A STUDY OF COGNITIVE SKILLS IN COMPLEX SYSTEMS

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Ian Gordon Umbers, BSc, MSc

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ABSTRACT

The work described in this thesis is concerned with investigating certain aspects of human behaviour in control tasks requiring cognitive skill. The first chapter reviews evidence in the process control literature on,

(i) the characteristics of control behaviour,
(ii) development of process control skills,
(iii) individual differences,
(iv) factors that affect performance,
(v) structure of operators' behaviour,
(vi) models of the process operator,
(vii) methodology.

The next chapter describes a preliminary field study of the behaviour of gas grid control engineers. The investigation was carried out using observations and reports from the controllers as the main source of data. The results indicated that the verbal protocol technique might give useful and more detailed data on control behaviour. Chapter 3 investigates the controllers' behaviour using verbal protocols. Previous methods of analysing protocol data are reviewed. Three methods are used to analyse the protocols of the grid controllers. The results indicate that:

(a) peak activity occurred during the afternoon shifts,
(b) individual differences between controllers were associated with different types of predictive behaviour,
(c) some of the controllers appeared to make more accurate predictions than others.

The next chapter describes a comparative study of electricity grid control engineers. The procedures for investigation are similar to those of the previous two chapters. Results from the three types of analysis indicate that, (a) morning was the most active part of the day, (b) only 32% of goal orientated behaviour was concerned with predicting and decision making compared with 88% in the gas task. A detailed analysis of decisions shows several types of decision behaviour, which are combined into a general model of decision behaviour. Chapter 5 describes an experiment in which a simulation of a simplified version of the gas control task is used to examine the effect of certain types of predictive information on the performance of naive subjects, and to test their understanding of particular aspects of the task. Results show that although subjects' performance improved over trials, it was not affected by the additional predictive information. Results also show that only knowledge about certain task variables seemed to be relevant to good control performance. Chapter 6 describes another experiment using the simulator in which naive subjects are given predictive information but for more trials than in the previous chapter. Changes in behaviour due to skill acquisition during the trials are investigated using verbal protocols. The results indicate that even with twice as many trials subjects could not learn to use the predictive information effectively. The protocol data shows an increase in purposive behaviour and in particular an increase in predictive behaviour. Chapter 7 describes an experiment in which the grid controllers used a simulated version of the gas control task. The purpose of the experiment was to investigate controller behaviour under more difficult and controlled conditions, using verbal protocols. The results show that behaviour on the simulator was similar to behaviour on the real task with slight modifications to cope with the more difficult task. Performance was assessed using several criteria; only small differences were found between the controllers. Chapter 8 summarises and discusses the results of the experiments and field studies and relates these to the various areas of research reviewed in Chapter 1. In particular the possibility of fundamental cognitive abilities underlying control behaviour is discussed, as well as possible limitations in the information combining processes of the prediction and decision procedures. A suggested approach for further work on cognitive skills is also mentioned.

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CONTENTS

CHAPTER 1

This chapter reviews the evidence in the process control literature on the following topics:

1. Open and closed loop characteristics of process control tasks.
2. Development of process control skills.
3. Individual differences and their effect on performance.
4. Aspects of mental tasks that affect performance.
5. Organisation and structure of the operators' behaviour.
6. Models of process operators' control behaviour.
7. Methodological issues.

1. INTRODUCTION

Initial experience with computers originally led designers of process plants to thinking in terms of replacing existing manual with automatic control systems, and thus introducing the era of the unmanned plant (Baker and McIlheran, 1962; Knight, 1954). This approach was endorsed by certain human factors literature, Birmingham and Taylor (1954) state 'speaking mathematically he (man) is best when doing least' (p.1752). However, with the increase in automation it has gradually become apparent that man cannot be designed out of the control system. Edwards and Lees (1973) after conducting a survey on computers in the process industry have commented that, there are a number of functions which cannot easily be automated but which can be performed successfully by the human operator. de Jong and Koster (1971) endorse this observation and predict that in the next few years newly constructed plant for supervisory purposes will continue to rely on the human operator. The emphasis reflects Jordan's (1963) assertion that man and machine are complementary, so that according to Edwards and Lees (op cit) the sophistication of a control system is now judged by the extent to which there is a balance between the functions allocated to man and machine. Ketteringham and O'Brien (1974) in describing the development of a computer based predictive aid state that the 'integration of men and computers can offer a superior level of performance than present manual systems and may be easier to implement than fully automatic systems'.

The result has been the decline in demand for manual skills and the subsequent increase in mental or cognitive skills. However, Bainbridge, Beishon, Hemming and Splaine (1968) suggest that the lack of knowledge about mental skills is reflected in the relatively few training schemes for process workers. The recent survey by Edwards and Lees (op cit) reaches the same conclusion, and the situation appears to be similar on the other side of the Atlantic, US Department of Labor report (1970). Consequently as Kragt and Landeweerd (1974) point out, it is necessary to investigate human capacities and limitations in performing the necessary control functions.

The study of cognitive skills in control situations is therefore of real importance to process technology. It has also been suggested that such research has implication for cognitive theories. Bainbridge (1972) argues that someone interested in the study of man's interaction in a complex environment should choose process control as an example. Kelley (1968) suggests a more general relevance in the study of control behaviour by the statement that 'Most activity involves changing the environment in some way and may be subsumed under the category control'.

The following sections review, characteristics of control, development of control skill, individual differences in control behaviour, factors affecting control performance, structure of operator behaviour, models of the process controller, and analysis of verbal data.

1.1 The 'open' and 'closed' loop characteristics of control

This section is concerned with those aspects of the operators' behaviour that are a recurring feature of the control function.

1.1.1 Laboratory findings

Crossman and Cooke (1962) in their study of performance on the water bath task differentiate between two types of control strategy, closed and open loop. (The distinction between the two is defined by the relative weight given to contemporary system information.) In the closed loop mode contemporary system information is used exclusively in determining a control setting. In the open loop mode the contemporary information is ignored in favour of historical data. The behaviour of the subjects indicated that they considered both present and past behaviour of the system. Kragt and Landeweerd (1974), in a similar experiment using an air mixer apparatus, observed their subjects overshoot and then undershoot, ie hunting, a manifestation of closed loop behaviour. Later on more open loop behaviour was apparent, the subjects closed the valve, waited some time, opened it fully again waited some time and then made a final slight correction, ie similar to the behaviour observed in the Crossman and Cooke (op cit) experiment. Kragt and Landeweerd suggest that these laboratory findings confirm Sell, Crossman and Box's (1962) field observations of operator control behaviour in a hot strip rolling mill.

Brigham and Laios (1975) in an experiment using a 'leaky cans' apparatus found that the subjects' basic strategy was 'open loop'. In one experimental condition, where intermediate information was available, the subjects were able to develop an anticipatory model of the plant; again a finding similar to that of Crossman and Cooke's (op cit).

Cooke (1965) used the protocol technique to further analyse subjects' behaviour in the water bath experiment. The verbal reports indicated that all the subjects planned future control changes, and there were many more future than past statements. Cooke suggests that this implies that prediction is the concern of the highest 'conscious' activity of the brain, and that memorising the past is a function of a lower level. The finding indicates the predominantly predictive nature of the control activity.

1.1.2 Field and simulation studies

Sinclair, Sell, Beishon and Bainbridge (1966) in an ergonomic study of an L.D. waste heat boiler identified two types of control action that the operator makes (a) as a result of knowledge of the present system state, (b) as a result of knowledge of how the system is going to perform. The open and closed loop modes of behaviour are apparent in these descriptions. Beishon (1966) in an analysis of the stuff gate operator's behaviour in a papermill also found evidence for the open/closed loop strategies. The operators would make a control change by initiating an open loop action followed by a series of closed loop adjustments. Attwood (1970) also studying stuff gate operators' skills identified similar behaviour. Three basic functions were required of the operator

(i) Primary adjustment following a prearranged programme
(ii) Secondary adjustment needed to iron out any side effects from the primary adjustment or of other disturbances
(iii) Timing control to synchronise weight changes with reel changes.

Each of these could be carried out in either open or closed loop mode depending on whether the operator had current knowledge of results. Beishon (1969) investigated the skills of an ovenman in baking cakes, using protocol and interviewing techniques. Eight fairly distinct routines for dealing with different phases of the task were observed. Here again open and closed loop strategies were fundamentals, e.g. Routine (3), control actions made to bring oven to suitable state for currant cakes, is a type of open loop behaviour and requires considerable past experience to know suitable baking times and temperature profiles for a given cake type. Routine (5), feedback and correction of inspection shows faults in cakes after preliminary settings in routine (3), is an example of closed loop behaviour.

Bainbridge 1972, 1974, 1975, Bainbridge et al (1968) are concerned with the same power demand task. Bainbridge (1974) presents the results of an experiment employing a simulation of a task involving the control of power supplied to five electric furnaces. Verbal protocols were used as the main source of data. Two major types of activity emerged from the resulting analysis.

(i) When the control variable values are within tolerance the operator notes for each furnace the stage it will go to next, and predicts the effect on overall power usage. If future power usage is unacceptable he chooses a suitable control action.

(ii) When the control variables are not within limits he checks whether a compensatory furnace stage change will eliminate the error. If there is no such event a suitable furnace is selected for a control action.

A large part of both activities is concerned with prediction, again demonstrating the anticipatory behaviour of the human operator in a control task.

1.1.3 General descriptions of control behaviour

To summarise the rather specific examples considered so far, some general descriptions of the human operator's activity in control tasks will be presented. Crossman (1960) suggests that decision making is the central feature of control skill, i.e. reviewing the possible control actions, their consequences and selecting the best for the given circumstance by predicting the consequences of each. Kitchin and Graham (1961) define control as requiring the operator to judge fluctuations within and outside acceptable limits and to decide on the necessary corrective action. Daniel, Puffler and Strizenec (1971) identify the following components of control skill, perception, prediction, and decision making. Kelley (1968) probably gives the most general and comprehensive description of the control activity:

(i) Goal conception - prediction of possible future states of the control variable

(ii) Goal selection - planning the desired future state of the control variable by choosing from the range of possible actions.

(iii) Programming the sequence of events in the environment required to bring the desired state about.

(iv) Carrying out the programmed sequence.

1.1.4 Conclusions

It is clear from this survey that the main feature of human behaviour in a control task, independent of the control system is open loop control, the ability to predict the future state of the control variable and then to be able to select a suitable compensatory action.

It is common, according to Kelley (op cit), for control literature to state that control systems function to reduce differences between input and output. This does not seem to be generally the case with the human controller, he has the ability to foresee future events and react to those, rather than being bound by the current state of affairs alone.

1.2 Development of the control skill

The last section showed the main features of the control activity, this section will deal with the small amount of evidence related to the development of that activity.

1.2.1 Changes in the control skill due to learning

Kelley (1968) suggests that learning a control skill consists largely of the human operator building an internal model by which prediction is made and that adaptation is the appropriate modification of the model when the control situation changes. This contention seems to be supported by Kragt and Landeweerd's (op cit) finding that during the initial stages of the experimental sessions subjects followed the temperature closely, a manifestation of 'closed' loop behaviour. Later, subjects behaved in an 'open' loop fashion. The open loop behaviour can be assumed to have developed through the subjects' experience with the experimental situation. Bainbridge (1975) gives more detail on this matter. Inexperienced controllers on the power demand task, at first used feedback (closed) loop control, i.e. changes in the process were unexpected and dealt with after the event. More experienced controllers predicted and anticipated these changes, exhibiting a form of feedforward control. With increased knowledge of the process dynamics the controllers made more accurate predictions about the effects of actions or events on future states. Data from Cooke's (1965) protocols indicate that subjects probably learned about the water bath experiment by forming hypotheses to explain its behaviour and generating strategies to direct the course of action.

1.2.2 Effects of type of training

Once a control skill has been learned the operator may not always find it easy to transfer to another control task even if it is similar. West and Clark (1974) using a distillation column, found that experienced operators (five years experience with the plant) seemed to have a fixed idea of how to handle a situation independent of the experimental condition (different displays) in the initial learning stage, however, later they gradually adapted their method of implementation to the display system available. This seems to reinforce an observation made by Crossman (1960), that operators cannot transfer from one process to another without relearning,the skill is specific to the situation in which it was acquired. Crossman and Cooke (1962) did, however, find quite good transfer from a difficult to an easy version of the water bath, showing that on the same basic task it is possible to influence skill development. They also found that the experimental group who did the easy followed by the difficult task, performed better on some trials than the group who did the difficult task on all trials. The results of an experiment by Duncan (1974), although concerning troubleshooting, indicates that the method of training can affect transfer and retention of a skill. He found that a group of subjects who developed their own plan of troubleshooting performed better on the two criteria (retention and transfer) than a group who were trained using a decision tree. Both Crossman and Cooke (1962) in the water bath experiment, and Kragt and Landeweerd (1974) in the air mixer task, found that groups of subjects given a scientific account of the apparatus did not perform better than those subjects given no information, in fact the informed group in the water bath task did markedly worse than the uninformed group. Brigham and Laios (1975) in the 'leaky cans' experiment found, however, that instructions about plant dynamics and structure, improved performance, although not significantly. Attwood (1970) also found that if paper machine operators were taught about the system and shown what plant responses were like, they could improve their performance. Thus the findings of Crossman and Cooke and Kragt and Landeweerd tend to argue against the need for physical understanding of the process in developing a control skill; the findings of Brigham and Laios and Attwood seem to show that relevant information can assist in such development. Brigham and Laios have commented on the conflict of results and suggest that the water bath and air mixer were simple systems and detailed information about them was superfluous. This may well be the case, the feature of the water bath and air mixer was complex response dynamics, if the subjects had been given information on plant response, as in Attwood's study, the results may have been different. This suggests that any information given to trainees should be on the key features of the process.

1.2.3 Conclusion

It is apparent that, as Kelley (1968) proposed, development of a control skill depends on the internal model the human operator builds through experience and interaction with the control system, i.e. the development of open loop control. It also seems that control skills do not transfer to other processes, equally it seems that initial training can affect the learning process, and the level and efficiency of final performance.

1.3 Individual differences and control performance

In this and the next section factors affecting control performance will be reviewed. In this section the concern will be with individual differences and the effect on performance, in the next the effect of environmental factors on control performance will be considered. It is realised that environmental and individual factors cannot be considered in isolation, as there is continual interaction between the two. However, for the sake of clarity the two are discussed separately.

1.3.1 Evidence on individual differences

Spencer (1962) investigated operator differences on a liquid washing plant. The aim was to discover the extent of individual differences and whether comparisons between good and poor operators would reveal the critical features of the particular process skill. Differences were found but they only occurred under abnormal conditions, consequently it was not possible for a proper investigation and the results were inconclusive. Cooke (1965) investigated the performance of limited intelligence subjects on the water bath task. Results showed that the subjects could not control the system adequately, not apparently through the failure to understand the objectives of the task but through an inability to form the correct strategy. They did not appear to realise the importance of trying to find a control setting rather than making a change. Attwood (1970) found that the stuffgate operators in the paper mill knew the stuffgate changes needed for various basis weights, but their figures and allowances differed materially between individuals. There is no indication however, of how this difference in knowledge affected performance. West and Clark (1974) observed variations between individual controllers by the types of strategy employed. Results indicated, as mentioned in the previous section, that individual operators used strategies developed from past experience. Unfortunately here again no real indication of the effect of strategy on performance is presented. They do conclude however, that variability of results is due to many outside factors influencing the operator's performance. Beishon (1966) had a similar problem with the water bath experiment. He found that individual differences accounted for much wider variation in performance than the experimental conditions. Sperandio (1971) made an interesting discovery regarding individual differences in a simulated Air Traffic Control task. He found that agreement over landing sequences between individuals varied depending on traffic density. The relationship is not as might be expected. Agreement is high at low traffic density and also high at high density, but low when density is middling. The explanation given is that at low density direct routings are available, at middle density there are more degrees of freedom, and at high density standard procedures are employed.

Bainbridge (1974) in comparing performance on the power demand task found several reasons for variations in performance. Some subjects were limited in their ability to use data flexibly, i.e. data gathered for one purpose and then required for another purpose had to be gathered again. Other subjects were poor performers, not because of an inability to think about the task, but because having chosen a suitable action were unable to commit themselves to make it.

1.3.2 Conclusion

Certain points emerge from this section. With in-plant studies difficulties arise in trying to relate individual strategies to performance, because of the small number of experienced operators available, the problem of trying to reproduce plant conditions, and often the difficulty in selecting suitable performance indicators. Simulated tasks have had more success. The result of Sperandio's indicates that there are differences in strategies between individuals, and that variations in an individual's strategy are due to changes in task demand, a finding dealt with in detail by Bainbridge (1974a). The results of Bainbridge (1974), although only preliminary, suggest a possible type of limitation in an individual's thought processes, and a type of personality with an inability to commission an action. This last finding might have relevance for the selection of process control operators. The general conclusion must be that individual differences are important in process control and that these differences may be identified with differences in personality, cognitive development, and level of skill.

1.4 Task factors and control performance

Three aspects will be considered in this section:

(i) type of information and how it is displayed

(ii) devices that help the operator understand system dynamics, ie predictor displays

(iii) task demand.

1.4.1 Types of information display

Cooke (1965) conducted several experiments to investigate the effects of displayed information on performance in the water bath task. He found that (a) No scale on the thermometer depressed performance, whereas provision of a control setting scale enhanced performance, allowing subjects to use previous satisfactory control settings. (b) Restricting the availability of information by varying possible sampling intervals only depressed performance when the sampling interval was increased beyond one minute. However, up to one minute meaningful control actions were made, indicating that subjects must predict future temperature values. West and Clark (op cit) also conducted a series of experiments investigating different types of display. There were three main findings:

(i) Loss of analogue chart recorders did not have as big an effect on performance as might be expected. They were most useful when changing to a new operating point.

(ii) Various rates of display of information on a teleprinter were tried. It was found that there was little difference between a two and a four minute log, but performance deteriorated at faster rates.

(iii) Digital displays were found to be subject to errors in reading.

Beishon (1966) in a study of papermachine operators found that poor control actions were due in part to inadequate displays. For example, with one gauge two operators thought a division equalled one unit and one thought it half a unit. Another attribute of poor performance was the failure of operators to take into account the effects of transient changes in weight due to water valve or slice adjustments. Attwood (1970) in a similar study of papermachine operators also found that the operators did not allow enough time for a control action to take full effect. A similar result was obtained by Attwood in a lab study using a task similar to the water bath apparatus of Crossman and Cooke (op cit) except that the exponential was replaced by a time-velocity lag. Performance was improved by only allowing a control action every five minutes thus ensuring that the full effect of the previous action had passed through the system. Crossman, Cooke and Beishon (1964) conducted a series of experiments and field studies to investigate the sampling phenomenon more thoroughly. They found that the sampling behaviour of operators in a papermill and subjects in the water bath experiment could be predicted with some success by the bandwidth of the variable being controlled. It seems the operators/subjects sample a variable so that they build up a 'picture' of the way the variable changes. The situation is complicated however, by other factors which also affect sampling behaviour, and Crossman et al suggest that a more detailed analysis is required of the factors contributing to operator uncertainty, its rate of growth over time, and the cost attached to sampling. Brigham and Laios (1975) have investigated the effect of providing intermediate information, instructions, chart recorders, and the records of an automatic controller, on performance. Results showed that intermediate information, (i.e. the subjects could actually watch the process) resulted in improved performance, and intermediate information and instructions gave the best overall performance, superior even to that of an automatic controller.

The availability of the chart recorder, (historical data), had practically no effect. Observation of the automatic controller performance, enabled subjects to perform almost as well as the instruction-information group, except when they departed from the controller's trajectory, then performance deteriorated. The subjects appeared not to have developed a satisfactory model of the plant and were unable to control it effectively outside a limited range of conditions. The authors conclude that the human operator's anticipatory model enables him to use the information about intermediate variables within the plant, whereas the automatic controller was only able to make use of the plant input and output. The subjects, however, were unable to give a detailed description of the way they used the intermediate information.

The results of this discussion on information presentation indicate

(i) the need for information to be displayed unambiguously with clearly marked scales.

(ii) Chart recorders seem to be useful for detecting an instrument malfunction, Anyakora and Lees (1972), and obtaining a quick impression of how a plant is responding but not for fine adjustments.

(iii) The most important finding is that operators need to develop an 'idea' of how a controlled variable will behave and that to do this successfully the operator needs information on the dynamic functioning of the process he is controlling.

1.4.2 Predictor displays

Several attempts have been made recently to assist the operator with the problem of understanding the complex interrelationships between variables. Smith and Crabtree (1975) provided subjects engaged in a scheduling task with a predictive facility. Comparison of performance levels between a control and experimental group favoured the prediction group. However, the solution seeking strategies of the experimental group were relatively unaffected by the predictive facility. Ketteringham and O'Brien (1974) provided soaking pit operators with a predictive display in a simulation of the real task. Tentative results indicated an improvement in performance. Kelley (1968) describes several applications of predictive displays. He claims that a novice can in 10 minutes or less learn to operate a complex and difficult control system as well as highly skilled operators using standard displays. The reason he gives for this is that an operator must spend many months learning the dynamics of the system. The operator with a predictor knows from the start what his system will do. An experiment by Rouse (1970) with predictive displays in ATC, qualifies Kelley's statements. The experiment showed that predictive aids were beneficial only in tasks of medium difficulty: for easy tasks they are unnecessary, for difficult tasks the controller becomes overloaded and responds intuitively, ignoring the aid.

1.4.3 Task demand

Sperandio (1971) as described in 1.3 found that Air Traffic Controllers varied their strategies depending on task demand. According to Cooke (1965) certain tasks do not permit high level processes to consider and evaluate each decision that is made. For example he conducted an experiment using an electric analogue of the water bath, but running 100 times faster. Results showed that a group with a temperature scale performed no better than a no-scale group. It seemed that the time pressure did not allow the scale group to take advantage of additional information. Bainbridge (1975) in the power demand task found that subjects would often have two methods of finding a data value. She suggests that the quicker less accurate methods would be employed when there is a time pressure, hence producing a deterioration in performance. Beishon (1966) has shown the importance of developing efficient strategies in an experiment using water tanks. The provision of a memory aid did not improve subjects performance. Analysis of protocols indicated that the way the subjects tackled the task and the strategies employed seemed to be the major determinants of performance. Bainbridge (1974a) has summarised some relevant work on task demand. She concludes that the strategy used by an operator is adapted to task demands so that task performance increases with task demands for constant mental work. The strategy used is adapted so the amount of mental work matches mental capacity. If there is no strategy which matches both task demands and capacity then performance deteriorates.

1.4.4 Conclusion

The discussion in this section reveals two requirements for satisfactory control performances:

(i) The operator must have enough knowledge about the process dynamics to select a suitable control action, e.g. size of action, and to be able to anticipate system uncertainty, e.g. time taken for control action to take effect in the papermachine.

(ii) The operator needs a repertoire of control strategies to adapt to variations in task demand.

1.5 Structure of operator behaviour

The preceding sections have been concerned with characteristics of control activity, development of control skill, differences between individuals, and factors affecting performance. The underlying feature of these previous sections is the ability of the human controller to anticipate: it distinguishes a good from a bad, a skilled from an unskilled, and a human from an automatic* controller. In the following two sections a more detailed examination of control behaviour will be attempted. This section will consider evidence on the organisation of control behaviour. The next section will discuss the models, processes and mechanisms postulated by various workers to explain observed behaviour.

In the following discussion the activities that make up an operator's control behaviour, and in particular the relationships between the activities will be examined. The activities tend to be task specific, the organisation of these activities to achieve a particular goal, less so. It may therefore be possible, through the study of the behaviour structure, to make more generalised statements about cognitive behaviour in different tasks.

1.5.1 Structure of behaviour in different tasks

Kelley (1968) has made a general statement about the organisation of the control activity, which will serve as an introduction. Human control activity is organised around the selection and pursuit of goals. Analysis of these goals shows that they tend to be organised into hierarchical structures, with those nearer in time leading toward the more remote. Some important features about goals are, (i) there may be several routes to the same goal, and (ii) choice of route is a goal selection process in itself.

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*Three term controller, i.e. feedback of terms proportional to error, derivative of error, integral of error.

Cooke (1965) summarising the results of protocol data obtained in the water bath task, postulates a hierarchical structure of activities. The relationship between the different levels however, is not that between a superordinate and subordinate in the computer sense but more like that between a good manager and his assistants. Rasmussen and Jensen (1974) studied the mental procedures of skilled electronics repairmen by analysis of verbal protocols. The procedures found were organised as search through a system which is viewed as a hierarchy of subunits. The general structure of the search was broken down into a sequence of search routines which were used to identify the appropriate subsystem, stage, or component. They also found that routines were used independently of goals, e.g. in the check measurements routine; of 75 total, 45% were used to confirm a reference to the location of the fault, 30% to confirm a hypothesis, and 20% as individual measurements in an overall topographic search. Smith and Crabtree (1975) identified two main categories of behaviour from their protocol analysis of subjects in the scheduling task. These were planning, and operational decision making. Planning they defined as behaviour directed towards the organisation of a framework, acquired from experience, that would predict the system requirements over the course of the experiment and guide all decision actions. Operational decisions were related to moment to moment considerations that were not possible to resolve at the planning stage. Unfortunately they only give a brief description of their analysis so that it is not possible to discover any more details of the planning behaviour. They do comment, however, that statements in the protocol referring to the planning structure are more 'fuzzy' seeming to be poorly comprehended or verbalised by the subjects. Beishon (1969) in a study of ovenmen baking cakes also found evidence of an advanced planning routine which was concerned with organising the ovenman's activity over a half hour or hour period. A feature of this advance planning is the apparent arbitrary way an ovenman will jump from one routine to another and frequently a routine will not be carried through to completion without interruption. The routines mentioned here are sections of protocol which are clearly purposive and goal directed.

The most detailed analysis of operator behaviour has been Bainbridge's study of the protocol of a subject doing the power demand task (first reference Bainbridge et al 1969). A brief description of the aspects of her work relevant to the present discussion is given below and is based on Bainbridge (1972) and (1975). Her analysis describes behaviour as a goal orientated branching structure. Four levels of organisation are identified, 'overall' sequence, other or lower sequences, routines, and the lowest level operations. The routine is the basic unit and consists of a set of instructions or operations, i.e. basic cognitive processes, which are involved in finding a data item (goal). The sequence level determines when and how a routine occurs, and the 'overall' sequence level determines which general type of behaviour or main sequence is used. The organisation of the behaviour is not hierarchical.The reason for this demonstrates why it is difficult to identify the levels in any real behaviour, and why a hierarchy is an inadequate description of behaviour. The key to these limitations lies in the lack of unique links between goals (data items) and routines for implementing them; it was shown in the last section that an operator may have several methods of achieving the same goal. Consequently if goals are free to call on any routine, then a particular routine may be called on by any of these levels, so that its own level can only be defined in relation to a particular context not in general. The result is that it is not possible to draw a unique or 'tree' type of description.

1.5.2 Conclusion

It seems that goals are organised in some sort of hierarchy, that is, behaviour is organised at several levels of complexity, e.g. Bainbridge (1975) described four. Whether it is a strict hierarchy in the sense that it can be represented as a tree structure, seems unlikely according to the findings of Cooke, and Bainbridge. The main reason is that a goal can be achieved by several means, or a particular routine can be used to achieve several different goals. For example, basic operations such as adding and subtracting can be used for a variety of purposes. At a more specific level Rasmussen's electricians used the same search routine for three different purposes. In the same way the goal of crossing a road may be fulfilled by a different series of sub-goals and actions every time this has to be done. The essence of the behaviour is adaptability, the same thing is never done exactly the same way twice. It is this flexibility of behaviour that is important, and why Beishon, Bainbridge, and Smith and Crabtree suggest a planning routine which will select goals and choose the best way of achieving them. Verbal evidence for planning routines is scant. Smith and Crabtree (1975) indicate that verbalisations about the planning stage were 'fuzzy' and poorly comprehended. Bainbridge (1974) comments that protocols contain very few phrases describing an operator's strategy, and although she succeeded in describing how most of the observed behaviour was determined, a mechanism was still required in certain cases to choose an appropriate routine. Beishon (1969) has suggested that this lack of evidence for planning behaviour is because it is done in anticipation of events, and hence activities seem to be carried out for reasons that might not be apparent from the current situation. On the other hand it might be proposed that some planning and choice behaviour is not easily accessible to consciousness. The next section will be concerned in more detail with this executive function and the mechanisms and processes used to model observed control behaviour.

1.6 Models of the Process Controller

Most of the models described in this section are of the information processing type. Bainbridge (1975) exemplifies the rationale of this approach when she states that her protocols were analysed by the usual method of attempting to develop programmes which would produce the same sequence of behaviour as in the protocols. This approach originates from the pioneering work of Newell, Shaw and Simon (1958) and their elements of a theory of human problem solving.

1.6.1 Models of subjects' behaviour in the water bath task

Cooke (1965) examined the problems of modelling the behaviour of subjects doing the water bath task. It was clear from his work and the results of Crossman and Cooke (1962), that attempting to predict subjects behaviour from a linear feedback system was inadequate. A second approach was the use of a system state model. Skilled decisions depend on a number of factors which affect decisions and the number of alternative decisions that can be made. The model suggests that each of these relevant factors is judged or classified into one of a limited number of factor states. Any conjunction of the possible states of each factor can be called a 'system state', and the model suggests that a given decision alternative is associated with a particular system state. An experiment was conducted where subjects developed their own system state diagrams and used them as a set of operating rules. Results indicated that subjects did not make their decision rules in the way suggested by the model. Cooke concluded that it was a performance model, more adapted to representing well practised decision situations than tasks in which the subject's experience was limited. The model could not account for learning, memory or prediction. Beishon (1966) has also criticised control theory approaches because they are 'black box' by nature, and pay little attention to the processes inside the box. Crossman and Cooke's (1962) answer to this problem was to suggest that, if it is not possible to find out how a subject solves a problem by asking him, a mechanism can be constructed to solve the same problem. By invoking Turing's criterion, performance of the mechanism may be regarded, to a first order approximation, as a valid representation of the human behaviour. By using protocol techniques it is possible to get some idea of how the human solves problems thus improving the authenticity of the explanatory mechanism. However, as has been demonstrated in the previous section, there are still types of behaviour where there is no direct (verbal) evidence of how they occur.

On the basis of his experimental and protocol data, Cooke (op cit) proposed an information processing (I.P.) model that would produce the observed control behaviour. The model consists of mechanisms representing, an internal model, the generation of hypotheses, strategies, and tactics. It is apparent from the experimental results (already reviewed), that a human must possess an internal model of the world around him to anticipate some of the future happenings. The water bath protocol provides several instances of prediction, (a) simple extrapolation, (b) reasoned out effects of control changes, (c) prediction of future control changes, (d) hypothetical prediction of control or temperature changes. The last three categories are best explained by postulating an internal model. Predictions about future effects of different control settings involves knowing when something will happen and a dynamic model is necessary. There was also evidence from the protocols to show that hypotheses were formed to explain the behaviour of the water bath although there was no evidence to show how these were formulated. Thus the internal model represents the observed relationships, and the hypotheses explain them. While hypotheses are formed to explain the observed behaviour of a process, it is suggested that strategies may be generated from a particular hypothesis to direct a course of action, i.e. a plan of action. Tactics are then required to implement the course of action directed by a given strategy. The strategy can be thought of as establishing goals and sub-goals. The tactics can be considered as devising the means to achieve the various goals. It is important to note that the level of tactical activity was inferred as a necessary mediation between strategy and response, as it was rarely discussed in the protocols. The description of Cooke's model given here is only brief, he does give descriptions of the mechanisms required to operationalise the concepts mentioned. In assessing the validity of the model he remarks that the need for the internal model and mechanisms to form hypotheses, strategies and tactics was clearly shown. Less certain were the deductions made about levels of operation and parallel autonomous operations of the major elements. A major difficulty,Cooke suggests, with such a complex theory is the need to test its predictive capabilities, the theory presented here is intended to represent functionally the decision making mechanisms of an individual rather than normative behaviour.

1.6.2 Model of an Ovenman's behaviour

Beishon (1969) has presented an I.P. model of the ovenman's behaviour. Analysis of observations, interviews and protocols, indicated that there were a number of routines for dealing with different phases of the task. In most cases a body of facts was associated with each routine an needed to enable a particular routine to function. For example, for each cake type there was a preferred baking time and temperature profiles. This suggested that the ovenman had a number of look up tables in memory store to which he had access. For several reasons the two components, routine and look up table were not sufficient to account for all the behaviour of the ovenman. A single routine was not always followed through continuously, a new routine was often started before the current one had finished. There were also external events which could interrupt a current routine and which had to be dealt with before the original routine could be resumed. Jumps from a completed routine to the next were difficult to account for. In some cases the progression was virtually dictated by the process, as when a batch of cakes arrived, which the ovenman had been expecting. In other cases even the ovenman could not give a clear cut reason for a choice of activity. As was mentioned in the last section, this indicates an 'advance planning' routine or executive which is conerned with organising his activity. The fact that the sequence of routines is not entirely directed by external events suggests that the executive routine is concerned with handling and resolving the often conflicting demands placed upon the ovenman by the process demands. The executive routine responsibilities can be set out as follows:

1. Entering and retrieving call-ups for future entry to specific routines
2. Handling externally-initiated interrupts.
3. Searching through future expectancies for anticipatory activities.
4. Keeping and updating a list of activities to be done next.

The main responsibility is 4., this is composed of routines from the main procedure, and activities associated with interrupts and anticipations. To test this model Beishon has suggested an alternative to developing a computer program, it is called the 'control game'. It is similar in concept to the Turing test. It involves presenting a novice with the task, and giving him the model to follow to see whether he will achieve a performance similar to that of an experienced man. The objection to developing a suitable computer program is that perceptual judgement required in many of the routines could not be incorporated in a computer program.

1.6.3 Model of behaviour in the maximum demand task

The most detailed analysis and subsequent model of a process operator has been due to Bainbridge's investigation of subjects' behaviour in the simulated power demand task.

Two approaches were used in the initial attempt to get at the underlying decision processes employed by subjects, Bainbridge et al (1968). The first approach was the action/information tree model. The basis for this model is that subjects have a prescribed set of aims to fulfil, and associated with these aims a set of possible actions or action strategies. The resulting structure shows that for certain decisions the operator has to travel much further down the information tree than for others.

These should take much longer to process, and be more critical when there is time pressure. The verbal protocols obtained from the subjects revealed that they did not follow a continuous path down a tree structure. The second approach was a program model similar, though less sophisticated than those of Newell and Simon (1963). With this approach several routines dealing with component parts of the task were identified. There were two main drawbacks with this approach:

(i) An executive which selects a particular routine is required at a particular time and this can be complicated.

(ii) Another limitation is that although subjects use routines, they vary the way they use them.

Bainbridge (1975) gives the most recent and detailed account of the concepts she has evolved to overcome these problems. These concepts have been specifically developed to model the flexibility and parsimony of the protocol data. Most important, it was found that the behaviour could be modelled by making the use of working storage in the routines explicit. In this descriptive technique the routine is centred round the data item required, which is named as its 'head box'. The data item is presented in three parts, item's name, location or 'box' for storing present value, and a link to the routine(s) by which the value can be found. This contrasts with the rigid traditional method of description, in which the aim or data required is not named until the end. The present technique is particularly useful because the same sequence of operations may be used for several purposes, e.g. obtaining similar data items in different parts of the task. The independence of routine and purpose allows one routine to be called from several data value storage points, or one of these points to call on several different methods of finding the same value. This provides a mechanism for flexible behaviour. Parsimonious behaviour can be provided by only repeating a sequence of behaviour when the head box is empty.

The number of routines identified in the protocol was about 12, and these found the values of a dozen main items. With these basic units distinguished the variables determining the sequence in which they occur can be identified. These variables can then be described by flow diagrams employing conditional statements. The conditional statements describe the decisions between alternative behaviours. About five different sequencing diagrams were developed from the conditional statements, and these determine the routines to use when the control error is acceptable or unacceptable. The sequencing diagram is a level of organisation above the routines, as the sequencing determines how the routines are used.

Two types of working storage were needed in the diagrams to describe the task. Temporary storage, for data items found in a routine and used again later in the same routine. Longer term, 'cross referenced', storage for data values which are found during one routine and made use of during another. All temporary storage occurred within the routines level of organisation. Cross referenced data items were mostly from within the sequencing level. Although this relation between level of organisation and durability of storage is an empirical finding, it is necessary for any I.P. organisation in which routines are independent of the purpose for which they are used. For example, data values found in one use of a routine are not necessarily relevant the next time the routine is used; and data values relevant to a particular purpose must be stored separately from the routine to avoid loss or confusion.

The flow diagrams described above represent the controller's knowledge of appropriate information processing operations. Besides this knowledge the controller must know about the static, and dynamic characteristics of the furnace process. The former is his knowledge of data and relationships in the task, of process characteristics. The latter is the temporary storage of the items which are relevant at a particular time. The static and dynamic knowledge taken together could be identified as the controller's 'mental model' of the external world. The values in this knowledge could be the data value representations referred to by the pointers from the storage locations in the routines and sequences. The working storage data or 'mental picture' would be the subset of these possible values which actually exist at a particular time. The pointers from the storage location to these values would be links between program and mental model. Bainbridge has mentioned however, that the distinction between program and data is not as clear as may be implied from the description given above. The distinction may be an artefact of the technique used here to describe cognitive activity. The fact that there are similarities between distinct routines and sections of protocol that do not match, might imply that the controller has a general structure of knowledge about the process and the operations that he can carry out. It seems possible that from this general structure of knowledge the controller can generate sequences of behaviour for a particular purpose. The consistently repeated sequences of behaviour identified as routines, might appear because the same circumstances recur and the response to them becomes over-learned.

Most of the sequences of activity can be determined by decision points in the routines, for example at the 'overall' sequence level, the order in which activities were done was determined by the acceptability of the control error. However, two types of executive function or decision making must be superimposed on the flow diagrams besides the sequencing mechanisms already described. One is the mechanism for dealing with external interrupts. The other is concerned with the decision between alternative behaviours implicit in the 'head box' mechanism. The head box mechanism may point to several routines for finding necessary data, either by analogue or digital means. The decision which to use provides a speed accuracy trade-off in information processing. To postulate the existence of such a decision mechanism it would be necessary to identify points at which analogue rather than digital routines were used. Unfortunately rigorous evidence is difficult to obtain, as the controllers did not usually comment on this aspect of their behaviour.

1.6.4 Conclusions

The models described in this section show an increase in sophistication and detail. Cooke's formulation although based on protocol and experimental data from the water bath, is rather general in nature. He seems to have used the evidence of the different types of activity observed in the protocol as a basis for a model of human behaviour that would learn to control processes besides the water bath. The later models of behaviour are less general and attempt to model the observed behaviour of the operators more exactly. Beishon's model describes the basic acitivites (routines) of the ovenman, but postulates a fairly complex executive to organise these activities for which there is unfortunately little direct evidence. Bainbridge's model seems to have been more successful in accounting for the operators behaviour (she claims in fact to have accounted for 80% of the protocol data, the others make no claims). This is due mainly to the more detailed analysis and the emphasis on the importance of goals (data items) in representing the observed flexibility and parsimony of human behaviour. However, it is not so much the type of technique employed to describe this behaviour that is important in her analysis, but the realisation, through the use of these mechanisms, of how skilled behaviour seems to be organised. Bainbridge (1972) however discusses some of the shortcomings of her technique when considering their application to other cognitive tasks. For example, she is not confident that the techniques are sufficient, to cope with the complexity of Beishon's ovenmen's task, to account for any hierarchy of goals, to choose between behaviour at interrupts, or for scheduling future activities. Bainbridge (1975a) indicates that a considerable amount of research is needed into the details of operator's methods of thinking about future activities, particularly in control tasks in which plans for the future interact with the state of the process and its control requirements. The more able an operator is at predicting future events and process behaviour, the more adaptive his control. This suggests that to obtain a further understanding of a skilled operator's behaviour it will be necessary to specify more fully the general structure and organisation of his knowledge about the task. This may pose some intractable problems for existing methods of collecting and analysing data from cognitive tasks.

1.7 Verbal protocol as a viable source of data

Most detailed evidence on cognitive behaviour reviewed here and elsewhere (see for example Newell and Simon, 1972) is obtained from the verbal reports of subjects and operator as they think aloud about the task they are doing. Although this method has become more accepted in recent years for investigating thought processes, it still has many pitfalls. As the verbal protocol technique has become such an important tool in analysing cognitive behaviour an assessment of its drawbacks is essential for a realistic interpretation of data gathered by the method.

1.7.1 The relation of thought to language

Newell and Simon (op cit) paraphrase Dewey (1910) regarding this problem. They state:

(i) The surface structure of language and language strings, are the garb of thought necessary not for thought, but for conveying it.

(ii) While linguistic deep structure is not thought it is necessary for thinking.

They also assert that language must be essential to thinking, otherwise one would have to postulate a distinct set of deep structures holding the meanings of the surface structures carried in parallel with non-linguistic representatives: an unparsimonious arrangement. Vygotsky

(1962) expresses a similar point of view when he suggests that thought and speech unite into verbal thought through word meaning. However he goes on to say that verbal thought does not necessarily include all forms of thought or all forms of speech. Piaget has maintained,Flavell (1963), that language is a symptom of underlying intellectual orientation. Some recent experimental findings seem to endorse this view. For example Youniss, Furth and Ross (1971) were able to train deaf children in the use of logical symbols. The outcome of the experiment was taken to support Piaget, and to be critical of those theories that suggest that the employment of logical symbols stems from linguistic structures. Ferreiro and Sinclair (1971) are of a similar opinion, and state that language will not explain thought but that it is cognitive operations that will provide a basis for explaining language. Whorf (1956) on the other hand from his comparisons of different languages, has made the controversial suggestion that language not only gives us the means of ordering the environment but it causes us to order the environment in differing ways. There is a considerable divergence of opinion on this subject.

Herriot (1970) has commented that the present condition of the field of language and thought is utterly confused. Jenkins (1969) however, has successfully summarised the situation. He has suggested a combination of all the main points of view, i.e. that thought is dependent on language, thought is language,and language is dependent on thought.

1.7.2 Applications of the protocol technique

In the light of the preceding discussion the practical problems associated with interpreting protocol data should be easier to appreciate.

Several workers who have used the technique have not been able to obtain very full reports from subjects on certain types of task. Crossman and Cooke (1962) were not able to extract much information from the subjects' protocols obtained in the water bath experiment, except to show that there was little conscious decision making in connection with control changes. Brigham and Laios (1975) in the leaky cans experiment found that subjects were unable to give a detailed description of the way they used information. Cooke (1965) has suggested that a lack of verbalisation does not necessarily indicate unawareness. In his series of water bath experiments subjects in their verbalisations seemed to select different items for comment at different times, in an apparently unpredictable way. The technique has, however, been used with some success. Rasmussen and Jensen (1974) used verbal protocols to successfully analyse the mental procedures used by skilled electronics repairmen . Leplat and Bisseret (1966) have used verbal data to investigate the behaviour of Air Traffic Controllers. They make several criticisms about the method. They suggest that real thought processes may be distorted when the controller endeavours to become aware of them. More difficult processes are less likely to be reported than easy ones; this may be expected from secondary task experiments. It is also possible that the controller will only give the approved or formal description of how to do the task. Finally it cannot be certain how exactly the controller's explanations represent his actual thinking. Bisseret and Girard (1973) also investigating Air Traffic Controllers comment that it is difficult to analyse elementary operations. They found that when they attempted to question controllers for increased details of their thought processes, the controllers resented this as they were not certain of the validity of their explanations, their more detailed thoughts being apparently subconscious. Bainbridge (1972) endorses some of the criticisms of Leplat and Bisseret (op cit) particularly with regard to the use of interviews. She suggests that using this technique of obtaining verbal data allows the operator to structure his replies in a way which does not truly represent his knowledge of the task. The use of protocols instead of interviews helps to overcome this problem. Subjects seem to make little comment about strategy, most of the protocol is statement of fact. It is also possible to check the validity of some of these statements by cross checking with performance data. In the power demand task described by Bainbridge data from the protocol was checked with the computer log and this indicated that the protocol was a valid source of data. There is also evidence that verbalising can affect the efficacy of certain types of thinking. Gagné and Smith (1962) found that subjects required to verbalise while practising a problem solving task,facilitated both the discovery of general principles,and their employment in solving problems. It seems unlikely, however, that this would happen with skilled operators.

1.7.3 Valid uses of the protocol technique

Although there are many problems with the protocol technique, all techniques are fallible, as Radford (1974) maintains "infallibility of method does not exist in science". In this context it is important to consider suitable uses for the technique. Dennett (1968) has maintained that the trouble with using verbal protocols is the idea that a model of human information processing can be proved or disproved on the grounds of strict comparison between protocol and machine trace. He argues instead that protocols are the best source of hypotheses available about how a task is done. Bainbridge (1972) concurs, and suggests that at the present stage of understanding cognitive tasks, collecting examples and making suggestions is all that can realistically be achieved. This approach has received support from certain radical theoreticians who have questioned the current conduct of 'scientific' psychology. Jordan (1968) has argued that the importance of predictability in present day psychology is de-humanising. He suggests that there are sciences, which do not entail prediction, but have instead developed techniques for checking the correctness of their statements. Here, statement means a statement about a state of affairs which is expressed logically, and checking means making the logic explicit, and verifying that the logic has been used correctly. Thus non-predictive sciences such as geology can classify the phenomena that interest it into sets defined by general properties, a logical operation par excellence. If psychology chose to adopt this approach, he suggests that its main task would be the careful observation of specific behaviour or actions of people.

Recently Hutt and Hutt (1970) have in fact adopted such an approach in their attempt to show that an objective quantitative descriptive science of behaviour is viable. Their procedures have been based on descriptive methods of classification borrowed from ethologists.

In the light of the above discussion it is submitted that verbal protocols, together with a suitable descriptive analysis, e.g. Hutt and Hutt or Bainbridge, constitute a potentially useful method of analysing cognitive behaviour.

1.8 Summary

The review of the literature on process control in this chapter reveals the following:

(i) The underlying characteristic of the human controller is his ability to predict.

(ii) As a skill develops there is evidence of more open loop (predictive) control behaviour.

(iii) Control skills do not seem to be easily transferable, but types of training can affect learning and final performance of a control skill.

(iv) Comparison of individual differences on in-plant studies can be difficult because of the problem of reproducing similar task conditions.

(v) Individual differences can be identified with different personalities, stages of cognitive development, and level of skill

(vi) The requirements for satisfactory control performance include knowledge about the process dynamics, so that a suitable control action can be selected, and the ability to anticipate system uncertainty.

(vii) The controller requires a repertoire of strategies to adapt to task demands.

(viii) Behaviour seems to be organised around a series of goals, with a variety of routes to the same goal.

(ix) There seems to be a lack of evidence for planning routines which might be responsible for organising control behaviour.

(x) By separating purpose from method and making working storage explicit, Bainbridge (1975) has succeeded in modelling some of the flexibility and parsimony characteristic of skilled behaviour.

(xi) Inadequacies of Bainbridge's model suggest that more needs to be known about the structure and extent of an operator's task knowledge

(xii) At the present descriptive stage of analysing cognitive tasks, verbal protocol as a method of collecting data seems adequate, in default of other satisfactory sources of data.

In the following chapters a series of experiments and field studies are conducted into the skills required by operators to control the supply of gas and electricity on a regional grid system, using verbal protocols as the chief source of data. The results of the investigations are intended to, provide more evidence about individual differences, skill development, the structure of behaviour in control tasks, and to elucidate some of the problems of modelling cognitive behaviour.

CHAPTER 2

This chapter describes:

1. The gas supply and transmission system.
2. Requirements of the control task.
3. Personnel arrangements in the control room.

The purpose of the investigation was to obtain sufficient information about the Grid Controllers' behaviour to test the possibility of carrying out a more detailed study using verbal protocol techniques. In particular it was hoped to compare different controllers' behaviour and examine associated differences in performance.

The results of the investigation give a detailed description of controller behaviour with evidence of differences between individuals. It was concluded that a more detailed study using verbal protocol techniques would be worthwhile.

2. PRELIMINARY GAS GRID CONTROL FIELD STUDY

This chapter describes an initial study of the task of grid control at the West Midlands Gas, Regional Headquarters, Solihull. The investigation of this particular task was chosen for a number of reasons, some relating to the conclusions made in the previous chapter.

(i) The task of a grid controller had not been studied previously.

(ii) It is a complex control task.

(iii) Efficient performance of the task can affect the community in terms of the safety and cost of gas supply.

(iv) Computer assistance was introduced just prior to the proposed investigation.

(v) There was the possibility of comparing the performance of individual grid controllers.

(vi) Most important, the management and grid controllers were prepared to take part in an investigation of the grid control task.

2.1 Gas transmission and distribution

In this section a description of the distribution and transmission system will be given, and also an outline of task requirements and personnel arrangements.

2.1.1 Description of the transmission and control systems:

Historically three phases can be distinguished in the development of bulk transmission systems. In the first phase gas was produced from coal at low pressure and transferred to the customer, firstly by holder pressure and then by mechanical compression. Information required to operate this system could be sent from manned stations to a central point via telephone. In the second phase the production of high pressure gas enabled the integration of several existing systems by mechanical pumping. The result was a reduction in the number of input points to the system and an increase in remotely controlled injection points (governor stations) to feed local areas. The industry adopted telemetry (via GPO wires or microwave) to obtain information about the state of the system, and where desirable to initiate actions. The third and present phase was due to the discovery of North Sea gas, and opened the way for a National System of bulk supply. The result has been the integration of regional systems with the National system. Although a central control room at Hinckley is responsible for overall supply of gas to the country, regions also have control rooms which are responsible for the supply and distribution of gas in their own area. Control of these integrated systems has become too complex for manual optimisation and the data handling, so that in recent years regions have introduced computers to assist in the control of gas supplies.

At the time of the investigation (1973) the West Midlands had two distinct supply systems: Manufactured Gas (MG) and Natural Gas (NG). (As conversion to NG has proceeded the MG system has gradually disappeared over the intervening years.) NG is available from the National Transmission System at pressures up to 1000 lbf/in^2 (70 bar), MG is available from reforming plants at up to 300 lbf/in^2 (20 bar). Gas is supplied at about 10 ins water gauge (25-30 mbar), so that considerable pressure reduction takes place. As much as possible of the energy available in high pressure gas should be used for transmission

PLATE I WEST MIDLAND GAS CENTRAL CONTROL ROOM

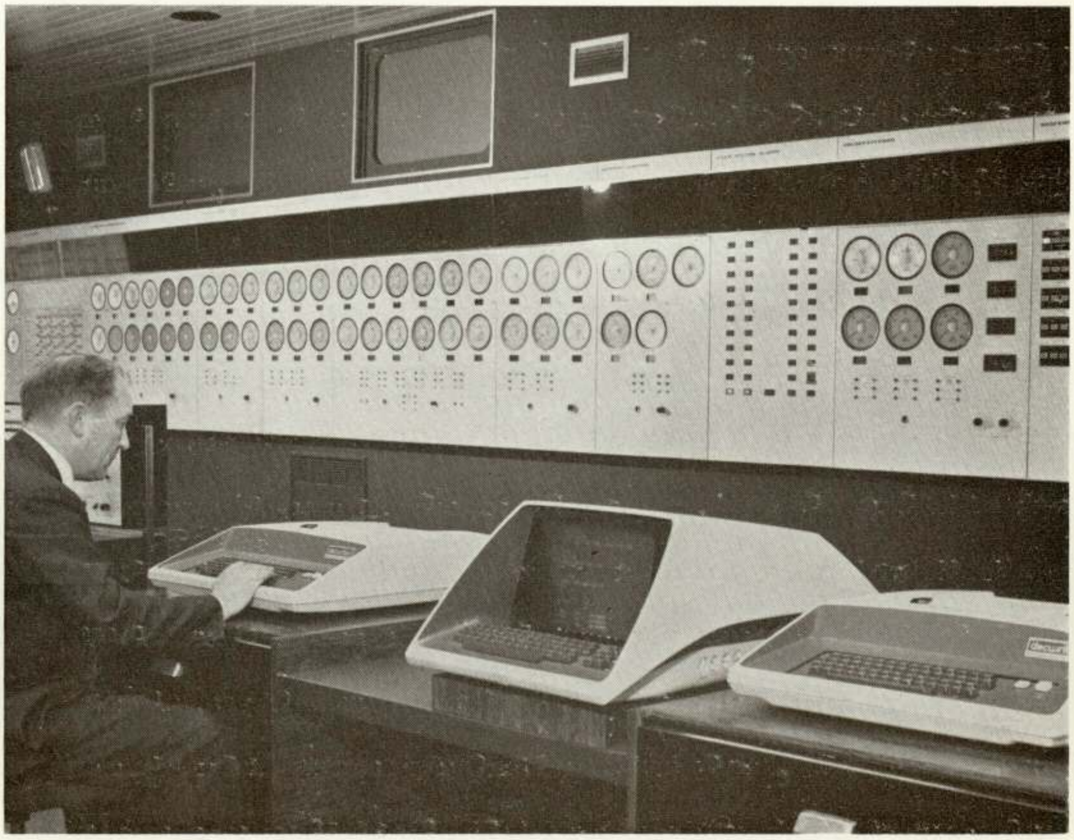
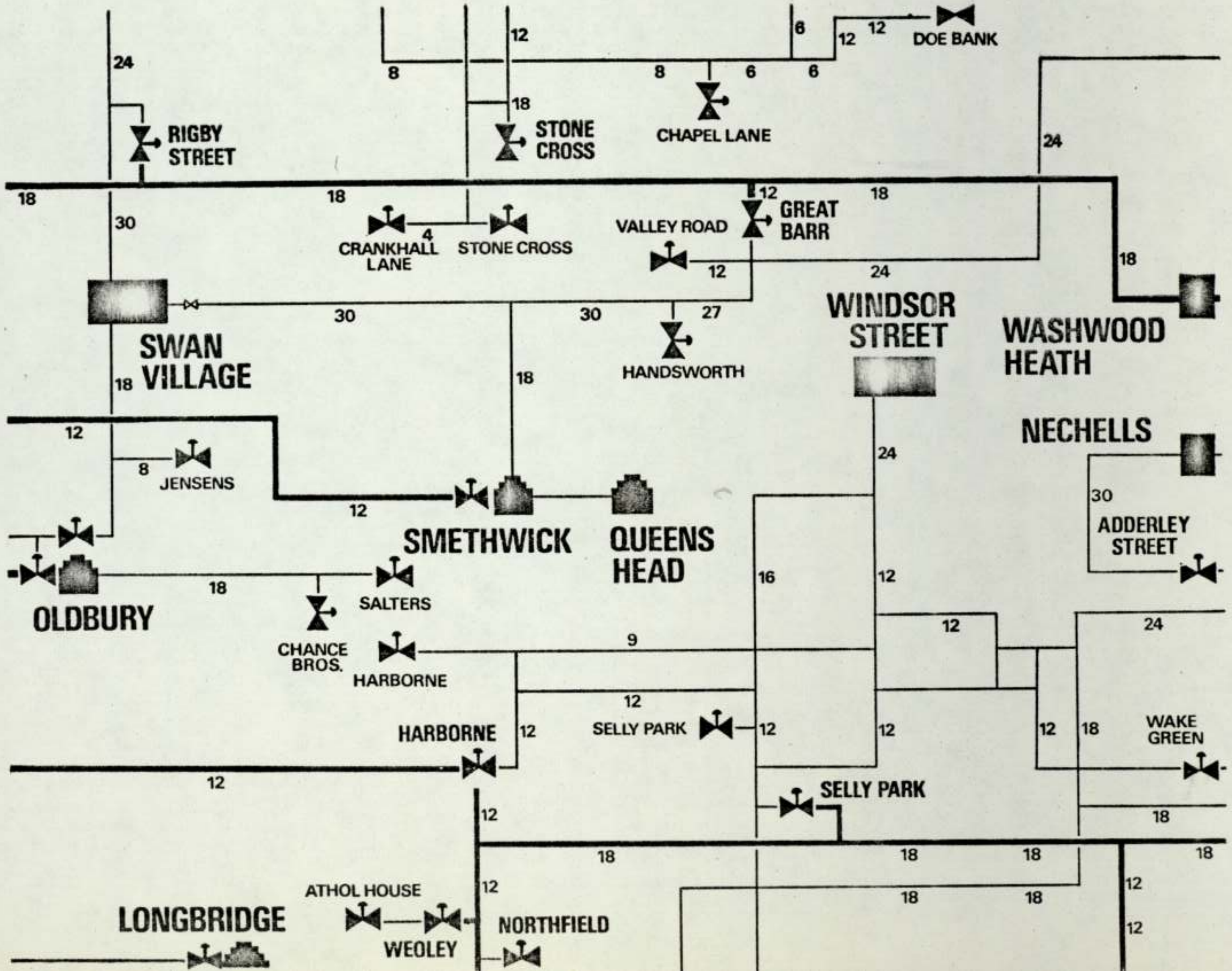


PLATE II THE INFORMATION PROCESSOR CONTROL DESK purposes rather than rejected as heat and noise. In particular it is desirable to store gas at the highest pressure possible prior to releasing to the distribution system operating at the lower pressures.

The control system is based on a Serck Controls Ltd. telemetry system, which comprises alarm scanning, monitoring selective station displays, routine data logging and remote control. The telemetry system is linked to a PDP-15 computer running under RSX which stands for Real-time Systems Executive. The computer examines 500 readings every hour, and these 500 measurements are sufficient to describe the state of the supply and distribution systems. The computer records the 500 readings in an "as now" data base, which can be accessed by visual display. The computer also monitors a microwave net-work scanning 1,000 potential alarm conditions from unmanned stations, every half second. The system further provides forward predictions of short term demand, and data for a model simulating future states of the distribution network. Telemetry data about this stage of individual governor stations can be monitored through self-selecting multi-purpose wall displays (see Plate I for a view of the control room). The computer communicates via dec-writers (DEC line printers), and a visual display unit installed in the control room (see Plate II). Beside these dynamic information sources, there is also a schematic layout of the whole of the regions' distribution system, Fig. 2.1 shows a detail from this layout. Communication with manned plants and stations can be conducted through ordinary telephone and Telex lines. Fig 2.2 shows an input-output model of the grid control task with various information sources, channels of communication, and lines of control.

FIGURE 2.1



Schematic layout of part of the Board's distribution system.

Fig. 2.2 INPUT-OUTPUT MODEL OF THE GRID CONTROL TASK

INFORMATION INPUT			INFORMATION OUTPUT
Source	Channel		Source and channel same as for Input. Lines of control shown
Offline			
1. Senior management	Written/mouth		
2. Gas Corporation, Hinckley & London	Telephone		Same Channel
3. Grid and distribution engineers	Telephone or Written		Same Channel
Online			
1. Production works	Telex, telephone	OPERATOR	Indirect control
2. Holder stations	Telex, telephone		Indirect control
3. Telemetry outstations (pressures and flows)	Telecoms		Direct control
↳ COMPUTER PROCESSING	Line printer VDU Teletype		
4. Weather	Observation Telephone		
5. Pressures and flows for NG Control Rugby & Barlaston	Data reduction Computer		Direct control

NB All the information sources and channels can be reversed to pass information but only those indicated in the Information Output column are concerned with controlling the system, and identify the control loops that the operator closes.

2.1.2 Requirements of the Grid Control task

The main objective of grid control is to supply gas as cheaply and as safely as possible. The simplest and most effective way of achieving this is to maintain NG and MG input to the distribution systems constant, and to allow gas held in storage to meet the hourly fluctuations in demand. Fig. 2.3 and 2.4 show respectively, variations in gas demand, and stock level over a 24 hour period. The process of grid control necessary to satisfy these requirements can be outlined as:

(a) estimating demand

(b) arranging that gas input is available

(c) utilising the energy available in the input to the maximum extent

(d) verifying that input and output remain in balance and making necessary adjustments.

(a) Accurate demand forecasting is probably the most crucial feature of supply control. At the beginning of the day (06.00 hours) an initial prediction is made using the expected average temperature in conjunction with records of previous years demand. Each hour after this the computer presents an estimate based on an empirical formula utilising information from the same day the previous week. The controller also has to make his own judgement about the effect of humidity, wind, national holidays etc.

