A HUMAN FACTORS APPROACH TO MANAGING COMPETENCY IN HANDLING PROCESS CONTROL DISTURBANCES

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Process plant training often fails to provide, in a systematic and comprehensive way, the skills and competencies required for control room operators and engineers to handle process disturbances. Such failures have been implicated in high profile incidents such as Longford and Milford Haven. Based on the underlying psychology of handling process disturbances, this paper proposes methods for capturing the experience and strategies used by experienced personnel to provide a better framework and content for training. It also discusses the use of simulators and strategies for maintaining competencies for process disturbance handling. This can both reduce the likelihood of high consequence incidents and improve production efficiencies through keeping the system within desired limits.

INTRODUCTION

The Longford gas plant explosion in 1998 (Hopkins, 2000) raised many issues with regard to how process operators should be trained to more effectively manage process disturbances. It was widely accepted that problems arose in the diagnosis of the nature of the plant disturbance and the formulation and implementation of corrective actions. These errors contributed to the fatalities and major economic losses that resulted from the incident. Involvement in a project reviewing the training issues in this incident led to an appraisal of the training approaches adopted across the industry. This paper, based on this work, sets out a framework for panel operator training that, if applied across the oil and gas industry, should ensure that plant personnel would be able to respond more effectively to challenges such as those experienced by the Longford operators.

Training in the process industries is normally based on a methodology called Competency Based Training (CBT). In CBT, operators initially receive a short period of classroom based training to familiarise them with the basic principles of process operation and safety issues. The majority of operational skills are then transferred by on the job training, where trainees are supervised by experienced operators. Although this approach may be adequate for simple plant based activities such as routine process operation or maintenance, it does not systematically address the more complex skills required for panel operations in process control. In particular, it does not provide a firm basis for training in the management of process disturbances. We often find that skills and CBT matrices for panel operators and engineers comprehensively specify proceduralised tasks and emergency response training requirements, but do not address competencies that relate to handling process disturbances.

For disturbance handling training to be effective, the first requirement is to comprehensively specify the different types of situation likely to be encountered. This allows the most effective ways to handle these disturbances to be codified and documented as the basis for training content. Often, the strategies that are trained using on the job mentoring may not be those that achieve the best results. Lack of consistency in training also creates potential problems if panel operators move between different operating teams. Handling a complex disturbance is likely to involve a closely coordinated response by the operating team. Lack of a consistent approach to training will reduce the ability of a team to work together, as it will impede effective communications, and will also lead to difficulties with regard to the assignment of roles and responsibilities within the team. Reliance on unstructured on the job training also means that it may take a considerable period of time before the trainee encounters the full range of situations that need to be handled. This means that the training period is likely to be extended such that the required completeness of coverage may never be attained.

Process disturbance management is generally considered in the context of infrequent but high profile incidents such as the Milford Haven Texaco Refinery incident (Health and Safety Executive 1994) or the Longford gas plant explosion (Hopkins, 2000), where there were major plant losses. In fact, process plant panel operators cope with many minor disturbances on a day to day basis which do not progress to the stage of being a major incident. In this paper it is argued that the strategies used by operators to handle these disturbances are a valuable source of information that can be collected and utilised for training purposes.

In addition to safety issues, the ability of the panel operator to respond to disturbances in a timely and effective manner also has a considerable impact on the economic aspects of the plant operation. For example, there is often a narrow operating range for a process within which production is optimal. By intervening to maintain the process within this range, the panel operators may improve both the quality and the quantity of the outputs, as well as minimising the consumption of expensive feedstocks. Thus, the argument for optimising panel operator performance has both a safety and an economic basis.

