SAFETY SYSTEMS

Some fundamental objectives of a society are the safety, prosperity, happiness, and well-being of its people. Safety is of paramount importance because it is the brickwork on which the other aspirations of the society must stand upon. Several factors affect safety, and they are the focus in this article.

ELECTRICAL SAFETY

Many people are killed every year, and many more are injured, while in contact with electrical energy. Of the 3740 work-related deaths reported by the Bureau of Labor Statistics for 1984 in the United States (1), 10% of the fatalities, or about 370, were the direct result of electrocution at work. Unlike other industrial accidents, electrical accidents often happen to knowledgeable workers and professionals. For instance, in Great Britain, of the 805 accidents reported in factories in a typical year, 47% were electrical accidents involving skilled workers (see Table 1) (2). Many of these deaths and injuries could have been prevented by the use of appropriate safety equipment and techniques. Table 2 shows that ignorance, negligence, and forgetfulness account for most of the electrical accidents recorded in a typical year.

Electric Shock

When the human body forms a conduction path for electric current, the effect it causes on the body is called electric shock. The three main hazards of electricity are shock, arc, and blast. Since the low resistance of the body diminishes its ability to withstand the passage of electric current, most electrical systems can be hazardous. Even a minor electric shock can create a serious injury due to a fall as a result of reflex action. Electric shock is a safety hazard in most laboratory environments, and it can be caused by improper use or handling of electrical appliances or equipment. It can also come from faulty equipment: equipment with a factory defect that causes it to malfunction, or equipment failure as a result of fatigue or aging. Shorted cables or worn electrical conductors can leak electric current away from its desired path and cause electric shock. The severity of the effect on the body may include tingling, a burn on the skin at the point of contact, muscular contraction, inability to control the muscles, and loss of grip on the electrical conductor or equipment at the inception of the electric shock.

Threshold of Electric Shock. The level of electric shock differs from one individual to the other and depends on sex, age, weight, and chemical balance (a function of the physical condition of the person). The effect of a shock largely depends on the frequency, duration of contact, and the amount of electric current passed through the body, rather than the voltage. For instance, a shock from a 100 V source can be as deadly as that from a 1000 V source. Low frequency currents from 60 Hz (power line frequency) down to direct current cause more severe shock because they penetrate the skin more deeply and quickly and burn the flesh much faster. Currents of higher frequencies change direction several times per second, at a rate much faster than the rate of a normal heart beat. Thus, high-frequency currents have less tendency to initiate fibrillation of the heart than low-frequency currents. Currents as low as 1 mA can be perceived as an electric shock. The accepted maximum harmless current intensity is 5 mA, and this is also the maximum current allowed to leak from home appliances and still pass Underwriters Laboratories (UL) specifications (3). A current of 100 mA or above will cause ventricular fibrillation, which prevents the heart from pumping blood; death may result.

Estimation of Electric Shock Current. An electric shock results when an electric current passes through the body causing physical stimulation of the body. The magnitude of the current I in amperes (A), obeys Ohm's law,

$$I = \frac{V}{R} \tag{1}$$

where V is the applied voltage in volts (V), and R is the total resistance in ohms (Ω) of the current path, which may include the ground on which the person is standing, the boot being worn, and the human body. When these resistances are accounted for, Eq. (1) is modified to

$$I = \frac{V}{R_A + R_B} \tag{2}$$

where R_A is the resistance of ground plus boot, and R_B is the resistance of the body. For example, if the resistance of shoes to ground of a man holding a pair of pliers is $R_A = 1000\ \Omega$ and the resistance of the body is $R_B = 5000\ \Omega$, then for a 110 V fault voltage, the total current through the man's body from Eq. (2) is

$$I = \frac{110\,\text{V}}{(1000 + 5000)\,\Omega} = 18.33\,\text{mA} \tag{3}$$

The current of 18.33 mA is over the paralysis threshold as shown in Table 3 (4). The victim cannot release the pliers, and the result may be fatal. The numbers used in this example are only approximate. The actual values will depend on

J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*. Copyright © 1999 John Wiley & Sons, Inc.

Table 1. Electrical Accidents Analyzed by Occupation

Occupation	Fatal	Total
Skilled		
Supervisory staff	2	37
Switchboard substation attendants	—	2
Testing staff	—	18
Electrical tradesmen and their mates	7	278
Engineering apprentices (under 18)	—	7
Engineering apprentices (over 18)	1	17
Unskilled		
All men not included in the above	16	396
All women not included in the above	—	50
Total	26 (3.2%)	805 (100%)

several factors, which include the contact resistance between man and metal and his weight and physical condition. The nominal resistances of various parts of the human body are given (5) in Table 4, and the resistances of various materials are given in Table 5.

Investigators have also established that the resistance of the body from hands to feet depends on the area of contact and on whether the skin is wet, moist, or dry. These values range from 1000 Ω and 10,000 Ω. An empirical formula is given by

$$RV^k = C \tag{4}$$

where R is the resistance in ohms, V is the voltage in volts, and $k = 0.83$ and C are constants. Table 6 (6) shows the electrical characteristics of the human body at 50 Hz in dry condition computed with Eq. (4).

HAZARDS

Hazards can in general be natural, technological, or caused by an act of sabotage. Examples of natural hazards are earthquakes, floods, chemical spills during transportation, hurricanes, and lightning. Examples of technological hazards are automobile, marine, and airplane failure as well as fire and explosion in mines. Electrostatic hazard due to capacitive discharges can be a source of ignition in the presence of or in the vicinity of explosive mixtures or in an explosion-prone environment, as for instance in a gunpowder manufacturing plant. In this category also are the accidents in a manufacturing plant or assembly line and nuclear accidents in a nuclear power plant, including nuclear-propelled vehicles, submarines, and aircraft carriers, as well as hazards inherent in the restarting of nuclear plants. Nuclear war and nuclear-weapon accidents are technological hazards as well. An example of hazard due to sabotage is the explosion of an airplane due to a terrorist bomb.

Table 2. Conditions Leading Up to Accidents in One Year

Cause	Fatal	Total
Failure or lack of testing	5	91
Testing	5	87
Ignorance, negligence, forgetfulness, and inadvertence	24	354
Accidents resulting from fault of persons other than injured person	18	160
Working on live gear deliberately	3	108
Misunderstood instructions or failure of permit-to-work system	1	16

Hazards can also be broadly classified as environmental, physical, chemical, and biological. Typical environmental hazards include falling objects, improperly enclosed workplaces, and improperly lighted shop floors. Physical hazards include lifting heavy objects, being exposed to heat, bright lights, excessive noise or vibration, and mild doses of radiation, and being shocked by improperly grounded equipment or undersized power cables. Irrespective of the cause and type of hazard, hazardous conditions should be avoided or eliminated where possible by redesigning the workplace and wearing the appropriate protective clothing and equipment. These and other hazards result in injuries and loss or damage of property. When hazards are not contained, they cause work-related accidents which include minor to severe burns, physical and bodily injuries, back pains due to physical exertion, loss of hearing or vision, or death.