(b) Having estimated demand, the quantity of gas required can be calculated as, estimate of demand + (required closing stock - opening stock). Dividing by 24 hours gives the average hourly input. With MG this rate will be arranged with the production plant. With NG this

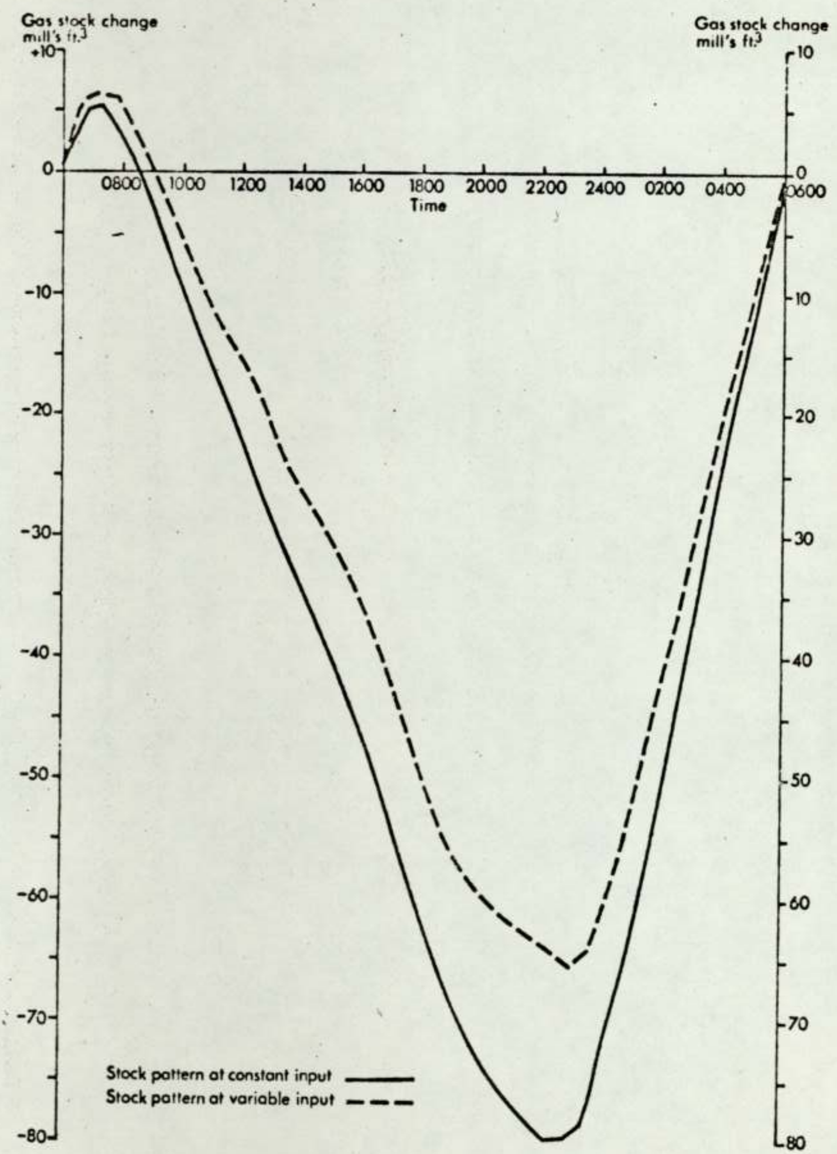


Fig. 2.4 GAS STOCK PATTERNS IN AN AREA BOARD SYSTEM
TOTAL GAS SALES 600 MILL'S FT.^{3}/DAY

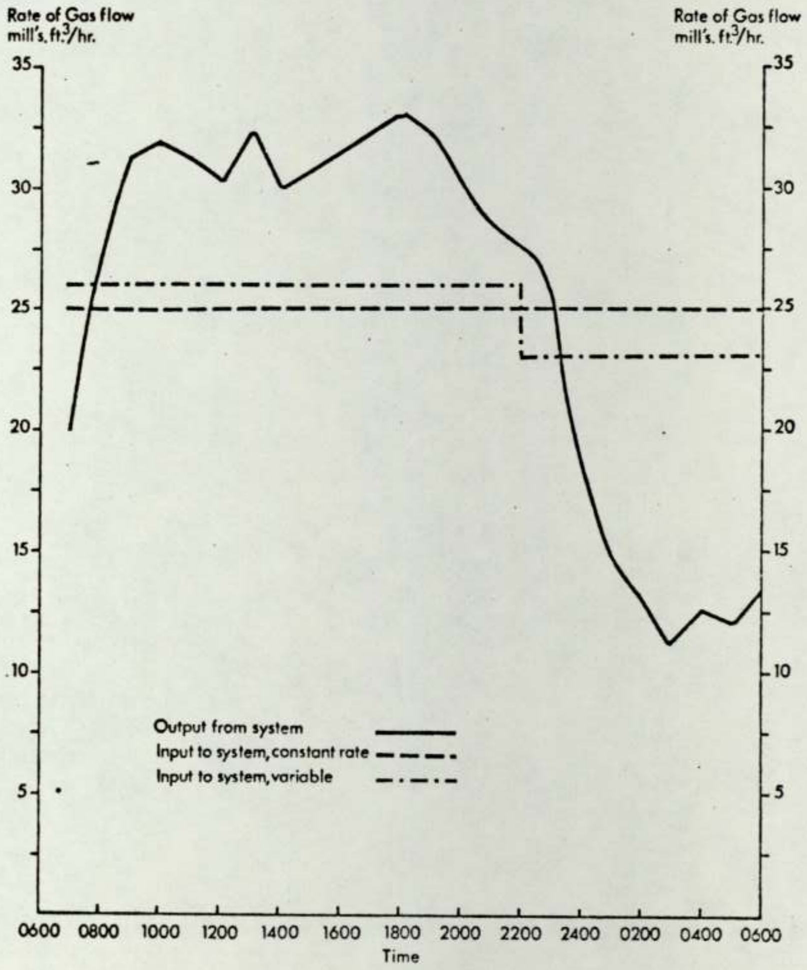


Fig. 2.3 GAS OUTPUT FROM AND INPUT TO
AN AREA BOARD GRID SYSTEM
TOTAL GAS SALES 600 MILL'S FT.^{3}/DAY

has to be negotiated with National Control, since there are restrictions on the size of change permitted at any one time. It is usually preferable to keep the input constant, but depending on hour to hour conditions it may be necessary to vary the input.

(c) Energy is required to transmit gas along the grid network to the customer. Provision of external energy by compression is expensive, consequently it is important that as much use of the pressure energy of the gas is made in distribution. At the same time maximum use must be made of available storage, which means that in practice some gas will have to be extracted from low pressure holders.

(d) The grid controller cannot assume that his initial forecast is correct and as indicated in (a) this forecast is continually updated. He must therefore ensure that overall input and output are in balance. The method is to calculate the expected closing stock based on present demand forecast, and compare this with the desired closing stock. The computer makes this calculation every hour and presents the relevant information along with the demand estimate as in (a). It is then up to the controller to adjust input if necessary. In the case of MG this is not usually difficult as the production plants are fairly flexible. However, with NG there is a restriction which will only allow the controller to alter the input rate by 5% of the current rate at any one time. Four hours notice is required for the first change of the day, subsequent changes require two hours notice.

2.1.3 Personnel arrangements

To meet the requirements of grid control three shifts of three engineers man the system round the clock. Each of the three engineers on a shift has a particular responsibility. The senior engineer is the Grid controller, he has overall responsibility for supply and distribution to the system, which includes liaison with Gas Corporation and other regions; he also has to make an assessment of supply and maintenance priorities. He is supported by an Assistant controller who also controls supply and distribution to the system but under the direction of the Grid controller. The third person on the shift is the Shift operator. He is required to operate the computer information system, answer routine phone calls, log relevant data, and do any 'housework' necessary. A particular feature of the personnel arrangements for grid control is that the Grid controllers were trained to write their own programs for the computer and were responsible for commissioning the system. This has the advantage that it permits the controllers to present the data they require in a format that is most satisfactory. In the event of a computer crash or unforeseen program error there is always someone on duty who has intimate knowledge of the system software and is in a position to rectify the problem. Also as a result of the controllers' experience with the system they can be continually modifying and improving the system. The Assistant controllers have not been trained as computer programmers, their experience with the distribution system however, is greater than the controllers, as the latter were brought in especially for the introduction of the computer system. Most of the Assistant controllers on the other hand have been responsible for control under the original manual system, unlike the Grid controllers. Both groups, controllers and their assistants require each others co-operation for successful operation of the system, and to date this seems to have presented no problems. Qualifications of the Grid controllers were of HND or degree level, plus several years experience in the gas industry.

2.2 A preliminary study of the Grid controllers' behaviour

The main purpose of the study was to identify the types of behaviour the grid controllers exhibited as they maintained control of the grid system. This first objective was dependent on the second objective, which was to develop a suitable method of recording and reporting relevant data. Finally it was hypothesised from the conclusions in Chapter 1 that prediction, and decision making would be fundamental to grid control.

2.2.1 Method of collecting data

Several weeks were spent talking to the five Grid controllers; Assistant controllers and Shift operators were not included in the preliminary study. Investigations were restricted to the most senior person on a shift. During this time it was possible to obtain the confidence of each controller, appreciate the principles of the task, and to formulate a method of investigation. Control of gas supplies is a discrete process, the grid controller is not continually involved in manipulating the system. This permits the controller's activity to be investigated by recording his transactions with the system. Although it is fairly simple to observe the controller's communications with the system and ask for a retrospective explanation, there are obviously many occasions when the controller thinks about the task but does nothing. To overcome this problem it is necessary to explain to the controller that all his behaviour and in particular his thought processes are of relevance. Considerable co-operation from the controller is required for this to work effectively, and as with all verbal data techniques it can never be certain whether the controller is giving away all his secrets. It also has the added disadvantage of being retrospective (see Section 1.7.2). It may be argued that the verbal protocol techniques should have been employed. There are however several objections:

(i) Two of the controllers were not prepared to be tape-recorded.

(ii) Protocols are better for more detailed investigations, at this stage only preliminary data was required to direct further investigations should this first enquiry prove successful.

(iii) This method enables the investigator to learn more about the task by being on the spot asking questions.

(iv) Should a protocol analysis be required later it ensures that the controllers understand what is required of them, and have practice in introspection and explanation. Fortunately a good rapport was developed with the controllers and they found it relatively easy to explain what they were doing and thinking.

Procedure:

It was decided to record the behaviour of each controller throughout a whole shift. To try to control against the effects of different sales patterns on different days of the week and at different times of the day, investigations were carried out on the same day of the week (Thursday), for five consecutive weeks (each week with a different controller), on the afternoon shift (1400 - 2200 hours). A practice session was run with each controller the day before the assigned day. Each indication of controller interaction with the system and any reported thought processes were recorded as events with the approximate time of occurrence.

2.2.2 Discussion of results

Initial analysis:

The basic data were the records of events taken from each of the five shifts. Events were classified into routine and non-routine categories. Routine events refer to the review made by the controller of the updated information presented by the computer each hour. This hourly information is presented in MG and NG summary and sendout summary displays (see Appendix 2.1). Events were further classified into those involving control decision, and these were further subdivided into those that led to a control action. Finally any actions other than control actions, i.e. maintenance etc. were noted. Fig. 2.5 shows an example of the classification of events for one of the controllers. Table 2.1 indicates that routine events vary between 8 and 13 for the five controllers, theoretically they should be the same (between 8 and 9), as the computer information is only updated once an hour. The discrepancy could be due to inaccuracy in data collection or an indication that the assistant controller might have dealt with some of the routine work. The most likely explanation is that the controller sampled the computer information more than once in an hour. When this is taken into account events only vary between 8 and 9 for four of the controllers. Controller 1 has six recorded events, it seems that either he never consulted the computer information on two hours of the shift or the recording technique failed to pick them up.

Fig. 2.5

Event	Approx time	Routine	Non Routine	Poss.C-Decision	C-Actions	Other Actions
1	14.00	✓(s+h)		✓		
2	14.25	✓(h)		✓	✓	
3	14.44		✓			✓
4	14.49	✓(s)				✓
5	15.22	✓(h)		✓	✓	
6	15.27		✓			
7	15.33		✓			
8	15.40		✓			✓
9	15.59		✓	✓	✓	
10	16.06		✓	✓	✓	
11	16.07	✓(s)				
12	16.15		✓	✓	✓	
13	16.16	✓(h)		✓	✓	
14	16.48		✓			
15	17.13	✓(h)		✓		
16	18.18	✓(h)		✓		
17	19.08		✓	✓	✓	
18	19.15	✓(h)		✓		
19	20.04		✓			
20	20.30	✓(h)		✓		
21	21.16	✓(h)		✓		
TOTAL			10	13	7	3

s = shift routine

h = hourly

TABLE 2.1 CLASSIFICATION OF EVENTS FOR THE 5 GRID CONTROLLS

	CLASSIFICATION OF EVENTS					
Controllers	Routine	Non Routine	Control Decision	Control Actions	Other Actions	Number of Events
1	8	10	10	2	12	18
2	13	7	14	6	8	20
3	11	10	13	7	3	21
4	12	10	10	3	8	22
5	11	17	21	9	5	28
TOTAL	55	54	68	27	26	109

There are also variations in the number of control decisions and actions recorded for the controllers. This is most likely due to the difference in demand conditions between the various days on which the recordings were made. For example, Controller 5 was on duty a month later than No. 1, at a time of year, September, when sendouts* start to move towards winter loads.

Analysis of types of event:

It was decided to restrict the more detailed analysis of events to those concerned with control decisions, as they appeared to be the fundamental part of the control activity. No control actions were evident without some kind of decision process. The method of analysis was to find common patterns of control behaviour for a particular individual and to compare them with those from other controllers.

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*Appendix 2.1 provides a glossary of gas control and other related terms.

In 68% of decisions that resulted in a control action the following four stages of behaviour were identified:

(1) Obtaining information from the system (wall displays, computer etc.)

(2) Deciding if a control action was necessary

(3) If yes to (2) deciding what suitable action could be taken

(4) The control action.

Fig. 2.6 compares examples of routine control decisions for the 5 controllers and how the descriptions of behaviour identify with the four stages mentioned above.

Discussion of stages (1) and (4)

By counting references to different types of information and different types of control action it is possible to compare input and output aspects for the controllers. Table 2.2 (a condensed version of Table 2.3) shows the three major sources of information and the number of times they were sampled by the controller in a shift. It is clear that there is a significant difference in the number of times the information sources are sampled. There is also a significant difference in the amount of information used by the controllers. Controller 5 uses three times as much information as controller 1. Table 2.3 shows in more detail the sources of information, and particularly that wall display sampling is a feature of non routine decision making. It also shows that when all the information sources are taken into consideration there is no significant difference between the controllers. It does show, however, that there is considerable difference between controllers in their use of information in non-routine events, and that in particular this difference is due to the use of wall displays by

Figure 2.6 COMPARISON OF MG, ROUTINE CONTROL DECISIONS

	CONTROLLERS					
	1	2	3	4	5	Similarities
	14.00	15.00	16.00	18.00	14.00	
STAGE 1	MG figs, handover sheet	MG Summary	MG figs, wall displays previous records	MG figs, of production summary	MG figs, of previous days data	
STAGE 2	If sendout increases and is also high tomorrow, will require a high make. If the decision to do this is left until later, may not be able to maintain stock with max. production	Summary suggests a drop of 0.5mft^3/hr. Total <u>input</u> is expected to be 130mft^3. The sendout calculated by the morning shift was 135mft^3. The hourly estimate is 123mft^3. Expects sendout to be 127mft^3, so will ignore -0.5mft^3/hr change, which is based on the (123mft^3) figure.	Cumulative sendout shows 14mft^3 up on yesterday. This confirms that sendout could be above 155mft^3, hourly est shows 160mft^3. Weather is expected to be warmer tonight so do not expect the 160m. Grid is coming down quickly even at 16.00 hrs, this confirms the possible 10mft^3/hr sendout for the next 4 hrs.	Sendout hourly estimate = 160mft^3 0.8mft^3/hr above required rate for stock at 6.00. Will not leave until later, since tea almost over, no increase in sendout expected (ie reasonable weather forecast). An action left until later may be too drastic. Will reduce production.	Hourly estimate gives 210 mft^3 sendout, compared with 196 mft^3 for a comparable day. Today 82·7mft^3 has been sold, at an hourly rate of 9.8 mft compared with the similar day when 78.6mft^3 had been sold at 14.00 hrs, at a rate of 9.2m/hr. i.e. an increase of 0.6m/hr. Over 16 hrs this increase gives 9.6m, 4m extra has been sold to 14.00hrs, expected overall increase over the similar day = 13.6mft^3. This satisfies him that 210mft^3 is a reasonable estimate. On the basis of the 210mft^3 estimate the 14.00 hr figures recommend 0.13mft^3/hr drop in production to 75mft^3 stock. He decides to make no changes, and will wait to see how things develop. Furthermore smallest economic production change at the moment is 1b/air = 0.25mft^3/hr	All except 1 evaluate the estimated sendout. 3 and 5 do this by referring to past records. 4 accepts the 160m ft^3 estimate. 2 is not explicit about his 127mft^3. 1 is cautious and bases his control strategy on the worst outcome likely. Weather forecast is probably the most important single factor in evaluating sendout estimate.
STAGE 3	All high pressure works are flat out + Windsor St. and a ballast air m/c at Coleshill. The only increase in production available is 1 ballast air m/c at Tipton 0.5 mft^3/hr. Ballast air put on.	No change	Second ballast air at Tipton committed to max. production. Because of high tea time load, going to take gas out of W-H holders	Production summary shows Tipton & Coleshill have high load factors (100%). Reduce the outputs of these by 0.3mft^3/hr & 0.2mft^3/hr each. Their load factors will now be 80% along with Washwood Heath, the most economical value.		Control actions seem to be based on what is available and/or the most economical way of controlling the system.
STAGE 4						

TABLE 2.2 FREQUENCY OF INFORMATION SAMPLES FROM THE 3 MAIN SOURCES INVOLVED IN CONTROL DECISIONS

	INFORMATION SOURCE			
Controllers	Computer	Wall Display	Previous Records	†Total
1	8	-	-	$8^{(15.6)}$
2	9	4	2	$15^{(15.6)}$
3	8	7	2	$17^{(15.6)}$
4	8	3	-	$11^{(15.6)}$
5	8	15	4	$27^{(15.6)}$
TOTAL*	$41^{(26)}$	$29^{(26)}$	$8^{(26)}$	78

*(a) Difference in frequency of information sampled from the 3 sources $X^2 = 21.46$ $p<0.001$

+(b) Difference in frequency of information sampled by the controllers $X^2 = 13.54$ $p<0.01$

Null hypothesis in (a), information sampled from each source should be the same.

Null hypothesis in (b), information sampled by each controller should be the same.

Controller 5. As mentioned earlier the effects of individual differences and task demand are always confounded in an investigation of this nature. However, it does seem likely that the considerable difference between controller 5 and the rest could be attributable to individual differences. This assertion is supported by the fact that controller 5 was the only one of the five to have been an assistant controller, and so would be

TABLE 2.3 DETAILS OF THE INFORMATION SAMPLED BY THE CONTROLLERS

	COMPUTER VDU						VARIOUS SOURCES					WALL DISPLAYS				$^{+}$TOTALS	
	MG			NG													
Controllers	Send & Sum	Stock Details	Prod. Details	Send & Sum	Stock Details	Intake Details	Verbal	Phone	F/c	Past Records	D.R.C.	Grid Press Flow	Grid Press Flow	Gover.	Holders	Total	Non-Routine
1	8	1	1	8	1	1	(1)	(1)	-	-	1	-	-	-	-	23	2
2	9	-	-	9	3	-	1(1)	-	-	2	3	1(1)	1(1)	-	-	32	3
3	8	1	-	8	1	-	-	1	2	2	-	-	4(3)	-	-	30	3
4	8	1	2	8	4	1	-	(1)	-	-	3	1	2	-	-	31	1
5	8	(1)	-	8	1	-	-	-	2	4	(3)	(5)	(3)	-	1(1)	42	18
TOTAL	41	4(1)	[illegible]	41	10		3(2)	3(2)	4	6	10(3)	8(6)	14(7)	(3)	2	158	27

(Figures in brackets non-routine events)

Key: Send & Sum - Sendout summary, and Summary displays
Prod. - Production details, i.e. state of production plant
F/c - Weather forecast
D.R.C. - Data reduction computer, used only for controlling NG offtake valves on the National Grid
Gover. - Governors, valves that control pressures

$^{+}$(a) For total information sampled by the controllers $X^2 = 5.86$, $p<0.05$
Based on the null hypothesis that each controller samples the same amount of information
(b) For total non-routine information sampled by the controllers $X^2 = 37.25$, $p<0.001$

more familiar with wall displays as these are closely connected with distribution control. This suggestion is supported by the evidence from Table 2.4 which shows that all controller 5's actions are non-routine and that he is the only controller to have been recorded adjusting governor pressures. It is difficult however, to draw any other unequivocal conclusions from Table 2.4 about individual differences.

TABLE 2.4 FREQUENCY OF DIFFERENT TYPES OF CONTROL ACTION

	MG							NG		GOVER.	
				HOLDERS							
Controllers	Prod	B/A	BUT	in	comp.	jet	stop	R	B		TOTAL
1	-	1	-	-	-	-	-	-	1	-	2
2	-	-	-	-	1	-	-	4(1)	3(1)	-	8(2)
3	-	3(1)	1	1(1)	-	-	1(1)	-	-	-	6(3)
4	2	-	1	-	-	-	-	2	1	-	6
5	-	-	-	-	-	1(1)	2(1)	2(2)	3(3)	3(3)	(11)
TOTAL	2	4(1)	2	1(1)	1	1(1)	3(2)	8(3)	8(4)	3(3)	33(11)

(Figures in brackets non-routine actions)

Key: Prod - Production
B/A - Ballast Air
BUT - Butane enrichment
in - Gas into holder
comp. - Gas out of holders by compression
jet - Gas out of holders by jet booster
R - Rugby offtake from National Grid
B - Darlaston offtake from National Grid

Stages (2) and (3):

These two stages describe the intervening processing between information receiving (stage (1)) and information transmission (stage (4)). In stage (2) the controller predicts the behaviour of the system some time in the future. The time scale of these predictions seems to vary, depending on whether a routine or non-routine event is being dealt with in the control behaviour. A routine event with the necessary, Summary, and Sendout Summary displays is aimed at predicting total sendout, and the input rate required to meet this and the closing stock. A non-routine event is more likely to be concerned with maintaining pressures at desirable levels.

The net result however, of behaviour observed in stage (2) is a prediction of the likely state of the system, or part of the system at a time t in the future, and a decision whether the predicted state at time t is acceptable. If the system state is going to be unacceptable a suitable control action has to be arranged, stage (3). For MG routine events this is usually achieved by varying production, which entails choosing one or more of the three reformer plants to change output. The decision of which to choose is usually based on maintaining economic load factor on all plants. For NG, control can only be effected by two off-takes from the National Grid.

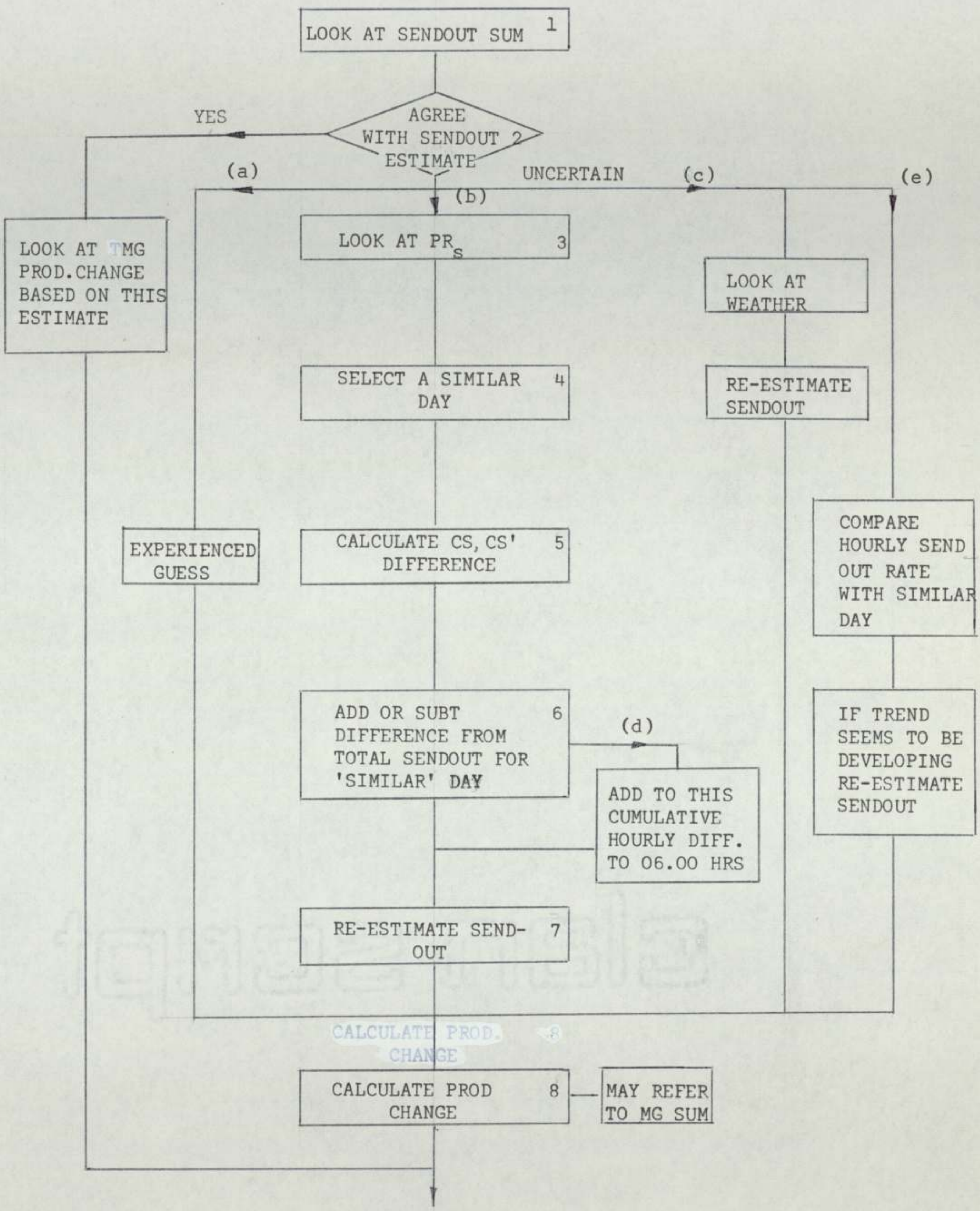
Non-routine control actions are not normally concerned with supplying gas to the system, but ensuring that gas is distributed economically throughout the system. The control actions are usually aimed at maintaining suitable pressure throughout the network. This is done in the main by using buffer storage to take gas into or out of the distribution system. The process is complicated and undertaken by the assistant controller. The behaviour descriptions here are therefore limited.

The description of control behaviour for stage (2) and (3) has only been general. To produce a more detailed description from the available data a means of clearly representing control behaviour is required. The technique employed here is a conventional information flow diagram Figs. 2.7 - 2.10. Alternative methods of obtaining a certain result are shown by additional loops (a), (b) ..... etc. A description of the general methods used by the 5 controllers is given below with evidence from recorded explanations.

The control decision for MG routine events is chosen here as this is the most complicated. Details of NG flow diagrams are similar to MG, and are therefore not shown. The behaviour for the 5 controllers in stages (2) and (3) breaks into three parts. Closer analysis of stage (2) indicates the existence of two sub-stages; this is because predicting system behaviour i.e. estimating sendout, and deciding if a control change is necessary seem to be independent activities. The simplest way to explain the flow diagram and related processes is to consider the description of a control decision given by one of the controllers, and show how this translates into the relevant diagram. For example controller 3, Fig. 2.6.

His first statement is "Cumulative sendouts show 14 mft^3 up on yesterday". This indicates that he has looked at the Sendout Summary, box 1, in Fig. 2.7. It shows that he is comparing todays cumulative sendout with yesterdays. This suggests that he might be uncertain about the computer estimate, box 2, and is looking for further information about likely sendout. He takes branch (b), looks at the previous records, and selects a similar day, in this case yesterday, box 3 and 4. In

Fig. 2.7 MG SENDOUT ESTIMATION



box 5 he calculates that 14 mft^3 more gas has been sold at 1600 hours than the same time yesterday. The next statement is "This confirms that sendout could be above 155 mft^3, hourly estimate shows 160 mft^3 for the day". The 14 mft^3 calculated in box 5, has been added to yesterday's final sendout, which was 130 mft^3, (the 130 mft^3 comes from references to final sendout in other events, although not explicit in this one), giving 144 mft^3 box 6. There are still 14 hours to go until 0600 hours, so he appears to allow 11 mft^3 for this period, and re-estimates sendout at 155 mft^3 or more, box 7. He quotes the 160 mft^3 computer estimate as a comparison, and this is considered as part of the process in box 7, as he is probably using the information to assist him in re-estimating. the next statement, "Weather is expected to be warmer tonight, so do not expect the 160 mft^3", shows that he is still not satisfied about re-estimating and so carries out the procedures in loop (c), the result makes him suspect the 160 mft^3. and accept the 155 mft^3. He does not explicitly calculate the required production change. The last statement says "Grid coming down quickly even at 1600 hours, this confirms the possible 10 mft^3/hr sendout for the next 4 hours." This is difficult to deal with; he has looked at the supergrid, and uses the information to predict the hourly sendout for the following 4 hours. It is uncertain whether he uses this in confirming his estimated sendout of 155 mft^3 or to estimate the likely state of the grid, (grid refers to the high pressure main which is supplied by the three production plants), over the next 4 hours. This statement is ambiguous and has therefore been omitted from the diagram.

In stage (2i) and (3), Figs 2.8 and 2.9, the first statement is "second ballast air at Tipton, committed to maximum production." It

Fig. 2.8 CONSIDERING WHETHER AN ACTION IS NECESSARY

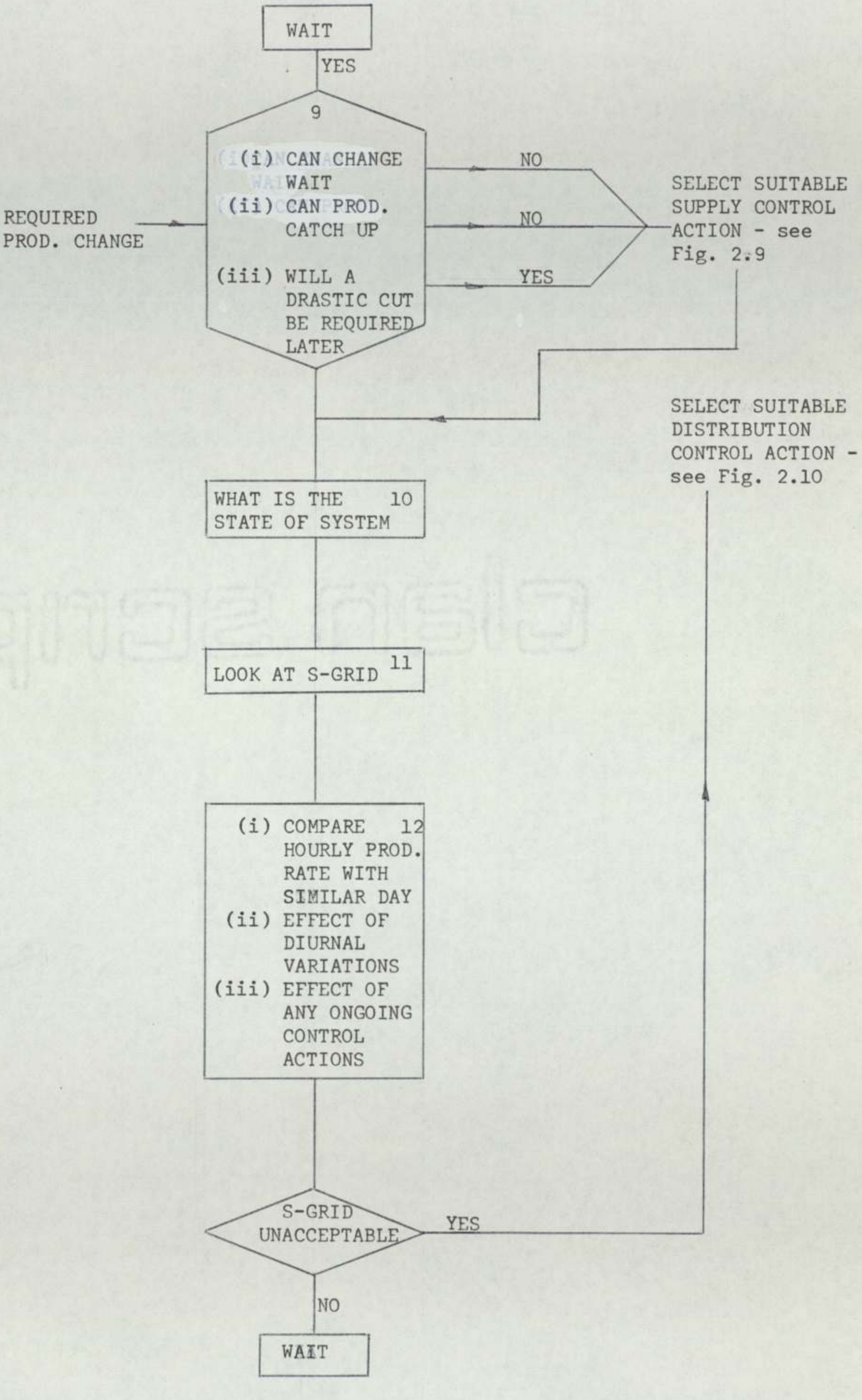
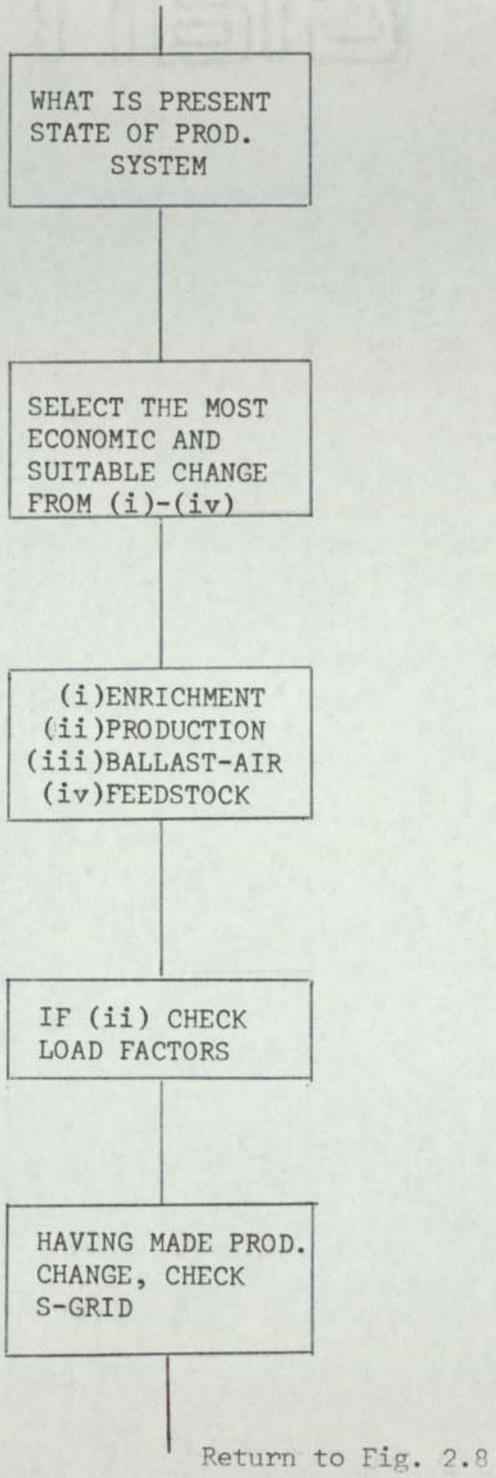


Fig. 2.9 SELECTING A SUPPLY CONTROL ACTION

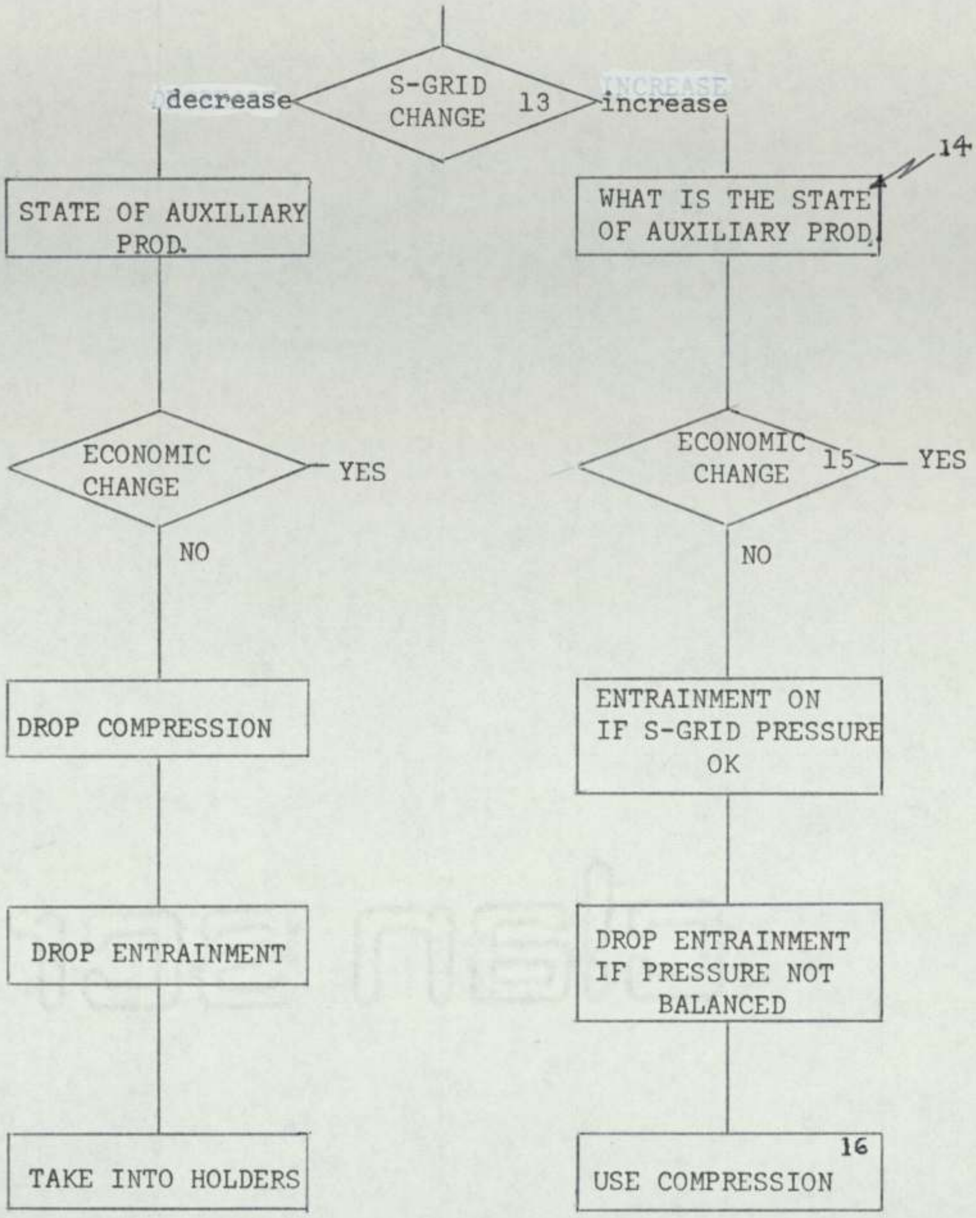


can be inferred from this that a production change is required immediately. This is to be expected, referring to the previous hours records, the total production for the day at the present rate would be 147 mft^3, 8 mft^3 low on the 155 mft^3 estimate. Box 9, shows that if production cannot catch up an action must be selected. The "committed to maximum production" indicates that his choice of action was straight-forward the only available extra production being the Tipton ballast air.

After having selected the control action Fig. 2.9 he states "Because of high tea-time load, going to take gas out of holders at Washwood Heath." This indicates that having selected a production change he checks the state of the grid, or refers back to the earlier ambiguous statement. On the flow diagram he returns from selecting a production change, to assess the present state of the distribution system, boxes 10 and 11. From the state of the grid he predicts a heavy tea-time load, box 12, and thinks that the grid is likely to be in an unacceptable situation. It is therefore necessary for him to increase supergrid pressure, box 13. There is no suitable auxiliary production plant to rectify the situation, hence the need to take gas out of holders, boxes 13, 14, 15 and 16, Fig. 2.10.

This detailed demonstration of the flow diagram, indicates that there is not enough evidence to support all the inferences necessary for their production. Also some controllers interchange stages (2) and (3), or do things in a different order neither of which are successfully described by the diagrams. In fact the problems that Bainbridge et al (1968) and Bainbridge (1972) found with conventional information diagrams

Fig. 2.10 SELECTING A DISTRIBUTION CONTROL ACTION



These action suggestions do not necessarily have to be done in the indicated priorities. Economy and Safety must be the final criteria in making a suitable choice.

are becoming apparent here. However, the analysis does show most of the distinct strategies and gives reasonable indications of how the controllers make their control decisions, despite the detailed limitations.

2.2.3 Conclusions

The sub-section discusses the possibilities of using the verbal protocol technique and a simulation model, as methods for more detailed investigations.

Verbal protocols:

It was mentioned earlier why this technique was not used in the initial study. The work so far, however, indicates that it might now be advantageous to employ this technique for a more detailed study of the controllers' behaviour. A more detailed analysis would perhaps provide data that could be compared with the work of Bainbridge described in the last chapter, similarities between such different cognitive tasks might be of importance in the theoretical study of cognitive behaviour. It would also allow comparison of protocols from different controllers, something not attempted so far. Finally it would allow an assessment of the retrospective technique employed in this initial analysis.

Simulation:

A suitable simulation of the information presented by the computer every hour programmed with past days data, would make it possible to compare the control behaviour of the controllers in similar situations: something that is impossible in real life. This would also enable an investigation of suitable performance indicators, for as is apparent from this initial study, confounding of individual differences with task demands prohibits this. It would also be possible to investigate controller behaviour under extreme conditions, for it is in such situations that individual differences become most important. Besides using the actual controllers, it would be possible to use a simplified version of the task with naive subjects. This would enable some experiments to be carried out investigating:

(i) development of a control skill
(ii) the importance of accurate weather forecasts on predictive behaviour
(iii) the relevance of historical data
(iv) types of training
(v) information presentation.

The first three of these suggestions are investigated in chapters 5 and 6.

CHAPTER 3

The design of the study is discussed and previous methods of analysing protocol data reviewed. Three different methods of analysing protocol data were described. The results from these three analyses indicated that:

(a) more activity was observed for the controllers during the afternoon shifts to achieve task goals than on either morning or evening shifts;

(b) several methods of predicting final gas sales were employed by the controllers;

(c) certain of these methods were more effective than others;

(d) individual differences between controllers were associated with different types of predictive behaviour, and aspects of control decisions.

3. A STUDY OF THE GAS GRID CONTROLLER USING THE VERBAL PROTOCOL TECHNIQUE

3.1 Objectives

In the last chapter it was concluded that the verbal protocol technique might be used successfully for a more detailed investigation of the grid controller's behaviour. This chapter describes a study carried out with some of the grid controllers using the verbal protocol technique; it describes how the recordings were made, the method of analysis used, and a discussion of the results. In particular it was hoped to observe different patterns of behaviour associated with:

(i) each of the three controllers,

(ii) different shifts, since demand varies during the day.

It was also expected to be able to compare this technique of investigating behaviour in the field with that used in the last chapter, and to assess the feasibility of using protocol techniques in the field.

3.2 Procedure

Unfortunately two of the five controllers were not prepared to take part in this second investigation; however the remaining three were quite happy to co-operate. Recordings were made with a controller wearing a neck microphone connected to a cassette recorder. The microphone had a remote control switch so that the controller could activate the recorder when he wished to say something. The microphone had a long lead to allow the controller freedom of movement; it was impractical however, to have it the full length of the control room, so there were occasions when the controller had to disconnect the lead. After some practice sessions it was found that the controllers recorded what they were doing and thinking unselfconsciously, and without prompting from the experimenter. Comparison of this practice data indicated that the controllers were recording more events and in greater detail than with the retrospective technique. This suggested that it would be worth while carrying out an extensive study using protocols.

3.2.1 Design of the study

To obtain the data necessary to fulfil the objectives of the study, each controller was asked to record a protocol for two morning shifts (07.00 - 14.00), two afternoon shifts (14.00 - 22.00), and two evening shifts (22.00 - 07.00). It was felt that if more data were collected at this stage problems would arise because of the time required for analysis. Bainbridge (personal communication) has indicated that analysis can be very time consuming, particularly as there are no conventional methods of dealing with protocol data. However, it would always be possible to collect more data if it became necessary. Recordings were made in March, April, May, June and September, 1974. Besides the protocol data, weather reports, and 'summary' printouts were collected for the days on which recordings were made. This provided evidence for checking the accuracy of protocol data.

3.3 Methods of analysis

3.3.1 Techniques used in other studies

Bainbridge (1972) is the only worker in the field of process control to give a detailed account of analysing protocols. The methods employed are intended to uncover recurring sequences of behaviour in the protocols, and to indicate how the different sequences are interrelated.

Initially the protocols are divided into sequences of phrases, and the referents of the words in these phrases identified. The phrases are separated into minimum grammatical units. It is then possible to find out what the majority of phrases are about, and to list them. These phrases can be grouped into blocks in which all the phrases have a common referent. To analyse the sequences of operations underlying the blocks of phrases three techniques may be used:

(i) developing flow diagrams
(ii) frequency counting
(iii) rank ordering.

In (i) routines are developed by combining evidence from similar sequences. This is done by taking a group of phrases and producing a flow diagram. A second group of phrases is matched against the first; phrases are identified as the same if they are statements about the same variables. If intervening phrases do not form part of the same sequence as justified by the content of later phrases, then it must be assumed that two different behaviours have occurred, and a separate routine must be developed. The same process must be adopted if no phrases match in the two groups of phrases being compared.

Some protocol consists of irrelevant material such as false starts etc., this tends to confuse the task of identifying the major patterns of behaviour. Using technique (ii), frequency counting, it is possible to test how many times a phrase appears in a given group of phrases; a phrase which occurs once or only 5% of the time can be omitted.

Although it was suggested in 1.7 that verbal protocol may be randomly selected for report by the subject, if the underlying behaviour has a consistent sequence then the first item should always appear before the next item reported. Technique (iii) can establish the ordering of items in a sequence of behaviour.

The above techniques identify consistent sequences of behaviour within the protocol. Consistent sequences in which operations are concerned with just one item of data are the most common and are referred to as routines. It is necessary, having identified the various routines, to examine the contexts which determine the occurrence of a particular routine. The methods employed are the same three techniques used above, but have the routine rather than items as the unit of analysis. The description of the resulting order of units of behaviour, and the conditions determining alternative behaviours, are referred to by the word 'sequences'. Analysis of sequencing is made difficult because one routine may appear in several different contexts. Analysis of the sequencing determinants gives purely inferred data; this is because the operator never mentions his sequencing decisions. It is necessary therefore, to study the alternative behaviours and try to extract a minimum number of task dimensions which would account for the alternative behaviours.

Rasmussen and Jensen (1974) give a brief description of protocol analysis in which recurrent routines were identified by coding the records according to a predefined set of elementary events. The coded events were then presented graphically, which enabled routines to be identified easily. Routines identified by this method were re-analysed from the original record according to their information processing characteristics. One problem encountered with this method was that every time a new class of routines was introduced it became necessary to check all the existing classes for overlap or inclusion. Unfortunately Rasmussen and Jensen do not give much detail of their method of analysis. The predefined events code method of identifying routines could have been usefully compared with Bainbridge's techniques.

3.3.2 Techniques of analysis used on the controllers' protocols

Besides the technique of frequency counting described in 3.3.1, some other techniques were developed to analyse the protocols of the grid controllers. The overall objective of looking for recurring patterns of behaviour was the same, the techniques were specifically devised so that comparisons could be made between controllers.

The initial analysis was similar to Bainbridge, the protocols were separated into sentence like statements. In some cases this was difficult, as verbal behaviour does not follow rigorous grammatical rules. Sentences become conjoined, and the place where one subject is dropped and another begun can become blurred. Three types of analysis were conducted using the initially derived statements. In the first type of analysis information sampled from the displays by the controllers is identified and recorded. As previously demonstrated in the last chapter, 2.2.2, comparison of information usage by different controllers indicated considerable individual differences.

In the second type of analysis, the cognitive activities represented by protocol statements are described. This description is an attempt to develop a taxonomy of cognitive activities used by the controllers. The important feature is that the descriptions should be content free and so applicable to other cognitive tasks. Using this data it may be possible to compare the amount and complexity of an individuals cognitive behaviour in different task situations, as well as being able to make similar comparisons with the behaviour of other individuals.

The third type of analysis identifies sequences of statements that are involved in achieving a particular goal. The identification of goal orientated sequences and relevant processing, permits the comparison of the different goals and processing that controllers might use to achieve task objectives. The following sections present the analysis and results due to these three approaches.

3.4 Details and results of the information analysis

For each individual statement a note was made of the information or data item that the controller used. Data items that were the result of calculation or processing of some kind were not included, analysis was restricted to the information that could unambiguously be identified with a source in the information system of the control room. Table 3.1 gives abbreviations of the 40 or so types of information that the controllers used in the protocols. These

TABLE 3.1 KEY TO INFORMATION ABBREVIATIONS*

Common to both manufactured (MG) and natural (NG) gas

HS	Hourly sendout (at a given hour)
HS'	Hourly sendout comparative day (at a given hour)
CS	Cumulative sendout (at a given hour)
CS'	Cumulative sendout comparative day (at a given hour)
ES	Estimated sendout (based on % day)
FS'	Final sendout, comparative day
ES'	Estimated sendout, comparative day
ESt_{23}	Estimated stock level at 23.00 hours
ESt_{06}	Estimated stock level at 06.00 hours
$RS_{06,23}$	Required stock level at 06.00 or 23.00 hours;
SC	Stock change
Gov. PRESS	Governor pressures
STOCKS	Individual holder details

MG only

p	Estimated total production for the whole day
$\dot{p}$	Hourly input, production
plant $\dot{p}$	Hourly production, individual plants
S-G	Super grid pressures
CH	Change in production to reach required stock
CR	Change in production rate to reach required stock
L/f	Load factors on individual plants
$\Sigma\hat{\dot{p}}$	Max. possible total production available.

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*A foldout reference list of these information abbreviations is presented for easy access in Appendix 9.1.

TABLE 3.1 (continued) KEY TO INFORMATION ABBREVIATIONS

NG only

Alloc	Gas to be taken from the National Grid and authorised by National Control
DIR	Direct natural gas, i.e. gas sold directly to the consumer.
PROD	Gas required to meet production requirements
TOT	Sum of DIR and PROD
IR	Hourly input rate
ENRICH	Gas for enrichment

General

Weather	Present weather conditions
Weather'	Weather conditions at a given time on the comparative day
F/cast	Weather forecast
F/cast'	Weather forecast at a given time on the comparative day
Te	Temperature
Te'	Temperature at a given time on the comparative day
Te, Te	Max. and Min. temperatures
Y-Chart	Prediction chart based on temperatures
J-boosters	Jet boosters, gas from holders (either MG or NG)
FS,FSt	Final sales and stock (at 06.00 hours)

NB ES is calculated using the average % day $ES = \frac{CSi \times 100}{Av\% \; day}$

The suffix i indicates the time of day.

The method of calculating the estimated final sale assumes that the cumulative sale by i hours will be the same percent of final gas

TABLE 3.1 (continued) KEY TO INFORMATION ABBREVIATIONS

sales as the average percent of final sales usually sold on that particular day of the week. The average percent is a weighted average and is calculated by taking the average percent and the actual percent from the same day last week and computing a weighted average of the two. The equation is empirical and is given as:

Av% day = (3 x Av% day last week + the actual % last week)/4

Thus each new week uses last weeks averages and actuals to calculate the current weeks averages.

TABLE 3.2 TOTAL NUMBER OF ITEMS OF INFORMATION SAMPLED ON THE 3 SHIFTS

	M	A	E		
Totals	469	706	521	1696	$X^2 = 57.14$
*Expected	494.7	565.3	636		$p<0.001$

*Expected frequencies are weighted, because morning shifts are only 7 hours long, whereas evening shifts are 9 hours long. The null hypothesis is that the number of items of information sampled per hour is constant.

abbreviations will be employed throughout the text. The information types have been classified into three categories. These are, (i) information common to both the MG and NG systems, (ii) specific to one or other of the systems and finally, (iii) general information. Most of the information comes from the 'sendout summary', and 'summary' displays (see Appendix 2.1), the computer displays showing the state of the stocks for individual holders, and the state of the MG production plants. The other sources of information are the wall displays, past records, and the weather forecasts.

The validity of the data was assessed by comparing the value of items mentioned in the protocol with the computer printouts of MG and NG sendout summaries. The comparison showed that in over 95% of data items sampled, controllers read the information to the nearest 1% of final sales. It seems therefore that at the level of information sampling the protocols give accurate data. Information tables for each controller were condensed so that suitable comparisons could be made, (i) between morning, evening and afternoon shifts for each individual controller, (ii) between morning, evening and afternoon shifts for all the controllers, (iii) in the use of different types of information by the controllers. Table 3.2 shows the number of items of information used by all the controllers on the morning, afternoon and evening shifts. X^2 analysis indicates that there is a considerable difference in the amount of information used. The afternoon shift uses more information items than expected, and the evening shift uses less. Table 3.3 shows that this trend is a feature of all controllers' information sampling behaviour. These two findings indicate that the controllers probably do more in the way of information processing during the

TABLE 3.3 SUMMARY OF THE NUMBER OF ITEMS OF INFORMATION SAMPLED BY THE CONTROLLERS ON THE 3 SHIFTS

CONTROLLER	M	A	E	TOTALS	X^2	
1	187 (206.2)	305 (235.6)	215 (265.1)	707	31.79	$X^2 0.001=13.82$ df=2
2	104 (93.9)	142 (107.3)	76 (120.7)	322	28.96	$X^2 0.001=13.82$ df=2
3	178 (194.5)	259 (222.3)	230 (250.1)	667	9.17	$X^2 0.02 =7.82$ df = 2

Figures in brackets are expected frequencies, and are weighted similarly to those in Table 3.2. Null hypothesis prepared on similar basis as Table 3.2.

afternoon shifts. Informal discussions with the grid controllers indicate that the afternoon shift is probably the busiest, because it has the period of peak demand and is also the time when accurate prediction of final sale is most critical. In the morning there is usually time to make a corrective control action if the sales prediction is not accurate, whereas at night the time until the end of the 24 hour period is rather short for a major control action to take effect, so that the afternoon/early evening, seems to be the most important for selecting a suitable control action. More evidence for this suggestion is reviewed in the following sections.

Table 3.4 shows differences in the types of information that the controllers use most frequently. There seems to be significant

TABLE 3.4 COMPARISON OF THE FREQUENCY WITH WHICH TYPES OF INFORMATION ARE SAMPLED BY THE CONTROLLERS

	Information Code	CONTROLLERS					
		3	2	1	Total	X^2	
MG	HS	49	30	52	131		
	HS'	43	28	46	117		
	CS	45	17	29	91		
	CS'	40	14	28	82		
	ES	44	20	69	133	6.7	$p<0.05$, df=2
	FS'	11	12	10	33	6.4	$p<0.05$, df=2
	ESt_{06}	29	10	43	82		
	$\Sigma\dot{p}$	20	1	25	46	9.0	$p<0.02$, df=2
	PLANT $\Sigma\dot{p}$	6	2	7	15		
	RS	6	4	2	12		
	CH	17	3	-	20	18.9	$p<0.001$, df=2
	S-GRID PRESS	10	3	7	20		
	L/Fact	1	2	2	5		
	$\dot{p}_i$	4	1	7	12		
NG	HS	46	29	54	129		
	HS'	43	27	48	118		
	CS	44	15	32	91		
	CS'	40	14	33	87		
	ES	41	18	21	130	9.9	$p<0.01$, df=2
	FS'	10	10	8	28		
	ESt_{06}	23	6	40	69	9.4	$p<0.01$, df=2
	Alloc	15	5	17	37		
	TOT	13	5	10	28		
	PROD	4	-	6	10		
	IR	5	-	1	6		
GENERAL	WEATHER	12	6	-	18	12.6	$p<0.01$, df=2
	Te	12	10	3	25	11.2	$p<0.01$, df=2
	F/cast	8	17	12	37	17.6	$p<0.001$, df=2
	F/cast'	7	4	1	12	15.2	$p<0.001$, df=2
	STOCK	3	3	10	16		
	TOTAL	651	315	674	1640	154.6	

(Expected values calculated from the null hypothesis that the frequency with which info. sources are sampled is independent of the controllers doing the sampling.)

(Low frequency categories have been omitted or combined to comply with Cochran's rule for calculating X^2.)

difference in the use of weather information. Controller 2 for example, uses the weather forecast and current temperature more frequently than his colleagues. Controller 1 on the other hand, seems to use less current weather information than the other two, although more forecast information than controller 3. There are also significant differences in the use of the computer sales estimate (ES), and the 06.00 estimated stock level, these seem to be favoured most by controller 1. The use of yesterday's final sale as a guide to prediction seems to be preferred by controller 2.

These results will not be discussed further in this section, their relevance will become apparent in analysing the different methods the controllers use in fulfilling certain sub-goals.

3.5 Details and results of the activity analysis

The method of analysis in this section was influenced by Hutt and Hutt's (1970) discussion of naturalistic observation. They have pointed out that it is possible to have an objective, quantitative and descriptive science of behaviour; considering the descriptive nature of protocol data such an assertion may suggest a promising method of analysis. The approach adopted by Hutt and Hutt is developed from analytic techniques employed by ethologists. It differs from experimental psychology in that a taxonomy of an organism's activities, (ethogram), is required before any experimental study may be undertaken. Studies of this type often apply no stimulus, but merely record behavioural elements as they occur in sequence. Thus an experimenter/ observer will, while watching a bout of activity, describe it with a list of descriptive terms derived from everyday language. The list may be added to each time a further bout is observed. An attempt may then be made to define each of the activity words. As more bouts are observed, it is frequently found that some definitions overlap, and re-definition of certain terms may be necessary. The final result is a repertoire of behaviours observed for a particular organism in a particular environment. The resulting behaviour elements in a sequence of behaviour may be identified further in terms of their morphology, (pattern of behaviour) and function. This last level of analysis is similar to the sequence level of Bainbridge (1972) see 3.3.1 and will be the subject of the next section.

The analysis in this section is concerned with describing the cognitive activity of a controller represented by each statement of a given protocol. The result is a list of activity definitions common to the three controllers, and is presented below. Ten main categories of activities have been identified.

3.5.1 Details of the cognitive activities

1. Information acquisition

NOTE Mentions a particular value or state of a display observed from within the control room. eg* 1.18.5.74(2a) "Sales for the morning are 2.9 on MG and 6.8 on NG." Here the controller has looked at the 'sendout summaries' for both NG and MG, and has mentioned the sale for the last hour (HS) which is shown on the 'sendout summary' display.

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*An example protocol is given in Appendix 3.1

1 = Controller (2a) = event and statement

ADVICE Mentions information sent into the control room from outside, usually via telephone or telex, eg 1. 18.5.74 (5a) "Just had a request from supergrid department, for permission to increase pressures at outlet. Codsall off-take station and reduce Penn to facilitate taking gas out of a stretch of the transmission main between Coven and Ebstree, and also permission to shut off Swindon NG off-take station."

2. Arithmetical operations

COMPARE Computes the difference, in a digital or analogue fashion between two or more variables, eg 1. 18.5.74(7c) "On the NG sale of 7.5, no comparison at all to yesterday when the sale was 11 (at this hour)." Here the controller has made an analogue comparison and has not bothered to actually calculate the difference, he has just noticed that one is much larger than the other.

CALCULATE Carried out a series of analogue or digital computations. This differs from the above, in that it can include other arithmetical operations besides subtract and is usually more complex. EG 1. 18.5.74(2h) "..... the minimum make we can get is round 3m/hr which gives a total make over the day of 72m." The arithmetical operation here is 24 x 3.

3. Estimating procedures

PREDICT Works out what the controller thinks the value of a certain variable is likely to be sometime in the future. This is often the final stage in a series of operations. EG 2. 22/9/74(3b)

"..... and the way the sales are running above the Sunday that we are looking at, it looks as though the direct sales are going to be at least 211 that the % is indicating."

UPDATE Revises the value of a recently predicted variable, usually as the result of more information. EG 1. 18.5.74 (9e) "The NG looks as though it could be a little less, (than originally predicted), perhaps around the 140 mark."

4. Evaluating

EVALUATE Works out the effect of a change or changes in one or more variables on other variable(s). Conditional statements are a characteristic of this type of activity. EG 2. 22.9.74 (2g) "The 260m which we were down for today could, if we do get a lift in sales above what we are showing at present leave us with a too low stock in the morning."

5. Decisions

CHOICE Choosing a particular piece of information from other information, usually to assist in further processing, quite often historical information is the subject of this activity. EG 1. 18.5.74(2b,c) "Unfortunately we've got nothing to really compare today's sales with, (c) so we'll have to work to a certain extent on what we sold yesterday."

AFFIRM Usually the result of obtaining evidence that establishes more firmly a prediction or decision. EG 1. 18.5.75(11a) "We don't want as much as that so the 5% cut which we instigated on the last hour is perfectly correct."

CONSIDER 1 Weighs the merits of making or not making a control change. EG 1. 18.5.74(11f,g) "So at some time this afternoon we will need an increase in make, (g) but there is plenty of time for this, there is plenty of turn up, and it may be worth letting it go for a couple more hours, just to see whether we're going to sell below the 70 mark or not."

