An Introduction to Electrical Safety for Engineers

NIOSH Instructional Module

SHAPE
Safety/Health Awareness
for
Preventive Engineering

U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES
Public Health Service
Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health

CDC
CENTERS FOR DISEASE CONTROL AND PREVENTION

AN INTRODUCTION TO ELECTRICAL SAFETY FOR ENGINEERS

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DISCLAIMER

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ABSTRACT

The primary objective of this instructional module is to familiarize engineering faculty and students with the occupational safety and health concerns which should be inherent to every electrical system. In designing, operating, and maintaining electrical systems, the engineer must consider the occupational and environmental hazards associated with electrical components as well as the safety of the surrounding community from fires and explosions. This module can be studied separately or as a component of an upper-level engineering design course.

Unit I provides background on basic safety and electrical engineering concepts which are expanded upon in later modules. Unit II identifies the different types of electric shock hazards, their effects on the body and methods to control these hazards as well as the inadvertent activation of equipment.

Unit III is concerned with the electrical ignition of flammable and combustible materials, resulting in fires or explosions, from overheating components, static electricity and other sources. Methods to control ignition and explosion hazards are discussed.

Unit IV summarizes pertinent safety standards, such as the National Electric Code, and those organizations promulgating the standards, such as the National Fire Protection Association and the Occupational Safety and Health Administration. Unit V provides examples of both inductive and deductive methods of systems safety analysis and how these methods identify the hazards associated with the design, operation, and maintenance of electrical systems.

Unit I

AN INTRODUCTION TO SAFETY AND SOME BASIC ELECTRICAL ENGINEERING CONCEPTS

PURPOSE:

To introduce students to: 1) the importance of safety in dealing with electrical systems, and 2) basic electrical engineering concepts.

OBJECTIVE:

To acquaint the student with:

1. Definitions of safety-related terms
2. Basic electricity concepts
3. Basic circuit laws and analysis

SPECIAL TERMS:

1. Hazard
2. Danger
3. Damage
4. Risk
5. Accident
6. Safety
7. Electric current
8. Conductors
9. Insulators
10. Resistance
11. Impedance
12. Voltage
13. Direct current
14. Alternating current
15. Capacitance
16. Ohms
17. Hertz
18. Amperes

INTRODUCTION

The struggle to provide an acceptable degree of safety in the modern world depends on the give-and-take relationship between the cost of accident prevention and the moral regard for human life and well-being. Conceptualizing safety with such a simple statement, however, disguises the complexity of the issue. What is the "modern world"? What is the "cost of accident prevention"? What does "moral regard for human life and well-being" entail? What exactly is "safety"? What is an "acceptable degree" of safety? First, we'll try to answer these questions, and then we'll see how this all applies to engineers.

"Modern world," as used here, applies to the time period following the Industrial Revolution. During the last half of the nineteenth century, the Industrial Revolution made a profound impact on the United States. American production methods changed from craft shops to mechanized factories, first in New England in the textile industry and soon throughout the entire country. The National Safety Council (1988) notes that these changes in production methods can be summarized as:

- the substitution of steam and other inanimate power sources [e.g., electricity] for animal sources;
- the substitution of machine power for human power and skills;
- the development of new processes for making iron, steel, industrial chemicals, and other materials; and
- the reorganization of work from craft shops to large factories or mills with an efficient division of labor.

These production methods greatly expanded the quantity and types of products available to the average American. They also expanded the magnitude and types of hazards present in our everyday activities. The discovery of electricity and its subsequent use in industry and in the home was an integral part of this period and presented a variety of new and unique hazards to the public.

A few definitions

Since we have used the term "hazard" several times so far, this may be a good time to define some of the terms we'll be using throughout this book (Bloswick, 1992).

Hazard

A *hazard* is a condition that has the potential to cause injury, damage to equipment or facilities, loss of material or property, or a decrease in the capability to perform a prescribed function.

Danger

The *danger* inherent in a situation depends on the relative exposure to a hazard. For example, a high-voltage transformer is a significant hazard but may present little danger if locked in an underground vault.

Damage

Damage is the severity of injury or magnitude of loss that results from an uncontrolled hazard. A worker near a 220 volt line is exposed to the same hazard (potential for electric shock) and is in the same danger (exposure to electric energy) as a worker near a high voltage (1000 volts and greater) line. The possibility of damage (severity of injury in this case), however, is much greater in the latter case.

Risk

Risk is a function of the probability of loss (danger) and the magnitude of potential loss (damage). It can be thought of as (probability of loss) × (magnitude of potential loss).

Accident

An *accident* is an unexpected event that interrupts the work process and carries the potential for injury or damage. Accidents may or may not result in fatality, injury, or property damage, but they have the potential to do so. An accident may be attributed to a human factor, a situational factor (operations, tools, equipment, and/or materials), or an environmental factor.

In public health, practitioners are avoiding the term "accident" because it does not convey the predictability and thus preventability of many fatalities and injuries attributed to "accidents." The public health interest is to encourage society to begin regarding fatalities and injuries as preventable events rather than as unexpected, chance events, as conveyed by the term "accident."

Safety

Although it has been defined in many ways, *safety* can be thought of as the absence of hazards or minimization of exposure to hazards. Firenze (1991) also notes that *safety is the control of hazards to an acceptable level.*

This last statement, "safety is the control of hazards," is a theme that you will see throughout this book. Each time we discuss a hazard, we will present some methods by which the hazard can be controlled. The last part of the statement, "... to an acceptable level," is most difficult to ascertain. This is where the real conflict begins between the cost of methods to control a hazard and the likelihood of an accident occurring. How much risk are you willing to take? How much risk is your company willing to take? How much risk is acceptable to the public?

Economics and safety

Perception of the cost of providing safety varies over history and among individuals and organizations. In 1893, a railroad executive said that it would cost less to bury a man killed in an accident than it would to increase safety by putting air brakes on rail cars. At that time, in purely economic terms, that may well have been true. But society has since realized that the economic costs of injuries and deaths is significant. The National Safety Council (1989) notes for 1988:

- that 10,600 workers were killed on the job;
- that deaths and injuries (about 2 million annual injuries) in the workplace cost an estimated $47.1 billion; and
- that each death costs approximately $550,000 and each disabling injury, $16,800 with each worker having to produce goods or services in the amount of $410 just to offset these accident costs.

These are only the economic costs for workplace injuries and deaths. These numbers only include the economic costs incurred by industries; they do not include financial losses by the injured parties or families of the deceased. When the cost of civil lawsuits, medical charges, insurance, property damage, and many other indirect expenses related to injuries and deaths outside the workplace are considered, the economic liabilities to individuals and society resulting from such incidents become astronomical.

When events outside the workplace are included, these figures increase to more than 90 thousand deaths and about 9 million disabling injuries per year, amounting to a total financial loss of more than $100 billion.

More than $

Of course, there is more to injuries, and particularly deaths, than economics. The emotional costs are more difficult to measure but are equally important in the aftermath of an injury or death. In fact, the financial liabilities are often easier to recover from than are the emotional losses. This may be on an individual level, where family, friends, fellow workers, etc., suffer emotionally from an injury or loss of friend or loved one (which may undermine the productivity of all involved). The emotional consequences may affect society or the reputation of an entire organization. When the Space Shuttle Challenger exploded in mid-air, the Nation watched in disbelief. Shuttle launches were put on hold for about 2 years, and NASA may never fully recover from the effects of that event. When an oil tanker spilled its cargo in the pristine wilderness of Prince William Sound, Alaska, the Nation was outraged. You can be sure that the oil company will feel the effects of the clean-up and damaged reputation for many years. On a more personal level for engineers, imagine being responsible for a system that failed, especially if the failure resulted in death or injury. Proper attention to safety can save society, organizations, individuals, and your own conscience from the emotional trauma and the economic consequences of such incidents.

Moral obligations

As engineers, we have a moral obligation to provide safe products, environments, and workplaces. This is where the tough decisions must be made—the cost of incorporating hazard controls versus the cost of an injury or fatality versus ethical concerns. People want safe products and services, but they may not be willing to pay for the features that protect them or the persons providing them from harm. Further complicating the issue, what's safe for one individual may not be safe another individual because of different perceptions of safety, or our different abilities, or different predisposition to certain types of harm. For example, a high voltage device with exposed energized conductors may be safe in the presence of an electrical engineer because of knowledge and training but would never be safe in the home environment.