Sources of Hazards

Hazardous conditions may be unnoticed or ignored. Exposed conveyor belts in a workplace can catch a finger or entangle clothing. The light from an arc-welding machine can be too bright unless for the naked eye. The noise level from a grinding machine or metal cutting tool may be too intense if protec-

Table 3. Current Range and Effect on a 68 kg (150 lb) Man (4)

Current (60 Hz)	Physiological Phenomenon	Sensations and Lethal Incidence
Less than 1 mA	None	Imperceptible
1 mA	Perception threshold	
1–3 mA		Mild sensation
3–10 mA		Painful sensation
10 mA	Paralysis threshold of arms	Cannot release hand grip. If no grip, victim may be thrown clear. (May progress to higher current and be fatal.)
30 mA	Respiratory paralysis	Breathing stops (frequently fatal if not treated promptly).
75 mA	Fibrillation threshold 0.5%	Heart action is discoordinated (probably fatal).
250 mA	Fibrillation threshold 99.5% (5 s exposure)	
4 A	Heart paralysis threshold	Heart stops during current passage, restarts normally on current interruption (usually not fatal from heart dysfunction).
5 A	Tissue burning	Not fatal unless vital organs are burned.

Table 4. Nominal Resistance Values for Various Parts of the Human Body

	Resistance	
Condition (area to suite)	Dry	Wet
Finger touch	40 kΩ–1 MΩ	4–15 kΩ
Hand holding wire	10–50 kΩ	3–6 kΩ
Finger–thumb grasp	10–30 kΩ	2–5 kΩ
Hand holding pliers	5–10 kΩ	1–3 kΩ
Palm touch	3–8 kΩ	1–2 kΩ
Half around 1.5 in. pipe (or drill handle)	1–3 kΩ	0.5–1.5 kΩ
Two hands around 1.5 in. pipe	0.5–1.5 kΩ	250–750 kΩ
Hand immersed	—	200–500 Ω
Foot immersed	—	100–300 Ω
Human body, internal, excluding skin	—	2–1000 Ω

tive equipment is not worn. Workers neglect to wear helmets in situations where falling objects are commonplace. Inadequate boots are worn in areas where heavy tools can drop and hit a toe. Rubber gloves are not worn around chemicals. Thermally insulated gloves are not used to handle hot objects. Work paths clearly marked are not followed. Restricted areas are not observed. Thus, the following conditions constitute hazards:

- Unmarked walk paths to guide movement of workers within a plant
- Heavy tools dropping on the floor from the workbench
- Dropping objects around construction sites
- Very high noise levels around workshops
- Extremely bright lights from welding machine
- Exposed conveyor belts
- Objects falling from overhead crane
- Absence of proper warning against radiation-intensive area
- Existence of radiation sources
- Lack of proper skill required to operate heavy road construction equipment
- Lack of adequate training necessary to properly carry out a prescribed function in a factory or workshop
- Toxic, odorless fumes in accessible areas
- Absence of or inactive fire extinguisher
- Absence of clearly marked and visible exit signs
- Viruses from sick or dirty animals in animal clinics
- Bacteria from improperly disinfected or nonsterilized needles and syringes
- Spread of bacteria from contaminated foods
- Food processing plants in dirty or poorly maintained environment
- Exertion of physical strength far in excess of the individual capability, such as lifting heavy loads
- Mental and psychological stress as a result of long hours of work at a computer
- Fatigue due to continuous hours of work without break, or from the neglect of break times stipulated by management
- Financial pressures dictating long and continuous shift hours beyond the safe limit of a worker

Table 5. Nominal Resistance Values for Various Materials

Material	Resistance
Rubber gloves or soles	>20 MΩ
Dry concrete above grade	1–5 MΩ
Dry concrete on grade	0.2–1 MΩ
Leather sole, dry, including foot	0.1–0.5 MΩ
Leather sole, damp, including foot	5–20 kΩ
Wet concrete on grade	1–5 kΩ

Table 6. Calculated Electrical Characteristics of Human Body at 50 Hz in Dry Conditions

V (V)	R (Ω)	$I = V/R$ (mA)
12.5	16,500	0.8
31.3	11,000	2.84
62.5	6,240	10.0
125	3,530	35.2
250	2,000	125
500	1,130	443
1000	640	1560
2000	362	5540

Electrical Hazards and Their Prevention

Various electrical hazards are considered and safety practices are suggested:

- Any electrical installation of 600 V and above should be guarded with a physical barrier to keep out unqualified persons or unskilled personnel.
- A second person capable of helping in case of emergency must be present when one person is working on a live line.
- Lines and electric equipment are assumed live, unless positively established as deenergized.
- Operating voltages of all equipment must be known before attempting to work on them.
- If the nature of the system requires it to remain energized, as when troubleshooting a circuit or if deenergizing interferes with the operation or proper function of a safety system, then the system can remain energized, so long as the personnel are competent and aware that it is live.
- Only qualified personnel should be allowed to switch on or switch off any live system.

The primary safety procedure is to deenergize the parts of the system exposed to the worker. This eliminates the hazard of shock, arc, and blast. Thus, before working on lines, grounding jumpers such as are shown in Fig. 1 (7) should be used to bridge a deenergized line. These conductors, also called safety ground, ensure that an accidental reenergizing of the system will not cause injury, short-circuiting and grounding of conductors throughout the service.

Figure 2 (8), in which R_j is the resistance of the ground wire (typically 0.001 Ω), shows two applications of ground wires. The short-circuit bridge intentionally placed across lines for safety must be removed before switching on the lines. A second opinion for line clearance should be obtained before energizing. Protective devices and specially designed flame

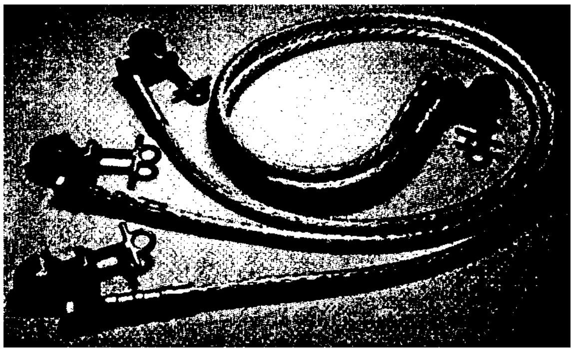

Figure 1. Safety ground jumper. (Courtesy AB Chance Corp.)

retarding clothing should be worn to provide safety against arc and electric burns. Thermal flash suits and thermal uniforms should also be used to protect the body, arms, and legs, and insulating hard hats to protect the head. The hands should be protected with rubber gloves reinforced with leather protectors. Safety glasses, goggles, and face shields should be worn to protect the eyes. Hot sticks should be used to close or open pole-mounted circuit breakers and fuses. They allow workers to manipulate energized conductors from a safe distance. Pliers, screwdrivers, wire cutters, and similar tools should be electrically insulated, to prevent shock when in contact with an energized conductor.

