3

Factors Affecting Human Performance in the Chemical Industry

3.1. INTRODUCTION

In the previous chapter, a comprehensive description was provided, from four complementary perspectives, of the process of how human errors arise during the tasks typically carried out in the chemical process industry (CPI). In other words, the primary concern was with the process of error causation. In this chapter the emphasis will be on the why of error causation. In terms of the system-induced error model presented in Chapter 1, errors can be seen as arising from the conjunction of an error inducing environment, the intrinsic error tendencies of the human and some initiating event which triggers the error sequence from this unstable situation (see Figure 1.5, Chapter 1). This error sequence may then go on to lead to an accident if no barrier or recovery process intervenes. Chapter 2 describes in detail the characteristics of the basic human error tendencies. Chapter 3 describes factors which combine with these tendencies to create the error-likely situation. These factors are called **performance-influencing factors** or PIFs.

In the nuclear power industry the term **performance-shaping factors** (PSF) has been used to describe a similar concept to PIFs (Swain and Guttmann, 1983). The decision to use the alternative term was taken for the following reasons. First, the concept of PSFs has largely been applied in the context of quantifying human error probabilities. In this book, and other applications, PIFs have been used primarily in a qualitative sense, particularly with respect to designing and auditing systems to minimizing the likelihood of error. When used in quantitative risk assesment (QRA). applications (see Chapter 5), the two terms are more or less synonymous. Another reason for using an alternative term is to emphasise the fact that the factors which influence performance in the CPI may be different from those which affect human error in nuclear power systems. This is a similar distinction to probabilistic safety analysis (PSA) used in nuclear power, and quantitative risk assessment (QRA) used in the CPI. Although broadly the same methods are used, there are differences in emphasis.

In general terms, PIFs can be defined as those factors which determine the likelihood of error or effective human performance. It should be noted that PIFs are not automatically associated with human error. PIFs such as quality of procedures, level of time stress, and effectiveness of training, will vary on a continuum from the best practicable (e.g., an ideally designed training program based on a proper training needs analysis) to worst possible (corresponding to no training program at all). When all the PIFs relevant to a particular situation are optimal then performance will also be optimal and error likelihood will be minimized.

It should be noted that, even with optimal PIFs, errors are still possible. There are two reasons for this. Even in the optimal case, some random variability in performance will remain. These random variations correspond to the "common causes" of process variability considered in statistical process control. Variations in PIFs correspond to the "special causes" of variability considered within the same framework.

Taking the hardware analogy further, PIFs can be seen as corresponding to the design, operational, and maintenance factors which affect the reliability of hardware equipment. The reliability of a pump, for instance, will be influenced by a number of factors such as:

- Type and temperature of liquid processed
- Presence of safety devices (e.g., nonreturn valves, remotely operated isolation valves)
- Any power supply problems
- Effectiveness of maintenance
- Environmental conditions (e.g., presence of corrosive vapors)
- Operational problems (e.g., allowing the pump to run against a closed delivery valve)

It is important, however, not to take this analogy too far. In general, the performance of a piece of hardware, such as a valve, will be much more predictable as a function of its operating conditions than will human performance as a function of the PIFs in a situation. This is partly because human performance is dependent on a considerably larger number of parameters than hardware, and only a subset of these will be accessible to an analyst. In some ways the job of the human reliability specialist can be seen as identifying which PIFs are the major determinants of human reliability in the situation of interest, and which can be manipulated in the most cost-effective manner to minimize error.

Further links exist between the PIF concept and topics considered in previous chapters. In Chapter 2 the sequential model developed by Rasmussen to represent the error process from its initiator to its consequences was described (Figure 2.9). In this process, the PIFs were shown as being involved in both the initiating event and the internal error mechanisms. In the application example of the model in Appendix 2C, the PIF which constituted the initiating event was the distracting environment, and poor ergonomics of the panel was a PIF which influenced the internal error mechanism.

Another link exists between the PIF concept and the sociotechnical assessment methods described in Section 2.7 The checklists used in the TRIPOD methodology are essentially binary questions which evaluate whether the sets of PIFs making up each of the general failure types are adequate or not. The hierarchical sets of factors in HRAM are essentially PIFs which are expressed at increasingly finer levels of definition, as required by the analyst. The audit tool which forms MANAGER also comprises items which can be regarded as PIFs which assess both management level and direct PIFs such as procedures.

In the nex⁺ section of this chapter, some application areas for PIF analyses will be described. This will be followed by a classification scheme for PIFs based on the demand–resource mismatch model of error described in Chapter 1, Section 1.6. Subsequent sections will describe each of the PIF categories in turn, followed by examples where appropriate. These sections are followed by a discussion of the effects of interactions between PIFs and the implications of high levels of stress in emergencies for human performance.

3.2. APPLICATIONS OF PERFORMANCE INFLUENCING FACTORS

In subsequent sections the application of PIFs to various aspects of error reduction will be described. One of the most important of these applications is the use of comprehensive lists of PIFs as a means of auditing an existing plant to identify problem areas that will give rise to increased error potential. This is one aspect of the proactive approach to error reduction that forms a major theme of this book. This application of PIFs can be used by process workers as part of a participative error reduction program. This is an important feature of the human factors assessment methodology (HFAM) approach discussed in Section 2.7.

Another application area is the use of PIFs as part of the process of incident investigation. Any investigation which seeks to establish the underlying causes of minor or major incidents will benefit from a systematic framework for evaluating the factors which can contribute to the human contribution to such incidents. This topic will also be discussed in Chapter 6.

Performance-influencing factors analysis is an important part of the human reliability aspects of risk assessment. It can be applied in two areas. The first of these is the qualitative prediction of possible errors that could have a major impact on plant or personnel safety. The second is the evaluation of the operational conditions under which tasks are performed. These conditions will have a major impact in determining the probability that a particular error will be committed, and hence need to be systematically assessed as part of the quantification process. This application of PIFs will be described in Chapters 4 and 5.

The PIF concept is also useful during the process of design. Design guidelines to maximize the usability of plant and to minimize the potential for error can be based upon comprehensive descriptions of PIFs such as the factors which determine the most effective presentation of information in control rooms, or the characteristics of usable and clear operating instructions.

For some applications, for example, human reliability analysis, a situation needs to be rated on a numerical scale. In these cases, values such as those shown in the left-hand column of Table 3.1 can be generated by comparing the situation being evaluated with the descriptions in the second, third, and subsequent columns which represent other PIFs relevant to the situation being assessed. These represent the worst, average, and best conditions that are likely to occur in chemical plants in general and correspond to ratings of 1, 5, and 9 on the numerical scale in the left hand column of Table 3.1. Obviously,

TABLE 3.1
Examples of PIF Scales

PIF EVALUATION SCALE (QUALITATIVE AND QUANTITATIVE)	PROCEDURES	PHYSICAL WORK ENVIRONMENT
WORST 1	• No written procedures, or standard way of performing tasks • Not integrated with training	• High levels of noise • Poor lighting • High or very low temperatures and high humidity or wind chill factors
AVERAGE 5	• Written procedures available, but not always used • Standardized method for performing task	• Moderate noise levels • Temperature and humidity range
BEST 9	• Detailed procedures and checklists available • Procedures developed using task analysis • Integrated with training	• Noise levels at ideal levels • Lighting design based on analysis of task requirements • Temperature and humidity at ideal levels

it is possible to interpolate among these values for situations that are intermediate between the descriptions provided.

Unlike the hardware component in a system, human performance is much more variable and difficult to predict. The same combination of input conditions will produce nearly similar effects on hardware. This is not the case for humans who will process the inputs in the light of their intentions and biases in a unique manner.

3.3. A CLASSIFICATION STRUCTURE FOR PERFORMANCE-INFLUENCING FACTORS

The classification structure for PIFs used in this chapter is based on the model of human error as arising from a mismatch between demands and resources which was described in Chapter 1, Section 1.6 (Figure 1.6). In this model demands were seen as requirements for human performance which arise from the characteristics of the process environment (e.g., the need to monitor a panel or to be able to fix a seal in a flange) and the nature of the human capabilities to satisfy these demands (e.g., skills of perception, thinking, and physical action). These demands are met by the individual and group resources of personnel and the extent to which the design of the task allows these resources to be effectively deployed. Where demands exceeded resources, errors could be expected to occur.