Perception of risk

People's perception of risk, and what risks are acceptable to them individually or as a society, complicates the ability to arrive at an "acceptable level of safety." Although we are not always rational in our decision making processes, our determination of an acceptable risk is affected by, among other factors, whether the risk exposure is voluntary or not, whether it is job related, and how the risk is presented to us.

Exposure to risk

Voluntary

Consider the risks you voluntarily expose yourself to and those that you have no control over. For example, you may voluntarily ride three-wheel, all-terrain sport vehicles. During the 5 years before they were taken off the market in the United States, nearly 900 people died (about half of them under 16 years old) and 300,000 were injured while using them (Martin and Schinzinger, 1989). As much fun as they may be, a user voluntarily exposes him/herself to a significant risk of injury or death. This same person, however, may be adamantly opposed to being exposed to the relatively minor risks associated with a high-voltage, overhead powerline running near his home.

> *We are loath to let others do unto us what we happily do to ourselves.*
>
> Chauncey Starr

Risk on the job

On the other hand, many people accept greater risks at work than they would in other environments. The reasons for this are complex, but to a certain degree, people will accept the risks because they like their job, or they need their job, or they may fear dismissal if they were to complain.

Assessment of risk

Another factor that affects the type and degree of risk people will accept depends on their ability to accurately assess a risk based on the available information. The information people use to make their decisions greatly influences how risks are perceived. Take for example the following information (Tversky and Kahneman, 1981, as reported by Martin and Schinzinger, 1989).

Imagine that the United States is preparing for an outbreak of an unusual disease, which is expected to kill 600 people. Four alternative programs to combat the disease have been proposed. Assume the exact scientific estimate of the consequences of the programs are as follows:

— If program A is adopted, 200 people will be saved.

— If program B is adopted, there is 1/3 probability that 600 people will be saved, and 2/3 probability that no people will be saved.

— If program C is adopted, 400 people will die.

— If program D is adopted, there is 1/3 probability that nobody will die, and 2/3 probability that 600 people will die.

Which of the four programs would you choose?

If you haven't already noticed, programs A and C are identical, as are programs B and D. And statistically, each program has the same expected value: 200 people will survive and 400 will not. Only the way the information is presented is different.

Skewed perceptions

In an experiment, programs A and B were presented to one group of people, and programs C and D were presented to another group (about 150 people in each group). In the first group, 72 percent of the people chose program A, and 28 percent chose program B. In the second group, however, only 22 percent chose program C (which is identical to program A), and 78 percent chose program D (which is identical to program B). Apparently, people will choose options that provide definite gains over options that appear risky or only probable. In addition, options whose chances of success are perceived as probable will be favored over options that emphasize definite losses. Such decision making influences are certainly not rational, but they are real.

Nor is our reaction to large-scale accidents a rational one, nor to those that happen to someone we know. For example, whenever a large-scale airplane crash occurs, we are deluged with grizzly scenes and descriptions of the disaster by the media. The emotional trauma suffered by the friends and loved ones of the victims leaves an impression on us. Some people refuse to fly, whereas others fly in fear. Of course, flying is a safer mode of transportation than is traveling by car. If you need to travel an appreciable distance, you are far safer flying than driving. Yet, the magnitude of an air disaster skews people's perception of the risks, leaving many overly fearful of flying. (Relating to the above discussion, people may also be affected by the lack of control they feel when flying, since they are mere passengers at the mercy of the pilot(s) and technology.)

Perception of potential risk may also be skewed if we or people we identify with or have relationships with are the potential victims. Again, imagine ourselves or a loved one as the victim of a plane crash shown on TV, or imagine a child trapped in a well as the Nation follows the rescue attempts for several days. Such things can affect us more acutely than does the continuous, but anonymous, death and injury occurring on the roadways (until it happens to someone we know, that is).

An individual's perception of risk and whether or not that risk is acceptable is a complicated function of many external and internal factors. Arriving at absolute safety, then, or providing a measure of safety that satisfies all individuals and organizations under all conditions, is neither attainable nor affordable. As engineers, however, we must do all we can to provide safe products and environments.

Drawing the line

Where and how do we draw the line on what is safe and what is acceptable? Because of the numerous concerns throughout the design, manufacturing, distribution, sales, use, maintenance, and disposal of a product, there is no definitive answer to this question. The following case example illustrates the difficulties involved.

When the Ford Pinto was in the development stage, crash tests revealed that the windshield could not withstand a prescribed test crash without breaking; this violated a standard. To solve this problem, the drive train was moved back, changing the way energy was absorbed during impact. The new location, however, was close enough to the gas tank that during certain rear-end collisions the drive train would collapse the fuel tank and cause an explosion (Martin and Schinzinger, 1989). At least one engineer was concerned by the potential safety consequences, but he was ignored by corporate officials. The Pinto was produced and sold with this known defect, probably because of the up-front costs of redesigning. At the time, Ford was in a serious competition with foreign car makers to put a fuel- efficient model on the market at a competitive price. Once on the market, Pintos did explode during rear-end collisions; deaths and injuries and huge civil liability lawsuits resulted. It is debatable whether the final economic costs to Ford, in lawsuits, insurance, and damaged reputation, outweighed changing the defective design in the first place.

Dispelling a myth

A myth that engineers can no longer claim is that operator error and negligence is the principal cause of most adverse events. An engineer is a professional problem solver. When these events repeatedly occur during the use of a particular product, a problem undeniably exists. Just as a part that fails due to fatigue before a product's useful life is complete, this event is an abnormal and undesirable incident—a failure—and must be treated the same. We cannot blame the user every time someone is electrocuted. "He knew it was a high voltage line—it's his own fault for touching it." Obviously, if "he knew...," he wouldn't have touched it, or he touched it inadvertently.

An engineer's familiarity and interest in technology tend to make many of the concepts and associated hazards second nature. We begin to think of any hazards as obvious. What is obvious to an engineer may, however, be a mystery to the user of an unfamiliar product or system. Moreover, knowledge of a hazard does not preclude an accident. Knowledgeable workers are the most frequent victims in electrical accidents. Is this because of worker carelessness? That's one way to look at the problem, but if we truly desire to "fix" the problem, as an engineer should, then we must look at it as a system failure. Armed with the knowledge that people make mistakes while operating or maintaining a product, what can we do to minimize the probability of an accident in such situations? Many techniques are available; only some will be covered in this text. Be advised that this is only a glance at safety theory and practices and at electrical safety in particular. Throughout your career you must research specific topics on your own and expand on the knowledge recorded by others.

HAZARD CONTROL AS A DESIGN CRITERIA

In the past, engineers often believed the theory that dangers and unsafe conditions would be learned once the product was designed and sold. By studying the events that invariably occurred, they could learn the hazards and control them in future designs. Although studying such incidents is very instructive for future safety, we can no longer afford to let after-the-fact information be our primary guide. Today, engineers must treat hazard control as any other design criteria, from the day a product idea is first conceived through the day the last remnants of the product exist. Fortunately, rigorous hazard analysis techniques are available and will be discussed in the last course unit (Systems Safety Analysis).

The second unit covers the hazard of electric shock and some general control strategies. The third unit discusses the fire hazards associated with electrical equipment and again describes some general abatement strategies to eliminate or minimize the hazards. Standards and professional liabilities, topics covered in the fourth unit of this course, also provide engineers with a minimum level of safety information and features for many products and components.

Design for people

Together with the vast amount of information now available to the engineer, these pages provide a basic understanding of electrical safety. Safety considerations (not a "necessary evil," as some may tend to believe) are the essence of good engineering. We design technology for people; we do not attempt to manipulate people to fit with or serve technology. A system that is difficult or dangerous to operate isn't meeting its optimal potential and is contributing to adverse events; it is—pure and simple—poorly designed.

