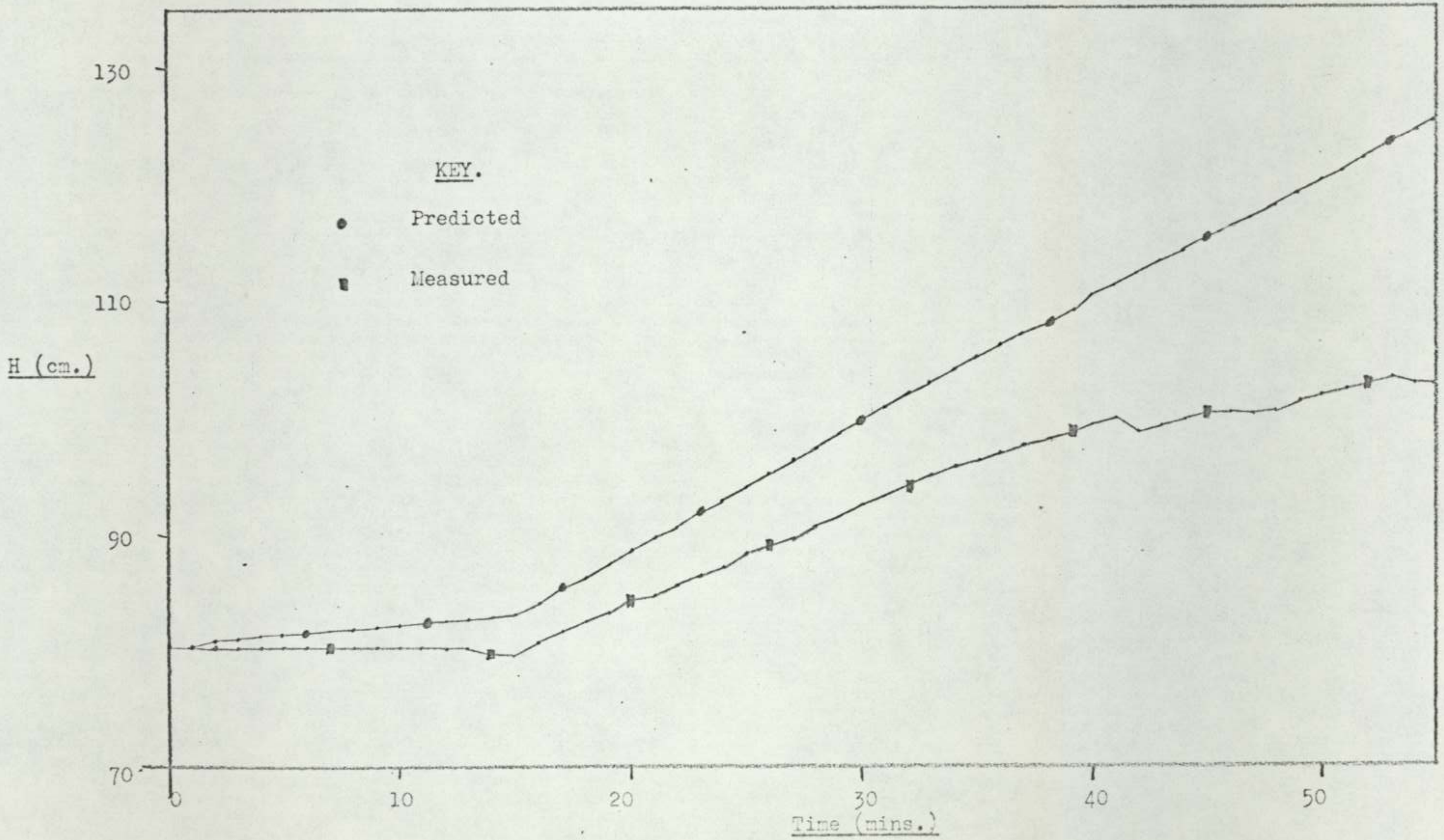


FIGURE 5.5K Predicted Liquid Flow Rate exit Preheater Shell, (M(4)).

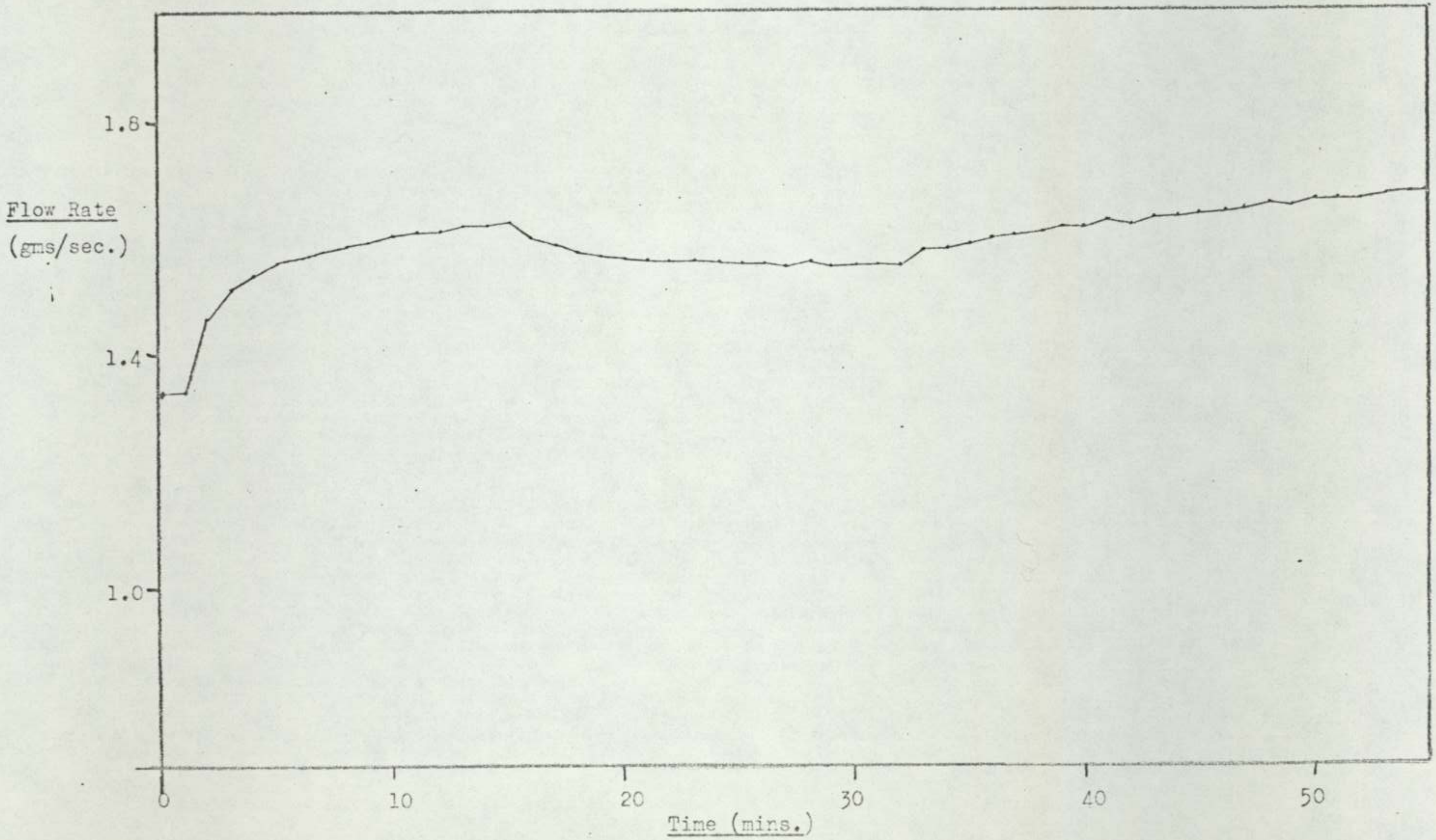


FIGURE 5.5L Predicted Liquid Flow Rate exit Condenser Shell, (M(10)).

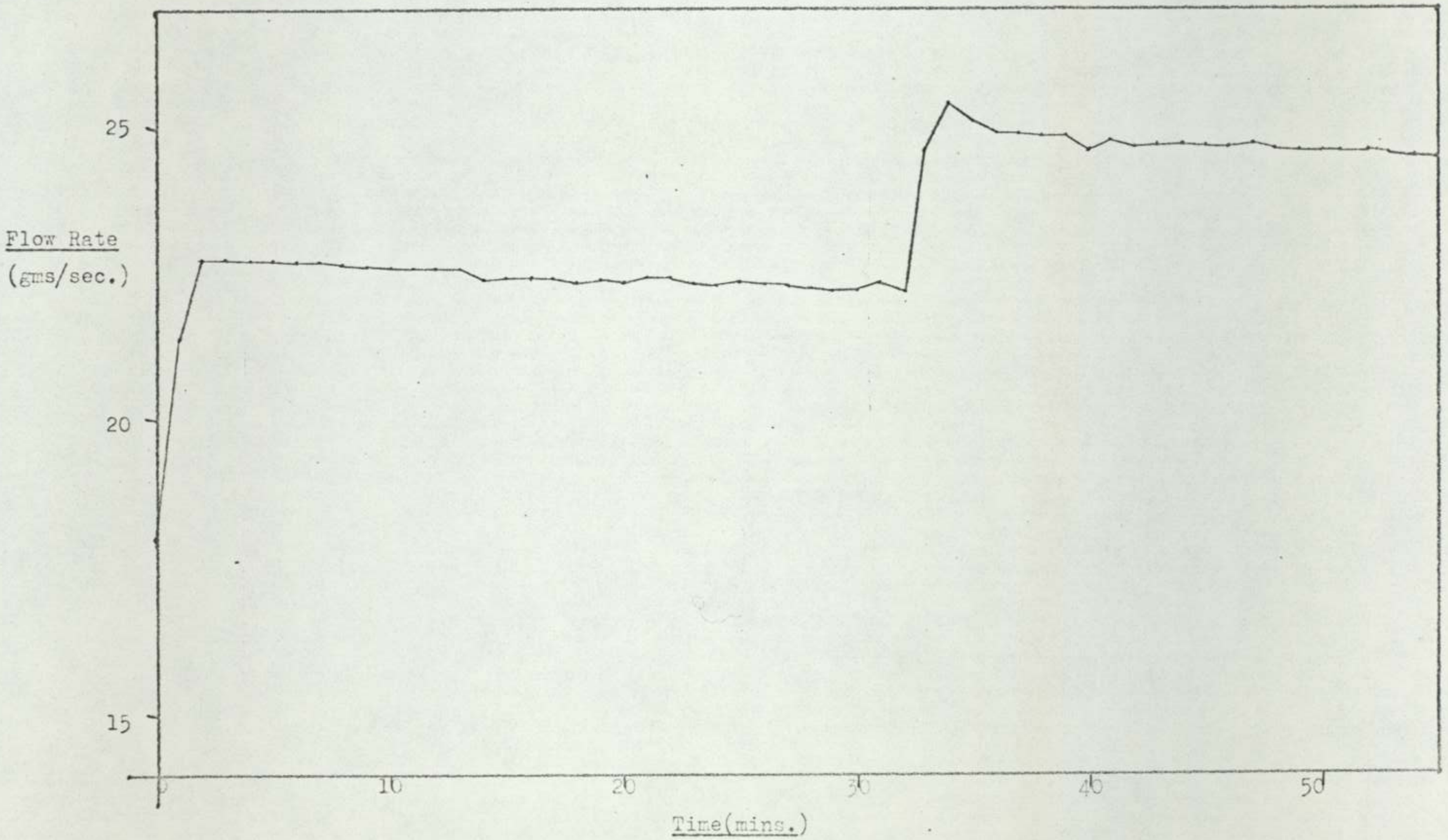


FIGURE 5.5M Predicted Liquid Flow Rate exit Second Effect Shell, (M(10)).

FIGURE 5.5N Predicted Vapour Flow Rate exit Cyclone,(V(3)).

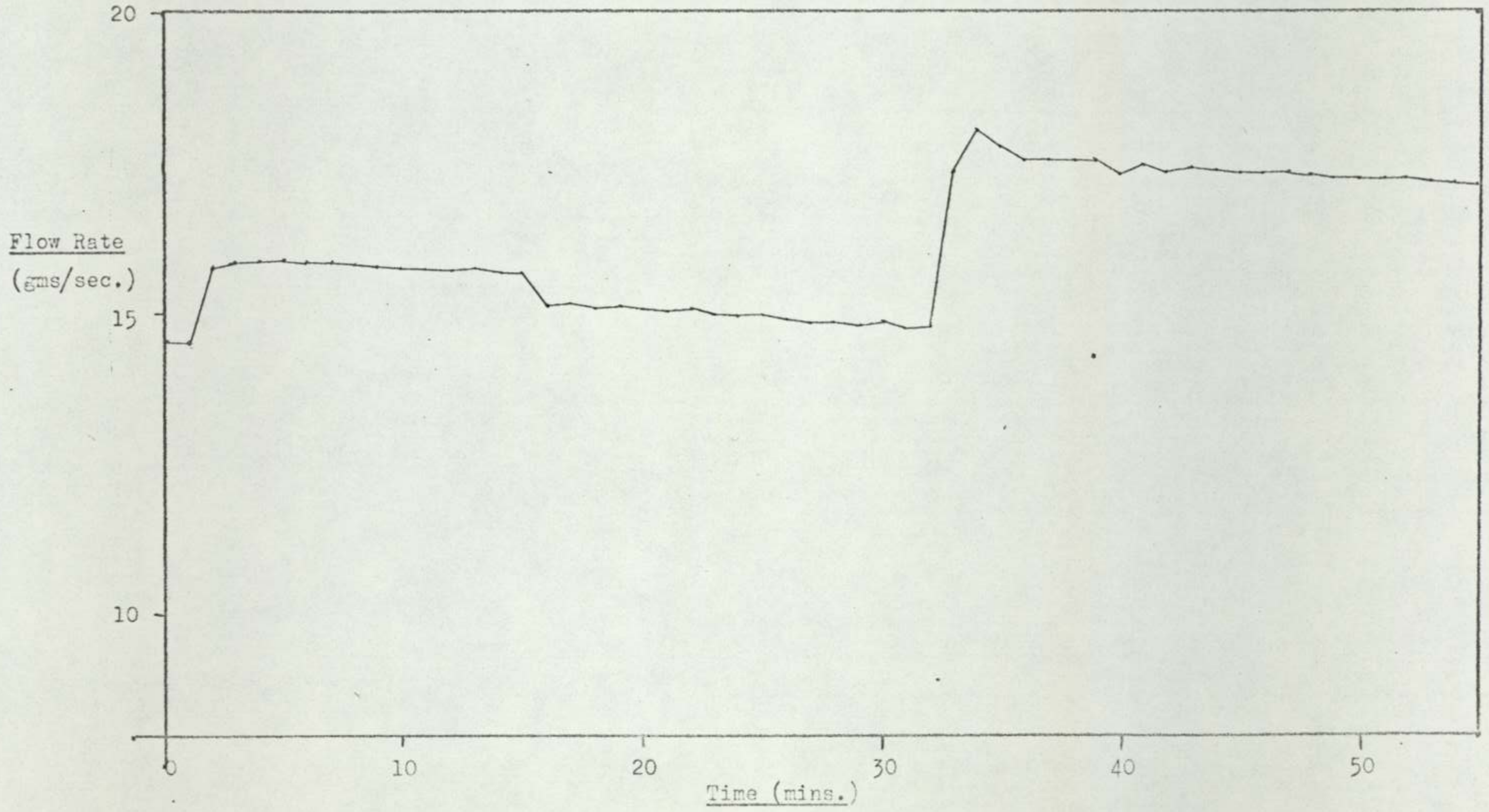


FIGURE 5.50 Predicted Vapour Flow Rate exit Preheater Shell, (V(4)).