In terms of the model, both demands and resources could be influenced by management policy. Demands can be set to fall within the range of human capabilities by ensuring that correct allocations of function are made between humans and machines (including computers). Resources can be maximized by optimizing the PIFs in the situation. This model provides a useful basis for classifying PIFs, since it implies that at least three categories of PIFs need to be considered, those relating to demands, resources, and policies.

As can be seen from Table 3.2, the classification scheme divides PIFs into four major groups and twelve intermediate categories (the numbering system corresponds to the sections in this chapter). The first group addresses those factors related to the chemical and work environment within which the task is carried out such as process hazards, novelty of events, time shortage, lighting, noise, work hours, shift rotation and others. The second group comprises those associated with the workers and their interaction with their tasks including design of control panels and equipment, job aids, procedures, and training. The third group concerns individual characteristics of the workers such as operating experience, personality traits, health, and age. The final group comprises the organizational and social environment and includes topics such as teamwork and communications, safety policies, design policies, systems of work, and others that affect human performance in an indirect manner.

TABLE 3.2

A Classification Structure of Performance Influencing Factors

3.4 OPERATING ENVIRONMENT	3.5 TASK CHARACTERISTICS
3.4.1 Chemical Process Environment 3.4.1.1 Frequency of Personnel Involvement 3.4.1.2 Complexity of Process Events 3.4.1.3 Perceived Danger 3.4.1.4 Time Dependency 3.4.1.5 Suddenness of Onset of Events **3.4.2 Physical Work Environment** 3.4.2.1 Noise 3.4.2.2 Lighting 3.4.2.3 Thermal Conditions 3.4.2.4 Atmospheric Conditions **3.4.3 Work Pattern** 3.4.3.1 Work Hours and Rest Pauses 3.4.3.2 Shift Rotation and Night Work	**3.5.1 Equipment Design** 3.5.1.1 Location/Access 3.5.1.2 Labeling 3.5.1.3 Personal Protective Equipment **3.5.2 Control Panel Design** 3.5.2.1 Content and Relevance of Information 3.5.2.2 Identification of Displays and Controls 3.5.2.3 Compatibility with User Expectations 3.5.2.4 Grouping of Information 3.5.2.5 Overview of Critical Information and Alarms **3.5.3 Job Aids and Procedures** 3.5.3.1 Clarity of Instruction 3.5.3.2 Level of Description 3.5.3.3 Specification of Entry/Exit Conditions 3.5.3.4 Quality of Checks and Warnings 3.5.3.5 Degree of Fault Diagnostic Support 3.5.3.6 Compatibility with Operational Experience 3.5.3.7 Frequency of Updating **3.5.4 Training** 3.5.4.1 Conflicts between Safety and Production Requirements 3.5.4.2 Training in Using New Equipment 3.5.4.3 Practice with Unfamiliar Situations 3.5.4.4 Training in Using Emergency Procedures 3.5.4.5 Training in Working with Automatic Systems

3.6 OPERATOR CHARACTERISTICS	3.7 ORGANIZATION AND SOCIAL FACTORS
3.6.1 Experience 3.6.1.1 Degree of Skill 3.6.1.2 Experience with Stressful Process Events **3.6.2 Personality Factors** 3.6.2.1 Motivation 3.6.2.2 Risk-Taking 3.6.2.3 Risk Homeostasis Theory 3.6.2.4 Locus of Control 3.6.2.6 Emotional Control 3.6.2.6 Type "A" versus Type "B" **3.6.3 Physical Condition and Age**	3.7.1 Teamwork and Communications 3.7.1.1 Distribution of Workload 3.7.1.2 Clarity of Responsibilities 3.7.1.3 Communications 3.7.1.4 Authority and Leadership 3.7.1.5 Group Planning and Orientation **3.7.2 Management Policies** 3.7.2.1 Management Commitment 3.7.2.2 Dangers of a "rule book" Culture 3.7.2.3 Overreliance on Technical Safety Methods 3.7.2.4 Organizational Learning

It should be emphasized that the PIFs considered in this chapter, although generally considered important by human reliability specialists, are not meant to be exhaustive in their coverage. Other selections, such as those considered by the methods such as TRIPOD and HFAM (Chapter 2), are possible. It is recommended that the advice of an experienced human reliability or human factors specialist is sought when deciding which PIFs should be covered in a specific situation.

3.4. OPERATING ENVIRONMENT

There are three elements of the operating environment which play a crucial role in human reliability, namely:

- **The chemical process environment** which refers to the complexity and novelty of the process events, their perceived danger, and the imposed time constraints on the workers
- **The physical work environment** which includes conditions of lighting, thermal conditions, atmospheric conditions and noise levels
- **The patterns of work** such as work hours and pauses, night work and shift rotation

3.4.1. Chemical Process Environment

All of these factors determine the stress experienced by the workers and the extent to which operational errors will be recovered before disastrous consequences have ensued. In this context, hazard identification techniques, such as hazard and operability studies (HAZOP), failure modes and effects and criticality analysis (FMECA), fault trees, and others are useful in making the process environment more forgiving.

Throughout these guidelines it is argued that when engineering techniques for the design and assessment of process equipment and control systems are supplemented with human reliability techniques, then performance of both the hardware and humans will be optimized.

A characteristic of the PIFs that follow is that although they may not affect performance in a direct manner, they may interact with other factors such as inadequate procedures, training, and worker experience to give rise to errors.

3.4.1.1. Frequency of Personnel Involvement

The frequency with which a task is performed or a process event has been dealt with in the past, affects the likelihood of success. Process skills that are not frequently practiced (e.g., for tasks that are only required on an irregular basis), may not be retained adequately and performance can deteriorate. Whether or not this deterioration will give rise to a significant error will depend on other factors which will be described in later sections such as refresher training, detailed procedures and so on.

Performance problems may be exacerbated during unfamiliar or novel process events, for example, situations not covered in the emergency procedures or in refresher training. These events require knowledge-based information processing for which people are not very reliable. The types of errors associated with knowledge-based performance have been discussed in Chapter 2.

3.4.1.2. *Complexity of Process Events*

Apart from the degree of novelty of a process event, its complexity (e.g., the range of operations to be carried out), the interrelationships of the process variables involved and the required accuracy, will affect performance. Start-up and shutdown operations are examples of tasks which, although are not entirely unfamiliar, involve a high degree of complexity.

3.4.1.3. *Perceived Danger*

One of the most serious stressors to personnel working in many chemical processes is the perception of danger by the workers arising from ineffective control and supervision of these systems. Despite the fact that modern plants are equipped with automated protection systems, there is always some perception of potential risk in their operation. Serious threats can be posed not only for those within the plant, but also for the neighboring public. An environment that is perceived as being highly dangerous will increase the stress experienced by the workers and may have a detrimental effect on their performance.

3.4.1.4. *Time Dependency*

Time dependency refers to the time available to cope with a process event. Time pressure is a well-known stress factor which affects human performance. Here, the time response of plant equipment and chemical processes will determine the time available to respond to an incident.

3.4.1.5. *Suddenness of Onset of Events*

In a process disturbance, the suddenness of the onset of the event will also play a significant role in human performance. This category refers to the time required for the process symptom to develop to the extent that it becomes detectable by the workers. If the symptom develops gradually, this leaves some scope for the workers to switch to a high mode of alertness. This allows them to develop an adequate mental model (see Chapter 2) of the process state. If an adverse condition develops extremely slowly it may not be detected by workers, particularly if its development spans more than one shift.