CONSIDER 2 Weighs the merits of the most suitable type of control action. EG 1. 18.5.74(21,m) "One way would have been to take a stream off, (m) It's a bit late for this weekend, so the other way is to reduce one stream to absolute minimum make and constituted virtually out of the production system."

DECIDE 1 Decides whether a control change is required. EG 1. 18.5.74(3n) "This is again a rather false position (referring to 23.00 hours stock position), but it's satisfactory at the present moment." Can embody a complex decision rule, this aspect will be discussed later.

DECIDE 2 Decides on the most suitable type of control action. EG 1. 18.5.74(1d) "So the first thing we're going to do is to get Washwood Heath to take one of their streams down to absolute minimum make of around 0.3m/hr."

6. Memory

RECALL Recall of events that occurred earlier in a shift. Maximum storage time is the length of a shift. EG 2. 29.3.74(3b) "In view of the fact that Tipton are going to increase the make later."

7. Details of a control action

DESCRIBE Discusses actual or possible details of a control action, and or events related to a control action. EG 1. 18.5.74 "We'll bring the No.3 stream at Washwood Heath to a make of 1m, allow the plant to settle down, and then adjust the makes to give us a total make of 70 for the day a little later." The describe statement in most cases is an extension of decide 2, the division between the two is sometimes blurred. The 'describe' statement may be thought of as the details implemented by the preceding decide 2.

8. Explanations and descriptions of the controller's behaviour

REASON Gives the reason why he has either done, or is going to do, something. EG 2. 22.9.74(1a) "... and we'll have to compare with other Sundays because this is a unique day of the week."

PLAN Describes what he is intending to do in the future, EG 1. 18.5.74(6g) "... we've got plenty of turn up, and rather than have a higher make and too much stock, we'll stay on the lower make and then if necessary increase later on in the day."

STATE Indicates what he's going to do next. EG 2. 22.9.74(3a) "We've got to give the estimate of NG requirement by 16.00 hours to London."

9. Explanations and descriptions of system behaviour

COMMENT Comments on the prevailing state of the system gives some indication of his knowledge of the system, and its behaviour. EG 1. 18.5.74(2h) "Unfortunately with four streams making gas in these weather conditions unless we use total butane enrichment the minimum make we can get is around about 3m/hr."

EXPLAIN Explains a particular event in the systems behaviour. EG 2. 22.9.74(10c) "(It will be noted that 23 hours there was an excessive sale on the 8.9.74), this was due to an error in manual figures which the system was running."

10. Summary

SUMMARIES Recapitulates the important aspects or general conclusions from a series of statements. EG 2. 22.9.74(3n) "So therefore I will raise the allocation today to 270 and request 325 for tomorrow."

These twenty-one activities are common to all controllers and only these will be considered in the analysis that follows. They account for 99% of all the activities observed in the controllers protocols. It may be argued that those activities that are left out are controller specific and so consequently could provide evidence on controller differences. This does not seem to be the case; the remaining activities observed were 'Wait', 'Deduce', 'Call', 'Look', and 'Search', none of which occurred with a frequency great enough to show anything about an individual controller's behaviour that would distinguish him from his colleagues.

However, before examining the frequencies associated with the various activities, it is necessary to discuss the relationship of the ten activity categories to each other. The activities cannot be said to be at the same level of processing as each other, since the information combining nature of categories 3 and 5 indicates that they implement other activities such as those in 1, 2, 4, 6. It also seems that the 'evaluate' activity is closely associated with predicting and deciding, as these also are characterised by conditional statements in some instances. The difference is that an evaluative statement does not indicate a course of action, or a choice between alternatives.

Categories 8 and 9 give information on the controller's strategy, and also his knowledge of the system, these may often explain behaviour in categories 3 and 5 as an afterthought on the part of the controller, and as with category 10, may be considered to be an artefact of the protocol technique.

In general, categories 1 and 2 are concerned with current information from the system whereas the other categories are concerned with past experience of the system. In this sense the object of trying to define general cognitive activities applicable to more than one cognitive task may have been only partially successful. The reason is that the protocol data is not detailed enough to enable examination of the structure of the cognitive activities. However, there are some tentative abstractions besides categories 1 and 2 which may be generalisable. For example the <u>evaluative</u> or conditional behaviour* that seems evident in categories 3, 4, and 5 is of a general nature. In particular it seems to indicate an aspect of the underlying structure of cognitive behaviour. This assertion can be supported by the evidence of Piaget and his work on formal operational thinking. As Piaget (1962) says of this, the last and adult stage of cognitive development, ".... the child becomes capable of reasoning not only

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*Conditional behaviour is identified in the protocol by statements of the form 'if ... then ...'. The controller is hypothesizing about what may happen to certain variables if a particular event takes place.

about objects, but also about hypotheses or propositions", i.e. the child (adolescent) can reason that if a certain view of reality is true then certain consequences follow. This is typical of the conditional statements made by the controllers. The operations underlying this behaviour are regarded as structures belonging to the simple forms of equilibrium attained by thought activity, i.e. the characteristics of the structures are their reversibility, they are always self compensatory. The importance of this is, as Piaget (1971) states "Once an area of knowledge has been reduced to a self-regulating system or 'structure', the feeling that one has at last come upon its innermost source of movement is hardly avoidable." This brief digression indicates the relevance of looking for the structure underlying cognitive behaviour. However, the discovery that formal operational thinking can be identified in the protocols does not necessarily indicate a locus of performance limitation; unless of course a particular controller has not reached this level of thinking. Experience of past system behaviour seems more relevant to good control performance. The finding does seem, however, to have possible implications for classifying the difficulty of a task. The percent of statements in a protocol that suggest formal operational thinking would be an indicator of the nature and extent of task demand. This possibility will be investigated in the following sub-section which will analyse the frequencies associated with the individual activities. If this does turn out to be so a higher proportion of conditional statements may be expected during the afternoon shifts.

3.5.2 Results analysis

Activity tables for each controller were condensed so that it was possible to investigate the following:

(i) differences between morning, afternoon and evening shifts, for each controller,

(ii) differences in morning, afternoon and evening shifts for all the controllers,

(iii) the use of different types of activity by the individual controllers,

(iv) differences in the apparent use of formal operational thinking as defined by conditional statements.

Table 3.5 shows a significant difference in the number of activities counted on the different shifts, a result similar to that shown in Table 3.2 on information sampling. The result is the same for controllers 1 and 2, but not 3, (Table 3.6) this is unexpected. Examination of the two evening shifts for controller 3 gives no indication of why this should be, except for a high level of activity. Table 3.7 shows the differences between the controllers in the types of activity employed. Controller 2 uses more 'predictive', 'update' and 'choice' activities than expected, but less data input, i.e. 'Note' activities than expected. Controller 3 gives more information on what he is doing, i.e. 'state' activities, than might be expected and also seems to spend more time 'considering' the details of the necessary control actions. Controller 1 on the other hand actually 'decides' what his control actions are going to be, more times than might be expected. These results seem to indicate that controller 2. is more concerned with prediction than the other controllers, who seem to spend more activity choosing the most suitable control actions. The category totals show that more time is spent in collecting data

TABLE 3.5 TOTAL NUMBER OF COGNITIVE ACTIVITIES USED ON THE 3 SHIFTS

	M	A	E	
TOTALS	664	916	713	2293
*EXPECTED	669.1	764.7	860.2	$X^2 = 55.56$; $p<0.001$

*Expected frequencies are weighted, because morning shifts are only 7 hours long, whereas evening shifts are 9 hours long. Null hypothesis is that number of activities per hour are constant.

TABLE 3.6 NUMBER OF COGNITIVE ACTIVITIES USED BY EACH CONTROLLER ON THE 3 SHIFTS

Con-trollers	M	A	E	TOTALS	X^2	
1	278 (266.0)	385 (304.0)	249 (342)	912	47.41	$p<0.001$; df=2
2	126 (138.2)	200 (158.0)	148 (177.8)	474	17.23	$p<0.001$
3	260 (264.5)	331 (302.3)	316 (340.1)	907	4.61	

Figures in brackets are expected frequencies, and are weighted similarly to those in Table 3.5

Null hypothesis prepared on a similar basis to Table 3.5

TABLE 3.7 COMPARISON OF THE ACTIVITY FREQUENCIES FOR THE THREE CONTROLLERS

ACTIVITY	3	2	1	Totals	Category Totals	X^2
1 NOTE	322(335.1)	130(173.6)	386(332.9)	838	858	16.33^{ooo}
ADVICE	7(7.9)	7(4.1)	6(7.9)	20		
2 COMPARE	205(188.0)	103(98.2)	167(188.7)	475	577	
CALCULATE	37(40.4)	18(21.1)	47(40.5)	102		
3 PREDICT	42(53.8)	42(28.1)	52(54.0)	136	155	9.63^{o}
UPDATE	1(7.5)	14(3.9)	4(7.6)	19		33.49^{ooo}
4 EVALUATE	17(19.0)	13(9.9)	18(10.1)	48	48	
5 CHOICE	2(5.1)	7(2.7)	4(5.2)	13	408	9.00^{o}
CONSIDER 1	29(24.9)	12(13.0)	22(25.0)	63		
2	23(13.4)	4(7.0)	7(13.5)	34		11.39^{oo}
DECIDE 1	76(78.7)	52(41.2)	71(79.0)	199		
2	8(13.8)	2(7.2)	25(13.9)	35		15.15^{ooo}
AFFIRM	28(25.3)	20(13.2)	16(25.4)	64		7.83^{o}
6 DESCRIBE	36(32.0)	16(16.8)	29(32.2)	81	81	
7 RECALL	5(6.7)	3(3.5)	9(6.7)	17	17	
8 REASON	12(11.5)	6(6.0)	11(11.5)	29	70	
PLAN	3(2.8)	2(1.4)	2(2.8)	7		
STATE	23(13.4)	7(7.0)	4(13.5)	34		13.66^{oo}
9 COMMENT	10(10.3)	3(5.4)	13(10.3)	26	32	
EXPLAIN	1(2.4)	4(1.2)	1(2.4)	6		
10 SUMMARISE	8(6.7)	4(3.5)	5(6.7)	17	17	
	895	469	899	2263		145.17^{+}

(a) Expected frequencies based on the null hypothesis that the frequency with which activities are used is independent of the controller using them.

(b) Some activities which occur with low frequency have been omitted to comply with Cochran's criterion for calculating X^2.

$oX^2_{0.025} = 7.37$ df=2

$ooX^2_{0.005} = 10.6$ "

$oooX^2_{0.001} = 13.82$ "

$^{+}X^2_{0.001} = 73.40$ df=40

and initially processing it than any other activity, in fact 63.4% of all activities are of these two types 1 and 2. Predictive statements are only 6.8% of all activities and decision activities only 18.0%. This shows that the controllers must spend a considerable amount of time in data reduction.

Table 3.8 shows that there is a shift difference in the use of conditional statements, this lends support to the suggested relationship between this behaviour and task demands. It is, however, apparent that only a few of the 'evaluate', 'consider', 'decide' and 'predict', activities exhibit hypothetical behaviour, in fact 6.6%. There is also evidence for individual differences, controller 3 seems to make over twice as many 'conditional' type statements as the other controllers, there seems to be no reason why this should be so, Table 3.9.

Generally, the analysis in this section shows several differences between the controllers, possible explanations for these differences are not, however, immediately apparent. Some reasons for the findings will become clearer in later sections when the goal orientated sequences of behaviour identified for the individual controllers are analysed.

3.6 Details and results of sub-goal analysis

The preceding two sections were concerned with analysis at the statement level of protocol data, and have given information about the controller's behaviour at this level. However, there is little indication of how or why the controller organises his processing.

TABLE 3.8 FREQUENCY OF CONDITIONAL STATEMENTS OBSERVED IN 'CONSIDER', 'DECIDE', 'PREDICT' and 'EVALUATE' ACTIVITIES FOR THE 3 SHIFTS

	M	A	E	TOTAL	X^2	
TOTALS	5	18	11	34	6.68	$p<0.05$ df=2
*EXPECTED	9.9	11.3	12.75			

*Expected frequencies weighted as in Table 3.5, null hypothesis that the number of conditional statements per hour constant.

TABLE 3.9 FREQUENCY OF CONDITIONAL STATEMENTS FOR EACH CONTROLLER ON THE 3 SHIFTS

Controller	M	A	E	TOTAL	EXPECTED
1	1	2	5	8	11.3
2	2	5	1	8	11.3
3	2	11	5	18	11.3

$X^2 = 5.99$; $p = 0.05$; df = 2

Null hypothesis that controllers use the same number of conditional statements as each other.

Attention must therefore be paid to the function and morphology of the controller's behaviour as suggested by Hutt and Hutt (1970) (see section 3.5). This section will be concerned with function and the next section with the morphology of the controllers' behaviour apparent in the protocol data.

3.6.1 Identification of sub-goals

As mentioned in the previous section certain activities such as 'decide' and 'predict' are usually the final stage in a series of processes. This indicates that 'decide' and 'predict' implement 'lower' level behaviour in terms of data collecting and initial processing. Careful examination of routine events shows that the controller will organise his behaviour into several sequences with the object of:

(i) predicting total sales,
(ii) deciding if a change in supply conditions is required, and
(iii) deciding on the most suitable control action.

This observation is similar to the identification of stages 2 and 3 in chapter 2. All three controllers satisfy these three sub-goals in their endeavour to satisfy the overall task goals. These three types of sub-goal are usually easy to detect as they nearly always end with a prediction or decision activity. It has to be admitted however, that there is no rigorous method of determining the purpose of a sequence of activity, it is a matter of judgement. In some cases the purpose of a sequence of activity may be obscure, the only defining characteristic being that the preceding and succeeding sequences are well defined with easily identified goals. The example below shows the protocol data of a typical NG control decision taken from 1. 23.5.74(4 k, l, m, n)

	Activity
k) On NG we've got a predicted usage for production of 67.2, a direct sale of 263.3 which gives us a total usage of 330.5, we're taking 317, we've got a further 10 in the pipeline.	Notes NG, prod., dir., tot., & alloc. Recalls increase on the way
l) So with the increase sale, bringing it up to 273, we would end up with a stock of 161.3	Predicts FS Calculates ESt
m) So another 5% increase is definitely required.	Decides' to increase
n) So we'll work out the figures, work out the new rate, and the new take for the day and pass these on to London as soon as possible.	States what he will do.

In the example (k) and (l) indicate preliminary processing of information for the decision in (m).

Besides the three major types of goal there are several subsidiary goal orientated sequences of behaviour. Below are listed all the purposive types of behaviour divided into four related categories with codes to identify their goal orientation.

1. Behaviour concerned with predicting final sales
   - (i) CWF: Collecting and processing weather information, often precedes a prediction.
   - (ii) SCD: Selecting a suitable basis for making predictions, often a prerequisite to prediction.
   - (iii) PS(PS'): The controller processes information with the intention of predicting the final sale for the day. Often the controller

will use information found in (i) and (ii), certainly the results of these are not used for any other purpose, so it might be suggested that PS will implement CWF and SCD, it is not, however, clear when or how this happens. On most occasions SCD orientated behaviour occurs at the beginning of the shift and the result is used as the basis for all predictions unless information comes to the notice of the controller that undermines this basis. CWF orientated behaviour usually becomes apparent if the controller is concerned about the weather situation.

The primed PS' is used to code sequences that follow processing similar to sequences coded by PS except that the controller is not explicit about a predicted value. It seems that the controller has tacitly accepted his previous estimate, and the information he has processed adds nothing new.

(iv) PSt, PSw: These are variations on PS. The first is a prediction for tomorrow. The second is a prediction of final sales but based entirely on weather information unlike the majority of predictive behaviour, it seems to be an extension of CWF.

2. Behaviour concerned with making control decisions

(v) MC_i(MC'): Sequences of behaviour with this code indicate that the controller is concerned with making an MG control decision. There are several different sequences of behaviour all with the same intention, these are distinguished by the suffix i, these variations will not however, become important until the next section. The primed version MC' is used in the same way as PS'.

(vi) NC_i(NC'): Sequences of behaviour with this code are the same as MC above only they are concerned with NG.

(vii) DC_i(DC'): This indicates that the behaviour in the sequence is concerned with making distribution control decisions rather than (v) and (vi) which are concerned with supply control.

3. Behaviour concerned with selecting suitable control action

(viii) SSC: This indicates behaviour that is concerned with selecting a suitable control action and is usually implemented by NC, MC, DC sequences. In some cases SSC, type behaviour can be subsumed in NC_i MC_i and DC_i sequences.

4. Miscellaneous and off-line behaviour

(ix) I: Non-specific information collecting behaviour

(x) J: Behaviour which explains why something happens or was done. It may be considered as an artefact of the protocol technique.

(xi) As: Sequence of behaviour which will give the controller a general picture of the state of the system.

(xii) DSD: Supervisory discussions, usually concerned with longer term planning and arrangement of system parameters.

(xiii) MAC: Maintenance control decisions and actions.

(xiv) FD: Equipment fault detection/rectification.

(xv) SU: Summarising

(xvi) UE: Unexpected events

The remainder of this sub-section analyses the frequencies associated with the different goal types. The goal types identified above, account for 91% of all goals observed in the protocols. The following topics will be examined:

(i) differences between morning, afternoon and evening shifts for each controller, and

(ii) for all the controllers,

(iii) the use of different sub-goals by the individual controllers.

3.6.2 Analysis of sub-goal frequencies

The results of the sub-goal analysis show remarkably different results from the sections on information and activity analysis. Table 3.10 shows no significant difference in sub-goal orientated behaviour over the three shifts, and Table 3.11 shows no difference for the individual controllers. This is an interesting finding, it tends to suggest that controllers will be involved in the same number of functional activities over the three shifts, but that the amount of processing required to achieve the various sub-goals varies depending on the time of day. To be more specific, the controllers seem to have to do far more mental work during the afternoon than at any other time during a 24 hour period, to achieve the same results.

TABLE 3.10 TOTAL NUMBER OF SUB-GOALS ON THE 3 SHIFTS

	M	A	E	TOTAL	
TOTAL	203	240	220	663	
*EXPECTED	193	221	249	$X^2 = 5.53$	$p>0.05$

*Null hypothesis that the number of sub-goals used per hour is constant.

TABLE 3.11

CONTROLLER	M	A	E	TOTALS	X^2
1	74 (75.5)	97 (86.3)	88 (97.1)	259	2.31
2	52 (49.3)	66 (56.3)	51 (63.4)	169	4.24
3	77 (68.5)	77 (78.3)	81 (88.1)	235	1.75

Null hypothesis is as in Table 3.10

Table 3.12 shows variations in goal directed behaviour for the controllers. The main differences seem to be concerned with predictive behaviour, and involvement with the distribution system. Controller 2 selects a suitable basis for prediction, as well as indulging more often in definite i.e. PS predictive behaviour than any of the other controllers. If PS' and PS are combined, however, and PS' assumed equivalent to PS, the differences between the controllers disappears. The difference still remains in their approach to prediction with controller 2 exhibiting four times more SCD behaviour than the other two controllers.

On the other hand Controller 2 has very little involvement with distribution control, whereas controller 1 spends more time describing distribution control actions than expected. A difference here might be expected on the basis of the findings in the last chapter where one

TABLE 3.12 COMPARISON OF SUB-GOAL FREQUENCIES FOR THE THREE CONTROLLERS

SUB-GOAL CODE	3	2	1	TOTAL	X^2
PS'	26(29.3)	9(23.0)	52(34.7)	87	17.52^{ooo}
$^{++}$PS	53(56.3)	63(44.2)	51(66.5)	167	11.80^{oo}
*PSw	4(6.1)	11(4.8)	3(7.2)	18	11.08^{oo}
SCD	1(6.4)	15(5.0)	3(7.6)	19	27.30^{ooo}
$^{+}NC_i$	47(38.8)	22(30.4)	46(45.8)	115	4.05
$^{+}MC_i$	54(49.9)	36(39.1)	58(58.9)	148	0.69
$^{+}DC_i$	10(9.4)	1(7.4)	17(11.1)	28	8.81^{o}
SSC	9(7.7)	3(6.1)	11(9.2)	23	2.14
	204	160	241	605	94.47

$oX^2_{0.025} = 7.37$ df = 2

$ooX^2_{0.005} = 10.6$ df = 2

$oooX^2_{0.001} = 13.82$ df = 2

Expected frequencies based on the null hypothesis that frequency of sub-goal usage is independent of which controller uses them.

[+] All these have combined the primed versions as the frequency of the primed versions was low and would not be analysable by X^2. This is true of AS, DSD, MAC, which have been omitted because they would not satisfy Cochran's 20% of expected frequencies below 5.

[*] PSw combines CWF, more than 20% of expected frequencies below 5.

[++] PS combines PSt, more than 20% of expected frequencies below 5.

The other sub-goal types mentioned earlier are not included because of low frequency of occurrence and not being common to all three controllers.

of the controllers made much greater use of wall displays, and it was suggested that this was due to the fact that he had had more experience of distribution control. Unfortunately for this explanation it is controller 3 who had the distribution experience and not controller 1. Another possible explanation is that some of the distribution control actions were due to the assistant controller, and the grid controller has described his behaviour, rather than his own.

Finally, Table 3.13 (a), (b) (c) shows the differences between the three controllers in the amount of information sampled, number of activities employed, and number of purposive sequences of behaviour. It is clear that controller 2 is the odd one out on all three of these criteria. There are several possible reasons for this, and they are that the controller is:

(i) less verbose,
(ii) less able to introspect than his colleagues,
(iii) thinks and organises his behaviour in a different way to the other two controllers,
(iv) has reached a different level of skill.

If (iii) is true, it is not apparent from the results examined so far. To establish any evidence for (iv), some indicator of performance level is required and this is considered in the last section. Subjective impressions of controller 2 suggest him to be taciturn in nature compared with his other two colleagues.

TABLE 3.13 COMPARISON BETWEEN THE CONTROLLERS OF THE AMOUNT OF INFORMATION, ACTIVITIES AND SUB-GOALS USED

(a) Information sampled

	1	2	3	TOTAL	
TOTAL	707	322	667	1696	$X^2 = 159.6$
EXPECTED	565	565	565		$X^2_{0.001} = 13.82$ df=2

(b) Activities

	1	2	3	TOTAL	
TOTAL	912	474	907	2293	$X^2 = 165.5$
EXPECTED	764.3	764.3	764.3		$p < 0.001$

(c) Sub-goals

	1	2	3	TOTAL	
TOTAL	259	169	235	663	$X^2 = 19.65$
EXPECTED	221	221	221		$p < 0.001$

Expected frequencies based on the null hypothesis that each controller uses the same amount of information, activity, and goal sequences.

3.7 Analysis of purposive sequences of behaviour

In the last section the types of sub-goals the controllers selected in their performance of the task were identified, coded and counted. This section is concerned with the way the controllers achieved the various sub-goals, in particular the behaviour associated with prediction, deciding on a control change, and choosing a suitable control action. The method adopted is similar to that described in Bainbridge (1972) outlined at the beginning of this chapter. For a particular sequence of behaviour the information sampled by the controller is listed in a column down the left of the page. The number of times an item of information is used can then be counted for all examples of the given sequence, indicating the most important information used for a particular purpose. There is a draw-back however, with this technique, and is that there are different methods of achieving the same goal, each having different information requirements, and each therefore having to be distinguished from other methods with the same purpose. To make a distinction requires judgement and a careful examination of the context in which a sequence occurs. Often 'plan', and 'reason' statements can give valuable insight. The next two sub-section(s) deal with analysing sequences of behaviour associated with the PS, MC, NC, and SSC goal codes.

3.7.1 Analysis of predictive behaviour

Methods of prediction:

In the majority of predictive behaviour one of two methods is used by the controllers. The choice of which method is appropriate is usually found in the sequences of behaviour coded SCD. In these sequences the controller looks at past days records and tries to find a day similar to the current one. As an example of this type of behaviour,

2. 28.4.74(3c) "However, sales so far indicate on MG we are going to be somewhere to or slightly above the Sunday 17.3.74. (d) On NG the sales are falling away from 24.3.74 which was indicated, but are in front of the figures on 17.3.74. (e) However, 17.3.74 seems to be the best day to follow as well on NG." Besides using hourly sale (HS) and cumulative sale (CS) as criteria for comparison, the controller also uses weather, and day of the week, to help him select a suitable day. The rationale behind this procedure is to find a day which is likely to have a demand pattern similar to the current day.

The use of a comparable day is the basis for one of the main prediction procedures. This method, designated type B, can only be adopted however, if the search for a comparable day has proved successful. If the selection procedure has been successful, the controller will assume that the hourly sales will remain similar during the day to those of his comparison. Any difference in cumulative sale between the two days at a particular hour may be added or subtracted from the final sale of the comparative day to give an adjusted prediction. For example, if at 13.00 CS=40, CS'=45, and FS'=180, the controller will make his prediction by the following calculation,

PS=FS' + (CS-CS') = 180 + (40-45) = 175

This assumes that the controller is satisfied that HS=HS' for the remainder of the day. In cases where HS and HS' become radically different, the controller will either look for another comparable day, or abandon this method of prediction for the other main method. This second method is the one that would have been adopted had the controller been initially unsuccessful in finding a comparable day.

The method designated type A uses the computer estimate ES, and makes necessary adjustments to this as experience dictates. In some cases, for example, the controllers employ a rule of thumb based on experience which suggests that a change in temperature of 1°C can affect NG sales by 5-10 mcf depending on the time of year.

These two basic procedures, A and B, are not followed rigidly all the time, and in several cases the controller will combine information from the two methods. This will often occur if the controller is uncertain about the result given by one or both of the two methods. This combined method will be referred to as type A/B.

In addition to these two main types and their derivative, three other types have been identified which, although they occur infrequently, are worthy of description. Type C combines types A and B as well as weather information. In these types of prediction it is not usually clear exactly how the controller combined the information.

In type W, the controller makes his prediction based on weather information. Type U, are cases where it is not clear how the controller makes a prediction.

Table 3.14 shows how often the various methods are employed by the individual controllers. Type B is the most popular followed by type A. With regard to the use of different methods by each controller; it is apparent that controller 2 uses type A rather less than might be expected, and instead prefers to use type B.

TABLE 3.14 FREQUENCY OF USAGE OF DIFFERENT METHODS OF PREDICTING BY THE THREE CONTROLLERS

CONTROLLER	A	B	A/B	W	C	U	
1	16 (15.4)	21 (24.5)	8 (5.9)	-	2	5	52
2	11 (18.3)	36 (29.2)	8 (7.0)	2	4	1	62
3	25 (18.3)	26 (29.2)	4 (7.0)	2	-	5	62
	52 X^2=6.46	83 X^2=2.53	20 X^2=2.27	4	6	11	176

$p<0.05$

Table 3.15 shows the types of information sampled in the three most frequently used prediction methods. As might have been expected, the main differences are in the use of ES and FS', since these are the significant features in the initial identification of types A and B. It might have also been expected that there would be differences in the use of the other information. The only observable difference is in the use of HS', where in type B this information is used more often than expected. The reason for this appears to be that on some occasions the controller will use two comparative days. It is of particular note that in type A methods, the controllers still make comparisons with a comparable day. This evidence suggests that the controllers are continually evaluating their method of prediction, and considering whether type A or type B is the most acceptable at a particular time.

TABLE 3.15 COMPARISON OF THE MOST FREQUENTLY USED ITEMS OF INFORMATION IN THE MAIN PREDICTION METHODS

	A	B	A/B	TOTAL	X^2	
HS	49(50.3)	76(70.8)	18(19.1)	143	3.62	
HS'	36(48.2)	82(67.8)	19(18.3)	137	8.78	$p<0.02$; df = 2
CS	38(37.3)	54(52.5)	14(14.2)	106	2.27	
CS'	35(34.8)	50(49.0)	14(13.2)	99	2.07	
FS'	5(17.2)	35(24.3)	9(6.6)	49	15.13	$p<0.001$;df = 2
ES	50(26.0	14(36.6)	10(9.9)	74	37.61	$p<0.001$;df = 2
ES_{i-1}	8(2.8)	0(4.0)	0(1.1)	8	14.85	
	221	311	84	628	84.33	$p<0.001$;df = 2

Expected frequencies based on the null hypothesis that the frequency of information type used is independent of prediction method.

Table 3.16 shows the only difference in the types of information sampled by the controllers in either of the main prediction methods. It appears that Controller 1 continues to mention ES when he is using method B to make predictions. This is further evidence of controllers continually reviewing the suitability of their current method of prediction.

TABEL 3.16 COMPARISON OF THE MOST FREQUENTLY USED INFORMATION BY THE THREE CONTROLLERS IN METHOD 'B'

	1	2	3	
HS	21	28	27	76
HS'	27	28	27	82
CS	15	16	23	54
CS'	19	16	15	50
FS'	9	10	16	35
ES	10	-	4	14
	101	98	112	311

Although the various types of prediction method have been described, it is useful to make explicit the possible rules of information combination that are involved in these methods. In particular this will emphasise the way the controllers can combine results from two or more methods.

Prediction rules:

Single methods -

Type A : $PS_A = ES \mp e$ - (a)

Type B : $PS_B = FS' + (CS-CS') + k\ (HS-HS') \mp e$ - (b)

Type W : $PS_W = y\ (\text{weather})$ - (w)

Derivative methods -

Type A/B : $PS_{A/B} = (PS_A + PS_B) \times \frac{1}{2}$ - (a/b)

Type C : $PS_C = PS_{A/B} + x\ (\text{weather})$ - (c)

Equation (a) is relatively simple, the predicted value PS_A is equal to ES plus an adjustment due to 'e' which refers to any relevant experience. This experience can include, day of the week, time of the year effects, as well as demand changes due to special events such as holidays or cup final Saturday etc.

Equation (b), as discussed earlier, assumes that in an ideal situation HS will equal HS' for the remainder of the current day, so that the predicted value is yesterdays final sale plus the difference in cumulative sale. However, on many occasions there is a discrepancy between HS and HS'; the k (HS-HS') in the equation, is the adjustment the controller may make to allow for $HS \neq HS'$. The 'k' is the controller's estimate of the effect this discrepancy might have on overall sales. An examples of this is 2. 29.3.74 (12a) "Sales are still coming closer so the total sales over night should be similar to last Friday nights, (b) Cumulatively we are now 13m below last week's sales, if the sales are the same this would give 196 (c) But as they are not quite in line, 195 for MG." In fact the method of prediction in equation (b) is a more general form of the method B outlined earlier in this sub-section.

Equation (w), this equation shows some unspecified item of weather information being converted by a conversion factor 'y' into a prediction of the final sale. In the majority of cases where the controllers use only weather information for prediction, the information is used to adjust a prediction made by another method, hence the more common derivative method represented in equation (c). There is however, a method whereby the controller can predict final sale directly from weather information. An example, 3. 4.5.74 (le) "Well we've had a look at the temperature forecast for yesterday, that's for the 24 hours starting 06.00 this morning, and according to the computer prediction chart it's showing 170 and this is what we think we're going for so far as MG is concerned, and we are budgeting for 170." The computer conversion chart referred to here is called the Y-Chart, hence the conversion factor 'y' in equation (w). Through the years data has been collected, and processed by computer, correlating temperature with sales. The resulting Y-Chart allows the controller to make a prediction from this historical data, by selecting the correct week of the year, and the expected temerature for the day in question. Unfortunately with the change from MG to NG this data has not been of much practical use recently. An example of the sort of discrepancy that can occur is 3. 15.5.74(lj) "Looking at the computer forecasts (Y-Chart), yesterdays effective temperature was 53. (k) On NG we should have sold 258, we in fact sold 239."

In equation (a/b) the controller calculates using (b), takes the result of (a) and combines the two. The equation shows that the average of the difference has been taken, however, this does not always happen, a controller will sometimes weight one result more than the other. On some occasions he might even extrapolate from the two results, especially if he has an 'e' term included. An example of equation (a/b) is 1. 3.6.74 (2c) "NG 'send', this hour was 9.7m compared to 10.5m on 20.5.74, cumulative of 142.9 compared to 157.2, an ES = 191.1 (d) So we are 14m down on 214 sale, so that gives us a max. sale of round about 200m, but as the figures (ES), have been so consistent over the last hours the most we feel we'll sell is round about the 195."

Equation (c) combines prediction information from (a) and (b) methods, as well as including a weather weighting. The weather in this case can refer to prevailing conditions, a change in forecast, maximum expected temperature etc. The controller can use this information to modify predictions made by methods (a) and (b). Although the method of combining information in equation (c) has been represented as a calculation it is not clear how the controller combines the relevant data. An example shows this, 2. 23.9.74 (1b) "MG, the hourly sale this time is 5.9, a fortnight ago it was 5.3, cumulatively we're 2.5m up on an 82.5 (c) In view of the fact that we've got rather strong winds and lowish temperatures forecast, I think the sales will be somewhere near the 90m mark, in fact the % (ES) is now indicating 82.9m." The controller beginsin this example with a type B which would give PS = 85m (2.5 + 82.5). He then adds another 5m because of expected bad weather giving 90. He confirms this result with a type A, so that he arrives at the same predicted value by two independent methods. It is evident that the controller has not processed information in exactly the way prescribed by equation (c). The processing in the example can be represented by a variation of equation (c):

$$PS_C = (PS_A)_{/n} + (PS_B + k\ (\text{weather})\ )/m, \text{ where } m = n = 2$$

This makes the point that the prescribed equations are only an approximation to the way information is combined; depending on the circumstances the controller will adapt the basic rules embodied in these relationships. Thus the controller might well add a weather term to either equation (a) or (b) if the forecast suggests a change. There are several factors that seem to influence which methods are used, and as already shown, these are usually assessed in SCD coded sequences of behaviour. The controller looks for a similar day, and depending on how satisfactory his search, i.e. how close the comparison is that he finds, may require additional confirmation from the computer estimate (ES). Also if the weather situation is uncertain the controller has to account for this uncertainty by assessing in someway the likely effect of a change in weather on his prediction. The relative importance attached to these three major prediction factors, (i) ES, (ii) comparative day, (iii) weather, by the controller may vary during a shift. Consequently the method of prediction employed by the controller will process information from the three important sources of, ES, comparable days, and weather. The choice of method or combination of methods will depend on the confidence a controller has in the accuracy of a method in a given set of circumstances. The instances where controllers have combined the basic methods produce the prediction types A/B and C. Evidence indicates that the methods used in combining the information in A, B and W are fairly consistent, whereas the methods used in A/B and C tend to be vague and less specific. This seems to suggest that controllers might have a limit to the amount of information they can easily combine.

3.7.2 Analysis of decision behaviour

Outline of the main decision procedure:

The information used in most decision behaviour is associated with information from MG or NG 'summary' displays. The function of this display is to show what will happen to the level of stocks at 23.00 and 06.00 hours, if the computer estimate (ES) is correct, and the amount of gas put into the system is that given by Allocation on NG and $\Sigma\dot{p}$ on MG. These estimated stock levels are ESt_{23} and ESt_{06}. By comparing these estimates of stock with the required stock levels (RS_{23}, RS_{06}), it is possible to determine the change in allocation or $\Sigma\dot{p}$ needed to satisfy RS_{23} and RS_{06}. An example of this type of procedure is 3. 3.6.74 (2c) "Looking at the stocks, the estimated stocks from the MG 'sum', we find that we're making 100.6, selling an estimated 94.7, this will give us a stock of 62.3 in the morning which is much too high, we want a stock of round about 57. (f) We've got an estimated reduction rate change (CR) of -0.660, and we feel that it is necessary to take this off." The majority of decisions identified in the protocols of the three controllers are made on this basis. The procedure can be represented as an equation:

$$CH = RS - ESt \qquad - (o)$$

This can be expressed as a rate of change (CR), by dividing CH by the number of hours until 06.00. In the example quoted here it is evident that there must be some threshold value of CH which has to be exceeded before the controller will decide to make a change. The threshold in the example above will be something less than 5.3 (62.3 - 57). Factors which appear to affect threshold values will be discussed later. All decision sequences that exhibit the type of procedure represented in the equation (o) have been coded MC_o or NC_o. Those decision sequences that do not follow this procedure have been coded MC_{1-6} and NC_{1-3}. Table 3.17 compares the relative frequency of occurrence of main and alternative decision sequences.

TABLE 3.17 COMPARISON OF THE FREQUENCY OF MAIN DECISION SEQUENCES WITH ALTERNATIVES FOR THE THREE CONTROLLERS

	1	2	3	
MC_o	31	19	29	79
MC_i	9	14	20	43
	40	33	49	122
NC_o	34	16	32	82
NC_i	4	5	13	22
	38	21	45	104

Table 3.18 shows the frequency of occurrence of the six MG alternative sequences, and the three NG alternative sequences. Details of the procedures embodied in these sequences will be presented later.

TABLE 3.18 FREQUENCIES OF THE ALTERNATIVE DECISION SEQUENCES FOR THE THREE CONTROLLERS

		1	2	3	
MC_i	1	2	4	4	10
	2	2		1	3
	3	2	2	5	9
	4	2	3	3	8
	5	2			2
	6	1	4	6	11
		11	13	19	43
NC_i	1			3	3
	2	4	3	5	12
	3	1		2	3
		5	3	10	18

Evidence on decision behaviour from the types of information sampled:

Table 3.19 and 3.20 show the most frequently used information from the MG and NG 'Summary' displays. As might have been expected ESt is the most frequently sampled item of information. On the basis of equation (o) it might also have been expected that RS would have a similar frequency of occurrence. This is not so, the frequency is much lower. One explanation is that the controller seems to make tacit comparisions between ESt and RS, probably because RS does not change during a shift, unlike ESt. For example 3. 12.5.74(7k) "NG 'sum' is showing a total usage of 279.5 on 214 sendout (ES), this gives us a

TABLE 3.19 COMPARISON OF THE MOST FREQUENTLY USED ITEMS OF INFORMATION IN THE MAIN MG DECISION SEQUENCES (MC_o) FOR THE THREE CONTROLLERS

	1	2	3	
$\dot{p}$	15	1	15	31
ES	25	4	18	47
ESt	27	9	24	60
*PS	8	2	2	12
RS	2	4	5	11
CH	-	2	13	15
*cESt	5	-	-	5
	82	22	77	181

*Calculated or estimated items

TABLE 3.20 COMPARISON OF THE MOST FREQUENTLY USED ITEMS OF INFORMATION IN THE MAIN NG DECISION SEQUENCES (NC_o) FOR THE THREE CONTROLLERS

	1	2	3	
Alloc.	16	6	11	33
ToT	12	3	11	26
*PS	10	4	5	19
ES	26	3	17	46
ESt	33	10	26	69
*cESt	9	-	4	13
	106	26	74	206

stock in the morning of 178.5 (ESt_{06}), which is OK, if the sendout doesn't rise greater than that (referring to ES)." The second explanation is that on the MG 'sum.' display CH is already calculated so that it is not necessary for the controller to calculate RS-ESt.

Included in the tables is a calculated, and an estimated data item cESt and PS. This shows that there are a number of occasions where the controller is not satisfied with ES as a prediction, and consequently recalculates ESt using his own prediction of final sale PS. An example of this is 1. 23.5.74(15e) "And on NG an estimated stock (ESt) of 176.6, that's on a 266.6 sale (ES). (f) A slightly higher sale is possible with a maximum round about the 270 (PS) mark which would bring us down to a stock of about 173 (cESt) ...." The decision procedure expressed in equation (o) can be modified to accommodate this additional type of behaviour:

$$CH = RS - \underset{\substack{\uparrow \\ ESt + (PS-ES)}}{cESt} \qquad - (i)$$

Individual differences:

There are some individual differences apparent from Tables 3.17 - 3.20 in the sampling of information. The most striking difference is in the total amount of information actually used in making decisions. Controller 2 only uses a third of the information that his colleagues use. Table 3.17 indicates that this might be because he is involved in making fewer decisions. Calculation of the information per sequence, however, shows that this is not so, with controller 1 using 2.6, controller 2 only 1.1 and controller 3 2.6, items of information for each decision on MG, and on NG 3.1 for controller 1, 1.6 for controller 2 and 2.3 for controller 3. Another explanation, though less plausible, is that controller 2 has to make fewer decisions of commission. Examination of the number of control actions also shows this reasoning to be untenable, with controller 1 making 5 major control actions, controller 2, 7, and controller 3, 5. It seems therefore that controller 2 must either do less processing of information, less processing of information that is open to introspection, or remember more items of information so that he does not have to re-sample information that remains unchanged. A similar difference in processing rates is observed in predictive behaviour, where controller 1 uses 4.7, controller 2, 2.6, and controller 3, 4.8 items of information per sequence. As will be shown in section 3.8 a low rate of processing does not seem to be associated with any inaccuracy in making predictions. Table 3.21(a) shows the information sampled per sequence in the decision and prediction sequences, as well as information sampled per sequence in all the sequences identified in each controllers' behaviour. Table 3.21(b) shows that there is a significant difference between the controllers in the information sampled per sequence in all sequences identified in their behaviour, when the analysis is made on the average for each of the six sample shifts. Thus the individual differences in information processing seems to hold for all of the controllers' behaviour.

TABLE 3.21 COMPARISON OF INDIVIDUAL DIFFERENCES IN INFORMATION SAMPLED PER SEQUENCE

(a)

TYPE OF SEQUENCE		CONTROLLERS		
		1	2	3
DECISION	MG	2.6	1.1	2.6
	NG	3.1	1.6	2.3
PREDICTION		4.7	2.6	4.8
ALL		2.7	1.9	2.8

(b)

VARIATION	SS	df	MS	F	
CONTROLLERS	3.08	2	1.54	6.41	$p<0.01$
ERROR	3.58	15	0.24		
TOTAL	6.66	17			

Evidence on decision behaviour from alternative decision procedures:

It is not possible to carry out a comparison between the types of information used in the alternative decision sequence, because their frequency of occurrence is too low to make this meaningful. However, the difference between these and the main decision sequences, is that they appear to use different decision procedures. The list of alternative decision types shown below indicates other dimensions of decision behaviour. With the exception of type (4) on MG and type (1) on NG each of these indicate different decision procedures or different factors that have to be taken into account if a realistic decision is to be made:

MC types:

(1) Decision influenced by the state of the production plant.

(2) Decision to wait for an earlier action to take effect.

(3) Decision influenced by system constraints such as pressures and holder stocks.

(4) Considering a possible change, but deciding to wait for a while.

(5) Decision based on a general assessment of the situation, e.g. weather and supergrid pressure.

(6) Decision based on a prediction sequence.

NC types:

(1) Considering a possible change, but deciding to wait for a while.

(2) Decision based on a prediction sequence.

(3) Unspecifiable.

Types MC (5), (6) and NC (2) suggest possible decision procedures that are different or in some way by-pass the usual decision procedure. In types MC (6) and NC (2), the controller will make a prediction and then automatically make a decision without any apparent processing. For example 2. 22.9.74(4a) "We are now 1.4 on the hour up on the Sunday we are following and 5 cumulatively, even if the sales didn't run above it that would give us 88, so it now looks as though the sales are going to lift nearer the 95 mark. (b) In view of the fact we have not got a lot of sales in hand we are bringing all works to maximum makes." The probable explanation for this type of decision sequence is that the controller does not refer to any information from the 'summary', because he can remember all the necessary information from the last time the display was sampled. Type MC (5), which only occurs twice, makes a decision based on a variety of information but with no real indication of a different decision procedure. An example is 1. 18.5.74(8a) "In view of the current embarrassment with high plant capacity for production, the continuing good weather and forward weather forecast of warm and sunny for the next few days and the prospect of the Whitsun holiday coming next weekend. We've decided to take the No.1 stream at Washwood Heath off-line." This type of sequence, rather than indicating any different decision procedure, is probably a summary of a discussion with another member of the control room staff. The controller has therefore only mentioned the most salient factors that influenced his decision instead of giving a detailed description of how these were processed. Alternatively the controller may use some analogue procedure to combine the information. A more detailed explanation of this type of processing is given later.

Types MC (1), (2), (3) indicate factors not included in the decision equation (i) which can influence decision making. MC (2) can be included directly in equation (i)

$$CH = RS - cESt \mp (\Delta\dot{p} \text{ or } \Delta IR) \qquad - (ii)$$

Types 1 and 3 suggest another dimension of making a decision, i.e. timing. Equation (ii) will only process information about the size of the control action. Type 1 suggests a third dimension of making a control decision, and that is how the decision is to be implemented.

A careful scrutiny of the decision sequences both MC_o, NC_o and NC_i, MC_i, indicate five factors that influence when a decision is made:

(a) State of available plant

(b) State of pressures and holder stocks

(c) Peak hour soon

(d) Weather situation for immediate future

(e) On-going changes

All these factors are concerned with the immediate state of the system, whereas the information combined in equation (ii) is relevant to the long term state of the system. It is not possible to combine the information in the above list into an equation easily because of the difficulty of expressing the effect of each factor exactly in a common metric. There is very little evidence in the protocol data to suggest how the information might be combined. As argued above, any combination of information by ordinary arithmetical operations seems unlikely. An alternative is to suggest that information from these disparate sources may be combined by assessing the value of a particular factor approximately and combining such assessments in an analogue as opposed to a digital process. For example 2. 23.3.74(3a) "Holders are not losing much stock over this hour, so far with what information we've already got in for 14.00-15.00 hours. (b) In view of the fact that Tipton are going to increase the make later, it has therefore been decided to do a reduction at this time." This sequence may be reinterpreted by rewriting it in equation form, and expressing the effect of the Tipton change in terms of its influence on the hourly stock change.

$$\text{Total effect on stock} = SC + \Delta\,\text{plant} \qquad - (i)$$

The controller may consider the, Δ plant, to be equivalent to 2 stock units, and the 'not losing much stock' as a stock unit. The result of equation (1) will be +1, which may be assumed as his decision threshold as he decides to reduce make. It may be argued that all this type of procedure is doing, is to use ordinary arithmetical operations on approximate as opposed to more exact units of measurement. This may be true; there are however, two points that suggest that this procedure is different from a digital computation. The first is that combining approximate units of measurement, of size less than 10, can usually be carried out with a minimum of processing. The second is that when the value of one variable has to be converted from one domain to another without any exact rules of conversion, it is likely that this process will be limited by the controller's capacity for making absolute judgements. This suggests that the controller will only be able to classify one variable in terms of another in not much more than 7 units. For example the controller may collapse information about the weather into having a small, medium or large positive effect on stocks, or a small, medium, or large negative effect, as in 3. 2.5.74(11a) "Weather very dull looks a possibility of rain. (b) Keeping a careful eye on super-grid pressure, at the moment the tendency is for it to increase. (c) We still don't feel that we need to increase the make at Tipton and Coleshill to target as the sendout doesn't warrant it." This example may be expressed as follows:

$$\begin{array}{ccccc} \text{Effect on stock} & = & \text{S-Grid pressure} & + & \text{weather} \\ 0 & = & +1 & - & 1 \end{array}$$

If the interpretation of the above example is correct, it seems reasonable to suppose that the controllers carry out a combination of the relevant information in an analogue as opposed to digital process. The term analogue is used as in Bainbridge (1971), to refer to a computational process that is inaccurate and requires less mental processing than an equivalent digital process which would be more accurate but require more processing.

Factors affecting the type of action selected

Evidence from the protocol suggest five factors which can affect the controller's choice of a suitable control action:

(a) Availability of cheapest plant

(b) Naphtha feed stocks in or out

(c) Butane enrichment in or out

(d) State of gas characteristics (if characteristics are near the lower limit it is inadvisable to use peak plant.)

(e) Plant likely to be required in the next day or so.

The key decision rule is to choose the cheapest control action, unless there are system constraints, such as bad gas characteristics, or plant production restrictions. An example of a typical selection procedures is 2. 29.3.74(3c) "Load factors indicate that the bulk of the reduction will be at Washwood Heath, with the remainder at Coleshill, as we cannot do anything with Tipton at the moment. (d) Reduction will be 0.3/hr at Washwood Heath, 0.2/hr at Coleshill, giving a total reduction between now and 06.00 in the morning of 7.5m". The load factors mentioned in this example refer to the optimum load a plant will run under. Plants usually run most efficiently, and therefore most economically at about 82% of maximum load. Consequently when the controller makes a change he tries to ensure that he keeps the load factors near the optimum value for the different plants. In the example it was not possible for the controller to execute this strategy completely because of the Tipton restriction. Unfortunately the statement does not give enough detail to suggest how the controller modified his strategy.

It is not possible to represent the action selection procedure formally because of the lack of information on how certain combinations of constraints affect the choice of action. It might be suggested, however, that the best way of representing the controllers' behaviour would be as an algorithm, since the selection procedure is in effect a series of discrete decision processes. This is because the controller has to choose between a series of decision alternatives, using economic and system criteria, e.g. production constraints, as the basis for this selection. Economic criteria could be expressed in an equation, but to combine this with various system constraints, which are usually discrete, would not be possible.

NG selection procedure is straightforward, as there are only two valves from the National Grid that can be controlled directly. These valves control the flow of gas into the storage mains connected to each valve. The controller will adjust the intake depending on the pressure in the storage main at either of the two intake stations. As an example, 1. 23.5.74(13k) "The Barlaston differential is much smaller than the Rugby differential, in fact the Rugby main is down to about 495 in pressure. (1) So we'll put the largest amount of increase onto the Rugby side, put 0.6 in Rugby and 0.3 onto Barlaston."

Factors influencing the decision threshold

As mentioned earlier there must be some value of CH, see equation (ii), which must be reached before the controller decides that a control action is necessary. Unfortunately there is not enough data from the protocols to estimate thresholds with any accuracy. The few threshold values that are available vary from 3-13% of the particular RS_{06}. Some decision sequences indicate however, that there are certain factors that can influence the decision threshold. For example, 1. 23.5.74(1), The controller predicts MG final sale at 140 using a type B prediction procedure. In the subsequent decision sequence he says, "Looking at the stock position at 13.00, MG side, we've got a total make of 126.5, a predicted sendout of 134.6, which gives a stock at 23 hours of 35.9 which is quite satisfactory, no problems there, but a stock of only 54 at 06.00 tomorrow. (i) To hold a stock at 62m we need an increase of nigh on 0.5m an hour (CR) which we might just get from the two ballast air machines." This part of the decision process is straightforward, the 13% discrepancy between ESt and RS is above threshold. The change in hourly input rate to correct for this is 0.5, which can just be met. In the next statement it is apparent that he has also included PS=140, and taken into account the available change in production. The percentage discrepancy between cESt and RS is 3, which is below threshold. The mention of Friday and Whit weekend indicates that the controller is prepared to accept a larger discrepancy between required and estimated final stock, than would be normal because sales on the following day might be lower than originally expected. This suggests that any forward information about sales or plant restrictions etc. may affect the controller's decision threshold.

3.8 Comparison of the controller's prediction error

It is difficult to compare the performance of the controllers with each other because task demands are never identical. However, even if this problem did not exist it would be difficult to select a suitable performance indicator. The simplest criterion would be the number and size of control actions used to supply gas over a given period of time, since these can be directly related to the cost of supplying gas to the customer, although the exact relationship is difficult to specify in practice.

The alternative solution adopted here is to compare the error of the predictions made by each controller with his colleagues, and also to compare these predictions with the computer estimates (ES). It may be hypothesised that there will be a difference in the error of predictions made by the controllers because of their use of the different types of prediction method, see Table 3.14. It is also hypothesised that prediction error will decrease during the day, i.e. the most accurate predictions being made during the evening shift. Finally, it is hypothesised that controller 3 predictions would be similar to the computer predictions, as he uses this as the basis for most of his predictive behaviour.

TABLE 3.22 COMPARISON OF THE CONTROLLERS PREDICTIONS

SOURCE OF VARIATION	SS	df	MS	F	CRITICAL F	[+]df'	CRITICAL F'
A (Controller)	37.76	2	18.88	6.31	$F_{0.01} = 6.01$		
B (MG, NG)	22.90	1	22.90	7.66	$F_{0.05} = 4.41$	1, 3	
C (M,A,E)	152.00	2	76.00	25.41	$F_{0.01} = 6.01$	1, 3	$F_{0.05} = 10.1$
AB	16.70	2	8.35	2.79			
AC	61.40	4	15.35	5.13	$F_{0.01} = 4.56$	1, 3	
BC	33.90	2	16.95	5.66	$F_{0.01} = 3.55$	1, 3	
ABC	20.21	4	5.05				
WITHIN	53.90	18	2.99				
	399.10	35					

[+] Because the three controllers are observed under conditions B & C, the design is a form of repeated measures. The usual significance tests tend to yield too many significant results in this design. Winer (1970) suggests using the Greenhouse and Geisser (1959) procedures, which makes the critical values somewhat larger than would otherwise be the case. The procedure adjusts the degrees of freedom of the F ratios on those factors on which repeated measures occur, (B and C here). df' and Critical F' show the degrees of freedom and critical F ratios associated with the adjustment.

Values of PS were collected on morning, afternoon and evening shifts, for both MG and NG, and for each of the three controllers. The error in prediction was computed by expressing the difference between PS and FS* as a percentage of FS. The results were analysed using a 3x2x3 analysis of variance. Table 3.22 shows the summary table of the analysis according to Winer (1970) with the Greenhouse and Geisser (1959) adjustments for the critical F ratios. The results support the hypothesis proposed above.

Fig. 3.1 shows the interaction effect of AC. Controller 2. although more accurate at predicting during morning and evening shifts, than the other two, is not so accurate at afternoon predictions. Fig. 3.2 shows the BC interaction where MG predictions are worse in the morning and afternoon shifts than NG, but become slightly better in the evening. There seems to be no apparent reason for these interactions. Table 3.23 gives the summary table for an analysis of the simple effects of A for C, Winer (1970) it shows that the real difference in the controllers' predicting occurs in the morning. Examination of overall prediction accuracy shows controller 2. to have the most accurate performance and controller 3. to have the least accurate.

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*FS is the final sale for the day in question.

Fig. 3.1 GRAPH SHOWING ERROR SCORE PLOTTED AGAINST SHIFTS FOR THE THREE CONTROLLERS

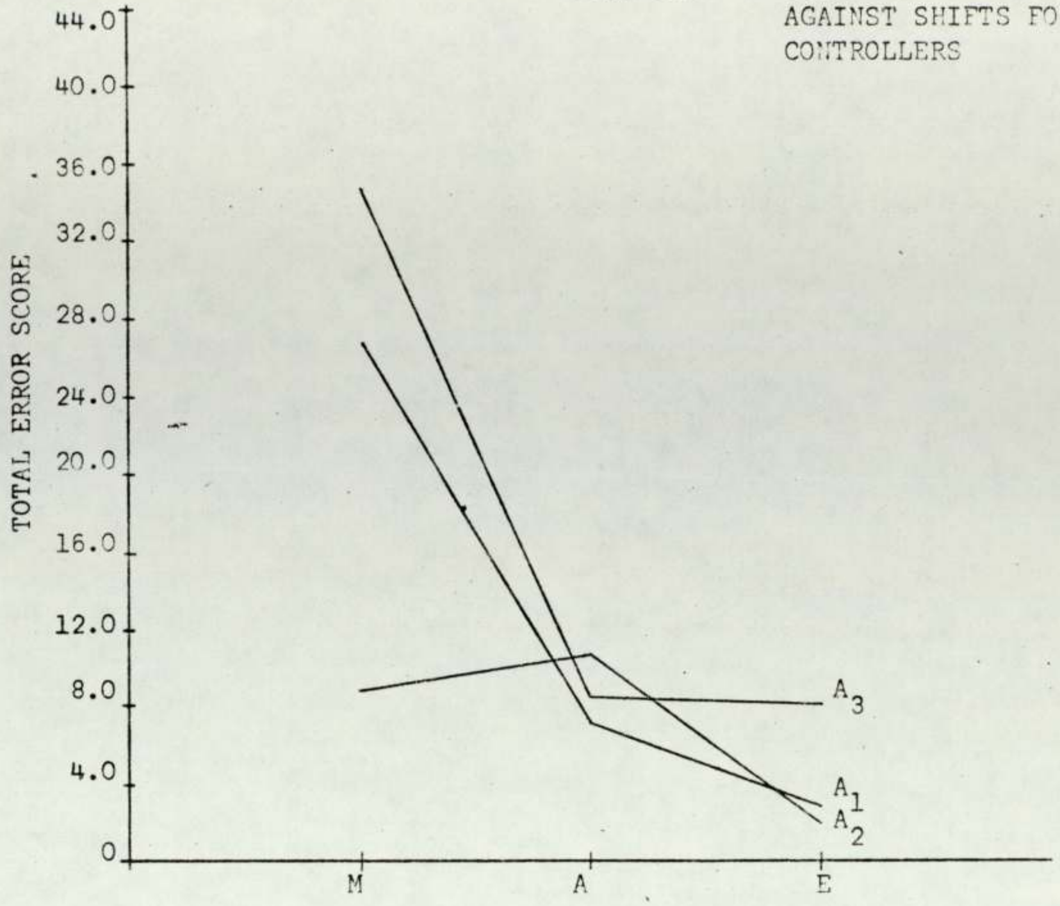

Fig. 3.2 GRAPH SHOWING ERROR SCORE PLOTTED AGAINST SHIFTS FOR MG & NG SYSTEMS

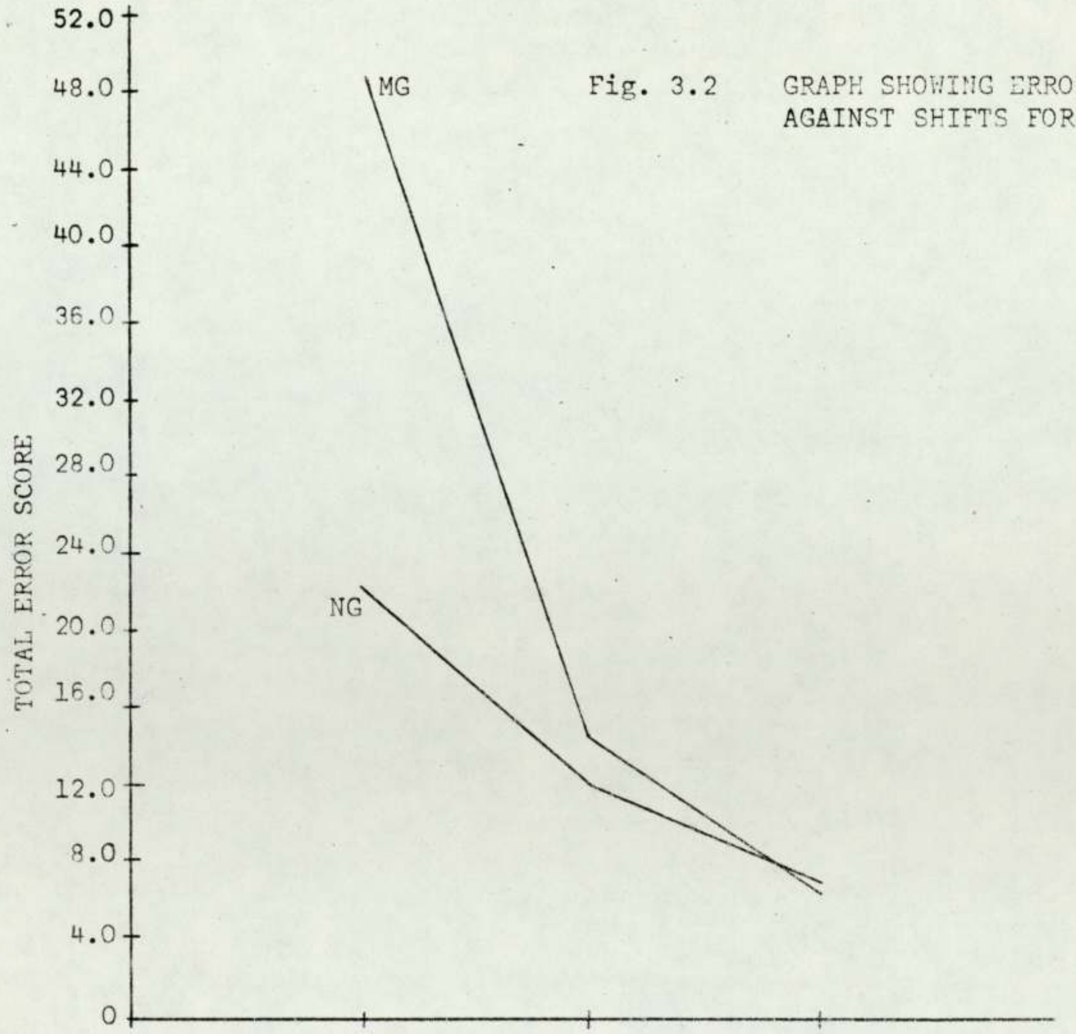

TABLE 3.23 SIMPLE EFFECTS OF A FOR C

SOURCE OF VARIATION	SS	df	MS	F	CRITICAL F
A for M	93.3	2	46.65	15.60	$F_{0.01}$=6.01
A for A	1.78	2	0.89		
A for E	5.37	2	2.68		
Within Cell	53.9	18	2.99		

To examine controller prediction more closely and to test the last hypothesis concerning controller 3 and ES accuracy, PS error was compared with ES error.