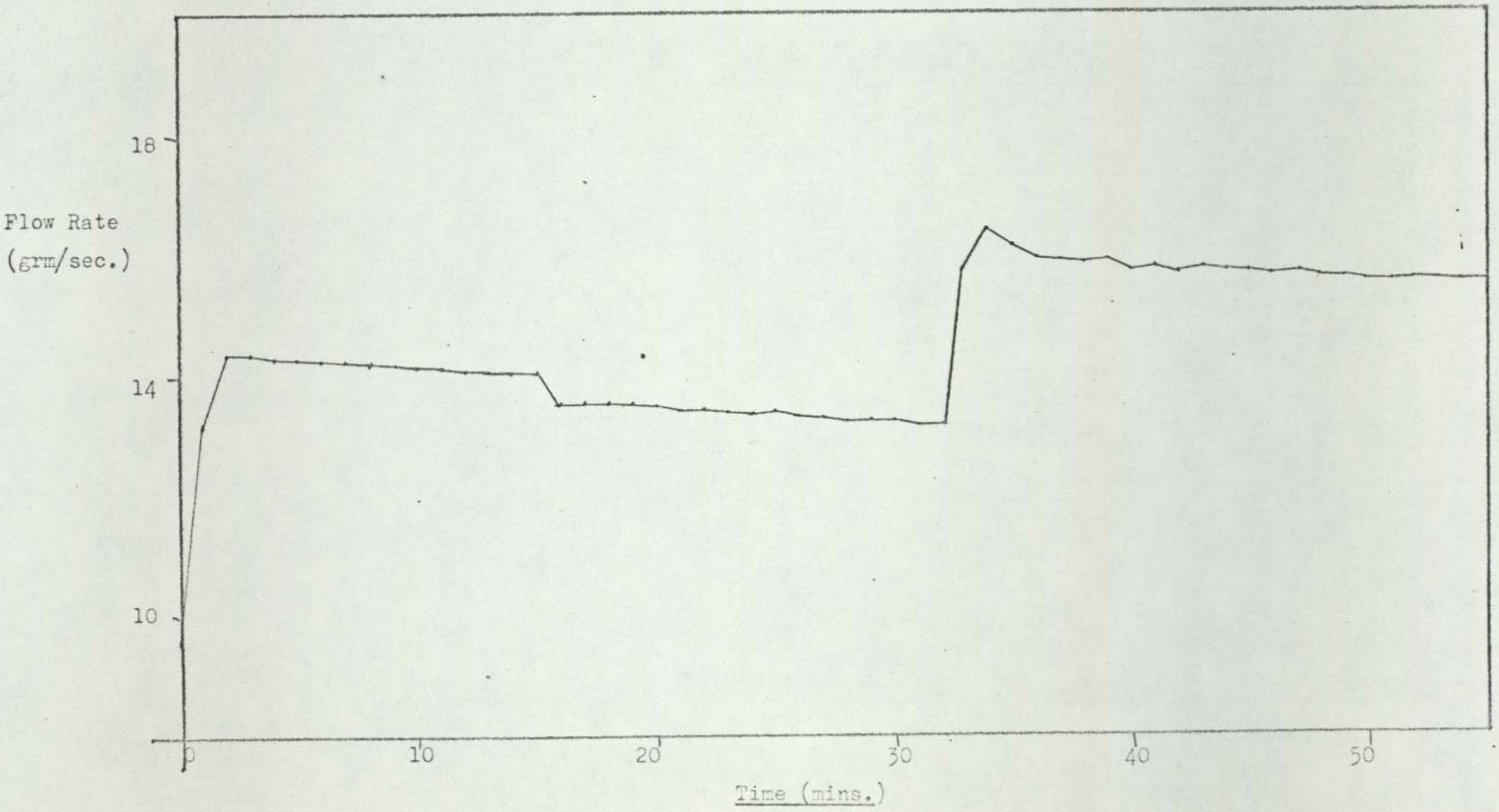


FIGURE 5.5P Predicted Vapour Flow Rate exit Second Effect Separator, (V(9)).

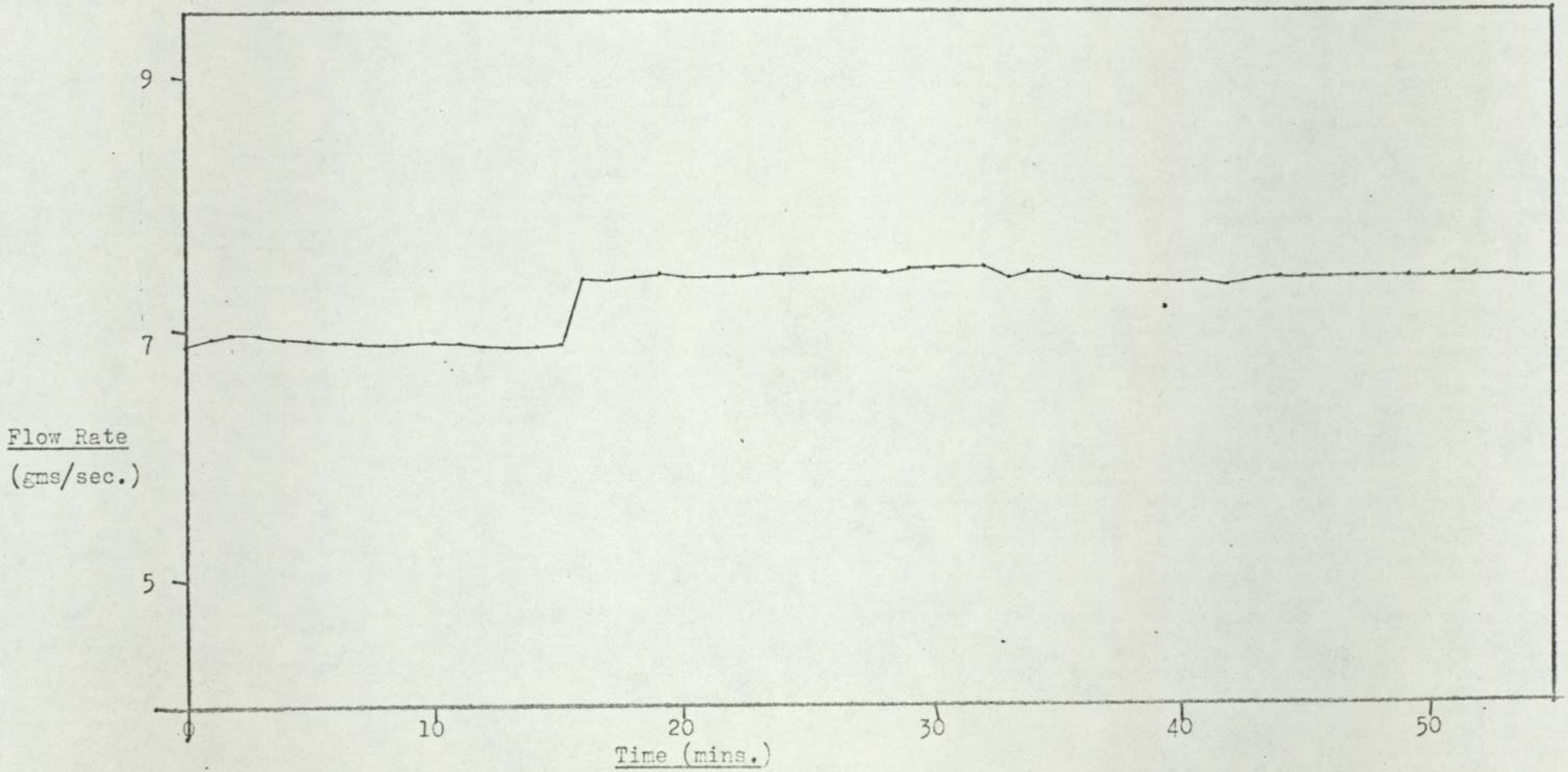


FIGURE 5.5Q Predicted Vapour Flow Rate exit Second Effect Shell, (V(10)).

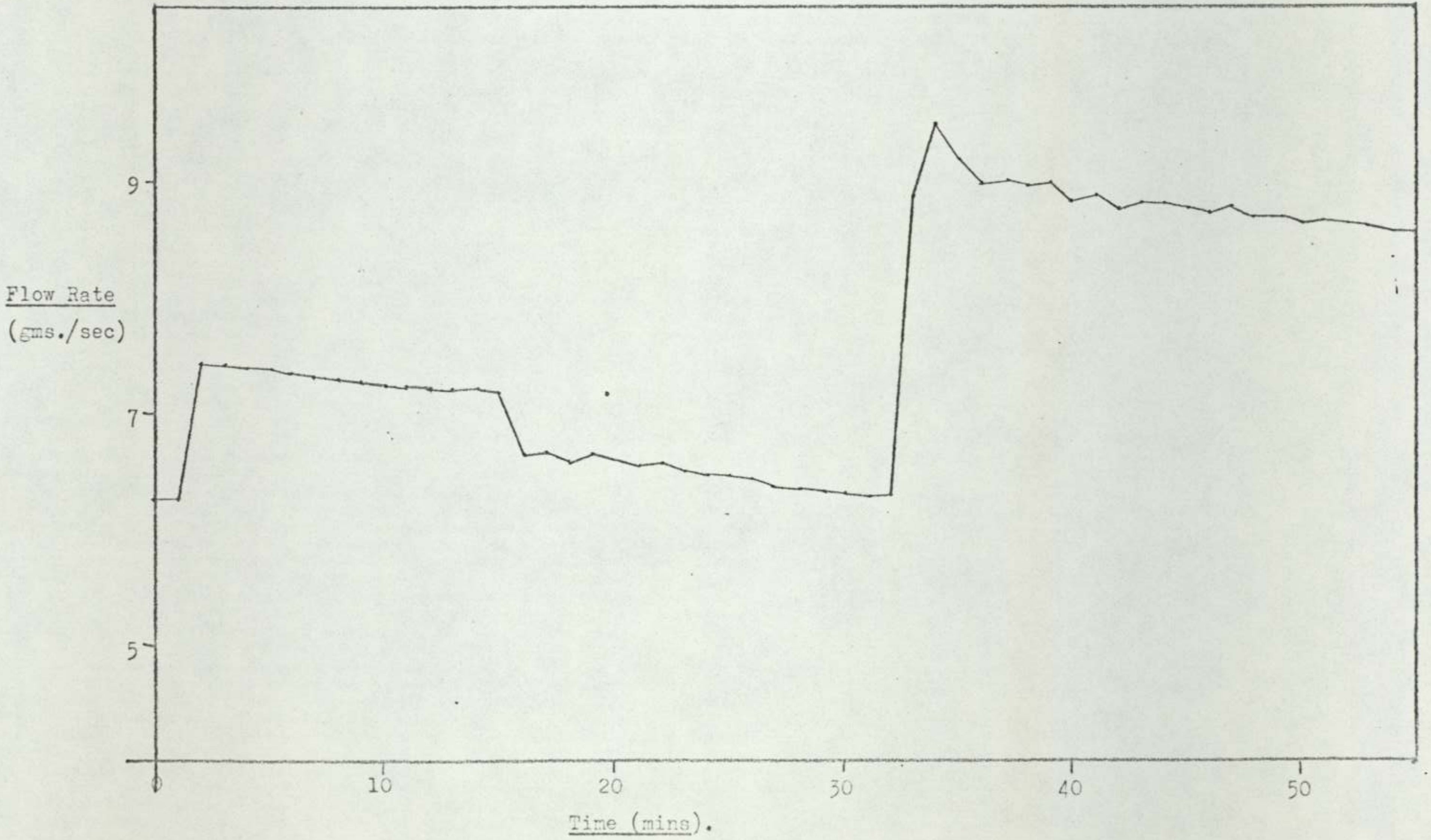


FIGURE 5.5R Predicted Heat Transfer Coefficient for Preheater.

FIGURE 5.5S Predicted Heat Transfer Coefficient for First Effect.

