

A Manager's Guide to

Reducing Human Errors

**Improving Human Performance
in the Process Industries**

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***A Manager's Guide to
Reducing Human Errors***

**Improving Human Performance
in the Process Industries**

**Prepared under contract by
D. K. Lorenzo, P.E.,
EQE, International Inc.**

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PREFACE

Human errors have either directly caused or significantly contributed to many major accidents in the process industries. The American Chemistry Council, American Petroleum Institute, and their member companies recognize the importance of reducing human errors to enhance the safety, productivity, and quality of their manufacturing processes. But to improve human performance, managers need specific advice on what can be done to help prevent mistakes and to reduce the likelihood that such mistakes will lead to process upsets or accidents.

This Guide is intended for an audience of middle managers to senior executives who have different levels of knowledge about human factors engineering. It is designed to equip them with a basic understanding of the causes of human errors and to suggest ways for reducing human errors at individual facilities. It also describes how to incorporate human reliability analysis (HRA) into process safety management activities. To convey this information, we use the following steps:

- Establish a basic vocabulary (Glossary) needed to discuss human factors engineering and HRA with experts in the field
- Identify factors affecting human performance, especially those that managers can control
- Suggest ways to reduce human errors
- Describe how HRA can be incorporated in process safety management activities

Section 1 discusses the importance of improving human performance and also discusses the objectives of this Guide. Section 2 defines human error and discusses its most common causes. Section 3 identifies many specific factors in the workplace that increase the likelihood of human errors and discusses ways to improve human performance.

If a manager requires a numerical estimate of the probability of human error, there are several HRA techniques available for that purpose; Section 4 describes how these techniques can be used in conjunction with quantitative risk assessment techniques. Some concluding comments are offered in Section 5. Appendices 1 and 2 contain self-evaluation questionnaires, and Appendix 3 contains an example HRA.

We hope this Guide will help you identify ways to reduce human errors in your own facilities. However, the extent of human factors engineering knowledge that has been accumulated far exceeds what is contained in this Guide. An extensive bibliography has been included to help you find additional information about particular topics. You are strongly encouraged to use these resources in addition to this Guide.

EXECUTIVE SUMMARY

During the past 30 years, the 100 largest accidents at chemical and hydrocarbon processing facilities have severely injured or killed hundreds of people, contaminated the environment, and caused more than \$8 billion in property damage losses.^{1,2} The actual cost of these accidents was much higher because of the associated business interruption costs, cleanup costs, legal costs, fines, losses of market share, and so forth. Human error was a significant factor in almost all of these accidents. In systems where a high degree of hardware redundancy minimizes the consequences of single component failures, human errors may comprise over 90 percent of the system failure probability.³

Any serious attempt to improve process safety must address the fact that human errors in the design, construction, operation, maintenance, and management of facilities are the root causes of almost all quality deficiencies, production losses, and accidents. Too often, managers believe that workers can be selected, trained, and motivated to properly operate any system. Therefore, they believe that human errors are the result of carelessness or stupidity, and that the only way they can reduce human errors is to discipline the guilty parties when errors occur.

Enlightened managers realize that careless or unfit workers account for only a small fraction of the human errors at their facilities; most mistakes are committed by skilled, careful, productive, well-meaning employees. Rather than simply blaming the individual involved, these managers attempt to identify the root causes of the error in the work situation and implement appropriate corrective actions.

Human factors engineering, or **ergonomics**, is the design of equipment, operations, procedures, and work environments that are compatible with the capabilities, limitations, and needs of the workers. It is a vital complement to other engineering disciplines that primarily seek to optimize hardware performance and/or minimize capital costs with little or no consideration of how the equipment will actually be operated and maintained. For example, a salvaged dial thermometer attached to a nozzle just below the third level platform might be a very inexpensive way to accurately measure temperature in a tower. But from a human factors standpoint, it is a less-than-adequate design if operators must climb up three caged ladders and peer down through the metal grating of the platform in order to read the temperature (which must be controlled within 5 degrees) from a dial graduated in 100-degree increments.

This Guide focuses on techniques that managers can use to improve human performance by identifying and eliminating error-likely situations that may not be as obvious as the one described above. The basic strategy is to reduce the frequency of human errors by applying principles of human factors engineering to the equipment that must be operated and maintained, to the work tasks that must be performed, and to the work environment. In order for this approach to be successful, it is essential that the workers themselves be involved in the design process. From a management standpoint, it would not be cost-effective to ignore the workers' knowledge, which is a valuable resource that already exists within every company. The earlier that workers and human factors specialists are involved in the design process, the more successful and efficient this strategy will be.

Because some human errors will inevitably occur, this Guide also discusses methods that managers can use to reduce the probability that undesirable consequences will result from them. This can be accomplished by designing ways to detect human errors or mitigate their effects. Involving the workers in this activity will also help ensure its success.

One of the tools that managers can use to improve human performance is human reliability analysis (HRA). Like other risk assessment tools (e.g., fault tree analysis), HRA can provide both qualitative and quantitative information. The qualitative results identify the critical actions that a worker must accomplish to successfully perform a task, identify erroneous (unwanted) actions that can degrade the system, identify error-likely situations, and identify any factors that would mitigate errors in the performance of any action. The quantitative results are numerical estimates of the probability that a task will be performed incorrectly or that unwanted actions will be performed. As mentioned in the American Chemistry Council's and Center for Chemical Process Safety's *Evaluating Process Safety in the Chemical Industry: User's Guide to Quantitative Risk Analysis*,⁴ these results are a necessary input to comprehensive quantitative risk assessments of process units or facilities. However, managers should realize that the qualitative results of an HRA are as valuable as any quantitative estimates of human error probabilities.