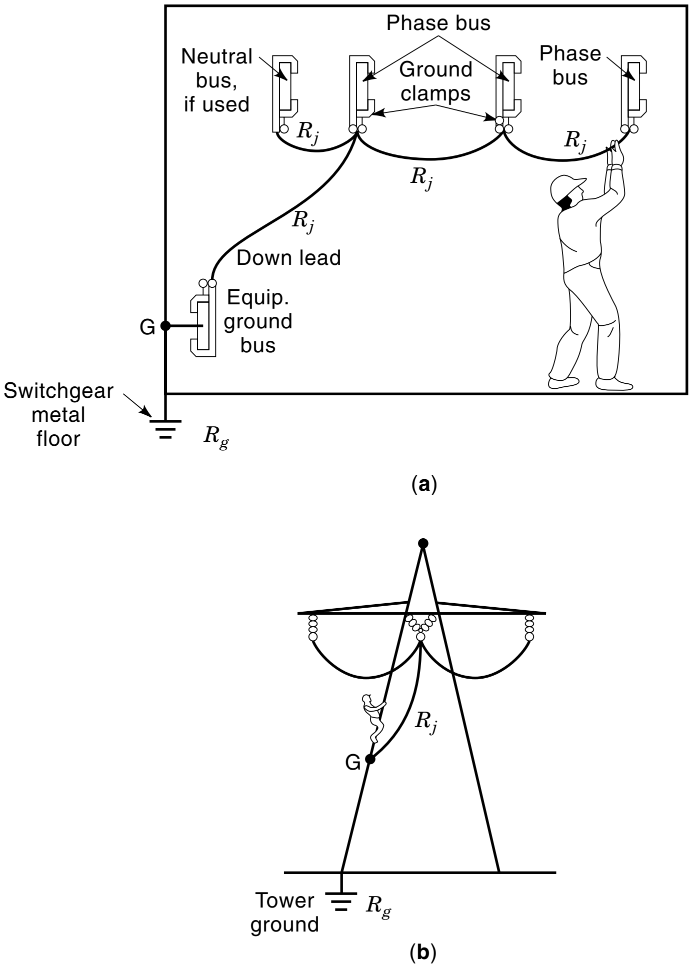

Figure 2. Examples of the use of safety ground on deenergized lines. (a) Switchgear, (b) metal tower.

Barricades should be used to prevent workers' access to hazardous places. Signs should be placed conspicuously to warn personnel of immediate hazard. Typical hazard signs (9) are shown in Fig. 3. Electrical equipment should not be handled with wet hands and feet, or when perspiring or when standing on wet floor. Whenever possible, only one hand should be used when working on an energized circuit. Rings or metallic-band watches should be avoided when working with electrical equipment.

A safety electrical one-line diagram (SEOLD) showing breakers or fuses that control power in a household or power system should be available, with ratings clearly marked and regularly updated in case of changes. A typical one-line diagram of a power system (10) is shown in Fig. 4. This is used as a safety measure to isolate any portion of the house or workplace before embarking on repairs.

Hazard of Untried Software

The proliferation of household computers and industrial as well as military software multiplies the hazards of relying on untried software, especially in critical safety systems. The reason is that software may perform as expected under common circumstance while containing weaknesses that are extremely difficult or impossible to detect until revealed by unusual circumstances.

Prevention of Electrostatic Hazard

All conducting parts of any installation should be properly grounded in order to reduce capacitive ignition buildup. Moreover, safety demands that the grounding be inspected periodically. All persons entering environments prone to explosion must wear conducting footwear that will ensure that the path to ground is free of insulating layers, which inhibit the discharge of electrostatic buildup. In general, the methods to avoid or dissipate static electricity can be summarized as (11): grounding of all conducting surfaces, increasing the conductivity of the conducting materials, increasing the surface conductivity through the raising of the relative humidity or through surface treatment, increasing the conductivity of the air, maintaining sufficiently low working speed, choosing proper contact materials, and maintaining proper control of the contact temperature of the surfaces.

Hazards in Electrical Laboratories

There are special hazards associated with laboratories, which require special awareness and laboratory safety procedures. The main hazard in an electrical laboratory is that of electric shock.

Figure 3. Hazard signs. (Courtesy Ideal Industries, Inc.)