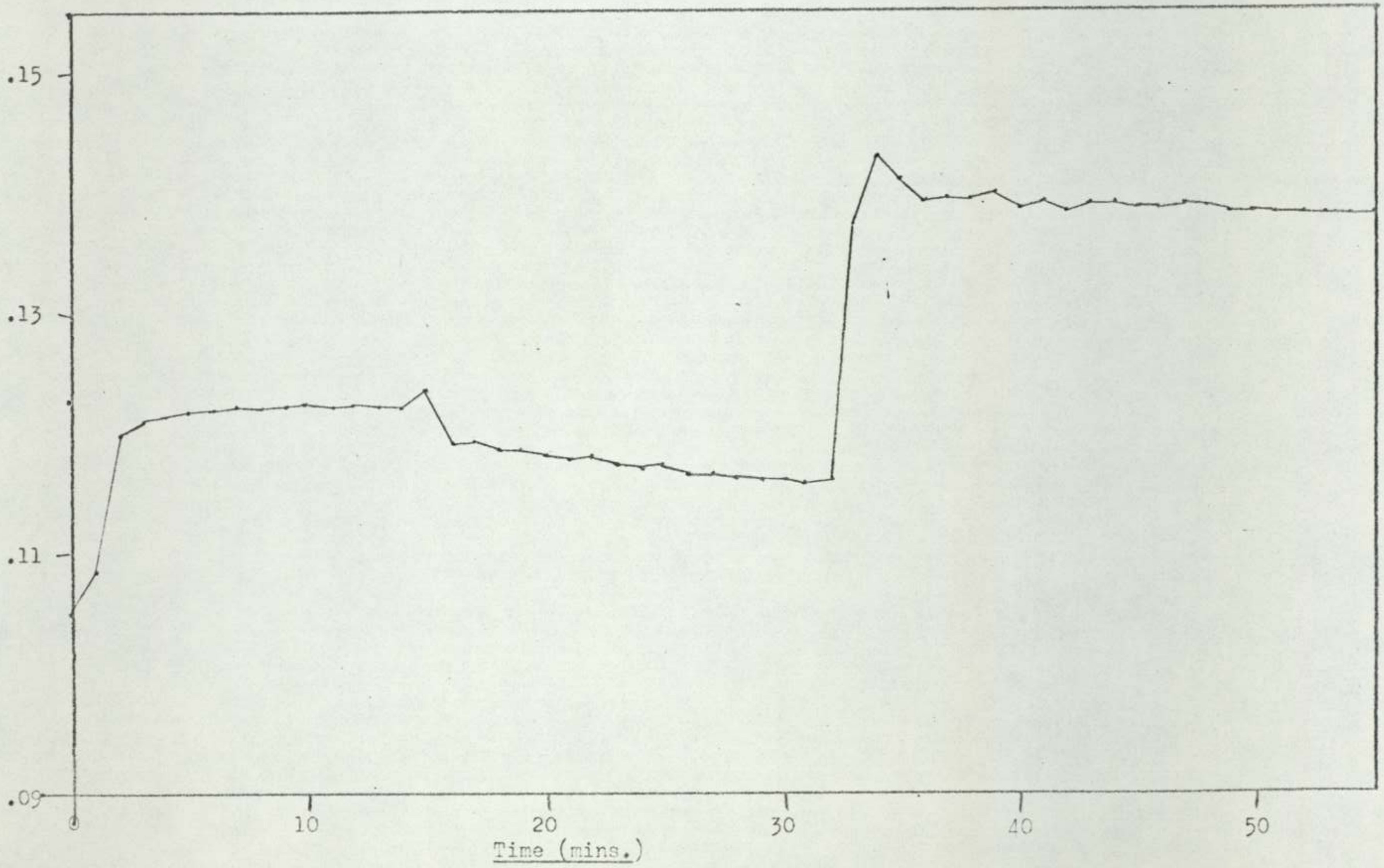


FIGURE 5.5T Predicted Heat Transfer Coefficient for Second Effect.

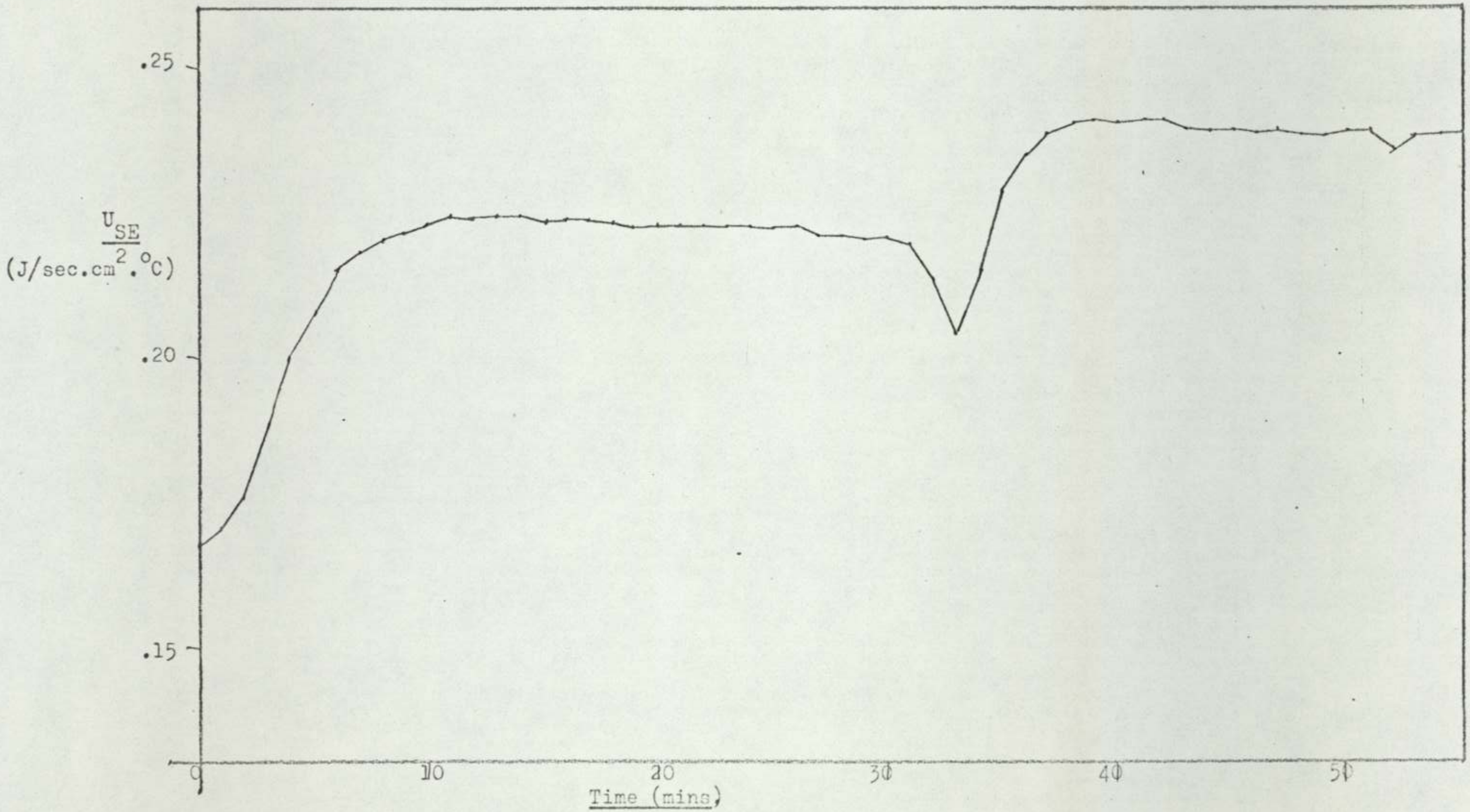


FIGURE 5.5U. Predicted Heat Transfer Coefficient for Condenser.

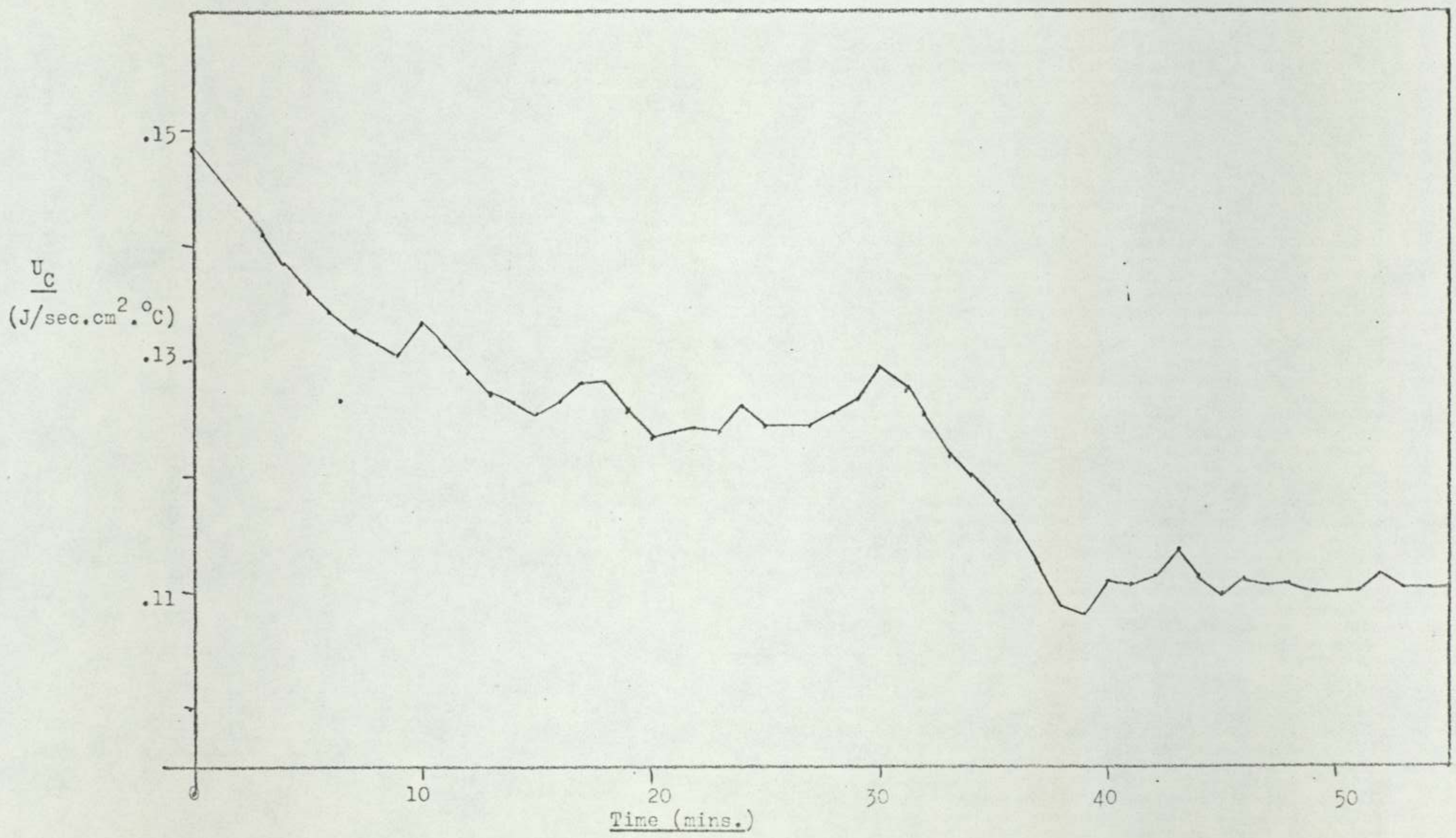


FIGURE 5.5V Temperature, (T(1)), into Preheater Tubes.

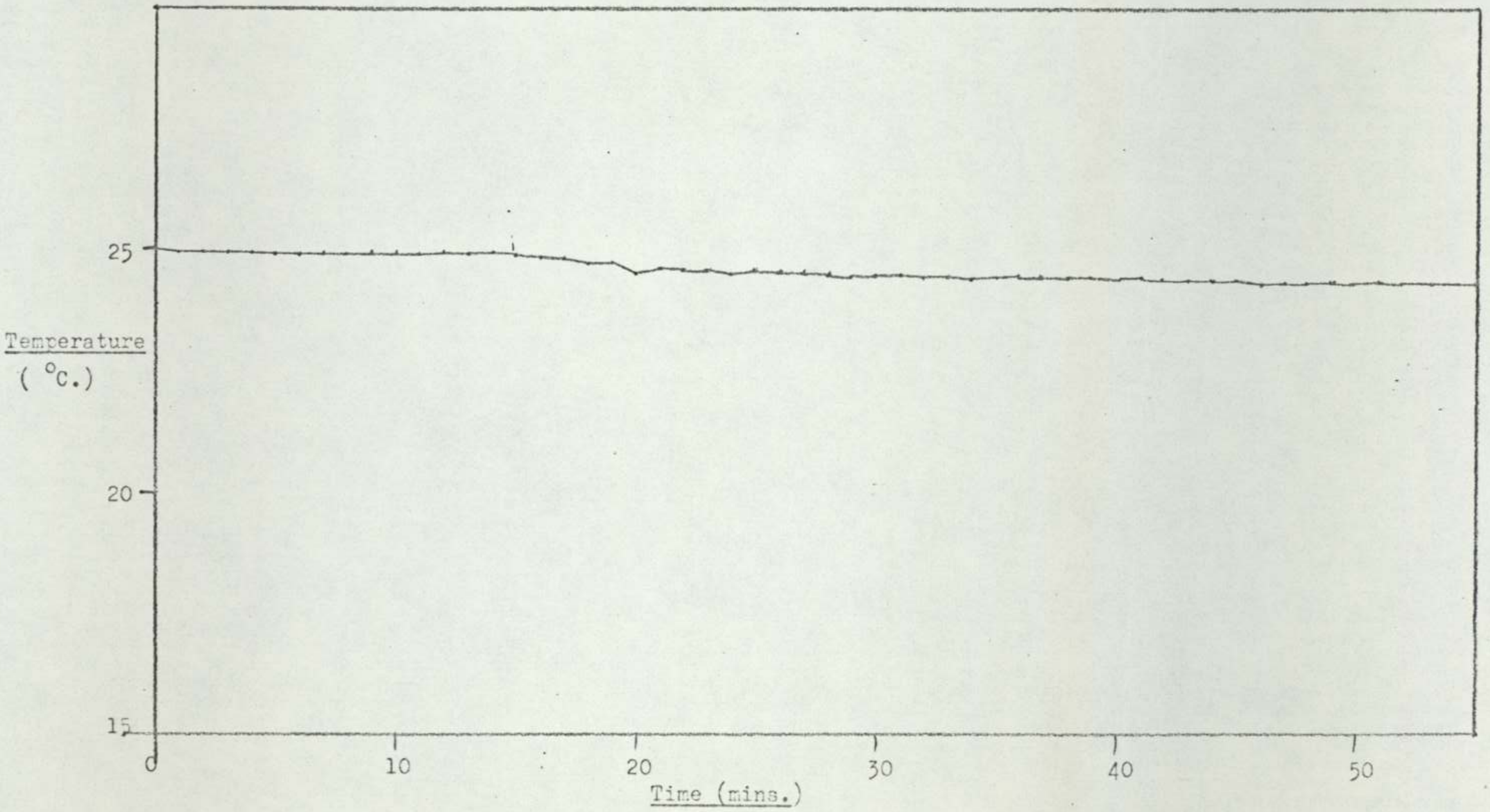


FIGURE 5.5W. Liquid Flow Rate (M(12)), Cooling Water to Condenser Tubes.