REVIEW OF THE FUNDAMENTALS OF ELECTRICITY AND CIRCUITS

Modern theory states that all matter is made up of atoms. The basic structure of an atom consists of a nucleus of packed neutrons and protons surrounded by orbiting electrons. Neutrons have no electric charge, protons are positively charged, and electrons are negatively charged. In its normal state, an atom has no overall charge. That is, the number of protons (+) is equal to the number of electrons (-), leaving a net charge of zero for the atom. Applying energy to atoms, however, can result in a loss of one or more electrons and cause the atom to have a net positive charge. Likewise, an atom can gain electron(s), and have a net negative charge. When a conductive material, such as a copper wire, is charged (either positive or negative) at one end, electrons flow from atom to atom in the direction necessary to balance the charge difference.

Electric current

Benjamin Franklin (1706-1790), without the benefit of our modern atomic theories, surmised that electricity traveled from positive to negative, setting a convention that we still use today. Based on modern theories described above, however, we note that the path of electron flow in a material is actually from negative to positive. Therefore, conventional current, which we use in circuit analysis, is the movement of positive charges. The movement of electrons in the material (called electron current) is actually in the opposite direction. See Figure I.1.

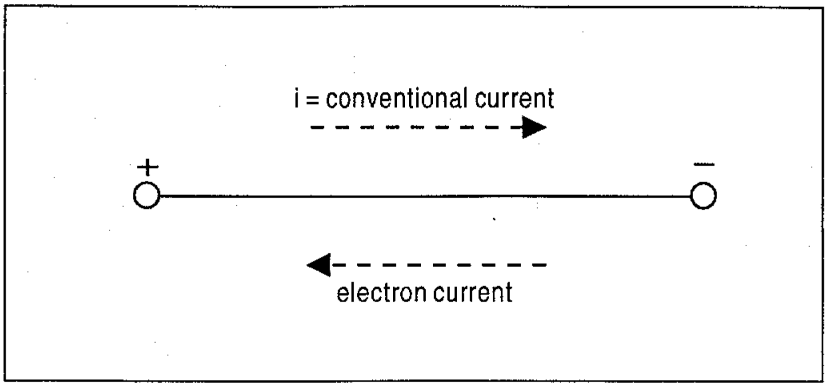


Figure I.1. In circuit analysis, the positive direction of a conventional current moves from positive (+) to negative (-). The actual flow of electrons, however, is from negative to positive.

Basic electrical engineering concepts are briefly summarized below.

Conductors

Very simply, a conductor is any material in which, due to its atomic make-up, electrons are easily moved. Examples of conductors include metals and water. Since humans consist mostly of water, we are also conductors.

Insulators

Conversely, materials in which electrons are not easily moved about are called insulators. Rubber, plastics, glass, and air are all examples of insulators. Insulators are used to stop the flow of electric current or to keep a conductor from being in contact with other conductors. For example, the coating over an electrical cord keeps the current from passing to your body when you grasp it.

Resistance

When currents flow in conductors, the electrons collide with the lattice of atoms that make up the material. This impedes, or resists, the motion of the atoms. The greater the interference with electron movement in a material, the greater the resistance of that material. All conductors exhibit resistance to some extent at room temperature (although researchers are busily trying to devise "super conductors," that would have no resistance at room temperature). Resistance is measured in "Ohms," named after Georg Simon Ohm (1787-1854), a German physicist. The Greek letter omega (Ω) is used to designate Ohms.

Impedance

As an alternating current passes through a circuit under an applied voltage, it is impeded. This impedance may be due to resistance, inductance, capacitance, or a combination thereof and is measured in Ohms (Ω).

Voltage

If electrons are to move in some concerted manner through a conductor (i.e., as an electric current), there must be some potential difference applied to the material. For example, the ends of a wire must have a charge difference (potential difference), so that the electrons will flow to equalize it. Such a potential difference is referred to as voltage. In other words, if we want to move charge through a wire, we must apply a force (electromotive force [EMF]) that causes a potential difference, or voltage. Without a voltage, there will be no current.

Direct current (dc)

A direct current, or dc, is one in which the direction of flow does not change and may remain at a constant level over time, as shown in Figure I.2 (a).

Alternating current (ac)

An alternating current, or ac, is one that changes with time, as shown in Figure I.2 (b). In the United States, household current is a sine function with a frequency of 60 cycles/second (60 hz). That is, the current alternates back and forth 60 times each second. As we will see later, the frequency of an alternating current has significant implications for human safety. Depending on the application, alternating currents may have many different waveforms other than a sine wave.

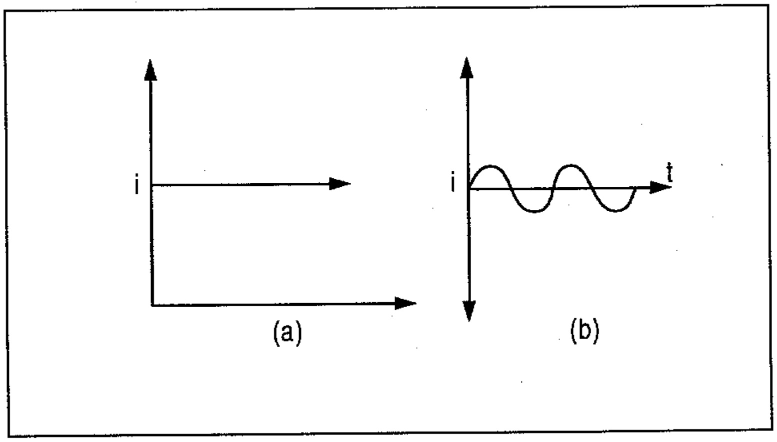


Figure I.2. (a) Direct current is constant over time; (b) alternating current fluctuates over time.

Capacitance

A capacitor is a device consisting of two conducting materials separated by a dielectric medium. A dielectric is a nonconducting material, such as air. Because of this arrangement, the flow of current in a capacitive element is nonlinear, taking the form

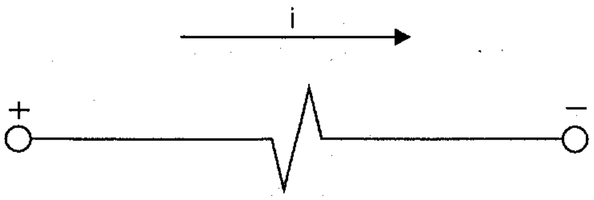
$$i = C \frac{dv}{dt}$$

where i is the current (measured in amps), C is the capacitance (measured in farads) and dv/dt is the rate of change of voltage (measured in volts/second). The higher the frequency of the voltage, the lower the resistance to current flow. For a steady state direct current (dv/dt) = 0), then, a capacitor would act as an opening in the circuit and no current would flow through the element.

Review of basic circuit analysis

It is assumed that you have already had experience solving electric circuit problems using Kirchhoff's current law (KCL) and Kirchhoff's voltage law (KVL). As a refresher, we present some of the very basic concepts.

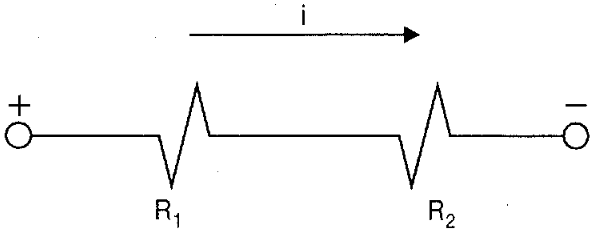
For a resistor, the current (i) and the voltage (v) are related such that the current in a resistive element is directly proportional to the voltage. The required voltage equals the current multiplied by the resistance (R) of the element, or



$$V = iR$$

So, if the resistance is 1000 Ω and the current is 0.5 ampere (amp), the voltage in the element is (1000 Ω)*(0.5 amp) = 500 volts.

When resistors are in series (one after another in succession), the values can be added together and treated as one element. The current remains constant, and

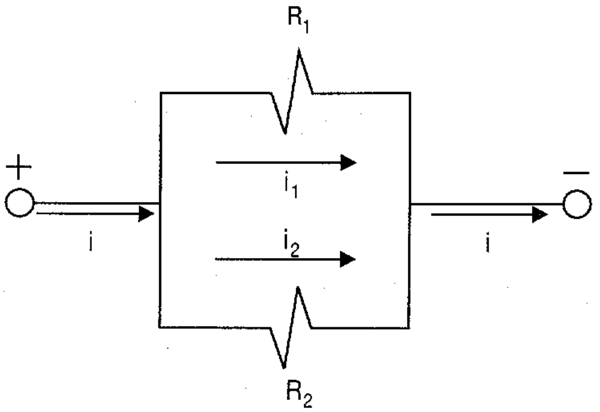


$$V = iR_1 + iR_2 = i(R_1 + R_2) = iR_{eq}$$

$$R_{eq} = R_1 + R_2$$

where R_{eq} is the equivalent resistance.