3.4.2. Physical Work Environment

The next four PIFs (noise, lighting, thermal conditions, atmospheric conditions) refer to the quality of the worker's environment. In general, if the quality of these factors is poor, they may cause anxiety and fatigue which may result in errors. Some of these stressors, such as noise and heat, produce psychological as well as physiological effects on performance. Even moderate levels of such stressors in the control room can interfere with task performance because workers can be distracted, lose concentration, and become irritated. Working under these stressors means that more work and more attentional and memory resources will have to be expended on each individual action. The existence of such stressors can also indicate a lack of management concern for the well being of the workers which can increase unsafe behavior.

Most of the research on the effects of these stressors on human performance has been done on simple laboratory tasks rather than actual work situations. As a result, the extent that such findings can carry over to tasks in the CPI is debatable. In addition, most of these studies have examined the effect of a single stressor (e.g., noise or heat) only, rather than the combined effect. Nevertheless, some useful guidelines about optimal levels of these stressors are available in the ergonomics literature (e.g., McCormick and Sanders, 1983; Salvendy, 1987).

3.4.2.1. Noise

The effects of noise on performance depend, among other things, on the characteristics of the noise itself and the nature of the task being performed. The intensity and frequency of the noise will determine the extent of "masking" of various acoustic cues, i.e. audible alarms, verbal messages and so on. Duration of exposure to noise will affect the degree of fatigue experienced. On the other hand, the effects of noise can vary on different types of tasks. Performance of simple, routine tasks may show no effects of noise and often may even show an improvement as a result of increasing worker alertness.

However, performance of difficult tasks that require high levels of information processing capacity may deteriorate. For tasks that involve a large working memory component, noise can have detrimental effects. To explain such effects, Poulton (1976, 1977) has suggested that "inner speech" is masked by noise: "you cannot hear yourself think in noise." In tasks such as following unfamiliar procedures, making mental calculations, etc., noise can mask the worker's internal verbal rehearsal loop, causing work to be slower and more error prone.

Another effect of noise on tasks involving monitoring and interpretation of a large number of information sources is the "narrowing of the span of attention." In a noisy environment, personnel monitoring the control panel would tend to concentrate on the most obvious aspects of the situation which seem to be familiar to them and fail to incorporate any novel features of the situation. Apart from causing distractions and communication difficulties, permanent exposure to a noisy environment may reduce any opportunities for social interaction and thus make the job more boring.

3.4.2.2. *Lighting*

Apart from physical discomfort and irritation, poor lighting can induce errors in reading valve labels or instruments on the control panel. Direct or reflected glare can be another problem in many work situations. Having to avoid the glare may constitute another task the worker has to perform, which can divert him or her from the primary job responsibility.

Example 3.1. Effects of Glare

Swain and Guttmann (1983) cite an incident in which the problem of glare had been so severe that the workers disconnected many of the lamps, with the result that a flashlight was considered a standard accessory for reading certain displays.

3.4.2.3. *Thermal Conditions*

The effect of high or low environmental temperature on skilled performance is important for industrial or service personnel. Operators often have to work in extreme thermal conditions, such as in furnaces or when they need to operate a pump in cold weather at night. Errors of omission are quite often due to the workers trying to minimize the time period they have to be exposed to high or low temperatures. Particular emphasis has been placed on the effects of cold on manual performance. Cold can affect muscular control, reducing such abilities as dexterity and strength.

Experience and familiarity with the task will affect the relationship between temperature and performance. Experience and practice will make performance largely skill based, and therefore, more resistant to impairments due to high temperatures. This explains why unskilled workers are affected more adversely when they have to work in extreme heat.

3.4.2.4. *Atmospheric Conditions*

Many operations may expose the workers to dust, fumes, gases, etc., and apart from causing personnel injuries these may lead to human errors. This is because protective clothing and apparatus is usually uncomfortable. Attempts to get the job finished quickly may therefore result in errors.

3.4.3. Work Pattern

Two important work pattern PIFs are the duration of work hours and rest pauses, and the type of shift rotation.

3.4.3.1. Work Hours and Rest Pauses

On many occasions, long hours of work are required because the worker may have to stay on duty at the end of the shift to fill in for someone on the next shift or because there are plant start-up or shutdown operations.

In some plants, workers voluntarily request 12-hour shifts in order to benefit from the long periods away from the job that this regime brings. However, on the basis of everyday experience one would expect the fatigue arising from prolonged work to give rise to performance decrements and errors. In this section we will review the evidence on this question from two perspectives: sleep loss and sleep disturbance and prolonged working hours.

Sleep Loss and Sleep Disturbance

The effects of acute sleep deprivation where subjects are deprived of sleep over successive days have been studied extensively. Research findings have demonstrated clear decrements in psychological performance and resulting behavioral impairments (see Froberg, 1985 for an overview). In particular, tasks of 30 minutes or more in duration; low in novelty, interest, or incentive; or high in complexity have been shown to deteriorate in a situation of prolonged work duty and no sleep. Memory has also been found to be affected in people who are required to stay awake (Wilkinson, 1964). However, such effects are reversed with only 1 to 2 nights of recovery sleep even in the longest deprivation studies.

The effects of chronic sleep deprivation or cumulative minor sleep losses have been relatively under investigated. Little is known about the relationships among the size of the sleep deficit, its rate of accumulation, the amount and timing of optimum recovery sleep, and their effect on human performance and productivity.

Those studies of partial sleep deprivation that have been carried out show that people can tolerate a degree of sleep loss and are able to keep up their performance level with sleep periods shorter than normal. The limit of tolerance for prolonged spells of reduced sleep seems to be around 4–5 hours of sleep per day. This seems to represent an obligatory quota. Providing this quota can mostly be reclaimed or retained, it is possible for psychological performance and day time tiredness to be maintained at normal or near normal levels. However, this depends on subjects maintaining a regular sleep schedule. People who are forced to take less sleep but who cannot maintain sleep regularity will have increased difficulty because of insufficient time to adapt.

In conditions of acute sleep deprivation, "microsleeps" will occur more and more often. These very short sleeps do not have the recuperative value of normal sleep, and the sleep-deprived person still feels sleepy and performance still degrades even though there may be a large number of microsleep periods.

The Effects of Prolonged Working Hours

Extended working weeks of 60 hours or more were common in the nineteenth century, but for much of the twentieth century the norm has been a 5-day/40-

hour working week. Inevitably much of the work related to the productivity and performance implications of extended working hours stems from studies carried out in atypical periods such as during and immediately following both world wars. Allusi and Morgan (1982), in their review of temporal factors in human performance and productivity, summarized the result of many of these early studies. The overall conclusion reached was that improvements in industrial productivity have generally been found following reductions in the total hours of work in both the work day and work week.

This increase in productivity is accounted for partly by a decrease in absenteeism and accidents as well as a general increase in working efficiency. For example, Vernon (1918), found that when women in a munitions factory worked a 12-hour day they incurred 2.5 times more accidents than when they worked a 10-hour day. One of the more comprehensive studies of the effects of total hours of work was carried out after World War II by the U.S. Department of Labor (Kossoris and Kohler, 1947). This covered over 3500 men and women in 78 work units. Data were collected on accidents and absenteeism as well as productivity. The overall findings were that exceeding the 8-hour work day, 5 days/40 hours work week resulted in lower productivity and higher absenteeism and accident rates.

Such historical evidence is always vulnerable to methodological criticisms. However, following the fundamental shift in working practice which subsequently occurred, such studies represent the only significant body of field studies which have assessed the repercussions of prolonged working hours in an industrial setting. Some more recent studies looking at the work of, for example, hospital doctors have reported on sleep loss and the effects of long hours of work. Studies such as that of Folkard and Monk (1985) which examined self-reports of work impairment show that a considerable percentage of junior doctors who responded (over one-third) felt that their ability to work with adequate efficiency was impaired by the long hours of duty. Objective tests of performance such as those used by Poulton (1978), again looking at hospital doctors, show less conclusive results. It is also difficult to generalize findings from such a highly specific work situation to other types of working environments.