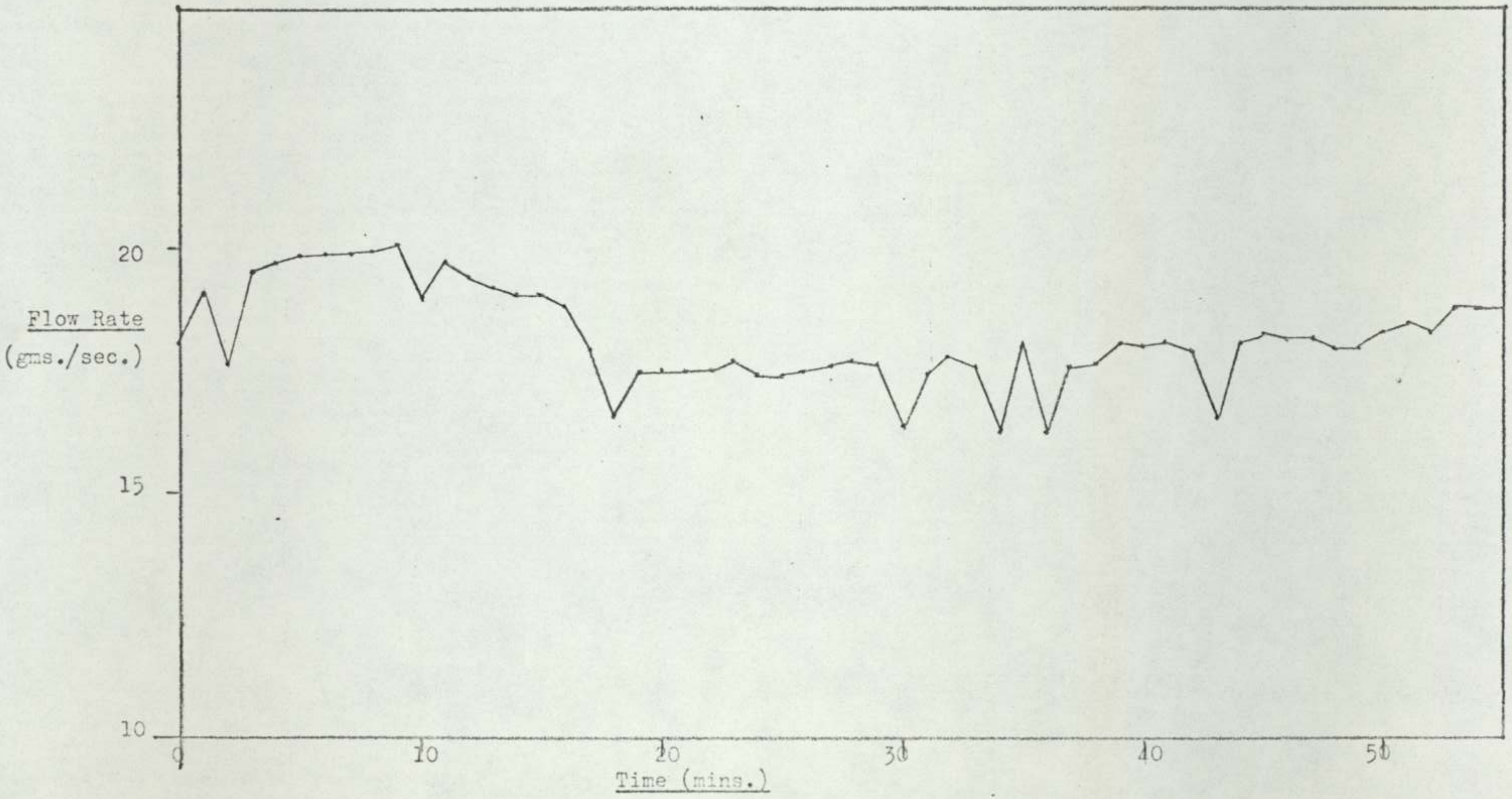


FIGURE 5.5X. Liquid Flow Rate (M(1)), into First Effect Tubes.

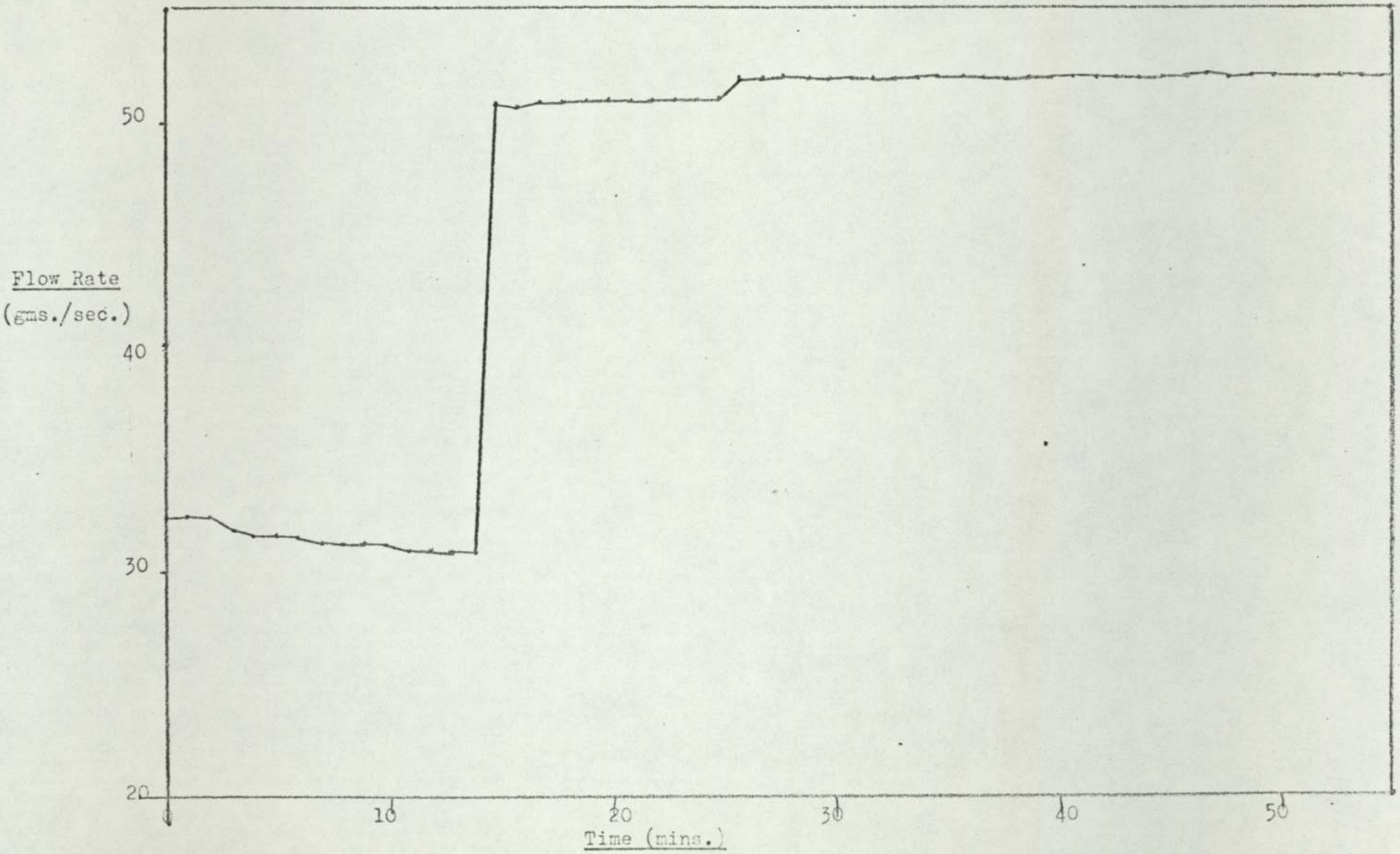
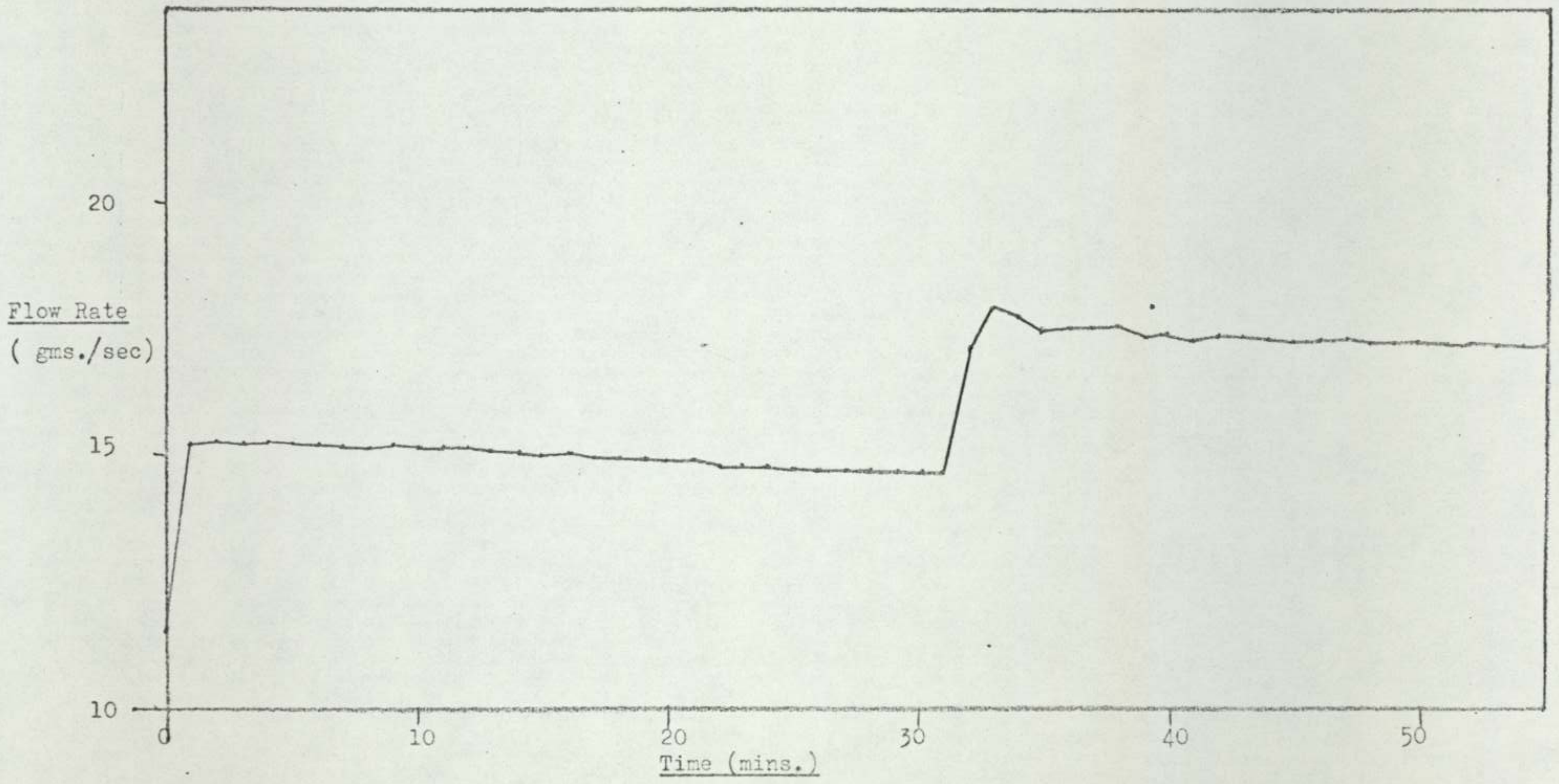
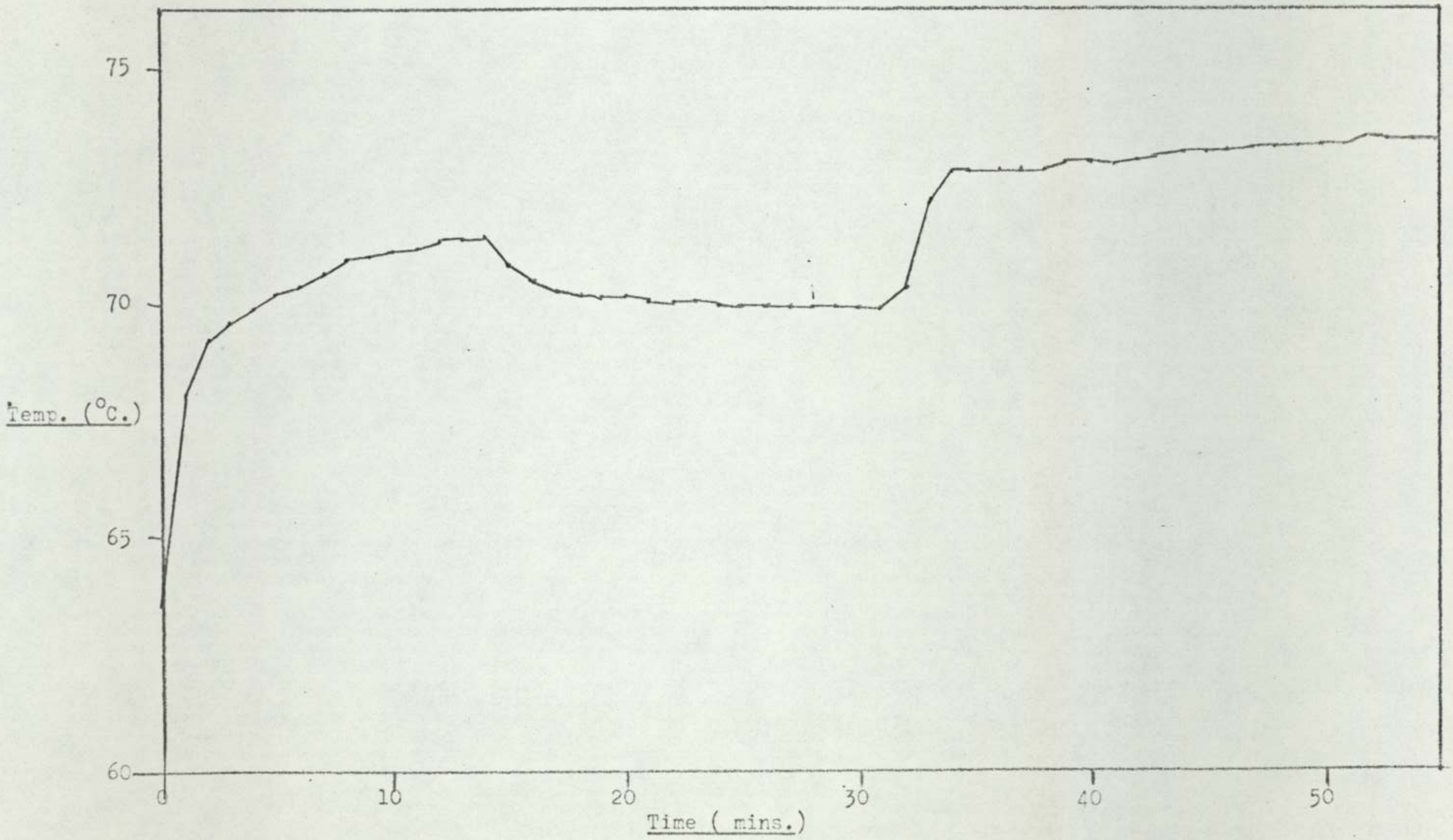


Figure 5.5Y Measured Steam Flow Rate into First Effect Shell.