Anticipating and controlling the potentially adverse impacts of human actions or human/system interactions are integral parts of process safety management. Therefore, many process safety management activities are directed toward improving human performance. For example, maintaining current plant procedures will help ensure that workers have correct instructions for the tasks they must perform. Increasing training will help ensure that workers can diagnose process upsets and respond correctly to emergency situations. Scrutinizing designs before they are installed will help eliminate design errors and identify ways to reduce the likelihood of human errors that could adversely affect quality, productivity, or safety.

Ultimately, the term “human error” should connote no more sense of blame or emotion than the term “hardware failure.” Rather than seeking to blame or punish a worker when an incident occurs, managers should look for the root causes in the work situation. Only if managers recognize and accept their responsibility to identify and eliminate error-likely situations in the workplace will there be a significant reduction in the frequency and severity of human errors. Directly involving the workers in these efforts is the best way to achieve your goals. Human factors engineering is an important tool that managers can use in their quest for an ever safer and more productive organization.

Section 1 INTRODUCTION

1.1 IMPORTANCE OF IMPROVING HUMAN PERFORMANCE

What caused the last process upset at your facility? The last quality problem? The last unscheduled unit outage? The last accident? Chances are you blamed **human error** as either the direct cause (e.g., an operator opening the wrong valve) or as a significantly contributing cause (e.g., an operator failing to start the spare pump quickly enough) of the process upset. And now that the guilty individual(s) has been counseled, disciplined, or fired, you feel sure that a similar mistake will never happen again.

During the past five years, about 30 major accidents at chemical and hydrocarbon processing facilities have severely injured hundreds of people, contaminated the environment, and caused more than \$2 billion in property damage losses.^{1,2} The actual cost of these accidents was much higher because of the associated business interruption costs, cleanup costs, legal costs, fines, losses of market share, and so forth. Human error was a significant factor in almost all of these accidents. The total cost (including forced outages and off-specification products, as well as accidents) of human errors in the process industries is incalculable.

Historically, managers have found human errors to be significant factors in almost every quality problem, production outage, or accident at their facilities. One study⁵ of 190 accidents in chemical facilities found that the top four causes were insufficient knowledge (34 percent), design errors (32 percent), procedure errors (24 percent), and operator errors (16 percent).^{*} A study⁶ of accidents in petrochemical and refining units identified the following causes: equipment and design failures (41 percent), operator and maintenance errors (41 percent), inadequate or improper procedures (11 percent), inadequate or improper inspection (5 percent), and miscellaneous causes (2 percent). In systems where a high degree of hardware redundancy minimizes the consequences of single component failures, human errors may comprise over 90percent of the system failure probability.³

Clearly, human errors were considered the cause for an overwhelming fraction of the accidents that were evaluated in these studies. But when you stop and think about these results, they are not really surprising because there is the potential for human error in every aspect of production, refining, or manufacturing, as indicated in Table 1.

The challenge for a manager is to devise effective ways to reduce the frequency of human errors associated with these activities and to reduce the probability that any error that does occur will adversely affect a facility. Managers must also devise ways to learn from the actual and near-miss incidents that do occur and to implement appropriate corrective actions. The reward for creating and implementing such programs will be tangible improvements in process safety, quality, and productivity.

^{*} The percentages total more than 100% because more than one cause could be listed for an accident.

Table 1 Opportunities for Human Error

Research/Development/Exploration	The chemist failed to report that the compound expanded when it froze
Design	The engineer failed to specify heat tracing for a heat exchanger bypass line that subsequently froze and ruptured
Construction/Installation	The contractor failed to install the specified heat tracing on a heat exchanger bypass line that subsequently froze and ruptured
Training/Procedures	The operators did not know where to turn on the heat tracing for a heat exchanger bypass line that subsequently froze and ruptured
Operation	The operators neglected their daily check of the heat tracing, which eventually failed, allowing the heat exchanger bypass line to freeze and rupture
Maintenance/Inspection	The pipefitters failed to replace the heat tracing they pinched while repairing a flange leak, allowing the heat exchanger bypass line to freeze and rupture
Plant Management	The manager delayed activation of the heat tracing system to save energy, but unpredicted cold weather froze and ruptured several pipes and vessels
Corporate Management	The corporate management cut the plant budget, forcing such severe staff reductions that the heat tracing was not all activated when cold weather arrived, resulting in a plant shutdown because of frozen lines

1.2 OBJECTIVES AND ORGANIZATION OF THIS GUIDE

The primary objective of this Guide is to help you understand human factors engineering principles that you can use to improve human performance at your facilities. For simplicity, this Guide focuses on ways to reduce operating and maintenance errors, but many of the ideas could also be applied to research, development, design, construction, training, and management activities.

The first part of this Guide is designed to equip you with a basic understanding of human error and some of the jargon you will encounter in the field of human factors engineering. But the bulk of this Guide is designed to help you recognize some of the causes of human errors, and the errors are illustrated with simple case histories. Integrated with these descriptions are suggestions for eliminating the error-likely situations that you identify. Appendix 1 contains a questionnaire you can use to help critically evaluate the potential for human errors in your facility.

The final portion of this Guide is devoted to explaining how human factors engineering and human reliability analysis (HRA) interrelate with other process safety management activities. In particular, it discusses how HRA can be used in conjunction with any qualitative or quantitative risk assessment techniques you may employ as part of your process safety management program. Appendix 3 shows how HRA can be applied to a practical process problem.