Table 3.24 shows the mean of the percentage errors for ES and PS errors. Table 3.25 shows the result of 't' tests carried out on the differences between ES and PS error. There are no significant differences, in fact all the differences are very small, and in only two cases is the PS error less than ES error. Controller 1. predicts NG sales better than ES, and controller 2. predicts MG sales better than ES. Generally, Table 3.24 shows that controller 1's predicting is as good as ES, controller 2 is better and controller 3 worse. This suggests that probably controller 2's methods of prediction are better than his colleagues as well as being better than ES. Table 3.14 indicates that over half the methods of prediction used by controller 2. were type B. This tends to suggest that the method embodied in type B can be used successfully when a suitable day is selected for comparison.

TABLE 3.24 COMPARISON OF MEAN ES AND PS PERCENT ERROR

		PS error	ES error
1.	MG	4.5	3.8
	NG	1.6	2.2
		6.1	6.0
2.	MG	1.7	2.7
	NG	2.0	1.4
		3.7	4.1
3.	MG	5.4	2.6
	NG	3.3	2.8
		8.7	5.4

TABLE 3.25 RESULTS OF 't' TEST ON DIFFERENCES BETWEEN ES AND PS ERROR

	MG	NG
1	0.23	-0.57
2	-0.58	0.78
3	1.3	0.27

The findings from this analysis and outlined above must be treated with caution. The results were only based upon 18 observations, six for each controller. To obtain more reliable results a larger number of observations selected at random for each controller over a year would be required. However, the results do suggest that this method of analysis is a useful means of comparing this aspect of control performance.

3.9 Conclusions

The three methods of analysis developed in the chapter, successfully detected individual differences in behaviour, as well as detecting overall differences in behaviour caused by varying task demand.

3.9.1 Individual differences

The main individual differences are related to the behaviour of controller 2. The information analysis indicated that he used FS' more often than his colleagues. The activity analysis indicated that he had a greater concern with predicting, and the sub-goal analysis showed him exhibiting more SCD sequences than either of his colleagues. Analysis of the prediction procedures used by the controllers reflect these differences. It is apparent that controller 2. particularly favours type B procedure hardly using type A. The analysis of prediction performance shows controller 2. to be the most accurate, and therefore suggests that the type B prediction procedure associated with controller 2. produces the most accurate predictions.

Individual differences are also apparent in decision making. Controller 2. uses half the number of items of information per decision sequence than his colleagues. It might be suggested that controller 2. is less capable of making effective decisions, except that a similar finding in prediction sequences did not mean that controller 2. was inaccurate at making predictions, in fact the contrary was true. Other plausible reasons for this difference are, that the controller describes his behaviour in less detail or, that he remembers previous information items so that he does not have to re-sample unchanged values.

3.9.2 Differences in behaviour over the shifts

Differences in behaviour over the three shifts shows that the amount of information and cognitive activities used is highest during the afternoon shift and lowest during the evening. The number of goal orientated sequences however, does not vary over the shifts. This suggests that at certain times of the day, more information processing is required to achieve the task goals than at others. The most processing occurs during the afternoon because this is probably the most important period during the day for making accurate predictions and decisions.

3.9.3 Similarities in prediction and decision procedures

There are several similarities in the procedures used by the controllers to predict and decide. The controllers use one or a combination of prediction procedures. The procedure or combination chosen is determined in part by the controllers' confidence in the information available. There is evidence which shows that the controllers' are continually revising the efficacy of the procedures being employed at any one time. There is also evidence which suggests that the controllers do not have well defined procedures for combining information from more than one of the basic prediction procedures. This may indicate a basic limit in human information processing.

Three dimensions of decision making were identified in the behaviour of each of the controllers:

(a) Size of a control change, given by the decision equation.

(b) Timing of a control change, influenced by a series of disparate factors, probably combined by an analogue process.

(c) Implementing a control action, processing probably taking the form of an algorithm, and guided by economic considerations, and system constraints.

The decision threshold, associated with the decision equation, seems to be influenced by forward information about sales trends and production constraints.

CHAPTER 4

The procedures for investigation used in this chapter were similar to those of chapters 2 and 3. The purpose of the investigation was:

(a) to see whether the methods of protocol analysis developed in chapter 3 were applicable to another cognitive task, and

(b) to analyse the skills of the electricity grid controllers and compare these with the gas controllers.

Results from the three methods of protocol analysis indicated that,

(a) there was more activity during the morning shift as well as more task goals to be achieved,

(b) only 32% of goal orientated behaviour was concerned with predicting and decision making compared with 88% in the gas task.

Analysis of decisions showed several types of decision behaviour. These various types of decisions were combined into a general decision model. The model was used to examine aspects of the decision procedures likely to affect performance.

4. A COMPARATIVE STUDY OF CEGB GRID CONTROL ENGINEERS

This chapter describes the task of grid control engineers controlling the supply of electricity to the West Midlands. The study was carried out at the Grid Control Centre, Warwick House, West Heath, during the summer of 1974. The main purpose of the study was;

(i) To compare the types of control skill required by grid controllers working in the gas and electricity industries, and to look for similarities

(ii) To discover whether the technique of describing cognitive activities developed in the last chapter could be generalised to the behaviour exhibited by the CEGB controllers

(iii) To study the control skill in its own right.

The main objectives of Electricity grid control are similar to those of Gas grid control, i.e. supplying electricity economically, safely, at correct voltage and frequency, with the minimum of power cuts. The following two sections will briefly describe the grid control system, and the requirements of the grid control task.

4.1 The grid control system

4.1.1 The National Grid system

The early developments of the electricity supply industry consisted of a generating station with a localised distribution network. Generation stations were usually planned with spare generators to cover breakdown and allow for routine maintenance. The undertakings were rarely connected, and there were large areas of the country without electrical power because it was not economic to provide it.

In 1927 the Central Electricity Board was formed, and they undertook to couple the localised networks and generating stations to 132 KV overhead lines. This enabled the most efficient utilisation of economic generating plant. Thus by 1936 with the completion of the network, spare plant capacity had dropped from 71% in 1926 to 26%, cutting the cost of generation from 0.42d to 0.12d/KWh.

Nationalisation in 1948 gave impetus to further planning, and the 275 KV grid was super-imposed on the existing 132 KV system, thus taking advantage of cheap generation on the coal fields. The 275 KV network allowed the installation of larger generators with the consequent reduction in cost. With the growth of demand for electricity showing no signs of slackening in the late 1950's, and the technical development of large generating stations (2,000 MW), the 275 KV system was extended to 400 KV. This introduction eased the growing transmission requirements and increased load carrying capacity, and is now the existing transmission system.

Co-ordination of generation to meet demand without overloading the network, is initiated by Central Control in London, and implemented by seven Grid Control Centres located at strategic points around the country. As well as implementing Central Control policy, the Area Grid Control Centres are responsible for ensuring that the voltage and frequency of the electricity supply is maintained within statutory limits at bulk supply points in the Area Boards.

4.1.2 Area Grid Control

The Grid Control Centre at Birmingham is responsible for supply of electricity to the West Midlands Area. Control is carried out from three rooms; the main control room for the whole area, and two district control rooms, one being concerned with the west side of the area (Wenlock) and the other the east (Arden). The area control room takes instructions from National Control and is responsible for the area's 400 and 275 KV system, i.e. the supergrid system; it is the functioning of this control room that will concern the study described later. The two district control rooms are concerned with the 132 KV grid system.

The Area Control room has three main wall displays:

1. The first is the switching board with the details of the state of all the isolators, circuit breakers, maintenance work and planned outages. One member of the three man shift team is continually engaged in operating the switching borad, keeping it up to date and supplying information to maintenance engineers in the field. Information is fed to thewall displays by a standard telemetry system similar in concept to that used in the Gas control room.
2. The second wall display shows the interconnection of the seven areas of the grid. Lights show which part of the grid is isolated.
3. The third is the loading display and is similar to (1.) in topography, but instead of having details of the switch configurations, it has dials showing the line flows around the area's supergrid network. Unfortunately no photographs were available of the control room to show these three wall displays.

The remaining two control engineers sit at a console facing the loading diagram. Around the console are a series of displays showing the state of output from the various control stations in the area's supergrid system. These displays are also connected to the telemetry system. Communication with the individual stations is carried out by telex, telephone or an automatic instructor which conveys standard commands to the individual stations by pressing a button with the appropriate instruction. Besides these displays on the console, which are a mixture of analogue and digital types, there are three chart recorders. The first shows both the total generation of the area and the total demand in MW. The second shows transfer to or from the area, (Transfer = Total demand - Total generation). The third shows the frequency (speed) of the electricity being supplied to the country. Connected with the frequency is a digital clock which shows how fast or slow the integrated frequency is compared with the statutory 50 HZ.

4.2 Task requirements of grid control

4.2.1 Outline of the task

There are three main requirements of operation:

(a) Load despatching to meet the demand and maintain inter area transfer. This includes short term load estimating often referred to as 'driving'.

(b) Giving instructions for the operation of the circuit breakers and isolators controlling the Grid system.

(c) Sanctioning the issue of safety documentation which includes permits to work on parts of the transmission system.

The description in this section will be restricted to (a) as it is the subject of the study described in the remainder of the chapter.

In order to assess demand, the day is broken down into four basic six hour periods. The periods are numbered 1 - 4 and are subdivided to cover the peaks and troughs of demand, Appendix 4.1 shows a typical demand curve split up into these periods. The peaks and troughs are variable in time depending on the demand pattern. An estimate of the demand of the specific features has to be made taking account of previous demand, weather forecasts and any other relevant information available.

For each of the characteristic features of the demand pattern, the National Control Engineer allocates a basic transfer*of power between Areas. To do this he has to take into account what information he has on availabilities of plant and the total expected demand within the country. Consequently in each Area, the Area Grid Control summates the Area's demand, basic transfer, spare plant allowance to cover errors in estimation, weather changes, the loss of largest item of plant, and the regulation of the system. This total is called the area commitment. Generation is then allocated to meet the Area commitment. This is done by allocating generation to plant that must run for security and special reasons, i.e. transmission limitations, voltage control, or generating station requirements. The remaining requirement is met from available plant loaded in merit (cost) order. The level of cost to meet the Area Commitment is obtained together with the cost of increasing or decreasing the level of generation. These costs from all the Areas are submitted to National Control where they are optimised to meet the overall demand at the cheapest cost. This may result in

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*Transfer: some Areas have more generation than they require to meet their own demand, hence they transfer or export electricity to those Areas that do not have enough generation.

a revision of some of the programmes. Finally agreed transfers are then given to each area, the algebraic sum of which will normally be zero. On receipt of the final Area Commitment the required plant is then ordered with the aim of fully loading the most economical plant and delaying the use of more expensive plant. In doing this, changes of demand must be balanced to maintain correct transfer and apply bias to the transfer should the frequency deviate from target (normally 50 HZ). Account has to be taken of sudden irregular demands for power, e.g. after the end of a TV programme. It then becomes important for Area Control to anticipate the amount of demand and the time of its occurrence. To meet this type of demand which increases very rapidly, fast response steam plant and gas turbine (GT) generators are instructed to full load. The period of high demand is usually of short duration (5-10 mins).

4.2.2 Manning in the Control room

To achieve the task of controlling the grid, three control engineers are required to man the system on a three shifts per day basis. The morning shift runs from 08.00 - 14.30, afternoon from 14.30 - 22.00, and evening from 22.00 - 08.00. On each shift responsibility is split between the three engineers for doing certain parts of the task. As stated earlier one engineer is permanently engaged in switching operations. One of the other two is usually responsible for arranging for plant to be ready and ensuring that the most economic plant will be fully loaded when required by the programme issued by National Control. The remaining control engineer is concerned with 'driving', i.e. ensuring that moment to moment fluctuations in demand are met as economically as possible. The control engineer responsible for driving is usually the Senior Controller, (equivalent to the Grid Controller in Gas Grid Control) and has overall responsibility for everything that happens on a shift. Qualifications of Control Engineers were at either HND or degree level, plus several years experience in the electricity industry.

4.3 Preliminary investigations

Several weeks were spent at the Control Centre talking to the Senior Control Engineers, getting to know them, and learning the details of the system and their jobs. Familiarity with the Gas Control System helped in the appreciation of the principles of Electricity Grid Control. Unfortunately only two out of the six Senior Controllers were prepared to co-operate in the preliminary investigation. This was not entirely unexpected as Senior Management had indicated that not all the controllers would view such an investigation favourably. A possible reason for this reticence on the part of the controllers is the sudden and momentary fluctuations in demand which are characteristic of the electricity supply system. It seems that some of the controllers felt they could not concentrate fully on the task and verbalise their thought processes. Another reason is that unlike their counterparts in the gas industry, the electricity controllers had probably been over exposed to people, particularly student trainees, requiring explanations of the function of the controller. The novelty of being investigated had worn off. It was not felt however, that a small sample would inhibit the proposed research, particularly as the main purpose was to make comparisons with the gas controllers.

4.3.1 Procedure

The procedure was similar to that employed with the gas controllers, described in Chapter 2. A practice session was held with each of the two controllers. They were asked to describe and explain their thought processes, so that the experimenter could record these in a note book. This preliminary investigation was carried out on two Thursday morning shifts.

4.3.2 Results of the preliminary investigation

As in the corresponding phase of the gas investigations the data only permitted the identification of purposive sequences of behaviour. Two main sequences were apparent, and were concerned with predicting and making decisions; the remaining activity was mostly concerned with receiving instructions from National Control or advising individual power stations of required changes in generation. The prediction sequences were concerned with making demand estimates for specific periods during the day. The decisions, however, were concerned with the sudden fluctuations in the system indicated by changes in frequency or generation.

Predicting

Both controllers seemed to have fairly similar methods of predicting demand. Interestingly these seemed to be fairly similar in principle to method 'B' employed by the Gas Controllers. The basis of the method is comparison with previous demand curves. The choice of a similar day is based on three criteria;

(a) weather, temperature, cloud, precipitation

(b) day of the week

(c) approximate time of the year.

It is not clear which of these is most important or how many of the conditions have to be fulfilled in selecting a suitable comparison. It seems from the evidence here that they are only used as a rough guide to selection. It is apparent, however, that pattern matching of the demand curves is fairly crucial. This is done usually by careful scrutiny, and occasionally the controller will even measure parts of the curves with a ruler. There seems to be little evidence however, for any formalised method of prediction employed by either controller. When asked to describe in more detail how they usually made predictions, they only seemed able to give a general description adding little to their initial descriptions.

Decision making

The decisions here are concerned with changes in demand that can be met by adjusting spare plant capacity viz. short term control. Some of the changes in demand can be anticipated, others can only be dealt with as they develop. The first controller was observed to have made only four decisions and subsequent actions. Two of these were anticipated changes in demand due to lunch time drop and pick up. The other two were due to sudden changes in frequency and demand. The second controller, however, anticipated six changes in demand, including two similar to those anticipated by the first controller. Comparison of these two events showed differences in the timing of the actions made by the two controllers. This may have been due to individual differences, different spare plant, or different demand characteristics. The difference in the number of events predicted by the two controllers is more difficult to explain. One suggestion might be that the first controller was less efficient. Efficiency, however, of control performance is not a matter of missing an anticipated change. If there had been a demand change the controller would have had to make a control action, otherwise the frequency may well have gone outside statutory limits. Efficient control consists of anticipating the time and the size of the demand change. Error in prediction of either of these can mean that unnecessarily expensive plant is brought up to load. A second suggestion for this difference is that the controller forgot to tell the experimenter what he was doing. This seems quite possible as the first controller was reticent about several events, and the experimenter had to encourage him to explain what was happening on these occasions. A third explanation is that the demand characteristics were different on the two days in question. This explanation seems unlikely as the two days in question were both Thursdays and separated by a week.

Both controllers were only recorded having reacted to sudden change in the system state twice. The changes that triggered this type of decision behaviour were deviations of the frequency from the target value. A discrepancy of 0.05 HZ is supposed to indicate a required change in generation of 40 MW.

In both anticipated and sudden decisions, control actions were made by picking up or dropping spare plant in merit order. This was a general finding. The following section describes a more detailed analysis of the electricity grid controller's behaviour using the verbal protocol technique.

4.4 An investigation of the Electricity Grid Controller using verbal protocol techniques

4.4.1 Objectives

To reiterate, the main reasons for carrying out this investigation were;

(i) to analyse the electricity controllers behaviour

(ii) to compare this behaviour with the Gas Grid Controllers'

(iii) to see how successfully the methods employed in Chapter 3 could be adapted to analyse behaviour on a different task.

4.4.2 Procedure

Unfortunately only one of the two controllers from the preliminary study was prepared to take part in this second investigation. Recordings were made using a radio microphone. This consisted of a transmitter carried in the controller's pocket, with the attached microphone worn on his jacket lapel. The controller had the facility of activating the receiver and recorder via an additional switch connected to the transmitter. The radio microphone permitted greater freedom of movement than with the hand microphone and cable used in the Gas Study.

Two practice sessions with the controller using the equipment, produced more detailed data than the preliminary study. This indicated that it would be worth continuing the investigation, using a similar procedure to that adopted in the Gas Study.

The controller recorded protocols for two mornings, two afternoons and two evening shifts, during the months of July and October. Unfortunately some problems were encountered with the reed switch in the receiver, and on two occasions recording had to be completed using the ordinary hand microphone technique. Also because of this trouble, some of the first words of certain events were not recorded; in most cases this was the time at which the event took place. The hand microphone technique was more reliable although less convenient.

4.4.3 Details of information sampled

Below is an explanatory list* of all the information sources shown in Table 4.1. The Table accounts for 84% of all information sources sampled by the controller over the six shifts. Sources that occurred with a frequency of less than 1% were omitted:

1. FR This indicates that the controller has sampled the frequency display and given a particular value of the frequency.

2. ΔFR This shows that the controller has noted a change in frequency, he often says frequency increase or decrease. Because the frequency is recorded on a pen-recorder the controller can note the change in frequency immediately whereas with a digital display he would have to compare $FR_i : FR_{i-I}$

3. LOL Lower operational limit of the frequency, 49.8 HZ

4. CE Clock error, cumulative effect of frequency variation in seconds, e.g. if the frequency is above 50 HZ, an electric clock will run fast, and vice versa.

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*A foldout reference list of these information abbreviations is presented in Appendix 9.1 for easy access.

5. T_F Target frequency, the frequency usually requested by National Control (NC) to maintain CE at zero.

6. T_R Transfer, the net amount of MW being imported or exported from the area. West Midland is an importing area.

7. T_T Target Transfer, again requested by NC

8. D Demand in MW from the customers

9. D' Refers to a previous demand value usually when the controller is looking through his past records

10. E_D Estimated demand, i.e. demand predicted for a given period. In the protocol it usually refers to an estimate made by a previous shift which the controller is now considering updating.

11. ΔTGO Change in total generation for the area

12. PLANT STATE The controller has a log sheet on his desk which shows all the plant in the area and their present status. As a control action is made or information received, the controller will note this change in plant state with approximate time of occurrence on the sheet. Plant state refers to the general state of plant in the area as shown on the log sheet.

13. WTHR Refers to the present weather situation

14. F/c Weather forecast

15. T_F* New request target frequency

16. T_T* New requested target transfer

17. PROG* New programme

18. INDIVIDUAL PLANT INFO Refers to information or telephone conversation with individual stations about their state of plant. It will include information about whether a set is on or off, whether it is synchronising, whether there is a change of availability, due to a break down, a set tripped[+]etc.

4.4.4 Results of information analysis

Table 4.1 shows that there is a considerable bias towards information sampling in the morning. It may be recalled that most information in the Gas task was sampled in the afternoon, and it was suggested that this was because afternoons were the most critical period of the day. With electricity it seems that the morning is the critical time. This is probably because the controller has to gradually bring on all his day plant as the morning load increases through breakfast time. A mismatch in bringing on all the plant (2000 MW in 2 hrs) will have a detrimental effect on frequency. Also during the morning shift there are three critical features of demand, the breakfast peak 2A (see Appendix 4.1), pre-lunch peak 2B and post lunch peak 3A.

The table also shows the types of information most frequently sampled.

[+] A temporary isolation of a set due to an overload or similar fault condition occurs automatically for protection.

TABLE 4.1 COMPARISON OF INFORMATION SAMPLED ON THE 3 SHIFTS

	SHIFT			
	M	A	E	TOTAL
FR	19	11	6	36
ΔFR	9	8	4	21
LOL	1	1	1	3
CE	1	4	2	7
T_F	10	6	3	19
T_R	16	6	8	30
T_T	13	5	7	25
D	7	2	2	11
D'	2	3	2	7
E_D	1	2	2	5
ΔTCO	1	-	-	3
PLANT STATE	2	-	1	3
WTHR	4	-	-	4
F/c	4	1	2	7
$T_F{}^x$	1	4	1	6
$T_T{}^x$	3	2	-	5
PROG^x	2	2	-	4
INDIVIDUAL PLANT INFO	17	7	10	34
TOTAL	113	64	53	230
EXPECTED*	59.2	79.7	91.1	

$X^2 = 67.92$

$p << 0.001$

df = 2

*Expected frequencies are calculated under the null hypothesis that information sampled per hour is constant.
Thus Expected afternoon consisted of two shifts one 7.5 hrs long plus one 10 hrs (Sunday afternoon shifts are longer) divided by total number of hours sampled i.e. (17.5/50.5) x 230.

These fall into two general categories:

(i) information about the state of the grid system, ΔFR, FR, T_F, T_R, and T_T, and

(ii) information about the state of individual plants in the production system.

It is of particular interest to examine the sampling rates for some of the variables in category (i). For example FR and ΔFR combined gives 57, over a period of 50.5 hours, i.e. a rate of 1.1 an hour. This seems remarkably low for a variable that is of great importance in controlling the system, and where the frequency meter is positioned directly in front of the controller on his control desk. Two reasons are proposed for this; one is that the protocols give insufficient or inaccurate data on the controller's behaviour, the second is that he only mentions critical values, i.e. when he is considering making a control change. To examine the suggestion of accuracy it was possible in some cases to correlate the value of frequency given in the protocol with frequency traces. A sample of 13 hours of frequency traces was obtained, and it was found that the nine values of frequency mentioned in the protocol corresponded exactly with those from the trace. This does not however, answer the problem regarding insufficiency of data. Inspection of decisions where frequency is the main source of information reveals that the number of decision of this type is 17, and is less than the frequency of occurrence of either ΔFR or FR. To be certain that all the decisions were recorded; two shift protocols were checked with the logging sheet, and a complete correlation was found between control actions on the sheet and in the protocol. This finding suggests that the controller mentions frequency more often than would be necessary to deal with frequency determined decisions, and so the protocol does not give insufficient data on important events.

4.4.5 Details of activity types

Below is an explanatory list of all the activities shown in Table 4.2. The activities in the Table account for 85% of all activities observed in the protocols. As with the information sources, activities with a frequency of occurrence less than 1% have been excluded. There are 17 different types of activity and these are collected in 8 categories similar to the activities in the Gas Controllers' protocols. Most of the examples that follow can be found in the sample protocol Appendix 4.2.

1. Information acquisition

NOTE	Identical to that in Chapter 3
ADVICE	Identical to that in Chapter 3
REQUEST	This is usually a command or instruction from NC (National Control) to change one of the operating constraints: T_F or T_T e.g. 10/7/74 (17d) "He's (NC) also revised his requirements for the early afternoon period and more of our plant is required in cost than was required for the original programme."

2. Arithmetical operations

COMPARE	Identical to the activity in Chapter 3

3. Estimating procedures

PREDICT(S)	This is short term prediction i.e. predicting variations in demand over a period of between a few minutes and half an hour. e.g. 10/7/74 (18b)"And within the next few minutes the demand is going to start to fall."

PREDICT(P) The controller predicts the demand peak or trough for a given period. e.g. 10/7/74 (2b) "3200 is the breakfast time load, 3200, we're looking through the past records at least 3200, I think we might put in 3300 ---- for 2B" It is evident that there is some complex processing going on under the rubric of predict(p), however in most cases the controller gives little indication of what this might be.

4. Evaluating

EVALUATE Identical to the activity described in Chapter 3.

5. Decisions

DECIDE 1 As in the decide described in Chapter 3, the controller has to decide whether a control action is necessary. e.g. 10/7/74 (18b) ".... we'll anticipate this and drop some generation now." In the example he has predicted a drop in demand, presumably the size of the predicted drop has convinced him that a change in generation is required.

DECIDE 2 As in the activity described in Chapter 3 the controller decides on the suitable details of the control action. e.g. 10/7/74 (8b) "And we've instructed on the plant in 3 stations, that's a total of 7 generators and a total of some 200 MW"

CONSIDER 1, AFFIRM are identical to the activities described in Chapter 3.

6. Details of control actions

DESCRIBE Identical to Chapter 3

IMPLEMENT	This refers to the activity of following a program set by NC e.g. 10/7/74 (1h) "The 2B plant requirement would appear to be even more plant on the bars that's being instructed on, and a suitable amount of hot standby in addition has been instructed."
INSTRUCT	This implies that a decision has probably been taken but only the details of the change in plant required are actually given in the protocol. Because it cannot be certain that a decision has been made, the activity is taken at face value, and considered as a descriptive term. e.g. 10/7/74 (20a) "GT instructed off at Ironbridge 'B'."

7. Recall

Identical to Chapter 3 activities

8. Explain and comments

Identical to Chapter 3 activities

4.4.6 Results of activity frequency analysis

Table 4.2 shows the same morning shift bias as Table 4.1 and for the same reasons given in 4.4.4. The most frequent activities seem to occur in categories 1, 2, 5 and 6. However, of particular interest is the comparison of this table with 3.7 in the last chapter. Inspection of Table 4.2 shows that 14 of the 17 activities are similar to those in Table 3.7. The common activities account for 88% of all the observed gas controllers' activities and 85% of all the observed activities of the electricity controller. These results make it possible to compare most of the important cognitive activities in the

TABLE 4.2 COMPARISON OF ACTIVITIES FOR THE THREE SHIFTS

	SHIFT				
	M	A	E	TOTAL	
1 Note	43	27	22	92	135
Advice	15	6	7	28	
Request	5	9	1	15	
2 Compare	28	15	10	53	53
3 Predict(s)	4	6	2	12	24
Predict(p)	7	5	-	12	
4 Evaluate	5	1	2	8	8
5 Decide 1	6	4	1	11	66
Decide 2	21	18	5	44	
Consider 1	3	1	-	4	
Affirm	2	2	3	7	
6 Describe	6	6	22	34	63
Implement	2	2	2	6	
Instruct	5	8	10	23	
7 Recall	1	4	1	6	6
8 Explain	5	5	1	11	16
Comment	2	2	1	5	
TOTAL	160	121	90	371	
*Expected	95.5	128.6	146.9	$X^2 = 66.05$	

$p \ll 0.001$

df = 2

*Expected frequencies calculated on the same basis as in Table 4.1

two tasks, and at this level to examine differences in controller behaviour on the two control tasks.

Table 4.3 shows that the controllers in the gas task do more information sampling from control room sources, more basic arithmetical operations, and make more decisions type 1, than might be expected. The electricity controller's behaviour exhibits more 'advice', 'decide 2', 'describe' and 'explain' activities than expected.

These comparative findings may be summarised by the general statement that, more information is collected and processed in the gas control, whereas more control actions are made in electricity control. The probable reason for this, is the different nature of the two systems. The major distinction is that gas can be stored and used to meet the mementary fluctuations in demand. In the electricity system fluctuations can only be met by picking up or dropping generation. Consequently the gas controllers are more concerned with predicting final sale, so that stock can be maintained, whereas the electricity controllers are concerned with making decisions due to unexpected fluctuations in demand. The gas controllers have to make predictions nearly every hour which require a considerable reduction of information. The electricity controllers, on the other hand, only have to make a prediction for a given period once or twice a shift, but have to make two or three control actions an hour. Therefore, the gas controllers may be considered to operate more on a feed-forward basis, and the electricity controllers on a feed-back basis.

TABLE 4.3 COMPARISON OF COMMON ACTIVITIES BETWEEN GAS AND ELECTRICITY CONTROLLERS

	GAS		ELECTRICITY		TOTAL	X^2
	Frequency	Expected	Frequency	Expected		
Note	838	799.8	92	130.2	930	13.03^{oo}
Advice	20	41.3	28	6.7	48	78.70^{oo}
Compare	475	454.0	53	73.9	528	6.98^{o}
Predict	136	137.6	24	22.4	160	0.13
Evaluate	48	48.1	8	7.8	56	0.10
Decide 1	199	180.6	11	29.4	210	13.39^{oo}
Decide 2	35	67.9	44	11.1	79	113.45^{oo}
Consider 1	63	57.6	4	9.4	67	3.60
Affirm	64	61.1	7	0.9	71	0.98
Describe	81	98.9	34	16.1	115	23.14^{oo}
Recall	17	19.8	6	3.2	23	2.84
Explain	6	14.6	11	2.4	17	35.80^{oo}
Comment	26	26.6	5	4.3	31	0.22
	2008		327		2335	292.36*

^{o} $p<0.01$; df = 1

^{oo} $p<0.001$; df = 1

*$p<0.001$
df = 12

Null hypothesis is that the frequency of occurrence of the activities is independent of whether the observations were made on the electricity or gas tasks.

A final criterion for comparison is the number of conditional activities. In Chapter 3 it was suggested that conditional or hypothetical statements were indicators of the higher levels of cognitive functioning, and that the frequency of occurrence of this type of behaviour might reveal some feature of task difficulty. The number of such statements recorded for the six shifts was 6, approximately half the number noted on average for the gas controllers. However, expressed as a percentage of 'consider', 'evaluate', 'decide1', and 'predict' statements, it is the same as in the case of the gas controllers, i.e. 6.6%. This might suggest that the two tasks are similar on this indicator of task difficulty. However, with such a small sample the result must be treated with extreme caution, particularly as there are no prior grounds for supposing that the indicator has validity.

4.4.7 Details of sub-goal types

A list of the thirteen codes indicating goal types is given below. The sub-goals in the table account for 83% of all the sub-goals recorded in the protocols. Goal types with a frequency of 1% or less were omitted.

1. Decisions

MD_{a-h} This indicates all the control decisions, the subscripts a-h denote the characteristic feature of the decision process. Only types a, b, d & h are included here: e,f & g had a low frequency of occurrence. In type a, the decision variable is the frequency. Type b, there is more than one decision variable, usually frequency and transfer. Type d occurs through the controller anticipating a demand change. Finally type h is concerned with variations in volts, but is not directly relevant to the demand-generation relationship, which is the central feature of control.

2. Indirect decisions

C	Considers making a control change
Im	Implementing a NC program
In	Instructing changes in plant
Ds	Describing the details of control action

Most of these sub-goals are similar to the activities described in the previous sub-section. This is because they are characterised by short self contained statements, so that many activities in this task are not implemented by a higher level of goal activity.

3. Prediction

PL Sequences of behaviour coded thus are concerned with predicting demand for a particular period peak, e.g. 2B.

4. Information receiving

N	Notes, identical to the activity
Rq	Request, identical to the activity
Ad	Advice, identical to the activity

5. Information transmission

Rp	Information specially prepared for management report

6. Memory

Re	Recall identical to the activity

The majority of the sequences of behaviour associated with a particular goal are short and can be identified with basic activities. Most of categories 2, 4 and 5 are concerned with transmitting or receiving

TABLE 4.4 COMPARISON OF SUB-GOAL TYPES FOR THE THREE SHIFTS

		SHIFTS				
Class	Goal	M	A	E	TOTAL	CLASS TOTAL
1	MDa	6	9	2	17	44
	MDb	9	7	1	17	
	MDd	3	2	2	7	
	MDh	1	2	-	3	
2	C	1	4	-	5	64
	Im	4	3	3	10	
	In	4	6	8	18	
	Ds	5	5	21	31	
3	PL	9	6	3	18	18
4	N	3	3	6	12	46
	Rq	4	8	1	13	
	Ad	8	7	6	21	
5	Rp	2	1	-	3	3
6	Re	6	3	5	14	14
Total		65	66	58	189	
Expected		48.6	65.5	74.8	$X^2=9.41$	

$p<0.01$

Expected frequencies based on the null hypothesis that the goal orientated behaviour used per hour is constant.

information or instructions, requiring little or no processing on the part of the controller. It is only in categories 1 and 3 that the controller is involved in transforming information, and these only account for 32% of the total number of goal orientated sequences.

4.4.8 Results of sub-goal frequency analysis

Table 4.4 demonstrates a significant bias of more happening during the morning and less at night time, although to a lesser extent than shown in the information and activity analysis. This does not show the same result as the preceding chapter, where there was no bias in the number of purposive sequences of behaviour required to control the system. The possible reasons for this are that:

(i) the electricity grid has more fluctuations in demand during the morning, and

(ii) the electricity information system does not have the same hourly cycle that the gas computer does in information presentation.

There is little similarity at this level with the goal behaviour in the gas task. This is due to differences in the nature of the two systems as described in 4.4.6

4.5 Discussion of decision and prediction procedures

These two functions seem to be the most important aspects of the controller's behaviour. In particular, the decisions deal with correcting short term fluctuations in demand, whereas the predictions are longer term and comparable with the prediction behaviour of the gas controllers.

4.5.1 Decision procedures

This sub-section deals with the following aspects of decision procedures:

(a) Basic type of decision procedures as identified in 4.4.7,

(b) Similarities between the different procedures,

(c) Combinations of different decision procedures,

(d) A decision equation,

(e) The decision threshold,

(f) Possible modifications of the decision model,

(g) Features of the decision model likely to limit performance.

(a) The basic types of decision procedure:

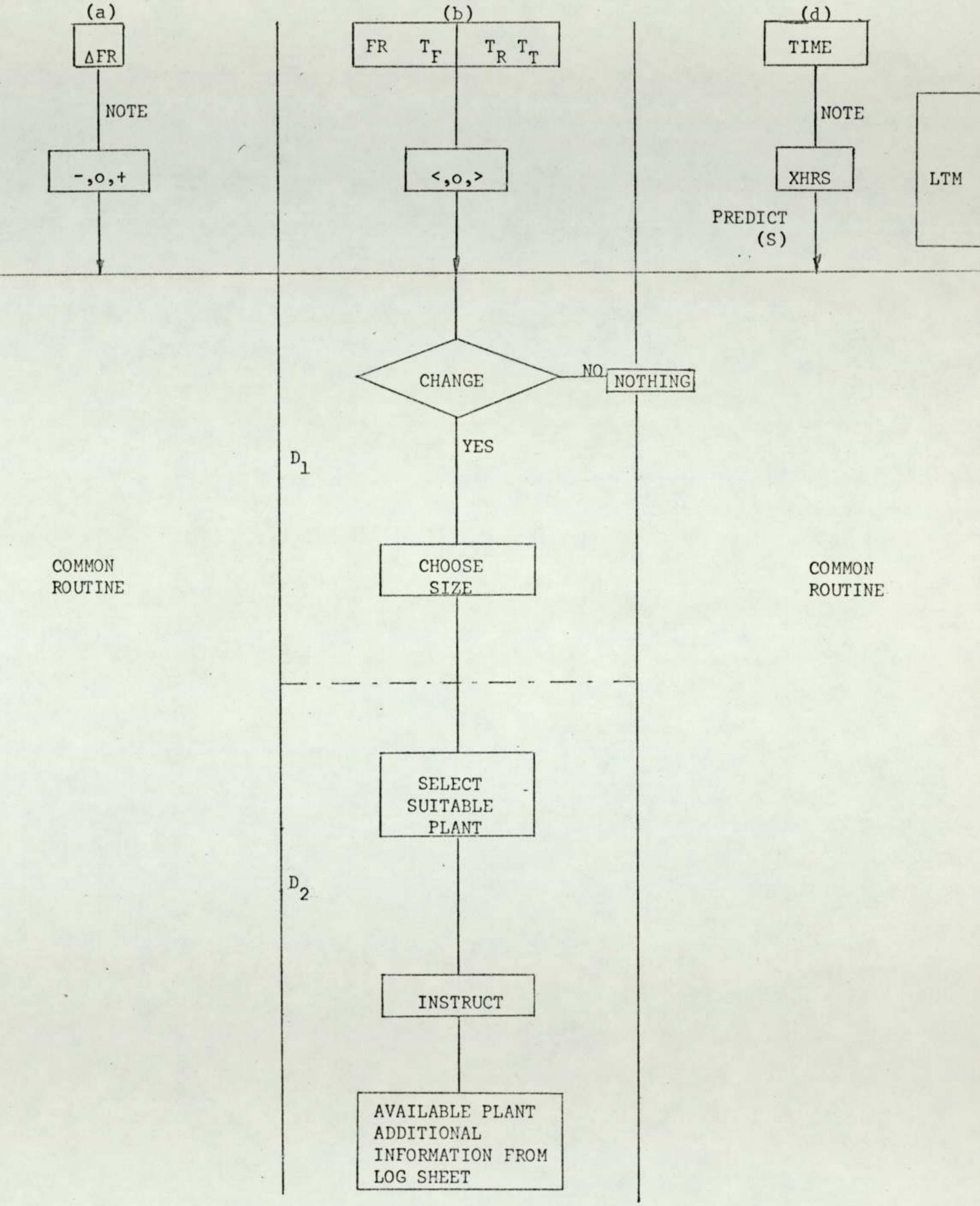
In both types (a) and (b) the controller operates in a closed loop manner. He observes an unacceptable change in system parameters and corrects by a change in generation. The difference between the two types is in the particular parameters that determine the control procedure. In type (a) a change in frequency is the important feature that triggers corrective action. In type (b) more than one source of information is important in bringing about a control action. The types of information are usually FR compared with T_F and T_R compared with T_T, and occasionally the actual demand D. The other frequently occurring decision procedure is (d). This is fundamentally different from (a) and (b) because it is open loop control. The controller predicts the time and size of a demand change sometime in the future.

The remaining types of procedures of interest are (e), (f) and (g); although not included in Table 4.4, these are relevant because they indicate additional types of information that are considered by the controller in decision making. Type (e) is concerned with choosing a suitable control action, i.e. 'decide 2' activity, and follows a type (a, b, d). Type (f), the controller receives advance information about a change in plant generation, usually due to a breakdown, and selects a suitable plant for replacement. Type (g), NC changes the operating constraints, e.g. transfers target, so that the controller has to adjust his plant position accordingly.

(b) Similarities between decision procedures a, b and d:

Fig. 4.1 shows the different initial processing stages of (a), (b), (d), but also shows a common decision routine based on the two activities 'decide 1' and 'decide 2'. At this level of analysis it is difficult to say how the decision for a change is made, or how suitable plant to implement the change is selected. With regard to choosing the size of an action, this must be related to the size of disturbance that triggered decision procedures in the first place. There is evidence that the controllers convert frequency excursions into a MW change by the general rule 0.05HZ = 40MW. With excursions of T_R from target transfer, no conversion is required: the information is already in MW, i.e. a 1 to 1 transformation. With predicted changes in demand, type (d) the controller probably has the expected size of change already in MW, stored in long term memory. Since the controller can convert all changes in systems parameters to MW, the real decision must be whether the change in the demand is large enough to warrant a change in generation, viz. there must be some kind of threshold; this will be discussed later.

Fig. 4.1 INITIAL PROCESSING STAGES OF (a), (b) AND (d) CONNECTED TO A COMMON DECISION ROUTINE



The selecting of suitable control action, a 'decide 2' activity, is based on choosing the cheapest plant available to meet the desired change in generation. The controller can do this easily by looking at his log sheet which will tell him which plants are carrying spare capacity, or are on stand-by. In some cases the controller is so familiar with the plant in his area that he can remember which plants to pick up or drop without even looking at his log sheet.

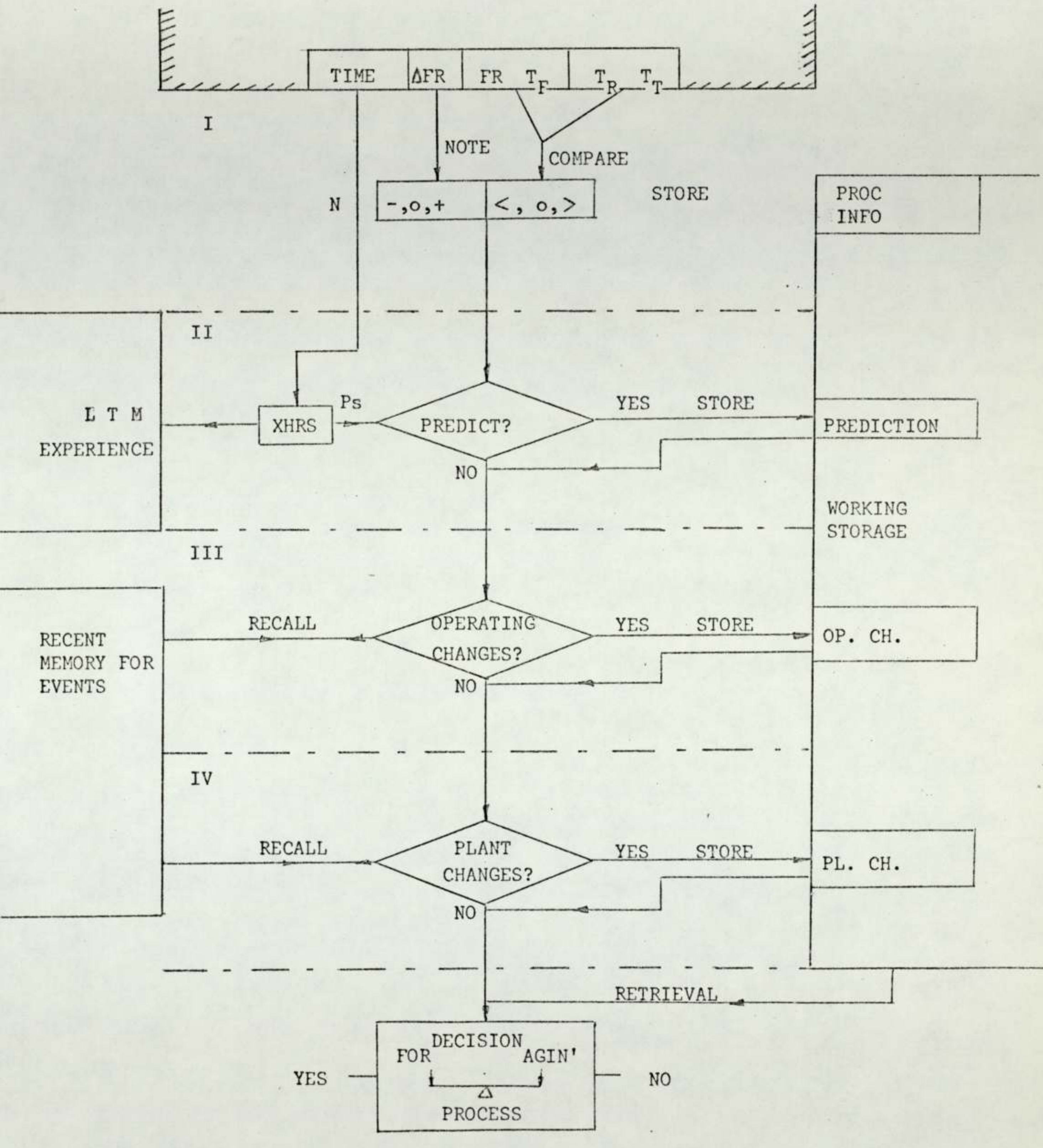
(c) Combinations of various decision procedures

Besides the occurrence of (a), (b) and (d) individually, there are examples of combinations: (b) + (d) occurs twice, and (a) + (d) once. This might suggest that the three main types are just instances of a general procedure which can adapt to deal with specific circumstances. There is also evidence that the main types are combined with the infrequent (f) and (g). For example the controller combines (a) and (g), as well as (b) and (f).

Fig 4.2 shows a flow diagram split into four stages, each stage represents a particular factor or factors that can influence decision making. Stage I refers to types (a) and (b), i.e. decisions based on information about the system parameters. Stage II refers to type (d), i.e. predicted fluctuations in demand. Stage III refers to type (f), i.e. where a change in T_F or T_T can implement a control action. Stage IV refers to type (g), i.e. a change in plant state can implement a control action.

It seems from the evidence here that information relevant to any of the four stages can be determinants of decision behaviour. It also seems

Fig. 4.2 DIAGRAM OF GENERALISED DECISION ROUTINE



from the evidence on combinations of decision types, that although information relevant to a specific stage may initially trigger decision behaviour, the controller must also consider current information relevant to the remaining 3 stages. The information relevant to each stage is indicated by the questions in the diamond boxes. If the answer to any of the the questions in the boxes is no, they will not be mentioned in the protocol. There is no indication from the protocol whether there is an order of priority suggesting which stage should be carried out first. It seems likely, however, that the controller considers information relevant to each of the four stages every time decision behaviour is implemented.

This suggestion leads to problems regarding sequential processing and is the raison d'etre of the proposed working storage. When each of the four stages is carried out, the result is held in working storage until the controller collects all the relevant information and 'weighs' it in the decision process. Whether the stages are processed sequentially is a matter for conjecture, Neisser (1963 & 1967) considers the possibilities of multiple processing. Protocol data is produced sequentially so no direct evidence on multiple processing can be expected. Presumably however, if the relevant information from the stages is in a compatible form, i.e. expressed in MW; it would greatly assist in the speed of combining information ready for the decision. The more skilled the controller the quicker his processing, and the less working storage required, so that in some cases the information from different sources may be combined almost immediately. This introduces the problem of how the relevant information is combined, or 'weighed'.

(d) The decision equation:

The combination process in the diagram is depicted as a see-saw balancing the 'fors' and 'against'. This might appear to be a naive representation of a covert process. Examination of relevant evidence suggests however, that this might not be such a simple minded formulation. For example 10/7/74 (26) "Demand will increase slightly between now (14.00) and 14.30, FR is above T_F and T_R above T_T, should cater nicely for pick up in demand over next half hour". It seems that the controller is 'balancing' the effect of an expected demand pick up against the over generation indicated by FR and T_R. The result of this 'balancing' is that he eventually picks up 42 MW of generation. This suggests that the expected increase in demand was 42 MW greater than the over generation indicated by FR and T_R. The 'balancing' described here could be usefully represented as an equation:

S.C. (size of change) = estimated demand increase - over generation - (i)

The situation however, is not as simple as this, determination of the last term, over generation, is the problem. FR - T_F gives the discrepancy between the state of the national system's generation and demand. This can be converted into MW at the area level by the use of the conversion rule described earlier. However, T_R - T_T gives the discrepancy between the area's generation and demand. T_R - T_T does not necessarily equal FR -T_F and consequently the controller has to decide which information is most important. This can depend on a number of factors, particularly related to the state of spare plant available, and the cost of altering the spare. Equation (i) is therefore modified by the addition of weighting factors:

$$S.C. = (T_T - T_R)k + x(FR - T_F)c + (\Delta Dp) \quad - \text{(ii)}$$

k = weighting factor

x = conversion rule HZ to MW

c = weighting factor

ΔDp = predicted change in demand

Unfortunately there is not enough evidence to determine values of k or c, although by a careful correlation of decision sequences with frequency and transfer traces this could be achieved. There are examples in the protocols where either the T_R or FR discrepancy dominates, in most cases the discrepancies are in the same direction. On the occasions when the discrepancies are in opposition, the FR discrepancy takes priority, so that k = o.

Equation (ii) can be modified to include information relevant to Stages III and IV. To allow for changes in operating constraints two terms $(T_T - T_T^*)$ and $(T_F^* - T_F)x$ may be added, and to account for changes due to variation in total generation a term (ΔG) may be included. Thus an equation combining all the information relevant to making a decision may be expressed as:

$$S.C. = (T_T - T_R)k + x(FR - T_F)c + (\Delta Dp) + (T_T - T_T^*) + (T_F^* - T_F)x + (\Delta G) \quad - \text{(iii)}$$

In the majority of cases only two or three terms will be included in the equation.

Although the combination of information has been formalised as a series of arithmetical operations, it is not clear that this is the way the controller behaves. In a few cases there is evidence that he does use numerical values and might therefore carry out a digital computation, but this seems to be reserved for the simpler decisions. For example, 10/7/74 (b) "100 MW dropped on 6 stations to regain the steam spare. (b) Frequency slightly above target, and we're 100 MW above the 10 o'clock revised program". The controller has converted the $T_R - T_T$ discrepancy into a control action, the frequency information seems to have only been used as a confirmation of $T_R - T_T$ rather than having been included in any calculation. In the majority of decision examples, the controller talks as if he is combining information in an analogue manner similar to the analogue procedures discussed in 3.7.2. The evidence for this is that of 43 decisions identified, in only four of them is there a mention of a specific value of a variable. In the remainder, references to variables and comparisons with target values are expressed in analogue terms such as 'above', 'below' etc. It is not certain whether information is read directly from the meters in an analogue form or is converted from digital to analogue for the purposes of combining information. Certainly the actual actions have to be expressed in a digital manner. As an example 10/7/74 (26) "We'll pick up some more generation, we'll pick up 42 MW, (b) demand will increase slightly between now and 14.30 (c) Frequency is above target, the transfer is above program, that should cater nicely for the pick up in demand over the next half hour, its 14.03."

There may be several reasons for the use of analogue procedures:

(i) The controller cannot be bothered to work out the equation digitally because the degree of accuracy required from the calculation is not great.

(ii) He does not have time to carry out a digital calculation

(iii) in most cases the controller is so skilled that he combines the information subconsciously.

Hypotheses (i) and (iii) seem most likely. On several occasions the information to be combined is very simple so that (iii) would be quite possible. Evidence for (i), although plausible, is hard to obtain, the accuracy with which he gives generation changes might be an indication of this. If the accuracy required is not great and several terms in the equation have to be combined, an analogue procedure would be the easiest to perform. As regards suggestion (ii), observations of the controller did not indicate that he experienced any situation where he would not have time to make a digital calculation if he had so wished.

An example of a possible analogue computation using the decision equation is given. It is proposed that the controller codes excursions of the pen recorders into 7 chunks, 3 above target and 3 below. Suppose $(T_F - T_T)$ is categorised as 'medium above' and a predicted demand increase is estimated as 'small', the net result should be a 'small' decrease in generation. There is however the problem of converting the chunk 'small' back into digital form. A chunk may for example represent a unit of approximately 40 MW, in which case the controller might choose to decrease generation by 40 MW. The most important feature of this analogue procedure however, is that it requires the controller to do less information processing, and trade accuracy for a reduction in mental effort. Support for this possible trade-off is apparent in the protocol, 27 instructions to power stations are given to the nearest 10 MW, whereas only 10 are given to the nearest 1 MW.

(e) Decision threshold

So far attention has only been paid to how relevant information might be combined. The result of a combination is given as S.C. in the decision equation. There must be some value of S.C. at which the controller decides that a control action must be implemented , i.e. S.C. must have an action threshold. Examination of the protocol data shows that the smallest size of control action taken was 17 MW and the next 20 MW. This would suggest that his threshold is less than 17. It would be interesting to speculate whether the chunks used in the analogue calculations are threshold units. Unfortunately however, the situation is complicated by an interaction of factors. The limits on the size of the action threshold may be expected to vary according to the uncertainty* of the information used in calculating S.C.; with uncertain information the limits are likely to be larger than if the information was certain. The threshold value may also be influenced by the availability of suitable plant. For example, if S.C. is just over threshold, but there is no plant suitable to implement the control action, the controller will probably make no change, so that the effective threshold will have increased. This threshold can be identified with the 'decide 1' activities.

(f) Possible modifications to the decision procedure:

The four stages represented in Fig. 4.2 have a common feature, they are all indicators of factors likely to change the state of the system. Only four factors have been identified here, it is feasible that there are other factors that might affect the state of the system: factors that the controller may not have experienced before. The controller

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*Certainty here refers to whether he expects the values of information in the equation to change unexpectedly.

will therefore have to adapt to cope with a new situation. This presupposes that, (i) the new information is recognised as being relevant to the system, (ii) the existing decision procedure can be altered to accommodate the new information.

An example of partial failure to adapt to an unusual situation was actually recorded in one of the shift protocols. 15/7/74 (13) "So its a little unusual, the car workers are on holiday, it's a slightly different load pattern, we thought we'd allowed for that but its a bit difficult we could have done with the plant on a bit later than we actually synchronised it." The protocol shows that the operator received the information and realised its relevance to the system. The problem was, however, to interpret this information in terms of the exact effect on the system. To do this he must have used past experience of load pattern changes due to works holidays. But either because he did not have the relevant experience, or because he did not extrapolate his past experience successfully he mistimed the synchronisation. More information than is available from the protocol is necessary however, to be able to identify the cause of this failure.

(g) Features of the decision model likely to affect performance: Each of the four stages I to IV will be assessed from this point of view.

Stage I

The chief source of error in this stage is likely to be either mis-reading displays, or mis-interpreting trends shown on the pen traces. The first point is self explanatory. The second refers to situations where the controller has to ensure that a particular excursion from target has stabilised, before he initiates a control action. In one event an unnecessary control action was nearly initiated, because the frequency unexpectedly took a turn for the worse as the controller was about to drop generation.

Stage II

This is an important feature of control skill. Accuracy in predicting demand and adjusting suitable plant to meet change in demand can reduce costs by keeping the plant required to maintain targets at a minimum. For example, if the controller is too late in anticipating a demand change he will have to select plant that picks up very quickly, and which may therefore be expensive. Alternatively if he is too early in his estimation he will have to pull back plant that he originally picked up, this is also uneconomic control behaviour. Over or under-estimating the size of a demand pick up will have the same effect as mistiming. Over estimating will require the controller to drop plant already picked up; underestimating will require the controller to put on rapid pick up plant such as gas turbines.

The implication of this, besides the need for accurate prediction of the demand change, in size and time, is that the controller must be familiar with the performance characteristics of the plant in his area, and particularly those which are carrying his spare capacity. From conversations with the controllers they seem to successfully acquire this knowledge through experience with the system.

Stage III

The only detrimental effect this could have on performance would be if the controller forgot that a target change was imminent and was making an unnecessary control action for another reason.

Stage IV

The limiting feature here is similar to that in II, i.e. it requires the controller to have an intimate knowledge of individual plant performance characteristics.

4.5.2 Prediction procedure

As mentioned earlier there is only a little evidence on how the controller makes longer term predictions. Of the 18 sequences coded P_L, only 5 give any real indication of the method(s) he employs. Relevant details of the five sequences are given below:

9/7/74

(17) 18.75 (1)	(15) 17.52 (1)
(a) 2A, 2B, tomorrow breakfast and lunch time peak. (b) Slightly less than this morning (c) But a much less fine morning forecast (F/c). 3000 MW for each	(a) Estimate 1B (minimum overnight) (b) 1560 fraction over last night 1B

10/7/74

(2) 08.41 (1) & (2)	(9) 10.45 (1)	(25) 13.39 (1) & (2)
(a) 2B; F/c 15°C moderate rain (b) 3200 is breakfast load, looking through past records at least 3200, might put in 3300 2B	(a) Estimate 3080 for early afternoon peak. (b) F/c rain going to clear still 8/8 cloud, Temperature a bit less (c) if weather clear 3080 will be a little high (d) have doubts about the F/c; so 3080 will be a medium between 3180 if the weather does not clear	(a) 3C estimate 3080 (b) look at weather, similar Wednesday last year 3000 to 2800 to 2750. That's 4B

It is difficult to detect a discernible pattern in these five sequences. The evidence does suggest that the controller uses weather, day of the week, time of the year as criteria for selecting a similar day, in the same way as the Gas controllers selected a suitable record. Sequence (2) shows that the controller is looking through past records, but does not indicate how he makes a selection. In (15) and (17), the controller seems to be using the present day to predict for tomorrow, but with an adjustment due to the difference in the weather forecast. In (9) there is no suggestion of the controller using a comparison, he may be doing this tacitly. There is, however, evidence that he converts weather information into differences in demand. If the weather clears he predicts that 3080 will be a little high; if the weather does not clear he predicts 3180, eventually he compromises with the 3080. Besides using a similar day comparison method, discussions with the controller indicated that he used two other prediction methods. Unfortunately there is no real evidence in the protocol data for these methods, so only a brief description will be given here. The basis of the first method is the use of the relationships that seem to exist between certain key features of the traces, on certain days of the week and times of the year. There is a possible example of this in (17) where he gives 2A = 2B. This method uses past records in a more sophisticated way than the direct comparison method. With the knowledge that 2A = 2B for example, the controller can apply this rule to any suitable day and not have to match exact levels of demand as in the exact comparison method. In the second method used, the controller will extrapolate from the curve for the day in question, by sketching the way he considers that demand will develop. It seems probable that the controller uses the last two methods if he is not successful in obtaining an exact match by the initial selection procedure.

4.6 Conclusions

The three methods of analysis using frequency counting, provide evidence about variations in the controller's behaviour during the day, and suitable data for comparison with the behaviour of the gas controllers.

Unlike the gas control task there is a bias toward greater activity and information sampling in the controller's task during the morning. The difference is also apparent in the number of goal orientated sequences observed. This indicates that the controller has to satisfy more task goals during the morning shift than at any other time. Comparison of the information sampled per sequence does show however, that the goal orientated sequences require more information processing during the morning with 1.7 items per sequence, compared with the afternoon at 1.0 items per sequence, and the evening with 0.9 per sequence. This finding is similar to the increased information processing required during the afternoon goal sequences in the gas task. The probable reason for a bias at the sequence level in the electricity task, is that the information system does not have an hourly cycle unlike the gas system.

Comparison of the cognitive activities observed in the gas and electricity task shows that the 14 common activities account for 85% of activities in both tasks. This suggests a possible basis for a taxonomy of cognitive activities. Comparison of the frequency of occurrence of the different activities shows that a high level of information sampling was the main characteristic of the gas controllers' behaviour, whereas a high level of control actions was the main characteristic of the electricity controllers behaviour. These differences in behaviour are caused by the basic difference in the electricity and gas supply systems.

Analysis of the decision procedure produced a decision equation similar to the decision equation of the gas controllers. Evidence suggests that operations used to combine information in the equation are in the main analogue. The decision threshold associated with this equation appears to be influenced by the confidence the controller has in the available information. Accurate prediction of short term fluctuations seems to be an important factor in economic control performance. Longer term prediction procedures seem fairly similar to the procedures used by the gas controllers.

CHAPTER 5

The purpose of this experiment was to investigate the effect that information relevant to predicting final gas sales had on control performance. A simulation of a simplified version of the gas control task was presented to naive subjects who had received prior instructions and training. Subjects were allocated randomly to three experimental conditions, consisting of no additional information, total information and partial information. At the end of each of two experimental sessions a questionnaire was presented to the subjects. It was designed to test their understanding of the relationships between the variables in the task. A control group was also included which did not answer the questionnaire. Results showed that:

(a) even with a simplified version of a complex task that it was not possible to train a large number of subjects sufficiently to use predictive information reliably,

(b) subjects improved performance over the two trials,

(c) only knowledge about certain of the task variables seemed relevant to good control performance.

5. AN EXPERIMENT INVESTIGATING THE EFFECT OF CERTAIN TYPES OF INFORMATION ON CONTROL PERFORMANCE IN GAS GRID CONTROL

5.1 Object of the experiment

Chapter 3 indicated that controllers used different methods of predicting final sale; the methods were dependent on weather forecast information, previous days records, and the computer predictions (ES). The purpose of the experiment described in this chapter was to investigate:

(a) the effect of restricting the use of some or all of the information used for making predictions, and

(b) how understanding of the relationships between variables affected control performance.

Some preliminary experiments using a simulator and verbal protocols had indicated that if a subject did not understand the relationship between variables, this would affect the strategies he developed to control the system, and would in some cases degrade control performance. It was the intention of this second part of the experiment to test the subject's knowledge with a suitably prepared questionnaire, and then relate the answers to control performance. The rationale for this part of the experiment was provided by the results of a pilot study. The indications from this study were that subjects showed more knowledge about the system when asked certain questions, than was apparent from verbal protocol data. Also it seemed that inadequate strategies used by a subject in controlling the system were based on a lack of knowledge about the interrelationships between relevant variables. This might be expected in the early stages of skill development. Fitts and Posner

(1967) suggest that in the first stage of skill acquisition the subject learns what the variables represent. Laughery and Gregg (1962) state that, "The manner in which a subject forms relationships between objects in the environment will be an important factor in determining the way he will operate upon the environment." Consequently it was intended, by asking relevant questions about variable interrelationships, to indentify those relationships most crucial to performing the control task.

5.2 Method

5.2.1 Simulation of the gas control task

The simulation task was based on the NG supply system. Subjects had to predict final gas sale and ensure that they had enough gas from their hourly input rate to meet this demand and satisfy 23.00, and 06.00 stock requirements.

The basis of the simulation was an iterative loop that presented information to the subjects, similar to NG 'Sendout Summary' and NG 'Summary', on an hourly basis. The program for the simulation was written in FOCAL and run on a PDP 15 computer. Past days' data could be accessed by the program so that it was possible to simulate the demand conditions of several different days.

The subject controlled the system by predicting the total amount of gas required for the 24 hour period, i.e. allocation. This figure could be typed into the computer which would then calculate the percentage change required in the current input rate to achieve allocation. The restrictions on making changes in input rate were similar to those of the real task, i.e. 4 hours delay for the first 5% change, and 2 hours delay for every subsequent change of 5% after that. A more detailed description of the task is given in Appendix 5.1 which is the instruction sheet given to the subjects.

