CHAPTER 74
SAFETY ENGINEERING

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74.1 INTRODUCTION

74.1.1 Background

More than ever before, engineers are aware of and concerned with employee safety and health. The necessity for this involvement was accelerated with the passage of the OSHAct in 1970, but much of what has occurred since that time would have happened whether or not the OSHAct had become the law.

As workplace environments become more technologically complex, the necessity for protecting the work force from safety and health hazards continues to grow. Typical workplace operations from which workers should be protected are presented in Table 74.1. Whether they should be protected through the use of personal protective equipment, engineering controls, administrative controls, or a combination of these approaches, one fact is clear; it makes good sense to ensure that they receive the most cost-effective protection available. Arguments in support of engineering controls over personal protective equipment and vice versa are found everywhere in the current literature. Some of the most persuasive discussions are included in this chapter.

74.1.2 Employee Needs and Expectations

In 1981 ReVelle and Boulton asked the question, "Who cares about the safety of the worker on the job?" in their award-winning two-part article in *Professional Safety,* "Worker Attitudes and Perceptions of Safety." The purpose of their study was to learn about worker attitudes and perceptions of safety. To accomplish this objective, they established the following working definition:

WORKER ATTITUDES AND PERCEPTIONS As a result of continuing observation, an awareness is developed, as is a tendency to behave in a particular way regarding safety.

To learn about these beliefs and behaviors, they inquired to find out:

1. Do workers think about safety?
2. What do they think about safety in regard to:
   (a) Government involvement in their workplace safety.
   (b) Company practices in training and hazard prevention.
   (c) Management attitudes as perceived by the workers.
   (d) Coworkers' concern for themselves and others.
   (e) Their own safety on the job.
3. What do workers think should be done, and by whom, to improve safety in their workplace?

Table 74.1 Operations Requiring Engineering Controls and/or Personal Protective Equipment

Acidic/basic process and treatments	Grinding
Biological agent processes and treatments	Hoisting
Blasting	Jointing
Boiler/pressure vessel usage	Machinery (mills, lathes, presses)
Burning	Mixing
Casting	Painting
Chemical agent processes and treatments	Radioactive source processes and treatments
Climbing	Sanding
Compressed air/gas usage	Sawing
Cutting	Shearing
Digging	Soldering
Drilling	Spraying
Electrical/electronic assembly and fabrication	Toxic vapor, gas, and mists and dust exposure
Electrical tool usage	Welding
Flammable/combustible/toxic liquid usage	Woodworking

The major findings of the ReVelle–Boulton study are summarized here.*

Half the workers think that government involvement in workplace safety is about right; almost one-fourth think more intervention is needed in such areas as more frequent inspections, stricter regulations, monitoring, and control.

Workers in large companies expect more from their employers in providing a safe workplace than workers in small companies. Specifically, they want better safety programs, more safety training, better equipment and maintenance of equipment, more safety inspections and enforcement of safety regulations, and provision of more personal protective equipment.

Supervisors who talk to their employees about safety and are perceived by them to be serious are also seen as being alert for safety hazards and representative of their company's attitude.

Coworkers are perceived by other employees to care for their own safety and for the safety of others.

Only 20% of the surveyed workers consider themselves to have received adequate safety training. But more than three-fourths of them feel comfortable with their knowledge to protect themselves on the job.

Men are almost twice as likely to wear needed personal protective equipment as women.

Half the individuals responding said they would correct a hazardous condition if they saw it.

Employees who have had no safety training experience almost twice as many on-the-job accidents as their fellow workers who have received such training.

Workers who experienced accidents were generally candid and analytical in accepting responsibility for their part in the accident; and 85% said their accidents could have been prevented.

The remainder of this chapter addresses those topics and provides that information which engineering practitioners require to professionally perform their responsibilities with respect to the safety of the work force.

74.2 GOVERNMENT REGULATORY REQUIREMENTS†

Two relatively new agencies of the federal government enforce three laws that impact many of the operational and financial decisions of American businesses, large and small. The Environmental Protection Agency (EPA) has responsibility for administering the Toxic Substances Control Act (TSCA) and the Resource Conservation and Recovery Act (RCRA), both initially enforced in 1976. The Occupational Safety and Heath Act (OSHAct) of 1970 is enforced by the Occupational Safety and Health Administration (OSHA), a part of the Department of Labor. This section addresses the regulatory demands of these federal statutes from the perspective of whether to install engineering controls that would enable companies to meet these standards or simply to discontinue certain operations altogether, that is, can they justify the associated costs of regulatory compliance.

74.2.1 Environmental Protection Agency (EPA)

Toxic Substances Control Act (TSCA)

Until the TSCA, the federal government was not empowered to prevent chemical hazards to health and the environment by banning or limiting chemical substances at a germinal, premarket stage. Through the TSCA of 1975, production workers, consumers, indeed every American, would be protected by an equitably administered early warning system controlled by the EPA. This broad law authorizes the EPA Administrator to issue rules to prohibit or limit the manufacturing, processing, or distribution of any chemical substance or mixture that "may present an unreasonable risk of injury to health or the environment." The EPA Administrator may require testing—at a manufacturer's or processor's expense—of a substance alter finding that:

- The substance may present an unreasonable risk to health or the environment.
- There may be a substantial human or environmental exposure to the substance.
- Insufficient data and experience exist for judging a substance's health and environmental effects.
- Testing is necessary to develop such data.

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This legislation is designed to cope with hazardous chemicals like kepone, vinyl chloride, asbestos, fluorocarbon compounds (Freons), and polychlorinated biphenyls (PCBs).

Resource Conservation and Recovery Act (RCRA)

Enacted in 1976 as an amendment to the Solid Waste Disposal Act, the RCRA sets up a "cradle-to-grave" regulatory mechanism, that is, a tracking system for such wastes from the moment they are generated to their final disposal in an environmentally safe manner. The act charges the EPA with the development of criteria for identifying hazardous wastes, creating a manifest system for tracking wastes through final disposal, and setting up a permit system based on performance and management standards for generators, transporters, owners, and operators of waste treatment, storage, and disposal facilities. It is expected that the RCRA will be a strong force for innovation and eventually lead to a broad rethinking of chemical processes, that is, to look at hazardous waste disposal *not* just in terms of immediate costs, but rather with respect to life-cycle costs.