When resistors are arranged in parallel, the current arriving at the junction must divide in proportion to the resistance of each branch. The following relationships can be proven to hold for resistors in parallel.

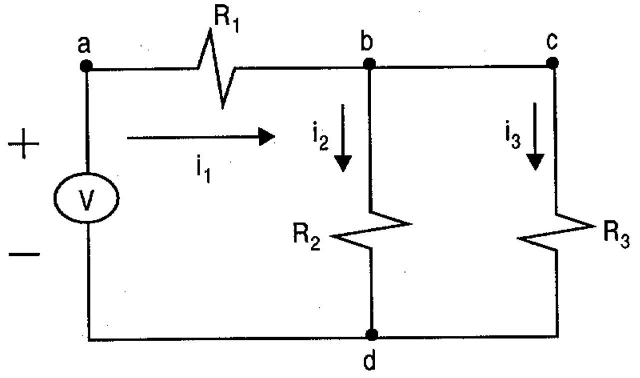


$$R_{eq} = \frac{R_1R_2}{R_1+R_2}$$

$$i_1 = \left(\frac{R_2}{R_1+R_2}\right)$$

$$i_2 = i\left(\frac{R_1}{R_1+R_2}\right)$$

Now lets apply these concepts to a single circuit.



Where $R_1 = 1000\ \Omega$, $R_2 = 500\ \Omega$, $R_3 = 250\ \Omega$, and $V = 110$ volts. Let V_{ab} be the voltage between points a and b, V_{bd} the voltage between points b and d, and V_{cd} the voltage between points c and d. We know that

$$i_1 = i_2 + i_3$$

$$V_{ab} = i_1R_1$$

$$V_{bd} = i_2R_2 = V_{cd} = i_3R_3$$

and we can calculate the equivalent resistance as follows

$$R_{eq} = R_1 + \frac{R_2R_3}{R_2+R_3} = 1000\ \Omega + \frac{(500\ \Omega)(250\ \Omega)}{500\ \Omega + 250\ \Omega}$$

$$R_{eq} = 1166.67\ \Omega$$

Then

$$V = i_1R_{eq} = 110 \text{ volts} = i_1(1166.67\ \Omega)$$

$$i_1 = \frac{110 \text{ volts}}{1166.67\ \Omega} = 0.0943 \text{ amp}$$

$$0.0943 \text{ amp} = i_1 = i_2 + i_3$$

The amount of current flow in R_2 is dependent on the ratio of resistances of the two branches, R_2 and R_3.

$$i_2 = i_1\left(\frac{R_3}{R_2+R_3}\right) = \frac{(0.0943\text{ amp})(250\ \Omega)}{750\ \Omega}$$

$$i_2 = 0.0314\text{ amp}$$

This same can be done for R_3

$$i_3 = i_1\left(\frac{R_2}{R_2+R_3}\right) = \frac{(0.0943\text{ amp})(500\Omega)}{750\ \Omega)}$$

$$i_3 = 0.0629\text{ amps}$$

$$V_{ab} = i_1R_1 = (0.0943\text{ amp})(1000\ \Omega) = 94.3\text{ V}$$

$$V_{bd} = V_{cd} = i_2R_2 = i_3R_3 = (.0314\text{ amp})(500\ \Omega) = (.0629)(250\ \Omega) = 15.7\text{ V}$$

This problem could have been solved in a more streamlined manner, but the method used illustrates basic concepts you should be familiar with. If you need additional review, please consult one of the many available circuit analysis texts.

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SAMPLE QUIZ QUESTIONS

1. Define "safety."
2. Is there any difference between "hazard," "danger," and "risk?" Explain.
3. Discuss the difficulties faced when trying to determine what "an acceptable degree of safety" is for a given product or process.
4. Discuss the difficulties faced when trying to determine the "cost of safety." Do you think the "cost" refers to the upfront cost of safety features, the costs incurred when an injury or fatality results from lack of safety, or both?
5. What are some of the hidden costs associated with adverse events? Explain.
6. Briefly discuss some of the factors that affect a person's perception of risk.
7. Describe a hazard that you voluntarily expose yourself to (e.g., a sport or driving or riding in an automobile). Then compare that risk to one is forced on you–one that actually presents less of a risk (e.g., something at work, flying, etc.). Which activity actually presents the greater risk? Which risk do you feel the most comfortable accepting?
8. Review the risk perception study adapted from Tversky and Kahneman (pg. I-5). Discuss the implications of the results and comment on what they say about human risk perception.
9. Describe a risk that you are generally unwilling to take in your life. Compare that risk with others that you do accept. Is there a rational basis for the risks you have identified as acceptable versus those you will not accept?
10. What would you do if:
    - (a) You were aware of a life threatening defect in a product that your company was ready to put on the market?
    - (b) Assume you informed your superiors of the defect and the potential consequences and their response was that you had better not mention it to anyone else because it would be too costly to stop production now.
11. Develop an argument against this statement: "Lawnmowers are inherently dangerous. People know that, and if they are dumb enough to put their hands and feet into the blades, then they deserve to lose them."
12. Locate a newer model lawnmower, and describe the safety features that have been incorporated into the design and operation to protect people from being injured by the blades.
13. Refer to the circuit on page I-11 and solve for the currents i_1, i_2 and i_3, and the voltages V_{ab}, V_{bd}, V_{cd} at each resistor using the following values: $R_1 = 2{,}000\ \Omega$, $R_2 = 1{,}000\ \Omega$, $R_3 = 2{,}500\ \Omega$, $V = 220$ volts.

Unit II

ELECTRIC SHOCK HAZARDS AND CONTROLS, AND INADVERTENT ACTIVATION OF EQUIPMENT

PURPOSE:

To introduce the student to the concepts of electric shock and inadvertent activation of equipment

OBJECTIVE:

To acquaint the student with:

1. Causes of electric shock
2. Effects of shock on the body
3. Shock hazards in special environments
4. Methods to control the shock hazard
5. Consequences of inadvertent activation of equipment
6. Methods to prevent inadvertent activation

SPECIAL TERMS:

1. Electric shock
2. Short circuit
3. Open circuit
4. Insulation
5. Interlocks
6. Isolation
7. Grounding
8. Bonding
9. Ground-Fault Circuit Interrupter (GFCI)
10. Lockout/tagout

AN EXAMPLE OF ELECTRIC SHOCK

A man is building a storage shelf in his garage. He's drilling holes in the wood with an electric drill that has been designed without a third wire ground (we will discuss grounding later). Or, as is often the case, the ground prong has been removed because the electric socket in his garage does not have a three-wire grounded receptacle. Inside the drill, an energized conductor comes into contact with the external case of the drill, which in this particular drill is also a conductor. It's a hot, humid day, and he is working without a shirt. Preparing to drill, he holds the tool with both hands and braces his shoulder against a metal beam. The beam extends from the roof down to the floor, where it is imbedded into the earth for structural stability. As soon as he energizes the drill, his muscles freeze, and he is unable to let go of the tool. Within seconds, he falls to the floor unconscious. An hour later, he is found dead. The autopsy report identifies respiratory arrest due to electric shock as the cause of death. The report also notes burns on his hands and back and a contusion on the left side of his head. See Figure II-1.

