Chapter

6

Human Factors in Process Plants and Facility Design

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6.1 Introduction

A common characteristic of large-scale technological facilities such as chemical processing plants, refineries, energy conversion and generation systems (e.g., nuclear, fossil fuel, thermoelectric power plants, gas processing facilities), offshore rigs, and high-capacity compressor and pumping stations is that large amounts of potentially hazardous, flammable, combustible, or pressurized materials are concentrated and processed in single sites under the centralized control of a few operators. The immediate effects of human error in these facilities are often neither observable nor reversible; therefore, error recovery is either too late or impossible. Catastrophic breakdowns of these systems, resulting from human and natural causes, pose serious, long-lasting health and environmental threats. For the foreseeable future, despite increasing levels of computerization and automation, human operators will remain in charge of the day-to-day controlling and monitoring of these systems. Thus the safe and efficient operation of these technological systems is a function of the interactions among their *human* (i.e., personnel and organizational) and *engineered* subsystems. This chapter attempts to (1) review critical human factors (micro- and macroergonomic) considerations that play a significant role in the safe and efficient performance of industrial facilities and (2) present an actual example demonstrating the instrumental effect of the lack of such considerations in a major accident at a chemical plant.

6.2 Significance

Human ingenuity can now create technological systems whose accidents rival in their effects the greatest of natural disasters, sometimes with even higher death tolls and greater environmental damage. Potential catastrophic breakdowns of the above-mentioned technological systems, caused by an error or an accident, could pose serious threats with long-lasting health and environmental consequences for the workers, for the local public, and possibly for the neighboring region and country.[1]

The accidental release of methyl isocyanate (MIC) at the Union Carbide pesticide plant in Bhopal, India, on December 4, 1984, was caused primarily by a series of "design-induced" human and organizational systems' errors.[2,3] It resulted in the death of "more than 4000 people"[4]; some estimates said "as many as 15,000 have died since the time of the accident."[5] More than 300,000 others had been affected by the exposure; "about 2000 animals had died, and 7000 more were severely injured."[3] On average, two of the people who were injured at the onset of this disaster died every day in 1990.[6] Those who survived the gas initially "are continuing to suffer not only deterioration of their lungs, eyes, and skin but also additional disorders that include ulcers, colitis, hysteria, neurosis, and memory loss."[7] Moreover, the MIC exposure has even affected the second generation, "mortality and abnormalities among children conceived and born long after the disaster to exposed mothers and fathers continue to be higher than among a selected control group of unexposed parents."[7] Also, according to a report issued by the National Toxic Campaign Fund, on the basis of laboratory tests, several toxic substances were found in the Bhopal environment, raising further questions about the additional long-term environmental effects of the disaster.[8]

6.2.1 The requirements for incorporation of human factors in chemical processes and plant design

Human factors and organizational problems have, historically, plagued the safety and operation of petrochemical plants and refineries. According to many accident investigations, including several by the U.S. Occupational Safety and Health Administration (OSHA), between 19 and 80 percent of all incidents and accidents at these facilities are caused by "human error." Moreover, the Chemical Manufacturers Association, which is the major U.S. trade association of petrochemical companies, has acknowledged that "Managers in the [petro-]chemical process industry have found human errors to be significant factors in almost every quality problem, production outage, or accident at their facilities" (p. 1).[9]

OSHA has estimated that between 1983 and 1987, an average of 265 fatalities and 901 injuries or illnesses were associated with major accidents involving hazardous materials.[10] One way to reduce these numbers is by regulation and rule making.