Section 2

UNDERSTANDING HUMAN ERROR

2.1 DEFINITION OF HUMAN ERROR

Every task that must be performed by a human is an opportunity for error. But even though neither two people (nor even one individual) will perform the same task in exactly the same way twice, minor variations in the performance of a task are usually inconsequential. Only when some limit of acceptability is exceeded is a variation considered a human error. Thus, a practical definition of **human error** is any human action (or lack thereof) that exceeds the tolerances defined by the system with which the human interacts.

Any discussion of human error must consider the specific actions and limits involved in a particular task. For example, an operator might be told to add 10 pounds of catalyst after a batch reactor is heated to 200 degrees. The operator can add more or less catalyst; add catalyst sooner or later; add the catalyst quickly or slowly; add a different catalyst; or forget to add any catalyst at all. The operator might also choose a blue or red scoop to measure the catalyst. Any of these variations is inconsequential unless it has the potential to cause a runaway reaction (accident), to extend the processing time (production loss), or to generate off-specification product (quality problem). Only then would the variation be considered a human error. Unfortunately, the limits on human performance are seldom well defined until someone has exceeded them at least once under circumstances that resulted in an actual problem.

In general there are two types of human errors: unintentional and intentional. Unintentional errors are actions committed or omitted with no prior thought. We typically think of these as “accidents”: bumping the wrong switch, misreading a gauge, forgetting to open a valve, spilling coffee into the control console, and so forth. If the worker intended the correct action, but simply did it wrong, the error is sometimes called a “slip”; if the worker forgot to perform the action, the error is sometimes called a “lapse.”

Intentional deviations (errors) are actions we deliberately commit or omit because we believe, for whatever reason, that our actions are correct or that they will be better (i.e., quicker, easier, safer, etc.) than the prescribed actions. When workers misdiagnose the true cause of an upset, they will intentionally perform erroneous actions as they attempt to respond. For example, operators on other interconnecting oil platforms actually worsened the fire on Piper Alpha in 1988 because they did not understand what was happening and did not respond appropriately. Other intentional deviations are “shortcuts” or “violations” that are not recognized as human errors until circumstances arise in which they exceed the system tolerances. Examples of such errors include failing to electrically ground containers of flammable liquids, attempting to restart a furnace without purging the firebox, adding a little extra catalyst to accelerate the start of a reaction, and so forth.

There is an important distinction between intentional deviations and malevolent behavior: motive. An intentional deviation is not intended to harm the system, but its effect on the system may turn out to be

undesirable. A malevolent act (e.g., sabotage) is not an error at all – it is a deliberate action intended to produce a harmful effect. As used in this Guide, the term human error does not include malevolent acts.

2.2 THEORY OF HUMAN ERROR

Human diversity is both a blessing and a curse: it enables us to learn, adapt, specialize, and fulfill all the different roles in our society, but it also enables us to do things in ways that systems cannot tolerate. At any moment, any individual is able to feel, think, and do any one of countless things. Considering the very large number of things that we could do at any moment, it is amazing that we accomplish so many tasks successfully.

Humans are extremely interactive and adaptable parts of any system. As illustrated in Figure 1, human interactions with a system can be simply modeled as five distinct functions. First, the system hardware or another human in the system must provide some external input. The input may be as obvious as a flashing, ringing alarm, or as subtle as a slight change in the pitch or intensity of background sounds. We must then become actively aware of the input by discriminating it from other inputs that are sensed and recognized. This awareness may be modified by internal feedback, as indicated in the figure, because (1) our mental models and expectations influence our perception of new information and (2) our own responses affect our ability to perceive new information. For example, you are less likely to hear and understand what someone else is saying if you are speaking yourself.

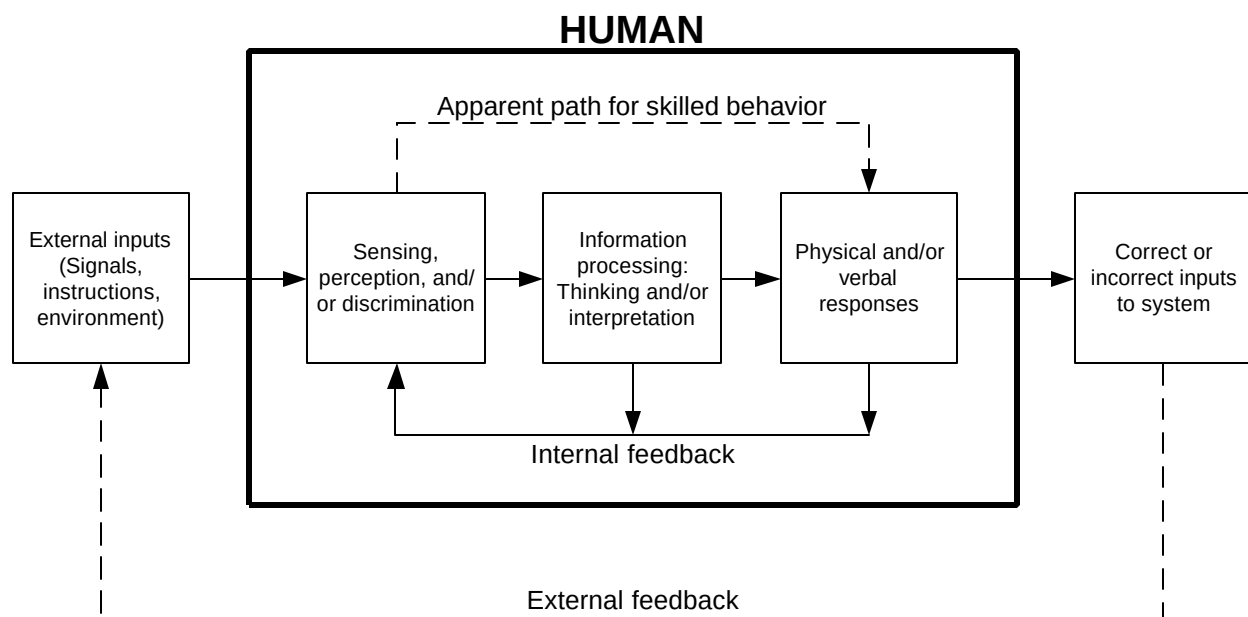


Figure 1 Simple Model of Human Behavior as a System Component (Based on Figure 3-1 in Reference 7)