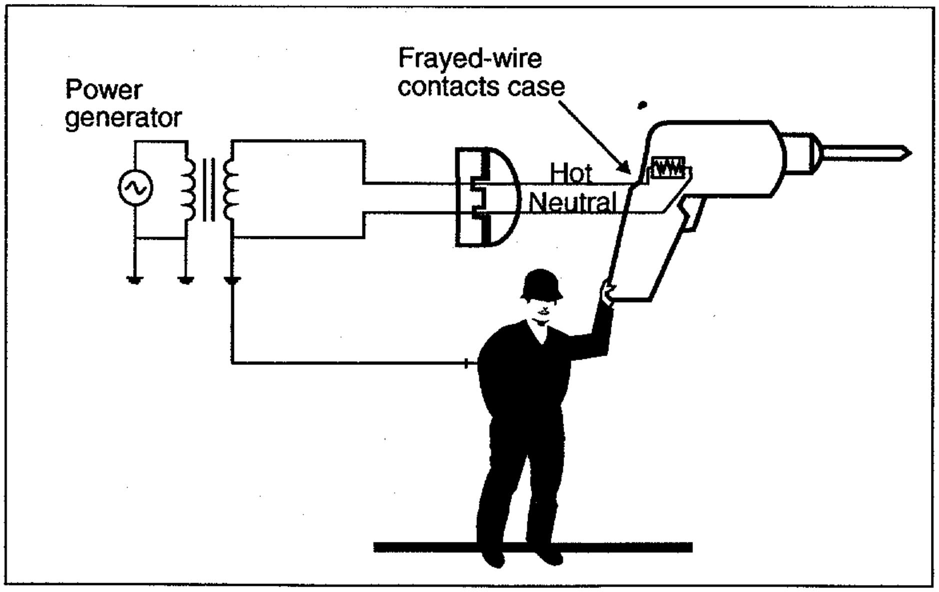


Figure II-1. Schematic showing the path of the current in the example. A frayed wire touches the conducting case of the tool (short circuit), energizing it. The current passes from the energized case, through the man's arms, exiting at his shoulder. The current loop is completed through the ground.

This is one hypothetical example of the many ways that a person can be shocked by electricity. In this case, the man became part of the electrical circuit; as the current flowed from the energized drill through his body to the ground, it caused his heart to stop and burned him at the points of current entrance and exit. The contusion on his head was caused by his head striking an object or the floor when he fell.

Fortunately, this type of incident can be avoided. In this course module, we will discuss the hazard of electric shock and the effects of electric shock on the human body. It will conclude with some methods to control the hazard through design and safety procedures.

WHAT IS ELECTRIC SHOCK

Electric shock is a sudden stimulation of the body's nervous system by an electric current (Hammer, 1989), which can cause pain, injury, or death (Bahill, 1981). Although it is usually painful, electric shock is not always associated with actual damage to the body tissues. The most common sensation is stabbing and numbing pain at the points of current entry and exit and sometimes along the path of the current through the body.

Any time a person comes in contact with an energized conductor there is a potential for electrical shock. As in the example, current will flow through the human body if it becomes part of an electric circuit when the potential difference (voltage) is adequate to overcome the body's resistance (Hammer, 1989). In the example, the man became part of the circuit because his body became a path of least resistance to ground.

The five principal ways that people experience electrical shock will be discused in detail:

1. contact with a normally bare energized conductor,
2. contact with a normally insulated conductor on which the insulation has deteriorated or been damaged so that it is no longer protective,
3. equipment failure that results in an open or short-circuit, which, in turn causes the current to flow in an unexpected manner,
4. static electricity discharge, and
5. lightning strike.

Contact with a normally bare energized conductor

One common situation and a frequent cause of electrical injuries, is contact with live, overhead power lines. Examples include the boom of a crane, the boom of a "cherry picker," a raised dump truck bed, a metal ladder, the metal mast of a sailboat, or any number of construction, maintenance, or recreational tools and vehicles inadvertently coming into contact with high-voltage, overhead lines. When this happens, and a person is in contact with the tool or vehicle, the high voltage often means severe injury or death.

NIOSH ALERT: Request for Assistance in Preventing Electrocutions from Contact Between Cranes and Power Lines *

Contact between cranes and overhead power lines is a major cause of fatal occupational injuries in the United States...approximately 2,300 lost workday occupational injuries...These 2,300 injuries were extremely severe, resulting in 115 fatalities and 200 permanent total disabilities [in 1981]...Comparable statistics...from 1964 to 1976 produced an estimated annual average of 150 fatalities resulting from such incidents...

*This is an excerpt; see reference materials at the end of this book for a complete copy of this Alert.

For example, a rig was being positioned over a well so that a pump motor could be lifted. One operator drove the truck, while another operated a 34-foot boom. The boom came into contact with a 12-kilovolt overhead line; the boom operator was killed instantly. The driver, hearing the noise of the contact, stepped out of his cab to investigate. As one foot touched the ground, a large current driven by the full 12-kilovolt charge shot through his body. His body had become the path of least resistance to ground. He died a few hours later from massive burns and internal bleeding.

NIOSH ALERT: Request for Assistance in Preventing Electrocutions of Workers Using Portable Metal Ladders Near Overhead Power Lines*

Contact between portable ladders and overhead power lines causes serious injuries...Data show that during the years 1980 through 1985, the contact of metal ladders with overhead power lines accounted for approximately 4% of all work-related electrocutions in the United States (e.g., 17 out of 382 deaths for 1985).

NIOSH ALERT: Request for Assistance in Preventing Grain Auger Electrocutions*

...The grain auger is an essential piece of farm equipment which is used to move grain from one location to another. However, every year accidents occur when this piece of equipment is improperly moved in the elevated position and it comes in contact with high voltage power lines. This has resulted in one or more fatalities per incident...

*These are excerpts; see reference materials at the end of this book for complete copies of these Alerts.

Other common situations involving contact with high-voltage overhead power lines affect workers whose duties require them to be in proximity to energized lines. People who work on roofs, TV antenna and cable installers, and power industry employees are all at risk of contacting bare conductors. Of course, unskilled people are also at risk when they attempt to perform home repairs, etc., near high-voltage lines.

High-voltage sources are not restricted to overhead lines. Although safety codes require high-voltage equipment to be enclosed, injuries and fatalities continue to occur. Failure to secure the enclosures against unauthorized entry has led to injuries involving people from the curious to the vandal. At a minimum, such enclosures should always be designed with a locking system that can only be opened by trained and authorized individuals. Other methods, such as a system that will automatically cut power when an enclosure is opened, will be discussed later in this module. We will also discuss necessary safety precautions for authorized and skilled workers when bare energized conductors are present (Hammer, 1989).

Electrical consumer products and appliances in the home are also potential sources of shock if protective covers are damaged or removed. Typically, some conductors inside electrical equipment are not insulated because unskilled human contact is not expected. When unskilled or unsuspecting people dismantle or break through protective enclosures, there is a potential for shock.

Contact with conductors when the insulation has failed

In many cases a conductor is covered with an insulating material that keeps a current from passing to another conductor, including the human body. If, however, the insulation is defective by design, deterioration, or damage, there is a high potential for equipment failure or electric shock. Deterioration or damage can be caused by a number of factors and in a number of ways. We will present an overview on the breakdown of insulating materials here, but be aware that there is a wealth of information and theory on the subject, which you should consult as needed.

There are four basic ways, listed below and summarized in Figure II-2, that insulation may fail. As you read this section, understand that these categories are not mutually exclusive—that these factors often combine to cause an insulator to fail.

1. Mechanical stress, as with friction, can cause tearing and crushing.
2. Excessive electrical stress can occur when equipment experiences voltages significantly beyond the levels it was designed for.
3. Temperature, either excessively high or low or temperature cycling, can cause differential expansion or contraction of a material.
4. Chemical and physical reaction, such as oxidation, can contaminate or leach important ingredients (Cooper, 1986).

Mechanical

Concerning mechanical failures, the best defense is through design. For example, design the physical product or device so that insulated conductors are not subject to mechanical loading. If that is not possible, be sure that the insulation used can withstand all foreseeable mechanical loading. An electro-mechanical industrial robot, for instance, may have insulated wires passing through multiple articulations and being subjected to continual bending, friction, and possible pinch points. As a designer, you would want to minimize as much bending as possible; minimize the friction either by guiding the wire so that it won't rub against (or be pinched between) other parts or by covering such areas with low friction materials. As always, proper inspection and maintenance procedures must be recommended by the designer and be followed by the user to ensure that, in this case, the insulation is in good condition.