74.2.2 Occupational Safety and Health Administration (OSHA)*

The Occupational Safety and Health Act (OSHAct), a federal law that became effective on April 28, 1971, is intended to pull together all federal and state occupational safety and health-enforcement efforts under a federal program designed to establish uniform codes, standards, and regulations. The expressed purpose of the act is "to assure, as far as possible, every working woman and man in the Nation safe and healthful working conditions, and to preserve our human resources." To accomplish this purpose, the promulgation and enforcement of safety and health standards is provided for, as well as research, information, education, and training in occupational safety and health.

Perhaps no single piece of federal legislation has been more praised and, conversely, more criticized than the OSHAct, which basically is a law requiring virtually all employers to ensure that their operations are free of hazards to workers.

Occupational Safety and Health Standards

When Congress passed the OSHAct of 1970, it authorized the promulgation, without further public comment or hearings, of groups of already codified standards. The initial set of standards of the act (Part 1910, published in the *Federal Register* on May 29, 1971) thus consisted in part of standards that already had the force of law, such as those issued by authority of the Walsh–Healey Act, the Construction Safety Act, and the 1958 amendments to the Longshoremen's and Harbor Workers' Compensation Act. A great number of the adopted standards, however, derived from voluntary national consensus standards previously prepared by groups such as the American National Standards Institute (ANSI) and the National Fire Protection Association (NFPA).

The OSHAct defines the term "occupational safety and health standard" as meaning "a standard which requires conditions or the adoption or use of one or more practices, means, methods, operations or processes, reasonably necessary or appropriate to provide safe or healthful employment and places of employment." Standards contained in Part 1910† are applicable to general industry. Those contained in Part 1926 are applicable to the construction industry; and standards applicable to ship repairing, shipbuilding, and longshoring are contained in Parts 1915–1918. These OSHA standards fall into the following four categories, with examples for each type:

1. *Specification Standards.* Standards that give specific proportions, locations, and warning symbols for signs that must be displayed.
2. *Performance Standards.* Standards that require achievement of, or within, specific minimum or maximum criteria.
3. *Particular Standards (Vertical).* Standards that apply to particular industries, with specifications that relate to the individual operations.
4. *General Standards (Horizontal).* Standards that can apply to any workplace and relate to broad areas (environmental control, walking surfaces, exits, illumination, etc.).

The Occupational Health and Safety Administration is authorized to promulgate, modify, or revoke occupational safety and health standards. It also has the authority to promulgate emergency temporary standards where it is found that employees are exposed to grave danger. Emergency temporary standards can take effect immediately on publication in the *Federal Register.* Such standards remain in

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†The Occupation Safety and Health Standards, Title 29, CFR Chapter XVIII, Parts 1910, 1926, and 1915–1918 are available at all OSHA regional and area offices.

effect until superseded by a standard promulgated under the procedures prescribed by the OSHAct—notice of proposed rule in the *Federal Register,* invitation to interested persons to submit their views, and a public hearing if required.

Required Notices and Records

During an inspection the compliance officer will ascertain whether the employer has:

- Posted notice informing employees of their rights under the OSHAct (Job Safety and Health Protection, OSHAct poster).
- Maintained log of recordable injuries and illnesses (OSHA Form No. 200, Log and Summary of Occupational Injuries and Illnesses).
- Maintained the Supplementary Record of Occupational Injuries and Illnesses (OSHA Form No. 101).
- Annually posted the Summary of Occupational Injuries and Illnesses (OSHA Form No. 200). This form must be posted no later than February 1 and must remain in place until March 1.
- Made a copy of the OSHAct and OSHA safety and health standards available to employees on request.
- Posted boiler inspection certificates, boiler licenses, elevator inspection certificates, and so on.

74.2.3 State-Operated Compliance Programs

The OSHAct encourages each state to assume the fullest responsibility for the administration and enforcement of occupational safety and health programs. For example, federal law permits any state to assert jurisdiction, under state law, over any occupational or health standard not covered by a federal standard.

In addition, any state may assume responsibility for the development and enforcement of its own occupational safety and health standards for those areas now covered by federal standards. However, the state must first submit a plan for approval by the Labor Department's Occupational Safety and Health Administration. Many states have done so.

Certain states are now operating under an approved state plan. These states may have adopted the existing federal standards or may have developed their own standards. Some states also have changed the required poster. You need to know whether you are covered by an OSHA-approved state plan operation, or are subject to the federal program, in order to determine which set of standards and regulations (federal or state) apply to you. The easiest way to determine this is to call the nearest OSHA Area Office.

If you are subject to state enforcement, the OSHA Area Office will explain this, explain whether the state is using the federal standards, and provide you with information on the poster and on the OSHA recordkeeping requirements. After that, the OSHA Area Office will refer you to the appropriate state government office for further assistance.

This assistance also may include free on-site consultation visits. If you are subject to state enforcement, you should take advantage of this service.

For your information, the following are operating under OSHA-approved state plans, as of September 1, 1997

Alaska	New Mexico
Arizona	New York
California	Oregon
Connecticut	Puerto Rico
Guam	South Carolina
Hawaii	Tennessee
Indiana	Utah
Iowa	Vermont
Kentucky	Virginia
Maryland	Virgin Islands
Michigan	Washington
Minnesota	Wyoming
Nevada	

74.3 SYSTEM SAFETY*

System safety is when situations having accident potential are examined in a step-by-step cause–effect manner, tracing a logical progression of events from start to finish. System safety techniques can

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provide meaningful predictions of the frequency and severity of accidents. However, their greatest asset is the ability to identify many accident situations in the system that would have been missed if less detailed methods had been used.

74.3.1 Methods of Analysis

A system cannot be understood simply in terms of its individual elements or component parts. If an operation of a system is to be effective, all parts must interact in a predictable and a measurable manner, within specific performance limits and operational design constraints.

In analyzing any system, three basic components must be considered: (1) the equipment (or machines); (2) the operators and supporting personnel (maintenance technicians, material handlers, inspectors, etc.); and (3) the environment in which both workers and machines are performing their assigned functions. Several analysis methods are available:

- *Gross-Hazard Analysis.* Performed early in design; considers overall system as well as individual components; it is called "gross" because it is the initial safety study undertaken.
- *Classification of Hazards.* Identifies types of hazards disclosed in the gross-hazard analysis, and classifies them according to potential severity (Would defect or failure be catastrophic?); indicates actions and/or precautions necessary to reduce hazards. May involve preparation of manuals and training procedures.
- *Failure Modes and Effects.* Considers kinds of failures that might occur and their effect on the overall product or system. Example: effect on system that will result from failure of single component (e.g., a resistor or hydraulic valve).
- *Hazard-Criticality Ranking.* Determines statistical, or quantitative, probability of hazard occurrence; ranking of hazards in the order of "most critical" to "least critical."
- *Fault-Tree Analysis.* Traces probable hazard progression. Example: If failure occurs in one component or part of the system, will fire result? Will it cause a failure in some other component?
- *Energy-Transfer Analysis.* Determines interchange of energy that occurs during a catastrophic accident or failure. Analysis is based on the various energy inputs to the product or system and how these inputs will react in event of failure or catastrophic accident.
- *Catastrophe Analysis.* Identifies failure modes that would create a catastrophic accident.
- *System-Subsystem Integration.* Involves detailed analysis of interfaces, primarily between systems.
- *Maintenance-Hazard Analysis.* Evaluates performance of the system from a maintenance standpoint. Will it be hazardous to service and maintain? Will maintenance procedures be apt to create new hazards in the system?
- *Human-Error Analysis.* Defines skills required for operation and maintenance. Considers failure modes initiated by human error and how they would affect the system. The question of whether special training is necessary should be a major consideration in each step.
- *Transportation-Hazard Analysis.* Determines hazards to shippers, handlers, and bystanders. Also considers what hazards may be "created" in the system during shipping and handling.

There are other quantitative methods that have successfully been used to recommend a decision to adopt engineering controls, personal protective equipment, or some combination. Some of these methods are:*

- *Expected Outcome Approach.* Since safety alternatives involve accident costs that occur more or less randomly according to probabilities which might be estimated, a valuable way to perform needed economic analyses for such alternatives is to calculate expected outcomes.
- *Decision Analysis Approach.* A recent extension of systems analysis, this approach provides useful techniques for transforming complex decision problems into a sequentially oriented series of smaller, simpler problems. This means that a decision-maker can select reasoned choices that will be consistent with his or her perceptions about the uncertainties involved in a particular problem together with his or her fundamental attitudes toward risk-taking.
- *Mathematical Modeling.* Usually identified as an "operations research" approach, there are numerous mathematical models that have demonstrated potential for providing powerful anal-

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ysis insights into safety problems. These include dynamic programming, inventory-type modeling, linear programming, queue-type modeling, and Monte Carlo simulation.

There is a growing body of literature about these formal analytical methods and others not mentioned in this chapter, including failure mode and effect (FME), technique for human error prediction (THERP), system safety hazard analysis, and management oversight and risk tree (MORT).

All have their place. Each to a greater or lesser extent provides a means of overcoming the limitations of intuitive, trial-and-error analysis.

Regardless of the method or methods used, the systems concept of hazard recognition and analysis makes available a powerful tool of proven effectiveness for decision making about the acceptability of risks. To cope with the complex safety problems of today and the future, engineers must make greater use of system safety techniques.

74.3.2 Fault Tree Technique*

When a problem can be stated quantitatively, management can assess the risk and determine the trade-off requirements between risk and capital outlay. Structuring key safety problems or vital decision-making in the form of fault paths can greatly increase communication of data and subjective reasoning. This technique is called fault-tree analysis. The transferability of data among management, engineering staff, and safety personnel is a vital step forward.

Another important aspect of this system safety technique is a phenomenon that engineers have long been aware of in electrical networks. That is, an end system formed by connecting several subsystems is likely to have entirely different characteristics from any of the subsystems considered alone. To fully evaluate and understand the entire system's performance with key paths of potential failure, the engineer must look at the entire system—only then can he or she look meaningfully at each of the subsystems.

Figure 74.1 introduces the most commonly used symbols used in fault-tree analysis.

74.3.3 Criteria for Preparation/Review of System Safety Procedures†

Correlation Between Procedure and Hardware

1. Statement of hardware configuration to which it was written?
2. Background descriptive or explanatory information where needed?
3. Reflect or reference latest revisions of drawings, manuals, or other procedures?

Adequacy of the Procedure

1. The best way to do the job?
2. Procedure easy to understand?
3. Detail appropriate—not too much, not too little?
4. Clear, concise, and free from ambiguity that could lead to wrong decisions?
5. Calibration requirements clearly defined?
6. Critical red-line parameters identified and clearly defined? Required values specified?
7. Corrective controls of above parameters clearly defined?
8. All values, switches, and other controls identified and defined?
9. Pressure limits, caution notes, safety distances, or hazards peculiar to this operation clearly defined?
10. Hard-to-locate components adequately defined and located?
11. Jigs and arrangements provided to minimize error?
12. Job safety requirements defined, for example, power off, pressure down, and tools checked for sufficiency?
13. System operative at end of job?
14. Hardware evaluated for human factors and behavioral stereotype problems? If not corrected, are any such clearly identified?
15. Monitoring points and methods of verifying adherence specified?

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†Reprinted from *MORT* Safety Assurance Systems, pp. 278–283, by courtesy of Marcel Dekker, Inc., New York.