We then select an appropriate response to the perceived information. This cognitive process is influenced by factors such as training, memory, goals, intentions, personality, attitude, motivation, mood, stress, and knowledge, but the ultimate result is to decide on a course of action. If the response to the perceived information is frequently practiced (such as braking your automobile when you see the brake lights of the vehicle ahead of you), the mental effort required is negligible. In such skill-based behaviors, we appear to leap directly from perception to response with no requirement for conscious thought.

Regardless of the mental pathway, we eventually make some response that we believe is appropriate. The response may involve movement of our limbs, use of our voice, or no action at all. Our response then becomes an input to the system as we manipulate controls, adjust equipment, or direct the actions of other humans. A well-designed system will feed back some information that will alter the external inputs that prompted our initial action. This will enable us to repeat the cycle as many times as necessary to achieve the desired system conditions, assuming enough time is available.

Human error is a natural and inevitable result of human variability in our interactions with a system. Whatever the task, human error is best understood in terms of human variability that reflects the influences of all pertinent factors at the time the actions are performed. There are three basic types of variability, and knowing which of these types occurs in a given case will help explain why errors occur and what can be done about them. To illustrate these types, let's consider a rifleman firing 10 shots at a target, and let's call any shot off the target an error.

1. Random variability is characterized by a dispersion pattern (Figure 2) centered about a desired norm — the bull's-eye in this example. When the variability is large, some shots will miss the target. Errors due to random variability are called *random errors*. Only reducing the overall variability of performance can reduce these errors. Personnel selection, training, supervision, and quality control programs are ways of controlling random variability. Random errors occur when these programs are deficient, when tolerance limits are too tight, or when workers cannot control key performance factors.

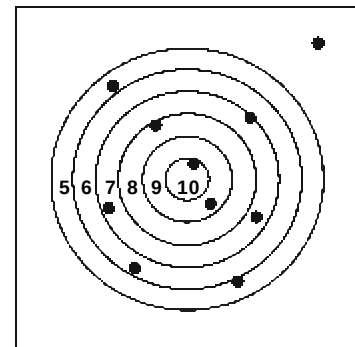


Figure 2 Random Error

2. Systematic variability is characterized by a dispersion pattern (Figure 3) offset from a desired norm. Although the variability may be small, the bias may cause some shots to be off target. Such errors are called *systematic errors*. Bias is often the result of only one or two factors and may be easily correctable. In the example, a gunsight adjustment (or glasses) may put the rifleman right on target. Systematic errors occur, for example, when workers are given only one limit instead of a lower and an upper limit; they may deliberately attempt to be on the apparently safe (unlimited) side. Biases can also exist in tools, equipment, instructions, or the worker's personality, training, or experience. Telling workers how well they are doing with respect to real goals will help reduce systematic errors.

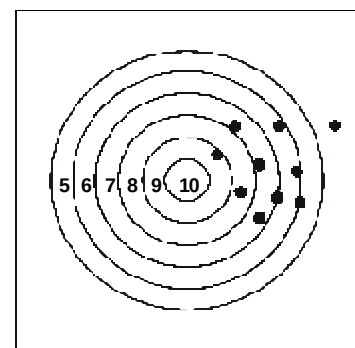


Figure 3 Systematic Error

3. Sporadic variability is characterized by an occasional outlier, such as a tight cluster of shots with one shot way off the mark (Figure 4) for reasons we might readily imagine — a sudden distraction, an involuntary twitch, etc. In work situations, where workers have been well trained and given a reasonable degree of control over major performance factors, most of the errors are due to sporadic variability. Such *sporadic errors* are the most difficult to predict or reduce because they occur infrequently and may not seem correlated to factors in the work situation. They are not correctable by additional training or indoctrination because they are not the result of inadequate knowledge or motivation. To reduce sporadic errors, we must categorize the errors and the conditions under which they occur in such a way that errors can be related to controllable conditions.

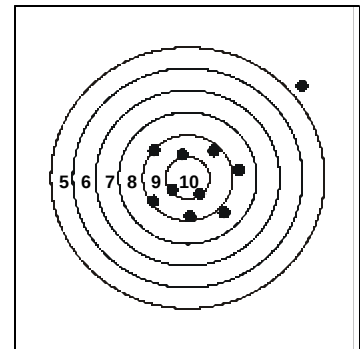


Figure 4 Sporadic Error

2.3 PERFORMANCE SHAPING FACTORS

One can think of the operator as an essential element of the overall process system as illustrated in Figure 5. To minimize human errors, managers must ensure that the operator-machine interface, which includes interactions with other workers as well as with the equipment and environment, is compatible with the capabilities, limitations, and needs of the worker. Anything that affects a worker's performance of a task within the process system is a **performance-shaping factor** (PSF). PSFs can be divided into three classes: (1) internal PSFs that act within an individual, (2) external PSFs that act on the individual, and (3) stressors. Table 2 lists some internal PSFs, which are the individual skills, abilities, attitudes, and