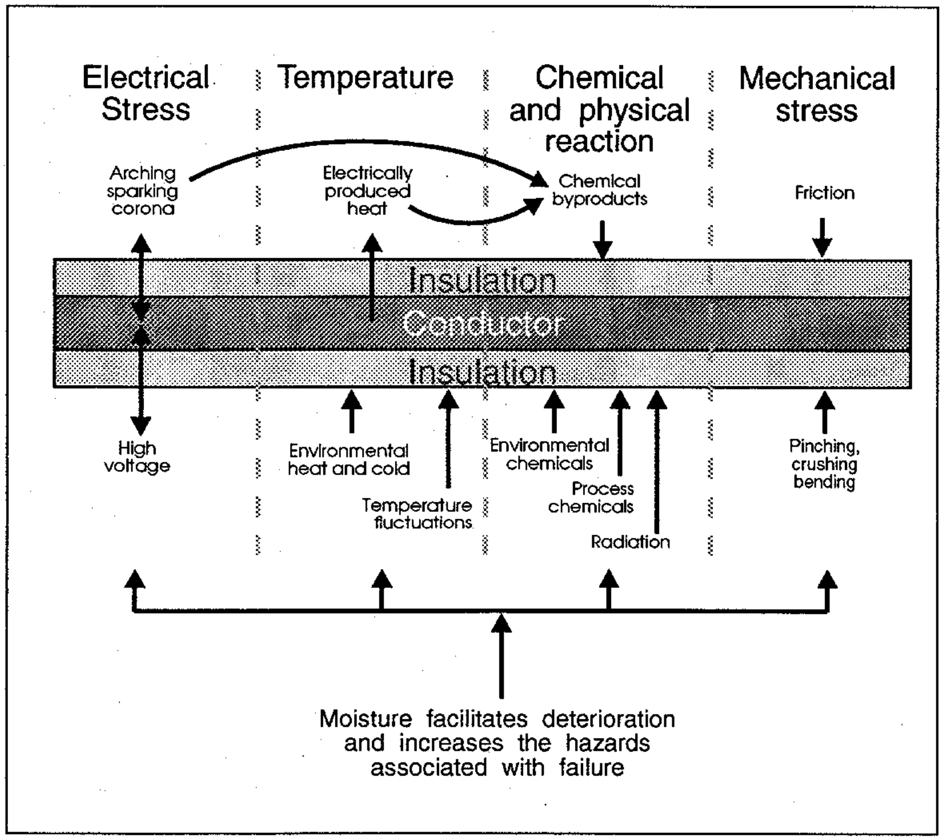


Figure II-2. Insulating materials are subject to deterioration or damage from electric stress, temperature extremes and fluctuations, chemical and physical agents, and mechanical stress. The presence of moisture will facilitate failure.

For a more common example of an insulated wire that is subjected to potential mechanical damage, check the wires supplying power to a car door (door light, electric locks and windows, etc.). Can you see how it was designed to withstand the mechanical loads of opening and closing the door? Is the insulation in good condition?

Electrical stress effects

Insulation breakdown related to excessive electrical stress is a complicated matter. A complete understanding of this subject involves concepts beyond the scope of this text, but in general, relatively high voltage is of concern. High voltages can cause localized electrical discharges (sparks, arcs, or coronas) that can create holes or chemical damage in an insulator. (Sparks, arcs, and coronas are also a fire hazard and are discussed in detail in the next unit.) Sparking may cause high, localized temperatures and produce ozone that, as discussed below, can react with insulating materials. A corona will produce nitrous oxide that reacts with moisture to form an acid that can damage an insulator.

Temperature effects

Extreme temperatures and cyclical temperature changes can also contribute to the breakdown of insulation materials. The flow of electric current always produces heat, and sometimes that heat production causes significant localized temperature increases. Even at moderate temperatures, some polymers will go through a slow but gradual breakdown.

The heat may also be part of the operating environment. For example, the insulating materials used in or near equipment that produces high temperature as a normal part of operation must be capable of withstanding the heat for the designed life of the system. Methods to control potentially damaging temperature increases that result from overload will be discussed when we cover fire hazards in the next unit. Essentially, circuit designs that require very low operating energies or design precautions that immediately cut power when an overload occurs are good preventive measures. Processes involving high temperatures as a normal operating characteristic call for a cooling system to remove heat.

Cold environments can also damage insulating materials. Some insulating materials may become brittle when exposed to cold environments. If you live in a cold climate, think of what happens when you leave a garden hose out for the winter. It becomes brittle and cracked. Similarly, fluctuations in temperature may also affect an insulator. Temperature fluctuations can expand and contract the insulating materials and possibly result in their mechanical failure and breakdown of the insulating properties.

Thus, whether you are responsible for the design or the operation of electrical equipment, temperature is an important consideration. The amount of heat produced by the insulating conductor, as well as by the environmental temperatures, must be accounted for in design, and appropriate insulating materials and temperature controlling systems must be chosen to minimize the potential for failure throughout the life of the product or system.

Chemical and physical reactions

Insulating materials are also susceptible to a wide range of chemical and physical reactions. Such reactions can be caused by electrical phenomena inherent in the equipment or may result from environmental factors.

Take oxidation for example. Oxidators such as oxygen and ozone occur naturally in the atmosphere. Sparks and arcs, typical occurrences when equipment such as motors and generators are operated, produce significant amounts of ozone. When the equipment is enclosed, as motors and generators often are, the ozone is contained and may reach high levels. Ozone is a much more unstable and reactive form of oxygen and may accelerate deterioration of some insulators. Ozone is also naturally present in the environment; its concentration varies with altitude, air pollutants, weather and season, geographic location, and solar radiation.

Solar and nuclear radiation, may also degrade insulation properties, especially polymers. Photochemical processes initiated by solar radiation can affect a variety of polymers, including natural or synthetic rubber, vinyl chloride, and vinyledene chloride. The degradation process may release other reactive agents that cause further damage to the insulator.

Chemical incompatibility between the insulating material and such things as acids (including acid rain), salts, lubricants, and solvents can lead to chemical breakdowns of insulators. Again, these chemical reactions can be caused by agents, materials, and electrical properties inherent in the system or may come from the environment.

Moisture

Environmental moisture and humidity can also dramatically affect the performance of an insulator. Some insulators, such as nylon, absorb moisture. Since water is a conductor, its presence may provide conductive paths through or over the insulation. An insulator that has been damaged, such as by cracking or tearing, may provide direct paths through the insulation to the conductor. If moisture seeps through, the potential for shorting or shock is dangerously increased. In fact, operating electric tools and equipment in damp environments commonly contributes to injuries and fatalities.

Even if the insulator is in perfect condition, the presence of moisture can provide conductive paths over or around it. Take, for instance, the case where a young child playing on the floor in her home received severe electrical burns in and about her mouth. This child, with a child's propensity to chew and suck on things, picked up an extension cord and inserted the junction (where a table lamp was plugged into the cord receptacle) in her mouth. When saliva seeped around the insulated cords and came into contact with the bare energized conducting prongs, the girl's tongue and cheek became part of the circuit linked by the saliva. Severe burns and permanent disfigurement resulted.

Moisture may also provide a good home for biological agents. Even without moisture, some insulators contain nutrients on which organisms feed. Whether these biological factors alone can damage or reduce insulating properties is not clearly understood, but the additional presence of moisture and possible degradation from other factors can exacerbate potential failure or breakdown of some insulators. Rodents such as rats and mice, as well as insects, may also feed on or debilitate insulating materials.

Considering all of the ways that insulation might fail, you can see that selection of materials for a design is a complicated, but critical, matter. Fortunately, past experience has taught us much and there are numerous sources to help designers choose appropriate insulating materials for particular applications. Even the best designed products will, however, require inspection and maintenance throughout their operating life.

Equipment failure that results in an open or short circuit

Any time a conducting element in a circuit comes in contact with another conductor, whether it is part of the designed circuitry or not, a short circuit or very low impedance connection can occur. If you've ever driven behind a car on which the tail lights kept dimming or randomly blinking, you have likely witnessed the results of a short circuit. A common scenario with vehicle electrical systems as they age is the breakdown and deterioration of the insulation covering wires throughout the vehicle. If the conducting wire touches the frame or another conductor, the current will flow in unexpected paths and reduce or eliminate the current from the intended path, such as to the tail lights. Similarly, if a conductor is severed, or if a path in a circuit is opened by other means, the open circuit may cause current to increase in other parts of the circuit, and to overload components, which may cause failure. Although failed vehicle tail lights certainly create a hazardous situation, we're more interested in the shock hazards associated with short or open circuits in this section.