On February 24, 1992, OSHA released the Final Rule of the Process Safety Management (PSM) Standard, 29 CFR 1910.119. According to paragraph (e)(3)(vi), "the process hazards analysis shall address human factors."[11] As OSHA has admitted, it "finally added" this paragraph, which requires that employers address human factors in the process hazard analysis (p. 6377).[11]

OSHA further elaborates: "The Process Hazard Analysis (PHA) focuses on equipment, instrumentation, utilities, human actions (routine and nonroutine), and external factors that might impact the process. These considerations assist in determining the hazards and potential failure points or failure modes in a process" (p. 6412)[11] Moreover, in late September of 1992, OSHA released the Compliance Guidelines for Process Safety Management Standard, wherein, under the PHA section, in reference to human factors it states, "Such factors may include a review of the operator/process and operator/equipment interface, the number of tasks operators must perform and the frequency, the evaluation of extended or unusual work schedules, the clarity and simplicity of control displays, automatic instrumentation versus manual procedures, operators' feedback, clarity of signs and codes, etc."[12]

6.2.2 Human-organization-technology Interactions

Stability, safety, and the efficient operation of technological systems, as well as their ability to tolerate environmental disturbances, are a function of the interactions among their *human* (i.e., personnel and organizational) and *engineered* (technological) subsystems. In other words, the survival of technological systems depends on the nature, formation, and interaction of their human, organizational, and technological (HOT) subsystems.[3,13,14] The connection of these three HOT subsystems, in the context of the total system, is represented in Fig. 6.1. This simplified and symbolic demonstration depicts only one critical system's reality—the role of each subsystem as a link in a chain—in the integrity of the whole system. It does not, of course, show all the needed subsystems' interactions and interrelationships.

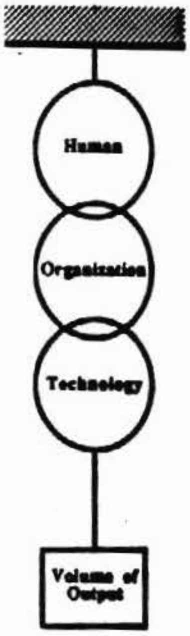

Figure 6.1 Major subsystems of a technological system.

The chain metaphor is also helpful in understanding the effects of output or production load, produced by the system, on its individual subsystems. Any increase in the output level or the capacity-utilization rate imposes strain on *all* subsystems.

Obviously, the chain (system) will break down if any link fails. This may occur if all the links (subsystems) are not equally strong and designed for handling the additional load or if they are not adequately prepared and reinforced to carry the extra load in a sustainable fashion. Research has shown that a majority of the accidents in complex large-scale technological systems have been caused by breakdowns of the weakest links in this chain, most often the human or organizational subsystems.[14,15,16,17]

6.3 Human Factors and Ergonomics

Human factors, or *ergonomics*, is a scientific field concerned with improving the productivity, health, safety, and comfort of people, as well as the effective interaction between people, the technology they are using, and the environment in which both must operate. While both *human factors* and *ergonomics* are used interchangeably, the term *ergonomics* is used when focusing on how work affects people.[18] This concerns issues such as fatigue due to prolonged monitoring tasks, injuries due to unsafe workstations, and errors due to a confusing console layout. Because of the various facets covered by the science of ergonomics, it is considered interdisciplinary and draws from several fields: engineering, physiology, psychology, industrial design, biomechanics, anthropometrics, information technology, and industrial management.[19]

A straightforward justification for the need for ergonomic considerations is that technological systems are being controlled by humans; therefore, they should be designed with the human operator's physical and psychological needs, capabilities, and limitations in mind. Ergonomics can be divided into two related and complementary areas of concentration: microergonomics and macroergonomics. Micro- and macroergonomic approaches build on each other and concentrate on the introduction, integration, and use of technology and its interface with the end-user population. The overall objective is to improve the safety and efficiency of the intended technological system.[20]

6.3.1 Microergonomics

Microergonomics, also called *human engineering*, addresses the relationship between humans, equipment, and the physical environment. It is focused on the human-machine system level and is, for example, concerned with the design of individual workstations, work methods, tools, control panels, and displays. Microergonomics includes studies of human body sizes, known as *anthropometrics*, physical and psychological abilities and limitations, information processing, and human decision making and error. It is noteworthy that according to studies of control room design of nuclear power plants: "The Human Error Probability (HEP) will be reduced by factors of 2 to 10 if the workstations (display and controls) are improved by the incorporation of standard human engineering concepts."[21]