5.2.2 Design of the experiment

There were three information conditions which consisted of:

(i) a weather forecast and a selection of comparative days

(ii) weather forecast only

(iii) no information.

The weather forecasts were identical to the actual forecasts for the day that was being simulated by the computer. Updated forecasts were presented at four hourly intervals from 08.00 to 24.00 hours. The comparative days consisted of a selection of six different records, one of which was the actual day the controllers used for comparison with the day used in the trial. Appendix 5.2 contains examples of weather forecasts, and appendix 5.3 examples of comparative days.

The data for the simulation was based on the demand patterns for some of the records obtained in the study described in Chapter 3. Demand patterns for two days were selected and matched for difficulty on two criteria. The criteria were, variation in ES over the day, and the minimum amount of control action required to reach target stock levels. These difficulty criteria were chosen as they correlated well with performance of subjects in a pilot experiment, and were also suggested as possible criteria by West Midlands Gas. The demand patterns were used as the basis of the two experimental trials. Appendix 5.4 shows print outs of the two demand patterns. The two demand patterns were presented to each subject in the same order.

Two indicators were used to assess the subjects' performance. The first was stock error, i.e. the difference between final and required stock levels at 06.00 hours, plus any short fall in stock at 23.00 hrs. The second was the sum of control actions made during a trial, given in percent. The two performance indicators were specifically chosen because they were directly related to the two main task objectives of (i) meeting the required stock levels ~~by,~~ (ii) the smallest number and size of control actions.

The questionnaire devised for the second part of the experiment is presented in Appendix 5.5. The questionnaire was designed to test the subjects' knowledge of the interrelationships between all the important variables presented to the subjects in the NG 'Sendout Summary', and 'Summary' displays. Ten questions were concerned with the relationships between the variables, two were concerned with assessing the subjects understanding of the effect of weather changes on demand, and the final question asked the subjects to state what they found most difficult about the task.

5.2.3 Procedure

Subjects were allocated randomly to the three experimental conditions, and one control condition, five subjects in each. The control group received all the information, but did not answer the questionnaire. This was done to check that the subjects' performance was not influenced by the questionnaire. The subjects received an hour of instruction (see Appendix 5.1) and training with the simulator. The training and instruction were based on similar procedures that were effective with subjects in the pilot study. The information groups had the details and the use of the weather forecast explained to them. Subjects using the comparative days were shown how to use this information according to method 'B' used by the controllers, (see Chapter 3).

The first trial followed the training session, and the second trial took place a few days later. Each trial was self paced and took between 1 - 1.5 hours for subjects to complete. A larger experiment with more trials would have been desirable, but the amount of computer time required was prohibitive. It was felt however, that should the results of this experiment prove to be favourable, a smaller and more specific experiment could be carried out at a later date. Subjects were post-graduates, undergraduates, and technicians at the University. They were all paid for their services.

5.3 Results

5.3.1 Analysis of the information conditions

Stock error data was analysed in 2 x 3 factorial design with repeated measures and unequal samples. The unequal sample was because the group with all the information only had four subjects. The data from one subject in this group indicated that he had aimed for the wrong target stock level and so had to be omitted from the analysis. The data was analysed according to Winer (1970) p.376, the unweighted-means solution for unequal groups. Table 5.1 shows the summary table of the analysis, with stock error as the dependent variable. There is no significant effect due to either information or trial. There seems to be more variability due to the subject differences than to the experimental conditions. To test whether this was a significant variability, the F ratios were inverted, but no significant values were obtained.

TABLE 5.1 SUMMARY TABLE FOR UNWEIGHTED MEANS SOLUTION (STOCK ERROR)

SOURCE OF VARIATION	SS	df	MS	F
Between Subj.		13		
A (Information)	33.40	2	16.70	0.23
Subj. W. Group	795.07	11	72.28	
Within Subj.		14		
B (Trials)	13.03	1	13.03	0.31
A x B	23.75	2	11.88	0.28
B x Subj. W. Groups	458.03	11	41.64	

Table 5.2(a) shows an analysis similar to Table 5.1 except that percent change in control actions (sum of control actions) was the dependent variable. The results show that the information supplied to the subjects had an effect on the amount of control action they used in controlling the system. Comparison of the mean scores for the three information conditions Table 5.2(b), shows the significant difference is between the 'all' and 'no' information groups. However, instead of more information enhancing performance the reverse seems to be true. The subjects with 'all' the information seem to make a larger amount of control action, than the 'no' information group.

Since there were two performance indicators with different requirements from the subjects, it was decided to rank performance on each criterion and combine ranks. In this way it was hoped that an overall performance criterion could be evolved. The combination of the two criterion tends to favour subjects who attempted to fulfil both task requirements rather than one.

TABLE 5.2(a) SUMMARY TABLE UNWEIGHTED MEANS SOLUTION (PERCENT CHANGE)

SOURCE OF VARIATION	SS	df	MS	F
Between Subj.		13		
A (Information)	208.55	2	104.28	4.07*
Subj. W. Groups	281.70	11	25.61	
Within Subj.		14		
B (Trials)	119.94	1	119.94	3.44
A x B	83.85	2	41.93	1.20
B x Subj. W. Groups	383.76	11	34.89	

*p<0.05
df(2,11)

TABLE 5.2(b) INDIVIDUAL COMPARISON OF MEANS FOR A (from Winer, 1970 p.378)

Order of Means

A3	A2	A1
28.16	36.76	41.40

Differences

	A3	A2	A1
A3	-	8.60	12.24
A2	-	-	4.64
A1	-	-	-

Comparing A1 & A3

F = 6.50 p<0.025

Comparing A2 & A3

F = 3.61 p>0.05

Key:
A1 = All information
A2 = Weather information
A3 = No information

A Wilcoxon matched-pairs signed ranks test between trial 1 and trial 2 using the combined ranks showed a significant improvement T = 17.5, $p<0.025$. A Kruskal-Wallis one way analysis of variance Siegel (1956) showed no significant effect due to the information, on either trial 1 or 2.

5.3.2 Analysis of the questionnaire data

The data used for the analysis were total scores on the questionnaire. A non parametric rather than parametric analysis was carried out on these data because the required assumption of the questionnaire scores being distributed as a normal distribution could not be sustained. A Wilcoxon Matched-Pairs Signed ranks test between trials 1 and 2 showed a significant improvement in questionnaire scores on trial 2, T = 7, $p<0.005$. This suggests that the subjects improved their understanding of the interrelationships between the important variables in the task. A Kruskal-Wallis one way analysis of variance showed no significant difference between the questionnaire scores of subjects exposed to the different information conditions, on either trial 1 or 2. It might have been possible that the exposure to the additional information could have improved subjects understanding of certain relationships; this does not seem to have been the case.

Correlation of performance scores with questionnaire scores, showed little relationship. Table 5.3 shows r_s values for correlations between the three performance criteria and questionnaire data. There seem to be low negative correlations between the criteria and questionnaire scores. This suggests that there is little relationship between ability to answer questions about the system, and ability to control the system.

TABLE 5.3 TABLE OF CORRELATIONS BETWEEN QUESTIONNAIRE AND PERFORMANCE CRITERIA SCORES

Performance Criteria	Combined trials
Stock error	-0.15
% change	-0.16
Overall	-0.29

TABLE 5.4 CORRELATIONS BETWEEN QUESTIONNAIRE AND OVERALL PERFORMANCE SCORE ON DIFFERENT TRIALS

		P_1	P_2
Questionnaire scores	Q1	0.31	-0.57*
	Q2	0.45	-0.291

*p<0.05

Table 5.4, however, shows intercorrelations between the overall performance criterion and questionnaire scores on trials 1 and 2. The results indicate that those subjects who performed well on the first trial were best at answering the questions about variable interrelationships. However, those subjects who performed best on the second trial seemed to be worse at answering the questionnaire. This might suggest that an understanding of the system is useful in the early stages of learning a skill, but is either a hinderance or no use in later stages of learning.

To test whether answering the questionnaire at the end of trial 1 effects performance in trial 2, the performance of the control group, which had been supplied with 'all' information, was compared with the performance of the experimental group on trial 2. Mann-Whitney U test for small samples showed that there was no difference in performance between the experimental and control groups, ($U = 7.5$, $n_1 = n_2 = 4$; $p<0.557$). This suggests that answering the questionnaire did not affect performance on the task.

5.4 Discussion of results

The results of 5.3.1 highlight the problem of choosing suitable performance indicators. Each analysis based on a different criterion shows something different. The result of the analysis based on size of control action suggests that the supplementary information, probably confused the subjects so that they made incorrect predictions. The 'no' information group performed better by following the computer estimate. The results of Chapter 3, in which the controllers predictions were compared with ES, showed that the controllers were not always better than ES, so it is hardly surprising that inexperienced subjects could not use the supplementary information successfully. Presumably the 'no' information group had no option but to follow ES in a closed loop mode. The result indicates that it probably takes considerable experience for a person to learn to control the gas task in an open loop mode.

Although the supplementary information affected the size of control action, it did not affect the stock error. The reason is probably that those subjects who mispredicted using the information had time to rectify their mistake, but made more control actions in an attempt to do this. It suggests that in some respects stock error is not a sensitive performance criterion. It was partly for this reason, and because the two performance requirements embodied in these two criteria conflict, that a combined criteria was employed. This overall criterion simply combined the ranks of performance on the two original criteria. It was felt that this was easier than trying to equate the value of units of stock error and action size to the system in some arbitrary way. This requirement would have had to have been fulfilled if interval level of measurement was to be maintained.

The advantage of the combined criterion is that it is sensitive to those subjects who successfully fulfilled both task requirements, and may therefore be a better overall indicator of performance. The results of the analysis using this criterion showed that overall performance improved on the second trial. This indicates that subjects must have been developing their control skill after only two trials. However, the finding that subjects in the information conditions did not perform better than those in the no information condition reinforces the suggestion that two trials were not enough for subjects to develop the more sophisticated skills associated with predicting sales.

The analysis of the questionnaire data 5.3.2 produced several interesting results. The initial finding that questionnaire scores improved after the second trial indicates that the subjects had learned more about the system through performing the task. However, the correlation between the questionnaire scores and performance showed little or no relationship. It suggests that knowledge of the variable interrelationships is necessary for controlling the system, but is not sufficient for good control performance. This is supported by the finding that there was a positive relationship between good performance and high questionnaire scores on the first trial, but a negative correlation between good performance and questionnaire scores on the second trial. It therefore seems that the knowledge of variable relationships is important in the initial stages of learning the control skill but not in the later stages. It would be useful to know if other sorts of knowledge become relevant in the later stages of skill development, as this could be of potential importance in training control operators.

CHAPTER 6

Four subjects were instructed and trained similarly to the subjects in Chapter 5. The subjects were allocated randomly to an 'information' condition, and to a'no information' condition. The subjects were required to do five trials with the simulated task; protocols were obtained from the 'information' subjects on the first and fifth trial. Subjects were asked to answer the questionnaire used in Chapter 5, after the second and fifth trial.

Results indicated that even with five trials subjects could not use the predictive information effectively. The protocol data showed an increase in the amount of predictive behaviour between trial 1 and 5. It also showed that behaviour was more purposive in trial 5 than trial 1. Analysis of the predictive behaviour indicated why this behaviour was not effective. Questionnaire data gave a similar result to Chapter 5, i.e. that only certain knowledge about task variables is relevant to good performance.

6. AN EXPERIMENT INVESTIGATING THE DEVELOPMENT OF A CONTROL SKILL

6.1 Introduction

The purpose of this experiment was to, (i) investigate further some of the issues raised in the last chapter, and (ii) investigate the changes of behaviour that take place during the development of a control skill.

In particular, the first aim of the experiment was to investigate the effect of supplementary information on control performance, but to use only two experimental conditions, 'all' or 'no' information, with fewer subjects over more trials. It was hoped that given more experience with the supplementary information subjects would learn to use this information to predict final gas sales more accurately than ES.

The second aim of the experiment was to investigate the changes in behaviour of the subjects as they developed the control skill, by using verbal protocols, and the methods of analysis used in chapters 3 and 4. Evidence presented in Chapter 1.2 suggested that subjects should gradually develop a feed forward or predictive model as they learn to control a particular system. It was predicted that a similar development would be apparent in the behaviour of the subjects in this experiment.

6.2 Method

The method was similar to that employed in the last chapter. The type of task and the format of the information remained the same. On this occasion subjects were randomly allocated to the two experimental conditions, two to each. Subjects underwent the same instruction and training as those in the experiment of Chapter 5. Subjects took part in five trials, each trial containing a different day's demand pattern. The demand patterns were presented in the same order to each subject. All four subjects were required to answer the questionnaire used in Chapter5 after the second and the last trials. In addition, the two subjects in the 'all' information condition were asked to verbalise their thoughts during the first and last trials. These were recorded on a cassette recorder. The two subjects in the 'all' information condition were chosen for the protocol study for two reasons;

(i) because this is most similar to the conditions experienced by the grid controllers,

(ii) because the verbal behaviour of subjects from two different experimental conditions would not be directly comparable.

Subjects were undergraduates and postgraduates from the Applied Psychology Department. They were paid for their services.

6.2.1 The problem of task difficulty

There was, however, one problem with the design of this experiment, and that was obtaining real demand patterns that were similar in their requirements of the subjects. Table 6.1 below shows the differences between the five days demand patterns used in the experiments. The two main criteria used for comparison of difficultyare as in Chapter 5, (a) variation of ES, (b) minimum amount of control action required to satisfy target stock levels. The variation in ES was calculated by taking the difference between the second highest and the second lowest value of ES over the 24 hour period. The second, rather than the lowest or highest, is taken to avoid extreme values which often occur at 07.00. The 'minimum amount of action' is the control action required to meet target stock levels, assuming final sale was predicted accurately at 07.00 hours (the beginning of the day). The two difficulty criteria show little agreement over which days demand is likely to be most difficult for the subjects. Because of the restricted number of suitable demand patterns available it was not possible to match the trials on the difficulty criteria as had been the case in Chapter 5. It was expected therefore, that learning effects would be confounded with task difficulty. The alternative of randomising the demand patterns over trials for each subject to avoid confounding was rejected. This was because it was necessary to compare the protocols of the two subjects under the same task demand conditions. This could not be satisfactorily achieved by randomising the order in which subjects performed the different trials, as this would require a larger design with more subjects.

TABLE 6.1 COMPARISON OF TRIAL DIFFICULTY ON TWO CRITERIA

TRIAL	VARIATION OF ES	MINIMUM AMOUNT OF ACTION
1	15.8	17.1
2	27.5	6.6
3	17.6	16.1
4	27.7	7.1
5	10.1	19.9

6.2.2 Performance indicators

Besides using the performance criteria of Chapter 5, two others were employed in this experiment. The first was evolved to replace stock error, because of its insensitivity to control changes. It was calculated by summing the modulus of the deviations of hourly input rate from the mean input rate required to meet the target stock levels, $|IP_i - \bar{IP}_o|$. To obtain a comparison with other trials this expression was divided by the mean input rate for target stock $\bar{IP}_o$. The result was then multiplied by a standard input rate IP_s to give numerically manageable figures.

$$\text{Transformed stock error} = \frac{|IP_i - \bar{IP}_o| \times IP_s}{\bar{IP}_o}$$

If the signs of the deviations are accounted for the sum of the deviations will be equal to the stock error. By not accounting for the signs the indicator becomes sensitive to deviations from the mean input rate, so that those subjects who make large control actions will be penalised.

The second indicator takes the average value of allocation predicted by a subject on a given trial, and expresses it as a percentage error of correct allocation for target stocks. This is similar to using prediction error as a performance indicator as in Chapter 3.

6.3 Results of performance analysis

The amount of control action as a performance criterion was analysed in a 2 x 5 factorial design with repeated measures, see Winer (1970), p.302. The summary table 6.2 is given; the results indicate that there

TABLE 6.2 SUMMARY OF ANALYSIS USING CONTROL ACTIONS AS A PERFORMANCE CRITERION

SOURCE OF VARIATION	SS	df	MS	F
Between subjects		3		
A (Information)	0.8	1	0.8	
Subj.within groups	121.6	2	60.8	
Within subject		16		
B (Trials)	376.7	4	94.2	7.78*
A x B	71.7	4	17.9	
B x Subj. within groups	96.5	8	12.1	

*p<0.01

is a considerable difference in performance over trials. A similar analysis of stock error gave no significant results. The transformed stock error, however, did give a significant result, the summary table is shown in Table 6.3.

TABLE 6.3 SUMMARY OF ANALYSIS USING TRANSFORMED STOCK ERROR AS A PERFORMANCE CRITERION

SOURCE OF VARIATION	SS	df	MS	F
Between subjects		3		
A (information)	3.80	1	3.8	
Subj.within groups	243.05	2	121.5	
Within subject		16		
B (Trials)	728.00	4	182.0	6.25*
A x B	36.70	4		
B x Subj. within groups	233.00	8	29.1	

*p<0.05

Analysis of the allocation error using the same design did not show a significant result. Fig. 6.1 compares the variation in the four performance criteria over trials, and for the two information conditions. The graphs show little effect on performance due to information. There is considerable variation in performance scores over trials. These reflect the confounding of practice and difficulty effects. Only percentage control action shows a possible decrease that might be due to practice. There does, however, seem to be some agreement between the performance scores on trial 5. The scores show a considerable increase in error on this trial, and tend to indicate that this demand pattern was particularly difficult to control.

A comparison of the information,'no' information groups using the 'overall'* performance criterion on a Mann-Whitney 'U' test, did not show a significant result. A Friedman two way analysis of variance on the trials showed a significant difference, $X^2_r = 10.7$, $p<0.05$. The conclusion drawn from these analyses on the various performance data is that 5 trials is not long enough for the subjects to learn to use the supplementary information successfully in predicting gas demand.

Assessment of the two additional performance indicators, transformed stock error, and allocation error, showed a high correlation between the overall performance criterion and transformed stock error, $r_s=0.69$, $p<0.01$, but a low correlation between the overall criterion and allocation error. This suggests that transformed stock error might be a suitable

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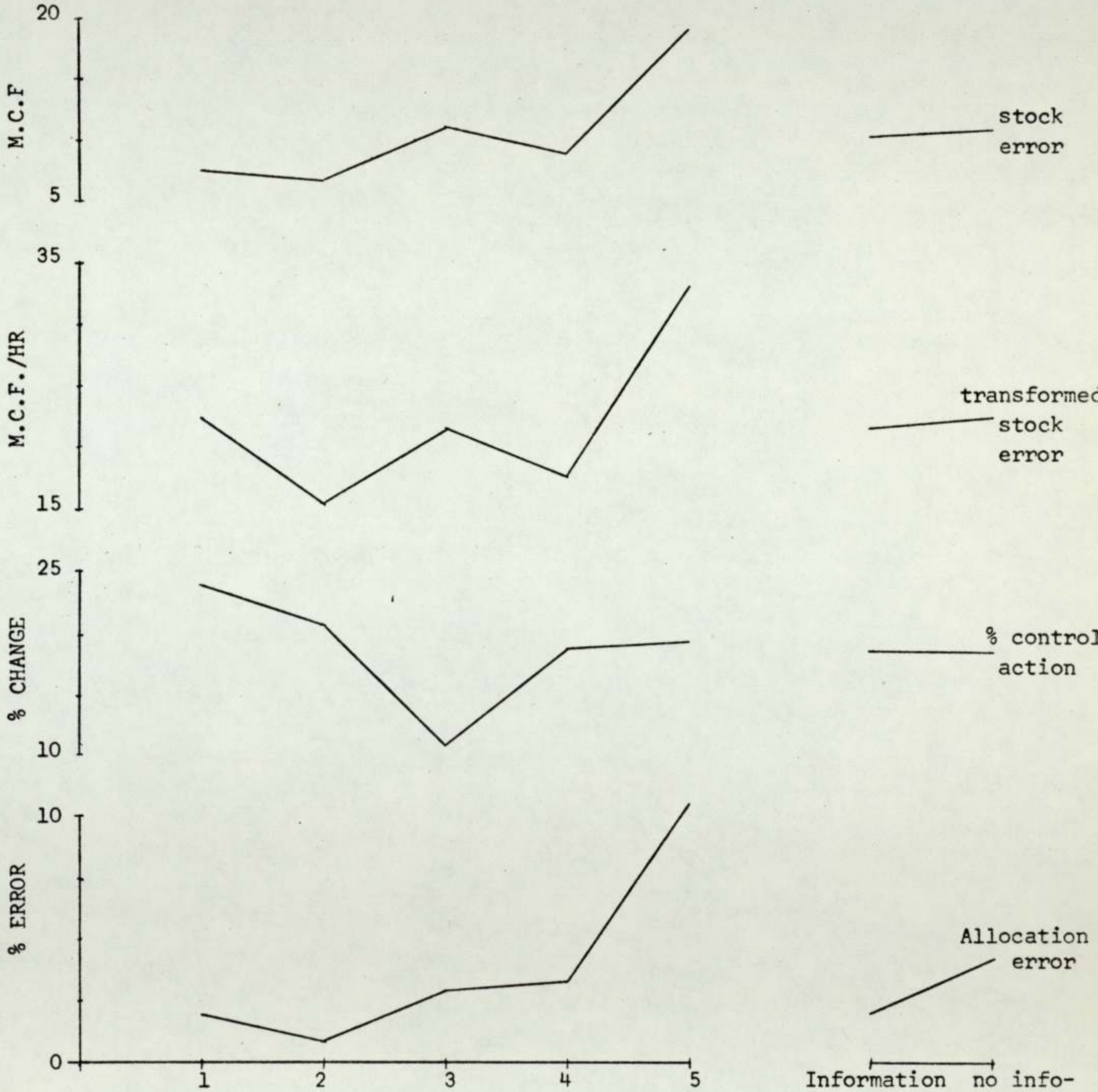
*The same 'overall' criterion as used in Chapter 5

Fig. 6.1 GRAPHS COMPARING THE SCORES OF THE FOUR PERFORMANCE CRITERIA FOR TRIALS AND INFORMATION CONDITIONS.



replacement for the overall criterion, as it seems to be sensitive to the same differences, but has the advantage of presenting data at an interval level of measurement. Allocation error could be useful as an intermediate indicator of performance since it does not assess a subjects skill at implementing a control decision successfully. This indicator could therefore be used in conjunction with transformed stock error to tease out subjects who have this skill, as well as those subjects who have the skill to decide on the correct allocation. Results from this sort of analysis could be useful in correlating certain patterns of behaviour identified in a protocol with different aspects of performance.

6.4 Results from the three methods of analysing verbal protocol data

This section is concerned with the comparison of the observed frequencies of information sampling, activity usage, and sub-goal sequences, for the two subjects on the two trials for which protocols* were recorded.

6.4.1 Details of the information, activity, and goal sequences identified in the protocols

Below is a list of major sub-goal codes as well as a list of new information items used by the controllers not included in the explanatory list of items given for the gas task in Chapter 3. The activities used in this analysis are identical to those of Chapter 3. Some new activities were observed in the protocols but their frequency of occurrence was so low, accounting for less than 2% of all activity,

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*Appendix 6.1 gives a sample protocol.

that they have been omitted from any analysis.

List of extra information:-

ASt	Actual stock level for the system at the particular time mentioned.
IR_{RS}	Hourly input rate for required stock level (see NG 'summary' display).
IRall	Hourly input rate for allocation (see NG 'summary' display)

Lists of codes for sequences of activities:-

The concept of goal orientated behaviour has been modified in this analysis of sequences of behaviour. The main reason was that certain goal orientated behaviour was not easily recognisable, repeated sequences of behaviour seemed in several cases to be identifiable by the information used, rather than having any purposive characteristics. This appears to be a feature of unskilled behaviour and will be discussed more fully later in the chapter.

St	Comparing stock, ESt, ASt, with RS
CD	Using previous day's data as a comparison with current events.
W	Comparing actual weather with forecasts, often triggered by the arrival of anew weather forecast.
Rv	Looks at information on the displays and supplementary information without an explicit purpose.
P_{FS}	Predicts final sale
P_{St}	Predicts final stock
P_{SC}	Predicts stock variations
D_P	Decision behaviour based on a CD sequence

D_R Decision behaviour based on a Rr sequence

DSt Decision behaviour based on a St sequence

D Decision behaviour which cannot be classified

6.4.2 Results of the frequency analysis

The analysis here is concerned with those changes in behaviour, over the five trials, that seem to be attributable to the development of the control skill. Consequently, the analysis will be restricted to examining similarities in the changes in behaviour of the two subjects.

Table 6.4 (a) and (b) shows the differences between the total frequencies of the three criteria on the two trials for each subject.

TABLE 6.4 DIFFERENCES IN THE 3 CRITERIA OF ANALYSIS OVER TRIALS FOR EACH SUBJECT

(a)

	SUBJECT 1					
	Trial					
CRITERIA	1	5	Total	X^2		
Information	195(127.5)	60(127.5)	255	71.47	$p<0.001$	df=1
Activity	213(145)	77(145)	290	63.77	$p<0.001$	df=1
Sequence	50(40)	30(40)	80	5.00	$p<0.05$	df=1

(b)

	SUBJECT 2					
	Trial					
CRITERIA	1	5	Total	X^2		
Information	129(141)	153(141)	282	2.04		
Activity	103(132)	161(132)	264	12.74	$p<0.001$	df=1
Sequence	23(28.5)	34(28.5)	57	0.12		

Expected frequencies based on the null hypothesis that information, activity, and sequences used per trial are the same.

There seems to be little similarity in the behaviour changes observed for the two subjects. The behaviour for subject 1 shows a decrease in activity, sequences, etc. whereas the behaviour for subject 2 shows a slight increase in activity etc. According to the criteria of difficulty and performance scores trial 5 was probably the most difficult. The differences in behaviour of the two subjects might reflect their differential reactions to a difficult task. Subject 2, according to performance data, was the most skilled subject, and seems to have been able to cope with the difficult situation, by increasing the level of information processing from 4.5 items of information per sequence trial 1, to 4.2 trial 5. Subject 1, who performed worse than subject 2, does not seem to have been able to cope and reduced his processing from 4.3 items of information per sequence trial 1, to 2.6 trial 5.

The frequencies of occurrence of individual types of information, activity, and sequences were compared for each subject over the two trials. In cases where frequencies were not too low, Chi-square tests showed no difference between trials on the three criteria for either subject. As there appeared to be no differences in the subjects behaviour over trials, data were combined so that the larger observed frequencies would permit a more extensive comparison of behaviour changes over trials. One important change was revealed from this analysis. Table 6.5 shows the frequency of occurrence of the sequences of behaviour on the two trials common to both subjects. The important result shows that no predictive sequences are observed in the behaviour of the two subjects on trial 1, but that by trial 5 the occurrence of this type of behaviour has increased significantly. This suggests that predictive behaviour is a characteristic of more developed control skill. The subjects are beginning to organise their behaviour specifically to predict the behaviour of the system.

TABLE 6.5 MOST FREQUENTLY USED SEQUENCES ON THE TWO TRIALS COMBINED OVER SUBJECTS

SEQUENCE CODE	Trial		Total	X^2	
	1	5			
W	9(6.6)	3(5.4)	12		
CD	14(10.4)	5(8.6)	19		
Rv	13(9.3)	4(7.6)	17	Other	
DSt	8(6.0)	3(5.0)	11	X^2 not	
Dp	9(8.2)	6(6.8)	15	Significant	
D_R	13(15.3)	15(12.6)	28		
$D\ {}^{D1}_{D2}$	(4.9) 2	(4.1) 7	9		
$P_{FS}\ P_{SC}\ P_{St}$	(6.1) -	(4.9) 11	11	13.69	$p<0.001$ df = 1
	68	54	122	27.97	$p<0.001$ df = 7

Expected frequencies based on the null hypothesis that the frequency of occurrence of sequences is independent of which trial they were sampled on.

Table 6.6 shows the changes in the frequency of occurrence over the trials, of the purposive and non-purposive sequences of behaviour for the two subjects. The results show that purposive behaviour increases with experience whereas non-purposive decreases. This seems to indicate that the subjects are learning the relevance of the displayed information in controlling the system. The increase in prediction sequences shown in Table 6.5 is a specific example of this phenomenon.

TABLE 6.6 FREQUENCY OF OCCURRENCE OF PURPOSIVE AND NON-PURPOSIVE SEQUENCES OF BEHAVIOUR

SEQUENCE CLASS	Subject 1		Subject 2		TOTAL
	Trial 1	Trial 2	Trial 1	Trial 2	
Purposive	15(30)	10(33.2)	14(61)	28(82)	67
Non-purposive	32(64)	6(20)	7(30)	6(18)	51
Others	3(6)	14(46.6)	2(9)	-	19
Total	50	30	23	34	137

Figures in brackets are percentages

6.4.3 Analysis of questionnaire data

Table 6.7 shows the raw scores for the four subjects after trial 2 and trial 5.

TABLE 6.7 RAW QUESTIONNAIRE SCORES

SUBJECT	TRIAL 2	TRIAL 5
1	12	12
2	20	16
3	13	11
4	10	9

Scores out of 21

The score totals show that the subjects did better answering the questions after trial 2 than after trial 5. This seems to further support the finding of Chapter 5, that the knowledge of relationships between variables is only important in the initial stages of skill development. The fact that subjects answer less of the questions correctly after trial 5, suggests that they have discovered which variables are most important in controlling the system, and have ignored those that are not relevant. Examination of the answers to the questionnaire shows in particular that knowledge about IRall, and IR_{RS}, had been forgotten over the trials. The frequency with which the controllers in Chapter 3 were observed to sample these types of information was low, and reflects their lack of importance to the skilled controllers. This lends support to the above argument, that as subjects become more skilled they learn to pay attention to the most important information sources.

6.5 Analysis of the main sequences of behaviour

6.5.1 Details of sequences common to both subjects

Table 6.8 shows details of the information that characterise the five main sequences of behaviour common to both subjects. The sequences prefixed D are identified as implementing a decision, as described in 6.4.1. Table 6.8(a) shows the information used in Dp sequences, i.e. decision sequences where the main characteristic is comparing current information with previous data. Fifty percent of all information sampled was from a previous day. The wide selection of information sampled seems to suggest that subjects might have been experimenting with different criteria for choosing a similar day; or experimenting with methods of predicting. Neither of these two activities were explicit in the sequences but were most likely intermediate stages in the decision making process.

TABLE 6.8 ANALYSIS OF THE MAIN SEQUENCES OF BEHAVIOUR

(a) Dp

Info.	Total	%
HS	3	4.7
HS'	3	4.7
SC'	3	4.7
ES	6	9.4
ES'	4	6.2
FS'	4	6.2
CS	2	3.1
CS'	2	3.1
ASt	2	3.1
IR	2	3.1
Wthr	4	5.2
Wthr'	3	4.7
Te	10	15.6
Te'	10	15.6
Av%	3	4.7
Av%	3	4.7
Total	64	

(b) Rv

Info.	Total	%
ES	11	14.2
SC	10	13.0
ESt	6	2.8
RS	7	9.1
ASt	5	6.5
IR	5	6.5
IRall	5	6.5
IR_{RS}	3	3.9
All	5	6.5
Te	12	15.6
Te_f	4	5.2
Wthr	3	3.9
Total	77	

<u>NB</u> ES, ESt, RS, All, IR_{RS} include 06.00 and 23.00 figures

(c) P_{FS}

Info.	Total	%
ES	3	15
FS'	3	15
ES'	2	10
F/c	1	5
Te	4	20
Te'	4	20
Wthr	1	5
SC	1	5
SC'	1	5
Total	20	

Table 6.8(b) shows the information used by Rv the review sequence. The most frequently occurring items of information ES, SC, RS and Te suggests that information is collected from both 'Sendout Summary' and 'Summary' displays. Analysis shows that 33.8% of observation definitely came from the 'Summary' display, whereas 28.6% came from the 'Sendout' display. The sequence is not associated with any purposive behaviour except for reviewing the current state of the system.

Table 6.8(c) shows the information used in the predicting sequence P_{FS}. The importance of comparative data is apparent, and as in Dp routines Te and Te' are the most frequently sampled types of information. The relatively high frequency of ES and FS' suggests that the subjects might be attempting type A and type B prediction procedures as described in 3.7.1.

Table 6.8(d) shows the information sampled in D_R sequences. The most frequently sampled items of information are similar to those in the Rv sequences. It seems likely that a decision probably develops from the Rv sequence when some of the information sampled indicates that a change is required. The relationship between Rv and D_R may be similar to the relationship between NC_o and NC' sequences.

Table 6.8(e) shows the information used in the D_{St} sequences. The most frequently sampled data items are concerned with stock, and account for 52.5% of the information used. This is to be expected as stock was the characteristic feature for identifying these sequences.

TABLE 6.8 (continued) ANALYSIS OF THE MAIN SEQUENCES OF BEHAVIOUR

(d) D_R

Info.	Total	%
ASt	11	7.9
SC	= 21	15.1
ES	29	20.9
ESt	5	5.7
RS	18	12.9
IRall	7	5.0
IR	8	5.7
IR_{RS}	5	3.6
All	12	8.6
Te	12	8.6
Tef	8	5.7
Total	139	

(e) DSt

Info.	Total	%
ASt	8	21.0
MSt	1	2.6
ESt	4	10.5
RS	8	21.0
IR	4	10.5
IR_{RS}	3	7.9
SC	3	7.9
ES	1	2.6
All	2	5.3
Te	1	2.6
IRall	1	2.6
SS	1	2.6
Total	38	

TABLE 6.9 FREQUENCY OF SEQUENCE USAGE FOR THE TWO SUBJECTS

	Subject 1		Subject 2		
	FREQUENCY	%	FREQUENCY	%	TOTAL
Rv	8	26.7	6	14.3	14
D_R	4	3.3	24	57.1	28
Dst	7	23.3	3	7.1	10
Dp	9	30.0	5	11.9	14
P_{FS}	2	6.7	4	9.5	6
	30		42		72

Table 6.9 shows the frequency of usage of the main sequences. They account for 52% of subject is sequences, and 52.5% of subject 2's sequences. The majority of the 48% remaining sequences in both subjects' behaviour are short and identifiable with basic activities. The most distinctive feature of Table 6.9 is the importance of D_R sequences in subject 2's behaviour. This suggests that subject 2 uses decisions based on review sequences rather than using the more specific sequences of D_{St} or Dp.

6.5.2 Changes in the information content of sequences over trials
This sub-section compares changes in information usage in the main sequences over the trials. Subject 1 has only two types of sequence that occur frequently in trials 1 and 5 Dp and CD, and these account for approximately 30% of the sequences in both trials. D_R and D_{St} only occur in trial 1. Rv only occurs once in trial5, and cannot be used for any meaningful comparisons.

Table 6.10 (a) and (b) shows the change in information content of CD and Dp over trials 1 and 5. Low frequencies make statistical comparison impossible. However, it seems that information usage in the CD sequence becomes more specific whereas usage in the Dp sequences becomes more diverse. These trends might be interpreted as suggesting that the information used in the non-purposive CD on trial 1 is now being used in purposive sequences. The more diverse nature of Dp in trial 5 might suggest that the subject is experimenting with different ways of using comparative information. It would seem therefore, that in the early stages in skill development the subject does not know how to use some of the information. By trial 5 the subject has started to try to discover which information is approrpriate to which purpose.

Subject 2 has two sequences common to both trials, Rv and D_R. These two account for 50% of the sequences in both trials. Dp occurs only once on trial 5, and precludes any inter trial comparisons. Table 6.11 (a) and (b) compares the change in information content for Rv and D_R over trials 1 and 5. Table 6.11 (a) shows little change in information usage for D_R. This suggests that the subject has not become more specific in the use of certain items of information contained in the routine. Analysis in the next section shows that the subject uses a variety of decision procedures in D_R routines, each employing different items of information. Table 6.11 (b) shows the change in information usage for Rf sequences. There seems to be little change in the types of information used, on the two trials.

TABLE 6.10 INFORMATION CONTENT OF ROUTINES Dp AND CD FOR SUBJECT 1

(a) Dp

	Trial 1 Frequency	%	Trial 5 Frequency	%	Total	%
HS	1	4.5	1	6.2	2	5.3
HS'	1	4.5	1	6.2	2	5.3
SC'	3	13.6			3	7.9
SC	1	4.5	1	6.2	2	5.3
ES	2	9.1	2	12.5	4	10.5
ES'	1	4.5	1	6.2	2	5.3
FS'	1	4.5	1	6.2	2	5.3
Ast			1	6.2	1	2.6
IR	2	9.1			2	5.3
IR'	2	9.1			2	5.3
Wthr			1	6.2	1	2.6
Wthr'			1	6.2	1	2.6
Av%			1	6.2	1	2.6
Av%			1	6.2	1	2.6
Te	4	18.2	2	12.5	6	15.8
Te'	4	18.2	2	12.5	6	15.8
	22		16		38	

TABLE 6.10 INFORMATION CONTENT OF ROUTINES Dp and CD FOR SUBJECT 1 (continued)

(b) CD

	Trial 1 Frequency	%	Trial 5 Frequency	%	Total	%
ES	2	3.5			2	3.0
ES'	4	7.1			4	6.1
FS'	3	5.3			3	4.5
SC	7	12.5			7	10.6
SC'	10	17.8			10	15.1
IR	3	5.3			3	4.5
IR'	4	7.1			4	6.1
Wthr	2	3.5			2	6.1
Te	9	16.0	4	40.0	13	19.7
Te'	10	17.8	4	40.0	14	21.2
HS	1	1.8	1	10.0	2	3.0
HS'	1	1.8	1	10.0	2	3.0
	56		10		66	

TABLE 6.11 INFORMATION CONTENT OF SEQUENCE D_R AND Rv FOR SUBJECT 2

(a) D_R

	Trial 1 Frequency	%	Trial 5 Frequency	%	Total	%
Ast	3	5.9	7	10.8	10	8.6
SC	6	11.8	12	18.5	18	15.5
ES	11	21.6	15	23.1	26	22.4
Est	5	9.8	2	3.1	7	6.0
RS	7	13.7	8	12.3	15	12.9
IRall	1	2.0	3	4.6	4	3.4
IR	2	3.9	5	7.7	7	6.0
IRrs	1	2.0	2	3.1	3	2.6
All	6	11.8	3	4.6	9	7.8
Te	5	9.8	5	7.7	10	8.6
Te_f	4	7.8	3	4.6	7	6.0
	51		65		116	

(b) Rv

	Trial 1 Frequency	%	Trial 5 Frequency	%	Total	%
ES	3	13.6	3	25.0	6	17.6
SC			3	25.0	3	8.8
Est	3	13.6	1	8.3	4	11.8
RS	3	13.6	1	8.3	4	11.8
Ast	1	4.5			1	2.9
IR	1	4.5			1	2.9
IRall	1	4.5			1	2.9
All	3	13.6			3	8.8
Te	3	13.6	2	16.7	5	14.7
Te_f	3	13.6	1	8.3	4	11.8
Wthr	1	4.5	1	8.3	2	5.9
	22		12		34	

6.6 Analysis of the decision and prediction procedures

6.6.1 Analysis of decision procedures

This sub-section is concerned with identifying the decision procedures used by the subjects. The analysis attempts to show what information determines the use of a particular sequence type, as well as the procedures used to make a decision. There are four decision rules which occur frequently in the sequences where a decision procedure is identifiable, i.e. in 44 out of 49 'decide 1' activities observed in the behaviour of the two subjects.

Type 1, is concerned with making a comparison of a selected day with the current day. The selection of a similar day is based mainly on similarities in temperature. Once the day has been selected it can be used as an independent estimate of how sales are going to vary. It is identical in this sense to type B prediction method used by the controllers in Chapter 3. However, the prediction is usually converted directly into a change in allocation, without examining the effect on stocks, e.g. Subject 1, trial 5, 08.00 "FS' = 270-265, under pretty much the same temperature conditions. So I think I'll alter my allocation to 265."

Type 2, is concerned with comparing current or estimated (ASt or ESt) stock levels with the required stock level (RS). A discrepancy beyond a certain limit will implement a control change, e.g. Subject 1, trial 1 10.00 "If I bear in mind the stock required if allocation is taken, if the allocation is taken I shall be something like 33 above my RS. So if I reduce my allocation by about 30 so I get 210, should be fair enough." In some cases the subject will make a similar assessment but using input rate information, e.g. Subject 1, trial 1, 08.00 "IR will give me greater stock than required over 24 hour period. I think I'll let it go again as it is, as I can always reduce it."

Type 3, decisions in this category are based on predicting sales using weather and weather forecast information. Thus if the subject thinks that sales are going to be more or less than present estimates due to variations in the weather, then a control change may become necessary. E.g. Subject 2, trial 1, 14.00 "Last F/c, should be fairly warm night, so perhaps we should reduce our allocation slightly."

Type 4. In some cases the subjects only react to the current state of the system, i.e. in a closed loop manner rather than feedforward. This usually happens when the hourly stock change (SC) is in the wrong direction, and the subject decides to alter the input rate to correct this trend, e.g. Subject 2, trial 5, 24.00, "We want to lose out of stock so we must reduce our allocation to below ES. Let's reduce down to 235."

Besides these four types of decision the subjects also take into account any ongoing control action before making a decision. For example in a type 4 decision, Subject 2, trial 5, 15.00 "Now putting gas into stock, whereas we're hoping to lose some, so as soon as this (referring to previous control action) is through I'll reduce our allocation slightly."

Table 6.12 (a) and (b) shows the frequency of the different decision procedures observed for each subject and for each trial. Table 6.12 shows initially that decision types are not observed with equal frequency. It seems that type 2 occurs more frequently, and type 3 less frequently than expected. This indicates that nearly half the decisions made by the subject are concerned with obtaining the correct stock levels at 23.00 and 06.00 hours. Type 2 decision procedure is similar to the main decision equation used by the controllers as described in Chapter 3.

TABLE 6.12 DISTRIBUTION OF DECISION PROCEDURES FOR SUBJECTS AND TRIALS

(a)

Decision Type	Subject 1 Frequency	%	Subject 2 Frequency	%	Total*	%
1	3	15.0	6	26.1	9	20.9
2	12	60.0	8	34.8	20	46.5
3	2	10.0	3	13.0	5	11.6
4	3	15.0	6	26.1	9	20.9
	20		23		43	

(b)

Decision Type	Trial 1 Frequency	%	Trial 5 Frequency	%
1	5	20.8	4	21.0
2	13	54.2	7	36.8
3	3	12.5	2	10.5
4	3	12.5	6	31.6
	24		10	

*X^2 = 11.60 for the total observation assuming that each decision type is observed with equal frequency of $43_{/4}$ (10.75), $p<0.01$

Table 6.12(a) shows the difference in control procedures used by each subject. Subject 1 uses type 2 in preference to other procedures whereas Subject 2 uses 1, 2, and 4 fairly regularly. This is associated with the fact that Subject 2 uses D_R sequences frequently.

Table 6.12(b) shows that type 2 was most popular in trial 1, but that on trial 5, type 4 was also being used quite frequently. This is perhaps an indication of the difficulty of the task. The subjects were forced to revert to a feedback level of control because their predictions had proved unsuccessful.

Table 6.13 gives details of how different decision procedures are associated with the D_R decision sequences. DSt is only associated with type 2 procedures. Dp is associated with type 1, eight times and type 3 twice, both prediction rules. D_R is, however, associated with all the decision types.

TABLE 6.13 DECISION PROCEDURES ASSOCIATED WITH D_R SEQUENCES

	Rule Type			
	1	2	3	4
D_R	2	12	4	3

Table 6.13 shows that procedure type 2 is most closely related to decisions in the D_R sequences, although 42% of the decisions are related to the remaining three procedures. This finding seems to suggest that the subject samples information relevant to D_R sequences

and only makes a decision when some new item of information indicates that a decision is necessary. In this sense the sequence is not triggered by any particular item of information, but several unlike Dst and Dp, which only use information directly relevant to the type of procedure embodied in the sequence.

6.6.2 Analysis of predictive procedures

This sub-section deals with the analysis of those sequences which are organised specifically to predict variations in sales. Although Dp sequences involve predictive behaviour, only sequences with the specific function of prediction are considered here. Specific prediction sequences do not become apparent until the later trial. The essence of prediction used by the subjects is found in decision rule 1, the subjects are attempting to use the type 'B' prediction method. Their ability to use it effectively seems limited as they are usually only able to make general statements, e.g. Subject 1, trial 5, 15.00 "It's a lot hotter than yesterday. I'll look back to see if we've got any comparable temperatures. Yes we've got one here with 15.00 it was 62, it was exactly the same type of day, estimated sendout 256, and ended up with a final sale of 272 as opposed to the day I am looking at now which is 265, and now I'm 243. So I'll probably use less." This example shows that he is not clear how to use the information he has processed, he produces conflicting results which he does not attempt to resolve. His original comparative day, which was cooler than the current day, had a final sale of 265; the second comparative day had a temperature identical to the current day but had a final sale of 272. The estimated sendout for the current day gives 243. The two comparisons the subject makes give conflicting estimates. The subject seems to take an average between 272, 265 and

243, so he indicates that final sales will be less than 265, (actual FS = 232).

With more experience the subject would have seen that HS was 0.6m less than HS'. This would have indicated a difference in sales pattern which, if carried on at the same rate for the rest of the day would have suggested a sale of 255 or less. Within the next two hours HS fell to 1.5 behind HS', with CS already 5 behind CS', which indicates a sale of 239, very similar to ES at 16.00 hours which was 241. The subject could therefore have made a reasonably accurate estimate if he had been more capable of using prediction type B. However, the subjects do on some occasions attempt to be more specific in their estimations, e.g. Subject 2, trial 5, 07.00 "ES is 226, but this is substantially lower than yesterday, and the day before that. So we'll assume that it should be somewhere in the region of 260 not 226"(FS' = 265).

The information content of the P_{FS} sequence shown in Table 6.8(c) provides additional evidence that the subjects have not completely grasped the concept of using comparative information for making predictions. It is apparent from Table 6.8(c) and 6.8(a) for Dp, that Te and Te' are the most frequently sampled items of information. HS, HS' and CS, CS', however, only appear to be sampled occasionally. This suggests that the subjects are able to make comparisons, and select days on the basis of similar temperature conditions, but have not reached the stage where they can make comparisons between sales trends, and use the data to make predictions by adjusting FS'.

Comparison of the 'allocation error' performance indicator for the two subjects shows no difference. This suggests that there was probably no difference in the subjects ability to predict sales. Comparison of the subjects behaviour on the 'transformed stock error' performance criterion, shows subject 2 to perform better than subject 1. This suggests that the main difference in the subjects' behaviour is in their ability to implement a control action. This could mean that subject 1 does not fully evaluate the effects of his predictions and required control changes on the future states of the system. It might be the reason why only two conditional statements are observed in subject 1's protocol, compared with 10 in subject 2's.

6.7 Summary and discussion of results

The results from section 6.3 showed that 5 trials were not long enough for subjects to learn to use the supplementary information and make effective predictions. The analysis of prediction procedures in 6.6.2 confirmed this result, and showed that the subjects had not fully grasped the concept of using previous records to make predictions.

Comparison of behaviour on the two trials, based on frequency data from the three methods of analysing the protocol showed differences for the two subjects. Subject 2 seemed to increase the level of information processing to deal with the difficult demand situation in trial 5. Subject 1 on the other hand tended to reduce the level of processing. It was suggested that because subject 2 was generally more skilled, according to the performance criteria, the level of skill allowed the subject to attempt to satisfy the task requirements by increased activity. Subject 1 according to the performance criteria was less skilled, and this may be related to the way he attempted to deal with the difficult task requirements, which was to reduce his level of processing.

One finding of importance from the frequency analysis was the increase in prediction behaviour for both subjects between the two trials. This is in agreement with other findings on control skill development, Chapter 1.2, where the literature reviewed suggestions that skill development was usually associated with an increase in open loop or predictive behaviour. The complementary result that purposive sequences tend to increase, and non-purposive decrease, suggests that the subjects are learning to use the information from the displays to satisfy particular task requirements in an organised fashion. The development of prediction sequence is a specific example.

Results from the questionnaire data indicated that subjects learn which are the most important variables and their relationship to the system, but forget the relationship to the system of those variables that are not important in its control.

Comparison of the information content for sequences common to both trials showed CD sequences becoming more refined in the information used, and Dp sequences becoming more diverse in the information used. It was suggested that subject 1 was attempting to discover which types of information were most useful in achieving a particular goal. No changes were observed in D_R and Rv, the sequences common to both trials in subject 2's behaviour.

The identification of decision procedures in the various decision sequences revealed the basic methods employed by the subject in making control decisions. Certain sequences that had been initially identified by their information content were also identified with particular decision procedures, e.g. DSt and D_R. This indicates that subjects were only using information relevant to a particular decision procedure, i.e. they were intentionally using a specific procedure to achieve a decision goal. This contrasts with D_R sequences which were associated with all the decision procedures. It seems that subjects sample all the main sources of information from the two displays, and then choose the most appropriate decision procedure. This suggests that the subjects were not clear when to use a particular procedure. The type of procedure chosen tended to be determined by distinctive features of the information displayed. This is different from the controllers who sampled information for a specific purpose.

CHAPTER 7

This chapter describes an experiment in which the grid control engineers controlled a simulated version of the gas control task. The purpose of the experiment was to use protocol techniques to,

(a) compare individual differences in behaviour under controlled conditions,

(b) investigate controller behaviour under difficult task conditions,

(c) compare the controller's behaviour on the simulator with his behaviour on the real task.

The results showed that the same individual differences in controller behaviour were maintained on the simulator with the exception of one of the controller's predictions. The methods of prediction and decision making used by the controllers in the field study were also used in the simulator, with slight modifications to cope with the more difficult task. The several criteria used to assess performance showed small differences between controllers. Some of these seemed to have been associated with different abilities of the controllers to predict and to implement decisions.

7. EXPERIMENTAL INVESTIGATION OF THE GAS GRID CONTROLLERS' BEHAVIOUR ON A SIMULATED TASK

7.1 Objectives of the experiment

The main purpose of this experiment was to:

(i) discover whether a simulated task was a useful means of investigating the behaviour of experienced controllers

(ii) observe the type of behaviour associated with controlling the simulated as opposed to the real task

(iii) compare the behaviour of the individual controllers under more controlled conditions than possible in field studies

(iv) observe the controllers' behaviour on an extreme demand task.

7.2 Method

7.2.1 The simulation task

The task was based on the version used by the naive subjects in the previous two chapters. On the advice of management and supervisory staff at West Midlands Gas, three additions were made to the existing task. These changes were intended to make the task more realistic, and similar to the basic control system the controllers interact with in the real task. The three additions permitted more detailed control of storage, extra gas supplies, and the facility to alter demand.

Control of storage was provided by specifying the five main types of storage and allowing the controllers to alter the input and output from these individual groups. This adds another dimension of difficulty which approximates to the real task. The controller has to ensure that he does not run some holders too low while leaving others full. Thus in situations where very high negative stock changes occur it might not be possible to meet this demand from stock because holders only have a limited output rate.

Extra gas supplies are available from three sources,

(i) peak plant
(ii) mixing butane and air
(iii) using gas stored at very high pressure.

The penalties associated with using the sources are:

(a) the very high cost, four times the price per therm than gas from the national grid, and
(b) time taken to get these sources on line, i.e. four hours for (i) and one for (iii).

The facility to alter demand is based on interruptible contracts West Midlands Gas has with certain industrial customers. These customers may purchase their gas at a reduced tariff but with the condition that their supply may be interrupted at four or eight hours notice depending on the contract. Using this facility the controller can artificially reduce demand but will lose the revenue from those customers who have been interrupted.

These three additions were built into the simulation program: the relevant computer displays are shown in Appendix 7.1. The modifications were made so that the controller could, choose the necessary control action and have the effect shown on the 'Sendout Summary', the 'Summary', and the 'stock' displays.

7.2.2 Procedure

The three controllers who took part in the field study were invited to take part in an experiment using the simulator, which they all agreed to do. Two simulated days data were prepared; the first day was a fairly ordinary demand condition and was designed as a practice trial. The test trial was more difficult with an extremely high sale which could only be met by using extra gas supplies and interruptions. The test trial was presented as the day following the practice day. The controllers were asked to verbalise* their thought processes on both trials in a similar manner to the field studies. Verbalising on the practice trial allowed the controllers the opportunity to re-accustom themselves to thinking aloud. Controllers were provided with weather forecasts, and an information sheet which gave details of flow rates into and out of different types of storage, and supply conditions for extra available gas. A verbal explanation of how the simulation worked was given to each controller. They required approximately 2.5 hours for each trial. A break of 1.5 hours was taken between the two trials.

Informed comments from the controllers about the task and simulation model were very encouraging. It was suggested that the task could be useful for training or as a fast time predictor, where the effect of certain control actions could be assessed, as in the Ketteringham and O'Brien (1974) soaking pit task, discussed in Chapter 1.

7.3 Results from the three methods of analysing verbal protocol data

7.3.1 The three methods of analysis:

The methods of analysis used here are the same as those employed in the

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*A sample protocol is included in Appendix 7.2

earlier chapters. The frequency of usage of different types of, information, activity, and goal orientated sequences, is noted for each individual. Comparisons using these criteria can detect individual differences in behaviour as well as differences in a particular controller's behaviour under conditions of varying task demand. This section presents the results of these comparisons, together with comparisons of the controllers' behaviour on the simulation and real tasks.

Certain types of new information and goal orientated sequences were observed in the behaviour of the controllers, and a list of these is given below. No new activities were observed.

New information:

RS_m	minimum allowable stock. Not to be confused with RS_{23} or RS_{06} which refer to management required stock levels.
SM	Storage main. This is one of the five different types of storage. Gas is stored at high pressure in a pipe-line and cascades into the distribution system.
LJ	Type of storage. Holders which use jet boosters to put gas into the system. This is the cheapest method of getting gas from holders at low pressure into the distribution system at a higher pressure.
LJM	Type of storage. Holders which use jet or mechanical boosters.
LM	Type of storage. Holders which use mechanical boosters. More expensive than LJ.
MC	Type of storage. Holders which use compressors, the most expensive method of getting gas into the system.

The new goal orientated sequences were associated with the interruption, and availability displays, and the choice of the most suitable control actions from them. The frequency of occurrence of these two types of sequence was low, and they are not therefore included in the analyses presented in the remainder of this chapter as they cannot be used for any comparisons. There were a few occurrences of sequences identifiable with a basic activity, but their frequency was also low, and are not included in any analyses.

The procedure for analysing information, activity, and goal sequences was identical to those employed in Chapter 3. For the purpose of comparison with the results of the field study, the 24 hours of the test trial were split into the three shifts: morning, 07.00 - 14.00, afternoon 14.00 - 22.00, evening 22.00 - 07.00.

7.3.2 Analysis of individual differences

Table 7.1 shows that there are considerable individual differences in the information sampled. Controller 1. samples only half as much information as his two colleagues. Tables 7.2 and 7.3 show similar trends. This result conflicts with those in Chapter 3, where it was controller 2 who sampled information less frequently and used less activities and goal sequences. The number of activities per sequence, however, show that there is only a relatively small difference between the three controllers; they were 3.1 for controller 1, 3.7 for controller 2, and 3.2 for controller 3. This suggests that the controllers had to do the same amount of information processing to achieve the task goals. Table 7.3 indicates, however, that controller 1 uses fewer goal orientated sequences of behaviour to control the simulator than his colleagues.

TABLE 7.1 FREQUENCY OF INFORMATION USED BY THE CONTROLLERS

Controllers	1	2	3		
Total	98	182	194	474	
*Expected	(158)	(158)	(158)	$X^2=34.6$	$p<0.001$

*Expected frequencies based on the null hypothesis that controllers sample the same amount of information.

TABLE 7.2 FREQUENCY OF ACTIVITIES USED BY THE CONTROLLERS

Controllers	1	2	3		
Total	129	235	229	593	
*Expected	(197.7)	(197.7)	(197.7)	$X^2=35.76$	$p<0.001$

*Expected frequencies based on the null hypothesis that controllers use same number of activities.

TABLE 7.3 FREQUENCY OF GOAL ORIENTATED BEHAVIOUR USED BY THE CONTROLLERS

Controllers	1	2	3		
Total	41	63	71	175	
*Expected	(58.3)	(58.3)	(58.3)	$X^2=8.38$	$p<0.02$

*Expected frequencies based on the null hypothesis that the number of sequences used by each controller is the same.

Table 7.4 shows the probable reason for this difference. It seems that controller 1 indulged in very little predictive behaviour, compared with controllers 2 and 3. This is unexpected, as it was shown in Chapter 3, that predictive ability was of paramount importance in controlling the system. The difference in predictive behaviour is confirmed by Table 7.5, which shows that there is a significant difference in the amount of predictive activity observed in the controllers' behaviour. The differences in the use of 'Note' and 'Compare' however, seem to indicate that there may be differences in types of predictive methods used by the controllers. It may be recalled that type B methods rely heavily on making comparisons with previous days, whereas type A use specific values of ES, without requiring any comparisons to be made.

The occurrence of conditional statements in the behaviour was similar to the findings of Chapter 3, with the exception of controller 1. The percentage of conditional statements in 'evaluate', 'consider', 'decide' and 'predict' activities was 0% for controller 1, compared with 4.9% in the field study, 7.5% compared with 6.7% for controller 2 and 19% compared with 10.9% for controller 3. The lack of conditional statements for controller 1 may be in part due to the very few predictions made by him. It may also be due to a lack of interest, and a subsequent lack of involvement in doing the task. Comparison of overall performance data, discussed in full later, indicates, however, that controller 1 performs no worse than his colleagues. Another possible explanation for the difference in behaviour of this controller is that he made several unintentional responses concerning displays that he wished to see; these responses had to be corrected. His

TABLE 7.4 COMPARISON OF THE FREQUENCY OF GOAL ORIENTATED BEHAVIOUR FOR THE 3 CONTROLLERS

	1	2	3	GOAL TOTAL	X^2
PS	1(4.8)	15(7.2)	5(8.5)	21	11.37^{+}
PS'	8(7.3)	5(11.6)	19(13.0)	32	6.69^{*}
NC	8(5.3)	8(8.4)	7(9.3)	23	1.96
NC'	6(5.3)	5(8.4)	12(9.3)	23	2.25
DC	6(8.0)	17(12.8)	12(14.2)	35	2.22
DC'	5(3.2)	4(5.1)	5(5.7)	14	1.33
Controller Total	34	54	60	148	25.82^{++}

Accounts for 84.6% of all goal orientated behaviour

$^{+}$ $p<0.01$ df = 2

* $p<0.05$ df = 2

$^{++}$$p<0.01$ df = 10

TABLE 7.5 COMPARISON OF THE ACTIVITY FREQUENCIES FOR THE 3 CONTROLLERS

Activity*	1	2	3	Activity total	X^2		
Note	72(51.8)	56(92.9)	108(90.4)	236	26.86	p<0.001	df = 2
Comparison	14(27.7)	64(49.6)	48(48.2)	126	11.46	p<0.01	df = 2
Calculate	8(5.7)	10(10.2)	8(9.9)	26	1.50		
Predict	3(5.9)	17(10.6)	7(10.3)	27	6.55	p<0.05	df = 2
Evaluate	3(4.4)	11(7.9)	6(7.6)	20	2.10		
Decide 1	8(5.7)	11(10.2)	7(9.9)	26	2.04		
2	11(8.1)	19(14.6)	7(14.2)	37	6.11		
Recall	1(1.7)	5(3.1)	2(3.1)	8	1.94		
Describe	2(1.7)	3(3.1)	3(3.1)	8	0.16		
State	1(8.1)	21(14.6)	15(14.2)	37	9.17	p<0.02	df = 2
Controller Total	121	217	211	551	67.89	p<0.001	df = 16

*Accounts for 93% of all activity.

Expected frequencies based on the null hypothesis that the frequency of activities is independent of a particular controller.

preoccupation with correcting these errors may have caused him to forget to verbalise his thoughts. On two occasions the controller actually played back the tape to see whether he had in fact forgotten to verbalise his thought processes.

7.3.3 Analysis of differences in behaviour over shifts

Tables 7.6, 7.7 and 7.8 show the amount of information activity and goal sequences used on the different shifts. It is evident from 7.6 and 7.7 that more information and activity are used during the morning shift than might be expected, based on the null hypothesis of constant usage per hour. This finding contrasts with the result from Chapter 3 where more activity etc. was observed during the afternoon shift than might have been expected. There is, however, a similarity between the two sets of results, and is that there are no significant differences between shifts in the number of goal sequences used in either case. It seems therefore that the same number of goal sequences are required per hour to control the system, but that the amount of information processing required to achieve these goals may depend on task demand.

A breakdown of activity and information usage for each controller shows that this bias is not universal. Tables 7.9 and 7.10 show that bias is only significant for controller 1. No individual differences were apparent for goal sequences so those data have not been presented. Controller 2 has an afternoon bias for information usage as in the field studies. Controller 3 is fairly consistent in his use of information and activity for the three shifts. The probable reason for the morning bias in processing for controller 1 is that he

TABLE 7.6 FREQUENCY OF INFORMATION USED ON THE 3 SHIFTS

		M	A	E	
Simulator	Total	161	173	140	474
	Expected	(138.2)	(158)	(177.7)	$X^2 = 13.2$; $p<0.01$
Field	Total	469	706	521	1696
	Expected	(494.7)	(565.3)	(636)	$X^2 = 57.14$;$p<0.001$

Expected frequencies based on the null hypothesis that the number of items of information sampled per hour is constant.