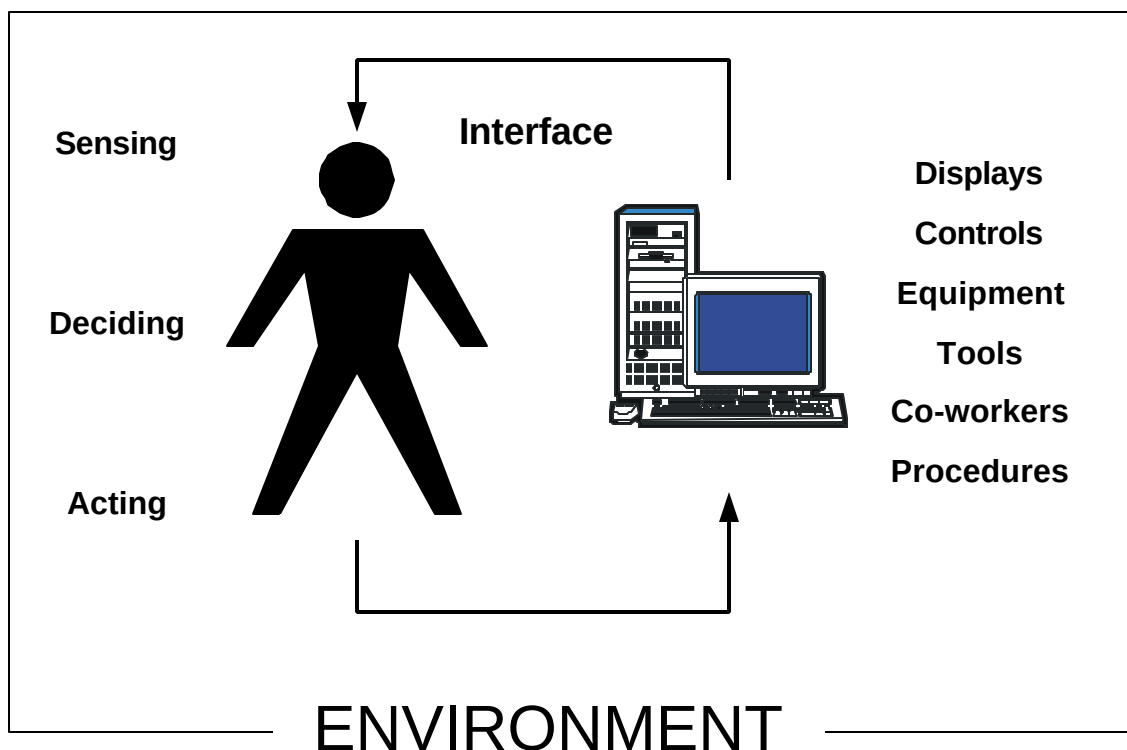


Figure 5 Operator as Essential Element of Overall Process System

other characteristics that a worker brings to any job. Some of these, such as training, can be improved by managers; others, such as a short-term emotional upset triggered by a family crisis, are beyond any practical management control. (However, a manager's style can influence workers' mental/emotional states, as can counseling programs.)

Table 3 lists external PSFs that influence the environment in which tasks are performed. These PSFs are divided into two groups: (1) situational characteristics and (2) task, equipment, and procedural characteristics. Situational characteristics include general PSFs that may affect many different jobs in the plant. Task and equipment characteristics are pertinent to a specific job or a specific task within a job. Job and task instructions are a particularly important part of the task characteristics because they have such a large effect on human performance. ***By emphasizing the importance of preparing and maintaining clear, accurate task instructions, managers can significantly reduce the likelihood of human errors.***

Table 2 Internal PSFs (Based on Table 3-2 in Reference 7)

Training/Skill
Practice/Experience
Knowledge of Required Performance Standards
Stress (Mental or Bodily Tension)
Intelligence
Motivation/Work Attitude
Personality
Emotional State
Gender
Physical Condition/Health
Influences of Family and Other Outside Persons or Agencies
Group Identifications
Culture

Table 3 External PSFs (Based on Table 3-2 in Reference 7)

SITUATIONAL CHARACTERISTICS	TASK, EQUIPMENT, AND PROCEDURAL CHARACTERISTICS
Architectural Features Environment (Temperature, Humidity, Air Quality, Lighting, Noise, Vibration, General Cleanliness, etc.) Work Hours/Work Breaks Shift Rotation Availability/Adequacy of Special Equipment, Tools, and Supplies Staffing Levels Organizational Structure (Authority, Responsibility, Communication Channels, etc.) Actions by Supervisors, Co-workers, Union Representatives, and Regulatory Personnel Plant Policies	Procedures (Written or Not Written) Written or Oral Communications Cautions and Warnings Work Methods/Shop Practices Dynamic vs. Step-by-step Activities Team Structure and Communication Perceptual Requirements Physical Requirements (Speed, Strength, etc.) Anticipatory Requirements Interpretation Decision Making Complexity (Information Load) Long- and Short-term Memory Load Calculational Requirements Feedback (Knowledge of Results) Hardware Interface Factors (Design of Control Equipment, Test Equipment, Process Equipment, Job Aids, Tools, Fixtures, etc.) Control-display Relationships Task Criticality Frequency/Repetitiveness

The interaction between internal and external PSFs creates stress in the individual performing the task. Mismatches between our internal and external PSFs result in disruptive stress that degrades our performance. If there is too little stimulation, we will not remain sufficiently alert to do a good job. For example, an operator who passively watches as a computer operates the process is unlikely to be alert enough to take control and continue operation when the computer fails. On the other hand, too much stimulation will quickly overburden us and degrade our performance. In such situations, we tend to (1) focus on the large or most noticeable signals and ignore some information entirely, (2) omit or delay some responses, (3) process information incorrectly and reject information that conflicts with our diagnosis or decision, or (4) mentally and/or physically withdraw. Disruptive psychological and physiological stressors are listed in Table 4.