Microergonomics aims to reduce incompatibilities between operator abilities and system requirements. The following list represents additional areas of microergonomics consideration:

- *Materials handling*. The materials-handling function includes the methods, equipment, and paths by which raw materials, work-in-progress, finished products, and process materials are moved into, within, and out of a facility. Materials handling should be evaluated from both the user's point of view and the safety of others in the facility. Examples (and areas of consideration): workplace layout, mobile racks, mechanical lifting, handling without twisting, two-way transport, marked transport ways, and clear escape-ways.
- *Handtool design and use*. Handtool use is especially critical in maintenance and construction areas but should be considered throughout

a facility. Attention should be directed at acute (single-occurrence) risks as well as chronic (long-term) risks and fatigue. Examples (and areas of considerations): locations of tools, pressure on joints or tissue, fatigue and soreness, pinch points, awkward hand positions, trays and carriers, special-purpose tools, safe power tools, hanging tools, hand support for precision, minimizing tool weight, handtool guards, tool vibration and noise, maintenance of tools, stable footing for power tool operators, insulation of handtools, handle design, switches, and stops.

- *Machinery design.* The interface between the operator and the machinery used is of prime importance. Effective displays can assist operators in determining action needs while contributing to their general facility knowledge. Ineffective machines and displays not only contribute to errors but do not provide essential operator feedback. Examples (and areas of considerations): mode of display, signal detection, auditory presentation, visual presentation, accidental activation, emergency controls, reaching controls, easy-to-distinguish foot pedals, easy-to-distinguish displays, legible labels and signs, markings on displays, easy-to-read symbols, warning signs, interlock barriers, feeding and ejection devices, enclosing moving parts, dial designs, control spacing, coding, resistance, and location.
- *Workstation design.* Workstation design involves the consideration of body measurements (anthropometrics) in the arrangement of equipment in the operator's immediate vicinity. Workstation design revolves around optimizing the physical interface between operator and workstation through comfort, body posture, reach, and sight. Examples (and areas of considerations): video display unit design, viewing angles, eye height, eyeglasses, elbow height, work reach consideration for smaller workers, space consideration for larger workers, objects within reach, sitting versus standing surfaces, adjustable chairs, adjustable work surfaces, adjustable terminals, platforms, steps, mechanical lifts, footrests, and armrests.
- *Workplace environment.* Workplace environment considerations include those physical aspects of the immediate environment which contribute to the workers' comfort and ability to perform their jobs without excess physical exertion or discomfort. Discomfort and sub-optimal environmental factors (such as lighting and temperature) interfere with the workers' ability to perform their job correctly and efficiently. Examples: use of daylight, wall/ceiling colors, brightness, sufficient lighting, glare prevention, visual task backgrounds, insulating hot surfaces, ventilation systems, reducing noise, sanitary facilities, break areas, reaches, and clearances.

For further information, design guidelines, and data on microergonomic considerations, see refs. 9, 18, and 22 through 32.

6.3.2 Macroergonomics

Ergonomics at the macro level, *macroergonomics*, is focused on the overall people-technology system level and is concerned with the impact of technological systems on organizational, managerial, and personnel (sub-) systems. Macroergonomics includes such areas as training, management, the planning process, information systems, internal review/inspection programs, performance measurement systems, reward structure, initial employee qualifications assessments, and personnel selection criteria.[33] Additional areas on which macroergonomics focuses include