THE PSYCHOLOGY OF HANDLING PROCESS DISTURBANCES

Training programmes for handling disturbance and process deviations should be based upon an understanding of the underlying mental processes involved in these situations. In general, two main approaches to training in handling process disturbances can be identified (Rasmussen, 1981, Rouse (1981). The first of these is based on the idea of developing an extensive repertoire of diagnostic and action rules to be invoked to handle the situation. Training then involves transferring these rules to the panel operator, and ensuring that he or she retains the capability to apply them after the initial training. The second approach addresses the question of how operators can be trained or supported in developing new rules to cope with novel situations that cannot be predicted in advance. This involves an understanding of the way in which the process operates, referred to as principle knowledge.

RULE BASED DISTURBANCE MANAGEMENT

In rule based disturbance management, the operator uses the pattern of symptoms which exist in a situation to move directly to a linked diagnosis. It is assumed that diagnostic knowledge is stored in the form of 'production rules'. For example:

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IF< symptoms X, Y, Z >
THEN<problem is situation A >
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Usually diagnoses are linked to appropriate actions by rules of the form:

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IF< Situation A >
THEN <Do action B >
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These symptomatic rules (S-rules) and action rules (A-rules) are acquired through training and experience. They are context dependent, in that they only apply to specific situations. An example of the application of an S-rule to diagnosing the reason for a car failing to start would be as follows:

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IF < the engine will not start >
AND < the starter motor turns>AND<the
battery is strong >
THEN < check the fuel gauge>
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An important characteristic of S-rules are that they involve little effort and are rapid in their retrieval and application, because they only require a match between local cues and the situation component of the stored rule. Similar considerations apply to A-rules.

One of the main disadvantages of S-rule based diagnosis is the danger that two different situations which have a large number of shared symptoms may be confused. This is particularly problematic if the two situations are very different in terms of the actions required, and the severity of the consequences that arise if the wrong actions are chosen. The likelihood that this type of error will occur depends partly on the extent to which the information which distinguishes these situations is readily accessible. If there is a high level of time pressure or stress, which makes it more difficult to spend time obtaining the additional information diagnostic information, there is a danger that the situation will be interpreted as one which is more frequently occurring and relatively innocuous, rather than a rare, dangerous scenario. This is a common phenomenon in high stress situations, where it is referred to as 'Cognitive tunnel vision.' Training and other strategies to overcome the effects of stress will be described in 'role of simulators in training' section.

THE ROLE OF PRINCIPLE KNOWLEDGE

The second main type of disturbance management strategy involves the use of the internal mental model that the operator possesses of the nature of the process that is being controlled, referred to here as 'principle knowledge.' This can be defined as knowledge of the designed working principles of a system, in terms of its structure, function and mode of operation (Chandrasekaran & Mital, 1983). There has been considerable debate with regard to whether diagnosis is primarily based on the use of rules, as described in the previous section, or whether principle knowledge makes a significant contribution. Intuitively, it seems reasonable to assume that diagnosis will be more effective if operators have some understanding of the nature of the process that they control. As a result, many process operator training courses include a substantial amount of chemical engineering theory. However, early research seemed to suggest that most operators used simple 'rules of thumb' or heuristics to perform diagnosis (Morris & Rouse 1985, Shepherd et al, 1977, Duncan 1981 and Marshall et al, 1981) rather than principle knowledge. Other more recent research involving observations of the actual performance of fault-diagnosis has suggested a critical role for knowledge of principles (Raaijmakers and Verduyn, 1996, Linou and Kontogiannis, 2004, 2005; Patrick and Haines, 1988). It is important to note that the type of principle knowledge referred to in this research was not in the form of high level chemical engineering theory, but rather operating principles relating to the specific system being managed and thus give important context to rule-based strategies.

CONCLUSIONS WITH REGARD TO PRINCIPLE VERSUS RULE BASED TRAINING

The research summarised above suggests that training strategies need to address both Principle and rule based approaches for handling process disturbances. Rule based approaches to training are often criticised because procedures cannot be formulated to handle every type of situation that might arise. Nevertheless, there is a strong case for developing as comprehensive a set of diagnostic rules as possible, to provide the basis for handling predictable disturbances. The rule based approach to disturbance handling has the advantage that it can usually be applied more rapidly and with less effort than using principle knowledge. The more S-rules are available, the less the operator will be required to work out a diagnosis and action strategy from first principles. This is particularly relevant to situations where there may be a limited amount of time available to handle the situation. Research by Hockey, Sauer and Wastell (2007) also suggests that S-rule diagnosis is more robust and less disrupted by stress than Principle-based diagnosis.