Graph 5.5Z Measured Temperature exit First Effect Tubes, $T(3)$.



APPENDIX FOUR.

Filtering Experimental Results.

Table 7.1A. Temperature, T(2), estimated from filter.

Time mins.	Measurements.	Q = 0	Q = .1	Q = 1	Q = 10	Q = 100	Q = 250	Adaptive.
0	56.76	56.76	56.76	56.58	56.76	56.75	56.76	56.76
1	56.82	56.76	56.76	56.59	56.81	56.82	56.82	56.82
2	56.85	57.3	56.99	56.99	56.86	56.84	56.85	56.85
3	56.8	57.4	57.34	57.06	56.82	56.79	56.79	56.79
4	56.9	57.46	57.34	56.93	56.79	56.86	56.87	56.84
5	56.81	57.73	57.51	56.64	56.57	56.78	56.8	56.8
6	56.95	65.7	65.22	62.47	58.19	57.09	57.01	57.06
7	56.71	62.27	61.91	60.1	58.15	57.76	57.73	57.66
8	58.52	60.79	60.60	59.86	59.15	58.89	58.87	58.88
9	59.60	60.14	60.1	60.06	59.84	59.64	59.62	59.6
10	59.98	59.96	60.02	60.31	60.22	60.01	59.99	59.98
11	60.36	59.71	59.83	60.38	60.53	60.39	60.37	60.35
12	60.66	59.57	59.72	60.45	60.76	60.67	60.66	60.65
13	60.8	59.7	59.86	60.66	60.95	60.82	60.81	60.8
14	61.22	59.89	60.11	60.99	61.35	61.24	61.23	61.22
15	61.17	60.17	60.48	61.19	61.37	61.19	61.18	61.17
16	61.01	60.1	60.28	61.04	61.2	61.04	61.02	61.01
17	60.36	58.	58.24	59.31	60.23	60.35	60.36	60.34
18	59.15	57.57	57.72	58.36	59.	59.13	59.14	59.14
19	57.99	56.91	57.0	57.42	57.88	57.98	57.99	57.99
20	57.03	56.5	56.6	56.81	57.01	57.03	57.03	57.04
21	56.4	56.5	56.15	56.31	56.39	56.4	56.4	56.4
22	55.82	55.9	55.92	56.	55.91	55.83	55.82	55.83
23	55.32	55.77	55.8	55.66	55.41	55.23	55.32	55.32
24	55.04	55.63	55.6	55.44	55.14	55.06	55.05	55.05
25	54.61	55.73	55.68	54.35	54.79	54.63	54.42	54.61
26	54.42	55.56	55.5	55.11	54.47	54.44	54.43	54.42
27	54.08	55.41	55.34	54.96	54.31	54.11	54.1	54.09
28	54.08		55.04	54.68	54.2	54.09	54.08	54.07
29	53.8		54.98	54.65	54.03	53.83	53.81	53.91
30	53.6		54.8	54.04	53.78	53.63	53.6	53.57
31	53.44		54.6	54.19	53.6	53.46	53.45	53.44
32	53.24		54.5	54.13	53.49	53.27	53.25	53.25
33	53.27		54.39	53.98	53.44	53.29	53.28	53.25

Table 7.1B. Temperature, T(10), estimated from filter.

Time mins.	Measurements.	Q = 0	Q = .1	Q = 1	Q = 10	Q = 100	Q = 250	Adaptive.
0	56.81	56.81	56.81	56.81	56.81	56.81	56.81	56.81
1	58.66	56.86	56.95	57.46	58.36	58.62	56.62	56.63
2	57.96	56.66	56.81	57.5	57.99	57.99	57.97	57.99
3	57.79	56.75	56.94	57.65	57.84	57.79	57.79	57.79
4	58.22	57.2	57.42	58.14	58.23	58.22	58.22	58.22
5	57.96	56.68	56.96	57.73	57.92	57.96	57.96	57.96
6	59.7	57.67	58.03	59.04	59.57	59.69	59.68	59.69
7	60.57	58.1	58.56	59.84	60.47	60.56	60.56	60.56
8	60.31	58.13	58.67	60.01	60.34	60.31	60.31	60.31
9	60.83	58.33	58.97	60.42	60.78	60.82	60.82	60.82
10	60.22	58.	58.77	60.13	60.26	60.23	60.23	60.23
11	60.48	57.98	58.78	60.24	60.44	60.48	60.48	60.48
12	60.57	58.25	59.12	60.53	60.59	60.57	60.57	60.57
13	60.48	58.6	59.55	60.74	60.56	60.49	60.49	60.49
14	60.92	58.88	59.85	60.99	60.9	60.91	60.91	60.91
15	60.74	58.83	59.56	60.67	60.71	60.74	60.74	60.74
16	55.7	54.55	59.56	56.36	55.87	55.72	55.72	55.72
17	54.92	52.64	50.58	54.61	54.76	54.89	54.89	54.89
18	52.57	51.88	53.74	53.42	52.81	52.6	52.6	52.6
19	52.57	51.51	52.58	52.89	52.55	52.57	52.57	52.57
20	52.23	51.15	52.22	52.43	52.22	52.23	52.23	52.23
21	51.53	50.88	51.94	51.96	51.6	51.54	51.54	51.54
22	50.6	50.8	51.8	51.47	50.8	50.68	50.68	50.68
23	50.55	50.66	51.61	51.13	50.73	50.74	50.74	50.74
24	50.66	50.86	51.76	51.11	50.71	50.67	50.67	50.67
25	50.44	50.68	51.43	50.72	50.48	50.49	50.49	50.49
26	50.49	50.4	51.21	50.52	50.46	50.48	50.48	50.48
27	50.49	50.08	50.84	50.27	50.42	50.48	50.48	50.48
28	50.49		50.83	50.35	50.51	50.49	50.49	50.49
29	50.49		50.58	50.23	50.46	50.48	50.48	50.48
30	50.49		50.43	50.21	50.45	50.48	50.48	50.48
31	50.49		50.28	50.2	50.46	50.48	50.46	50.48
32	50.49		50.1	50.16	50.45	50.48	50.48	50.48
33	50.49		50.08	50.24	50.47	50.49	50.49	50.49

Table 7.1C. Temperature T(11), estimated from filter.

Time mins.	Measurements.	Q = 0	Q = .1	Q = 1	Q = 10	Q = 100	Q = 250	Adaptive.
0	36.85	36.85	36.85	36.85	36.85	36.85	36.85	36.85
1	36.94	36.87	36.87	36.89	36.93	36.94	36.94	36.94
2	37.01	36.54	36.61	36.94	37.09	37.02	37.01	37.01
3	37.	36.34	36.44	36.88	37.06	37.01	37.01	37.01
4	37.01	36.25	36.46	37.26	37.31	37.05	37.03	37.03
5	36.93	36.26	36.7	38.34	37.87	37.06	36.98	36.95
6	37.08	25.99	26.8	30.78	35.66	36.91	37.01	37.01
7	36.96	29.08	29.67	32.54	36.1	36.87	36.92	36.92
8	37.37	32.28	32.56	34.09	36.54	37.27	37.33	37.33
9	37.38	34.51	34.54	34.85	36.67	37.29	37.34	37.34
10	37.15	36.16	35.96	35.46	36.48	37.07	37.12	37.12
11	37.24	37.55	37.17	35.96	36.59	37.16	37.21	37.21
12	37.42	38.83	38.33	36.6	36.84	37.34	37.34	37.39
13	37.66	40.09	39.46	37.21	37.1	37.58	37.63	37.63
14	38.02	41.28	40.54	37.85	37.48	37.95	37.99	37.99
15	37.69	42.55	41.68	38.36	37.31	37.63	37.67	37.67
16	37.38	43.95	42.91	38.84	37.1	37.33	37.35	37.35
17	34.27	21.84	21.61	22.64	30.61	33.82	34.09	34.09
18	37.04	8.34	9.63	17.71	32.45	36.52	36.83	36.83
19	36.75	11.09	11.16	17.11	32.42	36.27	36.56	36.56
20	36.45	6.94	8.76	17.1	32.2	35.97	36.26	36.26
21	36.29	12.16	11.4	17.33	32.14	35.03	36.11	36.11
22	36.01	7.13	9.36	17.49	31.89	35.55	35.82	35.82
23	35.71	13.05	11.81	17.92	31.81	35.27	35.53	35.53
24	35.62	8.01	10.39	18.23	31.81	35.19	35.45	35.45
25	35.15	13.07	12.14	18.51	31.51	34.74	34.99	34.99
26	35.07	9.23	11.41	18.79	31.51	34.66	34.9	34.9
27	34.27	12.72	12.55	18.98	31.21	34.32	34.56	34.56
28	34.75		12.52	19.48	31.38	34.37	34.6	34.6
29	34.41		13.21	19.62	31.06	34.03	34.26	34.26
30	34.16		13.52	20.01	30.98	33.8	34.01	34.01
31	34.06		14.02	20.38	30.99	33.71	33.92	33.92
32	33.83		14.37	20.48	30.73	33.47	33.73	33.73
33	33.87		14.96	20.97	30.90	33.53	33.68	33.68

Table 7.1D. Temperature, T(13), estimated from filter.

Time mins.	Measurements	Q = 0	Q = .1	Q = 1	Q = 10	Q = 100	Q = 250	Adaptive.
0	31.93	31.93	31.93	31.93	31.93	31.93	31.93	31.93
1	32.09	31.93	31.94	31.99	32.06	32.08	32.08	32.08
2	32.16	31.92	31.93	32.02	32.13	32.16	32.16	32.16
3	32.02	31.9	31.91	31.97	32.01	32.62	32.62	32.62
4	32.05	31.9	31.92	32.	32.05	32.05	32.05	32.05
5	31.93	31.89	31.93	32.4	31.99	31.92	32.00	32.00
6	32.2	31.08	31.16	31.55	32.05	32.19	32.19	32.19
7	32.02	31.25	31.32	31.62	31.95	32.02	32.02	32.02
8	32.39	31.57	31.62	31.8	32.26	32.38	32.38	32.38
9	32.47	31.76	31.78	31.95	32.33	32.45	32.45	32.45
10	32.13	31.87	31.87	31.88	32.05	32.12	32.12	32.12
11	32.11	31.96	31.94	31.9	32.03	32.1	32.1	32.1
12	32.39	32.03	32.02	32.03	32.27	32.38	32.38	32.38
13	32.68	32.1	32.1	32.16	32.52	32.66	32.66	32.66
14	32.96	32.16	32.16	32.28	32.75	32.9	32.9	32.9
15	32.64	32.22	32.2	32.21	32.5	32.62	32.62	32.62
16	32.23	32.28	32.24	32.1	32.16	32.22	32.22	32.22
17	32.04	31.33	31.3	31.13	31.81	32.13	32.13	32.13
18	31.09	29.3	29.45	30.18	31.44	31.69	31.69	31.69
19	31.38	27.18	27.62	29.72	31.21	31.38	31.38	31.38
20	31.08	28.16	28.25	29.61	30.97	31.09	31.09	31.09
21	31.16	27.04	27.66	29.67	31.05	31.18	31.18	31.18
22	30.44	28.53	28.38	29.62	30.85	30.95	30.95	30.95
23	30.6	27.24	27.91	29.57	30.58	30.62	30.62	30.62
24	30.59	28.3	28.54	29.64	30.57	30.61	30.61	30.61
25	30.12	27.59	28.22	29.54	30.19	30.15	30.15	30.15
26	30.23	28.87	28.66	29.63	30.28	30.25	30.25	30.25
27	29.92	28.01	28.52	29.56	30.02	29.96	29.96	29.96
28	30.09		28.82	29.68	30.17	30.12	30.12	30.12
29	29.87		28.82	29.65	29.99	29.9	29.9	29.9
30	29.58		28.98	29.61	29.75	29.62	29.62	29.62
31	29.63		29.07	29.69	29.8	29.45	29.45	29.45
32	29.41		29.17	29.65	29.61	29.45	29.45	29.45
33	29.58		29.29	29.76	29.76	29.61	29.61	29.61

Table 7.1E. Temperature, T(14), estimated by filter.

Time mins.	Measurements.	Q = 0	Q = .1	Q = 1	Q = 10	Q = 100	Q = 250	Adaptive.
0	51.48	51.48	51.48	51.48	51.48	51.48	51.48	51.48
1	51.56	51.48	51.49	51.51	51.54	51.55	51.55	51.55
2	51.56	51.48	51.49	51.53	51.56	51.56	51.56	51.56
3	51.51	51.48	51.49	51.52	51.52	51.51	51.51	51.51
4	51.65	51.48	51.50	51.56	51.62	51.64	51.64	51.64
5	51.55	51.48	51.5	51.56	51.56	51.55	51.55	51.55
6	51.71	51.48	51.51	51.61	51.69	51.71	51.71	51.71
7	51.72	51.48	51.52	51.65	51.72	51.72	51.72	51.72
8	51.93	51.48	51.54	51.74	51.89	51.93	51.93	51.93
9	51.97	51.48	51.56	51.82	51.95	51.97	51.97	51.97
10	51.75	51.48	51.57	51.79	51.78	51.75	51.75	51.75
11	51.81	51.48	51.58	51.8	51.81	51.81	51.81	51.81
12	51.96	51.48	51.60	51.86	51.94	51.96	51.96	51.96
13	52.0	51.48	51.62	51.9	51.99	52.	52	52.
14	52.38	51.48	51.65	52.06	52.3	52.36	52.36	52.36
15	52.17	51.48	51.68	52.09	52.19	52.17	52.17	52.17
16	51.61	51.48	51.68	51.93	51.71	51.59	51.59	51.59
17	51.14	51.48	51.65	51.67	51.24	51.15	51.15	51.15
18	50.45	51.48	51.59	51.26	50.59	50.46	50.46	50.46
19	49.99	51.48	51.51	50.84	50.08	49.99	49.99	49.99
20	49.57	51.48	51.42	50.41	49.65	49.48	49.48	49.48
21	49.21	51.48	51.32	50.01	49.28	49.22	49.22	49.22
22	48.83	51.48	51.2	49.62	48.9	48.83	48.83	48.83
23	48.45	51.48	50.93	49.22	48.52	48.45	48.45	48.45
24	48.27	51.48	50.78	48.91	48.41	48.27	48.27	48.27
25	47.83	51.48	50.63	48.55	47.91	47.84	47.84	47.84
26	47.61	51.48	50.47	48.23	47.66	47.61	47.61	47.61
27	47.31		50.32	47.93	47.37	47.32	47.32	47.32
28	47.28		50.16	47.71	47.29	47.28	47.28	47.28
29	47.04		50.	47.48	47.08	47.04	47.04	47.04
30	46.68		49.84	47.25	46.83	46.78	46.78	46.78
31	46.64		49.68	47.05	46.67	46.65	46.65	46.65
32	46.47		49.53	46.85	46.5	46.47	46.47	46.47
33	46.46		49.37	46.72	46.47	46.46	46.46	46.47

Table 7.1F. Liquid flow rate, M(8), generated by filter.