- *Job analysis*. Its purpose is to provide a description of what workers do on the job for which selection and training procedures are developed. The description should cover operations performed, equipment used, conditions of work, radiation, other hazards, and other special characteristics of the job; nature and amount of required basic, classroom, and on-the-job training; opportunities for transfer; and relation to other jobs and other pertinent information.
- *Training*. Operators should receive initial/introductory training as well as refresher and continuing-education training. Examples: training-needs analyses based on inputs from job analysis, tool skills, machinery skills, workstations, involvement in improvements, worker rewards, and task combination.
- *Communications*. This area includes formal and informal communications between all levels of employees and contract workers. Communication requires participation by all who are involved and provides operators and management with better ideas of facility conditions and responses required. Examples: ensuring the compatibility of organizational communication and decision-making networks, information sharing, feedback, and instructions.
- *Policies and procedures*. This area is related to both training and communications. Policies and procedures provide an outline of how issues should be addressed. It is very important that different departments do not have conflicting procedures and that they are consistently followed. Examples: design of the standard operating procedures and emergency operating procedures.
- *Organizational design*. It is well known that the two major building blocks of any technological system are the physical engineered com-

ponents and the human operators. The organization (and its structure) has an equally important supporting role, being perhaps analogous to the mortar—facilitating the interface, connecting and joining the blocks together. Example: design of the organizational structure of the control room crew of dynamic technological systems. Sometimes when complex technological systems, such as nuclear power plants, move from routine to nonroutine (normal to emergency) operation, the control operators need to dynamically match the new systems requirements. This requires the organizational reconfiguration of the operators' team and leads to some changes in team (organizational) communications.

6.3.3 Incorporation of ergonomic considerations

In order to prevent accidents in industrial facilities, an integrated approach to design and operation should be taken that is as attentive to human factors as it is to technical elements.[13,16] This approach should be based on a systems-oriented and integrated analysis of the processes, operations, procedures, workstations, management, organizational, and supervisory systems.

Recommendations for design. In order to ensure the relative safety of future (to-be-designed) large-scale technological systems, such as processing plants and refineries, a holistic, totally integrated, and multidisciplinary approach to system design, construction, staffing, and operation, based on sound scientific studies and human factors guidelines, is recommended. The *total system design* (TSD) constitutes such an approach. The TSD, according to Baily,[34] is a developmental approach that is based on a series of clearly defined development stages. TSD, which has been used extensively for computer-based systems development at AT&T Bell Laboratories, implies that, from the inception of the plan, *equal* and *adequate* consideration should be given to all major system components (i.e., human, organizational, and technological). The system-development process, therefore, is partitioned into a series of meaningfully related groups of activities called *stages*, each of which contains a set of design and accompanying human factors activities.

The early participation of all related and needed disciplines, including human factors, in plant system design and development is also strongly recommended. This mandates and encourages interdisciplinary dialogue among engineers, managers, human factors experts, and safety specialists. A recent joint publication by AT&T and the U.S. Navy[35] has attempted to operationalize some of these problems, labeled *latent design defects*, at the boundaries of systems. This approach to the integration of design and manufacturing is in accordance with what is proposed by Davidow and Malone as engineering design in *The Virtual Corporation:* "Everyone affected by design decisions becomes involved in the design process to make sure that the multiplicity of downstream needs (manufacturability, serviceability, market demand, and so on) are met."[36]

In addition to independent and isolated problems at the workstation (interface), job (task), and organizational (communication) levels, there was a serious lack of cohesive processes of data collection, integration, and coordination (as was demonstrated by many complex technological systems accidents). Logically, information is gathered from the interfaces (at the *workstation* site), analyzed according to the operators' stipulated job descriptions (at the *job* level), and passed through organizational communication network (according to the *organizational* structure) to the appropriate team members responsible for decision making. Thus this continuous process in the control rooms of large-scale technological systems must include[16]

1. A cohesive and integrated framework for data gathering from the interfaces (at the workstation site)
2. Displays, decision aids, and reference information to permit operator comprehension, analysis, and response (at the job level; as stipulated in the job descriptions)
3. A communication network for the passage of information (according to the organizational structure) to and from the appropriate decision makers

The design effort will be more effective if the design team understands and anticipates the micro- and macroergonomic considerations of plant operation.