The desirability of the standard 8-hour work day and 5-day/40-hour work week is currently being questioned in response to both economic and commercial pressures and worker preference for greater flexibility and leisure time. A variety of alternative schedules are now available and their introduction has led to a renewed interest in the effects of extended working times. In particular, these more recent studies have provided some further insights into the performance effects of long work days. For example, recent work by Rosa et al. (1986) has examined the effects of the introduction of the 12-hour day compressed work week. The principle underlying this schedule is to shorten the work week to 3 or 4 days by increasing the length of the work shift to 12 hours. However, there are persistent concerns about feelings of increased fatigue associated with long work days. Moreover, such concerns are supported by laboratory and worksite (Volle et al., 1979) comparisons of 8-hour and 12-hour days.

Rosa et al. (1986) evaluated changes in a range of variables associated with a switch from an 8-hour shift schedule with three rotations to a 12-hour shift schedule with two rotations. The workers involved were control room operators at a continuous processing plant. The authors report that, after 7 month's adaptation to the new schedules there were decrements in the tests of performance and alertness (National Institute of Occupational Safety and Health, NIOSH Fatigue Test Battery) attributable to the extra 4 hours of work per day. There were also reductions in sleep and disruption of other personal activity during 12-hour work days. In summary however, the study concludes that there have only been a few direct evaluations of the effects of long work days on individual functioning. Those that do exist have provided some suggestions of accumulated fatigue across a number of long work days. The overall conclusion is nevertheless that substantive further work is needed to clarify the performance effects of long work days.

Effects of Fatigue on Skilled Activity
"Fatigue" has been cited as an important causal factor for some everyday slips of action (Reason and Mycielska, 1982). However, the mechanisms by which fatigue produces a higher frequency of errors in skilled performance have been known since the 1940s. The Cambridge cockpit study (see Bartlett, 1943) used pilots in a fully instrumented static airplane cockpit to investigate the changes in pilots" behavior as a result of 2 hours of prolonged performance. It was found that, with increasing fatigue, pilots tended to exhibit "tunnel vision." This resulted in the pilot's attention being focused on fewer, unconnected instruments rather than on the display as a whole. Peripheral signs tended to be missed. In addition, pilots increasingly thought that their performance was more efficient when the reverse was true. Timing of actions and the ability to anticipate situations was particularly affected. It has been argued that the effects of fatigue on skilled activity are to regress to an earlier stage of learning. This implies that the tired person will behave very much like the unskilled operator in that he has to do more work, and to concentrate on each individual action.

Conclusions on Work Hours and Rest Pauses
In interpreting the above research findings it is important to consider a number of additional points.

- Most sleep deprivation experiments have used mentally and physically healthy young adults. For other types of individuals, particularly older people for whom the sleep function deteriorates in general, and also for "real world" conditions, sleep deprivation may be more significant.

- Fatigue effects associated with a long working day has been identified in the context of a 4 day week.
- Little is known about the cumulative effects of factors such as prolonged working hours and extra mural demands on workers and how such demands interact with workers performance reserves and productivity.

It is likely that a person experiencing fatigue over a long period of time would develop strategies to cope with the effects on his or her performance. Such coping strategies could include:

- Working more slowly
- Checking the work more thoroughly
- Using more memory "reminders"
- Relying on fellow workers
- Choosing to carry out less critical tasks

However, such strategies are vulnerable to additional factors such as increased time pressure, and working alone. The combined influences of such factors may be more important than each negative factor in isolation.

3.4.3.2 Shift Rotation and Night Work

There are two concerns about the effects of shift rotation and night work: disruption of "circadian rhythms" and sociological costs, that is, effects on the worker's family life.

The term *circadian rhythms* refers to variations in certain physiological variables (e.g., body temperature) over the 24-hour cycle. Individuals who are "day adjusted," that is, who are active and asleep during the normal periods of day and night, exhibit the characteristic variations of body temperature shown by the dark graph in Figure 3.2. Similar variations occur in psychological functions such as activation (see Chapter 2, Section 2.3.3) and self-estimates of alertness (shown by the light graph in Figure 3.2). These estimates are generated by asking subjects to rate how alert they feel by marking a scale between the range "almost asleep" and "fully alert." Figure 3.2 indicates the close relationship between body temperature and alertness. When individuals work on continuous night shifts for a protracted period, the circadian cycle gradually changes so that the peaks of body temperature and alertness tend to occur at night when the worker is active.

With regard to the effect of circadian cycles on performance, most studies have been carried out using individuals such as nurses or airline pilots, whose work involves shifts or the crossing of time zones. One study that specifically addressed process workers was carried out by Monk and Embrey (1981). In this study the body temperatures of six "day adjusted" workers working on a batch chemical plant were recorded over a one-month period of plant operations. The average temperature variations are shown in Figure 3.1, together with the workers" self-ratings of their alertness.

Research on circadian rhythms has generally indicated that performance on mental tasks broadly follows the same pattern of variations as body temperature and alertness. However, other work suggests that in fact this is only the case for mental tasks requiring little information processing capacity. For more complex "cognitive" tasks where working memory is more important, variations in performance are in the opposite phase to body temperature; that is, best performance, occurs when the body temperature is low (i.e., at night). This hypothesis was tested by asking the workers to perform two types of memory-based test every 2 hours. One test, the 2-MAST (memory and search test) involved a low memory load whereas the other (6-MAST) required a much greater memory load. These tests both involve the mental manipulation of numbers. The larger the sets of numbers, the greater will be the memory load. To some extent the tests mimic the mental demands of process control tasks of differing complexity. Performance on the tests is measured by the length of time they take to perform, better performance being indicated by a shorter time. Figure 3.3 confirms the predictions by indicating that performance on the 6-MAST (high memory load) was in opposite phase to the circadian body temperature cycle, whereas the performance on the low memory load task closely followed variations in body temperature.

The applicability of these findings for actual operational tasks was evaluated by considering the incidence of data entry errors recorded by the on-line plant computer system over the 24-hour shift cycles. It was judged that the data entry task, which involved evaluating the set point changes needed for

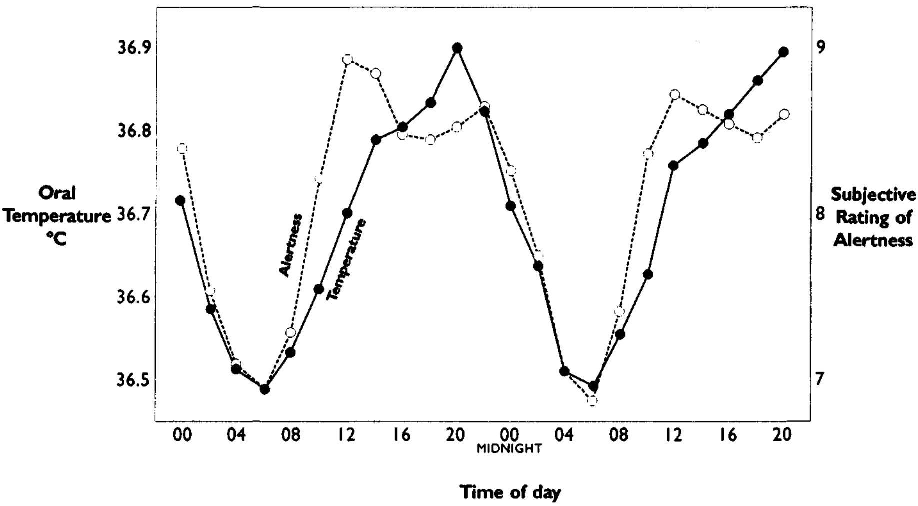

FIGURE 3.1. **Circadian Variations in Oral Temperatures and Alertness for Six Process Workers (Monk and Embrey, 1981).**