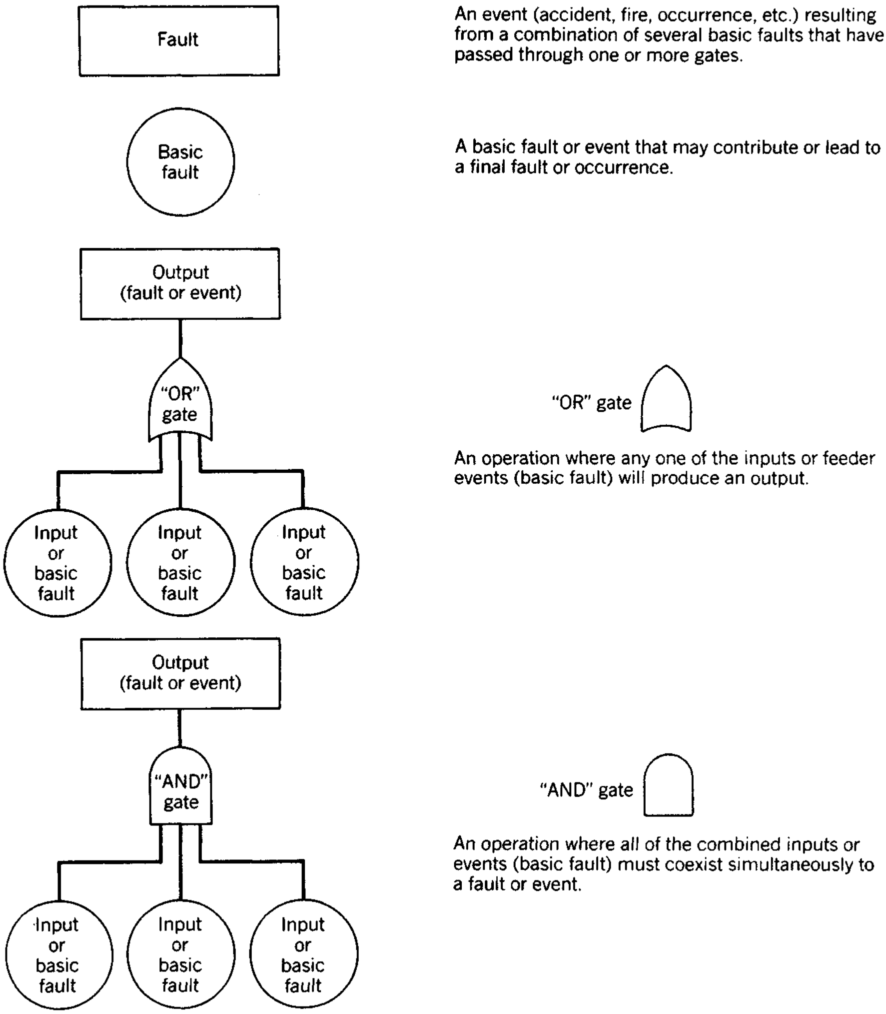

Fig. 74.1 Most common symbols used in fault-tree analysis.

16. Maintenance and/or inspection to be verified? If so, is a log provided?
17. Safe placement of process personnel or equipment specified?
18. Errors in previous, similar processes studied for cause? Does this procedure correct such causes?

Accuracy of the Procedure

1. Capacity to accomplish specified purpose verified by internal review?
2. All gauges, controls, valves, etc., called out, described, and labeled exactly as they actually are?
3. All setpoints or other critical controls, etc., compatible with values in control documents?
4. Safety limitations adequate for job to be performed?
5. All steps in the proper sequence?

Adequacy and Accuracy of Supporting Documentation

1. All necessary supporting drawings, manuals, data sheets, sketches, etc., either listed or attached?

2. All interfacing procedures listed?

Securing Provisions

1. Adequate instructions to return the facility or hardware to a safe operating or standby condition?
2. Securing instructions provide step-by-step operations?

Backout Provisions

1. Can procedure put any component or system in a condition which could be dangerous?
2. If so, does procedure contain emergency shutdown or backout procedures either in an appendix or as an integral part?
3. Backout procedure (or instructions for its use) included at proper place?

Emergency Measures

1. Procedures for action in case of emergency conditions?
2. Does procedure involve critical actions such that preperformance briefing on possible hazards is required?
3. Are adequate instructions either included or available for action to be taken under emergency conditions? Are they in the right place?
4. Are adequate shutdown procedures available? Cover all systems involved? Available for emergency reentry teams?
5. Specify requirements for emergency team for accident recovery, troubleshooting, or investigative purposes where necessary? Describe conditions under which emergency team will be used? Hazards they may encounter or must avoid?
6. Does procedure consider interfaces in shutdown procedures?
7. How will changes be handled? What are thresholds for changes requiring review?
8. Emergency procedures tested under range of conditions that may be encountered, for example, at night during power failure?

Caution and Warning Notes

1. Caution and warning notes included where appropriate?
2. Caution and warning notes precede operational steps containing potential hazards?
3. Adequate to describe the potential hazard?
4. Major cautions and warnings called out in general introduction, as well as prior to steps?
5. Separate entries with distinctive bold type or other emphatic display?
6. Do they include supporting safety control (health physics, safety engineer, etc.) if needed at specific required steps in procedure?

Requirements for Communications and Instrumentation

1. Adequate means of communication provided?
2. Will loss of communications create a hazard?
3. Course of action clearly defined for loss of required communications?
4. Verification of critical communication included prior to point of need?
5. Will loss of control or monitoring capability of critical functions create a hazard to people or hardware?
6. Alternate means, or a course of action to regain control or monitoring functions, clearly defined?
7. Above situations flagged by cautions and warnings?

Sequence-of-Events Considerations

1. Can any operation initiate an unscheduled or out-of-sequence event?
2. Could it induce a hazardous condition?
3. Identified by warnings or cautions?
4. Covered by emergency shutdown and backout procedures?
5. All steps sequenced properly? Sequence will not contribute to or create a hazard?
6. All steps which, if performed out-of-sequence, could cause a hazard identified and flagged?
7. Have all noncompatible simultaneous operations been identified and suitably restricted?
8. Have these been prohibited by positive callout or separation in step-by-step inclusion within the text of the procedure?

Environmental Considerations (Natural or Induced)

1. Environmental requirements specified that constrain the initiation of the procedure or require shutdown or evacuation, once in progress?
2. Induced environments (toxic or explosive atmospheres, etc.) considered?
3. All latent hazards (pressure, height, voltage, etc.) in adjacent environments considered?
4. Are there induced hazards from simultaneous performance of more than one procedure by personnel within a given space?

Personnel Qualification Statements

1. Requirement for certified personnel considered?
2. Required frequency of recheck of personnel qualifications considered?

Interfacing Hardware and Procedures Noted

1. All interfaces described by detailed callout?
2. Interfacing operating procedures identified, or written to provide ready equipment?
3. Where more than one organizational element is involved, are proper liaison and areas of responsibility established?

Procedure Sign-Off

1. Procedure to be used as an in-hand, literal checklist?
2. Step sign-off requirements considered and identified and appropriate spaces provided in the procedure?
3. Procedure completion sign-off requirements indicated (signature, authority, date, etc.)?
4. Supervisor verification of correct performance required?

General Requirements

1. Procedure discourages a shift change during performance or accommodates a shift change?
2. Where shift changes are necessary, include or reference shift overlap and briefing requirements?
3. Mandatory inspection, verification, and system validation required whenever procedure requires breaking into and reconnecting a system?
4. Safety prerequisites defined? All safety instructions spelled out in detail to all personnel?
5. Require prechecks of supporting equipment to ensure compatibility and availability?
6. Consideration for unique operations written in?
7. Procedures require walk-through or talk-through dry runs?
8. General supervision requirements, for example, what is protocol for transfer of supervisor responsibilities to a successor?
9. Responsibilities of higher supervision specified?

Reference Considerations

1. Applicable quality assurance and reliability standards considered?
2. Applicable codes, standards, and regulations considered?
3. Procedure complies with control documents?
4. Hazards and system safety degradations identified and considered against specific control manuals, standards, and procedures?
5. Specific prerequisite administrative and management approvals complied with?
6. Comments received from the people who will do the work?

Special Considerations

1. Has a documented safety analysis been considered for safety-related deviations from normal practices or for unusual or unpracticed maneuvers?
2. Have new restrictions or controls become effective that affect the procedure in such a manner that new safety analyses may be required?