Operating considerations. The first priority of operating management should be the close examination of human operators' physical and psychological needs, capabilities, and limitations in the context of plant operation during normal and emergency conditions. This also should be coupled with thorough analyses of critical workstations, panels, control rooms, and their design features; control room procedures and emergency situations; task-loading factors, job demands, and operators' mental workloads (during normal as well as emergency situations); emergency response system; organizational and administrative factors such as structure and hierarchy, communication, decision latitude, performance indicators, and rewards; managerial practices and supervisory styles; work and shift schedules; and training needs, programs, and methods.

In order to produce and maintain a better motivated, more flexible, safety conscious, and higher-skilled workforce, it is recommended that petrochemical plants implement the "skill-based pay system." This is fundamentally different from the conventional system of job-based pay, where employees are paid for the particular jobs they are performing, not for their ability to perform other tasks. In the skill-based pay system, operators are rewarded for both the skill and the knowledge they apply at work and their individual performance and contribution to team goals.[37] Moreover, this pay system will further foster and reward the formation of self-organized teams of operators which, as past experience also has shown, are critical in safe handling of emergency situations.

A summary of the proposed micro- and macroergonomic considerations for integration into the design and operation of industrial facilities is presented below.

1. Microergonomic-related areas
   - Workstation, control panels, and control room design
   - Physical layout of the process in the plant and its required controls
   - Control room procedures and emergency situations
   - Human-computer (user) interface design-related issues
   - Potential for "procedural traps"
   - Annunciators and emergency notification and response systems
   - Mental and physical workload (during normal as well as emergency situations)
   - Potential for distraction, unexpected interruptions, preoccupation, and premature exits during normal situations
   - Occupational stress analysis
   - Motivational factors
   - Anthropometric considerations
   - Human (physical and psychological) needs, limitations, and capabilities
   - Human decision-making and information processing
   - Causes of human errors
   - Potential for systematic human error
   - Job design and task loading factors
   - Rationale for prioritization of inputs to operators and their activities
   - Shift duration and rotation schedule

2. Macroergonomic-related areas
   - Safety culture
   - Organizational structures
   - Policies and standard operating procedures
   - Management of change
   - Management activities and capabilities
   - Management information systems and reporting structure
   - Internal review/inspection programs
   - Compliance with reviews and corrective actions
   - Selection and development of training programs
   - Qualifications and training of instructors
   - Definition and evaluation of skills and knowledge (for personnel training)
   - Ongoing performance and refresher training
   - Operating and maintenance procedures
   - Initial employee qualifications assessments
   - Performance measurement systems and their effectiveness
   - Records management

6.4 Lack of Human Factors Considerations: A Case Study of a Chemical Plant Accident

6.4.1 Background and introduction

In this case study, micro- and macroergonomic analyses have been used postmortem to identify hazards associated with human actions (routine and nonroutine) in a chemical plant. This chemical plant accident occurred in 1992 and caused major losses. About 280 operators, supervisors, and other employees lost their jobs. The plant, which was valued at around $20 million with revenues of $17 to $21 million a year, had to be closed. The mishap at this chemical plant was caused by a chain of events and problems that collectively contributed to a major accident. It has been concluded that both equipment failure (possibly caused by maintenance problems) and lack of human factors considerations, which are discussed below, caused this accident.

6.4.2 Facts and observations

The accident occurred in the chlorination area. The morning operator had informed the afternoon operator and his supervisor that the previous load from reactor 3 had been produced faster than normal (17 hours instead of 23 to 25 hours, which is the normal cycle). The morning operator left reactor 3 with a new load.

- Operators did not take any further action on this information.
- Supervisors did not take any action because they were not properly informed about the characteristics of the specific equipment.

The afternoon operator left his workstation to repair a fume tower, an action that he considered very important because it could prevent a "backup" of fumes and major problems later on. He closed all the chlorine valves in order to stop the plant process and prevent other accidents.

- The operator did not have a communication system with the supervisor or maintenance crew.
- As a result, the operator had to repair the tower himself instead of having the maintenance people take care of the problem.