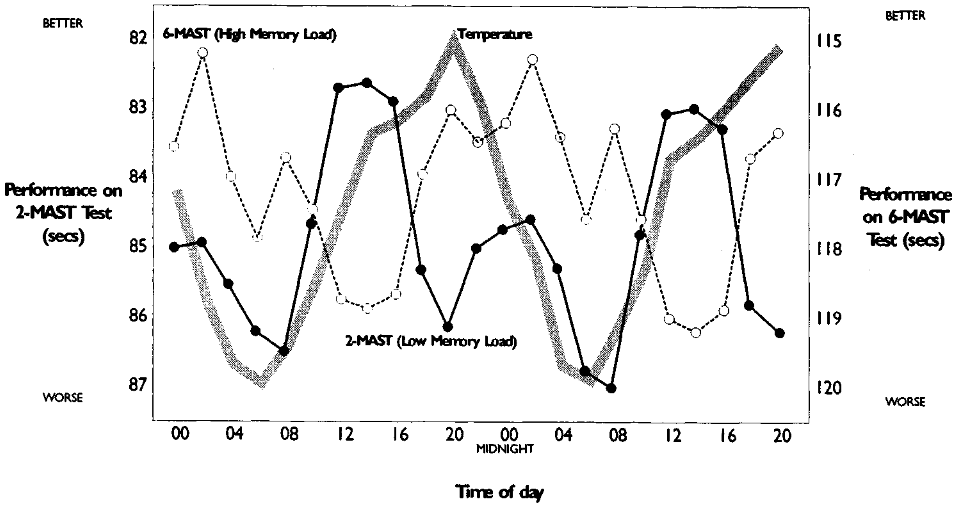

FIGURE 3.2. **Circadian Variations in Performance on High- and Low- Memory Load Tasks (adapted from Monk and Embrey, 1981).**

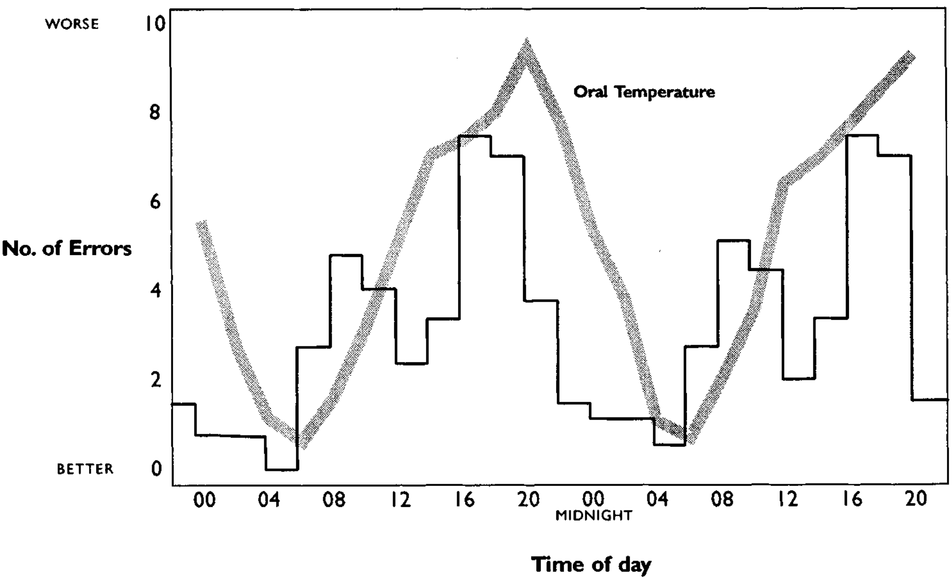

FIGURE 3.3. **Circadian Variations in Errors Made by Process Workers Compared with Body Temperature Changes (adapted from Monk and Embrey, 1981).**

the process and then entering these set points into the database, was a high memory load "cognitive" task. The results of the error evaluation, plotted in Figure 3.3, show that the variation in error rates follows the same temporal pattern as performance on the 6-MAST test shown in Figure 3.3 (this correlation was statistically significant) and is an opposite phase to variations in body temperature. (Note that the scales in Figure 3.3 are in the opposite direction to those in Figure 3.2, since more errors indicate worse performance). This appears to confirm the prediction that high memory load cognitive tasks would have lower error rates at night (for day adjusted workers).

The practical implications of this experiment are that when evaluating the effects of shift work due to circadian effects, the type of task being carried out by the worker must be taken into account. For example, skill-based tasks would be expected to exhibit the performance changes characteristic of low memory load tasks, whereas performance variations in knowledge-based tasks would be expected to follow the pattern of high memory load tasks. Performance on rule-based tasks may depend on the degree of frequency of use of the rules, which in turn may determine the memory load. If these results were confirmed by further process plant studies, it would have implications for when different types of operation (involving different levels of memory load) should be scheduled to reduce circadian rhythm effects and minimize errors.

Studies by Smith et al. (1982), Folkard et al. (1979), and Colquhoun et al. (1969), have investigated the disruption of circadian rhythms caused by having to be awake and work at unusual hours and by having to sleep during daytime. With respect to the sociological effects, studies by Kasl (1974) and Kahn (1974) concluded that fixed afternoon and night shifts lead to lower levels of social satisfaction because it becomes difficult to participate in family activities.

With regard to the scheduling of shift work, the general recommendation (putting aside social and lifestyle considerations) is that shifts should allow workers to either remain day or night adjusted. This is because it is the constant readjustment of circadian cycles which appears to produce the most acute feelings of fatigue and disorientation. This implies that permanent night or day shifts will be the most effective (In a union environment, where seniority provisions could lead to inexperienced operators being concentrated on the afternoon or evening shifts, there could be an offsetting problem of fixed shifts to rotating shifts.) Failing this, shifts should be operated over a sufficiently short cycle that they allow the operating team to remain day adjusted. However, it must be emphasized that determining optimal shift work regimes is a highly complex and controversial area of research. Comprehensive reviews of the state of the art are available in Folkard and Monk (1985) and Monk and Folkard (1991).

3.5. TASK CHARACTERISTICS

This section addresses aspects of the task which influence human reliability in both control-room and field operation situations. It includes the physical equipment to be used, control panels, job-aids and procedures, and the type of training provided.

3.5.1. Equipment Design

Plant equipment should have good access and controls and instruments should be clearly labeled. Under this category protective clothing and other equipment to enable safe operation is also included.

3.5.1.1. Location/Access

Process workers often complain that valves are inaccessible. Emergency valves should always be readily accessible but other valves, if they are operated, say, once a year or less often, can be out of reach. It is reasonable to expect workers to get a ladder or scramble into a pipe trench at this frequency. Designers should remember that if a valve is just within reach of an average person then half of the population cannot reach it. Equipment should be placed such that at least 95% of the population can reach it. Guidance on specific measurements to achieve this objective is available in a number of standard human factors textbooks (see Bibliography).

3.5.1.2. Labeling

Many incidents have occurred because equipment was not clearly labeled. Some have already been described in Section 1.2. Ensuring that equipment is clearly and adequately labeled and checking from time to time to make sure that the labels are still there is a dull job, providing no opportunity to exercise many technical and intellectual skills. Nevertheless, it is as important as more demanding tasks.

3.5.1.3. Personal Protective Equipment

The design and the enforcement of personal protective equipment can play the key role of protecting the worker from exposure to hazardous conditions. Such equipment includes goggles, gloves, breathing apparatus, helmets, earplugs, safety shoes, safety belts, and so forth. Standards for the design and performance of protective equipment are specified by regulatory agencies such as the National Institute for Occupational Safety and Health (NIOSH). A comprehensive overview of the human factors aspects of personal protection equipment is provided by Moran and Ronk (1987).

Many incidents are caused by the process workers not bothering to wear safety equipment or removing it during an operation. In these cases, blaming the worker is not necessarily appropriate, since a number of other factors may be held responsible, such as the difficulty of carrying out certain jobs when wearing safety equipment, or a work permit approach which emphasizes the use of equipment even for safe areas (see Examples 1.21 and 1.22)

3.5.2. Control Panel Design

The term control panel refers to the instrumentation console in a central control room through which process information is communicated to the process worker and via which the worker changes the state of the process. This category includes display elements such as chart recorders, bar indicators, dials, and modern VDU-based systems together with control elements such as buttons, switches, track balls and mice. The control panel is the human–machine interface (see Chapter 2) that has traditionally received the most attention from human factors specialists.