74.4 HUMAN FACTORS ENGINEERING/ERGONOMICS*

74.4.1 Human–Machine Relationships

- Human factors engineering is defined as "the application of the principles, laws, and quantitative relationships which govern man's response to external stress to the analysis and design

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of machines and other engineering structures, so that the operator of such equipment will not be stressed beyond his/her proper limit or the machine forced to operate at less than its full capacity in order for the operator to stay within acceptable limits of human capabilities."*

- A principal objective of the supervisor and safety engineer in the development of safe working conditions is the elimination of bottlenecks, stresses and strains, and psychological booby traps that interfere with the free flow of work. It is an accepted concept that the less an operator has to fear from his or her job or machine, the more attention he or she can give to his or her work.
- In the development of safe working conditions, attention is given to many things, including machine design and machine guarding, personal protective equipment, plant layout, manufacturing methods, lighting, heating, ventilation, removal of air contaminants, and the reduction of noise. Adequate consideration of each of these areas will lead to a proper climate for accident prevention, increased productivity, and worker satisfaction.
- The human factors engineering approach to the solution of the accident problem is to build machines and working areas around the operator, rather than place him or her in a setting without regard to his or her requirements and capacities. Unless this is done, it is hardly fair to attribute so many accidents to human failure, as is usually the case.
- If this point of view is carried out in practice, fewer accidents should result, training costs should be reduced, and extensive redesign of equipment after it is put into use should be eliminated.
- All possible faults in equipment and in the working area, as well as the capacities of the operator, should be subjected to advance analysis. If defects are present, it is only a matter of time before some operator "fails" and has an accident.
- Obviously, the development of safe working conditions involves procedures that may go beyond the occasional safety appraisal or search for such obvious hazards as an oil spot on the floor, a pallet in the aisle, or an unguarded pinch point on a new lathe.

Human–machine relationships have improved considerably with increased mechanization and automation. Nevertheless, with the decrease in manual labor has come specialization, increased machine speeds, and monotonous repetition of a single task, which create work relationships involving several physiological and psychological stresses and strains. Unless this scheme of things is recognized and dealt with effectively, many real problems in the field of accident prevention may be ignored.

74.4.2 Human Factors Engineering Principles

- Human factors engineering or *ergonomics,*† as it is sometimes called, developed as a result of the experience in the use of highly sophisticated equipment in World War II. The ultimate potentialities of complex instruments of war could not be realized because the human operators lacked the necessary capabilities and endurance required to operate them. This discipline now has been extended to many areas. It is used extensively in the aircraft and aerospace industry and in many other industries to achieve more effective integration of humans and machines.
- The analysis should consider all possible faults in the equipment, in the work area, and in the worker—including a survey of the nature of the task, the work surroundings, the location of controls and instruments, and the way the operator performs his or her duties. The questions of importance in the analysis of machines, equipment, processes, plant layout, and the worker will vary with the type and purpose of the operation, but usually will include the following (pertaining to the worker):‡
    1. What sense organs are used by the operator to receive information? Does he or she move into action at the sound of a buzzer, blink of a light, reading of a dial, verbal order? Does the sound of a starting motor act as a cue?

*Theodore F. Hatch, Professor (retired), by permission.

†The term *ergonomics* was coined from the Greek roots *ergon* (work) and *nomos* (law, rule) and is now currently used to deal with the interactions between humans and such environmental elements as atmospheric contaminants, heat, light, sound, and all tools and equipment pertaining to the workplace.

‡R. A. McFarland, "Application of Human Factors Engineering to Safety Engineering Problems," *National Safety Congress Transactions,* 1967, Vol. 12. Permission granted by the National Safety Council.

2. What sort of discrimination is called for? Does the operator have to distinguish between lights of two different colors, tones of two different pitches, or compare two dial readings?
3. What physical response is he or she required to make: Pull a handle? Turn a wheel? Step on a pedal? Push a button?
4. What overall physical movements are required in the physical response? Do such movements interfere with his or her ability to continue receiving information through his or her sense organs? (For example, would pulling a handle obstruct his or her line of vision to a dial he or she is required to watch?) What forces are required (e.g., torque in turning a wheel)?
5. What are the speed and accuracy requirements of the machine? Is the operator required to watch two pointers to a hairline accuracy in a split second? Or is fairly close approximation sufficient? If a compromise is necessary, which is more essential: speed or accuracy?
6. What physiological and environmental conditions are likely to be encountered during normal operation of the machine? Are there any unusual temperatures, humidity conditions, crowded workspace, poor ventilation, high noise levels, toxic chemicals, and so on?

- Pertaining to the machine, equipment, and the surrounding area, these key questions should be asked:
  1. Can the hazard be eliminated or isolated by a guard, ventilating equipment, or other device?
  2. Should the hazard be identified by the use of color, warning signs, blinking lights, or alarms?
  3. Should interlocks be used to protect the worker when he or she forgets or makes the wrong move?
  4. Is it necessary to design the machine, the electrical circuit, or the pressure circuit so it will always be fail-safe?
  5. Is there need for standardization?
  6. Is there need for emergency controls, and are controls easily identified and accessible?
  7. What unsafe conditions would be created if the proper operating sequence were not followed?

74.4.3 General Population Expectations*

- The importance of standardization and normal behavior patterns has been recognized in business and industry for many years. A standard tool will more likely be used properly than will a nonstandard one, and standard procedures will more likely be followed.
- People expect things to operate in a certain way and certain conditions to conform with established standards. These general population "expectations"—the way in which the ordinary person will react to a condition or stimulus—must not be ignored or workers will be literally trapped into making mistakes. A list of "General Population Expectations" follows:
  1. Doors are expected to be at least 6 feet, 6 inches in height.
  2. The level of the floor at each side of a door is expected to be the same.
  3. Stair risers are expected to be of the same height.
  4. It is a normal pattern for persons to pass to the left on motorways (some countries excluded).
  5. People expect guardrails to be securely anchored.
  6. People expect the hot-water faucet to be on the left side of the sink, the cold-water faucet on the right, and the faucet to turn to the left (counterclockwise) to let the water run and to the right to turn the water off.
  7. People expect floors to be nonslippery.
  8. Flammable solvents are expected to be found in labeled, red containers.
  9. The force required to operate a lever, push a cart, or turn a crank is expected to go unchanged.
  10. Knobs on electrical equipment are expected to turn clockwise for "on," to increase current, and counterclockwise for "off."