Nevertheless, it is clear that training should also aim to enhance the understanding of the overall principles of operation of the specific system involved. In order to provide the extra time required for principle-based diagnosis, there is an argument for developing a generic strategy, which can be applied in all situations, (particularly when the available rule based strategies have failed), for bringing and maintaining the system in a safe stable state.

A FRAMEWORK FOR TRAINING IN DISTURBANCE HANDLING

In this section, an approach to training for disturbance handling will be set out, based on the previous review of how diagnosis and action formulation are performed. The main issues that will be discussed are as follows:

- The development of diagnostic and action rules for training
- Development of principle knowledge
- The use of simulators
- Supporting diagnostic performance and minimising loss of competence over time

DEVELOPMENT OF DIAGNOSTIC AND ACTION RULES

The first stage in developing a training programme to support the effective handling of process upsets is to work with the operating team and other informants to describe and document the types of disturbance that arise and the strategies used to handle them. This is called a 'Disturbance Inventory.' There are two complementary approaches to this, the use of *disturbance management diaries* and *consensus groups*.

Disturbance management diaries are kept by experienced panel operators to record disturbances that they encounter, and to document how they handled these situations. The object of this exercise is to capture the strategies used by experienced operators regardless of the consequences that actually arise. In most plants, no record is retained of a successful intervention. Only failures to handle a situation will normally be documented. However, knowledge of successful interventions is as important from the point of view of training as knowing why things did not go as planned. In order to implement such a data gathering exercise, it is necessary to provide adequate time at the end of each shift so that interventions can be recorded as soon as possible after their occurrence.

The second approach to developing the Disturbance Inventory involves an interactive workshop, called a consensus group, where experienced personnel are brought together under the guidance of a facilitator. The facilitator is an individual trained in working with small groups, to manage the process and to ensure that all participants can make a contribution. The primary participants in the session will be plant operators and it is preferable not involve engineering or managerial staff at the beginning of the session, as this may inhibit open discussion. However, process engineers or safety specialists may be involved at a later stage of the process, to extend the discussion to scenarios that may not have been encountered previously by the operators, but for which training is deemed to be desirable.

The first stage is to break down the process being analysed in terms of the main types of activities involved. These should then be ranked in terms of the risk that they represent, using criteria such as the severity of the consequences if a disturbance is incorrectly handled and the likelihood that this will happen. Those activities with the highest predicted risks should be given priority in the development of training materials.

If a diary process has been implemented as described earlier, this will provide one set of inputs to the discussion. In addition, participants will be asked to describe the disturbances that they have experienced and have successfully managed. Discussion with regard to how disturbances can be recognised is encouraged, together with possible alternative approaches that different operating teams have used to handle similar disturbances.

One method for documenting diagnostic rules for training purposes is the Fault-Symptom Matrix (FSM) approach. A FSM is a table in which each row refers to a plant state (usually a failure or malfunction) and each column a corresponding set of symptoms or indications that are accessible to the operator. Table 1 shows an example for an electrically driven centrifugal pump. The example illustrates the fact that a wide variety of different symptoms can be used, ranging from noise, pressures, levels and flows to power supplied to the pump motor as a means of distinguishing between different types of failures.