Table 4 Stressor PSFs (Based on Table 3-2 in Reference 7)

Psychological Stressors	Physiological Stressors
Suddenness of Onset	Long Duration of Stress
High Task Speed	Fatigue
Heavy Task Load	Pain or Discomfort
High Jeopardy Risk	Hunger or Thirst
Threats (of Failure, of Loss of Job, etc.)	Temperature Extremes
Monotonous, Degrading, or Meaningless Work	Radiation
Long, Uneventful Vigilance Periods	Oxygen Deficiency
Conflicting Motives about Job Performance	Chemical Exposure
Negative Reinforcement	Vibration
Sensory Deprivations	Movement Constriction
Distractions (Noise, Glare, Movement, etc.)	Movement Repetition
Inconsistent Cueing	Lack of Physical Exercise
Lack of Rewards, Recognition, and Benefits	Disruption of Circadian Rhythm

Although stress usually has a negative connotation, some stress is actually necessary for humans to function at optimum performance, as illustrated in Figure 6. Facilitative stress is anything that arouses us, alerts us, prods us to action, thrills us, or makes us eager. When there is a good match between our internal and external PSFs, we experience facilitative stress and our performance is at its best.

Managers must recognize that most PSFs (including many internal PSFs) are within their control. By designing work situations that are compatible with human needs, capabilities, and limitations, and carefully matching workers with the job requirements, managers can create conditions that optimize worker performance and minimize human errors.

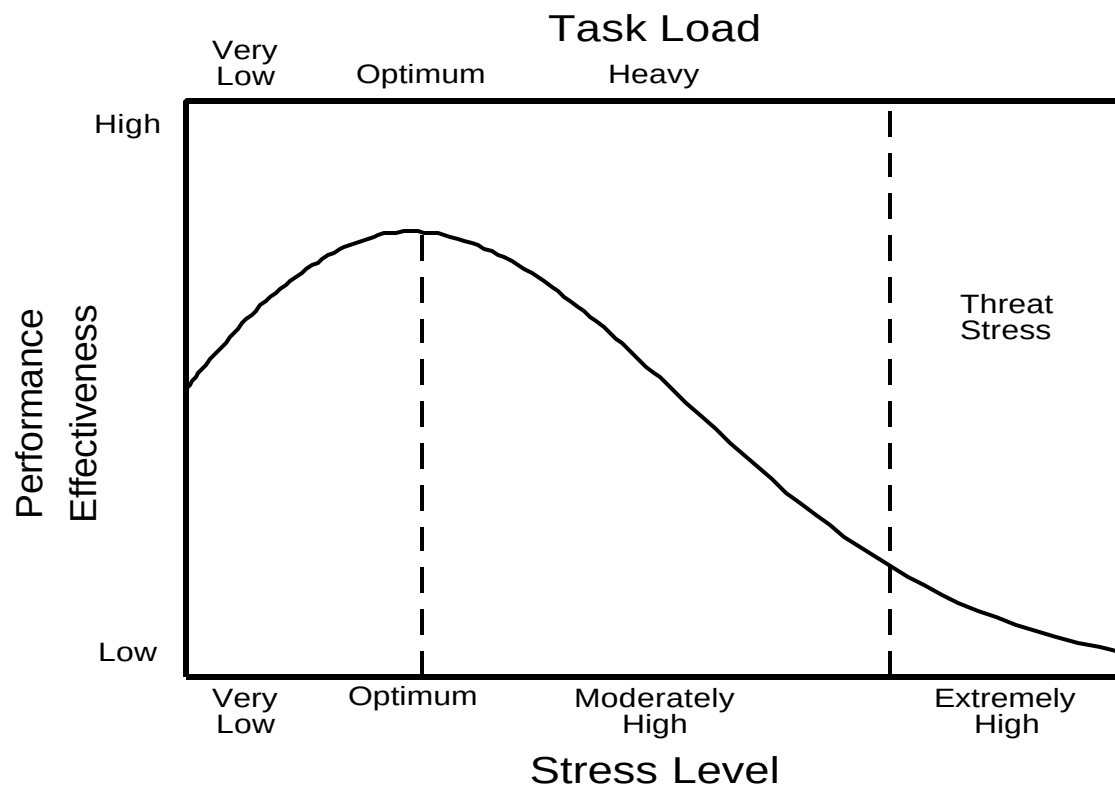


Figure 6 Relationship of Stress and Performance (Based on Figure 17-1 in Reference 7)

Section 3

STRATEGIES FOR IMPROVING HUMAN PERFORMANCE

When contemplating ways to improve human performance, there are two basic types of errors that managers must address: (1) errors whose primary causal factors are individual human characteristics unrelated to the work situation and (2) errors whose primary causal factors are related to the design of the work situation. Hiring and job assignment policies are important ways in which managers can reduce the causes of the first type of error. But on any given day, a worker could be emotionally upset, fatigued, taking medication/drugs, etc., and commit an error. However, human factors specialists estimate that only 15-20percent³ of workplace errors are primarily caused by such internal human characteristics.

The vast majority (80-85percent)³ of human errors primarily result from the design of the work situation (the tasks, equipment, and environment), which managers directly control. By providing the resources necessary to identify and eliminate error-likely situations, managers can improve the PSFs and dramatically reduce the frequency of human errors. This strategy is called the work-situation approach, and it involves the elements described in Table 5.