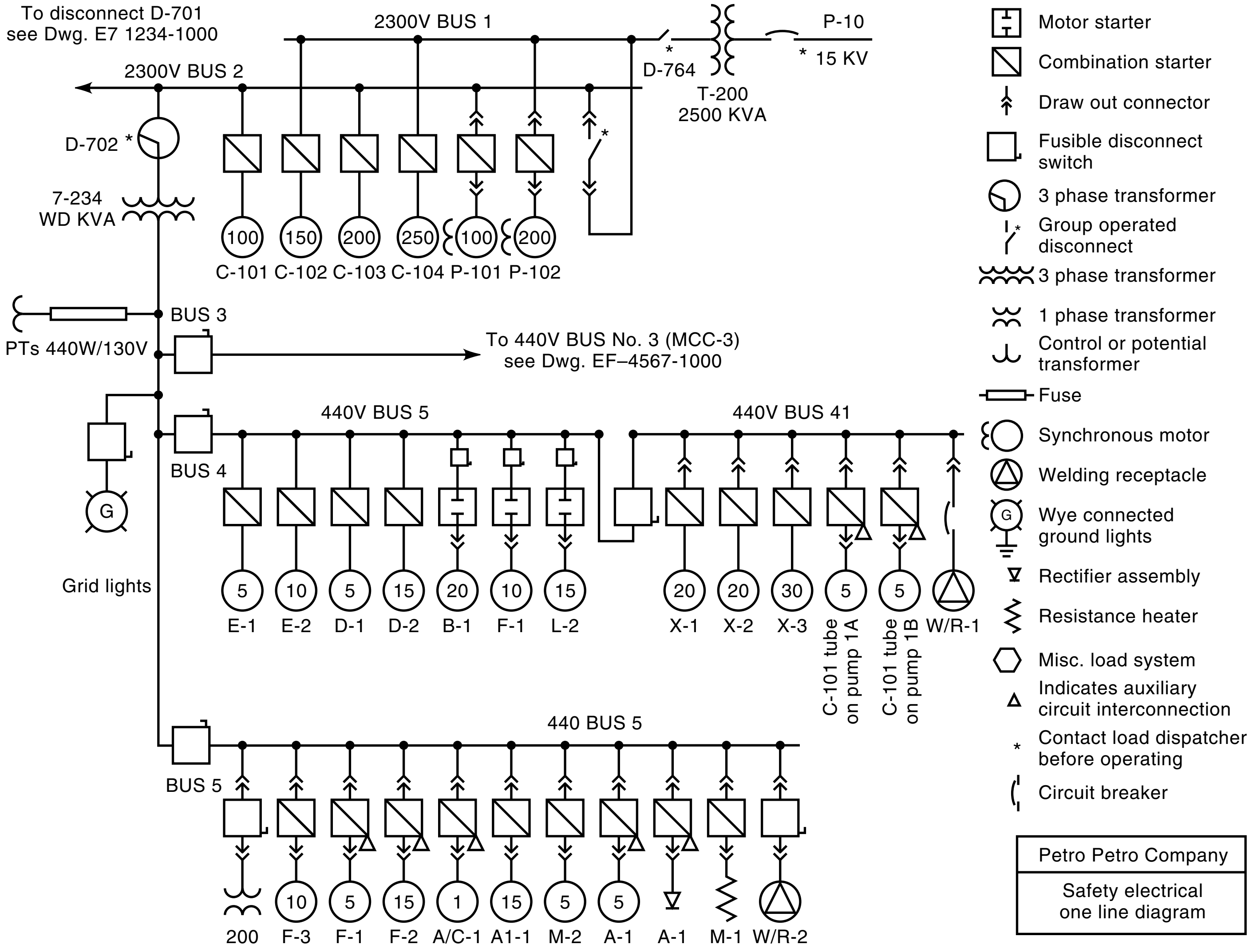

Figure 4. Safety electrical one-line diagram (SEOLD). (Courtesy Cadick Professional Services.)

Hazards in Chemical Laboratories

In a chemical laboratory the hazards of dangerous chemicals and toxic fumes are common.

Hazards in Manufacturing Plants

In a manufacturing plant, moving machinery, cranes, and vehicles are sources of hazard. Obscure exit signs and falling objects also contribute to hazards in a manufacturing plant.

ACCIDENTS

An accident is an unexpected event, especially if it causes injury or damage without reference to the negligence or fault of an individual. Accidents can also be seen as unintended and unforeseen events, usually resulting in personal injury or property damage. The basic causes of industrial accidents are, in general, unsafe conditions of machinery, equipment, or surroundings, and the unsafe actions of persons due to ignorance or neglect of safety principles.

Motor-Vehicle Accidents

The single greatest cause of accidents in the United States is the automobile. In 1991 in the United States, automobile accidents were responsible for about 49.4% of all accidental deaths, as compared with accidents in the home (about 23.3%); accidents in public places, including railroads and airplanes (about 20.5%); and work-related accidents (about 11.3%) (12). The second greatest cause of accidental deaths is due to falls, which account for some 13.9% of all fatalities. Automobile safety is concerned with the reduction of motor vehicle accidents by emphasizing safety in the design of roads and automobiles. In addition, highway traffic laws are continually reviewed, modified, and enforced to improve safety. Speed limits on highways are changed in response to needs. Mandatory inclusion of air bags in newer automobiles and the wearing of seat belts are some of the requirements aimed at improving automobile safety.

Prevention of Accidents

Organized efforts for the prevention of accidents began in the 19th century with the adoption of factory-inspection laws, first in Great Britain and then in the United States and other countries. Fire insurance and accident insurance companies made efforts to enforce safety rules and to educate the public. Factory inspectors and inspectors from fire insurance and casualty insurance companies carried on a campaign against unsafe conditions and actions, and at the beginning of the 20th century a new branch of engineering developed, devoted to finding and eliminating such hazards. Laws concerning workers' compensation were passed in Germany in 1884, Great Britain in 1897, and the United States in 1908. By placing the financial burden of caring for injured workers on the employer, such laws created an incentive for providing safe machinery and working conditions and for improved selection and training of employees. In the United States, the National Safety Council was formed in 1913. This noncommercial organization has since been a leader in accident-prevention activities, especially in the publication of educational literature; the compilation of statistics; and the coordination of safety in schools, clubs, industrial organizations, and state and municipal agencies.

ADVANCED MANUFACTURING TECHNOLOGY

The primary goal of manufacturing technology is to provide a competitive advantage through enhanced product performance, reliability, quality, and cost superiority. When combined with good marketing and product-support services, manufacturing technology is the basis for market share, growth, and stability of employment. Creation of wealth is essential to the advancement of the standard of living, quality of life, and level of employment. The Industrial Revolution originated in England in the second half of the 18th century with the discovery of the steam engine and spinning jenny. Similarly, the present day technology of microminiaturization in the form of transistors and microchips heralded the Robotics Revolution and the birth of advanced manufacturing technology. A distinct goal of advanced manufacturing technology is to provide enhanced product performance, reliability, and quality at a minimized cost. A competitive advantage is gained over competitors. The fruit of this is an expansion of the market or customer base, ensuring growth, prosperity, and stability of employment. In turn the national wealth and economy thrive. Thus, manufacturing creates wealth. Manufacturing is critical to the economy of any country. In the United States, it accounts for about two-thirds of the wealth created annually (17). A country cannot hope to remain a world political leader or even guarantee national defense by relying on other countries for the bulk of manufactured products. Manufacturing is the base source of income of a nation. Five forms of advanced manufacturing technology can be grouped as follows (18): computer-aided design (CAD), computer-aided manufacturing (CAM), group technology, flexible manufacturing, and robotics.

Computer-Aided Design

Computer-aided design (CAD) employs interactive computer-simulation, graphics, and database software that enables engineers to design and simulate a product. Some advanced CAD systems can even generate manufacturing-process instructions, programs for automatic machine tools with bills of materials, and orders used by vendors to procure parts and materials.

Computer-Aided Manufacturing

Programs, which are stored in microprocessors, are mounted on machine tools and used to perform drilling, boring, tapping, reaming, and other metal-cutting functions without the need of a human operator. CAM became popular with its application in the fabrication of large-scale integrated circuits.

Group Technology

This is a modern approach to manufacturing technology which increases productivity by reducing delays in material handling process, including the waiting time (delay) suffered by a job in order to go through a specific manufacturing phase.

Flexible Manufacturing

This is the ability to manufacture different finished products and adjust to changes in product design in response to market needs.

Robotics

Robots are central to advanced manufacturing technology and are widely used in enterprises ranging from the automotive industry to cosmetics. Robots are used in industry to replace humans in dangerous or repetitive tasks as well as handling of dangerous materials, such as radioactive fuels or waste. By the definition of the Robot Institute of America, "A robot is a re-programmable general-purpose multi-functional manipulator designed to move materials, parts, tools, or specialized devices, through variable programmed motions for the performance of a variety of tasks." While this definition emphasizes reprogrammability and multiple task performance, the Japan Industrial Association (JIRA) emphasizes intelligent function, meaning at least one of the following: judgement, recognition, adaptation, or learning.