It can also be seen that certain failure types are more confusable than others. Scenarios 3 and 5 for example, show identical symptoms apart from the presence or absence of noise symptom. On the other hand, scenarios 4 and 7 only share two symptoms and hence are unlikely to be confused. Where similar symptoms occur for scenarios that differ considerably in terms of risk if they are confused, training can highlight other symptoms that should be taken into account in order to successfully distinguish between the scenarios. This type of analysis is sometimes referred to as a Confusion Matrix. Documenting the symptoms associated with different scenarios may also need to consider the ways in which symptoms change over time as well as their initial states. Once a diagnosis has been developed for a set of symptoms, a diagnostic strategy needs to be developed. This should utilise inputs from operators from the successful management of previous instances of the scenario. It may

Table 1. Example of a fault – symptom matrix

Scenario	Symptoms							
	Downstream line pressure	Upstream line pressure	Feed tank level	Receiver level	Down stream flow	Ammeter reading	Motor light active	Noise
1. Motor failed	L	H	N	N	Zero	Zero	Yes	Silent
2. Empty feed tank	S	Zero	Zero	N	S	L	Yes	Rattling
3. Totally blocked filter	L	H	N	N	Zero	L	Yes	Rattling
4. Power failure	L	H	N	N	Zero	Zero	No	Silent
5. Sheared coupling	L	H	N	N	Zero	L	Yes	Motor Hum
6. Pump impellor eroded	L	H	N	N	L	L	Yes	Motor Hum
7. Cavitation	S	S	N	N	S	S	Yes	Rattling
8. Gate fallen off suction valve	L	Zero	N	N	Zero	L	Yes	Rattling

(Key: N = Normal, H = High, L = Low, S = Swinging)

also be valuable to involve engineering and safety specialists in the discussion to develop an agreed best strategy.

DEVELOPMENT OF PRINCIPLE KNOWLEDGE

Since the management of process upsets involves both fault-diagnosis and the implementation and evaluation of fault mitigation strategies, this reinforces the conclusion that plant operators need to receive training in principle knowledge in addition to rule based diagnosis. Focussing on principle knowledge provides support for trainees attempting to diagnose novel faults in fault diagnosis tasks, as well as faults that represent new instances of categories already seen, and faults that have already been encountered. Successful applications of principle knowledge in studies of fault diagnosis by Linou & Kontogiannis (2004), and Patrick & Haines (1988) have involved the presentation of overviews of the process plant layout describing the main components of the plant, descriptions of flows through the plant, and identification of causal relationships between the variables under control and process plant status indicators.

As discussed previously, the consensus group provides a good context for identifying scenarios where principle knowledge will be useful for diagnosis and implementation of fault mitigation strategies. This will enable any form of training in operating principles to be very tightly focussed on knowledge that can be readily applied to support plant operations, rather than being general or discursive in nature.

ROLE OF SIMULATORS IN TRAINING

Training simulators have been applied extensively in the oil and gas industries, both in the form of generic and process specific simulators. Research in a variety of high-stress work domains, such as law enforcement and fire-fighting, illustrates that such exposure can potentially inoculate operators from the impact of stress on their performance (Meichenbaum, 1985). The exposure to multiple scenarios and efforts to solve these can provide the operator with means of quickly appraising situations already encountered through recognition of specific cues provided by the process control system (Bainbridge, 1987). The effective use of simulators in training relies upon the selection of scenarios to represent a range of cases which provide an adequate breadth of experience to manage a wide range of process upsets, and the provision of appropriate rules to manage the fault-diagnosis and mitigation process. However, the level of realism does not have to approach that of a real plant in order to be beneficial in reducing stress levels. A high level of physical fidelity is also not considered essential to produce beneficial effects in disturbance handling training, since this is more dependent on the extent to which the simulator can mimic the degraded states of the process, display information similar to that provided by the real plant, and produce similar responses to interventions by the operator. More important is that the operating team have experience in successfully managing a range of simulated process disturbances.

Table-top simulation, where the control room team respond to scenarios generated by an experienced operator or process engineer acting as a facilitator can be effective as a low cost approach to training in disturbance management. In this context, the facilitator's role is to feed back to the trainees the expected response of the system to their interventions based upon his or her process knowledge and experience.