Time mins.	Measurements.	Q = 0	Q = .1	Q = 1	Q = 10	Q = 100	Q = 250	Adaptive.
0	22.4	22.40	22.4	22.4	22.4	22.40	22.40	22.40
1	22.26	24.67	24.38	23.85	22.93	22.66	22.63	22.63
2	23.1	24.54	24.47	24.01	23.35	23.13	23.11	23.11
3	19.64	24.47	24.24	22.87	20.45	19.73	19.67	19.67
4	11.69	24.47	23.66	20.23	13.83	11.94	11.79	11.79
5	21.66	24.48	24.36	23.60	22.15	21.72	21.68	21.68
6	9.62	5.71	5.9	7.03	8.98	9.54	9.59	9.59
7	9.61	2.87	3.2	5.15	8.5	9.48	9.56	9.56
8	9.61	2.34	2.69	4.77	8.39	9.47	9.55	9.55
9	9.61	2.14	2.5	4.63	8.36	9.46	9.55	9.55
10	9.61	1.99	2.35	4.52	8.33	9.46	9.55	9.55
11	9.06	1.87	2.21	4.25	7.85	8.92	9.0	9.0
12	9.61	1.91	2.27	4.46	8.32	9.46	9.55	9.55
13	9.61	1.85	2.21	4.41	8.3	9.46	9.55	9.55
14	9.61	1.81	2.17	4.38	8.29	9.46	9.55	9.55
15	9.61	1.66	2.03	4.28	8.27	9.46	9.55	9.55
16	9.61	1.59	1.92	4.23	8.26	9.45	9.55	9.55
17	9.61	9.27	9.28	9.36	9.54	9.60	9.61	9.61
18	9.06	9.14	9.13	9.1	9.07	9.06	9.06	9.06
19	9.92	9.26	9.29	9.47	9.81	9.91	9.91	9.91
20	9.62	9.26	9.28	9.37	9.55	9.61	9.61	9.61
21	11.09	9.29	9.37	9.88	10.79	11.06	11.08	11.08
22	9.62	9.26	9.26	9.36	9.55	9.61	9.61	9.61
23	9.62	9.19	9.22	9.34	9.55	9.61	9.61	9.61
24	9.61	9.17	9.19	9.32	9.54	9.61	9.61	9.61
25	9.07	9.12	9.12	9.1	9.08	9.67	9.07	9.07
26	10.44	9.12	9.18	9.56	10.22	10.41	10.43	10.43
27	9.07	9.06	9.06	9.06	9.07	9.07	9.07	9.07
28	10.89		9.13	9.66	10.58	10.85	10.85	10.85
29	9.72		9.08	9.27	9.61	9.70	9.71	9.71
30	9.08		9.	9.02	9.66	9.07	9.08	9.08
31	10.9		9.11	9.65	10.59	10.86	10.89	10.89
32	9.99		9.06	9.34	9.83	9.98	9.99	9.99
33	9.62		9.02	9.20	9.52	9.61	9.62	9.62

Table 7.1G. Estimates of Height generated from Filter.

Time mins.	Measurements.	Q = 0	Q = .1	Q = 1	Q = 10	Q = 100	Q = 250	Adaptive.
0	98.74	98.74	98.74	98.74	98.74	98.74	98.74	98.74
1	98.93	98.74	98.77	98.8	98.9	98.93	98.93	98.93
2	99.29	98.74	98.77	98.97	99.23	99.29	99.29	99.29
3	99.41	98.74	98.8	99.11	99.39	99.41	99.41	99.41
4	98.83	98.74	98.8	99.01	98.92	98.84	98.84	98.84
5	99.24	98.74	98.83	99.09	99.19	99.24	99.24	99.24
6	99.31	98.74	98.85	99.17	99.29	99.31	99.31	99.31
7	99.31	98.74	98.87	99.21	99.23	99.31	99.31	99.31
8	99.05	98.74	98.88	99.16	99.09	99.06	99.06	99.06
9	98.74	98.74	98.87	99.02	98.8	98.75	98.75	98.75
10	98.29	98.74	98.85	98.78	98.38	98.31	98.31	98.31
11	97.8	98.74	98.79	98.45	97.89	97.81	97.81	97.81
12	97.19	98.74	98.72	98.03	97.31	97.21	97.21	97.21
13	96.3	98.74	98.62	97.59	96.8	96.71	96.71	96.71
14	96.08	98.74	98.5	97.08	96.2	96.09	96.09	96.09
15	95.68	98.74	98.36	96.61	95.76	95.68	96.58	95.68
16	95.24	98.74	98.22	96.15	95.33	95.25	95.25	95.25
17	96.03	98.74	98.09	95.78	95.08	95.04	95.04	95.04
18	94.71	98.74	97.91	95.42	94.76	94.71	94.61	94.71
19	94.48	98.74	97.74	95.11	95.53	94.49	94.49	94.49
20	95.98	98.74	97.66	95.5	95.74	95.95	95.95	95.95
21	95.36	98.74	97.55	95.39	95.42	95.37	95.37	96.37
22	95.46	98.74	97.45	95.41	95.45	95.46	95.46	95.46
23	95.13	98.74	97.34	95.33	95.22	95.17	95.17	95.17
24	95.12	98.74	97.24	95.26	95.14	95.12	95.12	95.12
25	94.69	98.74	97.11	95.07	94.7	94.69	94.69	94.69
26	94.53	98.74	96.99	94.89	94.55	94.53	94.53	94.53
27	94.39	98.74	96.87	94.27	94.42	94.39	94.39	94.39
28	94.37	98.74	96.75	94.6	94.38	94.37	94.37	94.37
29	94.2	98.74	96.63	94.47	94.23	94.21	94.21	94.21
30	94.03	98.74	96.5	94.32	94.06	94.03	94.03	94.03
31	94.02	98.74	96.39	94.22	94.02	94.03	94.03	94.03
32	93.95	98.74	96.27	94.13	93.95	93.95	93.95	93.95
33	93.72	98.74	96.15	93.99	93.73	93.73	93.73	93.73

Table 7.1H. Estimates of M(4), from filter. (gm./sec.)

Time mins.	Q = 0	Q = 0.1	Q = 1.0	Q = 10	Q = 100	Q = 250	Adaptive.
0	2.605	2.605	2.605	2.605	2.605	2.605	2.605
1	2.605	2.605	2.606	2.606	2.606	2.606	2.606
2	2.631	2.63	2.62	2.606	2.606	2.606	2.606
3	2.645	2.63	2.62	2.606	2.606	2.606	2.606
4	2.645	2.631	2.618	2.605	2.605	2.605	2.605
5	2.642	2.643	2.611	2.603	2.605	2.605	2.605
6	3.07	2.942	2.804	2.652	2.62	2.62	2.62
7	2.783	2.782	2.716	2.651	2.644	2.644	2.644
8	2.742	2.732	2.706	2.705	2.665	2.665	2.665
9	2.715	2.715	2.714	2.711	2.683	2.684	2.684
10	2.711	2.714	2.722	2.715	2.711	2.711	2.711
11	2.702	2.705	2.722	2.732	2.731	2.731	2.731
12	2.694	2.701	2.731	2.734	2.744	2.744	2.744
13	2.702	2.706	2.738	2.738	2.748	2.749	2.749
14	2.709	2.718	2.749	2.761	2.753	2.753	2.753
15	2.716	2.725	2.756	2.763	2.752	2.752	2.752
16	2.72	2.723	2.75	2.762	2.75	2.75	2.75
17	2.646	2.652	2.682	2.665	2.744	2.742	2.745
18	2.635	2.641	2.658	2.658	2.731	2.73	2.728
19	2.618	2.645	2.631	2.608	2.65	2.65	2.649
20	2.608	2.605	2.614	2.608	2.62	2.624	2.626
21	2.595	2.618	2.605	2.605	2.608	2.608	2.608
22	2.59	2.59	2.604	2.59	2.593	2.594	2.593
23	2.587	2.489	2.581	2.583	2.583	2.583	2.587
24	2.585	2.583	2.58	2.583	2.57	2.568	2.569
25	2.586	2.585	2.578	2.57	2.562	2.563	2.569
26	2.528	2.581	2.571	2.568	2.556	2.553	2.55
27	2.58	2.571	2.57	2.562	2.552	2.552	2.551
28		2.57	2.569	2.554	2.552	2.551	2.551
29		2.57	2.569	2.552	2.541	2.54	2.541
30		2.566	2.562	2.544	2.536	2.536	2.536
31		2.563	2.56	2.538	2.521	2.506	2.52
32		2.56	2.54	2.531	2.506	2.506	2.503
33		2.558	2.536	2.520	2.506	2.506	2.502

Table 7.11. Estimates of M(10), from filter. (gm./sec.)

Time mins.	Q = 0	Q = 0.1	Q = 1.0	Q = 10	Q = 100	Q = 250	Adaptive.
0	12.89	12.89	12.89	12.89	12.89	12.89	12.89
1	12.89	12.89	12.89	12.89	12.89	12.89	12.89
2	13.01	13.21	13.04	12.89	12.89	12.89	12.89
3	13.03	13.21	13.03	12.89	12.89	12 89	12.89
4	13.03	13.21	12.99	12.89	12.89	12.89	12.89
5	13.03	13.22	13.02	12.88	12.89	12.89	12.89
6	16.42	15.72	14.93	13.08	13.	13.01	13.
7	14.76	14.68	14.09	13.05	13.03	13.03	13.01
8	14.22	14.03	14.03	14.02	13.03	13.02	13.03
9	14.09	14.08	14.09	14.09	13.83	13.72	13.7
10	14.08	14.08	14.16	14.04	14.06	14.04	13.97
11	14.02	14.02	14.16	14.25	14.21	14.2	14.24
12	13.95	14.03	14.22	14.2	14.28	14.09	14.22
13	14.02	14.02	14.25	14.26	14.31	14.31	14.31
14	14.03	14.09	14.32	14.39	14.32	14.32	14.3
15	14.07	14.12	14.39	14.4	14.32	14.32	14.32
16	14.09	14.11	14.32	14.4	14.31	14.31	14.3
17	13.45	13.03	13.63	13.08	14.28	14.28	14.3
18	13.25	12.94	13	13.01	14.2	14.2	14.22
19	13.04	12.92	13.02	12.89	13.03	13.03	13.03
20	12.89	12.88	13.02	12.89	13.01	13.1	13.02
21	12.85	12.86	12.89	12.87	12.89	12.88	12.92
22	12.83	12.8	12.86	12.83	12.83	12.83	12.83
23	12.8	12.75	12.71	12.73	12.73	12.73	12.73
24	12.79	12.78	12.71	12.73	12.64	12.63	12.63
25	12.8	12.81	12.73	12.5	12.44	12.44	12.43
26	12.8	12.71	12.71	12.52	12.32	12.31	12.31
27		12.7	12.7	12.49	12.31	12.31	12.31
28		12.71	12.68	12.42	12.26	12.25	12.25
29		12.74	12.65	12.4	12.15	12.15	12.11
30		12.71	12.52	12.39	12.09	12.1	12.09
31		12.7	12.52	12.36	12.06	12.06	12.06
32		12.67	12.36	12.15	12.01	12	12.01
33		12.66	12.33	12.25	12.01	12.01	12.01

Table 7.1J. Prediction of U_p, from filter. (J./sec.cm^2.°C.)

Time mins.	Q = 0	Q = 0.1	Q = 1.0	Q = 10	Q = 100	Q = 250	Adaptive
0	.0328	.0328	.0328	.0328	.0328	.0328	.0328
1	.0357	.0355	.0347	.0335	.0331	.0331	.0331
2	.0358	.0357	.0351	.0341	.0338	.0338	.0338
3	.0357	.0354	.0334	.0305	.0297	.0297	.0297
4	.0357	.0348	.0302	.0247	.0234	.0234	.0234
5	.1667	.1616	.1352	.1043	.0975	.0975	.0975
6	.0339	.0342	.0362	.0402	.0418	.0418	.0418
7	.0303	.0308	.0336	.0401	.0425	.0425	.0425
8	.0299	.0303	.0333	.0403	.043	.043	.043
9	.0298	.0303	.0333	.0408	.0434	.0434	.0434
10	.0297	.0302	.0333	.0407	.0437	.0437	.0437
11	.0296	.03	.0329	.0396	.0422	.0422	.0422
12	.0297	.0302	.0333	.0408	.0438	.0438	.0438
13	.0297	.0301	.0333	.0409	.0439	.0439	.0439
14	.0298	.0302	.0334	.0412	.0443	.0443	.0443
15	.0296	.0301	.0333	.0412	.0444	.0444	.0444
16	.0296	.0301	.0333	.0413	.0446	.0446	.0446
17	.0441	.0441	.0444	.0449	.0451	.0451	.0451
18	.0437	.0437	.0436	.0435	.0435	.0435	.0435
19	.0441	.0442	.0447	.0457	.046	.046	.046
20	.0442	.0442	.0445	.045	.0452	.0452	.0452
21	.0444	.0446	.0462	.0492	.0502	.0502	.0502
22	.0443	.0444	.0447	.0452	.0454	.0454	.0454
23	.0443	.0443	.0447	.0453	.0455	.0455	.0455
24	.0443	.0444	.0447	.0454	.0456	.0456	.0456
25	.0442	.0442	.0441	.0441	.0441	.0441	.0441
26	.0443	.0445	.0456	.0447	.0484	.0484	.0484
27		.0442	.0442	.0442	.0442	.0442	.0442
28		.0444	.046	.0491	.05	.05	.05
29		.0444	.0449	.0459	.0462	.0462	.0462
30		.0441	.0442	.0443	.0443	.0443	.0443
31		.0445	.0461	.0493	.0503	.0503	.0503
32		.0444	.0452	.0467	.0472	.0472	.0472
33		.0444	.0449	.0458	.0426	.0426	.0426

Table 7.1K. Prediction of U_{FE}, from filter. (J./sec.cm^2.^{o}C.)