The operator was informed that the load from reactor 2 was ready for transfer. While transferring the load, the operator felt air leaking from the pneumatic line that connects the temperature sensor on the reactor to the graphic display. From this line ran the signals to the control valve of the automatic cooling system.

- The automatic cooling system should have had its own temperature sensor instead of relying on information from the graphic display.
- The operator did not check the air pressure, which had to be 62 kPa (9 lb/in^2) for the pneumatic system to work properly.

When another operator patched a hole in the pneumatic signal line, the graphic display from reactor 3 increased drastically from 71°C (160°F) to 100°C (212°F). The reactor operator checked the display gauge, which showed the reactor temperature to be 75°C (167°F).

- The operator assumed that the 71°C and 75°C measurements were correct.
- Both the graphic and display gauges were showing incorrect temperatures.
- The supervisor approved the operator's assessment without any analysis.

After observing that all temperatures and pressures were "normal," the operator went back to the fume tower to continue repairs. During these repairs, the operator heard a rupture disk break; he started the gas observation pump and then monitored the reactors' temperatures and pressures. He saw that they were all correct but, upon leaning against reactor 3, discovered that it was extremely hot.

- The operator did not know which rupture disk broke, because after the rupture disk on reactor 3 burst, the pressure in the reactor went down into the normal (nearly atmospheric) range.
- The design did not include the typical alarms for high pressure.

At this point, the operator blocked the transfer of chlorine vapors between reactors 3 and 4 in order to stop the rise in temperature. While he was doing this, he heard a pounding at the water exit pipe. Thinking that cooling water was going into the reactor (a very volatile situation), he proceeded to shut down the cooling water for the whole system.

- Just before he heard the pounding, the operator's assessment of the situation was accurate. He thought that the automatic cooling valve did not work, and he was about to take the correct action, which was to open the water bypass valve. Instead, he aggravated the problem by shutting off the water.
- The operator had to rely solely on his previous experience in order to make a decision.

After closing the water valve, the operator thought that the problem was solved. He went and closed the chlorine valve from the storage tanks. Since the contents of reactor 3 were still getting hotter, thermal expansion of the liquid caused the level to reach the pipe for the rupture disk; this pipe was made of PVC, which melted and caused a spill. At the same time, the contents also reached the expansion tank, which contained nitrobenzene. This caused a reaction that produced a large amount of gas.

- The expansion tank should not have contained any material. On this occasion it was being used as a transfer tank.

At this time, supervisors started the emergency procedures, called the fire department, and evacuated the plant.

6.4.3 Summary of the critical events and actions

The mishap at this chemical plant was caused by a chain of events and problems that collectively contributed to a major accident. Three factors collectively caused this accident: *equipment failure* (possibly caused by maintenance problems), *lack of human factors considerations*, and *organizational factors*.

1. *On the role of equipment failure*
   a. The fume tower was not working properly. This caused the operator to leave his work area.
   b. The pneumatic line for the graphic display was leaking. This deprived the operator of accurate measurements.
   c. The display thermometer did not work properly. The operator could not have verified the correct temperature in relation to the graphic display.
   d. The design lacked an integrated alarm system for various elements of the process.

2. *On the role of human factors considerations*
   a. The operator had to rely too much on previous experience with the process (operating in normal regimes).
   b. There was a lack of training for emergency situations, both for operators and for supervisors.
   c. There were too many required decisions for one operator. There was a lack of decision aids for helping the operator in the decision-making process.
   d. Gauges were not located at a centralized place where the operator could stay and obtain all the necessary information.
   e. The use of an expansion tank for the storage of nitrobenzène was not the correct procedure. This action exacerbated damages caused by the accident.

3. *On the role of organizational factors:* No action was taken regarding the previous load, which was produced abnormally fast. This could be caused only by two factors: either an added amount of reactant or a rise in the reactor internal temperature. In the case of this process, the operator did not add any extra reactant, and therefore, from the posterior results, we can surely assume that the problem was caused by improper cooling of the reactor. This, in turn, was the cause for the temperature rise in the next load, which resulted in the accident. A careful analysis of these factors could have prevented this accident.