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11. For control of vehicles in which the operator is riding, the operator expects a control motion to the right or clockwise to result in a similar motion of his or her vehicle and vice versa.
12. Very large objects or dark objects imply "heaviness." Small objects or light-colored ones imply "lightness." Large heavy objects are expected to be "at the bottom." Small, light objects are expected to be "at the top."
13. Seat heights are expected to be at a certain level when a person sits down.

74.5 ENGINEERING CONTROLS FOR MACHINE TOOLS*

74.5.1 Basic Concerns

Machine tools (such as mills, lathes, shearers, punch presses, grinders, drills, and saws) provide an example of commonplace conditions where there is only a limited number of items of personal protective gear available for use. In such cases as these, the problem to be solved is not personal protective equipment versus engineering controls, but rather which engineering control(s) should be used to protect the machine operator. A summary of employee safeguards is contained in Table 74.2. The list of possible machinery-related injuries is presented in Section 74.10. There seem to be as many hazards created by moving machine parts as there are types of machines. Safeguards are essential for protecting workers from needless and preventable injuries.

A good rule to remember is: Any machine part, function, or process that may cause injury must be safeguarded. Where the operation of a machine or accidental contact with it can injure the operator or others in the vicinity, the hazard must be either controlled or eliminated.

Dangerous moving parts in these three basic areas need safeguarding:

- The point of operation: that point where work is performed on the material, such as cutting, shaping, boring, or forming of stock.
- Power transmission apparatus: all components of the mechanical system that transmit energy to the part of the machine performing the work. These components include flywheels, pulleys, belts, connecting rods, couplings, cams, spindles, chains, cranks, and gears.
- Other moving parts: all parts of the machine that move while the machine is working. These can include reciprocating, rotating, and transverse moving parts, as well as feed mechanisms and auxiliary parts of the machine.

A wide variety of mechanical motions and actions may present hazards to the worker. These can include the movement of rotating teeth, and any parts that impact or shear. These different types of hazardous mechanical motions and actions are basic to nearly all machines, and recognizing them is the first step toward protecting workers from the danger they present.

The basic types of hazardous mechanical motions and actions are:

Motions	Actions
Rotating (including in-running nip points)	Cutting
	Punching
Reciprocating	Shearing
Transverse	Bending

74.5.2 General Requirements

What must a safeguard do to protect workers against mechanical hazards? Engineering controls must meet these minimum general requirements:

- *Prevent Contact.* The safeguard must prevent hands, arms, or any other part of a worker's body from making contact with dangerous moving parts. A good safeguarding system eliminates the possibility of operators or workers placing their hands near hazardous moving parts.
- *Secure.* Workers should not be able to easily remove or tamper with the safeguard, because a safeguard that can easily be made ineffective is no safeguard at all. Guards and safety devices should be made of durable material that will withstand the conditions of normal use. They must be firmly secured to the machine.

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Table 74.2 Summary of Employee Safeguards

To Protect	Personal Protective Equipment to Use	Engineering Controls to Use
Breathing	Self-contained breathing apparatus, gas masks, respirators, alarm systems	Ventilation, air-filtration systems, critical level warning systems, electrostatic precipitators
Eyes/face	Safety glasses, filtered lenses, safety goggles, face shield, welding goggles/helmets, hoods	Spark deflectors, machine guards
Feet/legs	Safety boots/shoes, leggings, shin guards	
Hands/arms/body	Gloves, finger cots, jackets, sleeves, aprons, barrier creams	Machine guards, lockout devices, feeding and ejection methods
Head/neck	Bump caps, hard hats, hair nets	Toe boards
Hearing	Ear muffs, ear plugs, ear valves	Noise reduction/isolation by equipment modification/substitution, equipment lubrication/maintenance programs, eliminate/dampen noise sources, reduce compressed air pressure, change operations[a]
Excessively high/low temperatures	Reflective clothing, temperature controlled clothing	Fans, air conditioning, heating, ventilation, screens, shields, curtains
Overall	Safety belts, lifelines, grounding mats, slap bars	Electrical circuit grounding, polarized plugs/outlets, safety nets

[a]Examples of the types of changes that should be considered include:

- Grinding instead of chipping.
- Electric tools in place of pneumatic tools.
- Pressing instead of forging.
- Welding instead of riveting.
- Compression riveting over pneumatic riveting.
- Mechanical ejection in place of air-blast ejection.
- Wheels with rubber or composition tires on plant trucks and cars instead of all-metal wheels.
- Wood or plastic tote boxes in place of metal tote boxes.
- Use of an undercoating on machinery covers.
- Wood in place of all-metal workbenches.

Machines often produce noise (unwanted sound), and this can result in a number of hazards to workers. Not only can it startle and disrupt concentration, but it can interfere with communications, thus hindering the worker's safe job performance. Research has linked noise to a whole range of harmful health effects, from hearing loss and aural pain to nausea, fatigue, reduced muscle control, and emotional disturbances. Engineering controls such as the use of sound-dampening materials, as well as less sophisticated hearing protection, such as ear plugs and muffs, have been suggested as ways of controlling the harmful effects of noise. Vibration, a related hazard that can cause noise and thus result in fatigue and illness for the worker, may be avoided if machines are properly aligned, supported, and, if necessary, anchored.

Because some machines require the use of cutting fluids, coolants, and other potentially harmful substances, operators, maintenance workers, and others in the vicinity may need protection. These substances can cause ailments ranging from dermatitis to serious illnesses and disease. Specially constructed safeguards, ventilation, and protective equipment and clothing are possible temporary solutions to the problem of machinery-related chemical hazards until these hazards can be better controlled or eliminated from the workplace.

- *Protect from Falling Objects.* The safeguard should ensure that no objects can fall into moving parts. A small tool that is dropped into a cycling machine could easily become a projectile that could strike and injure someone.
- *Create No New Hazards.* A safeguard defeats its own purpose if it creates a hazard of its own such as a shear point, a jagged edge, or an unfinished surface that can cause a laceration. The edges of guards, for instance, should be rolled or bolted in such a way that eliminates sharp edges.
- *Create No Interference.* Any safeguard which impedes a worker from performing the job quickly and comfortably might soon be overridden or disregarded. Proper safeguarding can actually enhance efficiency, since it can relieve the worker's apprehensions about injury.
- *Allow Safe Lubrication.* If possible, one should be able to lubricate the machine without removing the safeguards. Locating oil reservoirs outside the guard, with a line leading to the lubrication point, will reduce the need for the operator or maintenance worker to enter the hazardous area.