TABLE 7.7 FREQUENCY OF ACTIVITIES USED ON THE 3 SHIFTS

		M	A	E	
Simulator	Total	210	199	184	593
	*Expected	(172.9)	(197.7)	(222)	$X^2 = 14.87$;$p<0.001$
Field	Total	664	916	713	2293
	Expected	(669.1)	(764.7)	(860.2)	$X^2 = 55.56$;$p<0.001$

Null hypothesis - number of activities per hour constant

TABLE 7.8 FREQUENCY OF GOAL ORIENTATED BEHAVIOUR OCCURRING OVER THE 3 SHIFTS

	M	A	E	
Total	63	51	61	175
Expected	(51.0)	(58.3)	(65.6)	$X^2 = 4.16$; $p>0.05$
Total	203	240	220	663
Expected	193	221	249	$X^2 = 5.53$; $P>0.05$

Null hypothesis - number of sequences used per hour constant

TABLE 7.9 TABLE SHOWING FREQUENCY OF INFORMATION USED BY THE CONTROLLERS OVER THE 3 SHIFTS

	M	A	E	Controller totals	X^2	
1	43 (28.6)	35 (24.0	20 (36.7)	98	28.59	p<0.001
2	57 (53.1)	76 (60.7)	49 (68.2)	182	9.55	P<0.01
3	61 (56.6)	62 (64.6)	71 (72.7)	194	0.19	
SHIFT TOTALS	161	173	140	474		

Figures in brackets are expected frequencies. Expected frequencies are based on the null hypothesis that the number of items of information sampled per hour is constant.

TABLE 7.10 FREQUENCY OF ACTIVITIES USED BY THE CONTROLLERS OVER THE 3 SHIFTS

	M	A	E	Controller totals	X^2	
1	52 (37.6)	48 (43)	29 (48.4)	129	13.87	$p<0.001$
2	80 (68.5)	80 (78.3)	75 (88.1)	235	4.01	$p>0.05$
3	78 (66.8)	71 (76.3)	80 (85.9)	229	2.65	$p>0.05$
SHIFT TOTALS	210	199	184	593		

Figures in brackets are expected frequencies. Expected frequencies are based on the null hypothesis that number of activities per hour is constant.

may have made most of his major decisions early in the day and then paid less attention to the hourly presentation of information than his colleagues, during the remainder of the day.

7.3.4 General comparisons of behaviour on the simulation and real tasks

Table 7.11 shows that there are considerable differences in the use of information activity and goal behaviour. Far more behaviour occurs in the data from the real task than from the simulator.

TABLE 7.11 TOTAL FREQUENCY COMPARISON BETWEEN FIELD AND SIMULATOR BEHAVIOUR ON THE 3 CRITERIA OF ANALYSIS

	Field	Simulator	Total			
Information	1696(1446.7)	474(723.3)	2170	X^2=128.89	$p<0.001$	df=1
Activity	2293(1924)	593(562)	2886	X^2=212.31	"	"
Goal behaviour	663(558.7)	175(279.3)	838	X^2=58.42	"	"

Expected values based on the null hypothesis that the information, activity and goal orientated behaviour used by the controllers is constant over time. Twice the number of hours data were recorded on the field than simulator task.

It could be argued that this difference is in part due to the occurrence of external interruptions in the real task. This assertion, however, cannot be sustained by the evidence that only 0.6% of all goal sequences were caused by external interruptions. Comparison of the mean number of activities per sequence shows 3.4 for both the simulation and the real task. This indicates that the differences in behaviour shown in Table 7.11 must be due to fewer goal sequences occurring in the simulation task rather than any differences in amount of processing.

This is because MG control behaviour is included in the field data. Unfortunately it is difficult to separate some of the MG from NG behaviour. A method of estimating the amount of behaviour associated with each system is to assume that behaviour is equally divided between the two. Thus the 663 sequences observed for the real task becomes 331.5 for NG and MG each. An adjusted comparison of the data in Table 7.11 is shown below in Table 7.12.

TABLE 7.12 ADJUSTED COMPARISON WITH THE DATA OF TABLE 7.11

	Field	Simulator	Total	
Information	848.0(881.3)	474(440.71)	1322	X^2=3.77
Activity	1146.5(1159.7)	593(579.8)	1739.5	X^2=0.45
Goal Behaviour	331.5(337.7)	175(168.8)	506.5	X^2=0.34

Table 7.12 shows that there is little difference in the behaviour of the controllers on the simulation and real tasks, if the correction for the MG system is made. This is encouraging, as it tends to indicate that the behaviour of the controllers is not radically altered by having to control a simulated task.

The total frequencies used in the previous two tables mask more detailed differences in behaviour on the two tasks. Table 7.13 shows that there are considerable differences in the frequency of usage of common goal orientated behaviour on the two tasks. All except PS' sequences show differences. On DC, DC', NC', more sequences occur in the simulated task. The reason for there being more DC, DC' types

TABLE 7.13 COMPARISON BETWEEN FREQUENCIES OF COMMON GOAL ORIENTATED BEHAVIOUR IN THE FIELD AND SIMULATOR STUDIES

	FIELD	SIMULATOR	TOTAL	X^2	
PS	*80(63.6)	21(37.4)	101	11.42	$p<0.001$
PS'	*43(47.2)	32(27.7)	75	1.14	
NC	105(80.6)	23(47.4)	128	19.95	$p<0.001$
NC'	10(20.8)	23(12.2)	33	15.16	$p<0.001$
DC	*12(29.6)	35(17.4)	47	28.27	$p<0.001$
DC'	*2(10.1)	14(5.9)	16	17.62	$p<0.001$
	252	148	400	93.56	$p<0.001$
% of Total Sequences	76	84			

*These observed frequencies are half of the actual frequencies as they include predictions and distribution control actions on the MG system.

Expected frequencies based on the null hypothesis that use of goal orientated behaviour is independent of whether controllers are controlling the real or simulated system.

in the simulated task is that the controller is directly involved in controlling storage, which would normally be done by the distribution controller. The important sequences of PS and NC, however, occur less frequently on the simulated task. This suggests that the controllers make fewer specific predictions and decisions on the simulation. The reason for this may be that the short time interval between events on the simulator. Consequently the controllers probably remember their conclusions from the last event and do not find it necessary to recap, hence the higher frequency of NC'. In the real task, however, decision and prediction events are often spaced at hourly intervals. Therefore the controllers probably find it necessary to make specific conclusions even though they may not differ from those made an hour earlier.

7.4 Analysis of prediction and decision rules

7.4.1 Prediction rules

In general, the types of rule identified on this task differed only a little from the main types identified in Chapter 3. Controllers used ES as a basis for prediction, type A, and a comparative day, for type B.

Table 7.14 shows the most important information used for predictions. It is immediately apparent that there are considerable individual differences in the information used by the controllers. Controllers 1 and 3 make little use of comparative information, but seem to concentrate on utilising weather information and the computer estimate. Controller 2 on the other hand seems to rely heavily on comparative

TABLE 7.14 FREQUENCY OF OCCURRENCE OF THE MOST COMMON INFORMATION ITEMS IN THE PREDICTIVE BEHAVIOUR OF THE 3 CONTROLLERS

CONTROLLER

(a) PS

	1	2	3	TOTAL
ES	1	6	2	9
CS	-	15	1	16
CS'	-	11	1	12
ES'	-	5	1	6
Av%	-	-	1	1
HS	1	15	-	16
HS'	1	14	-	15
TOTAL	3	66	6	75
Info. per Sequence	3.0	4.4	1.2	

(b) PS'

	1	2	3	TOTAL
Te	-	2	8	10
Wind	-	2	9	11
HS	-	5	2	7
HS'	-	5	-	5
CS	-	4	2	6
CS'	-	4	2	6
ES	8	2	16	26
SC	1	-	1	2
Wthr	4	-	9	13
$Wind_f$	-	-	1	1
IR	-	-	1	1
F/c	-	-	1	1
TOTAL	13	24	52	89
Info. per sequence	1.6	4.8	2.7	

information. Because he used more predictive behaviour than his colleagues, his predictive methods are discussed first.

Controller 2

Examination of the prediction rules indicates that controller 2 employs type B consistently throughout the trial, although he does on occasions contrast his results using this method with those using type A. For example at 21.00 hours he states "5 million up on the previous day. Cumulatively 84 million up roughly on the previous day. That would give us 658 by morning. I still tend to think it would be nearer to the 670 than the 691 predicted by the sales (ES)". This is a type A/B as discussed in Chapter 3, given by the equation

$$PS_{A/B} = (PS_A + PS_B) \times \frac{1}{2}$$

He uses type A/B on three occasions. He also uses type C by including weather information with a type A/B. However, he does not actually use the information exactly according to the equation but seems to use it to assess his confidence in his initial prediction.

For example at 15.00 hours "Sales are 4 million just over up on the previous day. 40 million roughly cumulatively. I still tend to suspect that the predicted sendout (ES) is showing too high. Perhaps 670 may be nearer the mark. Much will depend on whether the snow comes along. Wind is increasing as expected and cloud is still around so it may be that we're in for rather a nasty evening."

As suggested in Chapter 3, the controllers do not always combine relevant information according to the operations indicated in arithmetical formalisations. In this particular example the controller does not actually combine the information to modify the initial prediction of 670. This suggests that either the controller has difficulty in combining information from two different sources exactly, or, that he is uncertain about the accuracy with which he can predict the final sale, and so does not consider it worth while combining the available information into an exact prediction. Each of these interpretations is plausible in different circumstances. The first is discussed later, the second suggests that early in the day the controller will not give definite predictions because his uncertainty about his ability to make an accurate prediction will be greatest. As the day progresses the controller's uncertainty decreases and he will become more confident in making a definite prediction. It might therefore be expected that prediction sequences, where no specific predictions are made, would occur most frequently in the morning. Whereas sequences where specific predictions are made would occur more frequently later in the day. Comparisons of PS' and PS sequences from the field study are shown in Table 7.15. Data from the simulator were not used because of the considerable individual differences in predictive behaviour. The results in Table 7.15 confirm the suggestion that the occurrence of definite predictions tend to depend on the controller's confidence in the accuracy with which a prediction can be made.

Besides using the prediction methods described in Chapter 3, controller 2 uses a method of prediction not observed before. The basis of this method is to predict the average hourly sendout for a number of hours. For example, "And we're just over three million up on the hour now. We've sold 627 million and if we average 15 million an hour from now

TABLE 7.15 PS' and PS SEQUENCES FROM THE FIELD STUDY FOR THE 3 SHIFTS

		M	A	E	TOTAL
PS'	Observed	37	24	26	87
	Expected	(25.4)	(29.0)	(32.6)	$X^2=7.49$; $p<0.05$
PS	Observed	38	68	54	160
	Expected	(46.6)	(53.3)	(60.0)	$X^2=6.34$; $p<0.05$

Expected frequencies based on constant usage per hour

on, that is 60 million, we will sell 687. So 685 to 690 looks like the sale." This method relies particularly on the controller's experience. It requires him to know what periods of the day have a constant sendout. This is usually the evening. It also requires the controller to know what the hourly sendout rate will be, given prevailing conditions. It is not possible to represent completely this method by means of an equation as the controller does not make his method of predicting HS from prevailing conditions explicit. A possible formulation of some of the processing is given below, it is based on adjusting the hourly sendout at the time of making a prediction by an experience term.

$$PS_D = CS_i + (HS_i \mp e) \times 24 - i$$

The controller also uses this sort of approach with type A and type B methods of prediction. For example, "Now we're almost 5 million up on the hour again. We've now sold 609 million, and to get to the predicted (ES) 694 million we would need to sell about 17 million an hour or just over. This seems a little unlikely so I think the sales will now be about 685." (The 685 is the predicted value based on the previous hour which was type B).

Controller 3

Examination of controller 3's prediction behaviour shows that it is based on type A procedures. He makes very little reference to the previous day and this is perhaps explained by the comment, "The comparison with yesterday has now gone out of the window." The most common item of information sampled by this controller is ES, both in PS and PS' sequences. The large number of PS' sequences compared with PS seems to suggest that the controller has been using ES as his prediction but without actually stating a predicted value each time he examines the 'Sendout Summary'. It is not, however, entirely clear whether this is so. At 10.00 and 11.00 hours the controller predicts sendout on the basis of the peak ES value at 09.00 hours which was 690. He does not specifically mention a predicted value of sendout from 11.00 until 24.00 hours when he predicts sendout at 675 when ES is 674.9. Whether the controller abandons 690 soon after 11.00, and uses more recent values of ES for his guide to PS, as he appears to be doing by 24.00, it is not possible to ascertain from the protocol. It seems reasonable to assume that the controller tacitly affirms ES as his prediction throughout most of the shift when no specific predictions are mentioned.

The controller does however, use a novel procedure for predicting based on comparative data. He uses this method as a comparison with a type A prediction. At 10.00 hours he states, "We're running at the moment at a sendout of 129, and at 10 o'clock yesterday we had sold 108, so we're running 21 millions up, 19%. If we work that as a fifth and say 5 x 2 = 10, we should sell something like 674 at first look." This method is similar to a type B in that it uses previous days data. However, instead of assuming that the current hourly sendout is going to remain the same as the comparative day, he assumes that the discrepancy of 20 million for one fifth of the day will remain constant for the remaining four-fifths of the day. The total discrepancy will be, as he calculated, 100 million. The prediction procedure can be easily and accurately represented in the form of an equation.

$$PS_{B'} = FS' + \frac{100}{Av\%} \quad (CS - CS')$$

The value of 674 computed by this method contrasts with 690 affirmed in the preceding sequence. The controller does not however, explicitly compare or combine these two predictions. The only evidence that one of these is preferred by the controller is that he affirms 690 as his prediction the next hour at 11.00 hours.

Controller 1

Very little evidence of any explicit prediction is found in the protocol for this controller. The only definite prediction is at 07.00 hours, but the result is not given as an exact value only a trend. "Today we've got an estimated sale (ES) on the first hour of 683.8. Actual sale (HS) of 253 million which compares with the sale yesterday at the same hour of 21.0 million. So it is obvious that the sale is going to be greatly higher today than it was yesterday."

Apart from this vague prediction, eight PS' sequences have been identified in the controller's protocol. All of these eight sequences include ES so it seems possible as argued in the case of controller 3, that these might be tacit type A predictions.

As shown in Table 7.14 and discussed in 7.3.4, one of the main differences between the controllers' behaviour in the simulation and real tasks is in the use of prediction sequences. Table 7.16 shows a comparison of the number of prediction sequences occurring in the behaviour of the controllers on the real and simulated task.

TABLE 7.16 COMPARISON OF FREQUENCY OF OCCURRENCE OF PREDICTION SEQUENCES ON SIMULATED AND REAL TASKS

CONTROLLER	SIMULATION	REAL	TOTAL		
1	9(19.8)	50.5(39.7)	59.5	$X^2=8.83$	$p<0.01$
2	20(18)	34(36)	54	$X^2=0.33$	
3	24(21)	39(42)	63	$X^2=0.64$	

Expected frequencies based on the null hypothesis that the number of prediction sequences (PS and PS') used per unit time is constant. Twice the amount of data was recorded on the real than the simulation task.

Predicted sequences include PS and PS' because of the uncertainty about the status of PS' sequences. The result of the comparison shows that only controller 1 uses less prediction sequences than expected. There are a number of explanations for this difference.

The first is that the format of the simulation confused the controller. There seems to be no reason, however, why this should differentially affect his predictive behaviour.

A second reason is that the controller did not perform the simulated task with as much care and attention as he would the real task. This is a perennial problem with any simulated task, and exists because it is usually impossible to incorporate real life penalties and pay offs into a simulated task. Evidence presented earlier does suggest however, that the controller did take the task fairly seriously since the information processed per sequence in the simulated task did not differ significantly from the real task.

7.4.2 Supply decision rules

As with the results in Chapter 3, ESt is the most important type of information sampled with more emphasis on ESt_{23}, Table 7.17, than in the real task. This may be expected, since the extreme demand conditions of the test trial will pull stocks below absolute minimum unless the controller takes the necessary action. In the rather more normal demand conditions of the field studies, the probability of reaching absolute minimum at 23.00 hours is low, so that it should not be necessary for the controllers to check the likely state of the system at 23.00 hours very frequently. Another difference with the results of Chapter 3, Table 3.20 is that the controllers in the simulation task do not make their own calculations for Est based on a prediction (PS). However, since controllers 1 and 3 make four specific predictions it is unlikely that they would mention PS and

TABLE 7.17 FREQUENCY OF OCCURRENCE OF THE MOST COMMON INFORMATION ITEMS IN THE NC_o, NC' DECISION SEQUENCES

CONTROLLER

(a) NC_o

	1	2	3	TOTAL
ESt_{06}	7	1	7	15
ESt_{23}	8	-	7	15
RS_{23}	-	-	2	2
IR	-	2	1	3
IRall	-	2	1	3
F/c	-	1	1	2
All	2	2	-	4
ES	3	2	-	5
TOTAL	20	10	19	49
Info. per Sequence	2.9	1.4	2.9	

(b) NC'

	1	2	3	TOTAL
ESt_{06}	4	2	11	17
ESt_{23}	4	2	8	14
RS_{23}	-	1	1	2
IR	-	-	4	4
IRall	-	-	4	4
All	3	1	4	8
ES	2	2	-	4
RS_m	1	-	1	2
TOTAL	14	8	33	55
Info. per Sequence	2.5	1.6	2.8	

even less likely that they would calculate ESt on the basis of PS. Controller 2 according to Table 3.20, did not appear to make a habit of using PS to calculate ESt, so that it is perhaps not surprising that he does not describe this method in the simulation. A further difference is the occurrence of IR and IRall in the simulator task. This is because they are used as the basis of a control decision, in which IR has not been adjusted to meet IR for allocation and is not therefore a major control decision, but only a corrective action.

As with predictive behaviour there are considerable individual differences. These differences do not exist in the frequency with which decision sequences are observed for a given controller, but only in the frequency with which certain types of information are sampled. For example, in seven decision sequences controller 2 refers to ESt only once compared with his colleagues who mention ESt twice every sequence.

The net result is that controller 2 only appears to sample 1.4 items of information per sequence compared with 2.9 per sequence for controllers 1 and 3. A comparison with Chapter 3 indicates that the same result was observed in the real task. It was concluded on that occasion that probably less of controller 2's decision behaviour was open to introspection than his colleagues. There did not seem to be any evidence that he was making decisions using procedures radically different from his colleagues. The decision rules for the three controllers will be examined here to investigate this as well as to reveal any new methods of decision making.

Controller 1

It will be recalled from Chapter 3 that the basis for decision making was the comparison of estimated stock value at 23.00 hours or 06.00 hours with the required stock levels. The equation is presented below:

$$CH = RS - ESt$$

The majority of the decision procedures for controller 1 are of this type. However, because of the very high sales RS_{23} is abandoned as a suitable comparison. The controller instead works on the basis of keeping above absolute minimum stock. There is evidence in two of the observed sequences that the controller's safety margin becomes quite small under these extreme conditions. In the two examples, $ESt = 111$, and $RS_m = 110$ so that the difference is only 1, however, the controller decides in these cases that this safety margin is acceptable. A possible explanation for this low margin of safety could be that the controller is expecting a reduction in demand through interruptions which, at the time that these two decisions were made, had not come into effect. It is quite possible that the controller was tacitly adjusting ESt_{23} to account for this but did not calculate the relief on ESt_{23} exactly and so did not mention it.

Besides the usual method of making decisions, there is an example of a decision procedure which seems to have been developed to cope with the extreme demand conditions. At 24.00 he states "On that basis (refers to $PS_t = 650$) if we took a total of 650 NG into the system we would have sold by 23.00 hours tomorrow around about 530, taken in 460, which would require us to lose something like 70 million from stock which we could do quite reasonably and end up with a minimum stock at 23.00 hours of round about the 120 mark. So there doesn't seem to be any problem there."

The controller uses his prediction of tomorrow's sale to calculate the stock loss between 06.00 and 23.00 hours tomorrow. He then subtracts this value from his expected finishing stock on the current day. The result gives an estimated stock level at 23.00 hours the following day of 120, which he decides is acceptable. The reason behind this procedure is that ESt_{06} is 10 million below RS_{06}, and to increase ESt_{06} would require the use of expensive stored gas. By predicting the likely state of the system tomorrow at the critical time, he is adjusting his decision threshold. This particular sequence is a more explicit version of the example of threshold modification procedure given in 3.7.2. The procedure described here although similar in concept to the example in 3.7.2 is more highly developed to deal with the high demand situation. The controller has specifically calculated ESt_{23}, whereas in the field task only a vague assessment of tomorrow's stock position was attempted. The high demand situation requires a more accurate assessment.

Controller 2

As mentioned earlier this controller makes very few explicit references to ESt. However, from the way he phrases his statements it seems highly probable that he is comparing ESt and RS without giving the numerical values for these variables. For example, 08.00, "We have done some interruptions (the previous hour), but we are going to use further gas before the night otherwise we are going to run out of stock." It is reasonably clear from this statement that he has compared RS and ESt. Another example 10.00, is perhaps not so straight forward, "The total allocation is 645 now and we can afford to leave this for a short while longer in case the figure comes down." In this particular event the controller has predicted a sale of 660, but ES is showing 684.5 giving $ESt_{06} = 164.5$. From what he says it seems that he has recalculated ESt using PS, which would give 189, maintaining allocation of 648, compared with $RS_{06} = 200$. The difference is $\simeq$ 10 which must be near his threshold, as he decided to wait until the next hour for a firm decision. These examples of the controller's decision behaviour tend to support the suggestion that either the controller cannot comment on his decision procedures because they are difficult for him to verbalise or that he forgets to give details of his decisions. The latter suggestion seems rather unlikely as he describes his prediction procedures in considerable detail. A plausible additional reason, given in Chapter 3, is that the controller remembers the values of unchanged variables and does not verbalise these.

Controller 3

All the decision procedures exhibited by this controller, with the exception of two, are based on the general decision equation. The two exceptions are very similar to the procedure analysed for controller 1, concerning the reappraisal of the operational constraint RS and the associated threshold. For example 19.00 "But the changes I made by 5 million last hour on both the P.S.G. by increasing our intake of P.S.G. to 35, and increasing our ballast air from 25 to 30 has brought our minimum stock at 11 o'clock up to 112 and our stock at 6 o'clock to 181. I think that with the change in temperature there is a possibility we may have a fall off in sendout during tomorrow, which will enable us to pick up stock, so I'll be quite happy with 180-185 stock at 6 o'clock in the morning." The controller is predicting tomorrow's sales very approximately, and because he is satisfied that conditions are not likely to be as bad as the current day he is prepared to let stocks fall below RS_{06}. There must be a certain risk attached to this type of procedure, particularly as the forecast states that it could either snow or rain the next day. Both controllers 1 and 3 seem to think that it will rain so that sales will be lower than today.

The analysis in this section indicates that the controllers use the same types of decision procedures as in the field study. Some of these procedures the controllers have specifically developed to give more exact results, so that they can take a more calculated risk if they decide to ignore operating constraints. The limiting factor in this type of procedure is the accuracy with which predictions can be made.

7.4.3 Decision rules for selecting suitable control actions

There is not a great deal of detailed evidence on the way in which controllers decide on what is the best course of action to take in a given situation. Most descriptions of these types of decision only give the actual result, for example controller 1, 14.00 "So I am going to ask for a further 10 million on the peak shaving gas and 5 million on the butane air." There are however, a few examples which probably indicated the general rules and procedures that the controllers must use in choosing suitable control actions. The most complete example is controller 1, 09.00 "We've got 40 million coming from interruptible loads but most of that won't be coming for 8 hours. We have got gas available in an hours time from butane air (RB) or from B.G.C. stored gas (SG), and we have also got 50 million available from peak sharing gas but we can't get that for 4 hours. So it's got to be a compromise between time and cost at the present moment, so I propose to take 20 million of regional butane air and 30 million of butane air." Another example is controller 2, 07.00 ".... so we will interrupt the first two groups at once. We can leave the third group, group 3 because the interrupt notice there is considerably less and the saving is only going to be something like 14 million anyway and the difference in price charged and the cost of B.G.C. peak shaving gas is fairly small."

These two examples show that in choosing control actions the controllers have to trade time for cost. Immediate gas supplies such as B.G.C. stored gas cost the most at 9.5p/therm, whereas peak sharing gas costs 8.0p/therm but takes four hours until it is available. This trade off between time and cost means that the earlier the controller can predict the amount of gas he requires for the day the cheaper will be the cost of supplying the gas. The controllers on this task were fairly unanimous in their priorities for choosing control actions. All three groups were interrupted within the first two hours, and with the exception of controller 2, P.S.G. and R.B. were chosen within the first three hours. Controller 2 for some reason chose SG instead of RB. The controllers tended to make the cheapest control actions first. They were able to do this because they were prepared to take a risk and make control actions early in the day. Evidence reviewed in 7.5 shows that when the initial prediction is not accurate the controller may have to use expensive gas to keep stocks above minimum.

7.4.4 Decision rules and stock control

As there was very little evidence of stock control behaviour in the field study no comparisons can be made with the evidence for this type of behaviour on the simulation task. These decisions are concerned with meeting the hourly fluctuations in sendout with input or output from storage. Table 7.18 shows the types of information used by the controllers. Information about the storage main SM followed by the different types of holder seem to be most important. There seems to be little difference between the individual controllers in the information used in their decisions. One strange result is shown in the table, and that is there seems to be far less information used per sequence when a decision is made than when no decision is made. The reason for this seems to be that most decisions appear to be based in the main on the value of one variable, i.e. storage main stock, evidence for this is discussed below. As in the supply decision rules two types of decision have to be distinguished, the first whether a change in the holder stocks is required, the second which group of holders is to be selected to implement the control action.

Decision rules for a stock change:

Two types of information about the storage main seem to be important in determining a decision. The information can either be (i) the rate of change of stock in the storage main, or (ii) how full or empty the storage main is at a particular time. For an example of the first,

TABLE 7.18 FREQUENCY OF OCCURRENCE OF THE MOST FREQUENTLY SAMPLED ITEMS OF INFORMATION IN THE DC, DC' DECISION SEQUENCES

CONTROLLER

(a) DC

	1	2	3	TOTAL
ASt	1	-	2	3
RS_m	1	-	2	3
SC	2	1	1	4
SM	3	5	9	17
LJ	1	7	3	11
LJM	1	5	3	9
LM		5	3	8
MC		5	3	8
TOTAL	9	28	26	62
Info. per Sequence	1.7	1.8	2.2	

(b) DC'

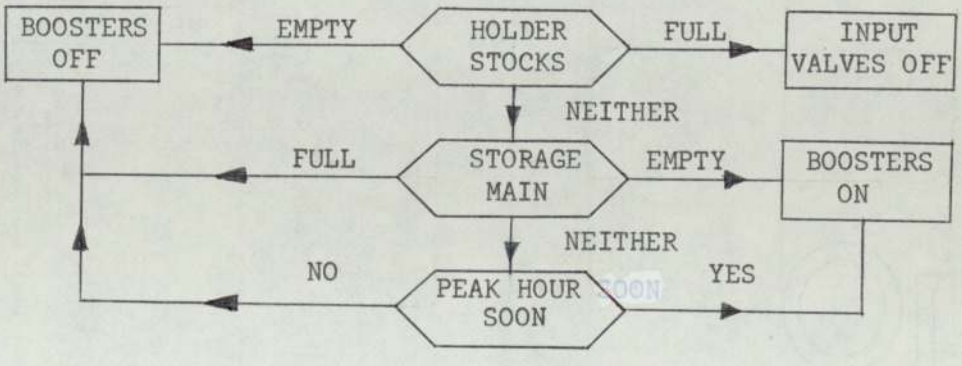
	1	2	3	TOTAL
ASt	-	-	2	2
SC	-	3	1	4
SM	6	2	2	10
LJ	5	4	3	12
LJM	3	2	3	8
LM	2	2	5	9
MC	2	2	3	7
TOTAL	18	15	19	52
Info. per Sequence	3.6	3.7	4.0	

controller 2, 09.00 "We've now stopped the high loss rate from the storage mains so at this point in time it is possible to shut down mechanical compression but at present leave on the jet boosters until increased input from the peak shaving gas and the stored gas becomes available." The storage main cannot be controlled directly but only by influence from the holders. Thus if input and output from holders is restricted, hourly stock changes will be met entirely from the storage main. In the example above the rate at which gas is being taken from the main has been slowed by supplying gas from the holders. Under fairly easy demand conditions stock variations can usually be supplied by the storage main, particularly in view of its large capacity. However, in higher demand conditions the main has to be supplemented by the gas from the holders. This explains why information about the storage main is so important in making stock control decisions. Another example of information about the storage main but of the second type is controller 3, 11.00 "I've taken all compression off now and have arranged for gas to go into the L.P. jet or mechanical boosters for a short time with a view to holding the storage main which is close on maximum." In this case because the main is almost full it has become necessary to take compression off.

Besides information about the storage main it is possible for the state of individual groups of holders to implement a control action, particularly when they reach maximum or minimum stock levels. For example, controller 3, 02.00 "L.P. jet booster holders 28 million, L.P. jet and mechanical booster holders 10 million, in the L.P. mechanical boosters 20 million, and in M.P. compressor stations 32 millions - we'll be shutting that off very shortly." In this example the stock in the compressor holders has reached a maximum, so he will therefore have to shut input valves.

Anticipation of the peak hour can also implement a series of control actions. For example, controller 3, 16.00 "And I'm looking now to bring the compression to work between now and 5 o'clock or at 5 o'clock, in view of the falling off now of storage to bring all the compression to work over the peak period." This procedure seems to be universal practice for all three of the controllers, since according to the computer log of control action, all three put all the boosters on between 16.00 and 18.00 hours. The variation in timing is probably due to differences in anticipating when the peak hour will occur. A flow diagram Fig. 7.1 summarises the evidence presented. The decision procedures cannot be represented as an equation because the overall process consists of a series of discrete decision processes. The diagram is not intended to be exact, since some of the processes are complicated and ill defined. However, it is intended to give an approximate scheme of the information processed and the resulting control actions.

Fig. 7.1 DIAGRAM SHOWING STORAGE CONTROL ALGORITHM



There is one example that seems to be solely the result of operating the system under high demand conditions, and cannot easily be included in the above diagram. In this particular example the controller has to resort to using a change in supply conditions to meet the very high negative stock changes occurring around the peak hour. Controller 1, 18.00 ".... we've got some to come from the peak shaving gas, but that's not expected for another couple of hours or so. At current loss from stock we're losing 15 million from stock - we won't be able to maintain this. Now putting jets back on to help the storage mains. With the jets on we should be able to sustain a loss of stock of 15 million for the next hour or so but after that we are going to be in a lot of trouble. Because of this I am going to ask for 20 million of storage gas from B.G.C." It appears from this example that the controller has not predicted the peak hour successfully as he would have probably had his jets on by this time. There is, however, another interesting point to be considered, and that is why he thought it necessary to put in stored gas when earlier in the same event ESt_{23} = 119, and indicates that stocks would be 9 above RS_m at 2300 hrs. Examination of the computer log shows that his input rate was not great enough to meet the allocation at 23.00 hours so that ESt_{23} = 119 was not a true estimate of events. If he had noticed this earlier it might not have been necessary to put in the expensive stored gas. The information about this discrepancy would have been easily discovered by comparing input rate for required stock at 23.00 hours with the current input rate. The computer log showed that there had been a discrepancy for some hours prior to 18.00 hours, before the controller realised, on the basis of his peak hour stock loss, that he was liable to run out of gas.

Selecting a suitable control action

There is only a little verbal evidence on why a particular group of holders is chosen to implement a control change. The computer log of the task indicates that the most frequently controlled holders were those which were cheapest to run, i.e. jet booster holders, and the most infrequently used were the most expensive, i.e. compressors. The same rationale applies to filling the holders in the evening, those filled first are the group with the cheapest boosting facility.

This rule of economics must however, be modified by the actual state of stocks in a given group of holders as shown in Fig. 7.1.

7.5 Comparison of performance

Four criteria were used to compare the controllers' performance. These were based on advice from West Midlands Gas, and expressed by the cost to the system. The four criteria were:

1. Cost of gas supplied

(2.5p/therm for pipeline gas, 8.0p/therm P.S.G., 9.0p/therm R.B., 9.5p/therm B.G.C.S.G.)

2. Cost of running boosters and compressors

L.P. Jet boosters	no charge
L.P. Jet and mechanical boosters	£9/m.c.f. (million cubic feet)
L.P. Mechanical boosters	£18/m.c.f.
M.P. Compressors	£40/m.c.f.

3. Penalties for being outside required stock level

Stock limit 195-205 m.c.f. Outside these limits penalised at the maximum price per therm of most expensive gas taken during the day.

4. Holder damage

Holders pulled below minimum stock level for more than one hour at discharge rate £40,000.

Criteria 1, 2 and 4 are based on fairly realistic costing. Criterion 3 is an arbitrary penalty as it is difficult to cost the effect of being outside stock requirements.

Table 7.19 shows the cost incurred by the three controllers supplying the gas during the trial.

TABLE 7.19 PERFORMANCE SCORES FOR THE 3 CONTROLLERS

	Controllers		
CRITERIA	1	2	3
1	21,564	21,042	20,700
2	1,077	910	1,098
3	-	52	21
4	-	-	-
Total 1+2+4	22,641	21,952	21,798

All figures £

The Table shows that the cost of gas is the most important factor in keeping overall cost down. This means that use of the more expensive forms of gas, i.e. S.G., will particularly affect the cost of supply. Controller 1 used S.G. and this is one of the reasons why his total gas cost was £500 more than his colleagues. The reason for S.G. having to be used was shown in the last section to be that he did not put enough gas into the system per hour to reach the 23.00 hours stock level. Fig. 7.2 shows the way in which the controllers adjusted their allocation during the day. It shows clearly the unnecessary excursions that controller 1 had to make to achieve his 23.00 hours minimum stock. It was suggested in the last section that the reason for this was that he had not realised his hourly input rate was below that required for 23.00 hours. Inspection of Fig. 7.2 suggests that the real reason for this was that he did not make a sufficiently accurate prediction early in the day. Consequently the control actions that he made in the middle of the afternoon, when he realised that sales were going to be higher than he originally anticipated, were almost too late to affect the 23.00 hours stock position, and required the use of expensive gas to implement them.

This analysis reinforces the importance of predictive ability in controlling this supply system. It may be suggested that the slightly poorer performance of controller 1 was connected with the lack of predictive behaviour observed in his protocol. Fig. 7.2 also shows that controller 2 predicted sales most accurately most quickly, and it will be recalled that he exhibited the most predictive behaviour. Unfortunately because of the few exact predictive statements made by controllers 1 and 3, it is not possible to make a direct comparison of prediction accuracy, as was possible in Chapter 3. However, an assessment of allocation error, as described in Chapter 6, was possible.

Fig. 7.2 GRAPH SHOWING CHANGES IN ALLOCATION MADE BY THE THREE CONTROLLERS

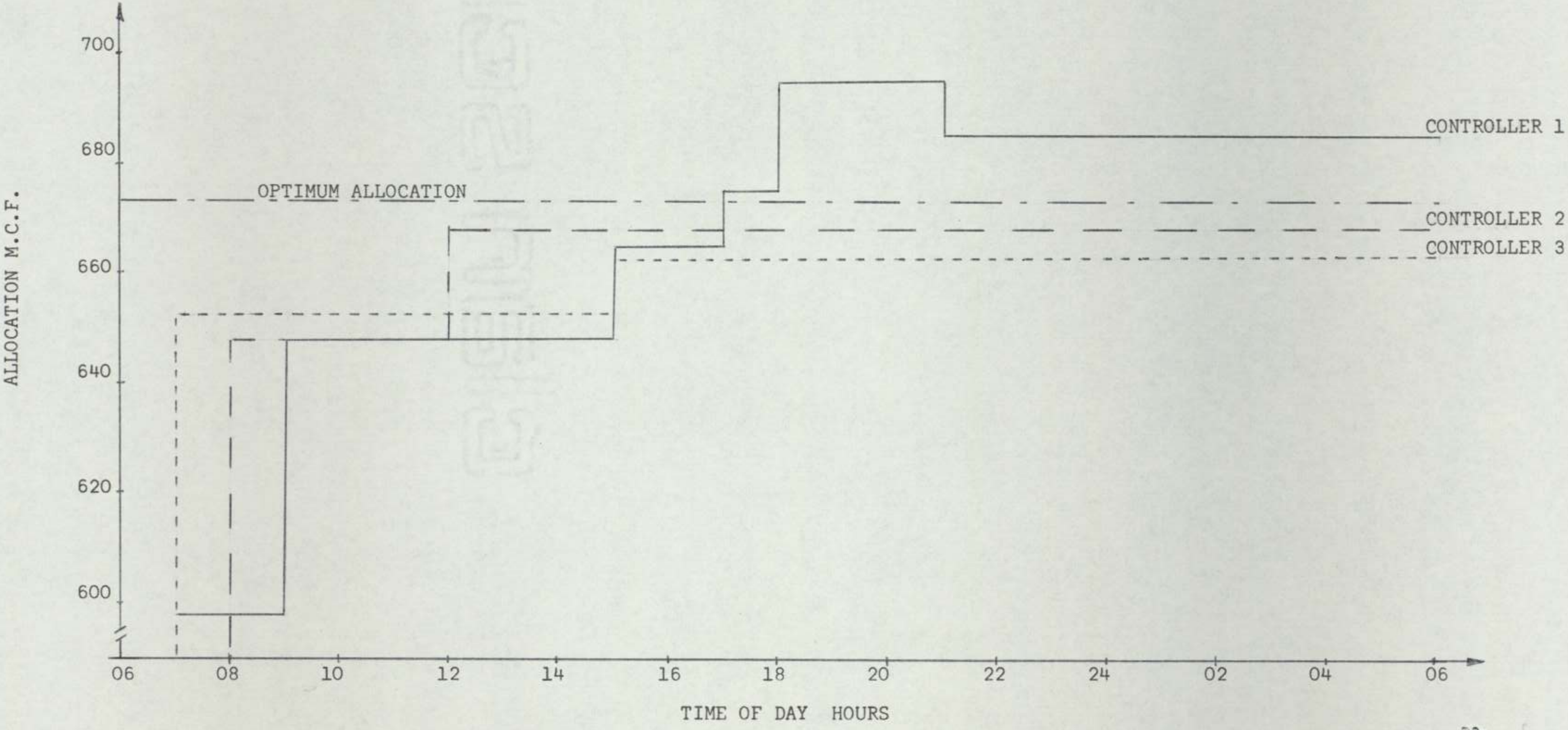


TABLE 7.20 COMPARISON OF ALLOCATION ERROR AND TRANSFORMED STOCK ERROR FOR THE 3 CONTROLLERS

CRITERIA	1	2	3
Allocation Error %	2.3	1.6	2.0
T.S.E.	46.2	20.4	18.4

Table 7.20 shows the allocation error made by the controllers, and confirms the observations made from Fig. 7.2. Also shown in the Table are the transformed stock errors for the controllers. These correspond exactly with the total cost of supplying gas, criterion 1, Table 7.19. The results also show that good allocation selection does not necessarily imply the most effective implementation of the relevant prediction and decision. The probable locus of this implementation ability is in the timing and selection of a suitable action. Thus controller 2 incurred a greater cost in gas supply because he used expensive stored gas. One reason for this use of stored gas was that he felt he would run out of gas by 23.00 hours if he did not make an immediate change. The other was that he asked for more P.S.G. than was available and had to compensate later.

The booster and compressor costs show a difference of £188 between controllers 2 and 3. The use of boosters etc. can be influenced by good predictions. If there is not enough gas being put into the system then boosters will have to run for a long period of time to maintain the storage main. Alternatively if there is an over prediction with too much gas going into the system, the gain in not using boosters will probably be lost in the cost of supplying the extra gas. This is probably the reason for controller 2 having the lowest booster costs. Controller 1 offset the use of his boosters by increasing the gas input. Controller 3 predicted less accurately than controller 2, and so had to use more boosting to reaching 23.00 hours successfully. A further reason for the higher cost incurred by controller 3 was that he appeared to be using some subtle procedures that would probably have been effective in the real system but not in the simulation. This involved pushing gas from one set of holders to another. This behaviour is not entirely unexpected because of the additional experience controller 3 had as a distribution controller.

Although controller 1 did not perform well in terms of predicting final sale he did make up for his early shortfall later in the day, and ended up without incurring a stock error penalty unlike his colleagues. The true cost of not incurring stock error, as mentioned earlier, cannot be easily assessed. With the arbitrary penalty scheme employed here the estimated cost of stock error is small in comparison with the cost of inaccurate prediction. However, it could be argued that if there was another heavy sale the following day, stocks could be run right down, and the 5 m.c.f. of gas saved by controller 1, could be the difference in maintaining or damaging a holder, a cost of £40,000. This illustrates the problem of devising satisfactory performance criteria in a complex task. Recently Lees (1974) has commented that it has always been a problem in process control to assess the value in terms of economic performance of a given level of control performance. Combining the four criteria of performance used here by ranking, gives the result that the three controllers perform equally well!

7.6 Conclusions

This chapter has one unifying theme, prediction. The results of section 7.3 indicated that the differences between, the individual controllers behaviour on the real and simulation tasks, and shifts, was due to the lack of predictive behaviour observed for controller 1. Section 7.4 showed that the major difference in the procedures adopted by the controllers was the way in which predictions were made. Finally section 7.5 showed that accurate prediction was the one most important factor in influencing the cost of supplying gas.

The chapter also showed that the accuracy with which a controller is prepared to carry out a particular prediction procedure may be influenced by the confidence the controller has in the accuracy of the result.

Some new methods of prediction were identified, and evidence from controller 2's protocol showed that a variety of methods were used in one sequence for the purpose of cross checking.

Analysis of decision behaviour showed that in difficult conditions controllers are prepared to ignore normal operating criterion if they feel sufficiently justified. The justification appeared to be based on long term prediction of sales.

The selection of a suitable control action both for supply and storage was determined by cost. In supply control this was further complicated by the need to consider the delay associated with a control action becoming effective.

CHAPTER 8

This chapter summarises and discusses the results of the experiments and field studies, and relates them to various areas of research reviewed in Chapter 1. Comparison of the control behaviour on the gas and electricity tasks shows certain similarities between the two, as well as similarities with behaviour on other control tasks. The study of skill development shows an increase in purposive behaviour with practice. Some of the changes in behaviour organisation indicate similarities with changes in behaviour associated with skill acquisition on perceptual motor tasks. The evidence on individual differences suggests that different abilities may underly different features of control behaviour. Analysis of prediction and decision procedures suggests that there may be limits or biases in the way controllers combine information to perform these functions. The structural similarities between the behaviour observed here and behaviour on other cognitive tasks, suggests that some form of structural analysis may be a useful way of looking for common determinants of cognitive behaviour. It is concluded that the protocol technique is particularly useful for providing hypotheses, and can also provide rigorous evidence on certain aspects of behaviour.

8. DISCUSSION AND SUMMARY OF RESULTS

8.1 Similarities between control behaviour in different tasks

This section is concerned with the types and similarities of behaviour required from the controllers in the electricity and gas grid control tasks.

The nature of control tasks, as presented in 1.1, seems to dictate the performance of certain basic functions necessary for keeping the controlled system in some kind of equilibrium. These have been identified for the two tasks considered here as:

(a) Prediction of possible future states of the independent variable.

(b) Evaluation of the effect of the predicted value on the system.

(c) Deciding whether this effect is acceptable.

(d) Selection of the most suitable compensatory action.

The functions described here are very similar to Kelley's (1968) assessment of the basic control functions.

In the gas and electricity tasks, prediction appears to be carried out by similar methods. Past experience, in terms of LTM and past records, are used by the controllers to reduce their uncertainty about the outcome of future events. With the electricity controllers it was necessary for them to predict small fluctuations in demand, as well as the characteristic peaks and troughs. The gas controllers only had to predict one aspect of demand, total sales for the day. Available evidence suggests that the electricity and gas controllers have evolved fairly similar methods for using past records to make the long term predictions.

Evaluating the effect of a prediction consisted of combining that information with other information about events that might affect the equilibrium of the system. In both the gas and electricity controllers' behaviour this process was represented as a linear equation which combined information from all the relevant sources. In both cases the net result was presented as a discrepancy between the likely state of the system some time in the future, and the required state of the system. It was then necessary for the controller to decide whether the computed discrepancy was acceptable. The analysis of the decision processes in the two tasks, showed similarities; with a postulated decision threshold, and a number of factors identified as influencing the size of the threshold and the variability of the computed discrepancy.

The selection of a suitable control action required the controllers, in both tasks, to consider two dimensions, timing, and cost, in making their choice. This is dictated by the nature of the two control systems. In the gas system, plant that can produce gas quickly costs more money to operate than plant having a slower response time. In the electricity system, each generator has its own performance characteristics and associated cost of electricity produced.

Usually the selection procedure presents no problem to the controller. However, in certain situations there may be a conflict in time/cost requirements, and then the controllers have to choose the action which is most beneficial to the system. An example of this decision procedure is given in 7.4.3.

This comparison of the main functions of control behaviour and the general methods employed to achieve them, shows considerable similarities between controller behaviour on the two tasks. The comparison of activities observed in the behaviour of controllers from the two tasks (see 4.4.6), shows that similar activities account for over 80% of the activities observed on both tasks. The content free activity descriptions used here may be a possible basis for quantitatively comparing behaviour from different tasks. Miller (1971) has expressed the view that an ideal taxonomy would be content free, and that the underlying processes may be functionally equivalent, e.g. translating English into Morse, or Fortran into machine code, but not logically equivalent. Comparison of the frequency counts for individual activities showed that the electricity task required more control actions, whereas the gas task required more predictive activity. These differences were interpreted as reflecting basic differences in the two grid control systems.

Besides these content free similarities there also appear to be some similarities in the processes involved in performing some of the basic functions in the two tasks. The processes underlying prediction, action selection, and particularly decision making seem to be comparable. Identification of similarities in the ways people achieve some of the basic functions required in control tasks, suggests that there may be some fundamental abilities that are necessary for good control performance. If this is so it would have special relevance for the more practical problems of training and selection of operators for control tasks. However, there are some important problems to be overcome. These are, selection of suitable performance criteria, and the construction of context free tasks that would test for the relevant abilities.

8.2 Development of control skill

In 1.2 it was concluded that an increase in feed forward activity seemed to be the major behavioural change associated with control skill acquisition. Chapter 6 investigates this and other possible changes using the verbal protocol technique. General statements about skill acquisition have suggested that understanding what the important variables in a task represent, is one of the earliest and most crucial stages in skill development. The results of a pilot experiment had indicated that the type of relationship that a subject thought connected certain variables, affected the way he attempted to achieve certain goals. Chapters 5 and 6 investigated this aspect of skill development using a suitably prepared questionnaire.

8.2.1 Results from performance and questionnaire data

The results of the performance data analyses in both chapters indicated that considerable experience and perhaps additional training is required before naive subjects can perform as successfully as experienced controllers. The results from Chapter 5 did show, however, that although naive subjects do not learn to use any of the prediction procedures used by the controllers they do show an improvement in performance after only two trials.

The results from the questionnaire data in Chapter 5, showed that the knowledge of what a variable represented seemed to be associated with good performance in the earlier trial. By the end of the second trial this type of knowledge was no longer associated with good control performance. The results obtained from the questionnaire data in Chapter 6 confirmed this finding, but also showed that subjects forgot exactly what the less important variables represented. These findings suggest that different types of knowledge about the task may limit the level of performance at different stages of skill development. This resembles the results from some of the extensive work of Fleishman, e.g. (1966) on perceptual motor tasks. The major purpose of his research has been to attempt to identify a series of basic abilities that account for performance on a wide range of such tasks. Particular studies concerned with complex tasks have shown that these basic abilities can have a differential role at different stages of learning a task. It may therefore be possible that certain types of knowledge or abilities could be identified as being critical at various stages of cognitive skill development. The tentative results discussed in 8.1 concerning fundamental processes suggests that this might be possible, and that an approach similar to Fleishman's on cognitive tasks may produce useful data about cognitive processes and abilities. The major problems associated with this type of research, are as mentioned in 8.1, finding suitable performance criteria, and suitable context free tasks testing a specific ability.

8.2.2 Results from protocol data

The most noticeable changes in behaviour shown by the protocols during skill development was the apparent increase in purposive sequences. In the first trial recurring sequences were more easily identified by the type of information that was being sampled. By the fifth trial more purposive sequences were observed. This seems to suggest that by this time subjects were specifically linking goals with the means of achieving them. Bainbridge (1975) has also found that on the power demand task, inexperienced subjects in particular know which data item they need the value of, but not how to find it.

The results in Chapter 6 showed that on the first trial subjects sampled certain types of information, e.g. stock information (St), comparative information (CD), and that when a decision was made it would only be at the end of such a sequence if the information sampled indicated that one was required. By the fifth trial most sequences were purposive, and subjects were sampling information specifically to satisfy a goal by a particular procedure. It seems probable therefore, that in the first trial the subjects were having to interpret what the variables indicated about the state of the system and learn the various decision procedures. By the fifth trial, however, the subjects had learned what the various types of information showed about the system, and how to use information relevant to achieving a particular goal. Thus in the first trial it seems that the subjects were developing their decision rules, by learning what a specific variable indicated about the state of the system, and then considering if a compensatory action was required.

Subjects only used information about four aspects of the system, weather, stock level, stock change, comparison of sales with a similar day, to indicate whether a control action was required. Each one of these can provide information about possible future states of the system. An appreciation of these relationships in the first trial may indicate the reason for the association between performance and questionnaire scores.

The four decision rules used by the subjects, and based on the above information, are similar in concept to the procedures used by the controllers. However, the purpose for which some of these were used tended to suggest that the subjects had not completely learned to distinguish between the functions of predicting, and deciding on a control change. In particular subjects would tend to base a decision on comparative information without evaluating its likely affect on the future state of stocks. However, the development of separate prediction sequences in trial five does indicate that subjects were learning to discriminate between these two basic functions. This further supports the suggestion that inexperienced subjects have to learn to link methods with goals.

It is instructive to consider how the development of a cognitive skill as discussed here compares with the more frequently observed changes associated with perceptual-motor skill acquisition. Fitts & Posner (1967) postulated three stages of skill development. The first is the cognitive stage in which the subject attends to cues, events, and responses that later go unnoticed. In the intermediate phase, old habits which have been learned as individual units during the early stage are tried out and new patterns begin to emerge. Errors, e.g. inappropriate sub-routines, etc. are gradually eliminated. In the final or autonomous phase, component processes become increasingly autonomous and less subject to cognitive control. In the results discussed here it has been shown that subjects tend to forget unimportant information, and gradually develop coherent purposive sequences of behaviour. These changes seem to be analogous to those prescribed in stages one and two. However, the results from the studies on the controllers suggest that autonomy and associated lack of conscious control over behaviour, are not key features of skilled cognitive behaviour. The controllers have well defined methods of achieving task goals, and these can be adapted to cope with changes in task demand. It is this organised flexibility which is characteristic of cognitive skill. However, verbal protocols could only be expected to give data on some kind of conscious behaviour. Differences between the naive subjects and the skilled controllers might have been expected to give some indication of a change in the level of behaviour accessible to verbal report. There was, however, no unequivocal evidence of this nature. In terms of autonomy, there does not appear to be any demonstrable equivalence between the final stages of perceptual motor and cognitive skill. The well organised recurring sequences of directed behaviour of the controllers, are, however, in keeping with other observable characteristics of perceptual motor skills. The flexibility associated with cognitive behaviour is also a feature of perceptual motor skill. Therefore structurally, there seems to be some similarity between the two types of skill.

8.3 Individual differences

Results from the investigations presented in the foregoing chapters have provided several examples of individual differences. These have been confined in the main to the results from the gas controller investigations. The data from the protocols have shown considerable differences in the quantity and detail of verbal behaviour from both field and experimental studies. The differences have been reflected in the type and frequency of information, activities and sequences observed in a particular controller's behaviour. Some of the differences appear to be an artefact of the protocol technique as a source of data, others seem to be related to certain differences in performance. Differences associated with the protocol technique will be discussed in 8.6.

8.3.1 Ability and experience

It was evident from some of the literature reviewed in 1.3 that finding a suitable performance indicator can be the limiting factor in any field study of individual differences. Fortunately in the gas task it was possible to use the accuracy with which predictions were made as a partial indicator of performance, and so attempt to relate behavioural differences to performance. Results indicated that a particular controller using a particular prediction procedure tended to produce marginally better predictions than his colleagues who used different combinations of procedures. This presents the problem of trying to decide whether it is the individual, or the method that is most responsible for this difference.

In the simulator study it was possible to use a variety of performance indicators. In particular it was possible to distinguish between a controllers skill in selecting the correct allocation, and his skill in implementing the required actions. The results showed that although a controller might be good at allocation selection, e.g. controller (2), his overall performance, indicated by total cost of gas supplied, and transformed stock error, may not be as good as a controller who was not as accurate in allocation selection, e.g. controller (3). This tends to suggest that there are at least two distinct aspects of performance that require different skills or abilities for their satisfactory execution. These differences may be due to abilities the controller brings to the task or to experience gained while doing the task.

An indication of which of these is most important in determining a level of performance would be useful in selecting and training new controllers. However, there is probably considerable interaction between these two factors. Even Piaget (1972) has maintained that formal operations although free from their concrete content, can only be so, "on the condition that for the subject the situation involves equal aptitudes or comparable vital interests." Evidence from the protocols on conditional statements shows that the controllers are functioning at the formal operational level. These operations will act on the controllers figurative knowledge acquired from experience on the task. This figurative knowledge may consist of static, and dynamic knowledge about the system, as well as current information about the values of particular variables. Both of these features of a controller's knowledge will be involved in any transaction he has with the task environment.

Recently Bainbridge (1974a) has proposed a model where both figurative and operational knowledge may be related to performance. In the model an operator will vary his strategies or methods, (figurative knowledge) of achieving a given task goal according to changes in task demand. Each strategy requires a particular level of mental processing, (operative knowledge). Thus to maintain a constant level of mental effort an operator must change his strategy. The difference in strategy used by the controllers in predicting might therefore be interpreted as differences in their processing capacity (operative knowledge). However, this is complicated by the fact that the controllers tended to process more information when task demand increased in the afternoon without any evidence that different strategies were being employed. This suggests that controllers were not working close to their processing capacity, and that the use of different strategies was personal preference.

8.3.2 Personality and motivation

Besides the two factors discussed above, there are two others that may be related to individual differences. These are personality and motivational factors. Evidence in 1.3 from Bainbridge (1974) showed that certain subjects could choose an action, but had difficulty in committing themselves to make it. This suggests that personality differences could be associated with certain idiosyncracies in decision making. There seems to be considerable evidence in the literature for this, e.g. Kogan & Wallach (1964). Motivational factors, particularly in the simulator task might be considered a source of individual variability. However, the possible effects of motivational factors are difficult to assess. For example in the field study one of the differences between the controllers' behaviour was the amount of information processing in goal orientated sequences. A replication of this was found in the simulator study. These results may be interpreted in several ways. Besides being attributed to variations in ability to verbalise thought processes, they may be attributed to the motivation a controller has, to make his thoughts public. Motivational factors may also be expected to affect performance. However, since behaviour samples were taken at irregular periods over several months, daily variations in motivation are less likely to have had any systematic effect. Daily variations in motivation may be superimposed on a general level of motivation towards doing the task. It is however, difficult to distinguish the effect this might have on performance from effects caused by different levels of skill.

Thus it seems that differences in performance observed for the controllers can be related to knowledge the controllers bring to the task, knowledge they acquire while performing the task, certain personality variables, and possible overall levels of motivation.

8.4 Possible performance limitations

In 1.4.4 it was concluded from the available evidence that knowledge of process dynamics and a repertoire of suitable control strategies were pre-requisites for good performance. The section here views evidence from the protocols on processes that may possibly limit control performance.

8.4.1 Predicting

In both gas and electricity tasks predicting demand is probably the one most important function that a controller has to perform. Analysis of the predictive behaviour of the controllers on both systems has indicated that they use a variety of methods and information in making these predictions. The discussion in the remainder of this sub-section will be restricted to the gas controllers' predictions, since not much detail was available on the electricity controllers' predictions. The apparent similarity of the methods used on both tasks suggests that comments made here may be relevant to predictive behaviour on both tasks.

Examination of the gas controllers' predictive behaviour showed two main methods of prediction, Types A and B; and an auxiliary method Type W, based on weather information. The procedures used in processing the information for application of these methods were well defined and appeared consistently in the predictive behaviour. However, sometimes the controller finds it necessary to combine the results from more than one method. It is discussed here whether the controllers combine all the available information on prediction effectively and accurately.

Usually controllers tend to reject one method of prediction in favour of another. This is done by assessing the likely accuracy of a prediction given by a method in a particular set of circumstances. The assessment is usually based on how successful a controller is in finding a comparative day that he considers will give a more accurate prediction than the computer based prediction. The controller, depending on his success, will choose either method A (computer estimate) or B (comparative day). As shown in the previous chapters, the controllers continually reassess their methods of prediction in the light of new information, their approach is therefore flexible. In some situations, however, a controller may not be able to choose between methods; on these occasions the controller may attempt to combine the results from A and B as well as additional information from type 'W' into an aggregate prediction. The procedures used for combining several results are not well defined or used with any consistency. It suggests that perhaps the controllers have difficulty in finding a procedure for combining the various results satisfactorily.

Recent work described by Kahneman & Tversky (1973) on the psychology of prediction has indicated certain types of error that seem to be inherent when people combine information to make predictions. Some of these seem to be relevant to the cases where the controllers combine results, and indicate possible sources of error in their behaviour. Kahneman & Tversky have proposed that humans make predictions under uncertainty by choosing the outcome that is most representative of the available evidence. This may be satisfactory in many situations. However, the representative approach ignores such factors as the prior probability of outcomes, and the reliability of the evidence which can affect the likelihood of outcomes, but not their representativeness. The results produced by Kahneman & Tversky confirm their hypothesis and show that intuitive predictions tend to erroneously predict rare events and extreme values if these are representative of the given evidence. Thus in the case of the controllers, representative evidence from their various methods may suggest extreme values of demand which the controllers may adopt even though the probability of such an outcome may be very low. There is no evidence from the protocol data that controllers refer to average values of sale. It cannot, however, be established unequivocally that the controllers make this type of error, as it is possible that conversion from MG to NG has made seasonal average sales, based on previous years sales, difficult to interpret and use in any prediction.

A complementary finding of Kahneman & Tversky which is of particular relevance to the occasions when controllers combine results, is that confidence increases with consistency. Thus for example if prediction methods A and B gave a sales value of Y, it is expected that a controller would be more confident in this result than if they had given X and Z. The intuition that consistent component predictions allow greater predictability than inconsistent component predictions seems compelling. Highly consistent patterns are however, more likely to be observed when the input variables are highly redundant or correlated. Hence people will tend to have greater confidence in predictions based on redundant input variables, and less confidence in predictions based on non-redundant information. However, it can be shown statistically that the accuracy of the correlation between input variables and criterion is inversely related to the correlation among inputs. Thus when a controller cannot choose between two methods of prediction, he will probably decide to combine the results, perhaps by taking the mean value. If the results of the two methods are similar, the controller is most likely to be more confident in a prediction made on this basis, than if the two results had been dissimilar; although the above argument suggests that a prediction in the second case is likely to be more accurate than the one in the first. This analysis suggests a possible source of error in the controllers predicting behaviour. Confidence in the possible accuracy of a prediction can influence the accuracy with which he will make the prediction. It can also be of some importance when the controller has to make a control decision based on the result of prediction sequences.

Unfortunately evidence for this sort of behaviour is difficult to obtain. It requires a series of detailed events where consistency in component predictions can be related to any increase in unnecessary control actions. Field studies are not a useful method for obtaining this type of evidence, but an experimental approach might be more productive. There are, however, some examples where component prediction methods give consistent results, e.g. 2. 22.9.74, having used a type B he says, "I think the sales today will be somewhere near the 90m mark, in fact the % is now indicating 89.9m." The controller is using the ES = 89.9 as a confirmation of his 90m. The fact that he does use this information in this manner, rather than using a more sophisticated combinatorial rule, suggests that the controller might be susceptible to the consistency bias.

Besides considering the effect of some of the apparently inherent errors people make in predicting, it is worth examining possible ways in which information presentation can limit performance of this function. This is particularly relevant to predictions using method type B. As practised at present controllers compare a previous day, by examining the discrepancies between hourly sales, after the initial selection criteria of weather and day of the week have been satisfactorily fulfilled. To do this the controller has to calculate the difference between HS and HS' for each previous hour by either an analogue or digital computation. Such a procedure does not permit the controller to detect trends as easily as would be possible with a graphical presentation as it requires unnecessary processing and storing of information. A graphical facility for the comparison and assessment of trends, would perhaps allow controllers to select or reject previous days' data on the basis of more completely processed information. It is possible that it is this procedure of selecting a comparative day accurately that enables controller 2 to make better predictions than his colleagues. The fact that many more SCD sequences are observed in controller 2's behaviour tends to support this suggestion. If this is so, then providing a better facility for selecting comparative days may contribute to more accurate predictions.