Robotics is a broad range of study spanning the design of mechanical and electrical systems with the use of sensor technology, artificial intelligence and computer hardware and software. Although the first industrial robot was manufactured in the United States, Japan surged ahead to become the leading manufacturer of robots. The first commercial computer-controlled robot was manufactured in the late 1950s. Two decades went by before the need for increased industrial productivity among the Western nations led to the establishment of robotics as a formal discipline of study. The development of industrial robots started in the late 1940s at the Oak Ridge and Argonne Laboratories with the development of remote-controlled mechanical manipulators for handling radioactive materials. For instance, the robots named "Rover" and "Louie" have been in use at the Three Mile Island nuclear power plant since 1982 to collect concrete and water samples from the crippled Unit 2 nuclear reactor. Also, an enormous robot nicknamed the "Workhorse" has assisted in cleaning out the basement of the containment building (19). The work of George C. Devol and Joseph F. Egleberger, in 1959, led to the first industrial robot introduced by Unimation Inc. This machine could be *taught* to carry out a variety of tasks independently. In the area of manufacturing technology, the robot could be reprogrammed and retooled to perform other jobs, as manufacturing needs changed. With the achievement of this milestone, robots offered a very powerful manufacturing tool which can be used in areas such as arc welding, spot welding, and paint spraying.

Advanced Manufacturing System

The need to mass-produce products of uniform quality was the drive behind the move by industries to automate manufacturing processes; automated manufacturing is based on machines designed to perform predetermined manufacturing functions. Originally, these machines were not flexible and were not easily adaptable to accommodate changes in product design. Their high cost and the need for a more flexible system led to the use of robots. Robots are capable of performing a variety of manufacturing functions at a lower production cost because they can be reprogrammed. Basically, an industrial robot is a general-purpose, computer-controlled manipulator consisting of several rigid links connected in series by joints. Each joint–link pair produces one degree of freedom. Motion of the joints results in the relative movement of the links. The assembly rests on a base and tools are attached to the free end. The robot uses the tools to perform assembly tasks. In essence, it is composed of an arm, a wrist, plus a tool designed to reach jobs within its area of operation. The wrist unit consists of three rotary motions namely pitch, yaw, and roll. It is the combined effect of these motions that enables the robot to orient the tools attached to its arm to suit the configuration and placement of the job. An industrial robot typically has six joints, which provide six degrees of freedom as illustrated by the Cincinnati Mailacron T3, and the Unimation PUMA 560 shown in Fig. 5 (20).

In a broader sense, a robot has three components: a mechanical unit comprising rigid bodies or links connected by joints, a power supply, and a controller. To pick up an object, a robot arm responds to the force of its actuators. Servomechanisms are used to exercise control via continuous feedback on the actuators. Vision with TV cameras and hearing with microphones gives robots some artificial intelligence, because they are now equipped with *eyes* and *ears.* The most powerful robot sensory capability is vision, which is commonly referred to as machine or computer vision. It can be subdivided into the six principal areas (21): sensing, preprocessing, segmentation, description, recognition, and interpretation. Each of these areas is an expert area of study.

MOTOR-OPERATED VALVES

Modern nuclear power stations are very complex. By comparison, approximately 40,000 valves are needed in a single US nuclear plant, while an oil- or coal-fired plant of a similar size requires only 4000 valves (22). The motor operated valve (MOV), actuated by a valve actuator motor (VAM), is one of such valves. They play a very indispensable role in nuclear power plants. They are called upon to perform safety-related services in case of nuclear accidents. Hence, all efforts must be made to ensure that after their installation they remain in good working condition, ready to function when called upon to do so. Since 1973, failures in nuclear power plants have been dominated by valve failures, 34% (23); followed by instrumentation, 16%; pumps, 8%; control rods, 8%; and diesel generators, 7%. Miscellaneous and human failures formed the remaining contribution. It is the combination of valve failure and the occurrence of a nuclear accident that spells a nuclear disaster. Thus, the MOV plays a critical role in the safe operation of nuclear power plants.

In general, MOVs are not continuously rated machines because they do not operate continuously. Rather, they are short-time-rated, high-torque machines, which operate for short periods of time when they are engaged to open or close a valve. They are not National Electric Manufacturer's Association (NEMA) designed motors, which are rated in horsepower, thus implying continuous operation. Instead, they are torque-rated, in pound-foot, for a given duration usually in minutes.

Special Properties of Valve Actuator Motors

VAMs are not ordinary motors. They are usually manufactured to specifications of the user. They are used for valve controls and are usually furnished in weatherproof, explosion proof, or submersible enclosures. They may run for only 30 s, just for the time required to stroke the valve. They are widely used in nuclear power plants. Their primary function is to open valves for water intake in case of emergency or a nuclear accident. Being high-speed high-torque machines, VAMs are made either from an induction motor with special design or from a dc compound wound motor. These two types of motor possess high starting torque capabilities because of their design. Special rotor construction is needed in order for the in-

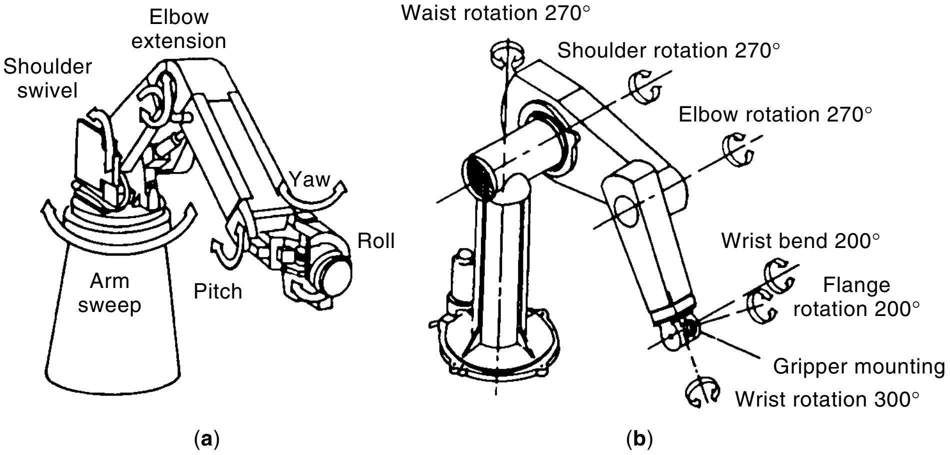

Figure 5. Industrial robots: (a) Cincinnati Malicron T3 robot arm (Courtesy of Cincinnati Milacron). (b) PUMA 560 series robot arm (Courtesy of UNIMATION, © Inc.) (20).

duction motor to be suitable as a VAM. In VAMs the locked rotor torque may be as high as 3 to 5 times that of an equivalent NEMA design B motor of the same nominal rating (24). Such high levels of torque are achieved while keeping the physical size of the motor small in order to reduce its inertia by the following means:

1. Increasing the flux level in the motor
2. By using special materials, such as magnesium which has a high resistivity
3. A combination of 1 and 2

Some of these ac motors are manufactured by Reliance Electric, Cleveland, OH. Similarly, Peerless Electric Division, of H.K. Porter Company, Inc., Warren, OH, manufactures dc motors. Both companies provide motor performance curves. These curves are used by Limitorque Corporation to properly match their actuators to the proper motor. The company does not manufacture the VAMs. Both the motor and actuator are assembled into a homogeneous unit. The projected life of a Limitorque actuator is 40 years if operated at ambient temperature. All motors are furnished with ball bearings and provided with grease seals. No lubrication of these motors is necessary, since they are lubricated at the factory for lifetime operation. All three phases of ac motors are of squirrel cage design, and dc motors are compound-wound.