Simulators can be used in a number of ways to support the approaches to training described previously. During the development of the Disturbance inventory using a consensus group, a simulator can be used to generate scenarios, based on those proposed or experienced by the participants and documented in the disturbance diaries.

They can also be used to generate new, potentially high risk scenarios, for which training will have a high potential return if it prevents significant accidents. The simulator can also be used to investigate which types of principle knowledge produce the greatest enhancement in the capability to cope with novel scenarios not previously experienced by operators.

SUPPORTING AND MAINTAINING COMPETENCY

An important practical training issue concerns the possible decline in the capability to handle unusual disturbances over time. Complex cognitive skills such as diagnosis and strategy formulation are known to decline more rapidly over time than simple physical skills. In the case of frequently occurring disturbances which are usually correctly handled, this is unlikely to be a problem. However, in order to remain effective in handling unusual potentially high-risk disturbances, training programmes need to include a specific strategy for maintaining these skills. This issue can be seen as a special case of the more general issue of how disturbance handling skills should be supported in practice. Although competencies acquired from training are an important aspect of successful disturbance management, these need to be combined with external sources of support such as procedures and job aids in order to combat skill loss over time. One of the most powerful tools for supporting competence is the Job Aid. A Job Aid is a method for assisting the operator in retrieving knowledge and skills that may have been acquired previously through training, but which are not invoked sufficiently often to be readily available on demand. A Job Aid usually has considerably less detail than a step by step procedure, since it is designed to support the retrieval of existing knowledge, rather than as a fully detailed documentation of the knowledge itself. A Job Aid for the handling of a blocked compression filter scenario is shown in Figure 1.

The first pane of the Job Aid provides some diagnostic rules for distinguishing between an actual and a spurious blocked filter alarm. The second and third panes set out the required actions once the diagnosis has been performed.

The question of whether disturbance handling should be supported by a job aid or a procedure rather than learnt competency alone, can be addressed by a simple decision process used in the CARMAN (Consensus based Approach to Risk Management) methodology described in Embrey (2005).

The matrix shown in Table 2 indicates the types of support that are appropriate, based on three factors, the frequency with which the situation is likely to arise, the complexity of the scenario and the severity of the consequences if it is handled incorrectly. The reasoning behind the matrix is that the ability to handle disturbances will decline more rapidly over time as the complexity of the disturbance increases. This is partly based on research findings, (Arthur and Bennett, 1998) but is also confirmed by common sense. The capabilities required to handle events that involve complex diagnosis and management strategies to be applied are more likely to be eroded over time than those required for simple situations. The task familiarity dimension refers to the frequency that a situation is encountered. Frequently occurring scenarios provide more opportunities for practice, thus reducing the rate of degradation in the competencies required to handle them. The final factor is a risk based consideration. The more severe the consequences of a scenario, the less reliance there should be on