Table 5 Elements of the Work-situation Approach

• Implementing good human factors engineering of control systems, process equipment, and the work environment • Providing clear, accurate procedures, instructions, and other job aids • Providing job-relevant training and practice • Providing ways to detect and correct human errors before an undesired consequence occurs • Providing avenues for workers to achieve their social and psychological needs
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To maximize the benefits of such a strategy, managers should involve the workers themselves at every opportunity. After all, it is the workers who can best identify factors that hinder their performance and who will enthusiastically support such a strategy if they are not penalized for telling the truth.

3.1 EXAMPLES OF ERROR-LIKELY SITUATIONS

This section briefly describes a number of work situations that are likely to lead to human errors. It is intended to serve as a starting point that will help you identify error-likely situations in your own facilities.

3.1.1 Deficient Procedures

Good written procedures help ensure that all qualified operators can correctly and safely operate a system. Procedures should explicitly state the proper actions a worker should take during startup, shutdown, normal operation, and upset/emergency conditions, and the reasons for those actions should be explained during training. Task instructions should be written in simple, understandable language in a format (including appropriate pictures and diagrams) that the workers would use (see items 49 through 57

in the bibliography). To help ensure that procedures are accurate and useful, managers should involve the workers themselves in writing and validating the procedures.

Unfortunately, not all facilities have complete, current procedures that are useful to the workers. Some facilities only have the original procedures drafted by the design engineers and/or startup crew; others have incomplete procedures or none at all. If there have been so many process changes since the written procedures were last updated that they are no longer correct, workers will create their own unofficial procedures that may not adequately address safety issues. Some “procedures” are really checklists that only an expert could follow; others are voluminous training manuals that are not suitable for everyday use. Erroneous, incomplete, nonexistent, or overly complex procedures set the stage for human errors, as the following example illustrates:

- ☞ A system designed to circulate a metallic salt solution through a filter was modified so it could occasionally be used to pump a peroxide solution through a filter bypass line. Verbal orders were issued to never pump peroxide through the filter, but the written procedures were not revised. Eventually, a new operator following the written procedures pumped the peroxide through the filter, which exploded when the peroxide contacted the metal contaminants collected on the filter.

3.1.2 Inadequate, Inoperative, or Misleading Instrumentation

Instruments are workers’ primary sources of information about a process. If the instruments are inadequate or inoperative, workers must “fill in the blanks” and deduce process conditions from other instruments or indications. This greatly increases the probability of human error. Worse yet, if an instrument is miscalibrated, misleading, or failed (but appears to be working), workers may be tricked into inappropriate actions (or inactions). This is particularly likely to occur when switches are relied upon to activate alarms (high pressure, low level, etc.) but are never tested or repaired unless they fail in such a way that operations are disrupted (i.e., spurious alarms or inadvertent shutdowns). The following incidents resulted from instrument failures:

- ☞ The relief valve on a low-pressure separator actuated during apparently normal operations. Operators verified that the separator pressure was normal, and in their haste to stop the release, they blocked in the “bad” relief valve before unblocking the parallel relief valve. The separator immediately ruptured and killed two operators. The pressure transmitter on the separator had failed, closing the normal discharge valve and sending a false signal to the control room.
- ☞ Operators relied on a pressure gauge to indicate the level in a concentrated caustic tank because the sight glass tended to plug up. Operators eventually overfilled (and ruptured) the tank because a low-density hydrocarbon layer accumulated on top of the caustic. The pressure gauge was a valid indication of tank level only as long as the density of the tank contents did not change.
- ☞ An operator forgot to open an air vent valve before filling the unit with monomer. The operators noticed the unit was filling more slowly than usual, but assumed the filling pump’s suction screen was plugging, as it had

in the past. Eventually, as the pump approached its maximum discharge pressure (90 psig), the trapped, compressed air and monomer reacted violently, and the explosion ripped the unit apart. The operators did not notice the pressure buildup in the unit because none of the pressure transmitters were accurate for pressures less than 250 psig. (Normal operating pressure was 750 to 1,000 psig.)

- ☞ The single level monitoring device on a light hydrocarbon storage sphere falsely indicated that the sphere level was low. Operators pumped hydrocarbon into the sphere until it ruptured as a result of being overfilled and overstressed. The vapor cloud ignited, and the ensuing fireball scattered burning debris throughout the plant. Adjacent storage tanks also caught fire and exploded, and eventually the entire tank farm was destroyed.

3.1.3 Insufficient Knowledge

Workers must develop an accurate mental model of the process system so they can diagnose process upsets and understand the consequences of their actions. The only way such mental models can be built is for operators to be thoroughly trained not only in what/how to do something but also in why to do it. Workers should be required to demonstrate their proficiency (via tests, talk-throughs, etc.) before being allowed to work independently. Training must be reinforced with periodic drills so workers can practice and perfect their skills. Inadequate knowledge inevitably results in human errors, such as those described below:

- ☞ The operator used the column bottoms volume as a surge tank, and he deliberately increased the level in anticipation of reduced feed to the column. The operator did not understand that the relief valve would not work properly when its inlet was flooded by the excess level in the column. When an overpressure occurred, the column ruptured.
- ☞ The operator did not understand the dangers of combining catalyst and reactants in an uncontrolled manner. When she found the agitator had tripped off, she immediately reset the circuit breaker and restarted the agitator. The sudden mixing of the stratified materials initiated a runaway reaction that blew the reactor head through the building roof.
- ☞ The supervisor did not realize how quickly wet hydrofluoric acid vapors attacked carbon steel, so he attempted to continue running until the upcoming turnaround rather than shutting down to repair the leaking condenser. The head blew off the badly corroded condenser a few days later, releasing a toxic vapor cloud.