Selection of a VAM

The correct selection of a valve actuator motor is critical to its ability to seat and unseat a valve in order to perform the safety-related function in case of a nuclear accident. Since the failure of a VAM is a hazard that may be attributed to an improper choice of actuator motor, a descriptive outline of the procedure, which will lead to a correct choice, is given. The five major types of valves commonly used are the gate valve, the glove valve, the plug valve, the ball valve, and the butterfly. Only the gate and glove valves are considered since the selection of other types of valves follow a similar procedure. Typically, all standard gate and globe valves require maximum stem thrust/torque to seat and unseat the valve against a given differential pressure. By using the Limitorque selection guide (SEL) (25), the steps are as follows:

1. Maximum thrust, or stem thrust (ST). The manufacturer usually provides ST. If not, this is given by:

$$\mathrm{ST} = \mathrm{TDP} + \mathrm{SP} + \mathrm{SL} \tag{5}$$

$$\mathrm{TDP} = \mathrm{DP} \times \mathrm{A} \times \mathrm{FV} \tag{6}$$

   where TDP is the thrust due to differential pressure, A is the seating area, DP is differential pressure, FV is the value factor given by SEL-3, SL is the stem load or piston effect, and SP is the stem packing or stuffing box load obtained from SEL-3.
2. Stem torque: The next step is to determine the stem torque from ST obtained from Step 1. The stem torque is given by:

$$\text{stem torque} = \mathrm{ST} \times \mathrm{FS} \tag{7}$$

   where FS is the value stem factor.
3. Overall or Unit Ratio: The unit or overall ratio (OA) is used to compute the motor torque so as to select motor size. The unit OA can only be computed after the stem torque determined from Step 2 is used to select the proper HMB- or SMB-type Limitorqe valve controls. By using the stem torque and SEL-9, the appropriate value control is picked:

$$\mathrm{OA} = \frac{\text{motor design (or rated) speed}}{\text{acutator or stem rpm}} \tag{8}$$

$$\text{actuator or stem rpm} = \frac{\text{stem speed}}{\text{stem lead}} \tag{9}$$

4. Calculated motor torque (MCT) is needed in order to select the proper motor size. This is given by:

$$\mathrm{MCT} = \frac{\mathrm{ST}}{\mathrm{OA} \times \mathrm{EFF} \times \mathrm{AF}} \tag{10}$$

   where ST is the stem thrust from Step 1, and EFF is the pullout efficiency, which is determined by the manufacturer through calculation and confirmation by test. A typical value of unit pullout efficiency is 0.4 (obtained from actuator manufacturer). AF is the application factor and it is used to give a conservative estimate of the MOV torque. It is also used to apply a reduced voltage for some motor calculations. A sample value for, AF is 0.9.
5. Selection of motor: The calculated motor torque from Step 4 is a guide used to select the next available motor from SEL-9. Thus, conservatively, the motor to be selected is of the next higher torque size. For example, if MCT = 51 ft · lbs, then choose the next higher motor size, which is the 60 ft · lb, 1800 rpm motor from SEL-9. Similarly if MCT = 30 ft · lb, then choose the 40 ft · lb torque motor.

Safety Guide

Although the motors are lubricated for lifetime operation, it is advisable to check the lubricant every six months. It is also important to see that the commutator brush on dc motors is clean and operates freely. It cannot be over-emphasized that proper size of wires should be used to insure against a large voltage drop at the terminals when the motor starts.

Standards

There are no unified standards by an industrial body, like NEMA, or from an educational and professional organization, like IEEE, to regulate the world of MOVs. However, there are some guides that have been developed by the American National Standard Institute in conjunction with the IEEE (26) and the US Nuclear Regulatory Commission (27–29) on the protection of MOVs used in nuclear generating stations. Because of the absence of a unified standard, the design, manufacture, and operation of MOVs are left to the judgement of the engineer and end user. One direct result of this is a variation in standard and application of MOVs from one nuclear power plant to the other. For example, in some cases, the thermal overload relay (TOL) is bypassed in the protection of MOVs, while in some others they are not. In fact, many investigators (30–32) have been alarmed by this lack of unified standards and have pointed out the dangers presented by such practices.

Constraints for Starting and Operation

MOVs are high-torque high-current starting and short-time-run motors. The usual requirements of maximum torque at starting (zero speed) with reduced starting current that applies to all types of motors are also desired for MOVs. Nearly all squirrel-cage induction motors are capable of starting at full rated voltage without being damaged. However, their starting current is so high and the power factor so low that the power supply may be adversely affected by an excessive voltage dip when the motor is started. For MOVs, the dc motor can be started at 70% rated voltage, while the ac motor will start at 80% rated voltage. While the 70% figure is well accepted for the dc motor, the 80% figure is not yet well established for the ac motor. At the upper limit, both types of motors may operate satisfactorily at voltages 10% above their rated values.

Failure of MOVs

In nuclear power facilities, the concerns for radiological exposure, fast emergency system operation, and the requirement to bring the plant to a quick and safe shutdown point to the indispensable and critical role that the MOV must play. Although everything possible is done to minimize the failure of MOVs, an Institute of Nuclear Power Operations (INOP) Study (33), which investigated 644 different Licensee Event Reports (LERs) submitted to the Nuclear Regulatory Committee (NRC) between 1974 and 1982, showed that failure of MOVs has indeed consistently occurred. The failures are attributed to mechanical, electromechanical, electrical, and motor control circuits (MCC) causes. Their analysis, shown in Table 7 indicates that 32% of the documented failures were due to electromechanical torque switches and limit switches. Since the summary also shows that 22% of the failures were mechanical in nature, then 54% of the total MOV failures analyzed were due to electromechanical components within the valve actuator.

Further evidence showed that the documented failures could be attributed largely to MOV hardware, equipment design, application, operation, and maintenance practices. However, the biggest cause of failure was the torque switches and the position limit switches. For this reason, Electric Power Research Institute (EPRI) funded EPRI NP-4254, Project 2233-2 (34) titled “Improvements in Motor-Operated Valves” in order to find remedies for the shortcomings in the design of the MOV. Other investigations on causes of MOV failures across nuclear power plants showed that one major difficulty was the problem of setting up the torque and limit switch set points accurately and correctly. Another was the difficulty of providing proper thermal overload relay protection for the intermittent duty actuator motor.