Time mins.	Q = 0	Q = 0.1	Q = 1.0	Q = 10	Q = 100	Q = 250	Adaptive
0	.4794	.4794	.4794	.4794	.4794	.4794	.4794
1	.4392	.441	.4514	.4695	.4748	.4748	.4748
2	.4377	.4386	.4462	.46	.4642	.4642	.4642
3	.4396	.4434	.4698	.5167	.5305	.5305	.5305
4	.441	.4528	.5232	.6474	.6841	.6841	.6841
5	.0668	.0686	.0822	.1082	.1102	.1102	.1102
6	.3412	.3372	.3113	.2783	.2678	.2678	.2678
7	.3754	.3694	.3348	.2766	.2598	.2598	.2598
8	.3786	.3717	.3301	.2747	.2565	.2565	.2565
9	.3774	.3711	.3356	.2729	.2541	.2541	.2541
10	.3769	.3698	.3342	.2703	.2512	.2512	.2512
11	.3774	.3713	.3386	.2786	.2606	.2606	.2606
12	.3763	.3702	.3348	.2705	.2512	.2512	.2512
13	.3775	.3711	.3354	.2703	.2507	.2507	.2507
14	.3763	.3702	.3344	.269	.2492	.2492	.2492
15	.3773	.3771	.3344	.2676	.2474	.2474	.2475
16	.3663	.36	.3242	.2589	.2393	.2393	.2393
17	.236	.2364	.2359	.2337	.2389	.2389	.2389
18	.2371	.2371	.2381	.239	.2393	.2393	.2393
19	.2344	.2331	.2306	.2256	.2241	.2241	.2241
20	.232	.2319	.2305	.2278	.227	.227	.227
21	.2309	.2289	.2209	.2068	.2026	.2026	.2026
22	.2308	.2295	.228	.225	.2241	.2241	.2241
23	.2289	.2292	.2272	.2237	.2227	.2227	.2227
24	.2301	.2293	.2271	.2234	.2223	.2223	.2223
25	.229	.2292	.2292	.2292	.2292	.2292	.2292
26	.2282	.2271	.2209	.2103	.2072	.2072	.2072
27		.2278	.2275	.2269	.2267	.2267	.2267
28		.2268	.2183	.2037	.1994	.1994	.1994
29		.2261	.223	.2173	.2157	.2157	.2157
30		.2269	.2262	.2251	.2248	.2248	.2248
31		.2244	.2158	.2009	.1966	.1966	.1966
32		.2246	.2201	.2121	.2097	.2097	.2097
33		.2243	.2213	.2161	.2145	.2145	.2145

Table 7.1L. Prediction of U_{SE}, from filter. (J./sec.cm^2.$^\circ$C.)

TIME MINS.	Q = 0	Q = 0.1	Q = 1.0	Q = 10	Q = 100	Q = 250	Adaptive.
0	.3657	.3657	.3675	.3657	.3657	.3675	.3657
1	.3538	.352	.35	.3454	.3442	.3442	.3442
2	.3572	.3557	.3508	.3498	.3514	.3514	.3514
3	.355	.3544	.3547	.3663	.3707	.3707	.3707
4	.3442	.3456	.3594	.394	.4042	.4042	.4042
5	.0762	.0829	.1145	.1633	.1759	.1759	.1759
6	.3233	.3189	.3059	.2948	.2934	.2934	.2934
7	.3241	.3181	.2983	.2820	.2822	.2822	.2822
8	.3239	.3172	.2978	.2854	.2882	.2882	.2882
9	.3183	.3111	.2923	.2797	.2825	.2825	.2825
10	.3245	.3165	.2969	.2835	.287	.287	.287
11	.3245	.3158	.2965	.2821	.2822	.2822	.2822
12	.3162	.3078	.2896	.2784	.2819	.2819	.2819
13	.308	.2996	.2841	.275	.2786	.2786	.2786
14	.3	.2927	.2804	.2734	.2773	.2773	.2773
15	.3072	.2988	.2864	.2753	.2777	.2777	.2777
16	.4033	.3914	.3747	.3591	.3626	.3626	.3626
17	.4112	.4	.3909	.3858	.3855	.3855	.3855
18	.4332	.4193	.4061	.4035	.4062	.4062	.4062
19	.441	.4254	.4047	.3967	.3976	.3976	.3976
20	.4513	.4317	.4035	.3924	.3931	.3931	.3931
21	.4562	.4343	.4	.3961	.4036	.4036	.4036
22	.4562	.4323	.3969	.3932	.3959	.3959	.3959
23	.459	.4314	.3914	.384	.3846	.3846	.3846
24	.4489	.4196	.3783	.3738	.3758	.3758	.3758
25	.4563	.423	.3776	.3704	.3709	.3709	.3709
26	.4592	.4221	.3709	.3621	.3637	.3637	.3637
27		.4275	.3718	.3617	.3621	.3621	.3621
28		.4203	.3605	.3532	.3563	.3563	.3563
29		.4215	.3595	.352	.353	.353	.353
30		.4199	.3553	.3483	.3495	.3494	.3495
31		.4171	.3478	.3401	.3423	.3424	.3424
32		.4164	.3457	.3391	.3405	.3405	.3405
33		.4105	.3405	.3379	.3403	.3403	.3403

Table 7.1M. Prediction of U_C, from filter. (J./sec.cm^2.^{o}C.)

Time mins.	Q = 0	Q = 0.1	Q = 1.0	Q = 10	Q = 100	Q = 250	Adaptive.
0	.0161	.0161	.0161	.0161	.0161	.0161	.0161
1	.0161	.016	.0161	.0162	.0162	.0162	.0162
2	.0162	.0162	.0161	.0163	.0163	.0163	.0163
3	.0163	.0163	.0161	.0161	.0161	.0161	.0161
4	.0163	.0162	.0159	.0159	.0159	.0162	.0162
5	.0163	.0162	.0155	.0156	.0159	.0159	.0159
6	.0218	.0213	.0189	.0167	.0163	.0163	.0163
7	.0196	.0193	.0178	.0164	.0161	.0161	.0161
8	.0179	.0178	.0173	.0165	.0162	.0162	.0162
9	.0169	.0169	0.127	.0164	.0163	.0163	.0163
10	.0162	.0162	.0164	.0162	.0161	.0161	.0161
11	.0156	.0157	.0161	.0161	.0159	.0159	.0159
12	.0151	.0152	.0159	.0162	.0161	.0161	.0161
13	.0146	.0148	.0158	.0163	.0163	.0163	.0163
14	.0142	.0144	.0155	.0162	.0163	.0163	.0163
15	.0138	.014	.0151	.016	.0161	.0161	.0161
16	.0133	.0135	.0148	.0159	.0159	.0159	.0159
17	.0257	.0258	.0247	.0191	.0176	.0176	.0176
18	.06	.0518	.0293	.0177	.016	.016	.016
19	.0361	.0375	.0295	.0176	.0159	.0159	.0159
20	.065	.0513	.0295	.0175	.0158	.0158	.0158
21	.322	.0368	.0295	.0178	.0161	.0161	.0161
22	.0649	.0482	.0293	.0178	.0161	.0161	.0161
23	.0302	.0362	.0287	.0176	.0159	.0159	.0159
24	.0582	.0439	.0285	.0176	.016	.016	.016
25	.031	.0362	.028	.0174	.0147	.0157	.0157
26	.05	.0402	.028	.0176	.016	.016	.016
27		.0359	.0277	.0175	.0158	.0158	.0158
28		.037	.0273	.0176	.016	.016	.016
29		.0359	.0271	.0176	.016	.016	.016
30		.0347	.0266	.0174	.0158	.0158	.0158
31		.0336	.0263	.0175	.0159	.0159	.0159
32		.0331	.0261	.0174	.0158	.0158	.0158
33		.032	.0257	.0175	.0159	.0159	.0159

Table 7.3A. Estimates of T(2) from On-line Experiment.

(°C.)

Time mins.	Estimate	Measurement	Prediction.	Time mins	Estimate.	Measurement	Prediction.
0	44.42	44.42	44.42	28	46.82	46.83	47.43
1	44.45	44.45	44.42	29	46.92	46.93	47.29
2	44.47	44.45	44.35	30	47.	47.	47.75
3	44.48	44.48	44.42	31	47.1	47.1	47.62
4	44.49	44.49	44.39	32	47.13	47.14	46.99
5	44.54	44.55	44.45	33	47.18	47.18	47.56
6	44.57	44.58	44.3	34	47.23	47.22	47.72
7	44.64	44.64	44.43	35	47.33	47.32	48.57
8	44.67	44.67	44.4	36	47.43	47.44	48.18
9	44.68	44.68	44.41	37	47.61	47.61	47.95
10	44.43	44.41	45.31	38	47.73	47.73	48.24
11	44.15	44.15	44.96	39	47.82	47.83	47.66
12	43.93	43.93	44.76	40	47.88	47.88	48.12
13	43.75	43.75	44.72	41	47.91	47.93	46.82
14	43.65	43.65	44.59	42	48.03	48.03	47.1
15	43.57	43.57	44.51	43	48.1	48.1	47.08
16	43.48	43.48	44.59	44	48.08	48.08	47.03
17	43.47	43.48	44.48	45	48.39	48.38	48.13
18	43.85	43.88	42.97	46	49.5	49.51	48.28
19	44.49	44.48	44.46	47	50.8	50.73	54.79
20	45.09	45.08	45.99	48	51.77	51.82	52.15
21	45.56	45.54	46.69	49	52.72	52.73	51.87
22	45.93	45.93	46.85	50	53.44	53.45	52.41
23	46.18	46.2	45.55	51	53.96	53.97	51.88
24	46.38	46.56	44.29	52	54.4	54.39	53.12
25	46.59	46.56	47.25	53	54.7	54.7	53.01
26	46.68	46.68	47.32	54	54.75	54.75	52.5
27	46.78	46.78	47.63	55	55.12	55.11	53.85

Table 7.3B. Estimates of T(10), from On-line Experiment. (°C.)

Time mins.	Estim-ate.	Measure-ment.	Predict-ion.	Time mins.	Estim-ate.	Measure-ment.	Predict-ion.
0	47.85	47.85	47.85	28	51.53	51.51	51.62
1	47.86	47.9	47.86	29	51.77	51.76	51.83
2	47.78	47.91	47.87	30	51.87	51.86	51.9
3	47.81	47.88	47.81	31	51.9	51.89	51.89
4	47.85	47.93	47.85	32	51.89	51.89	51.93
5	47.84	47.95	47.84	33	52.01	52.01	52.04
6	47.94	47.96	47.72	34	52.1	52.09	52.11
7	47.94	47.97	47.68	35	52.15	52.15	52.13
8	47.98	47.98	47.61	36	52.27	52.3	52.31
9	46.51	47.49	47.52	37	52.39	52.39	52.43
10	47.39	47.4	47.34	38	52.42	52.42	52.41
11	47.23	47.23	47.23	39	52.51	52.51	52.52
12	47.23	47.25	47.21	40	52.5	52.5	52.52
13	47.22	47.23	47.18	41	52.59	52.59	52.58
14	47.17	47.19	47.12	42	52.71	52.71	52.71
15	47.14	47.15	47.11	43	52.77	52.77	52.77
16	47.07	47.06	47.04	44	52.81	52.8	52.85
17	47.26	47.23	47.28	45	52.53	55.55	55.54
18	49.93	49.91	49.96	46	57.91	57.9	58.02
19	50,48	50.46	50.57	47	58.56	58.45	58.69
20	50.83	50.81	50.91	48	59.03	59.01	59.17
21	50.97	50.95	51.07	49	59.58	59.53	59.66
22	51.21	51.19	51.28	50	60.	59.96	60.06
23	51.31	51.3	51.39	51	60.19	60.18	60.26
24	51.39	51.38	51.47	52	60.41	60.39	60.46
25	51.45	51.43	51.52	53	60.64	60.64	60.71
26	51.5	51.48	51.56	54	60.72	60.72	60.76
27	51.5	51.49	51.57	55	61.02	61.02	61.1

Table 7.3C. Estimates of T(11), from On-line Experiments. (°C.)

Time mins	Estimate.	Measurement	Prediction.	Time mins.	Estimate.	Measurement.	Prediction.
0	28.1	28.1	28.11	28	28.92	28.93	21.76
1	28.17	28.17	28.14	29	28.94	28.95	21.2
2	28.29	28.28	28.55	30	29.03	29.02	19.94
3	28.37	28.38	28.55	31	29.13	29.13	19.39
4	28.46	28.46	26.56	32	29.25	29.25	19.48
5	28.49	28.5	27.21	33	28.27	28.57	16.36
6	28.51	28.51	28.99	34	29.34	29.4	17.06
7	28.54	28.54	28.88	35	29.56	29.58	15.16
8	28.65	28.65	28.99	36	29.73	29.73	14.77
9	28.71	28.71	29.13	37	29.89	29.89	14.63
10	28.72	28.74	27.72	38	30.03	30.05	13.71
11	27.99	28.75	27.32	39	30.16	30.16	13.95
12	28.85	28.85	26.8	40	30.2	30.22	12.81
13	28.87	28.88	26.22	41	30.27	30.25	14.39
14	28.87	28.88	25.6	42	30.29	30.3	13.59
15	28.83	28.84	24.8	43	30.29	30.31	12.51
16	28.81	28.83	23.88	44	30.25	30.25	11.39
17	28.68	28.7	26.33	45	30.41	30.44	11.26
18	28.69	28.63	28.32	46	30.71	30.57	23.06
19	28.57	28.54	30.46	47	30.68	30.72	19.87
20	25.52	28.58	28.49	48	30.96	30.94	22.01
21	28.53	28.53	26.99	49	31.27	31.27	22.81
22	28.53	28.54	25.97	50	31.58	31.59	22.58
23	28.57	28.57	27.57	51	31.99	31.98	24.34
24	28.67	28.63	30.32	52	32.38	32.48	22.55
25	28.64	28.71	24.5	53	32.79	32.78	23.24
26	28.76	28.76	23.56	54	32.96	32.95	24.91
27	28.82	28.83	22.31	55	33.42	33.45	22.31

Table 7.3D. Estimates of T(13), from On-line Experiment. (^{o}C.)