Short circuit

As depicted in Figure II-3, a short circuit may occur between a circuit element and a grounded conductor not intended to be part of a circuit (a) or between conductors within the same circuit.

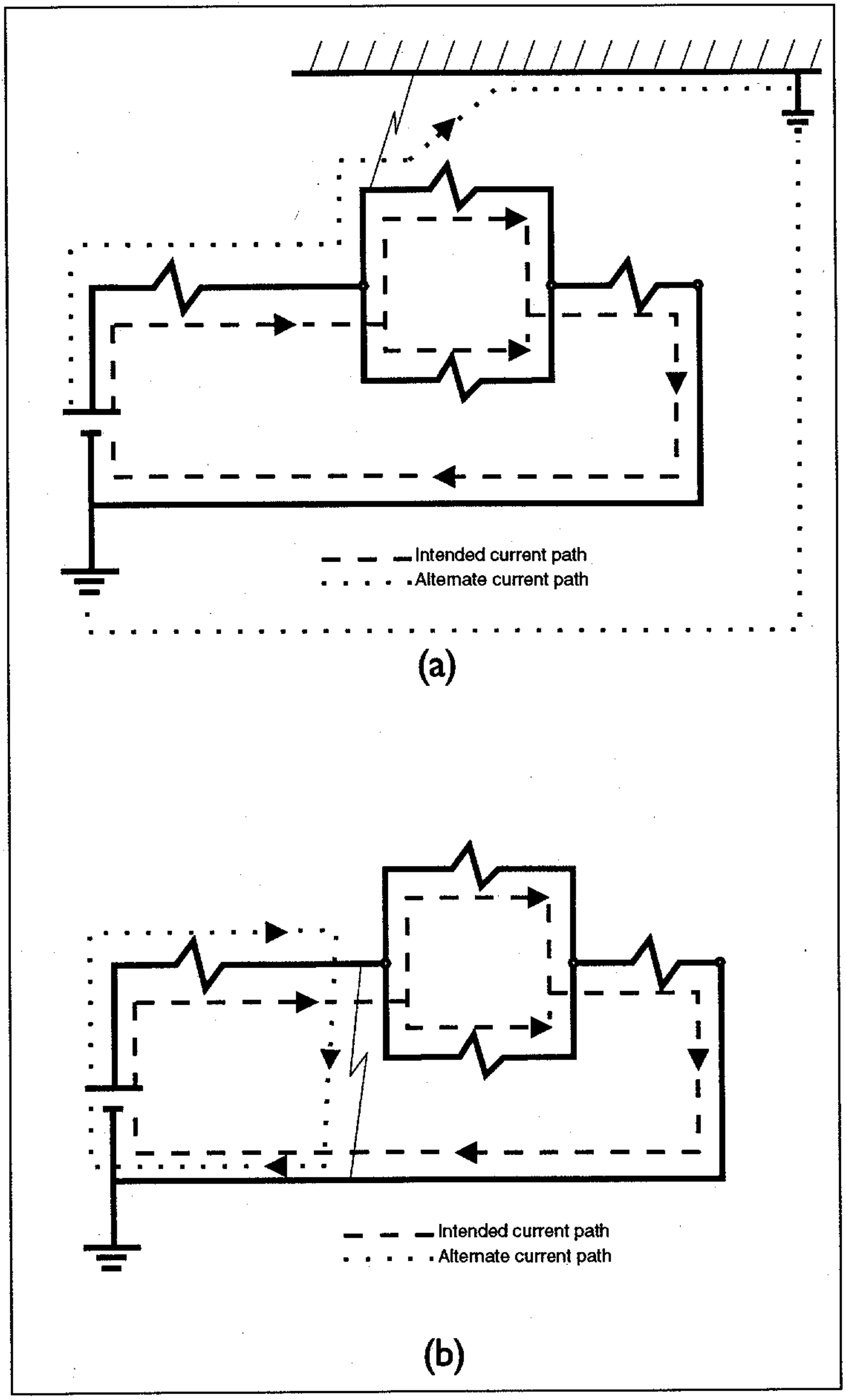


Figure II-3. A short circuit can occur (a) between a conducting element and a grounding conduction body, or (b) between conducting elements in the same circuit.

When a short sends current to an unintended conductor, such as the casing of an electric hand tool, the path to ground may be through a person, as in the case study at the beginning of this section (fortunately, newer power tools are being designed to minimize this type of failure and hazard).

When a short occurs between conducting elements within a circuit, some components may be loaded beyond their design capacity. This type of short is not necessarily an immediate shock hazard, but the overloading condition may lead to component failure that results in a shock hazard. An overloaded circuit is also a fire/explosion hazard; this will be covered in Unit III.

An open circuit will occur when a conductor in a circuit is severed. If the severed wire is in parallel with other conductor(s) in the circuit, it will increase the current in the parallel path(s) and possibly create an overload condition (see Figure II-4 (a)). The potential for shock is very high if a person comes into contact with the free end of a severed, energized conductor. The downed power line (Figure II-4 (b)) illustrates how a person will be severely shocked should he/she contact the energized wire and become a path to ground.

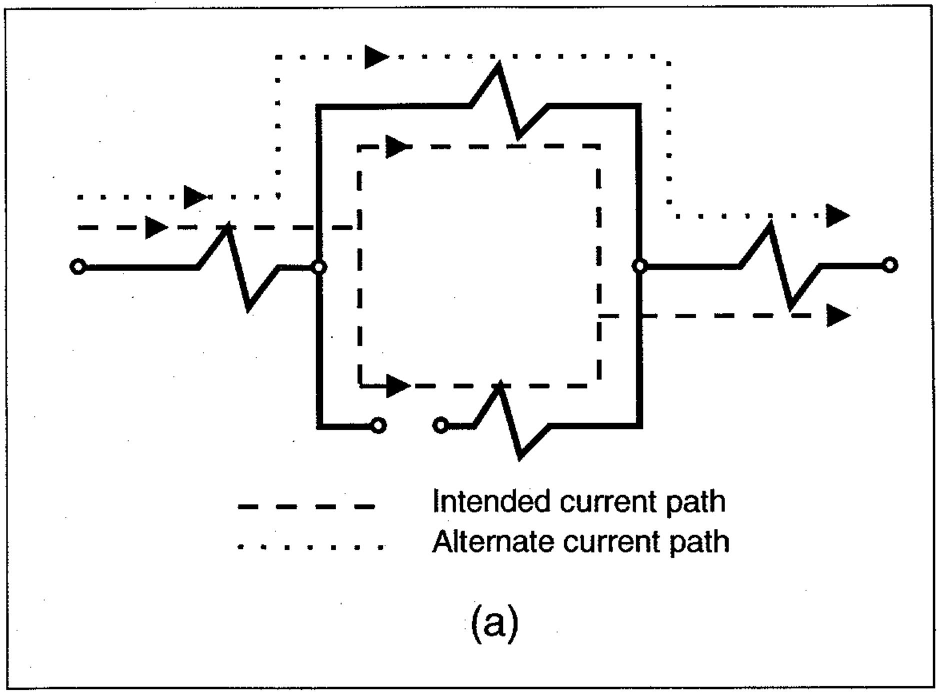


Figure II-4. (a) An unexpected open circuit may overload parallel components.