Table 7. MOV Failure Analysis—INPO Report 83-037 (12)

Type	Percent
Mechanical (failure to operate, bent stems, damage to valve seats, gear binding and damage)	22
Electromechanical (torque switch failure, torque switch adjustment, limit switch adjustment)	32
Electrical (motor, contacts, MCC and others)	27
All others (vibration, wear, other)	19

The most significant electrical cause of MOV failure is the overheating in the stator or rotor of the valve actuator motor during locked rotor condition (35). It accounts for 90% of the reported failures. The overheating caused by the stalled motor condition results in a high rate of temperature rise in the stator as well as in the squirrel cage rotor. It was found that squirrel cage rotors made of magnesium alloy had a significantly larger failure rate than those with aluminum rotors. The reason is that although the use of magnesium rotors provided the much-needed high starting torque, they are susceptible to cracking when overheated by sustained locked rotor current. Also, they are susceptible to corrosion when installed in a hot, humid environment. This weakness is due to the brittle nature of the magnesium alloy with its relatively low melting temperature and large galvanic potential between magnesium and steel used in the rotor lamination.

Protection of MOV

Measures that can limit or reduce the failure of MOVs include the following:

- Operator training
- Correct operational procedures
- Preventive maintenance
- Valve/actuator matching
- Periodic inspection of magnesium rotors

Any protection strategy for MOVs must be primarily temperature sensitive because excessive heat is the major cause of motor burnout. Since MOVs are specialized intermittent duty, high-torque, high-slip motors, wide fluctuations in current are their characteristics, and they are designed to withstand them. Hence, protectors designed to be current sensitive are likely to stop a motor that is functioning normally or fail to stop a motor that is overheating. Basically, three types of protectors are available for overload protection. They are:

1. Internal devices located on the stator windings: These are internal temperature sensors like thermistors or thermally actuated contacts located on the stator winding. They are good for motors that are stator temperature limited, but are ineffective for motors that are rotor temperature limited. MOV motors are classified as either *rotor limited* or *stator limited.* If the temperature of the rotor reaches its allowable limit before the stator reaches its own allowable limit, then the motor is referred to as rotor limited. However, if the temperature of the stator reaches its allowable limit before the rotor reaches its, then the motor is said to be stator limited. They are vulnerable to failure due to heavy vibration found in some actuator applications and are not easily accessible, thus creating maintenance difficulties.
2. External devices actuated by motor currents: These are bimetallic or eutectic thermal overload relays in the motor–starter circuit and the thermal–magnetic trip element in the circuit breaker. They provide protection for overload and locked rotor conditions. They usually consist of the current-carrying portion, which produces the

heat, and the tripping mechanism, which is actuated as a result of the heat.

3. Combination of internal and external devices.

More protection is provided by a combination of 1 and 2.

Whichever protection mechanism is selected, it must protect the motor from the following:

- Motor overheating due to locked rotor conditions
- Motor overheating due to anticipated overloads
- Nuisance trips during acceleration
- Nuisance trips due to anticipated overloads
- Nuisance trips during operation within the duty cycle of the valve

Maintenance of MOV

It is known that in many cases, MOV failures result from inadequate training of personnel and the failure to implement existing maintenance schedules. Therefore, preventive inspection/maintenance based on time or cycle provided by the valve manufacturer should not be ignored or overlooked. The manufacturer's recommendations should be followed. Use of lubricants specified by the manufacturer and careful attention to quantity, quality, and consistency must be adhered to. The Limitorque Corporation recommends the following maintenance practices for their actuators:

Lubricate main gearbox and geared limit switch.

Do not fill the actuator to 100% capacity. Leave an air space in the actuator to allow for thermal expansion of the lubricant.

Check shaft penetrations for seal leakage. Note that some oil leakage is expected and acceptable. Replace seals if abnormal grease leakage occurs.

Remove moisture if found in the limit switch compartment. Ensure cleanliness of electrical contacts and check terminal connections for tightness.

Inspect stem and stem nut. Internal and external wiring inside connection compartment should be checked for damaging abrasion cuts or distortion of conductor insulation.

Summary

MOVs are commonly used in direct gear-driven valve actuator assemblies in nuclear power plants. They are short-time rated, high-torque, high-slip motors. They are rated in torque (i.e., in lbs. · ft.) and *not* horsepower (hp) as in conventional motors. For normal operation of the valve actuator, the motor may run up and down the torque scale from light load to stall torque. The corresponding horsepower follows this same pattern. Thus, the horsepower fluctuates accordingly, making it useless as a means to rate the MOV.

Industry or professional society standards do not cover motors employed as direct gear-driven valve actuator motors. For this reason, there are no universally accepted methods of protecting the motor. Therefore, the design, manufacture, and utilization of the MOV are left to engineers, manufacturers, and end-users.

Because MOVs require a very high starting torque, they are manufactured from either a squirrel cage induction motor with specialized rotor design or from a compound-wound dc motor. Since it is required to drive a valve to a fully close or fully open position, the MOV is fitted with position limiting switches to stop the unit at the full open and full close positions. In addition to position limiting switches, valve motor actuators are equipped with a torque-limiting device. This torque switch is designed to limit the output torque of the actuator to the peak torque required by the valve usually to seat or unseat it.

While some manufacturers provide internal temperature sensors located on the stator windings, the most common mode of protection is through current-sensing devices located external to the device. The industrial or utility approach is to use thermal overload relays (TORs) as part of the combination starters provided in the MCC.

It is most essential to reduce the failure rate of MOVs because of the importance of their function in nuclear power plants, especially in case of nuclear accident. To this end, the Licensee Event Reports (LER) between 1974 and 1982 were reviewed (33) in order to identify the causes of the documented MOV failures. It was found that up to 54% of the failures were electromechanical in nature, while 27% were electrical. The report also indicated that a significant number of MOV failures were due to improper operator training.

In order to ensure that MOVs remain in a sound functional condition, they must be routinely maintained as recommended by the manufacturers. Some of the maintenance tips include lubrication of the main gearbox and geared limit switch and inspection of the stem and stem nut system and lubrication as necessary. Note that for lubrication purposes, the quantity and quality of grease recommended by the manufacturer must be adhered to. Finally, operator training is necessary in torque switch and limit switch setting, as well as in the protection and control of MOVs in order to reduce human error in their utilization.

REGULATIONS AND SAFETY STANDARDS

Regulations have been established by government agencies to guide the safety practices of its people. These days everyone must conduct his or her work in accordance with this statutory legislation. Some of these standards organizations and function are:

National Electric Code. National Electric Code (NEC) is one of the oldest, and was first developed in 1897. It sets standards that cover industrial, commercial, and residential electric systems to help minimize the possibility of electrical fires.

American Society for Testing and Materials Standards. The American Society for Testing and Materials (ASTM) Standards produces standards for safety equipment design, usage, and testing.

Occupational Safety and Health Administration. Occupational Safety and Health Administration (OSHA), an agency of the US Department of Labor, was established by an act of Congress in 1970. Its main responsibilities are to provide for occupational safety by reducing hazards in the workplace and enforcing mandatory job safety standards and to implement and improve health programs for workers. OSHA regulations and standards apply to most private businesses in the United States. OSHA has produced several safety standards which are federal laws that must be implemented by industries. They range from design safety standards to safety-related work practices.