74.5.3 Danger Sources

All power sources for machinery are potential sources of danger. When using electrically powered or controlled machines, for instance, the equipment as well as the electrical system itself must be properly grounded. Replacing frayed, exposed, or old wiring will also help to protect the operator and others from electrical shocks or electrocution. High-pressure systems, too, need careful inspection and maintenance to prevent possible failure from pulsation, vibration, or leaks. Such a failure could cause explosions or flying objects.

74.6 MACHINE SAFEGUARDING METHODS*

74.6.1 General Classifications

There are many ways to safeguard machinery. The type of operation, the size or shape of stock, the method of handling the physical layout of the work area, the type of material, and production requirements or limitations all influence selection of the appropriate safeguarding method(s) for the individual machine.

As a general rule, power transmission apparatus is best protected by fixed guards that enclose the danger area. For hazards at the point of operation, where moving parts actually perform work on stock, several kinds of safeguarding are possible. One must always choose the most effective and practical means available.

1. Guards
   - (a) Fixed
   - (b) Interlocked
   - (c) Adjustable
   - (d) Self-adjusting
2. Devices
   - (a) Presence sensing
     - Photoelectrical (optical)
     - Radio frequency (capacitance)
     - Electromechanical
   - (b) Pullback
   - (c) Restraint
   - (d) Safety controls
     - Safety trip controls
       - Pressure-sensitive body bar
       - Safety triprod
       - Safety tripwire cable
     - Two-hand control
     - Two-hand trip

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(e) Gates
Interlocked
Other
3. Location/distance
4. Potential feeding and ejection methods to improve safety for the operator
(a) Automatic feed
(b) Semiautomatic feed
(c) Automatic ejection
(d) Semiautomatic ejection
(e) Robot
5. Miscellaneous aids
(a) Awareness barriers
(b) Miscellaneous protective shields
(c) Hand-feeding tools and holding fixtures

74.6.2 Guards, Devices, and Feeding and Ejection Methods

Tables 74.3–74.5 provide the interested reader with specifics regarding machine safeguarding.

74.7 ALTERNATIVES TO ENGINEERING CONTROLS*

Engineering controls are an alternative to personal protective equipment, or is it the other way around? This chicken-and-egg situation has become an emotionally charged issue with exponents on both sides arguing their beliefs with little in the way of well-founded evidence to support their cases. The reason for this unfortunate situation is that there is no single solution to all the hazardous operations found in industry. The only realistic answer to the question concerning which of the two methods of abating personnel hazards is—it depends. Each and every situation requires an independent analysis considering all the known factors so that a truly unbiased decision can be reached.

This section presents material useful to engineers in the selection and application of solutions to industrial safety and health problems. Safety and health engineering control principles are deceptively few: substitution; isolation; and ventilation, both general and localized. In a technological sense, an appropriate combination of these strategic principles can be brought to bear on any industrial safety or hygiene control problem to achieve a satisfactory quality of the work environment. It may not be, and usually is not, necessary or appropriate to apply all these principles to any specific potential hazard. A thorough analysis of the control problem must be made to ensure that a proper choice from among these methods will produce the proper control in a manner that is most compatible with the technical process, is acceptable to the workers in terms of day-to-day operation, and can be accomplished with optimal balance of installation and operating expenses.

74.7.1 Substitution

Although frequently one of the most simple engineering principles to apply, substitution is often overlooked as an appropriate solution to occupational safety and health problems. There is a tendency to analyze a particular problem from the standpoint of correcting rather than eliminating it. For example, the first inclination in considering a vapor-exposure problem in a degreasing operation is to provide ventilation of the operation rather than consider substituting a solvent having a much lower degree of hazard associated with its use. However, substitution of less hazardous substances, changing from one type of process equipment to another, or, in some cases, even changing the process itself, may provide an effective control of a hazard at minimal expense.

This strategy is often used in conjunction with safety equipment: substituting safety glass for regular glass in some enclosures, replacing unguarded equipment with properly guarded machines, replacing safety gloves or aprons with garments made of material more impervious to the chemicals being handled. Since substitution of equipment frequently is done as an immediate response to an obvious problem, it is not always recognized as an engineering control, even though the end result is every bit as effective.

Substituting one process or operation for another may not be considered except in major modifications. In general, a change in any process from a batch to a continuous type of operation carries with it an inherent reduction in potential hazard. This is true primarily because the frequency and duration of potential contact of workers with the process materials are reduced when the overall

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Table 74.3 Machine Safeguarding: Guards

Method	Safeguarding Action	Advantages	Limitations
Fixed	Provides a barrier	Can be constructed to suit many specific applications In-plant construction is often possible Can provide maximum protection Usually requires minimum maintenance Can be suitable to high production, repetitive operations	May interfere with visibility Can be limited to specific operations Machine adjustment and repair often requires its removal, thereby necessitating other means of protection for maintenance personnel
Interlocked	Shuts off or disengages power and prevents starting of machine when guard is open; should require the machine to be stopped before the worker can reach into the danger area	Can provide maximum protection Allows access to machine for removing jams without time-consuming removal of fixed guards	Requires careful adjustment and maintenance May be easy to disengage
Adjustable	Provides a barrier that may be adjusted to facilitate a variety of production operations	Can be constructed to suit many specific applications Can be adjusted to admit varying sizes of stock	Hands may enter danger area—protection may not be complete at all times May require frequent maintenance and/or adjustment The guard may be made ineffective by the operator May interfere with visibility
Self-adjusting	Provides a barrier that moves according to the size of the stock entering danger area	Off-the-shelf guards are often commercially available	Does not always provide maximum protection May interfere with visibility May require frequent maintenance and adjustment

Table 74.4 Machine Safeguarding: Devices

Method	Safeguarding Action	Advantages	Limitations
Photoelectric	Machine will not start cycling when the light field is interrupted When the light field is broken by any part of the operator's body during the cycling process, immediate machine braking is activated	Can allow freer movement for operator	Does not protect against mechanical failure May require frequent alignment and calibration Excessive vibration may cause lamp filament damage and premature burnout Limited to machines that can be stopped
Radio frequency (capacitance)	Machine cycling will not start when the capacitance field is interrupted When the capacitance field is disturbed by any part of the operator's body during the cycling process, immediate machine braking is activated	Can allow freer movement for operator	Does not protect against mechanical failure Antennae sensitivity must be properly adjusted Limited to machines that can be stopped
Electromechanical	Contact bar or probe travels a predetermined distance between the operator and the danger area Interruption of this movement prevents the starting of machine cycle	Can allow access at the point of operation	Contact bar or probe must be properly adjusted for each application; this adjustment must be maintained properly
Pullback	As the machine begins to cycle, the operator's hands are pulled out of the danger area	Eliminates the need for auxiliary barriers or other interference at the danger area	Limits movement of operator May obstruct workspace around operator Adjustments must be made for specific operations and for each individual Requires frequent inspections and regular maintenance Requires close supervision of the operator's use of the equipment
Restraint (holdback)	Prevents the operator from reaching into the danger area	Little risk of mechanical failure	Limits movements of operator May obstruct workspace Adjustments must be made for specific operations and each individual Requires close supervision of the operator's use of the equipment