6.4.4 Analysis

As mentioned before, shutting off the main cooling water of the system was probably the most important error made by the operator. This systematic error occurred because the operator "heard a pounding at the water exit pipe and thought that the cooling water was going into the reactor." In his judgment, the operator was trying to follow the common wisdom and procedures to prevent "a very volatile situation."

An important category of errors within the context of monitoring and supervisory tasks in chemical plants (in which the operators typically have to respond to changes in system operation by corrective actions) is called *systematic error*. Also in this context, two causes of systematic errors seem to be important and should be considered; they are excessive workload and design traps.

Excessive workload. Research has shown that operators' responses to changes in a technological system will be systematically wrong if task demands exceed the limits of capability. In the case of the operator's job, demands and capability may conflict with several aspects of a task such as the time required, availability of needed information, and background knowledge on system functioning.

The physical and mental workload in an industrial plant is highly variable and sometimes could reach high levels. This is synonymous with having or lacking balance between task demands and an operator's capabilities. According to Tikhomirov,[38] high or unbalanced mental workload causes

- Narrowing span of attention
- Inadequate distribution and switching of attention
- Forgetting the proper sequence of actions
- Incorrect evaluation of solutions
- Slowness in arriving at decisions

Design traps. In addition to occasional unbalanced workloads, human factors–related problems of the workstation are a major cause of errors in plants. These types of errors, called *design-induced* or *system-induced errors*, are forced on operators.

Systematic operator error may be caused by several kinds of "procedural traps."[39] During normal working conditions, human operators are generally extremely efficient because of very effective adaptation to convenient representative signs and signals that they receive from the system. This is a very effective and mentally economical strategy during normal and familiar periods, but it leads the operator into traps when changes in system conditions are not adequately reflected in displays. Such mental traps often significantly contribute to the operator's misidentification of unfamiliar and complex system states. This misidentification, in turn, is usually caused by the activation of "strong but wrong" rules, where the "strength" is determined by the relative frequency of successful execution. When abnormal conditions der countermeasures from the operator, a shift in the mental work gies is needed. However, it is very likely that familiar a based on representative but insufficient information will prevent the operator from realizing the need to analyze a complex and/or unique situation. The operator may more readily accept the improbable coincidence of several familiar faults in the system rather than the need to investigate one new and complex "fault of low probability." In this case, the efficiency of the human operator's internal mental model allows him or her to be selective and, therefore, to cope effectively with complex systems in familiar situations but at the same time may lead him or her into traps that are easily seen after the fact.

The importance of the different categories of error depends on the task conditions. It is suggested that repetitive routine tasks in the plant, which are preplanned, such as responding to alarms, errors caused by demands exceeding resource limits, and errors resulting from procedural traps should be thoroughly investigated and subsequently removed by redesign of the task.

6.4.5 Lessons

This accident caused major losses, as stated in the beginning of the case description. Although accidents are always tragic and can have devastating effects, there are many lessons that society and industry can learn from them. The most important one is that there is a great need for thorough analyses of equipment reliability and human factors in order to prevent other similar major losses.

Most accidents start with equipment malfunction, a process upset, or operator error, but they are aggravated and propagated through the system by a series of factors that could be attributed to bad design, inadequate training, and lack of preparation. Attributing accidents to the action of front-line operators is an oversimplification of the problem. As research has shown, in most cases, operator error is only one attribute of the whole technological (plant) system—a link in a chain of concatenated failures—that could result in accidents. In order to prevent accidents in chemical plants and other facilities, as demonstrated by this case study, an integrated approach to the design and operation, as attentive to human factors as to technical elements, should be taken.[13,40] This approach should be based on a thorough and integrated micro and macro human factors (ergonomic) analysis of the process workstations, procedures, management, and supervisory systems.

6.5 References

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