8.4.2 Control decision making

Decisions made by controllers in both gas and electricity tasks consist of assessing the acceptability of possible states of the supply and distribution systems. Thus if stocks are likely to be outside certain levels, or frequency outside statutory limits, the controllers will have to make compensatory actions. The extent to which a controller is prepared to allow stocks or frequency to drift before implementing a control action has been termed the decision threshold. In both tasks the assessment of the state of the systems has been represented by equations which linearly combine information about the various factors likely to affect stock or frequency. Both equations include terms that represent predictions about future demand levels. The confidence that a controller has in his prediction or in the other information included in the decision equation, will affect the result computed by the equation. Thus an electricity controller might give the result from a decision equation as SC* ∓ t, where 't' is the tolerance level associated with the accuracy of the information in the equation, and is inversely related to confidence in the evidence provided by the equation. If SC ∓ t falls completely outside the decision threshold, DT, the controller should automatically initiate a compensatory action. If SC ∓ t falls inside DT no action should be required. However, should SC ∓ t be within the range of DT then the controller will be uncertain as to whether a compensatory action is required.

Evidence in Chapter 7 on the gas controllers' decisions showed that the situation can in some circumstances be complicated by certain

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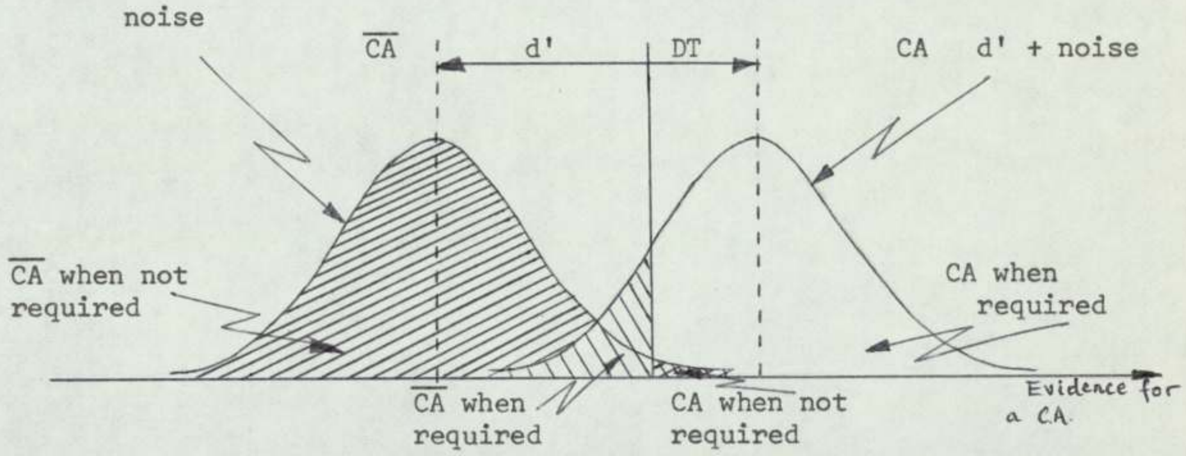
*SC = size of control action

factors that affect the size of DT. In some examples it was shown that forward information about the following day would tend to make the controller increase the size of his threshold. Evidence in Chapter 4 showed that the type and availability of a control action would also affect DT. It is possible to model these various features of decision making by utilising the signal detection paradigm*, see Fig. 8.1

FIGURE 8.1



The uncertainty associated with prediction accuracy and accuracy of other information included in the decision equation is represented as 'noise' in the system. d' is a measure of the ambiguity of evidence provided by the decision equation, and is some function of SC. Thus when the evidence is unequivocal the certainty that a control action is required will be high. Figure 8.1 shows graphically how a controller

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*I am grateful to Mr. D. Embrey for clarifying some of my thoughts on this formulation.

can make a control action when there is no real change in the system, and fail to make one when there has been a change in the system. This will become important when d' is small in relation to the standard deviation of the noise. On these occasions an increase in DT will increase the number of type II errors and a decrease will increase the number of type I errors. There are many assumptions involved in the calculation of statistics relating to SDT. It is doubtful whether these assumptions can be met in the decision situations. However, it is of interest to consider the information that could perhaps be obtained about controller decision making by attempting to draw suitable ROC curves. This could be achieved by presenting a controller with a number of hypothetical decision situations in which SC and hence d' remained constant. The controller would be asked on each trial to rate his certainty about the need for a control action. The resulting curves would indicate the effect of varying DT (ie cost of making a control action) on a decision, and the effect of varying ambiguity of evidence, d', on a decision. Controllers could then be made aware of the situations in which they would be likely to make type I and type II errors. Suitable training might reduce these types of error.

The analysis in 3.7.2 indicated that there were two additional dimensions which had to be considered when making a control action, besides assessing the size of action required. These were timing, and the selection of suitable plant to implement the required change. There were a variety of factors affecting the timing of an action, some of these e.g. availability of plant may also affect other aspects of decision making, such as the decision threshold (see 4.5.2(e)).

Action selection was shown to be dictated by the economics of the available decision alternatives, however, as shown in 7.4.3 there can often be conflict between timing and cost as the two tend to be inversely related. It is also possible that in certain circumstances the cost of making a particular action might conflict with size of action required. In some complex situations there might even be conflict between the requirements of all three dimensions of making a control action. So although the controllers have specific methods for assessing information relevant to each individual dimension, the above discussion shows that on some occasions a controller may have to make a compromise between the conflicting requirements of the various dimensions. In these situations the controller will have to decide which control alternative best satisfies each of the three dimensions, i.e. he must maximise the worth to the system. For example the decision equation might assess that a control action of size 10 units is required, however, to make this size of action may cost £100, whereas to make an action of only 5 units would cost £10, but take longer to implement. The controller then has to decide whether being 5 units of gas short and not satisfy the immediate needs of the system, is equivalent to a saving of £90. Besides the problem of combining information from three dimensions, which will be discussed below, there is also the difficulty for the controller of assessing the worth to the system of satisfying each dimensions requirements. As discussed in 7.5 there was a considerable problem in the gas task of evaluating the cost to the system of a short fall in stocks. It is therefore quite possible that each controller may have his own cost function associated with this and other requirements.

Certain experimental evidence e.g. Rigney & De Bow (1967) has shown that subjects have difficulty in combining information from more than two sources to produce an assessment of a situation. Since Miller (1956) it has been realised that humans have a limit in the number of conceptual units they can handle at one time. This would tend to suggest that when a controller has to combine information from more than two dimensions, he may not be capable of doing this efficiently. Shepard et al (1961) have described this as an attentional phenomenon, people can only take account of a very limited number of factors at anyone time. Work by Pollack (1962) seems to indicate that we can take account of a host of different factors individually, but can only consider one or two at a time. This is supported by research reviewed by Vaughan & Schumacher Mavor (1972) which indicates that people find it difficult to use more than one criterion at a time in evaluating an action.

This apparent limit in man's ability to combine information successfully from more than two sources, may be a possible explanation for the unnecessary expensive control action made by controller 2 on the simulator (see 7.5). In this situation the controller had to evaluate the importance of the size, timing, and cost of a control action. The controller chose the most immediate but most expensive control action. Almost the same result could have been achieved by a less expensive action.

8.5 The structure and organisation of control behaviour

Evidence reviewed in 1.5 indicated that behaviour on control tasks was organised around a series of goals. This also seems to be a feature of cognitive behaviour in other task environments, e.g. Newell & Simon (1972). Bainbridge (1975 and 1972) showed that in the power demand task, goals were identified as data items, and were usually the result of some numerical calculation. One or more basic operations were required to transform information and produce a data item. The organised performance of operation(s) to arrive at a required data item was called a routine, because their occurrence was frequent and followed a similar pattern of processing on most occasions. The occurrence of a routine in an operator's behaviour was determined by conditional statements embodying values of certain key data items. These conditional sequences appeared to be organised by an overall planning routine. To produce the flexibility and parsimony that is a characteristic of cognitive behaviour she proposed that means (operations etc.) should be separated from ends (data items), so that several goals could be satisfied by one routine, or one goal satisfied by several routines.

The behaviour of the controllers studied here shows a similar structure although the individual levels are not directly equivalent. Basically the controllers use a selection of operations organised in a sequence to achieve a particular goal. The rationale underlying sequence organisation can be thought of as the controllers' method of achieving that goal. The operations are identifiable with the formal and concrete operations which according to Piaget are fundamental to all cognitive functioning. As in Bainbridge's findings the organised sequences of these operations can be used to achieve certain goals, but in particular there can be two or more methods of achieving a particular goal. The organised sequences of operations observed in the gas and electricity controllers' behaviour were longer than Bainbridge's routines, because they were at a higher level of behaviour. However, they do not appear to be identical to the sequence level of Bainbridge's analysis as there seems to be little evidence of conditional statements determining the information to be processed by an operation. In the controllers' behaviour, information only seemed to be processed if it was relevant to the overall sequence goal; a lower level of goal orientated behaviour did not seem to exist. Consequently the sequences of processing implemented by a particular goal tended to vary from situation to situation, although the basic method underlying the processing would remain the same. For example, in the electricity controller's decision equation, information would only be included about factors that would be likely to affect the state of the system. This indicates that the controllers seem to have a general scheme for achieving a particular goal, and can adapt these general schemes to cope with a given situation.

The decision of what to do after a goal has been achieved is usually determined by the result of the goal. Thus if the result of a decision equation is larger than the decision threshold the controller will start processing information to achieve the next goal, which will be selecting a suitable action. These goals seem to be functionally equivalent to Bainbridge's 'head boxes', i.e. at the level where decisions about what happens next are made. This type of decision does not seem to have been easily accessible to introspection judging by the lack of evidence in the protocol here, as well as in Bainbridge's task and Beishon (1969). Beishon has suggested that this might be because people plan ahead and so the decisions about what to do next, have been made sometime beforehand. There is some evidence in the gas controllers' protocols, particularly in 'consider' activities, that they do plan ahead. It seems, however, that in many cases the choice about what is done next, is a logical consequence of the functioning of the system, and may therefore depend to some extent on the way a particular controller views this functioning. Another feature of behaviour that can obscure this type of decision making is that controllers may often store the result of a previous application of a sequence. For example, a gas controller may predict a final sales value, recall the value that he predicted last time and tacitly compare the two. If there is no difference, he will not bother to carry out a control decision sequence, because he will realise that nothing has changed since his last assessment of the state of the system.

There is, however, specific evidence in the gas controllers' protocols of how choices are made between using different methods of achieving the same goal. This behaviour is exhibited in SCD sequences where controllers decide on the best method of predicting gas sales. The behaviour in the sequences shows that controllers will try to use the method which they consider to be most appropriate in the prevailing situation.

There is also evidence from the behaviour of the controllers that shows that they carry out particular procedures at different levels of accuracy, and in some cases do not bother to pursue a sequence to a conclusion. This is a similar finding to the one described by Bainbridge (1975) where operators tended to trade speed of calculation for accuracy, or vice versa. In certain circumstances therefore, an operator may calculate the value of a data item by an analogue computation, and in others by a digital computation, depending on whether speed or accuracy was important in acquiring the value. The evidence from the controllers' protocols did not indicate however, that this was the basis they used for deciding whether to produce an accurate result from a sequence. Instead the controllers seemed to consider how accurately they could satisfy a particular goal and then processed information as accurately as this assessment dictated. It appears therefore, that decisions about which method to employ in satisfying a particular goal, will depend on assessing which method is most accurate in a given set of circumstances. Decisions about the way the method is to be executed however, will depend on the speed or accuracy required, as well as the level of confidence that may be expressed by the method being employed.

Goal orientated sequences are implemented when a particular sub-goal has to be achieved in the course of satisfying the overall task objectives. As discussed earlier, a decision about which goal follows another, is on many occasions determined by the functioning of the system. These goals seem to have been formed as a result of a controller evaluating the effect that changes in certain parameters will have on the system. This suggests that a pre-requisite for someone learning to control the system is an understanding of the interrelationship between variables, so that they will know what will affect the equilibrium of the system. Evidence discussed in 8.2 showed that inexperienced subjects knew what to do in the early stages of skill development, but that it is not until later with more detailed knowledge about the system that they learn how to do things. This may suggest that deciding what is to be done in a task is the highest level of cognitive behaviour and is a function of basic knowledge about key variables. This point of view is supported by Miller (1974) who in discussing a theory of cognitive organisation has suggested that a computer is capable of doing anything, if we know how to tell them to do it; but the trouble is we don't know what to tell them to do. If this is true, an information processor must first acquire a general knowledge of the various interrelationships between the different task variables. The i.p. must then be able to operate on this knowledge and reason out the effect of changes in particular variables, so that it will know what its compensatory goals must be.

8.6 The methodology of the verbal protocol technique

The investigations described in most of the chapters have been concerned with elucidating certain aspects of human behaviour in control tasks. Each investigation has employed the verbal protocol technique as the main source of data on this behaviour. It is important therefore that the technique should be assessed in its adequacy at providing relevant data.

8.6.1 Observational and verbal report data

Its main drawbacks, besides those discussed in 1.7, have been that it produces large quantities of data that are often quite difficult to analyse, and also that there are differences in the quality and quantity of data that individuals can produce in attempting to describe their thought processes. Where it has been possible, objective checks between computer printouts, logging sheets etc. and protocols, have shown the protocols to be a valid source of data. Comparision between behaviour from the preliminary observational studies, and the protocol studies, in both the gas and electricity tasks, showed a clear correspondence in the nature of the data produced by the two different techniques. In particular it was shown that the observational data based on verbal reports gave details of controller behaviour at the sequence level. Protocol data, however, provided more detailed evidence about the information sampled, and the activities employed. This is a further check on the validity of the protocol data. It also shows the level of detail about behaviour possible with the simpler observational/verbal report technique, compared with that produced by the verbal protocols.

8.6.2 Frequency counting and protocol data

The large quantity of data produced from verbal protocols has prohibited analyses using large numbers of subjects. Bainbridge (1972) based the whole of her analysis of behaviour in the power demand task on the protocol from one subject. The problem is further exacerbated by the lack of standardised methods of analysing protocol data. The method of frequency counting different types of behaviour was specifically evolved so that comparisons could be made between behaviour on different types of task, and investigating changes in behaviour associated with the effect of practice. The results from the various investigations revealed the following difficulties.

Within controller variability could often mask differences in behaviour associated with particular circumstances. This was particularly noticeable in the skill development study, and the experiment with the controllers on the gas simulator task. In the first case this might have been avoided by using more subjects. However, a result from Beishon (1966) on the water tank experiment showed that individual subject differences accounted for a much wider variation in performance than experimental conditions. This might suggest that considerable subject variability is a feature of fairly inexperienced subjects learning to do a complex task. With the controllers, the variability could probably have been avoided by allowing them more experience with the simulator, and sampling more of their behaviour, as in the field study. Another problem with the method was the difficulty of knowing whether consistently low frequencies associated with one controller, e.g. controller 2 were indicative of fundamental differences in control behaviour or an artefact of the protocol technique. As there were considerable similarities in the actual methods the controllers used in performing the control task it seems probable that the low frequencies were in some way an artefact of the technique.

8.6.3 Establishing sequence patterns

Although frequency analysis methods provided an objective way of making comparisons between individual controllers, they only provide evidence on what was done, not on how it was done. Inspection of the protocol data gave no indication of the processes underlying the basic activities such as 'recall', 'compare', 'note', etc. and it seems probable that these processes are not open to introspection. However, by examining the recurring patterns of information and activity associated with the various goals, and sub-goals identified in a person's behaviour, it was possible to reveal the methods used to achieve these goals. The problem with this type of analysis is the difficulty of setting out an objective procedure for doing it. The first stage of the approach is to identify a particular method used for achieving a particular goal, and the rationale behind it. The second stage is to look for specific examples where the method has been used in unusual circumstances. By examining the way the method has been accommodated in these examples, it is possible to develop a more generalisable version of the method. The decision equation (see 4.5.1) developed as a representation of the electricity controller's decision behaviour is a good example of this type of synthetic process. One of the main disadvantages however, with this analysis by synthesis is detecting whether an unusual procedure represents a novel method of achieving a particular goal, or has been produced as an artefact of the protocol technique. In several examples the controllers tend to miss out steps in an already identified procedure, the resulting sequence may therefore appear, on a cursory inspection, to be an example of a different or new method. In some difficult cases it may not be possible to decide whether an apparently novel sequence represents a new or an old method.

In summary, the protocols have provided data that can be used to study, individual differences, changes in behaviour associated with variations in task demand, and changes in task environment, as well as behavioural changes associated with skill development. However, to obtain results that are not easily masked by individual variability requires a large sample of behaviour. Unfortunately this may require a considerable amount of time spent in developing a procedure for analysis, and then actually analysing the data. This suggests that unless an ergonomic practitioner knows exactly what he is looking for, the less detailed observational/verbal report technique, used in the preliminary field studies, may prove to be a more useful analytic tool.

8.7 Conclusions

The discussion in this chapter has emphasised a number of issues related to cognitive skills in control systems.

Comparison of the behaviour of the electricity and gas controllers has shown functional similarities in their control activity. The difference in the frequency of the common activities associated with the two tasks reflects differences in the two control systems, and the way in which this affects controller behaviour. Analysis has also shown possible similarities in the detailed processing underlying some of these activities. If there are similarities in processing, it may present a basis for a cognitive taxonomy at a more detailed level, than the functional equivalence demonstrated between the activities on the two control tasks.

The study of skill development has indicated that there may be certain types of knowledge that are related to performance at different stages of skill acquisition, as is apparent in the development of perceptual-motor skills. Observation of the behaviour of the naive subjects shows an increased link between goals and methods of achievement during skill acquisition. This is particularly noticeable with predictive behaviour, and corresponds with findings in other control tasks. Comparison of the changes in behaviour that take place during the development of perceptual motor and cognitive skills has shown some organisational and structural similarities. This might be seen as supporting Piaget's contention that thinking is internalised action.

The research presented on individual differences has shown that different levels of performance can be identified with different facets of control behaviour. This has been interpreted as possible evidence for different cognitive abilities being associated with different features of behaviour on a task. It is not clear, however, whether these differences in performances have their origin in the invariant knowledge which a controller brings to the task or the empirical knowledge he may acquire whilst doing the task. A complete assessment of individual behaviour in the field study was not possible because of the usual problems of lack of control over task demand, and no suitable 'overall' performance indicator. For these reasons the simulator and the skilled controllers seem to be the best method of studying individual differences. The use of naive subjects cannot be recommended because of the time and resources required to train them to a reasonable level of skill.

The fairly detailed analysis of the controllers' behaviour made possible by using the protocol technique, has indicated certain processes of combining information in which there may be inherent limits in a person's capacity to carry out these processes successfully. The analysis of predictive behaviour has shown that the controllers may in certain circumstances accept extreme values of prediction when they are statistically unlikely. Also the controllers may be more confident in predictions based on redundant information than those based on non-redundant information. The analysis of the decision procedures has shown two distinct processes. The first was represented by a signal detection paradigm which characterised the interrelationships between the decision threshold and the noisy or inaccurate information. The relationships show how certain information may affect the likelihood of making a type I or type II error. The second decision process requires controllers to evaluate control alternatives on a number of dimensions, and by combining these evaluations, choose the alternative that will be of maximum benefit to the system. Evidence reviewed in 8.4.2 has suggested, however, that people have difficulty in combining information from more than two sources successfully. These limitations outlined here are only speculative, a series of experiments using the simulator would be required to assess the extent to which they affect control performance. If the limitations were found to be detrimental to control performance it would suggest a re-allocation of functions between the controller and the control system. In particular it would be better for the computer to combine information in a decision or prediction process, and for the controller to specify and supply the relevant component information, as in the Probabilistic Information Processor, Edwards (1962 and 1973).

The structural aspects of cognitive behaviour observed here show similarities with other cognitive tasks. These are, goal orientated behaviour with a variety of methods for achieving the goals, and certain rules that govern when a particular method is used to satisfy a goal. The order in which goals appear, seems to be determined by the controllers interpretation of the state of the system. Unfortunately evidence on this is minimal. The structural and organisational aspects of cognitive behaviour may be of fundamental importance, however, if the structuralists' assumption of there being structure underlying all human behaviour and mental functioning proves to be acceptable. Certainly the structuralist approaches of Chomsky, Piaget and Levi-Strauss have met with success in elucidating various aspects of cognitive behaviour. If some of the rules governing the relationship between units of cognitive behaviour can be defined, a theory of cognitive organisation may begin to evolve.

The protocol technique has provided useful and occasionally rigorous data on the various aspects of cognitive behaviour studied here. However, there are certain drawbacks, particularly with the variations in verbal behaviour, associated with individual differences. This can be overcome to some extent by giving more practice in using a simulator, and taking larger samples of behaviour. In some applications therefore, the verbal report method is a more useful and less time consuming technique. Other drawbacks with the protocol technique are that it can give ambiguous evidence about inferred processes. Also it gives no evidence on multiple processing or on the lower levels of cognitive operations, and it only gives a little evidence on the executive processes that determine behaviour organisation. Besides these limitations, the technique gives extensive descriptive data which is not available from other techniques. By careful analysis these data can provide hypotheses that may be tested by more rigorous methods. The predominantly descriptive nature of the data should, however, facilitate the collection and comparison of behaviour from several cognitive tasks, so that the consistent forms of behaviour underlying cognitive functioning may eventually be identified.

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APPENDICES

APPENDIX 2.1 MG and NG 'Sendout Summary' and Summary Displays, plus a glossary of terms used in the displays

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        MANUFACTURED GAS SUMMARY AT 1800 HRS  6/ 9/73
WORKS :CUM.PROD:HLY.PROD: TOTAL PRODUCTION:  AVAILABLE INC. IN PROD.  :
      : TO NOW :  RATE  : AT 2300: AT 0600: HOURLY : TO 2300: TO 0600:
-----------------------------------------------------------------------
TIPW  :  22113. :  1593. : 30078. : 41229. :    497. :  2485. :  5964. :
WSHW  :  19686. :  1644. : 27906. : 39414. :     56. :   280. :   672. :
COLE  :   -  0. :     0. :     0. :     0. :      0. :     0. :     0. :
WSTW  :   5661. :   479. :  8056. : 11409. :     41. :   205. :   492. :
SVLW  :      0. :     0. :     0. :     0. :    300. :  1500. :  3600. :
SBGW  :      0. :     0. :     0. :     0. :    240. :  1200. :  2880. :
BAIR  :      0. :     0. :     0. :     0. :      0. :     0. :     0. :
TOTAL :  47460. :  3716. : 66040. : 92052. :   1134. :  5670. : 13608. :
                                         :2300 HRS:0600 HRS:
      : PRODUCTION TO                    :  66040. :  92052. :
      : SENDOUT TO                       :  78612. :  94485. :
      : STOCK AT                         :  64834. :  74972. :
      : REQUIRED STOCK AT                :  58000. :  75000. :
      : REQUIRED CHANGE IN PRODUCTION TO :  -6834. :     28. :
      : REQUIRED CHANGE IN PRODUCTION RATE:  -1367. :      2. :


            NATURAL GAS SUMMARY   1800 HRS.   6/ 9/73
            ----------------------------------------

                                        :  2300 HRS: 0600 HRS. :

: PRODUCTION NATURAL GAS TO             :   31984.  :   44542.  :
: DIRECT NATURAL GAS TO                 :  121748.  :  160617.  :
: TOTAL NATURAL GAS TO                  :  153732.  :  205159.  :
: ALLOCATION                            :  148543.  :  210000.  :
: STOCK IF ALLOCATION IS TAKEN AT       :  161306.  :  171336.  :
: REQUIRED STOCK AT                     :  153000.  :  165000.  :
: INPUT RATE FOR REQUIRED STOCK         :    7118.  :    8252.  :
: INPUT RATE FOR ALLOCATION                  :     8779.  :
: PRESENT INPUT RATE                         :     8198.  :
```

```
   MANUFACTURED GAS SENDOUT SUMMARY      1800 HRS  THU  6/ 9/73
TIME  :HOURLY:STOCK :HOURLY:CUMULO :AVER.  :ESTI- :TEMP   :WEATHR:
      : MAKE :CHANGE: SEND :SENDOUT:  %    :MATED : AT    : AT    :
      :      :      :      :       : DAY   :SEND  :S-H-L :S-H-L :
-----------------------------------------------------------------
   700: 4080. :  582. : 3498. :  3498. :  3.3: 107.0:  60.  :FINE0 :
   800: 4100. : -976. : 5076. :  8574. :  9.0:  95.3:  60.  :FINE0 :
   900: 4045. :-1675. : 5720. : 14293. : 15.0:  95.3:  65.  :FINE0 :
  1000: 4050. :-1050. : 5100. : 19393. : 20.5:  94.6:  64.  :CLDY1 :
  1100: 4040. : -945. : 4985. : 24378. : 26.3:  92.7:  66.  :CLDY1 :
  1200: 4048. :-1534. : 5582. : 29960. : 31.5:  95.1:  67.  :CLDY1 :
  1300: 4068. :-1403. : 5471. : 35431. : 36.7:  96.5:  70.  :CLDY1 :
  1400: 4029. : -685. : 4714. : 40145. : 41.5:  96.7:  72.  :CLDY1 :
  1500: 3953. :  -23. : 3976. : 44121. : 45.9:  96.1:  75.  :SUN 1 :
  1600: 3641. : -678. : 4319. : 48439. : 50.5:  95.9:  76.  :SUN 1 :
  1700: 3690. : -980. : 4670. : 53110. : 55.9:  95.0:  78.  :SUN 1 :
  1800: 3716. :-1660. : 5376. : 58486. : 61.9:  94.5:  77.  :FINE1 :


               NATURAL GAS SENDOUT SUMMARY  1800 HRS  THU  6/ 9/73
TIME :TOTAL :  TO   :STOCK  :HOURLY:CUMULO  :AVER. :ESTI-: TEMP  :WEATHR:
     :HOURLY:T. GAS :CHANGE:SEND-  :SEND-   :  %   :SEND-:  AT   :  AT   :
     :INPUT :PROD   :      :OUT    :OUT     :DAY   :OUT  :S-H-L :S-H-L :
--------------------------------------------------------------------------
   700: 8778. : 1950. :  247. : 6581. :  6581. :  3.8:174.0:  60.  :FINE0 :
   800: 9158. : 1956. : -300. : 7502. : 14083. :  8.9:158.2:  60.  :FINE0 :
   900: 9518. : 1957. : -510. : 8071. : 22154. : 14.0:158.2:  65.  :FINE0 :
  1000: 9418. : 1954. : -222. : 7686. : 29839. : 18.9:157.9:  64.  :CLDY1 :
  1100: 9238. : 1957. : -275. : 7556. : 37395. : 23.7:157.8:  66.  :CLDY1 :
  1200: 8808. : 1972. : -668. : 7504. : 44899. : 28.4:158.1:  67.  :CLDY1 :
  1300: 8748. : 1971. : -745. : 7522. : 52421. : 33.0:158.9:  70.  :CLDY1 :
  1400: 8598. : 1949. : -262. : 6911. : 59332. : 37.2:159.5:  72.  :CLDY1 :
  1500: 7918. : 1956. :-1012. : 6974. : 66306. : 41.5:159.8:  75.  :SUN 1 :
  1600: 8198. : 1804. : -911. : 7305. : 73611. : 45.9:160.4:  76.  :SUN 1 :
  1700: 8068. : 1794. : -617. : 6891. : 80502. : 50.3:160.0:  78.  :SUN 1 :
  1800: 8198. : 1794. :-1113. : 7517. : 88018. : 54.8:160.6:  77.  :FINE1 :
```

APPENDIX 2.1

GLOSSARY OF TERMS

SENDOUT	Amount of gas sold to customers, sometimes referred to as sales or demand.
HOURLY SENDOUT	Amount of gas sold to customers in one hour.
CUMULATIVE SENDOUT	Amount of gas sold to customers since 06.00 hours.
ALLOCATION	Amount of gas requested from the National Grid to meet the estimate of the day's requirements.
GOVERNORS	Pressure control points in the distribution networks.
BUTANE	Used for enriching production gas so as to maintain the correct calorific value of the gas being supplied.
B/air	Ballast air, air butane mixture used to cope with peak demand.
DRC	Data Reduction Computer, used by the control room staff for set point control of the two Natural Gas off take stations on the National grid.
Super-grid	High pressure gas main which stores gas from production plants and feeds it to the districts at a lower pressure.

APPENDIX 3.1 Sample protocol

19.5.74 Evening

SEQUENCE DESCRIPTION

			CODE
1.	22.07	(1) Notes morning estimates and required stock levels	As
		(2) Checks state of production system	As
2.	22.11	(1) Examines MG 'send' - predicts	Ps
		(2) Examines NG 'send' - predicts	Ps
		(3) Notes targets and f/casts	As
		(4) Checks MG 'sum' - decides OK	MC$_o$
		(5) Checks NG 'sum' - considers change	NC$_o$
3.	23.12	(1) Checks NG stocks	I
		(2) Calculates max. stock and decides where gas is to go	DC
4.	23.12	(1) Examines MG 'send' - predicts and considers change	MC
		(2) Examines NG 'send' -	Ps'
		(3) Decides no MG + NG change necessary	MC$_o$ NC
5.	00.14	(1) Examines MG 'send' - predicts	Ps
		(2) Examines NG 'send' -	Ps'
		(3) Summarises MG and NG predictions	Su
		(4) Checks MG 'sum' - considers change	MC$_o$
		(5) Checks NG 'sum' - decides OK	NC$_o$
		(6) Considers details of MG CA	SS

6.	01.09	(1) Examines MG 'send' - calculates FS	Ps
		(2) Checks MG 'sum' - considers change	MC_o
		(3) Examines NG 'send' - predicts	Ps
		(4) Checks NG 'sum' - decides OK	NC_o
		(5) Predicts tomorrows alloc.	PS_t
7.	02.07	(1) Examines MG 'send' - predicts	PS
		(2) Examines NG 'send' - predicts	PS
		(3) Checks MG 'sum' - considers change	MC_o
		(4) Checks NG 'sum' - decides OK	NC_o
8.	02.27	(1) Decides to increase MG	MC_b
9.	03.12	(1) Examines MG 'send' - affirms PS	PS
		(2) Checks MG stocks for an error - OK affirms PS	PS
		(3) Recalculates NG	FD
10.	03.18	(1) Examines NG - predicts (describes error)	Ps
		(2) Checks MG 'sum' - decides OK	MC_o
		(3) Checks NG 'sum' - decides OK	NC_o
11.	04.09	(1) Examines MG 'send'	Ps'
		(2) Checks MG 'sum'	MC'
		(3) Examines NG 'send' - affirms ES	PS
		(4) Checks NG 'sum' - decides on a CA	NC_o

12. 05.09	(1) Examines MG 'send' - predicts	Ps
	(2) Checks MG 'sum' - decides OK	MC_0
	(3) Examines NG 'send'	Ps'
	(4) Checks NG sum - decides OK	NC_0
	(5) Describes next CA (NG)	SSC
	(6) Decides MG make rate OK	MC_1
13. 06.05	(1) Notes final sendout and final stocks MG and NG	N
14. 06.12	(1) Describes NG CA	D
	(2) Summarises	Su

	Activity
1. 22.07	
(a) I'll give you a quick resumé of what the f/cast was this morning, that is f/cast estimate.	States
(b) And the est. for send. this morning was 75 of NG and the NG send of 150m.	① Notes Es (MG+NG)
(c) The stock aim on both MG is 62.6 and NG 180.7	Notes RS$_{oc}$ (MG+NG)
(d) We have 3 plants at work, the 3b at C/hill, the 1c at Tipton, and No 3 at W.H, this gives us a total cum. make /hr of 4.2 approx. without B/air.	Notes plant $\dot{p}$
(e) B/air will give us something in the region of. Sorry a correction to the total available without B/air would be approx. 4.4 and there's 0.8/hr of b/air so that we can in fact make 5.2 with full NG, this is something in the region of 129-130 for the day.	Calculates $\dot{p} + \Sigma\dot{p}$ ②
(f) We don't contemplate using this much but there is the facility for taking NG off the reforming and putting Naphtha in, which will give us another increase of something in the region 0.30-0.35/hr.	Considers(2)
(g) So that we're not too badly off if the weather F/cast which they give for tomorrow has been mostly sunny and warm, with a max. of 68 and a mean of 58°F.	Notes f/c
(h) We shall cope with the send on MG with what we've got quite admirably.	Decides (1)
2. 22.11	
(a) Looking at MG send to date, and we sold 4.3 on the	Notes HS, CS

hour with a cum. of 56.5

(b) The send is showingat 70.4 and there's not a great deal we can compare with but we'll look on the basis of yesterday.

<u>Notes</u> ES

<u>Choice</u>

(c) We're a couple of 0.1m up on the hour, but we're 7m down overall, and we sold yesterday a total of 80m.

<u>Compares</u> HS, HS' and CS, CS'

①

<u>Notes</u> FS'

(d) So although there might be a little increase over this 80m for any start up that may occur, we're not too expectant of anything too great but we'll have to see how the shift progresses.

<u>Predicts</u> FS

(e) NG for 22 hrs shows a send of 7.4 with a cum. total of 101.6 compared with yesterday we sold 0.2 up, when they sold 7.2 last night and 109 all told.

<u>Compares</u> HS, HS' and CS, CS'

(f) So we're in fact 7.5m down on yesterday when we sold 145.7.

②

<u>Notes</u> FS'

(g) The send may get up 4 or 5m to about 143-145, but we'll have to see how things progress.

<u>Predicts</u> FS

(h) The total NG est for today is 195 and they f/cast a total for tomorrow take of 255.

<u>Notes</u> NG alloc. today + tomorrow.

(i) And they've also asked us to have a make ready for tomorrow of 4m this is getting towards **our** total, and we'll be heading towards that later on during the shift.

③

<u>Notes</u> $\dot{p}$ for tomorrow

(j) MG'sum' shows a total make of 76m, send is showing approx. 70m which we hope will get up a little higher if it doesn't,it doesn't matter too much because the stock showing is 61.2 and this is ample.

<u>Notes</u> $\Sigma\dot{p}$ and ES and ES_t

(k) The f/cast stock as I said was 62, so it needs 0.7 over the shift to pick up to 62, but 60'll do us, between 60-65 with a make on between 6 & 8 hours of 4m as requested, and we'll just toddle along at that.

④ Notes RS_{06}, CH

Decides (1)

(l) On the NG 'sum' shows a total intake of 195 as previously stated.

Notes NG alloc

(m) The send is showing 138, and the cum. send and prod. NG gives us a total 177 which leaves us a stock in the morning of 188.

Notes NG TOT, ES, and ES_{t06}

(n) Its a little much really bearing in mind that Gas Corp. aren't giving us the pressure to take this stuff, but we've got a little room in various holders which we'll tend to put a bit in, and if the send. gets up to the 143ish, then we should have something in the region of 183, if we can hold it, but we'll have to see how that goes on through the night to.

⑤ Evaluates effect of ES_t

Considers (2)

Evaluates effect of FS

Decides (1)

3. 22.31

(a) We've just been looking to see how much NG stock we can hold.

Search Stock Information

(b) We find that we can hold 4m extra in Coventry quite easily provided there is no obstruction to that, which we'll check a little later.

(c) We can hold another million, in W/hampton, 10m in Rugby storage 45m in Barlaston storage.

①

(d) Giving us a cum. increase on our current stock of 173 of 20m which is 193 so that we can do our 180-182 or 3 quite comfortably.

Notes AS_t

Calculates possible stock increase

(e) We may be able to get another 1 & $1\frac{1}{2}$ or so in depending on whether the painters have finished painting the K/winford holders and we're able to top K/winford up. ① *Notes* Stock at K/winford

(f) But we'll be looking into that when K/winford rings, and we're also looking into the situation as regards to Coventry, see if there's any restrictions there. *States*

(g) We've just found that Coventry have a restriction on the stock, the max. stock is 8.5 which they have virtually now. *Information* on Coventry Stock

(h) So that trims 4m off our available stock space which leaves with something like 16m that we're able to put away, giving is 185-189, so that we're still quite comfortable ② *Calculates* Max. Stock

(i) And we'll be putting it into W/hampton at the rate of 1m, 10m into Barlaston, sorry 10m in Rugby, 15m into Barlaston so there is no sweat. *Decides* (2)

4. 23.12

(a) And we're looking at 23 hr figs; the temp. this hour was 14.5°C weather's cloudy, and the hourly send was 3.4 giving us a cum. send so far of 60m, and the % is still holding at 70m. ① *Notes*, Te weather HS, CS, and ES

(b) It looks verymuch as though we're going to sell a little in excess of 70, not too much though by the look of it. *Predicts* FS

(c) So we're not doing a great deal about makes at the moment, we'll probably turn up later, between 6 & 8 to give them the required make for tomorrow. *Considers* (1)

(d) NG send hourly 6.8, as cum. of 108.4 and the % is showing 138.6. ② Notes HS, CS and ES

(e) I can't compare them with yesterday 'cos I've got them upstairs getting a f-copy of them for you, but we'll be comparing them at mid-night.

(f) 'Sum' will be showing much the same as they did last hour, so there's no point in running through these either. ③ Decide (1)

5. 00.14

(a) MG send for 12.00 was 3.1 with a cum. of 63, the % is now showing 71.3 ① Notes HS, CS and ES

(b) So it looks very much as though we're getting up to 73-74 by the look of it, possibly a little more. Predicts FS

(c) NG 6.6 on the hour with a cum. of 115, the % showing 140. ② Notes HS, CS, and ES

(d) So the tendency for both MG send and NG is to rise to the approx. levels that we thought earlier in the case of MG about 73-4 possibly, and 143-5 on NG. ③ Summarises

(e) So there is still no need to concern ourselves. Decides (1)

(f) The stocks are going to end up round 60-61. ④ Notes ESt_{06}

(g) We can make any increases required a little later if necessary.and the NG stock about 185 now. Considers (1) ⑤ Notes ESt_{06}

(h) So we're still holding quite nicely Decides (1)

(i) So we've been looking at the situation as regards increase makes and to keep the load factors lean gas at a reasonable level, we intend to bring W-H to a cum. of 1.4, which is an increase of 0.5 on what they're making currently. Considers (2) ⑥ Notes $\dot{P}$ W-H

(j) And we're going to bring Tipton to a cum. of 1.4

which is an increase of 0.4 on what they're making currently, and C/hill to a rate of 1m/hr which is an increase of 0.3 on what they're making currently.

Considers(2)

Notes $\dot{P}$ C/Hill & $\dot{P}$ Tipton.

(k) There's no great rush for this, we'll be looking at it hourly and then we'll decide later whether it's necessary to increase during this shift or whether to make provision for it between 6 & 8 o'clock this morning.

Considers (2)

⑥

6. 01.09

(a) And we're looking at MG send for 1 o'clock, on the hour we sold 2m with a cum. of 65.

Notes HS, CS.

(b) This based on last night, shows a reduction of about 0.5m on the hour, that is we're selling 0.5m less tonight than we decided last night.

Compares HS, HS'.

①

(c) And the cum. total at 1 o'clock is 65 as opposed to 72 last night, so we're running down on that by 7m, giving us a cum. send on that basis of about 73 always providing that the send. hourly send even out.

Compares CS, CS'

(d) At the moment the % are showing it at 72 and giving us a stock of 59.5

Notes ES, ES_{t06}

(e) So we're going to look at the pos. at 02.00 with the view to making the increases as described previously and this should give us in the region of 60-62m of stock provided we don't sell extra over the last 2-3 hrs.

Considers (1)

②

(f) So far as NG is concerned, we're selling 1.1/hr up compared with last night, and we're running something down at about 5m down overall.

Compares HS, HS'. and CS, CS'

③

(g) The % is showing 142.6 and rising so we think we'll sell about 146. This being so our stock in the morning for NG will be 184.2.

<u>Compares</u> ES_i <u>Predicts</u> FS <u>Calculates</u> ES_t

(h) So we've told Gas. Corp. that we're sticking to the 195 alloc. for today.

<u>Decides</u> (i)

(i) And we estimate our alloc of 255 for tomorrow, that gives us about 55 for MG and approx. 200 NG direct send.

<u>Predicts</u> FS_t MG+NG

7. 02.07

(a) MG hourly send 1.7 and cum. is showing 66.8 as opposed to yesterdays hourly of 1.4 and cum of 74.

<u>Compares</u> HS, HS' and CS, CS'

(b) We're running 7m down on the 80m that we sold yesterday.

<u>Notes</u> FS'

(c) So it looks good on for about 72-73, we'll be looking at the 'sum' shortly.

<u>Predicts</u> FS

(d) NG send for the hour we sold 5.4, and cum. is 126.4 this compares with yesterdays of 4.2.

<u>Compares</u> HS, HS'

(e) So we're a couple of 0.1 up tonight and 130, so that we're only running 4m down on yesterday which gives us about 14.2 by the look of it.

<u>Compares</u> CS, CS'

<u>Predicts</u> FS

(f) But we're still satisfied as it runs.

(g) MG 'sum' shows a make of 75, send of 72.4 giving us a stock in the morning of 59.

<u>Notes</u> Σ_p ES, ES_{t06}

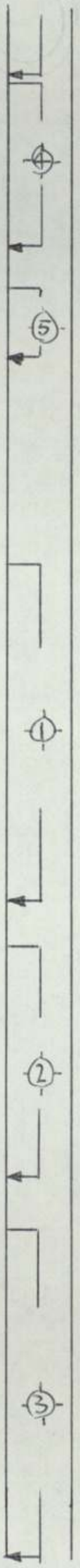
(h) 'Sum' indicates an increase in make of 2.9

<u>Notes</u> CH

(i) We're leaving things for this hour with a possible view of putting the increase on at around 4 o'clock time.

<u>Decides</u>(i)

<u>Considers</u> (i)



(j) NG 'sum' indicates a stock in the morning of 182.7 the send now showing 144.		Notes ES_t ES
(k) I don't think we'll sell a great deal much more than 144-6, but anyway there's no need to change it so we'll leave things right as they are.	④	Decides (1)
8. 02.27		
(a) We've looked at the situation again and we've decided on the face of it looks very much as though we'll see about 74m of MG.		Predicts FS
(b) So we're increasing the makes all round, W-H 0.5m, Tipton 0.4 and C/hill 0.3, a total of 1.2 to give us a stock somewhere in the region of 60-62 at 06.00.	①	Decides (1) Describes CA. Calculates effect on ES_t
(c) A message is going out to that effect now.		
9. 03.12		
(a) MG hourly sale was 2.3 bringing the total to 69.1 this compares yesterday 0.6 up on the hour on yesterday, and we're now 6.8 down on yesterday.	①	Compares HS, HS' and CS, CS'
(b) So its still looking around the 73-74		Affirms PS
(c) We're just going to have a look at the stocks to see if any mistake has been made.		States
(d) Yes the stocks appear to be alright we've got the increase to 3.3 but only 1m going in stock we anticipated a little more than that, it could be the difference between the gain we've been given in make which hasn't quite materialised, but even so the send is looking around the 73-74 at the moment.	②	Affirms Notes $\dot{P}_i$, SC_i Compares SC_i P_{SC_i} Deduce Affirms

(e) NG send looks to me to be a loaf of f- rubbish so I'll sign off and come back.

③ State

10. 03.18

(a) NG send that looks a bit better we've put Wellington stock at 12m instead of 12.5.

Describes

(b) The hourly send is showing 4.9 and the cum. 131.3, this compares with yesterday's of 4.4 and 134.5.

(c) So we're gaining quite quickly, we're 3m down overall at the moment, but we look like picking it up so it will be between 145-6.

① Compares HS, HS' and CS, CS'

Predict FS

(d) MG 'sum' is now showing a make of 78, send 73.5 giving us a stock of 60.3 with an increase of 1.7 to come, and we have something like an increase of 2.4 to come overall, so that'll give us 62.6 which we're quite happy with.

② Notes $\Sigma\dot{p}$ ES, ES_{t06} and $\dot{p}$

Calculates ESt06

Decides (1)

(e) NG 'sum' is now showing a send of 144.5 (if it) comes up the extra 2m we'll have a stock of 179.5 which we're quite happy with.

③ Notes ES

Calculates ESt06

Decides (1)

11. 04.09

(a) MG hourly send was 2.1 and cum. 71.3 this compares with yesterday when we sold 1.5 on the hour, which we're 0.6 up and 77 cum. and we're now 6m down on an 80.4 send.

① Compares HS, HS' and CS, CS'

Notes FS'

(b) 'Sum' indicates total make of 80, send of 74, we think it should get to 75-6 giving us a stock between 60-61 and 06.00.

② Notes $\Sigma\dot{p}$ ES

Calculates ESt06

(c) NG send 4 o'clock on the hour we sold 5.4 which compares with 3.3 yesterday so we're 2m up on the hour a total of 136.7 to date.

Compares HS, HS' + CS, CS'

(d) And the % is showing 146, we're now only 1.1 down on the same hour yesterday so it looks very much as though the 146 is going to materialise, possibly a little more.	③	Notes ES ES' Affirms ES
(e) 'Sum' indicates a stock of 178.3 and we're quite happy with that.		Notes ES_{t06}
(f) We shall be picking up the rate between 6-7 to an alloc. of 255, which we've applied for.	④	States
(g) Currently the input rate is showing a great deal more than it should so I shall ease off a little and then increase it between 6 & 7.		Notes IR Decides (1)
12. 05.09		
(a) And MG send summary is showing an hourly send of 1.8 this compares with yesterdays 1.3, we're 0.5m up, this is to be anticipated because Saturday into Sunday we tend to go down whereas, Sunday into Monday, the send should increase with the load coming on.	①	Compares HS, HS and Comments
(b) Cum. total to date is 73m, which compares with 78.7 for yesterday, and if we sell approx. 2m this next hour at 6 o'clock, possibly a little more we should end up with 75.5.		Compares CS, CS' Predicts FS
(c) This being the case the % is showing 74.8 and the 'sum' is showing a cum. make of 80, a send 74.8 which we think might (rise to) 75.5, giving us around 60m stock which I think is ample.	②	Notes ES Σ_p Recalls PS Calculates FS_t Decides(i)

(d) NG send for the hour at 0500 is 5.9, call it 6m its 5969, this compares with yesterday's 3.7, we're quite a bit up on yesterday, and cum. so far is 142.6.

Compares HS, HS'
Notes CS

(e) If we sell 6 or 7m at 0600 which looks pretty well on we should sell between about 148 & 148.5 the % is showing 147.8.

③ Predicts HS_{06}
Calculates FS
Notes ES

(f) And temp is 12.5 so its fairly high compared with this time yesterday morning when it was 9.5

Compares Te, Te'

(g) The 'sum' indicates a stock at 0600 of 176.6 which is quite enough.

④ Notes ES_t
Decides (1)

(h) We'll be increasing the alloc. to 10m/hr between 6-7 and we look like exceeding our intake by about 0.5m or so, but I don't think that is much to be worried about.

Describes
⑤ Compares Alloc, ΣIR

(i) MG make rate is now at the 4m requested and we shan't be making any increase at all above that 4m.

⑥ Notes $\dot{P}$
Decides (1)

13. 06.05

(a) MG send for the last 24 hours was 75.6 the NG send was 149.3 and we had a loss in stock, so we'll have a check out those stocks just in case.

Notes FS (NG+MG) and FS_t
States

(b) Yes, we've checked the stock and it is a correct one having reduced the intake into Barlaston storage, the tendency in the storage main is to lose.

① Comments

(c) I shall be altering this when we pick up shortly, as I said the stock loss in the NG was correct so the send stands as stated.

Summarise

14. 06.12

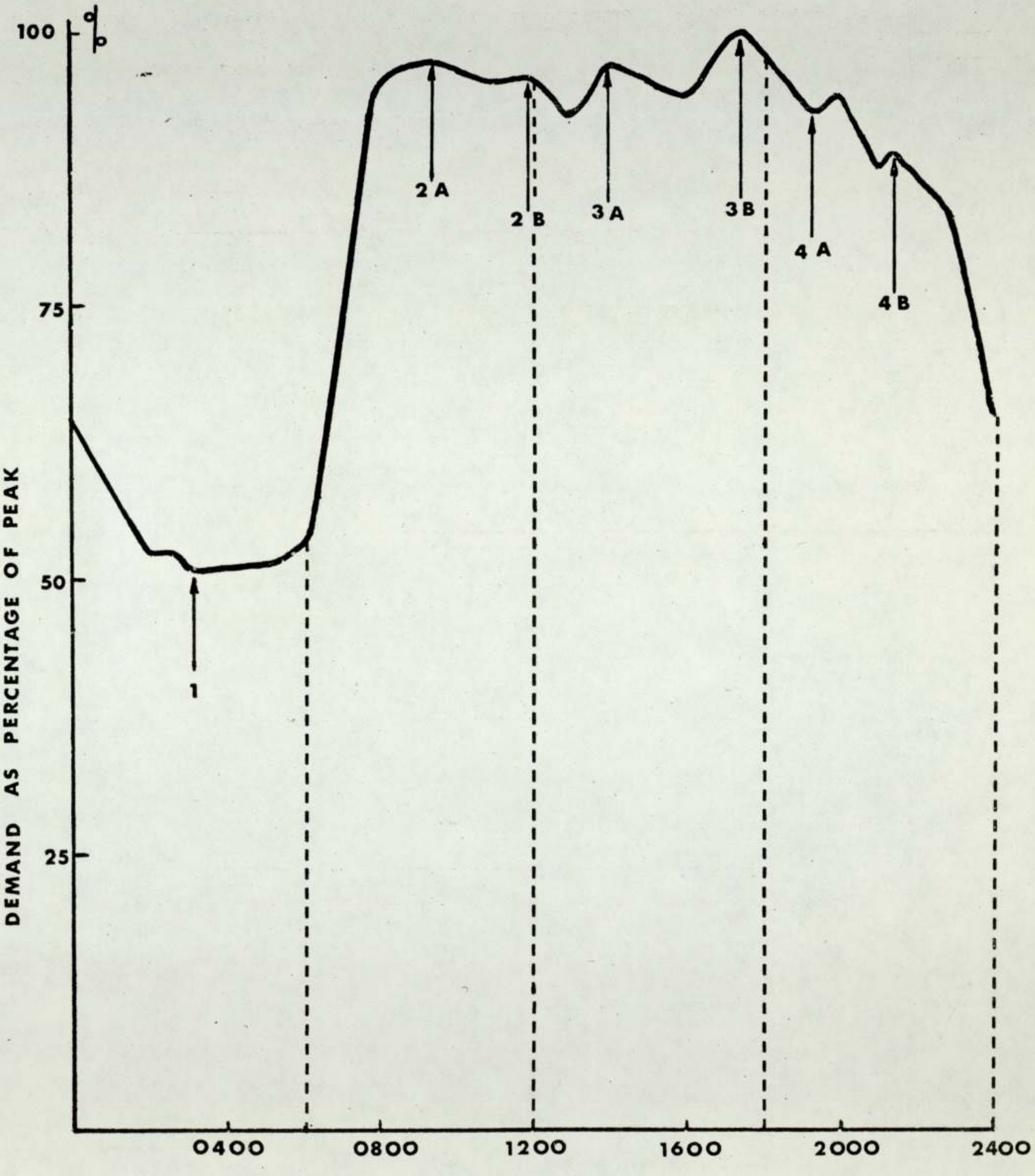
(a) I'm now increasing the NG intake to the hour rate of 10m, the actual rate is 10.6, but it should pick up 10.6 with the increase in load.

① Describes

(b) To sum up the MG send was 75.6, and we finished with a stock of 60m, and NG send was 149.3 and we finished with a stock of 176.5m our cum. NG intake was 196.4.

② Notes
FS. FSt
(MG + NG)

APPENDIX 4.1 Typical demand curve



DEMAND CURVE & COSTING PERIODS

APPENDIX 4.2 Sample protocol

10.7.74 Morning

SEQUENCE DESCRIPTION

			CODE
1.	08.39	(1) Makes decision re. present situation	MD_b
		(2) Deduces bad weather in general	
		(3) Prepares management report	R_p
		(4) Reviews present situation	Re
		(5) Implements 2B prog.	I_m
2.	08.41	(1) Predicts 2B	P_L
		(2) Affirms estimate	P_L
3.	08.52	(1) Makes decision plant on, for afternoon because of f/cast.	MD_c
4.	09.31	(1) Predicts for tea time.	P_L
5.	09.33	(1) Info. (NC) relief on transfer, decides to take GT off.	MD_g
6.	09.40	(1) Makes decision re. present situation (and to re-gain spare)	MD_b
7.	10.12	(1) Makes decision regarding present situation	MD_b
8.	10.40	(1) Makes decision re. expected afternoon increase	MD_c
9.	10.45	(1) Predicts for early afternoon	P_L

10.	10.47	(1) Makes decision re. freq. and set tripped	MDa
		(2) Makes decision re. info. gen off suddenly, GT on	MDf
		(3) Makes decision - further plant on	MDe
		(4) Recaps	
		(5) Makes decision re. freq. (nothing to be done)	MDb
11.	10.58	(1) Informs Nat. Con. on plant loss	Ad
12.	11.01	(1) Info. (NC) modified transfer	If
13.	11.07	(1) Logs failure of GT	Lg
14.	11.00	(1) Makes decision re. present state and sudden failure.	MDa
15.	11.17	(1) Reviews present situation	Re
16.	11.30	(1) Makes decision re. present state	MDb
17.	11.50	(1) Reviews present situation	Re
		(2) Makes decision re. relief on plant from Nat. Con.	MDg
		(3) NC request more plant on.	Rq
18.	12.13	(1) Makes decision re. freq. and predicts fall.	MDd
19.	12.18	(1) Instructs plant off	In
		(2) Makes decision re. max. MVar absorption	MDh

20.	12.23	(1) Instr. GT off.	I_n
21.	12.43	(1) Describes plant off.	D_s
22.	12.45	(1) Implementing prog. for afternoon peak	I_m
23.	13.07	(1) Notes metering fault	N
		(2) Makes decision re. new prog.	I_m
24.	13.36	(1) Instr. plant on.	I_n
25.	13.39	(1) Updates 3C predicts	P_L
		(2) Predicts 4B	P_L
26.	14.00	(1) Makes decision re. predicted changes in demand.	MD_d

1. 08.39

		Activity
(a) We've instructed full load on all the plant at 08.06, to cater for the fall in freq. the increasing import, and above program transfer, mainly due to the incorrect weather f/cast received at 05.00, which indicated a fine morning. (b) And in fact it's been pouring with rain from the breakfast time peak. (c) And the Est demand of 3030, I think it was, has turned out to be more like 3200.	①	Notes F_R Compares T_R, T_T Compares f/cast, weather Compares P_D, D Decides(i) full load
(d) And it would appear that the rain is fairly general in the country, so it will also follow that some other areas will have underestimated.	②	Notes general weather Deduce
(e) The management report(Pause) passed to Mr. Bellchamber at 08.20, details of the high merit plant, availabilities, National plant position etc. as usual.	③	Report
(f) The frequency since the pick up in generation at 08.06 rose to 50.2 stayed there for 5 minutes, and is now falling again, we were suitably under-programmed for that period. (g) Plant still instructed to full load, still under-programmed.	④	Notes ΔF_R Compares T_R, T_T Compares T_R, T_T
(h) The 2B plant requirement would appear to be even more plant on the bars, that's being instructed on, and a suitable amount of hot standby in addition has been instructed.	⑤	Implements

2. 08.41		
(a) 2B estimate required, f/cast, 15° moderate rain (2B being lunch time peak midday - 12.30)		Notes f/cast
(b) 3200 is the breakfast time load, 3200, we're looking through the past records, at least 3200, I think we might put in 3300 then Steve, for 2B.	①	Compares D, D' Predicts 3300
(c) They are now f/casting moderate rain now for 3B, they seem to have got that in hand.		Notes f/cast
(d) And its not going to be less than we've got now, 3300 is the demand estimate for the luch time peak.	②	Affirms prediction
3. 08.52		
(a) I will arrange for some plant this afternoon, for lunch time, but more especially for this afternoon.		Decides(1)
(b) Where the rain f/cast for lunch time is expected to continue during the afternoon, the plant position could be a little difficult.		Evaluates effect of rain
	①	
(c) If we don't instruct the plant on now, we shan't get the output from it this afternoon.		Considers(1)
(d) It's a slow set anyway and it is rather colder than usual.		Comments
4. 09.31		
(a) Estimate for the demand at 17.30, the tea time period, 3200.	①	Predicts 3200
5. 09.33		
(a) National Control at 09.33 checked the spare position, and has modified the program transfer in the light of		Info Relief on Transfer

the National spare position, and has given us 170 MW transfer relief, suggesting that some other areas, are perhaps not quite as hard hit as we are. ①

(b) And this will enable us to get a Gas Turbine off and to re-gain the normal spare on the steam plant. Decides (2)

6. 09.40

(a) 100 MW dropped on 6 stations, to re-gain the steam spare. Compares FR, TF

① Compares TR, TT

(b) Frequency slightly above target, and we're 100 MW above the 10 o'clock revised program Decides (2) 100 MW on 6

7. 10.12

(a) 150 MW on 6 stats. was dropped to correct for the rise in frequency. The actual transfer being above program. Notes ΔFR ① Compares TR, TT Decides (2) 150 on 6

8. 10.40

(a) We've received indications that the afternoon, early afternoon, tea time, plant requirements are increasing. Predicts ①

(b) And we've instructed on the plant in 3 stats, that's a total of 7 generators and a total MW of some 200 (MW) Decides (2)

9. 10.45

(a) And we've estimated 3080 MW for the early afternoon peak. Predicts

(b) The wf/cast is that the rain we've still got outside Notes f/c is going to clear up, still almost 8/8 cloud cover and temperature a bit less.

(c) If the weather does clear up, then the 3080 est. will probably be a little bit high.

(d) But I've got my doubts personally as to whether that weather is going to clear up quite as they f/cast, so we'll strike a medium note and est. 3080. ① Affirms prediction

(e) If the weather does continue with the moderate rain that we have had, then I think the demand will be closer to 3180, rather than 3080. Evaluates effect of rain

(f) But the 3080 should be a good average. Affirms 3080

10. 10.47

(a) We've received word from Wenlock control that Meaford 'B' generator 1, has tripped, further details not yet available, but it's a 56 MW set. Info.

(b) At this time the frequency was tending to droop anyway, and we've picked up generation, 100 MW to counteract falling freq. and replace the loss of Meaford 'B' plant. ① Notes FR Decides (2)

(c) We've just received a message from Arden control that generator 6 at Hams Hall 'C' is off. Info.

(d) We don't know whether its tripped off, or been taken off or what, we haven't got that detail yet.

(e) 10.46, we'll log that, and that's a 61 MW set, and won't assist with the frequency. ② Logs info.

(f) I think to help replace that we'll first put the GT on at Ironbridge 'B' 10.51 now (Phones Ironbridge, asks them for GT) Decides (2)

(g) We'll have to find some more plant. "We'll see if we can find some more to pick up. Drakelow 'A' can do 40 for us with no problem and Hams 'B' can do 240, and Nechells can do 140, and Hams 'C' I assume does 244 then Derek, no it'll be 5 less than that won't it 239, then please." (the "...." indicate a conversation with the controller in Arden) ③

Decides (2)
Describes further increase

Another phone call:- "..... so there's not such a hell of a lot left, we'll bring Walsall up to 150."

(h) So those calls are on the air. Let's just recap that.

Recaps

(i) We've lost another generator at Hams Hall 'C' 61 MW, we've instructed the GT on at Ironbridge that's not indicating on yet, it shouldn't be long. And we've picked up another 70 MW on other plants in 5 stats, and this will still leave us under program. ④

(j) Frequency has steadied up and is tending to rise now.

Notes FR

(k) And there's not much else we can do (something about basic spare left).

Decides (1)

(l) The weather is not improving, it may have stopped raining I can't see, it's still pretty dull.

Notes weather

⑤

(m) And the demand if it doesn't pick up, it'll stay where it is at 32 level for a little while at least.

Notes D

(n) Freq. is rising 49.9, and the transfer's beginning to recover with the gen we've picked up.

Notes FR, TR.

11. 10.58

(a) We've informed Nat. Con. that the plant that we had lost, we'd already told them that we'd lost approx. 120, we've told them that we probably won't have regained that plant for 3A period, that will be recalculated, and we've also informed them of the position of the rest of the plant which is 60 MW of steam spare left only.

Advise

12. 11.01

(a) Nat. Con. modified the program transfer to assist with the plant having lost the 120 at Hams Hall 'C' and Meaford 'B'.

Info on TR

13. 11.07

(a) We've just filled in the paper work for the failure of the GT at Ironbridge.

Log GT failure

14. 11.00

(a) Step change on the freq. 0.5 of $^{1}/10^{\text{th}}$ fall instantaneous, large generator would appear to be falling off, not one of ours, we've only got one on really, and our plant seem to be steady. It's still falling.

(b) 11.30 revised transfer, nicely placed for a fall in freq.

(c) Last few MW instructed to pick up freq. has now reached the operational lower limit, and we're correcting by 120 MW at the moment.

Notes ΔFR

Explain

Notes plant

Recall T_1^X

Predict (3)

Compares FR, LoL

Decides (2)

(d) The GT at Ironbridge, whatever the problem was, the engine flame out, has been resolved and that's on now. Info.

15. 11.17

(a) Freq. is rising, 49.83 at the moment showing a sign of recovery. Notes ΔF_R

(b) I don't think I mentioned earlier when I instructed the last of the plant to pick up to full load, Arden Control told me that Hams 'C' No. 6 had returned to service and gives us another 61 MW, and that's picking up together with the rest of the plant. Info.

(c) Don't know what went wrong with that set, station hasn't been able to inform us yet.

16. 11.30

(a) The freq. has recovered, it is up to target again. Compares F_R T_F

(b) And I'm slightly over program Compares T_R, T_T

(c) I was about to pull some generation back and the freq. seems to have taken a turn for the worse again. Consider (1) Notes ΔF_R

(d) So I'll hang on for a few mins, and see how it settles out. Decides (1)

17. 11.50

(a) Nat. Con. checked the spare position, we're still full load. Request Notes spare

(b) But on the last message we spoke about a sudden fall in freq., and that stabilised and the freq. then slowly over 20 min dropped $^{1}/_{10}{}^{th}$ HZ and during that Compares F_{Ri} Compares T_R, T_T

period our actual transfer picked up slightly above program to the position we're in at the moment.

(c) And Nat. Con. has given us a little bit of relief because the plant is still instructed to full load and this will enable us to pull back a little bit on the steam plant and get the GTs shut down again.

(d) He's also revised his requirements for the early afternoon period and more of our plant is req. in cost, than was required for the original prog.

(e) This is due to plant losses in other parts of the country, and that plant has already been catered for.

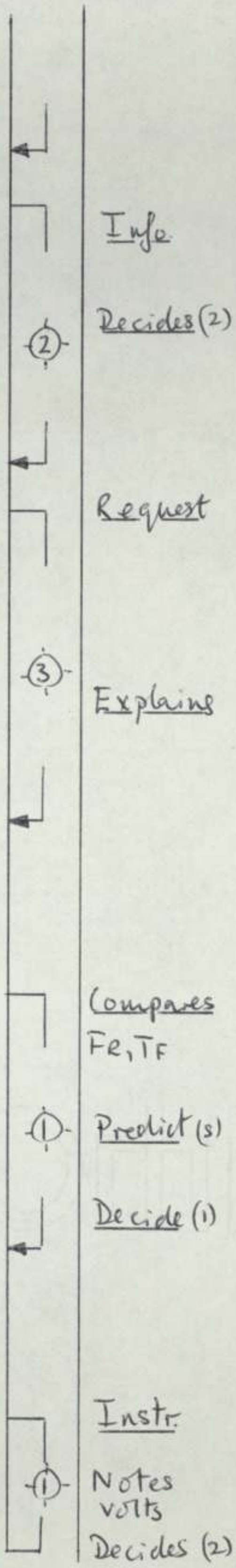
18. 12.13

(a) Freq. is approaching the target now, has been to 49.98, its picked up to 50, slightly over program.

(b) And within the next few minutes, the demand is going to start to fall, we'll anticipate this and drop some generation now.

19. 12.18

(a) 100MW more, instructed off and max MVar absorption on the primary system connected plant, to correct for the tendency at this time for the volts to rise.



20. 12.23

(a) GT instructed off at Ironbridge 'B' ① Instr

21. 12.43

(a) 300 MW dropped at 9 stats. ① Describes

22. 12.45

(a) The cold plant that was ordered on earlier to meet the afternoon peak is beginning to synchronise now. Notes plant synchr.

(b) It won't contribute many MW in the immediate future because its cold and slow to pick up. ① Evaluates effect

(c) And we've started off with 2 - 50 MW sets at Ironbridge synchronised at 12.30, its just been reported. Notes IIB synchr.

23. 13.07

(a) Metering error, generation trace has dropped 200 MW, caused by Hams Hall group metering, probably a temporary fault, sorting itself out, putting itself right now. Notes Δ TGO ① Explain

(b) Its 13.08 we'll start picking generation up again, in readiness for the increase in demand after lunch time. Decides (1)

(c) And the increase in transfer commitment that we've got we'll pick up 80 MW for a start at Ironbridge 'B', 80 MW on the one station. ② Decides(2)

24. 13.36

(a) We'll start off with 146 MW on 7 stations (pause) and we'll add another 82 at another station. ① Instr

25. 13.39

(a) 3C revised est 3080

(b) And now we'll do a 4B est. that's 4B tonight.

(c) Look at the weather similar Wednesday last year 3000 to 2800 to .... 2750 at this stage. That's the 4B est. 2750.

①
Updates 3c

②
Compares, wthr, wthr
Notes D'

Predicts
2750

26. 14.00

(a) We'll pick up some more generation, we'll pick up 42 MW

(b) Demand will increase slightly between now and 14.30.

(c) Freq. is above target, the transfer is above program, that should cater nicely for the pick up in demand over the next half hour, its 14.03. I'll put the equipment away ready to go home.

Predict(s)

Decides (2)

①
Compares
FR, TF

Compares
TR, TF

Evaluates

APPENDIX 5.1 Instruction sheet for subjects

APPENDIX 5.1

INSTRUCTIONS FOR THE GAS CONTROL TASK

OBJECTIVES

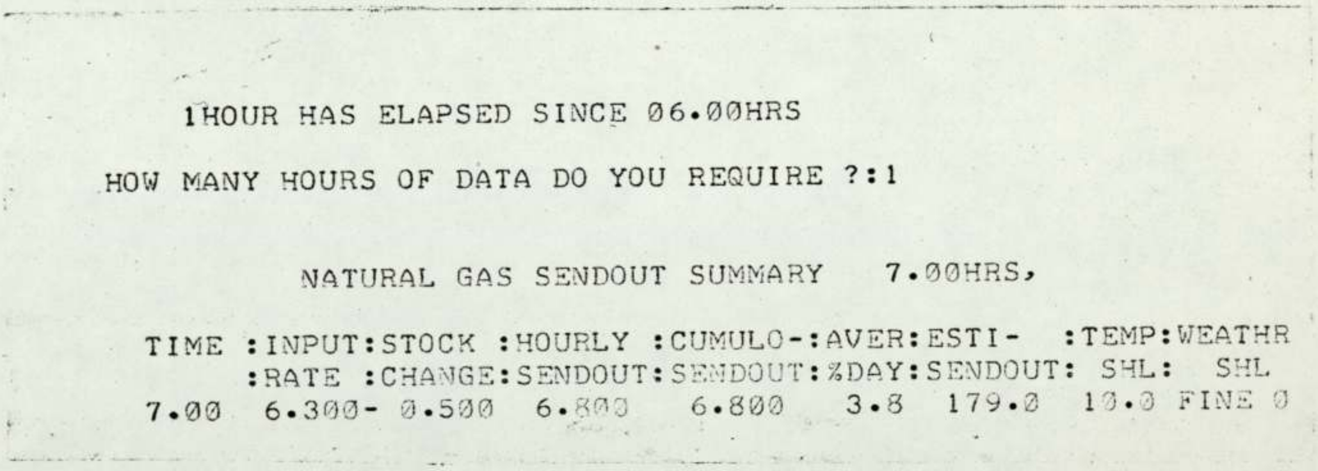
This experimental task is based on the real life task of a Gas Control Engineer. It entails supplying gas to a distribution network to meet consumer demand. The aims of the task are to maintain a supply of gas safely and economically.

Gas demand varies from day to day and hour to hour, the Controller has to anticipate these fluctuations. By predicting the demand successfully the controller can maintain a constant input rate and meet the hourly fluctuations by letting gas into and out of storage. The most economical control strategy is to keep the input rate constant whenever possible. Safe supply conditions will be maintained provided the stock-level does not fall too low or rise too high.

Your task is to attempt to supply gas to the system over a 24 hr. period. Here as in the real task the computer will provide most of the necessary information, in two displays, the 'Natural Gas Sendout Summary', and the 'Natural Gas Summary'. These two displays are presented every hour, on the hour. With the information from these displays it is possible to anticipate total demand for the 24 hr. period and adjust the hourly input rate accordingly.

COMPUTER DISPLAYS

The computer print out below shows the 'Natural Gas Sendout Summary'.