The content and organization of the displayed information are of critical importance in inferring the state of the process and subsequently evaluating the effects of alternative courses of action. The following factors will determine the demands of the control panel on the attentional and memory resources of the workers. For detailed data on the design of the control panel, the reader is referred to standard ergonomics textbooks (e.g., Salvendy, 1987).

3.5.2.1. Content and Relevance of Information

The first questions to be considered when designing a control panel are what information is required and how much of it will be appropriate. Too little information may increase the amount of inference that the worker is required to make to predict the state of process parameters that are not directly displayed. This is especially important for emergency situations where the human information processing system is taxed heavily with many tasks. On the other hand, too much redundant information can overload the worker. It is essential, therefore, that the information needs of the worker are identified through some form of task analysis and worker interviews.

The relevance of the information to the process worker is another factor in design. This principle is often violated with the introduction of new VDU-based computer systems where information needed to assist computer scientists or production managers is mixed with information relevant for the safe operation of the plant. Clearly, some kind of structuring and prioritization will be necessary for the different users of the system.

3.5.2.2. Identification of Displays and Controls

The issue of how controls and displays are identified on a control panel is usually referred to as coding. In the case of controls this can be achieved by techniques such as labeling, color, shape, location, or size. The relationship between displays and controls needs to be carefully considered. Comprehensive recommendations for displays and controls are available in Salvendy (1987).A recurring problem in many process plants concerns the lack of demarcation lines for the tolerance limits of various critical parameters. Workers need to know how rapidly a parameter is moving toward its tolerance limits in order to understand the urgency of the situation.

3.5.2.3. Compatibility with Personnel Expectations

Compatibility refers to the degree of similarity between the direction of physical movement of a control or an instrument indicator and the worker's expectations. Many errors are due to the fact that the operation of the controls or the layout of the displays is incompatible with population stereotypes. For instance, on a control panel it is customary to increase the value of a parameter by turning the appropriate switch clockwise and reduce its value by turning it counterclockwise. (Note that this stereotype is the opposite for controls which control flow directly, e.g., valves.) If such a stereotype is violated, errors may occur. Although such errors may be recoverable in the short run, under the stress of a process transient they may lead to serious consequences.

Example 3.2. Design Fault Leading to Inappropriate Worker Expectations

In the Three Mile Island power plant, the light of the pilot operated relief valve (PORV) status indicator was designed to come on when an electrical signal was transmitted to the valve to open, and go out when a signal was transmitted for the valve to close. When the worker pushed the button to close the valve, the signal was transmitted but it was not received by the valve due to an electrical fault. As a result the light went out, but the valve remained open. For two hours, the workers were under the impression that this valve was closed, which resulted in radioactive coolant discharging from the reactor circuit. This design violated the worker's expectation that the light would indicate the status of the valve and not that of the signal. Similar incidents have been described in Examples 1.16 and 1.17

3.5.2.4. Grouping of Information

This factor refers to the spatial organization of the information displays. In general, instruments displaying process parameters that are functionally related should also be physically close. In this way, it is likely that a given fault will lead to a symptom pattern that is easier to interpret than a random distribution of information. Although violation of this principle may not induce errors in a direct manner, it may hinder human performance. The following example illustrates this point.

Example 3.3. Poor Control Panel Design Causes Lack of Diagnosis

In a power plant a failure of the steam regulator in the turbine gave rise to a high pressure profile in the three condensers downstream. Previously, one of the three cooling water pumps had failed, activating a high pressure alarm in the affected condenser. The crew did not notice the pattern of pressure rise in all three condensers (which was rapid, large, and of a similar amplitude) and thus failed to diagnose the latent failure in the steam regulator. A careful examination of the displays showed that two 2-channel recorders were used instead of one 3-channel recorder, making it difficult to perceive the dynamics of the pressure rise. Second, the steam regulator display was positioned in a different section of the panel to that showing the condenser system. This made it less likely that any deviation would be detected through the normal strategy of checking related subsystems.

3.5.2.5. Overview of Critical Information and Alarms

With the increasing complexity of plants, overview displays of critical process information and alarms can be very useful particularly for plant disturbances. In this regard, several investigators (Goodstein, 1982; Woods et al., 1981) have advocated the concept of the integrated or polar display which can be implemented on modern computer-based systems. The different radial scales are adjusted so that normal operation is represented by a normal geometric shape, while departures indicate distortions. This type of display capitalizes on human "pattern recognition" capabilities and can support early detection of abnormal process states.

3.5.3. Job Aids and Procedures

3.5.3.1. Introduction

As process plants become more complex, it becomes apparent that it is not possible to rely exclusively on the process worker's skills and memory required to perform the task. Job aids and procedures are devices which aim to reduce the need for human retention of procedures and references as well as the amount of decision making required. Job aids assume a variety of formats including flowcharts, checklists, decision tables, etc., while procedures refer to other systems of documentation such as standard operating instructions and emergency procedures.

3.5.3.2. Common Problems with Procedures

Which often lead to violations. The following deficiencies may occur in any applications of procedures, from operating instructions to permit to work systems:

Procedures Do Not Correspond to the Way the Job Is Actually Done.
Procedures are often developed when a system is first commissioned and are seldom revised to take into account changes in the hardware or the operating regime. In addition, procedures are often not written on the basis of a systematic analysis of the task as perceived by the workers or other personnel who have to use them. The remedy for this is to make sure that individuals who are going to use procedures are actively involved in their development. In addition, effective updating and auditing systems need to be in place to ensure that procedures are correct, and available to the persons who need them.

The Information Contained in Procedures Is Correct, but It Is Not Cast in a Form Usable by the Individual at His or Her Workplace.
Very often, voluminous procedures gather dust in cabinets where they have lain since the system was commissioned. For simple skill-based tasks carried out by experienced workers, no procedural support will be necessary. Other activities such as trouble shooting or diagnosis may, as discussed in Chapter 2, involve the use of formal or informal rules which are used infrequently. In these cases some form of job aid or checklist is the most effective type of procedure.

Detailed procedures will only be required in unusual situations where the usual rules of thumb do not apply and the worker is likely to be in the knowledge-based mode. In Chapter 4, and case study 3 in Chapter 7, a systematic framework for developing procedures, in which their format and content is based on a detailed analysis of the tasks to be performed and the normal skill level of the person who will perform the tasks, will be described.

Only task elements which are particularly critical (from the point of view of the consequences of failure) or where errors are particularly likely, are included in the job aid. The development of procedures obviously has to be closely integrated with the content of training, since the design of procedures has to assume that the individual has received appropriate training for certain aspects of the task.

The Distinction between Procedures as Regulatory Standards and as Instructions to Perform a Task Is Not Adequately Made.
In many industries, rule books have a tendency to become enshrined as policy statements, either for internal or external regulatory purposes. Unfortunately, the format that is appropriate for a regulatory or standards document is unlikely to fulfill the requirements of an effective operating instruction or procedure to provide assistance in carrying out a task effectively.

Procedures Are Not Updated on the Basis of Operational Experience.
If procedures are obviously out of date or do not take into account lessons learned throughout a system, they rapidly lose their credibility and are likely to fall into disuse.

Rules and Procedures Are Not Seen to Apply to the Individuals or the Situation in Question.
If there are situations where ordinary procedures may be suspended for specific purposes, these need to be carefully defined and controlled by the proactive development of "rules" which explicitly state the boundary conditions for such interventions.

The User of the Procedures Does Not Understand the Underlying Reasoning behind Them and Therefore Carries Out Alternative Actions That Appear to Achieve the Same Purpose but Are Easier to Perform.
This type of failure underscores the earlier comment that individuals should, if possible, be actively involved in the development of procedures that they are required to use, so that they understand the underlying purpose behind them.