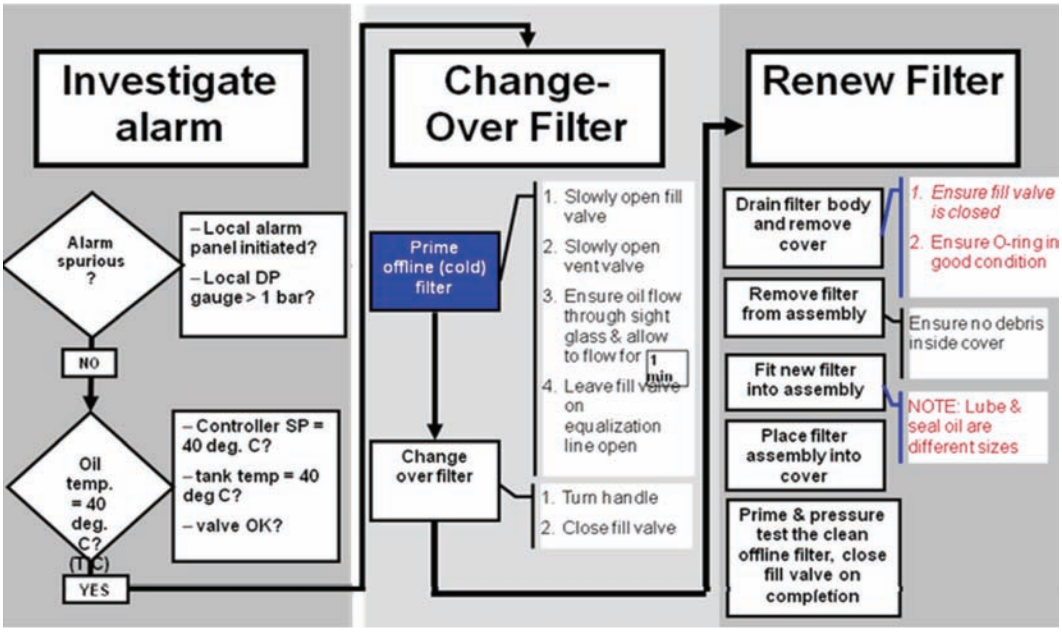

Figure 1. Example of a job aid to support the diagnosis and management of a blocked compressor filter

Table 2. Matrix for specifying level of support required for disturbance handling

Task criticality	Low			Medium			High		
Familiarity	Freq.	Infreq.	Rare	Freq.	Infreq.	Rare	Freq.	Infreq.	Rare
Complexity									
Low	NWI	NWI	NWI	NWI	NWI	JA	NWI	NWI	JA
Med.	NWI	NWI	NWI	NWI	NWI	JA	NWI	JA	SBS
High	NWI	NWI	JA	NWI	JA	SBS	JA	SBS	SBS

No Written Instructions required (NWI)
Job Aid recommended e.g. memory aid, checklist (JA)
Step by Step Instruction recommended (SBS)

competence alone, and the greater the degree of external knowledge, in the form of explicit procedures, should be provided.

The matrix suggests that for the majority of situations encountered by the panel operator, if training is effective, the principle knowledge and rules required for diagnosis and action will probably remain active and hence be readily available from memory. Only for infrequently occurring and more complex situations will it be necessary to provide additional support in the form of a Job Aid. For the most complex situations which are rarely encountered, but for which there are serious consequences if the event is mismanaged, then a detailed step by step procedure is necessary to support competence acquired by training. One caveat needs to be applied to this approach. If the nature of a situation is such that a speed of response is required that would not allow a job aid or step by step procedure to be consulted, then the possibility of providing drills or refresher training to maintain the ability to perform the required actions without recourse to other forms of support needs to be considered. Maintaining an infrequently exercised diagnostic and action capability by frequent drills is likely to be an expensive option. However, this may be the only solution if the severity of consequences of failure to manage the situation is extremely high.

CONCLUSIONS

In this paper, a comprehensive process has been described for ensuring that the training of process plant operators to handle disturbances it undertaken in a systematic manner. The first section provided a critique of the existing informal approach to acquiring expertise in handling process disturbances. An alternative approach was set out, based on ideas from human factors research suggesting that training in both procedural knowledge, in the form of diagnostic and action rules, as well as knowledge of operational principles, was necessary. A training programme was suggested to cover three main areas. The first of these was a process to identify and develop diagnostic and action rules for training purposes. It was proposed that this information was derived partly from diary studies compiled by operators, which documented the strategies developed based on practical experience. It was suggested that this knowledge was combined with other sources of information in a consensus group, which provided a forum for expertise to be evaluated, documented and shared. Suggestions for using both rules and principle knowledge in training were provided, together with the application of training simulators.

The final area discussed was the issue of how to maintain the competency acquired through training over time. A decision process derived from the CARMAN methodology was proposed, which indicated that the types of support for competence were a function of three factors, the severity of failures to diagnose the situation correctly, the frequency of occurrence of the situation, and its complexity. Depending upon the combination of these factors, support for competence could be provided by job aids or more detailed procedures.

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