Safety trip controls Pressure-sensitive body bar Safety tripod Safety tripwire cable	Stops machine when tripped	Simplicity of use	All controls must be manually activated May be difficult to activate controls because of their location Only protects the operator May require special fixtures to hold work May require a machine brake
Two-hand control	Concurrent use of both hands is required, preventing the operator from entering the danger area	Operator's hands are at a predetermined location Operator's hands are free to pick up a new part after first half of cycle is completed	Requires a partial cycle machine with a brake Some two-hand controls can be rendered unsafe by holding with arm or blocking, thereby permitting one-hand operation Protects only the operator
Two-hand trip	Concurrent use of two hands on separate controls prevents hands from being in danger area when machine cycle starts	Operator's hands are away from danger area Can be adapted to multiple operations No obstruction to hand feeding Does not require adjustment for each operation	Operator may try to reach into danger area after tripping machine Some trips can be rendered unsafe by holding with arm or blocking, thereby permitting one-hand operation Protects only the operator May require special fixtures
Gates Interlocked Other	Provides a barrier between danger area and operator or other personnel	Can prevent reaching into or walking into the danger area	May require frequent inspection and regular maintenance May interfere with operator's ability to see the work

Table 74.5 Machine Safeguarding: Feeding and Ejection Methods

<table>
<tr><th>Method</th><th>Safeguarding Action</th><th>Advantages</th><th>Limitations</th></tr>
<tr><td>Automatic feed</td><td>Stock is fed from rolls, indexed by machine mechanism, etc.</td><td rowspan="3">Eliminates the need for operator involvement in the danger area</td><td rowspan="2">Other guards are also required for operator protection-usually fixed barrier guards
Requires frequent maintenance
May not be adaptable to stock variation</td></tr>
<tr><td>Semiautomatic feed</td><td>Stock is fed by chutes, movable dies, dial feed, plungers, or sliding bolster</td></tr>
<tr><td>Automatic ejection</td><td>Workpieces are ejected by air or mechanical means</td><td>May create a hazard of blowing chips or debris
Size of stock limits the use of this method
Air ejection may present a noise hazard</td></tr>
<tr><td>Semiautomatic ejection</td><td>Workpieces are ejected by mechanical means, which are initiated by the operator</td><td>Operator does not have to enter danger area to remove finished work</td><td>Other guards are required for operator protection
May not be adaptable to stock variation</td></tr>
<tr><td>Robots</td><td>Perform work usually done by operator</td><td>Operator does not have to enter danger area
Are suitable for operations where high stress factors are present, such as heat and noise</td><td>Can create hazards themselves
Require maximum maintenance
Are suitable only to specific operations</td></tr>
</table>

process approach becomes one of continuous operation. The substitution of processes can be applied on a fundamental basis, for example, substitution of airless spray for conventional spray equipment can reduce the exposure of a painter to solvent vapors. Substitution of a paint dipping operation for the paint spray operation can reduce the potential hazard even further. In any of these cases, the automation of the process can further reduce the potential hazard (Table 74.5).

74.7.2 Isolation

Application of the principle of isolation is frequently envisioned as consisting of the installation of a physical barrier (such as a machine guard or device-refer to Tables 74.3 and 74.4) between a hazardous operation and the workers. Fundamentally, however, this isolation can be provided *without* a physical barrier through the appropriate use of distance and, in some situations, time.

Perhaps the most common example of isolation as a control strategy is associated with storage and use of flammable solvents. The large tank farms with dikes around the tanks, underground storage of some solvents, the detached solvent sheds, and fireproof solvent storage rooms within buildings are all commonplace in American industry. Frequently, the application of the principle of isolation maximizes the benefits of additional engineering concepts such as excessive noise control, remote control materials handling (as with radioactive substances), and local exhaust ventilation.

74.7.3 Ventilation

Workplace air quality is affected directly by the design and performance of the exhaust system. An improperly designed hood or a hood evacuated with an insufficient volumetric rate of air will contaminate the occupational environment and affect workers in the vicinity of the hazard source. This is a simple, but powerful, symbolic representation of one form of the close relationship between atmospheric emissions (as regulated by the Environmental Protection Agency) and occupational exposure (as regulated by the Occupational Safety and Health Administration). What is done with gases generated as a result of industrial operations/processes? These emissions can be exhausted directly to the atmosphere, indirectly to the atmosphere (from the workplace through the general ventilation system), or recirculated to the workplace. The effectiveness of the ventilation system design and operation impacts directly on the necessity and type of respiratory gear needed to protect the work force.

74.8 DESIGN AND REDESIGN*

74.8.1 Hardware

Designers of machines must consider the performance characteristics of machine operators as a major constraint in the creation or modification of both mechanical and electrical equipment. To do less would be tantamount to ignoring the limitations of human capabilities. Equipment designers especially concerned with engineering controls to be incorporated into machines, whether at the time of initial conceptualization or later when alterations are to be made, must also be cognizant of the principles of human factors (ergonomics). Equipment designers are aware that there are selected tasks that people can perform with greater skill and dependability than machines, and vice versa. Some of these positive performance characteristics are noted in Table 74.6. In addition, designers of equipment and engineering controls are knowledgeable of human performance limitations, both physically and psychologically. They know that the interaction of forces between people and their operating environment presents a never-ending challenge in assessing the complex interrelationships that provide the basis for that often fine line between safety versus hazard or health versus contaminant. Table 74.7 identifies the six pertinent sciences most closely involved in the design of machines and engineering controls.

It is both rational and reasonable to expect that, when engineering controls are being considered to eliminate or reduce hazards or contaminants, designers make full use of the principles established by specialists in these human performance sciences.

74.8.2 Process

A stress (or stressor) is some physical or psychological feature of the environment that requires an operator to be unduly exerted to continue performing. Such exertion is termed strain as in "stress and strain." Common physical stressors in industrial workplaces are poor illumination, excessive noise, vibration, heat, and the presence of excessive, harmful atmospheric contaminants.

Unfortunately, much less is known about their effects when they occur at the same time, in rapid sequence, or over extended periods of time. Research suggests that such effects are not simply

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