3.5.3.3. *Criteria for Selecting Job Aids*

To select the most appropriate method to support the process worker, one needs to consider the characteristics of the task and the type of support to be provided. Flowcharts and decision tables, for instance, offer a concise organization of the information and the job criteria required to perform fault diagnosis and planning tasks. Checklists are more suitable for tasks which involve remembering sequences of steps. Procedures, on the other hand, provide step-by-step directions with regard to how and when to perform various tasks which involve stringent memory requirements, calculation, accuracy, and difficult decisions. Standard operating instructions are usually provided for critical tasks involving changes in the plant operating conditions such as plant start-up or shutdown or changes of fuel firing in a refinery furnace. Emergency procedures are provided for tasks which involve diagnosing plant or instrumentation failures and stabilizing and recovering abnormal plant conditions.

An important issue is how much of the job requirements should be supported by job aids and procedures as opposed to training. If job aids are developed at the expense of adequate training, the worker may become tied to the aid and thus vulnerable to situations where the aid contains errors or unforeseen plant conditions occur. On the other hand, overloading the worker with too much information and skills to be learned during training may result in performance decrements in the long run. To determine the extent of job aid provision versus training, the investment required to generate and validate the aids as well as develop and carry out extensive training programs should be considered. Joyce et al. (1973) and Smillie (1985) provide a thorough discussion of the criteria to be taken into account when examining these trade-offs.

In general, job aids and procedures are useful for tasks which are performed rarely or require complex logic, for example, diagnostic aids. They are also applicable for situations which involve following long and complex action sequences, and where reference to printed instructions is not disruptive. Training should be emphasized for tasks which are performed frequently, require complex manual skills, depend strongly on team efforts or involve unforeseen plant conditions. These considerations can be seen to be directly related to the skill-, rule-, and knowledge-based classification discussed in Chapter 2.

In order to judge the extent that the job aids and procedures provided will facilitate process worker performance or engage him or her in a time-consuming search for information, we need to look closer at a number of factors .

3.5.3.4. *Clarity of Instruction*

- This refers to the clarity of the meaning of instructions and the ease with which they can be understood. This is a catch-all category which includes both language and format considerations. Wright (1977) discusses four ways of improving the comprehensibility of technical prose.
- Avoid the use of more than one action in each step of the procedure.
- Use language which is terse but comprehensible to the users.
- Use the active voice (e.g., "rotate switch 12A" rather than "switch 12A should be rotated").
- Avoid complex sentences containing more than one negative.

The following example highlights how lack of clarity of instructions can lead to errors of misinterpretation.

Example 3.4. Error Due to Lack of Clarity of Instructions

In one plant, the operating procedures required that valve A should be placed into the "manual closed position." The process worker misinterpreted this information and instead of placing the valve controller in the manual position, he closed the block valve manually and deprived the plant of an essential feed.

The format of the procedure is also important in this respect. There may be situations where alternatives to prose are more efficient and acceptable. A flow diagram or a decision table may help the process worker to concentrate more easily on what indications are presented, and what decisions and control actions he or she has to make (see Wright. 1977).

3.5.3.5. *Level of Description*

An important issue in the writing of procedures is how much information is necessary for the process worker in order to minimize the likelihood of error. Too little may be inappropriate for an inexperienced process worker while too much may encourage a highly experienced worker not to use the procedure. It is obvious that the level of worker expertise and the criticality of the task will determine the level of description. This example shows how lack of detailed information can lead to errors of omission.

Example 3.5. Error Due to Lack of Detail of Instructions (Kletz, 1994b)

A day foreman left instructions for the night shift to clean the reactor. He wrote "agitate with 150 liters nitric acid solution for 4 hours at 80°C." He did not actually tell them to fill the reactor with water first, as he assumed that this was obvious since the reactor had been cleared this way in the past. The night shift did not fill the reactor with water. They added the nitric acid to the empty reactor via the normal filling pump and line which contained isopropyl alcohol. The nitric acid displaced the isopropyl alcohol into the reactor, and reacted violently with it, producing nitric fumes. As a result the reactor, which was designed for a gauge pressure of 3 bar, burst. Although this accident can also be said to be due to failure of the night shift to use their knowledge of chemistry, it clearly demonstrates the importance of the appropriate level of detail in the instructions

3.5.3.6. *Specification of Entry/Exit Conditions*

Many of the difficulties in using operating procedures stem from the fact that the conditions for applying a given section or branch and the conditions for completing or transferring to another section are not clearly specified. This is particularly important in emergency situations where a choice must be made under time pressure and excessive workload.

3.5.3.7. *Quality of Checks and Warnings*

Checks of critical process parameters and warnings about hazardous conditions that can cause injury or equipment damage are important factors which determine the occurrence and recovery of human error. The purpose of these checks is to emphasize critical process information. Because of the critical nature of this information, checks and warning should be highlighted in a way that distinguishes them from other notes, and should be located where process workers will not overlook them.

3.5.3.8. Degree of Fault Diagnostic Support

Emergency procedures usually require the process worker to make the correct diagnosis in order to select the right compensatory actions, a task which is often performed poorly under the duress of an abnormal situation. To overcome this problem, some procedures provide fault diagnostic support such as fault-symptom tables or other graphical aids relating to each plant failure for which recovery actions are specified. The degree of fault diagnostic support and their particular format will influence the likelihood of a correct human intervention in an emergency situation.

3.5.3.9. Compatibility with Operational Experience

It is common practice that procedures and job-aids are often developed either by plant manufacturing companies or process designers with minimal participation by the end-users, usually plant workers. This has led to situations where the indicated sequence of actions was incompatible with the way the job is done in practice. This presents great problems for the workers who will have to reconcile a potential violation of procedures with a well established method of operation.

Although manufacturing companies and process designers may have a thorough knowledge of plant equipment, factors such as subsequent modifications, age, and working hours of the equipment, changes in the product specifications, and maintenance problems, may not be foreseen. In addition, experience with the dynamic response of the plant provides workers with insights into its detailed operating characteristics which need to be factored into the procedures. These considerations emphasize the importance of the active participation of the operating team in the design and maintenance of procedural aids.

3.5.3.10. Frequency of Updating

The above factors also highlight the importance of updating the procedures frequently. There are many occasions where control loops are introduced in the plant without proper modification of the procedures, which means that the process worker will not be able to explain the behavior of the plant or understand the required intervention on his part.

3.5.4. Training

Control panel design, equipment design, and job-aids and procedures are factors which change the demands of the task to be performed. Training is a factor which determines the capability of the worker to cope with a task by providing the required knowledge and skills. Process worker training can fulfill various requirements, for example, the ability to perform a job, to use new equipment, job aids and procedures, to respond to emergency situations, to maintain process skills with the introduction of automation, and finally, to make teamwork effective. These types of training will be considered in detail below, in order to examine how deficiencies in their design may dispose the worker toward error.

A distinction can be made between the previous forms of training and the methods to provide the required skills. In process control, we may consider training people off-the-job, on the plant itsefl—but not actually carrying out the job, and while they are carrying out the job. Off-the-job training is best seen as a means of preparing trainees to benefit from real experience and not as a sole training method. Diagrams of the flow of the product, decision trees, and other job-aids are all very useful for off-the-job training.

For training which is done "on-the-job," the actual plant can be used as a context of training. Operations can be taught by "walking through" with the trainee, possibly using an operating manual. When it is safe, an experienced process worker or the supervisor can demonstrate some operations on the plant and subsequently let trainees operate the plant under close supervision and guidance.

A combination of on-the-job and off-the-job methods is usually the best solution in most types of training. The following factors should be examined in order to analyze the role of training in preventing human error. Team training will be considered in the social and organizational factors which follow in other sections.

3.5.4.1. Conflicts between Safety and Production Requirements

One of the most important aspects of training is to highlight those steps during an operation at which production and safety requirements may potentially conflict. The following incident illustrates the importance of addressing such conflicts explicitly during training.

Example 3.6. Conflicts between Production Pressures and Safe Practices

In a refinery furnace, the panel man observed that the burner fuel flow and the smoke meter were oscillating. A process worker arrived and checked the conditions of the two oil burners from underneath the furnace. Burner "A" appeared to be extinguished and burner "B" unstable. On similar occasions, there were two alternative strategies to be considered: (i) maintain or reduce production by shutting the oil cock of burner "B" and improving stability of burner "A"; or (ii) shut down furnace by closing the oil cocks of both burners and purge furnace with air. Training must emphasize these production–safety conflicts and specify how one can cope with them.