Time mins	Estimate.	Measurement.	Prediction.	Time mins.	Estimate.	Measurement.	Prediction.
0	26.25	26.25	26.25	28	26.33	26.33	25.91
1	26.29	26.28	26.25	29	26.36	26.36	25.88
2	26.38	26.38	26.38	30	26.6	26.6	25.8
3	26.45	26.45	26.29	31	26.61	26.61	25.77
4	26.36	26.36	26.29	32	26.63	26.63	25.8
5	26.42	26.42	26.29	33	26.77	26.78	25.66
6	26.46	26.46	26.31	34	26.92	26.92	25.64
7	26.55	26.55	26.3	35	27.01	27.01	25.5
8	26.57	26.58	26.31	36	27.41	27.15	25.48
9	26.58	26.58	26.32	37	27.17	27.17	25.49
10	26.57	26.58	26.21	38	27.12	27.13	25.43
11	26.73	26.73	26.19	39	27.28	27.28	24.99
12	26.64	26.64	26.17	40	27.27	27.25	25.39
13	26.53	26.53	26.14	41	27.16	27.13	25.53
14	26.48	26.48	26.11	42	27.24	27.25	25.45
15	26.31	26.31	26.06	43	27.39	27.4	25.43
16	26.11	26.1	26.01	44	27.47	27.45	25.47
17	26.08	26.08	25.99	45	27.64	27.65	25.29
18	25.87	25.87	26.3	46	27.85	27.85	25.7
19	25.99	25.99	26.42	47	28.17	28.12	25.77
20	25.99	25.99	26.29	48	28.57	28.59	25.92
21	25.93	25.92	26.19	49	28.97	28.98	26.
22	26.04	26.05	26.14	50	29.26	29.27	26.
23	26.06	26.06	26.28	51	29.71	29.71	26.16
24	26.07	26.07	26.5	52	30.01	30.02	26.
25	26.16	26.17	26.06	53	30.41	30.41	26.07
26	26.23	26.23	26.01	54	30.55	30.55	26.22
27	26.25	26.25	25.93	55	30.85	30.86	25.99

Table 7.3E. Estimates of T(14), from On-line Experiment. (°C.)

Time mins.	Estimate.	Measurement.	Prediction.	Time mins.	Estimate	Measurement.	Prediction.
0	38.07	38.07	38.07	28	39.78	39.78	39.71
1	38.1	38.1	38.07	29	39.89	39.88	39.79
2	38.11	38.11	38.1	30	39.98	39.98	39.9
3	38.1	38.1	38.11	31	40.04	40.04	40.
4	38.15	38.15	38.11	32	40.15	40.15	40.05
5	38.18	38.18	38.15	33	40.25	40.25	40.15
6	38.19	38.19	38.18	34	40.31	40.31	40.25
7	38.2	38.2	38.19	35	40.33	40.33	40.32
8	38.19	38.19	38.19	36	40.41	40.41	40.34
9	38.22	38.22	38.2	37	40.46	40.47	40.45
10	38.24	38.24	38.21	38	40.54	40.55	40.52
11	38.2	38.19	38.22	39	40.65	40.68	40.59
12	38.2	38.2	38.2	40	40.72	40.72	40.67
13	38.22	38.22	38.21	41	40.87	40.88	40.72
14	38.18	38.18	38.21	42	41.03	41.05	40.89
15	38.13	38.13	38.18	43	41.04	41.04	41.03
16	38.04	38.04	38.11	44	41.06	41.06	41.04
17	38.	38.01	38.01	45	41.41	41.44	41.1
18	38.22	38.24	38.02	46	41.97	41.99	41.53
19	38.45	38.45	38.26	47	42.42	42.42	41.97
20	38.65	38.65	38.54	48	42.89	42.94	42.49
21	38.89	38.88	38.65	49	43.36	43.36	42.98
22	39.05	39.05	38.81	50	43.85	43.85	43.36
23	39.02	39.21	39.2	51	44.18	44.19	43.86
24	39.35	39.35	39.27	52	44.55	44.55	44.18
25	39.47	39.47	39.34	53	44.86	44.88	44.55
26	39.57	39.57	39.51	54	44.98	44.98	44.88
27	39.66	39.66	39.58	55	45.42	45.42	45.03

Table 7.3F. Estimates of M(8), from On-line Experiments.

(gm./sec.)

Time mins.	Estimate.	Measurement.	Prediction.	Time mins.	Estimate	Measurement	Prediction.
0	15.3	15.3	15.3	28	32.57	32.55	31.92
1	15.07	15.07	15.65	29	32.35	32.34	32.15
2	15.23	15.22	15.64	30	32.4	32.41	31.26
3	15.27	15.24	15.64	31	32.44	32.44	31.77
4	15.28	15.28	15.63	32	32.83	32.82	33.18
5	15.35	15.36	15.61	33	32.93	32.94	32.43
6	14.94	14.3	15.61	34	32.98	32.98	32.36
7	15.3	15.21	15.62	35	31.6	31.6	30.6
8	15.13	15.13	15.11	36	30.66	30.65	30.15
9	15.11	15.11	15.11	37	30.61	30.61	30.15
10	28.51	28.69	15.6	38	30.44	30.44	29.68
11	28.35	28.22	26.14	39	30.59	30.57	30.97
12	28.14	28.13	26.37	40	26.83	26.83	30.2
13	28.14	28.14	26.35	41	27.11	27.12	30.19
14	27.97	27.97	26.33	42	27.14	27.15	29.76
15	27.94	27.94	26.34	43	26.6	26.59	30.2
16	28.2	28.2	26.34	44	30.53	30.58	30.04
17	28.1	28.1	26.36	45	25.12	23.94	30.83
18	31.26	31.3	26.37	46	33.59	33.76	26.75
19	30.56	30.47	33.06	47	27.08	27.11	25.61
20	32.25	32.27	32.66	48	26.24	26.23	25.51
21	32.46	32.47	32.31	49	24.7	24.66	26.89
22	32.43	32.43	31.68	50	21.84	21.83	25.51
23	28.28	28.23	31.7	51	24.85	24.89	26.04
24	24.16	24.11	31.66	52	24.23	24.22	25.7
25	32.45	32.54	32.64	53	21.67	21.63	26.24
26	32.51	32.52	31.75	54	26.25	26.3	26.58
27	32.58	32.58	31.79	55	25.55	25.54	26.41

Table 7.3G. Estimates of H, from On-line Experiments. (cm.)

Time mins.	Estim- ate.	Measure- ment.	Predict- ion.	Time mins.	Estim- ate.	Measure- ment.	Predict- ion.
0	36.61	36.61	36.61	28	56.5	56.5	55.54
1	36.87	36.88	36.61	29	57.46	57.46	56.51
2	37.26	37.26	36.87	30	59.05	59.06	57.46
3	37.26	37.63	37.26	31	59.79	59.78	59.05
4	37.86	37.86	37.63	32	60.64	60.63	59.79
5	38.25	38.25	37.86	33	62.09	62.1	60.64
6	38.77	38.77	38.25	34	63.34	63.34	62.12
7	39.01	39.	38.77	35	64.23	64.23	63.34
8	39.26	39.26	39.01	36	65.19	65.19	64.32
9	39.68	39.68	39.26	37	65.93	65.93	65.19
10	40.71	40.71	39.68	38	66.6	66.59	65.93
11	41.83	41.83	40.71	39	67.69	67.69	66.6
12	42.42	42.41	41.81	40	68.45	68.45	68.4
13	43.65	43.56	42.42	41	69.06	69.06	68.4
14	44.45	44.45	43.59	42	69.99	69.99	69.13
15	45.28	45.27	44.41	43	71.36	71.37	69.04
16	46.1	46.03	45.28	44	72.31	71.3	71.34
17	47.27	47.27	46.12	45	73.05	73.05	72.31
18	48.07	48.06	47.26	46	74.32	74.33	73.01
19	49.56	49.57	48.09	47	75.45	75.45	74.38
20	48.99	48.96	48.98	48	76.56	76.56	76.56
21	48.77	48.78	48.98	49	77.49	77.49	76.57
22	56.18	56.2	49.77	50	78.11	78.11	77.49
23	51.36	51.35	50.18	51	78.81	78.32	78.82
24	52.26	52.25	51.36	52	79.17	79.14	79.19
25	53.51	53.51	52.56	53	79.87	79.87	79.16
26	54.68	54.68	53.51	54	80.29	80.28	79.87
27	55.54	55.54	54.67	55	80.35	80.35	80.29

Table 7.3H. Predictions of M(4), from On-line Experiment.

(gm./sec.)

Time mins.	Prediction	Time mins.	Prediction
0	1.062	28	1.211
1	1.063	29	1.261
2	1.072	30	1.221
3	1.076	31	1.222
4	1.082	32	1.224
5	1.092	33	1.224
6	1.094	34	1.23
7	1.108	35	1.241
8	1.109	36	1.249
9	1.109	37	1.261
10	1.082	38	1.272
11	1.064	39	1.277
12	1.037	40	1.28
13	1.016	41	1.281
14	1.007	42	1.29
15	1.006	43	1.297
16	1.003	44	1.297
17	0.996	45	1.311
18	1.032	46	1.572
19	1.061	47	1.613
20	1.137	48	1.683
21	1.16	49	1.729
22	1.183	50	1.804
23	1.204	51	1.842
24	1.205	52	1.899
25	1.207	53	1.903
26	1.208	54	1.904
27	1.21	55	1.928

Table 7.3I. Predictions of M(10), from filter. (gm./sec.)

Time mins.	Prediction.	Time mins.	Prediction.
0	5.481	28	5.694
1	5.491	29	5.699
2	5.493	30	5.703
3	5.495	31	5.711
4	5.506	32	5.712
5	5.517	33	5.723
6	5.518	34	5.725
7	5.52	35	5.738
8	5.521	36	5.802
9	5.521	37	5.911
10	5.486	38	5.903
11	5.463	39	5.921
12	5.432	40	5.92
13	5.411	41	5.921
14	5.409	42	5.941
15	5.409	43	5.949
16	5.409	44	5.947
17	5.397	45	5.947
18	5.433	46	5.944
19	5.461	47	6.327
20	5.526	48	6.518
21	5.583	49	6.708
22	5.591	50	6.772
23	5.621	51	6.831
24	5.684	52	6.904
25	5.692	53	6.948
26	5.687	54	6.941
27	5.694	55	7.03

Table 7.3J. Predictions of U_p, from On-line Experiments.

(J./sec.cm^2.^{o}C)

Time mins.	Prediction	Time mins.	Prediction.
0	.0559	28	.0598
1	.0549	29	.0625
2	.0556	30	.0606
3	.0558	31	.0554
4	.0562	32	.0598
5	.0543	33	.0605
6	.0555	34	.0691
7	.0551	35	.0637
8	.0551	36	.0592
9	.0784	37	.0609
10	.0754	38	.0552
11	.074	39	.0586
12	.0741	40	.046
13	.0728	41	.0478
14	.0726	42	.0468
15	.0742	43	.0457
16	.0735	44	.0559
17	.0546	45	.0406
18	.0514	46	.0813
19	.0585	47	.0487
20	.0619	48	.0433
21	.0615	49	.0424
22	.0469	50	.0361
23	.0365	51	.0423
24	.0611	52	.04
25	.0612	53	.0351
26	.064	54	.0441
27	.0618	55	.0421

Table 7.3K. Prediction of U_{FE}, from On-line Experiments.

(J./sec.cm^2.^{o}C.)

Time mins.	Prediction.	Time mins.	Prediction.
0	.1655	28	.2137
1	.1686	29	.2023
2	.1664	30	.2106
3	.1657	31	.2453
4	.1646	32	.2155
5	.1705	33	.2129
6	.1667	34	.1814
7	.1681	35	.1966
8	.1682	36	.2128
9	.1395	37	.2057
10	.1451	38	.2317
11	.1447	39	.2158
12	.1474	40	.2782
13	.1499	41	.2659
14	.1502	42	.275
15	.1466	43	.2808
16	.1479	44	.2296
17	.2243	45	.3226
18	.2447	46	.1599
19	.2151	47	.2757
20	.2023	48	.3192
21	.2042	49	.3226
22	.2719	50	.3863
23	.3583	51	.3273
24	.2072	52	.3509
25	.2072	53	.4051
26	.1968	54	.3189
27	.2058	55	.3368

Table 7.3L. Predictions of U_{SE}, from On-line Experiments.

(J./sec.cm^2.^{o}C.)

Time mins.	Prediction.	Time mins.	Prediction.
0	.5919	28	.5706
1	.5957	29	.5549
2	.5883	30	.5665
3	.5905	31	.6003
4	.603	32	.9734
5	.6037	33	.5975
6	.603	34	.5014
7	.5998	35	.6462
8	.5923	36	.6039
9	.5566	37	.6294
10	.5801	38	.6121
11	.5901	39	.6275
12	.6107	40	.6747
13	.7414	41	.6593
14	.8995	42	.6887
15	.8544	43	.6948
16	.6083	44	.6263
17	.6792	45	.6057
18	.5896	46	.3024
19	.547	47	.4635
20	.5309	48	.4956
21	.5461	49	.5021
22	.625	50	.5662
23	.7189	51	.5073
24	.543	52	.5404
25	.5502	53	.5961
26	.5417	54	.4995
27	.5604	55	.5195

Table 7.3M. Predictions of U_C, from On-line Experiment.

($J./sec.cm^2.^oC.$)

TIME MINS.	PREDICTION.	TIME MINS.	PREDICTION.
0	.015	28	.0155
1	.0149	29	.0156
2	.015	30	.016
3	.0151	31	.016
4	.0149	32	.0159
5	.0149	33	.0162
6	.0149	34	.0164
7	.0151	35	.0165
8	.015	36	.0167
9	.015	37	.0167
10	.015	38	.0165
11	.0154	39	.0167
12	.0153	40	.0167
13	.0152	41	.0164
14	.0153	42	.0165
15	.0151	43	.0167
16	.015	44	.0169
17	.0152	45	.0169
18	.0148	46	.0168
19	.0151	47	.0172
20	.015	48	.0175
21	.015	49	.0176
22	.0152	50	.0177
23	.0152	51	.0179
24	.0151	52	.018
25	.0153	53	.0181
26	.0154	54	.0182
27	.0154	55	.0182