3.1.4 Conflicting Priorities

Decision-making errors often result when workers have conflicting priorities, particularly between safety and production. If the rewards for production are much more tangible than the rewards for safety, many workers will do everything possible to keep a unit productive. If workers fear punishment/ridicule for shutting down a unit “unnecessarily” (even though it was the safe course of action), then workers may fail to shut down a unit in time to prevent a process upset from causing an accident. Managers should ensure that workers have clear criteria for shutting down a unit or discontinuing an activity so that the fear

of being second-guessed will not interfere with workers' decision making. The cases below illustrate how conflicting priorities can worsen emergencies:

- ☞ The operator recognized that pressure was rising in the polymerization reactor, but he was reluctant to inject the shortstop solution because it would take days to clear it out of the system. Only after exhausting all other options (stopping feeds, increasing cooling, etc.) did the operator inject the shortstop solution, but it was too late to prevent a runaway reaction.
- ☞ Firefighters were deluging a burning spill of pesticide with water. Even though the diked area had been completely filled with water, some secondary fires still burned in the unit. Rather than abandoning the unit and letting the fires burn out, the firefighters continued to apply water. The pesticide-contaminated water overflowed into the plant's storm sewer system and into other areas that were far more expensive to clean up than the value of the equipment saved by continued firefighting.
- ☞ The operator realized the mud density was too low, but decided to continue drilling. Before the proper mud density was restored, the drill hit a gas pocket, resulting in a well blowout.

3.1.5 Inadequate Labeling

One of the simplest ways to reduce selection errors is to clearly and unambiguously label all controls and equipment. Labeling is particularly helpful to new workers, to workers who only occasionally interact with a system, and to experienced workers in stressful situations (e.g., responding to an emergency). Even if good labels are installed in new units, they will quickly be torn off, painted over, covered with insulation, or outdated by changes in the equipment or process materials, unless an employee has the responsibility and resources to diligently maintain them. When labels are missing, incorrect, or misleading, workers make mistakes such as the following:

- ☞ An unlabeled, high-voltage rectifier for an electrochemical cell had been isolated for routine maintenance. The electrician left the area to get more tools, and upon returning mistook a similar, unlabeled rectifier for the one he had been working on. The electrician was electrocuted when he touched the energized rectifier.
- ☞ Truck drivers from the acid supplier were allowed to connect their own hoses to the storage tanks and unload without operator supervision because the same truck drivers made several deliveries daily. The substitute driver was given routine access to the unloading rack, but she hooked her hose to an adjacent rack. The acid reacted with the tank contents, releasing toxic fumes and melting the tank.
- ☞ In case of a toxic gas release, the sign (Figure 7) at the end of a hallway was intended to direct people down the right-hand corridor, but to keep them on the left side of it so the

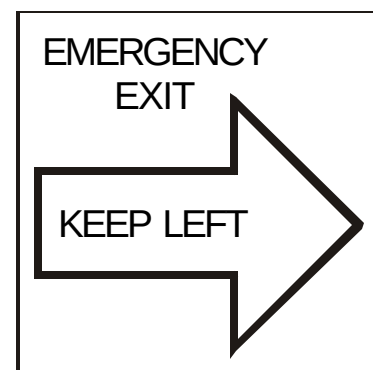


Figure 7 Exit Sign

emergency response team would have a clear path into the building. When an actual release occurred, several workers died trying to escape via the left-hand corridor because the sign required too much information processing when the workers were under time stress.

- ☞ The crude oil unit had been debottlenecked by squeezing a third feed preheater (“C”) in between the two original heat exchangers (“A” and “B”). A new operator was told to isolate the “B” exchanger to stop a tube leak, but she mistakenly assumed the middle exchanger was “B” and blocked in the new “C” exchanger.

When in control rooms and process units, managers should be alert for marks that workers have made on the instruments and equipment to correct labeling deficiencies. You will likely find grease pencil marks on gauge faces to indicate the normal values, masking tape on control panels to relabel controls or mark switch positions, and arrows drawn on three-way valves to indicate the normal flow direction. Rather than accepting such haphazard, temporary markings, you should ensure that clear, accurate, permanent labels are installed wherever they will help the workers.

3.1.6 Inadequate Feedback

Workers require prompt feedback that their actions are eliciting the desired system response. When such feedback is not provided, workers are prone to overreact, as illustrated in the following example:

- ☞ A computer-based control system was so overloaded by a process upset that it ceased to update the video terminals in the control room. Unaware that the displayed information was inaccurate, operators unknowingly moved valves to their fully open or closed limits while waiting for the display to show some response. The mispositioned valves worsened the upset, eventually causing an emergency shutdown of the unit when some relief valves lifted.

3.1.7 Policy/Practice Discrepancies

Written plant policies and procedures are meaningful only when they are enforced; otherwise, worker practices *are* the policy. Once discrepancies are tolerated, individual workers have to use their own judgment to decide what tasks are necessary and/or acceptable. Eventually, someone’s action or omission will violate the system tolerances and result in a serious accident like the ones described below:

- ☞ Even though procedures called for operators to verify the continuity of all electrical grounds and bonds on process equipment daily, only visual checks were actually performed. A severe fire resulted when a corroded connection was not observed, and a static spark ignited a tank’s contents.
- ☞ To resume production as quickly as possible after a furnace trip, operators were in the habit of relighting one burner and “jumping” the flame to adjacent burners (contrary to the written procedure). Supervisors were aware of the practice and allowed it to continue because it saved time and there had never been any significant problems. However, when one of the burners failed to light promptly, a flammable gas cloud accumulated in the furnace and exploded.