American National Standards Institute. American National Standards Institute (ANSI), which was founded in 1918, coordinates voluntary standards activities in the United States, approves American national standards, represents US interests in international standardization, and provides information on the standards prevailing in other parts of the world.

American Society of Safety Engineers. American Society of Safety Engineers (ASSE) is made up of safety professionals whose mission since its foundation in 1911 is to promote the advancement of the safety profession.

Institution of Electrical and Electronics Engineers. The IEEE was founded in 1963 when the American Institute of Electrical Engineers (founded in 1884) was merged with the Institution of Radio Engineers (founded in 1912). With the primary function of development of electrical standards and publication of technical journals, it is one of the world's largest professional and technical societies.

American Society for Testing and Materials. American Society for Testing and Materials (ASTM) was founded in 1898 and develops standards for products, systems, and services.

National Fire Protection Association. National Fire Protection Association (NFPA) was founded in 1896 for the purpose of protecting property, people, and the environment from fire.

National Electric Manufacturer's Association. National Electric Manufacturer's Association (NEMA) has established ratings for equipment, which ensure that companies manufacture equipment of the highest quality. Equipment tested to satisfy NEMA's specifications carries Underwriter's Laboratory (UL) seal of approval.

Nuclear Regulatory Commission. The Nuclear Regulatory Commission (NRC) is a Federal agency established to regulate the operation of nuclear power plants and nuclear related facilities.

Some of the organizations in the United Kingdom are described.

Health and Safety Executive. This is the main regulating agency and enforcement authority. Several Health and Safety at Work Acts are available, for instance the Act of 1974, and in case of electrical hazards Electricity at Work Regulations of 1989 apply.

British Standard. It is the benchmark for a wide variety of industrial sectors, and there are several British standards addressing diverse issues related to safety.

Institution of Electrical Engineers. The Institution of Electrical Engineers (IEE) has produced several regulations, which are adopted in several countries. An example is the IEE Wiring Regulations, which sets out the requirements for home and industrial electrical wiring.

BIBLIOGRAPHY

1. D. C. Wilburn, *Practical Electric Safety,* New York: Dekker, 1988, p. 17.
2. W. F. Cooper, *Electrical Safety Engineering,* 3rd ed., Stoneham, MA: Butterworth Heinemann, 1993, p. 5.
3. S. Wolf and R. F. M. Smith, *Student Reference Manual for Electronic Instrumentation Laboratories,* New York: Prentice-Hall, 1990, p. 48.
4. R. H. Lee, Electrical safety in industrial plants, *IEEE Trans. Ind. Gen. Appl.,* **IGA-7**: 10–16, 1971.
5. J. Cadick, *Electrical Safety Handbook,* New York: McGraw-Hill, 1994, p. 1.3.
6. Ref. 2, p. 54.
7. Ref. 2, p. 54.
8. Ref. 5, p. 2.64.
9. Ref. 5, p. 2.44.
10. Ref. 5, p. 2.71.
11. H. Hasse, *Electrostatic Hazards: Their Evaluation and Control,* New York: Verlag Chemie, 1976, p. 60.
12. Microsoft Home ENCARTA'95, Interactive Multimedia Encyclopedia, 1995.
13. A. Yaroshinskaya, *Chernobyl: The Forbidden Truth,* Lincoln: Univ. of Nebraska Press, 1995, p. 1.
14. P. M. Hassler, *Three Mile Island,* Metuchen, NJ: Scarecrow Press, 1988, p. 1.
15. Ref. 14, p. 2.
16. *Report of the President's Commission on the Accident at Three Mile Island, The Legacy of TMI,* pp. 70–73.
17. G. K. Chacko, *Robotics/Artificial Intelligence/Productivity,* Princeton, NJ: Petrocelli, 1986, p. 5.
18. T. D. Wall, C. W. Clegg, and N. J. Kemp, *The Human Side of Advanced Manufacturing Technology,* New York: Wiley, 1987, pp. 38–42.
19. Ref. 14, p. 27.
20. G. K. Chacko, *Robotics/Artificial Intelligence/Productivity,* Princeton, NJ: Petrocelli, 1986, p. 104.
21. K. S. Fu, R. C. Gonzalez, and C. S. G. Lee, *Robotics: Control, Sensing, Vision, and Intelligence,* New York: McGraw-Hill, 1987.
22. A week of billion-dollar headaches for the proponents of nuclear power: Coal's future could rival its past, *New York Times,* 22 January 1984, p. E9.
23. *Reactor Safety: An Assessment of Accident Risks in US Commercial Nuclear Power Plants. Appendix III and IV: Failure Data,* U.S. Department of Commerce, National Technical Information Services, PB-248 204, U.S. Nuclear Regulatory Commission, Report No. WASH-1400 (NUREG 75/014), October 1975, p. III-17.
24. R. V. Rebbaprogada et al., Design features and protection of valve actuator motors in nuclear power plants, *IEEE Trans. Energy Conv.,* **5**: 572–584, 1990.
25. FC-77, Limitorque Corporation, *Fast Closing Valve Operators,* updated.
26. ANSI/IEEE std. 741-1989, Criteria for the protection of Class 1E power systems and equipment in nuclear power generating stations.
27. Regulatory Guide 1.106, Thermal overload protection for electric motors on motor-operated valves, US Nuclear Regulatory Commission.
28. NUREG-1296, Thermal overload protection for electric motors on safety-related motor-operated valves—Generic issue II.E.6.1, US Nuclear Regulatory Commission.
29. NUREG/CR-4380-0RNL-6226, Evaluation of the motor operated valve analysis and test system (MOVATS) to detect degradation,

incorrect adjustments, and other abnormalities in motor operated valves, US Nuclear Regulatory Commission.

30. F. D. Baxter, The dangers of bypassing thermal overload relays in nuclear power plant motor operated valve circuits, *IEEE Trans. Power Apparatus Syst.,* **PAS-99** (6): 2287–2291, 1980.
31. H. B. Payne, Jr., Motor protection for valve actuators, *IEEE Trans. Ind. Appl.,* **IA-14**: 23–26, 1978.
32. A. W. Richards and C. D. Formica, Motor overload protection for motor actuated valves, *IEEE Trans. Power Apparatus Syst.,* **PAS-100**: 43–50, 1981.
33. Institute of Nuclear Operations, INOP 83-037, Assessment of motor operated valve failures.
34. EPRI NP-4254, *Improvements in Motor-Operated Valves,* Palo Alto, CA: Electric Power Research Institute.
35. J. D. Kueck, An investigation of magnesium rotors in motor operated valve actuators, *IEEE Trans. Energy Conversion,* **3**: 40–43, 1988.

CLARENCE N. OBIOZOR
University of North Florida