```
     1HOUR HAS ELAPSED SINCE 06.00HRS

  HOW MANY HOURS OF DATA DO YOU REQUIRE ?:1


              NATURAL GAS SENDOUT SUMMARY   7.00HRS,

    TIME :INPUT:STOCK :HOURLY :CUMULO-:AVER:ESTI-   :TEMP:WEATHR
         :RATE :CHANGE:SENDOUT:SENDOUT:%DAY:SENDOUT: SHL:  SHL
    7.00  6.300- 0.500  6.800   6.800   3.8  179.0  10.0 FINE 0
```

The first column indicates the time of day, each day starts at 06.00 hrs, and finishes at 06.00 hrs. the next day.

The second column is the 'input rate', this is the amount of gas taken into the system from the National Grid over the last hour. It must be remembered that this is the only source of supply to the system, as even the storage has to be filled from this source.

Third column, 'Stock change', this shows the amount of gas taken into or out of storage over the last hour. Gas will automatically come out of storage when demand is greater than input, and go into storage when input is greater than demand.

Fourth column, 'Hourly sendout', this is the amount of gas taken out of the system by the consumers in the last hour.

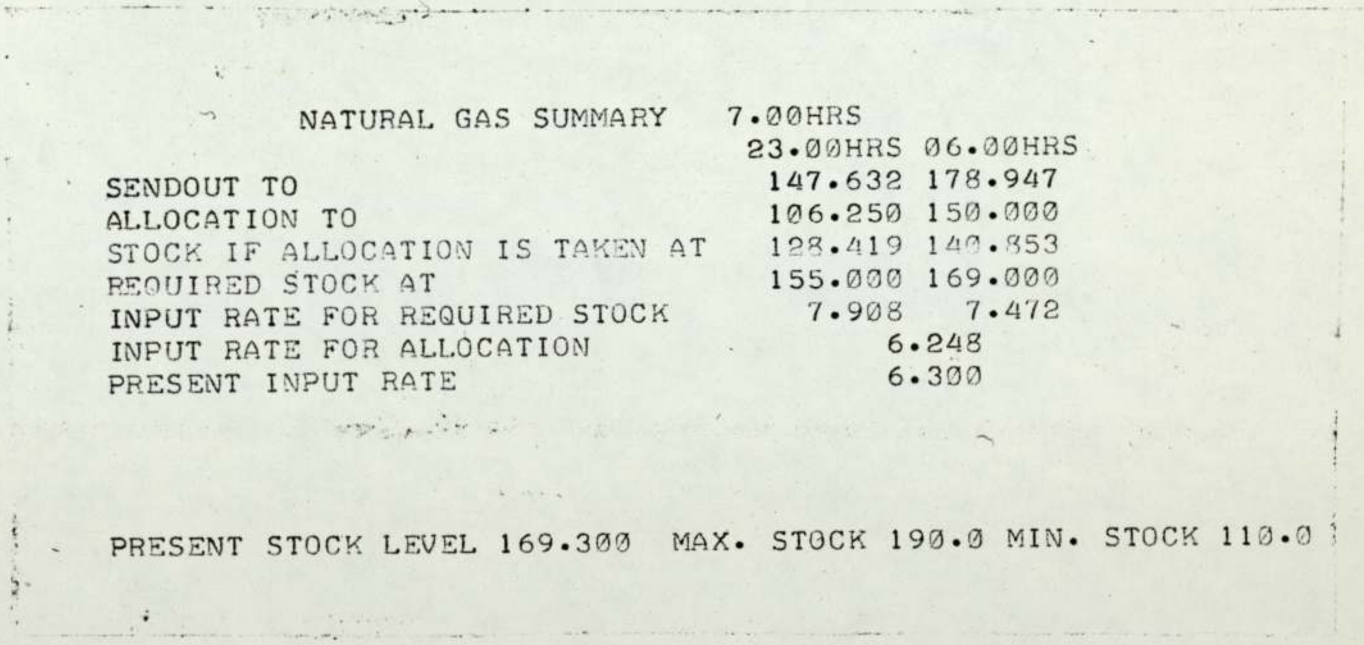
Fifth column, 'Cumulative sendout', this is the total amount of gas taken from the system by the consumer since the beginning of the day.

Sixth column, 'Average percent day', this shows the percentage of the total amount of gas usually sold by this time of day.

By doing the following calculation ('Cumulative sendout' x 100) /Aver. percent day, it is possible to obtain an estimate, based on the percent of the total sendout for the 24 hr. period. Thus the seventh column is 'Estimated sendout'.

The remaining two columns show 'Temperature' and Weather Conditions'. The figure after the weather condition abbreviation is wind force.

The second display is the 'Natural Gas Summary', this indicates what the state of the system will be at 23.00 hrs. and 06.00 hrs, if the present input rate and estimated sendout remain the same. The 23.00 hrs. column is provided because this is usually the time when stocks will be at their lowest, and any possibility of stocks falling below a safe level must be avoided.



```
          NATURAL GAS SUMMARY   7.00HRS
                                 23.00HRS 06.00HRS
SENDOUT TO                        147.632 178.947
ALLOCATION TO                     106.250 150.000
STOCK IF ALLOCATION IS TAKEN AT   128.419 140.853
REQUIRED STOCK AT                 155.000 169.000
INPUT RATE FOR REQUIRED STOCK       7.908   7.472
INPUT RATE FOR ALLOCATION               6.248
PRESENT INPUT RATE                      6.300



PRESENT STOCK LEVEL 169.300  MAX. STOCK 190.0 MIN. STOCK 110.0
```

The first row shows 'Estimated sendout' as shown in the first display.

The second row shows 'Allocation', this is the total amount of gas the controller expects to use to meet the demand and maintain stocks.

The third row, indicates what the total stocks will be if the quantity of gas allocated is taken from the National Grid, and the amount indicated by the estimated sendout is sold.

The fourth row, 'Required stocks', is the amount of gas senior management require in stock at 23.00 hrs. and 06.00 hrs. These are the stock figures that the controller has to aim for to keep the system in a safe position.

The remaining three rows give estimates in terms of hourly rates rather than the cumulative effect, as the first four rows did. The fifth row shows the input rate required from now to the end of the day if the required stock levels are to be met.

The sixth, shows the input rate required from now to the end of the day if it is intended to use the quantity of gas allocated. The seventh shows the present input rate. Finally the present stock level is shown.

CONTROL DECISIONS

After these displays have been presented you will have to decide whether you think the amount of gas allocated to meet demand and the 23.00 hrs. and 06.00 hrs. required stock levels, is sufficient. You will be given an option to change the present allocation. Remember you can change the allocation figure at will, it does not commit you to making a control action, it is your estimate of how much gas you think will be used.

However, to put this amount of gas into the system you will probably have to change the hourly input rate. This change cannot be brought about immediately because of the time it takes for the National Control to alter the supply from the North Sea.

The restrictions are as follows:

For the first change made you will have to wait 4 hrs. before the input rate may be changed, then you may only change it by up to 5% of the existing rate. For larger changes you will have to wait an extra 2 hrs. for each extra 5% change. Thus if an increase of 12% is required, you will have to wait 4 hrs. for the first 5%, another 2 hrs. for the nest 5% and another 2 hrs. for the final 2%. A total of 8 hrs. for the whole 12%. Thus of the inital input rate was 10, after 4 hrs. this would be changed to 10.0 + 0.5, after another 2 hrs, 10.5 + 10.5 x 0.05 = 11.025, and the final 2 hrs. 11.025 + 11.025 x 0.02 = 11.2455.

To avoid having to make tedious calculations the computer will calculate the percent change required from present input rate, each time you select a new allocation value.

Whatever percent change you decide upon the computer will make the changes at the appropriate times. It is also possible to make an alteration to a previously made decision provided it has not already been commissioned. For example, suppose you had decided after making a change of - 10%. that you only wanted a decrease of 6%. Provided the 10% had not been taken off i.e. you decided to make the alteration within the 6 hr. restriction period, all that would have to be done would be to put in the - 6% change. If you wanted to alter the change to 5% or less you would have to make the alteration in the first 4 hr. period, before the first 5% was taken off.

APPENDIX 5.2 Example of weather forecast sheet

WEST MIDLANDS GAS

WEATHER INFORMATION FOR Wed DAY 2 / /

WEIGHTED F'CAST ______ F'CAST 47.6 24 00 Hrs BAROMETER READINGS

WEIGHTED ACTUAL ______ ACTUAL ______

Max	Min	Mean

		ACTUAL		FORECAST °F															
		0300	0600	0900	1200	1500	1800	2100	2400	0300	0600	0900	1200	1500	1800	2100	240
0800	TEMP	45	42	46	50	54	53	49	45	42	40	45					
	WIND	5	3	9	12	12	10	8	6	5	5	4					
1200	TEMP			46	49	53	53	48	44	41	39	45	52				
	WIND			9	16	18	14	10	8	6	5	5	7				
1600	TEMP					49	51	48	44	40	40	45	52	54			
	WIND					15	14	10	8	6	5	5	8	12			
2000	TEMP						49	46	44	40	40	45	52	54	52	48	
	WIND						14	10	8	6	5	5	8	12	14	12	
2400	TEMP							45	40	38	39	42	48	54	59	55	5
	WIND							14	10	10	9	10	11	12	13	14	1
SOLI-HULL ACTUAL	TEMP	46	43	48	52	53	50	45	40	WEATHER SUMMARY							
	WIND	0	0	8	12	10	10	10	10								
EDGBASTON	MAXIMUM 0900 - 2100 HRS. MINIMUM 2100 - 0900 HRS.																

FORECAST FOR TOMORROW	TEMPERATURE			WIND SPEED	WEATHER SUMMARY	FURTHER OUTLOOK
	MIN	MAX	MEAN			
0800						
1200 (REVISION 1)						
1600 (REVISION 2)						
2000 (REVISION 3)						

APPENDIX 5.3 Example of a comparative day

APPENDIX 5.3

```
              NATURAL GAS SENDOUT SUMMARY   600 HRS
TIME :TOTAL :  TO   :STOCK  :HOURLY:CUMULO :AVER. :ESTI-: TEMP :WEATHR:
     :HOURLY:T. GAS :CHANGE:SEND-  :SEND-  :  %   :SEND-:  AT  :  AT   :
     :INPUT :PROD   :       :OUT   :OUT    :DAY   :OUT  :S-H-L :S-H-L  :
-------------------------------------------------------------------------
 700:7939            183. : 7757. :  7757. :  4.1:191.4:   50  :FINE0 :
 800:8179          -1714. : 9893. : 17650. :  9.3:190.4:   55  :FINE1 :
 900:8185          -2061. :10246. : 27896. : 14.6:190.4:   55  :FINE1 :
1000:7720          -1527. : 9247. : 37143. : 19.4:191.6:   60  :CLDY1 :
1100:8043          -1582. : 9625. : 46768. : 23.8:196.7:   63  :CLDY1 :
1200:7866          -1845. : 9711. : 56480. : 28.1:201.2:   65  :FINE1 :
1300:7590           -878. : 8468. : 64948. : 32.4:200.3:   68  :FINE1 :
1400:8154          -1065. : 9219. : 74167. : 36.6:202.5:   72  :SUNY1 :
1500:8051           -517. : 8568. : 82735. : 40.8:202.8:   73  :SUNY1 :
1600:7625           -712. : 8338. : 91073. : 45.0:202.4:   75  :SUNY0 :
1700:8123           -557. : 8680. : 99753. : 49.4:201.9:   74  :SUNY1 :
1800:8511           -500. : 9012. :108764. : 54.2:200.6:   73  :SUNY1 :
1900:8223           -429. : 8653. :117417. : 59.0:198.9:   73  :SUNY1 :
2000:8090           -566. : 8656. :126073. : 63.9:197.2:   70  :FINE0 :
2100:8134          -1001. : 9136. :135208. : 69.1:195.8:   68  :FINE0 :
2200:8154          -1247. : 9401. :144610. : 74.3:194.7:   66  :FINE0 :
2300:7934          -1115. : 9049. :153659. : 78.8:194.9:   62  :FINE0 :
2400:8190            338. : 7861. :161520. : 82.6:195.7:   58  :FINE0 :
 100:8131           1247. : 6884. :168404. : 85.6:196.7:   56  :FINE0 :
 200:8247           1076. : 7171. :175575. : 88.5:198.4:   55  :FINE0 :
 300:8055           2529. : 5526. :181102. : 91.2:198.5:   52  :FINE0 :
 400:8019           1882. : 6137. :187239. : 94.0:199.2:   50  :FINE0 :
 500:8210           2157. : 6053. :193292. : 96.9:199.6:   48  :FINE0 :
 600:8159           1602. : 6558. :199849. :100.0:199.8:   48  :FINE0 :
```

APPENDIX 5.4 Print outs of the two demand patterns

```
          NATURAL GAS SENDOUT SUMMARY   6.00HRS,

  TIME :INPUT:STOCK :HOURLY :CUMULO-:AVER:ESTI-   :TEMP:WEATHR
       :RATE :CHANGE:SENDOUT:SENDOUT:%DAY:SENDOUT: SHL:  SHL
  7.00 12.000   1.000 11.000   11.000   3.8   289.5   39.0 CLDY 1
  8.00 12.000- 3.600 15.600   26.600   8.9   298.9   45.0 CLDY 1
  9.00 12.000- 3.500 15.500   42.100  14.4   292.4   48.0 CLDY 1
 10.00 12.000- 2.600 14.600   56.700  19.7   287.8   48.0 CLDY 1
 11.00 12.000- 1.600 13.600   70.300  24.6   285.8   50.0 CLDY 1
 12.00 12.000- 0.300 12.300   82.600  29.1   283.9   52.0 CLDY 1
 13.00 12.389- 1.211 13.600   96.200  33.6   286.3   52.0 SUN  1
 14.00 12.389- 0.911 13.300 109.500  38.0   288.2   52.0 CLDY 3
 15.00 12.389- 0.711 13.100 122.600  42.3   289.8   53.0 SUN  3
 16.00 12.389- 0.911 13.300 135.900  46.6   291.6   52.0 SUN  3
 17.00 12.389- 2.311 14.700 150.600  51.0   295.3   52.0 CLDY 3
 18.00 12.389- 3.611 16.000 166.600  55.9   298.0   50.0 CLDY 1
 19.00 12.389- 3.411 15.800 182.400  60.7   300.5   48.0 CLDY 2
 20.00 12.389- 4.111 16.500 198.900  65.7   302.7   47.0 CLDY 2
 21.00 12.389- 3.911 16.300 215.200  70.9   303.5   45.0 CLDY 1
 22.00 12.389- 3.411 15.800 231.000  75.8   304.8   43.0 CLDY 1
 23.00 12.389- 1.311 13.700 244.700  80.2   305.1   41.0 CLDY 1
  0.00 12.389   1.389 11.000 255.700  83.8   305.1   40.0 CLDY 1
  1.00 12.884   3.784  9.100 264.800  86.7   305.4   39.0 RAIN 1
  2.00 12.884   4.884  8.000 272.800  89.4   305.2   40.0 CLDY 1
  3.00 12.884   4.784  8.100 280.900  92.0   305.3   39.0 RAIN 1
  4.00 12.884   4.584  8.300 289.200  94.5   306.0   39.0 RAIN 1
  5.00 12.884   4.384  8.500 297.700  97.0   306.9   39.0 CLDY 1
  6.00 12.884   3.484  9.400 307.100 100.0   307.1   40.0 CLDY 1
```

```
         NATURAL GAS SUMMARY    6.00HRS
                                23.00HRS 06.00HRS
SENDOUT TO                         0.000 307.100
ALLOCATION TO                      0.000 300.000
STOCK IF ALLOCATION IS TAKEN AT    0.000 162.900
REQUIRED STOCK AT                  0.000 171.000
INPUT RATE FOR REQUIRED STOCK      0.000  10.128
INPUT RATE FOR ALLOCATION            14.913
PRESENT INPUT RATE                   12.884
```

APPENDIX 5.4

```
                 NATURAL GAS SENDOUT SUMMARY   6.00HRS,

 TIME :INPUT:STOCK :HOURLY :CUMULO-:AVER:ESTI-   :TEMP:WEATHR
  -   :RATE :CHANGE:SENDOUT:SENDOUT:%DAY:SENDOUT: SHL:  SHL
 7.00 10.000  0.700  9.300   9.300   3.9  238.5  51.0 FINE 0
 8.00 10.000- 1.200 11.200  20.500   9.1  225.3  56.0 FINE 0
 9.00 10.000- 0.900 10.900  31.400  14.4  218.1  62.0 FINE 1
10.00 10.000- 0.500 10.500  41.900  19.4  216.0  66.0 FINE 1
11.00 10.000- 0.100 10.100  52.000  24.0  216.7  67.0 SUN  1
12.00 10.000  0.500  9.500  61.500  28.3  217.3  70.0 SUN  1
13.00  9.500- 0.300  9.800  71.300  32.7  218.1  71.0 SUN  1
14.00  9.500  0.100  9.400  80.700  37.1  217.5  72.0 SUN  1
15.00  9.025  0.325  8.700  89.400  41.1  217.5  73.0 SUN  1
16.00  9.025  0.025  9.000  98.400  45.3  217.2  75.0 SUN  2
17.00  9.025- 0.275  9.300 107.700  49.9  215.8  73.0 SUN  1
18.00  9.025- 0.275  9.300 117.000  54.9  213.1  72.0 SUN  2
19.00  9.025- 0.375  9.400 126.400  59.9  211.0  70.0 SUN  2
20.00  8.574- 1.226  9.800 136.200  65.0  209.5  67.0 FINE 2
21.00  8.574- 2.226 10.800 147.000  70.2  209.4  63.0 FINE 2
22.00  8.145- 3.155 11.300 158.300  75.3  210.2  61.0 FINE 1
23.00  8.145- 1.855 10.000 168.300  79.8  210.9  59.0 FINE 1
 0.00  8.145- 0.355  8.500 176.800  83.4  212.0  55.0 FINE 1
 1.00  8.145  0.945  7.200 184.000  86.3  213.2  51.0 FINE 1
 2.00  8.145  1.045  7.100 191.100  89.1  214.5  50.0 FINE 1
 3.00  7.738  0.738  7.000 198.100  91.7  216.0  50.0 FINE 1
 4.00  7.738  0.938  6.800 204.900  94.3  217.3  50.0 FINE 1
 5.00  7.351  0.151  7.200 212.100  96.9  218.9  50.0 CLDY 1
 6.00  7.351- 0.449  7.800 219.900 100.0  219.9  50.0 CLDY 1


                 NATURAL GAS SUMMARY   6.00HRS
                                     23.00HRS 06.00HRS
SENDOUT TO                              0.000 219.900
ALLOCATION TO                           0.000 210.000
STOCK IF ALLOCATION IS TAKEN AT         0.000 172.100
REQUIRED STOCK AT                       0.000 173.000
INPUT RATE FOR REQUIRED STOCK           0.000-  1.275
INPUT RATE FOR ALLOCATION                 5.176
PRESENT INPUT RATE                        7.351
```

APPENDIX 5.5 Questionnaire

"You may answer these questions in words; by a diagram or an equation, whichever you find most convenient."

(1) What will happen if the 'input rate' is less than the 'hourly sendout'?

(2) What variable(s) would you expect to cause an increase in 'estimated sendout'?

(3) What effect would you expect a drop in temperature to have on the system?

(4) What would you expect to happen to the system if the weather conditions changed from 'FINE' to 'CLOUDY'?

(5) How would you expect an increase in 'input rate' to affect 'estimated sendout'?

(6) How would you expect the 'hourly sendout' to fluctuate over the day.

(7) How is the 'estimated sendout' figure at 23.00 hrs. related to 'estimated sendout' at 06.00 hrs?

(8) If the 'estimated sendout' remained the same for two consectutive hours what would you expect to happen to the 'input rate for required stock', and why?

(9) If the 'input rate' increases what might you expect to happen to the input rate for allocation', and why?

(10) If the 'estimated stock' for 06.00 hrs. fluctuates, what variables would you expect to have influenced this change?

(11) What happens to the 'allocation' when the 'input rate is altered'?

(12) How would you expect the total stock level to fluctuate over the day?

(13) What do you consider the most difficult part of this task?

APPENDIX 6.1 Sample protocol

Subject 2, trial 1

SEQUENCE DESCRIPTIONS

			Code
1.	07.00	Compares 'wthr' with yesterday - decides to leave	Dp
2.	08.00	Compares 'wthr' - decides reduce alloc	Dp
3.	09.00	Compares p. day - decides to wait until 10.00	Dp
4.	10.00	Reviews Ast, ES, compares FS' - decides leave	DR
5.	11.00	Reviews - decides to wait to see if new f'cast confirms use of 4/6.	DR
6.	12.00	(1) Reviews SS	Rv
		(2) Compares with p. day and similar day	Dp
7.	13.00	(1) Examine 'send'	Rva
		(2) Compare p. day and similar day	CD
		(3) Checks 'sum' - decides leave	DR
8.	14.00	(1) Reviews SS - decides reduce alloc (=220)	DR
		(2) Decides size of CA (IR)	D2
9.	15.00	Reviews SS - decides to leave	DR
10.	16.00	(1) Reviews SS	Rv
		(2) Notes f/cast	W
		(3) Decides to leave	D

13.	19.00	Reviews SS - decides reduce	D_R
15.	21.00	Reviews SS - decides leave	D_R
17.	23.00	Reviews SS - decides leave (2 decreases in pipeline)	D_R
18.	24.00	(1) Reviews SS	R_r
		(2) Compares p. day - decides leave	D_p
		(3) Compares f/cast Te - affirms decision	W
20.	02.00	Reviews SS - decides leave	D_R

1. 07.00

Activity

(a) Comparing it with weather from previous days, pretty much the same, but the Te today is warmer. So for the moment we'll leave IR the same.

Compares weather, weather'
Decides (1)

2. 08.00

(a) Comparing the f/cast with the previous days.

(b) It seems to be a warmish day so we'll reduce our alloc., especially as we're getting near max. stock level and we're lower on the Av%.

(c) We'll reduce alloc to 230 over the whole day. I've made an error + 1, instead of - 1 ~~(Run back start again - 5)~~

Compares f/cast weather'
Notes f/cast
Compares AS_t, $\hat{MS}_t$; Ar, Ar'
Decides (1) reduce
Decides (2) alloc. = 230

3. 09.00

(a) Comparing it with previous day's weather

(b) Looking at f/cast should be OK

(c) Looking at stock change available, used less gas on average slightly, than other days.

(d) We'll not alter alloc., but will reserve judgement to the following hour.

Notes f/cast
Compares CS, CS'
Decides (1) wait

4. 10.00

(a) We're fairly near our max. stock level, but not dangerously so as yet.

(b) We're losing small amounts out of stock and the ES is more than our initial.

Compares AS_t, $\hat{MS}_t$
Notes 3c
Compares ES_i

(c) The actual % we've used is pretty much what one would expect.

① Affirms Ar

(d) And at the end of the day 1. in actual fact the sendout was 240 not 216 on the given day.

Compares FS', ES.

(e) So we'll leave alloc. as it is. And IR as it is.

Decides(1)

5. 11.00

(a) There's virtually no SC, so we're keeping pace with demand.

Notes SC

(b) ES has gone up, and weather turned sunny and Te fairly good.

Compares ES_i

(c) But f/cast, in actual fact its warmer than was f/cast and wind speed much worse than was f/cast.

Notes weather

Compares f/c, weather

(d) How are we doing as regard alloc? Still got sufficient stock in to meet management requirements, and we're still quite happily within the safety limits.

Compares ~~Est~~, RS ①

(e) We'll leave it as it is at the moment, and see what happens at 12.00 when we have our next f/cast, and see if that confirms whether in fact the actual pattern is much more like that of the 4/6 surprise, surprise. So we'll leave alloc. the same and IR same

Decides(1) wait

States

Affirms above decision.

6. 12.00

(a) So it's now midday. In actual fact the weather is warmer than the f/cast by a matter of 7°.

Compares T_e, T_{ef}

(b) But ES seems to be going up.

Compares ES_i

(c) Looking at 23 hours our alloc. to there is actually less than our ES_{23}, since our present stock level is well up we should cover that from stocks, without actually having to bother to alter rates, since our Est_{23} is still well above RS_{23}.

Compares ES_{23}, $alloc_{23}$

Notes AS_t

①

Compares RS, ESt_{23}

(d) Now looking at IR, have already asked for IR to be reduced, that should come through on the next run.		**Recalls** ΔIR
(e) So I'll leave our alloc. the same. In actual fact no. Looking at weather patterns, its significantly warmer already than our 14/(5)5. and compared with 4/6 it is much more like that, so we could in fact reduce it especially as our HS is less than it was on that particular day. Though wind speed higher. Perhaps we'll leave it the same for this hour.	②	**Compares** weather, weather', weather''. **Compares** HS, HS'' **Decides** (1)
7. 13.00		
(a) ES has gone up yet again, even though the Te has risen slightly still sunny.	①	**Compares** ES_i, Te_i.
(b) Used a small amount from stock.		**Notes** SC
(c) Still looks as if we're going to use less than on the 14/5, taking f/cast into consideration, and more than on 4/6.	②	**Notes** f/c **Predicts** sell less FS' " " FS''
(d) The IR will more than equal IR alloc.		**Compares** IR, IRall.
(e) At 23 hours ES will still be more than alloc., although $alloc_{06}$ will be more than ES_{06}, which should go to stock.	③	**Compares** ES_{23}, $alloc_{23}$; ES_{06}, $alloc_{06}$.
(f) We're not near any danger levels so we'll leave things as they are.		**Decides** (1)
8. 14.00		
(a) SC very low, HS dropped, presumably because now its a sunny afternoon.		**Notes** SC **Reason**
(b) ES has also dropped slightly. Est_{06} will be above max. stock, if we leave it as it is.	①	**Compares** ES_i **Compares** ES_t, $\hat{MS}_t$
(c) Last f/cast should be a fairly warm night, so perhaps we		**Notes** f/c

should red. our alloc. slightly.

<u>Decides</u>(1)

(d) If we compare previous days CS_{14} is - reducing, on the basis of those between the two days, reducing down to 220.

<u>Decides</u>(2)
alloc = 220

(e) If new alloc. was 220, we would req. a change of over 10%.

<u>Notes</u>
5%

(f) Not entirely sure that's a good idea, because of the ES_{23} being much higher than the alloc., though we can take a certain amount out of stock.

②

<u>Compares</u>
ES_{23}, $alloc_{23}$

<u>Compares</u>
ASt, RS_{23}

(g) So instead of -10 we'll take -5 for the moment.

<u>Decides</u>(2)
-5%

9. 15.00

(a) SC is slightly more into stock, decrease in HS mid afternoon.

<u>Notes</u> SC

(b) ES has stayed the same, but looking at the ES_{23} hours, ES is still much larger than the alloc, we shall still have enough in stock to cover the diff.

<u>Compares</u> ES_i

<u>Compares</u>
ES_{23}, $alloc_{23}$

<u>Compares</u>
ES_t, RS_{23}

(c) It should mean that we drop RS level ... anywhere near the min. stock.

①

(d) Our IR_{RS} is still much lower than IR, so in fact we may well avail ourselves with sendout.

<u>Compares</u>
IR, IR_{RS}

(e) We should all be alright on present alloc for the 06.00 level of stock.

<u>Compares</u>
ES_{t06}, RS_{06}

(f) So we'll leave things as they are for the moment.

<u>Decides</u> (1)

10. 16.00

(a) Te still going up, wind getting up.

<u>Compares</u>
Te_i, $wind_i$

(b) As before the $alloc_{23}$ is still less than the ES, but this should cover our stocks.

①

<u>Compares</u>
$alloc_{23}$, ES_{23}; ES_t, RS_{23}.

(c) Lets have a look at the f/cast, still warm, but now they reckon it will be a bit colder at night.

<u>Notes</u>
f/c

(d) Comparing with previous day's weathers; time now 16.00

they still look to be doing about right, CS rates

(e) So leave things as they are for the moment.

Decides(1)

(f) Have an instruction to reduce our rate of alloc. that should come pretty soon.

③ Recalls IR red.

(g) When did I ask for red. Should come through 18 hrs, 2 hr time.

13. 19.00

(a) ES dropped down to nearly 10m below alloc. Still warmer than f/cast.

Compares ES, alloc; Te, Te_f.

(b) Going to have too much gas in stock so must decrease again at 06.00 ... though the $alloc_{23}$ is less than ES_{23}.

① Compares ES_{t06}, RS_{06}; $alloc_{23}$, ES_{23}.

(c) So if we reduce it down, reduce it down to 215 (decrease by 10%)

Decides(2) red. to 215

15. 21.00

(a) Te dropping and is expected to drop quite a bit.

Compares Te_i

Predicts(w)

(b) ES has dropped slightly

Compares ES_i

(c) Still losing stock ? at 06.00 hrs

Notes SC

(d) Looking at 06.00, should be OK there when decreases come through.

Compares ES_{t06}, RS_{06};

① ES_{23}, $alloc._{23}$

(e) At 23 hrs ES still more than alloc, should have some spare in stock, should be able to meet RS.

Compares AS_t, RS_{23}

(f) Still have a bit of lee way left perhaps not enough. Leave things as they are.

Decides(1)

17. 23.00

(a) RS_{23} = 160 and we have 175, we're high there.

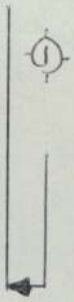
Compares RS_{23}, AS_t

(b) The ES_{06} has risen again, its now getting up to our actual personal est of 215.		<u>Compares</u> ES_{t06}, $alloc_{06}$
(c) Losing small amounts still from stock/	①	<u>Notes</u> SC
(d) HS has dropped, and the change in rate should come into effect 5% decrease.		<u>Compares</u> HS_i <u>Recall</u> ΔIR
(e) Te is dropping and slightly warmer than f/cast, so we'll leave things as they are as we have 2 decreases in the pipeline.		<u>Compares</u> Te_i <u>Compares</u> Te, Tef <u>Decides</u>(1) <u>Recalls</u> ΔIR
18. 24.00		
(a) Te dropped, has dropped again to below f/cast level.		<u>Compares</u> Te_i <u>Compares</u> Te, Tef
(b) Since we have a certain amount of lee way, alloc. still actually bigger than ES, still have stock in hand.	①	<u>Compares</u> ES, alloc <u>Compares</u> ES_t, RS
(c) IR is still higher than IR_{all}		<u>Compares</u> IR, $IR_{all.}$
(d) Another decrease due, SC + ve, done to spare capacity.		<u>Notes</u> SC
(e) Comparing with previous days for 24 hrs, CS still less than on 14/5, slightly larger %, when final amount was 240, we shouldn't need as much, but their Te were lower and still are lower.	②	<u>Compares</u> CS, CS'; Ar, Ar'. <u>Notes</u> FS' <u>Compares</u> Te, Te'
(f) Leave things as they are again for another hour.		<u>Decides</u> (1)
(g) Found new f/cast, fairly warm day tomorrow but not as warm as today, decrease is due stock level rising. Leave things as they are.	③	<u>Compares</u> Te, Tef. <u>Affirms</u> above decision
20. 02.00		
(a) So now ES has gone up to nearly the 215 which we alloc.		<u>Compares</u> ES, alloc.

(b) May in fact unfortunately go over that level but have plenty of stock to cover that over above RS

(c) Still putting gas into store, HS still dropping.

(d) Te now colder than estimated, so should belance out. Leave things as they are.



Compares AS_t, RS

Compares SC_i; HS_i

compares $\overline{Te}$, $\overline{Te}_f$

APPENDIX 7.1 Computer display for simulated task

```
           NATURAL GAS SENDOUT SUMMARY   7. 00HRS,

   TIME  :INPUT:STOCK  :HOURLY  :CUMULO  :AVER:ESTI   :TEMP:WEATHR
         :RATE  :CHANGE:SEND    :SEND    : %   :SEND   : AT  :  AT
         :      :       :OUT     :OUT     :DAY :OUT    :SHL  : SHL
   -------------------------------------------------------------------
   7.00 23.000  1.960 21.040  21.040   3.8 553.7   3.0·CLR  1


           NATURAL GAS SUMMARY   7. 00HRS
           ---------------------------

                                     23. 00HRS 06. 00HRS
 SENDOUT TO                           453. 467 553. 684
 TOTAL ALLOCATION TO                  393. 125 555. 000
 STOCK IF ALLOCATION IS TAKEN AT      145. 658 207. 316
 REQUIRED STOCK AT                    130. 000 200. 000
 INPUT RATE FOR REQUIRED STOCK         22. 154  22. 812
 INPUT RATE FOR ALLOCATION                  23. 131
 PRESENT INPUT RATE                         23. 000

 DO YOU WISH TO SEE ANY OF THE SUPPLEMENTARY DISPLAYS?

 ERROR?

 WHICH DISPLAY DO YOU WISH TO SEE FIRST?

 FOR STOCKS          TYPE SD

 FOR AVAILABILITIES TYPE AD

 FOR INTERRUPTIBLES TYPE ID

 TO REQUEST DISPLAY, TYPE CODE

           GAS STORAGE AT    7. 00HRS

   TYPE OF STORAGE                    MIN.    MAX.      NOW    STATUS
   ------------------------------------------------------------------
 L. P.  JET BOOSTERS                 13. 0    33. 0     30. 0     OFF
 L. P.  JET OR MECHANICAL BOOSTERS    3. 0    14. 0     12. 0     OFF
 L. P.  MECHANICAL BOOSTERS          10. 0    27. 0     23. 0     OFF
 M. P.  COMPRESSORS                  14. 0    38. 0     37. 0     OFF
 STORAGE MAIN                        70. 0   108. 0    106. 0
 --------------------------------------------------------------------
 TOTAL                              110. 0   220. 0     208. 0


 DO YOU WISH TO ALTER GAS OUTPUT FROM HOLDERS YES OR NO

 ARE JET BOOSTERS REQUIRED ON OR OFF?

 ARE JET OR MECHANICAL BOOSTERS REQUIRED ON OR OFF?

 ARE MECHANICAL BOOSTERS REQUIRED ON OR OFF?

 ARE COMPRESSORS REQUIRED ON OR OFF?

 ERROR?

 DO YOU WISH TO ALTER GAS INPUT TO HOLDERS, YES OR NO?

 DO YOU REQUIRE J-BOOSTER REFILL VALVES ON OR OFF?

 DO YOU REQUIRE J-OR MECHANICAL BOOSTER REFILL VALVES ON OR OFF?

 DO YOU REQUIRE MECHANICAL BOOSTER REFILL VALVES ON OR OFF?
```

```
DO YOU REQUIRE COMPRESSOR REFILL VALVES ON OR OFF?

ERROR?

DO YOU WISH TO SEE ANOTHER DISPLAY, YES OR NO?

TO REQUEST DISPLAY, TYPE CODE

GAS AVAILABILITY FOR THE REGION IS AS FOLLOWS AT   7.00HRS
PROD                         PRICE     AVAILABLE  USED
SOURCE                       P/TH       M.C.F.    BY 06.00
------------------------------------------------------
PIPE LINE ALLOCATION          2.5        598       555.000
B.G.C. 'PEAK SHAVING' GAS     8.0         50         0.000
REGIONAL BUTANE AIR           9.0         35         0.000
B.G.C. STORED GAS             9.5        117         0.000
------------------------------------------------------
TOTAL ALLOCATION                         800       555.000


DO YOU WISH TO CHANGE SUPPLY CONDITIONS, YES OR NO?

DO YOU WISH TO ALTER 'PEAK SHAVING' GAS, YES OR NO?
HOW MUCH 'PEAK SHAVING' GAS IS REQUIRED?

DO YOU WISH TO ALTER BUTANE AIR, YES OR NO?
DO YOU WISH TO ALTER STORED GAS, YES OR NO?
ERROR?

DO YOU WISH TO SEE ANOTHER DISPLAY, YES OR NO?

TO REQUEST DISPLAY, TYPE CODE

DETAILS OF INTERRUPTIBLE CONTRACTS AT    7.00HRS
GROUP:NO OF:AV LOAD:PRICE: INTERRUPT : INTERRUPT  :DAYS ALREADY
     :FIRMS: MCFD.  :P/TH :NOTICE(HRS):PERIOD(DAYS):INTERRUPTED
--------------------------------------------------------------
  1  :  10 :   1    : 3.0 :     8     :     45     :     3
  2  :  15 :   2    : 4.5 :     8     :     60     :     5
  3  :   4 :   5    : 7.5 :     4     :     75     :     2


DO YOU WISH TO INTERRUPT ANY OF THE 3 GROUPS, YES OR NO?

DO YOU WISH TO INTERRUPT 1, YES OR NO?

DO YOU WISH TO INTERRUPT 2, YES OR NO?

DO YOU WISH TO INTERRUPT 3, YES OR NO?

ERROR?

DO YOU WISH TO STOP INTERRUPTING GROUP 1, YES OR NO?

DO YOU WISH TO SEE ANOTHER DISPLAY, YES OR NO?




DO YOU WISH TO ALTER PIPE LINE ALLOCATION, YES OR NO?

WHAT DO YOU WISH THE NEW ALLOCATION TO BE ?

THIS ALLOCATION WILL REQUIRE A CHANGE OF  1.74%
DO YOU WISH TO ALTER THE INPUT RATE, YES OR NO?

TYPE 1, FOR INCREASE, -1, FOR DECREASE

WHAT % CHANGE DO YOU REQUIRE ?

ERROR?
```

APPENDIX 7.2 Sample protocol

Controller 1

DESCRIPTION OF SEQUENCES

07.00	(1) Examine 'send' - predict	Ps
	(2) Check 'sum' - decide booster on	NC_o
	(3) Examine 'availabilities'	SSC'_A
	(4) Examine 'interrupts' - decides to interrupt now 1,2,3	SSC_I
09.00	(1) Examine 'send'	PS'
	(2) Check 'sum'	NC'_o
	(3) Check 'stock' - decides put gas into system	DC
	(4) Decides on most suitable increase	SSC
10.00	(1) Checks 'sum'	NC'_o
11.00	(1) Examines 'send'	PS'
	(2) Checks 'sum' - decides OK	NC_o
12.00	(1) Check 'sum' - decides OK	NC_o
13.00	(1) Check 'stocks' - decides boosters off	DC
	(2) Check 'sum' - considers increase	NC_o
14.00	(1) Examines 'send'	PS'
	(2) Check 'stocks'	DC'
	(3) Check 'sum' - decides increase on PSG & RB	NC_o
	(4) Evaluates effect of CAs	E_{CA}

15.00	(1) Examines 'send'	PS'
16.00	(1) Examines 'send'	PS'
	(2) Check 'sum' - decides OK	NC_o
18.00	(1) Examines 'send'	PS'
	(2) Checks 'stock' - decides boosters on Checks 'sum' - decides SG	DC NC_o
19.00	(1) Examines 'send'	PS'
	(2) Checks 'sum'	NC_o'
	(3) Checks 'stocks'	DC'
20.00	(1) Checks 'sum'	NC_o'
	(2) Checks 'stocks'	DC'
21.00	(1) Examines 'send'	PS'
	(2) Checks 'sum' - decides cut SG	NC_o
22.00	(1) Checks 'sum' - decides OK	NC_o
23.00	(1) Checks 'sum'	NC_o'
	(2) Describes holder CAs	
24.00	(1) Review	Rv
	(2) Predicts tomorrows sale	PS_t
	(3) Calculates effect of PSt on stocks tomorrow	E_{PS}
01.00	(1) Checks 'stocks'	DC'

02.00	(1) Checks 'stocks'	DC'
03.00	(1) Checks 'stocks'-decides to shut LJ off	DC
04.00	(1) Checks 'stocks'-decides shut LM & LC off	DC
05.00	(1) Checks stocks - decides OK	DC'

Time 07.00 hours

Today we've got an estimated sale on the first hour of 683.8.

Notes ES

Actual sale of 25.3 million which compares with the sale yesterday at the same hour of 21.0 million. So it is obvious that the sale is going to be greatly higher today than it was yesterday.

① Compares HS, HS'

Predicts $PS > FS'$

Looking at the NG summary - we find that for the input of 598, which is the pipeline nomination, and a sale of 684, we would have a stock of 115 in the morning and 65.0 at 23.00 hours, which is an impossible situation. So before doing anything we'll get the jet boosters to work which will help to ease the situation a little bit before making the final decision.

Notes all, ES_{t06} ES_{t23}

② Decides (2) LJ on

We will have a look at the availability sheet and also at the interruptible gas supplies before deciding how to overcome the problem.

States

Looking at the print-out for the availabilities - we have 50 million of peak shaving gas, 35 million of regional butane/air, and 117 million of BGC stored gas.

Notes PSG, RB, and SG.

③ Notes interrupts 1, 2, 3.

And on the interruptible load we have 10 million available at 3 pence per therm, 30 million available at 4.5 pence per therm, and 20 million available at 7.5 pence per therm, which are all cheaper than other options available from BGC.

All in all, therefore we have 60 million available from interruptible gas. But of course there is an 8 hour waiting period for the first two categories, i.e. 40 million we have to wait 8 hours for, and for the further 20 million we've only got to wait 4 hours. So in the 24 hours we of course won't get the total of 60 million but somewhat less than this.

Calculation
Group 1+2+3
= ΣIL

Notes
1, 2 = 8 hrs;
3 = 4 hrs
wait

④ Evaluates
effect of delay

All in all therefore from interruptible gas we will only get something like 40 million for the day. Whereas the total deficit is 80 million for the day.

Calculates
Au. − ΣIL

I feel that at this point that we should give notice to the firms for the interruption of the supplies, which will give us 40 million over the day, and then look at the next couple of hours figures before deciding how to combat the further 40 million deficit.

Decides (2)
Interrupt
now

Time 09.00 hours

Looking at the sendout forecast for 09.00 hours - we find that we have an estimated sale of 690.6. We're losing 11 million from stock on the hour and we're heading for a stock of 108 in the

① Notes
ES, SC,
ES_{t06}, ES_{t23}

②

morning and 59.7 at 23.00 hours.

Looking at the stock summary - we are down to a stock of 180. We've got a minimum stock of 110. So at the current rate of loss we could go for seven hours. Obviously we've got to get some gas into the system fairly quickly. We've got 40 million coming from interruptible loads but most of that won't be coming for 8 hours. We have got gas available in an hours time from butane air, or from BGC stored gas. And we have also got 50 million available from peak shaving gas but we can't get that for 4 hours.

<u>Notes</u> AS_t, RS_{min}

③

<u>Calculates</u> $(AS_t - RS_{min})/SC$

<u>Decides</u> (1)

<u>Recalls</u> ΣIL and delay

<u>Notes</u> RB, SG, PSG, & delays

④

So its got to be a compromise between time and cost at the present moment. So I propose to take 20 million of regional butane air, and 30 million of peak shaving gas.

<u>Decides (2)</u> take 20 RB and 30 PSG

<u>Looking at the 10.00 figures</u>

We see from the summary that the situation has eased a little bit. We've got an estimated send-out of 684, a total input now at 658, which gives us a stock of 174.5 at 06.00 hours. But at 23.00 hours we've only got 107 million.

<u>Notes</u> ES, All., ES_{t06} ES_{t23}

①

Our minimum stock of course is 110 so at the present moment we are fractionally below this.

<u>Compares</u> ES_{t23}, RS_{min}

Time 11.00 hours

We are now starting to see a drop in the estimated sale which could of course be due to the fact that the interruptible load is starting to decrease. At the present moment we are showing a stock of 111, at 23.00 hours which we can safely meet.

Compares ES
Explains
Notes ESt_{23}
Decides (1)

Time 12.00 hours

The sale is still predicted at 679.5. We'll have 111 at 23.00 hours which means we're OK there but 6 o'clock stock is a little bit low.

Notes ES, ESt_{23}, ESt_{06}
Decides (1)

Time 13.00 hours

The input has dropped this hour, and looking at the stock position I find that storage mains are full and all the gas is coming out of the holders via jets. So we're going to knock those off so that we can get the rate back up again. The estimated sale is 675.6. The stock position at 23.00 hours is 107, and at 173 at 06.00 hours. So we are showing a stock at 23.00 hours, slightly below the minimum.

Compares IR
Explains
Notes SM_{st}, booster status
Decides (2) boosters off
Reason
Notes ES, ESt_{23}, ESt_{06}.
Compares ESt_{23}, RS_{min}

Might have to make further adjustments a little bit later on.

Still no sign of this predicted snow.

Consider (1)
Notes weather

Time 14.00 hours

Still got a predicted sale of 675. We are

Notes ES

starting to lose a bit from storage mains now. But the stock position is still not quite correct, so we'll need a little bit more gas into the system. Particularly for both 23.00 hours and 06.00 hours positions.

② Notes
SM_{st}

③ Notes
ESt_{06}, ESt_{23}

So I'm going to ask for a further 10 million on the peak shaving gas and 5 million on the butane air.

Decides (1)

Decides (2)
10 PSG
5 RB

Looking at the availabilities of pipeline gas, we have theoretically 20 available but as a third of the day has elapsed that's reduced that by a third. So there is only about 12 available so I have decided to ask for this. Similarly with butane air there was 15 theoretically available, there is only two-thirds of that left, which is 10, so I am going to ask for that as well.

Evaluates
effect of time left on above actions

④ Calculates
$PSG = 2/3 \cdot 20$

Calculates
$RB = 2/3 \cdot 15$

15.00 hours

Sales still holding up at 675. But still no sign of the snow yet.

① Notes
ES, weather

16.00 hours

Predictive sale 675 and now we've finally got the snow.

① Notes
ES, weather

At this present moment we've got an intake of 665 into the system which will give us 119-120

Notes All.,
ESt_{23}, ESt_{06}

stock at 23.00 hours tonight and 191 for the morning, which is not quite as high as we wanted, but at least it is a reasonable position to be in.

② Decides (1)

Time 18.00 hours

Predicted sale rapidly increasing due to the heavy snow.

① Compares ES Explains

Storage mains getting very low. Got a little bit of gas in the holders which we can get out with the jets. The position at the present moment is that we would expect to have a stock of around 119 at 23.00 hours tonight and 191.4 in the morning.

Notes SM_{st} Considers (2) LJon Notes ES_{t23}, ES_{t06}

We've still got some gas to come into the system. We're only taking 28.1 at the moment, we've got some to come from the peak shaving gas. But that's not expected for another couple of hours or so. At current loss from stock - we're losing 15 million from stock - we won't be able to maintain this.

Notes IR

② Recall increase expected

Notes SC

Now putting the jets back on to help the storage mains. With the jets on we should be able to sustain a loss of stock of 15 million for the next hour or so but after that we are going to be in a lot of trouble. Because of this I am going to ask for 20 million of storage gas from BGC.

Decides (2) LJ, LJM, LM, LC

Evaluates effect of jets

Decides (2) 20 SG

Time 19.00 hours

Predicted sale of 681. Still snowing. We've got a total input of 695 into the system which will give us 214.8 stock in the morning and 136.1 at 23.00 hours.

① Notes ES weather

② Notes All., ES_{t06}, ES_{t23}

Looking at the stock position - the holders have all been shut off now. They are all very low. We've got about 8.6 available from the storage mains at the **current** moment.

③ Compares LJ_{st}, LJM_{st} LM_{st}, LC_{st} with mins. Compares SM_{st}, SM_{min}

20.00 hours

The predicted sale has dropped slightly to 678 which would give us a stock of 218 in the morning with no problems at 23.00, we've got a stock of 138.7. I've knocked the final jets off now and we've got 75.1 in the storage mains which is 5.1 available gas.

① Notes ES ES_{t06}, ES_{t23}

② Describes CA. Compares SM_{st}, SM_{min}

Time 21.00 hours

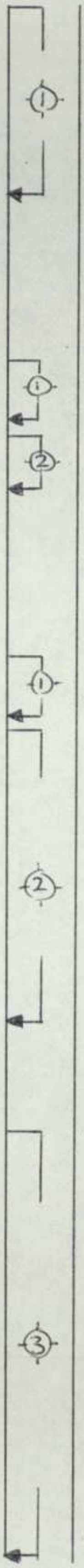
With the snow stopping the sales are starting to tail off now. At the present situation we'll have 220 stock in the morning and 140 at 23.00 hours tonight.

① Notes weather, ES

② Notes ES_{t06}, ES_{t23}

So it would seem that we could possibly cut the gas from storage that we've asked for from BGC down to 10 million.

Decides(?) Cut SG to 10m



22.00 hours

Sales 675, which would give us a stock of 211 in the morning and 134 at 23.00 hours tonight. That's with the allocation reduced to 685 which is quite OK. No problems at all.

Notes ES, ES_{t06}, ES_{t23}, All.

Decides (1)

23.00 hours

Predicted sale 673.6. We ended up with a minimum stock of 110 and we will start now to fill the holders and the storage mains.

Notes ES AS_t

Describes

24.00 hours

Stock now 117. Slowly filling the holders up. Predicted sale 673.9. I have had a look at the weather forecast. Slightly better day tomorrow. Max. temp of about 2° which is a little bit warmer than today, so the sale should be somewhat less than today, possibly in the region of about 650.

Notes AS_t, ES, SC

Compares $\bar{T}e$, $\bar{T}e_f$

Predicts PS_t

On that basis if we took a total of 650 NG into the system we would have sold by 23.00 hours tomorrow around about 530, taken in 460, which would require us to lose something like 70 million from stock which we could do quite reasonably and end up with a minimum stock at 23.00 hours of round about 120 mark. So there doesn't seem to be any problem there.

Calculates

$Av\%_{23} \times PS_t = x$

Calculates

$17/24 \times PS_t = y$

Predict

stock loss

$x - y = 7$

Calculates

Decides (1)

Time 01.00 hours

Filling the holders nicely. Jet booster holders up to 21.5. Other jet booster holders up to 8.2. Nothing into the storage main as yet.

①
Notes
LJst, LJMst,
SMst

02.00 hours

Jet booster stocks getting towards maximum. Again nothing into the storage main.

①
Compares
LJst, LJ min

03.00 hours

LP jet boosters 29.5. Going to shut these off now the same as with the other jet booster stations - a stock of 12.6. I'll allow a little bit more to go into the other holders but we'll start to fill the storage main now.

①
Notes LJst,
LJMst.
Decides(2)
input off LJ
Decides(2)
leave others

04.00 hours

Storage main - a little bit of gas gone in. Mechanical boosters - shutting them off and also the compressors so that now all gas will go into storage.

①
Decides(2)
shut LM, LC.

05.00 hours

Storage mains filling nicely now, up to nearly 86. Everything going OK.

①
Notes FS,
FSt, SMst
Decides (1)

06.00 hours

Final sendout of 672.9. We ended up with a total stock of 196.7 of which 100.8 was in the storage mains. A little bit of a drop from

Notes FS
FSt, SMSt

this morning but not enough to be worried about. We could probably have kept on the other 10 from storage, from BGC.

We should be in a reasonable position today if we take the 650, and carry on interruption of the customers already interrupted.

APPENDIX 9.1 List of information abbreviations

REFERENCE LIST OF INFORMATION ABBREVIATIONS USED IN CHAPTER 4

FR	Particular value of frequency
ΔFR	Change in frequency
LOL	Lower operational limit
CE	Clock error
T_F	Target frequency, requested by National Control (NC)
T_R	Transfer net amount of MW being imported or exported
T_T	Target transfer, requested by NC
D	Demand level
D'	Demand on a previous day
E_D	Estimated demand, i.e. predicted demand
ΔTGO	Change in total generation for the area
PLANT STATE	State of plant in the area as shown on the log sheet
WTHR	Present weather situation
F/C	Weather forecast
T_F*	New requested target frequency
T_T*	New requested target transfer
PROG*	New programme
INDIVIDUAL PLANT INFO.	Information about individual stations and the state of their plant.

REFERENCES LIST OF INFORMATION ABBREVIATIONS USED IN CHAPTERS 3, 6, 7, COMMON TO BOTH MANUFACTURED (MG) AND NATURAL (NG) GAS

HS	Hourly sendout (at a given hour)
CS	Cumulative sendout (at a given hour)
ES	Estimated sendout (based on Av% day)
FS	Final sendout
ESt_{23}	Estimated stock level at 23.00 hours
ESt_{06}	Estimated stock level at 06.00 hours
$RS_{06,23}$	Required stock level at 06.00 or 23.00 hours
SC	Hourly stock change
GOV. PRESS	Governor presssures
STOCKS	Individual holder details

MG ONLY

$\Sigma\dot{p}$	Estimated total production for the whole day
$\dot{p}$	Hourly input, production
plant_p	Hourly production, individual plants
S-G	Super grid pressure
C-H	Change in production to reach required stock level.
CR	Change in production rate to reach required stock level.
L/f	Load factors on individual plants
$\Sigma\dot{p}$	Max. total production available over the day

NG ONLY

ALLOC.	(All.) Gas to be taken from the National Grid
DIR	Direct natural gas
PROD	Natural gas to meet production requirements
TOT	Sum of DIR and PROD
IR	Hourly input rate

GENERAL

WTHR	Present weather conditions
F/C	Weather forecast
Te	Temperature

NB Symbols with (') above them e.g. HS' refers to a value on a comparative day.