Unfortunately, this was not the case for the plant in this example, and the worker wrongly chose to maintain production. By the time he arrived at the furnace, some of the fuel oil from burner "A" was deposited on the furnace tubes. Due to the heat from burner "B," the oil had vaporized and had been carried into the furnace stack. An explosion occurred when the mixture of air and unburned fuel came into the flammable range.

3.5.4.2. *Training in Using New Equipment*

On many occasions, new equipment is installed or process workers have to work in other similar plant units in order to substitute for one of their colleagues. Despite the overall similarity of the new equipment, there might be some differences in their operation which may sometimes become very critical. We cannot always rely on the operator to discover these potentially critical differences in equipment design, especially under time pressure and excessive workload. If multiskill training in a range of plant equipment is not feasible, then training should be provided for the specific new equipment. The incident below was due to lack of training for a canned pump.

Example 3.7. Lack of Knowledge of Safety Prerequisites before Carrying out Work on a Pump (Kletz, 1994b)

In canned pumps the rotor (the moving part of the electric motor) is immersed in the process liquid; the stator (the fixed part of the electric motor) is separated from the rotor by a stainless steel can. If there is a hole in the can, process liquid can get into the stator compartment. A pressure relief plug is therefore fitted to the compartment and should be used before the compartment is opened for work on the stator. One day, an operator opened the pump without using the pressure relief plug. There was a hole in the can which had caused a pressure build-up in the stator compartment. When the cover was unbolted, it was blown off and hit a scaffold 6 feet above. On the way up it hit a man on the knee and the escaping vapor caused eye irritation. The worker was not familiar with canned pumps and did not realize that the pressure relief plug should be used before opening the compartment.

3.5.4.3. *Practice with Unfamiliar Situations*

It is not possible to predict all the potential situations which the process worker will have to deal with. Unfamiliar situations sometimes arise whose recovery is entirely dependent upon the operating team. When this is the case, the likelihood of success will depend upon the problem solving skills of the process workers. These skills can be trained in refresher training exercises where the team will have to respond to unfamiliar situations. Training simulators can be particularly useful for such scenarios. Techniques for training the diagnostic skills of process operators are described in Embrey (1986).

One of the classical responses to unfamiliar situations is that people revert to previously learned well established habits and strategies which bear some sort of similarity with the new situation yet they are totally inappropriate. These strategies may have worked effectively in the past or have been emphasized in the emergency procedures or during training. People have to learn how to remain vigilant to changing plant conditions and reevaluate their initial hypotheses. Other types of human errors during emergency conditions are discussed in Section 6.

3.5.4.4. *Training in Using Emergency Procedures*

Another aspect of the response to plant transients is the effective use of the emergency procedures. The process worker needs training in order to be able to apply these procedures correctly under time pressure. Conditions of entry or transfer to other procedures, profitability–safety requirements, and the response of the automatic protection systems need to be learned extensively in training exercises.

3.5.4.5. *Training in Working with Automatic Control and Protection Systems*

Although training in using emergency procedures may refer to the operation of the various automatic control and protection systems, this factor needs to be considered in its own right due to its significant effect on performance. Any training course should consider the potential risk which may arise where the automatic systems are defeated (see Example 1.19). It should also consider any cases where workers tend either to overrely on the good operation of the automatic systems or to mistrust them without appropriate checking. An example of overreliance on automation was described in Example 1.20, while Examples 1.15 and 1.16 illustrate the tendency of some workers to blame the instrumentation for any abnormal readings. A useful strategy to overcome these problems is the "cross-checking" of instruments measuring the identical or functionally related parameters, for example, temperature and pressure.

3.5.4.6. *Developing a Training Program*

In general, little use is made in the process industry of more sophisticated approaches such as job and task analysis (see Chapter 4) to define the mental and physical skills required for specific types of work, and to tailor the training program accordingly. Instead, informal on-the-job training is common, even in more complex types of work such as control room tasks. Although the necessary skills will eventually be acquired by this process, its inefficiency leads to the need for extended periods of training. In addition, there is the problem that inappropriate or even dangerous practices may become the norm as they are passed from one generation of workers to the next. It is therefore essential that training programs are based upon a comprehensive and systematic procedure which involves the following stages:

- **Job and task analysis.** This involves applying techniques such as hierarchical task analysis (see Chapter 4) to provide a comprehensive description of the work for which training is required. The task analysis provides essential information on the **content** of training.
- **Skills analysis.** This stage of the training development process involves identifying the nature of the skills required to perform the job. For example, a control room job may involve perceptual skills such as being able to identify out of limit parameters on a visual display screen, and decision making skills in order to choose an appropriate course of action. By contrast, an electrical maintenance job may require training in fine manipulative skills. As discussed in Chapter 2, the classification of a task as being predominantly skill-, rule-, or knowledge-based can provide insights with which is the most appropriate form of training
- **Specification of training content.** The content of training, in terms of skills and knowledge required to do the job, is derived from the previous two steps. At this stage it is important to define the information that will be obtained from procedures (in the case of infrequency performed tasks) and generic knowledge that will be required for a wide range of different tasks and which the operator would be expected to know as part of the skill of the job.
- **Specification of training methods.** This stage of the design of the training system will specify the appropriate training methods to provide the skills and knowledge identified by the earlier stages. A wide variety of sophisticated training techniques exist, such as interactive videos, which can be used to impart the knowledge aspect of training. More complex mental skills such as those required for control room tasks benefit from the use of various types of simulation. In order to be effective as a training method, simulators do not have to be highly similar to the actual plant control room. Inexpensive personal computer-based simulators can be used to teach control, problem solving and decision making skills. Applications of simulations to training in the CPI are given in Shepherd et al. (1977), Patternotte and Verhaegen (1979), and West and Clark (1974). Craft-based mechanical skills are usually taught by experienced trainers, together with guided on the job training.
- **Definition of competence assessment methods.** The definition of formal methods of assessing competence is a neglected area in many training programs. It is obviously necessary to ensure that trainees possess the necessary skills to do the job at the end of the training program.

Competence assessment is also required if workers are assigned to new areas of work. In the offshore industry, considerable importance is being attached to the issue of demonstrating competence, following the recommendations of the inquiry that followed the Piper Alpha disaster.

- **Validation of training effectiveness.** The effectiveness of the training system in terms of its capability to equip people with the skills necessary to carry out a job safely and efficiently, can only be determined by long term feedback from operations. The types of feedback that are important in evaluating a training program include incident reports, which should explicitly identify the role of lack of knowledge and skills in accidents, and reports from line managers and supervisors.
- **Definition of skill maintenance training.** All skills decline with time and it is therefore important to specify the needs for skill maintenance training by means of refresher courses or other methods.

3.6. OPERATOR CHARACTERISTICS

This group of PIFs concerns the operator characteristics of personnel such as operating experience, personality, physical condition and age. Considerable emphasis is placed on individual differences by many managers. There is a strong belief that all problems can be solved by better motivation or more intrinsically capable people. However, although many of the individual factors discussed in this section might reasonably be expected to have an effect on human error, in practice there are few controlled studies that have actually established such a link. Nevertheless, it is important that engineers are aware of the wide range of factors that could impact on error.

3.6.1. Experience

Although training can provide workers with adequate practice in process control, some elements of expertise develop primarily with operational experience. The degree of skill and experience with stressful process events are two separate PIFs which will be discussed thoroughly in this section.

3.6.1.1. Degree of Skill

The amount of the "on-the-plant" experience of personnel determines the extent that well-known knowledge can be applied to real-life problems, particularly under time pressure and high workload. Although engineering schools make an effort to provide all the required theoretical knowledge to young graduates and process workers, many people find it difficult to apply such knowledge to the plant, especially in the beginning of their employment period.

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