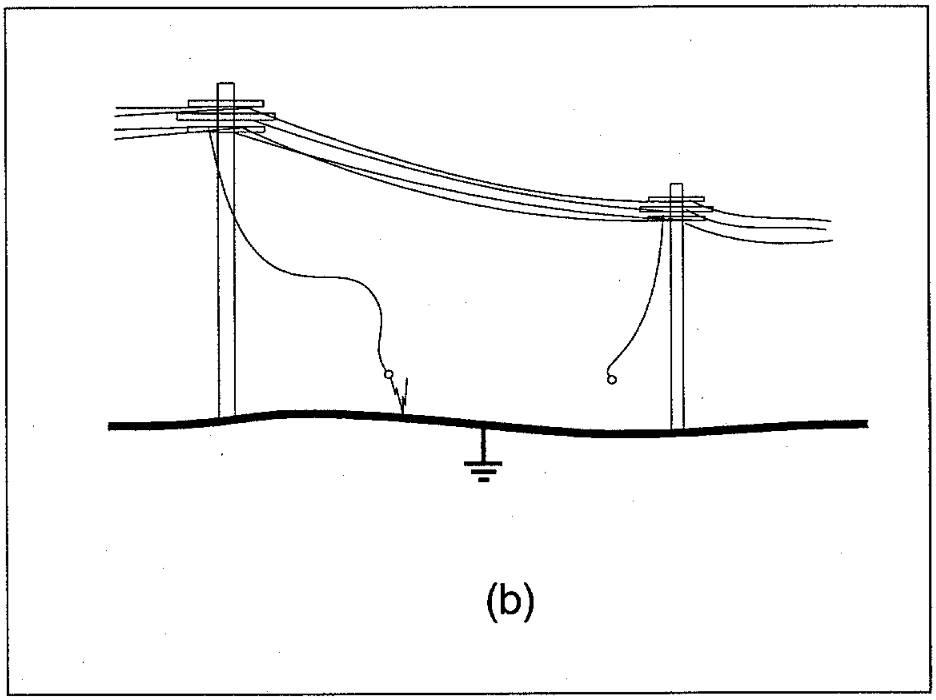


Figure II-4. (b) An open circuit that results from a severed high-voltage power line.

Static electricity and lightning

Static discharges and lightning strikes are significant fire/explosion hazards and the nature of each will be covered in detail in Unit III.

These events are also shock hazards. We've all experienced a shock from static electricity. Usually, it is little more than a rude surprise. Such a surprise, however, can and does cause people to suddenly move, possibly striking an object or falling. Falls are the third leading cause of accidental death in the United States, so this type of hazard is nothing to take lightly.

Shock from static electricity in the medical environment has been suggested as a possible cause of heart fibrillation for patients that have catheters passing through the skin and contacting the heart muscle. Significant efforts are taken to minimize the generation, accumulation, and discharge of static energy where patients may be at risk.

Lightning, which is a large discharge of static charge accumulations from the atmosphere, has the potential to shock a person, and even result in death, if they are directly hit or even nearby when it strikes. Lightning can also overload power lines and equipment, which has already been established as a potential shock hazard.

If you are outside during an electrical storm, you can do several things to protect yourself from injury. If an all-metal shelter or a structure that has lightning protection is available, seek shelter within the structure. Once inside, however, avoid contact with metal surfaces (e.g., any part of a metal structure) or electrical equipment that may become energized in the event of a lightning strike. The interior of the steel body of an automobile is considered an excellent shelter during an electrical storm, even if a high voltage line is touching it (the rubber tires insulate the vehicle from ground). If you attempt to leave the car while the line is energized, however, you will provide the path to ground and will be severely, probably fatally, shocked.

In an open area or in a boat on a body of water, away from high points, it is advisable to lie down so that you are not the high point acting as the least resistance path. On land ravines or depressions are the best place to lie down. A common error people make is to seek shelter from storms under large trees. The only tree in an area, or the highest tree, should be avoided because a lightning strike in the vicinity is most likely to hit that tree. In a wooded area, seek shelter near the smallest trees, well away from the tallest tree in the area. Always avoid contact with metal structures that may act as a path to ground for lightning, as you too will become a path to ground in the event of a strike.

Static electricity and lightning hazards deserve much more attention than we have afforded here. In Unit III we will investigate how static charges are generated, accumulated, and discharged. With that information, we will discuss methods to reduce and eliminate the hazards associated with lightning and static electricity.

EFFECTS OF SHOCK ON THE HUMAN BODY

The effect of electric shock on a human depends on characteristics of the current, the time the body is exposed to the current, and the path the current takes through the body. The magnitude, duration, frequency, and wave form of the current all affect the severity of the shock. In addition, the area of the body that receives the current, where it exits, the path it takes through the body, the health or physiological state of the body, and the resistance of the body tissues in the current pathway will affect the outcome. Depending on these factors, electric shock can have two damaging effects on a living body: tissue can be burned or normal physiological functions can be inhibited.

Whenever an electric current meets resistance, a certain amount of energy is released in the form of heat. The amount of heat, and thus the severity of the electrothermal burn of human tissue, depends on the magnitude, the voltage, and the duration of the current (Cabanes, 1985). A shock victim may receive superficial burns at the points of entry and exit of current and internal burns wherever the current passed within the body.

The human body is controlled by a vast network of nerves that communicate by passing small electrical signals. The nervous system is responsible for organizing all of the functions necessary to keep us alive, such as the muscle contractions that expand and contract the rib cage to make us breathe and the heart muscle contractions that keep our blood flowing. Electric shock can inhibit normal physiological function by interfering with the body's own "electrical communication" network of nerves; breathing and/or normal heart function, in the most severe cases, can be arrested. It is interesting to note that 50 to 60 Hz, which includes the alternating current frequency of most residences and industries, is the frequency at which human muscles are most likely to be excited to the point of involuntary contraction and, therefore, is quite hazardous.

Generalized effect of 60 Hz alternating currents

The magnitude of a current flow in the body is the most damaging factor. The effect of alternating current levels at 60 Hertz are outlined below (Table II-1 summarizes the current ranges and the general hazards). Understand that these are average values and that the method of current application and individual human differences may affect these values.

Table II-1
Summary of Effect of 60 Hz Alternating Currents
Through the Body of an Adult Human

AC Current Level	Effects on Human Body
1.1 to 5 mA	Threshold of perception
5 to 25 mA	Let-go threshold
20 to 75 mA	Very painful and injurious; potential respiratory arrest
70 to 300 mA	Potentially fatal without immediate first-aid; may cause ventricular fibrillation and respiratory arrest
2.5 A or more	Potentially fatal without immediate first-aid; may stop heart muscle completely; may cause respiratory arrest; causes burns to tissue

1.1 mA

The average person will perceive a shock, including sensations of tingling or heat. Some people may feel a current as low as 0.5 milliampere, whereas others may not feel it until a current level of 2 milliamperes. Women are believed to have a lower threshold of shock perception than men. Perception of shock at these current levels results mostly in inadvertent muscle reflexes. Such sudden motions can cause a person to jerk violently and possibly result in a fall or other event with a potential for injury (Cabanes, 1985).

5 to 25 mA

Current in this range is referred to as "let-go" current. Let-go current threshold can be defined as the maximum current at which a person holding an electrode in each hand can still let them go. Average let-go levels range from 9 to 16 milliamperes for men and 6 to 10.5 milliamperes for women. When a person's let-go threshold has been exceeded, the affected muscles "freeze," and it is impossible to voluntarily release the conductor. When this happens, the person may be exposed to current for a longer period, and the potential for injury is increased. The let-go threshold for direct currents occurs at 300 milliamperes or greater.

20 to 75 mA

Currents in this range can be very painful and injurious. Prolonged contact may result in a fall (always a potential source of injury), unconsciousness, and death as inhibition of the respiratory muscles stops breathing. Cessation of breathing can be caused by prolonged contraction of the respiratory muscles or by inhibition of the breathing control centers of the central nervous system. When breathing stops because of respiratory muscle inhibition, it usually resumes once the current is stopped or after first aid assistance is given. Death from asphyxiation will occur unless resuscitation is performed within 3 or 4 minutes maximum. Respiratory arrest of a central nervous system origin is rare and requires two things: a passage of current through the brain, and a higher current. Resuscitating such victims is more difficult (Cabanes, 1985; Hammer, 1989).

70 to 300 mA

Current in this magnitude range lasting as little as a quarter of a second can be fatal without immediate first aid. Currents in this range can cause ventricular fibrillation of the heart muscle, which results in the blood not being pumped through the body. The human heart is made up of four chambers that must contract in a specific synchronized way to keep the blood circulating. An external current applied to the heart muscle interferes with the synchronized contraction pattern, which causes fibrillation. When the heart muscle fibrillates, blood is not pumped and vital nutrients cease to flow to the body tissues. This is the most frequent cause of death in electrical contact events. Alternating currents in this range lasting one heart cycle or more will cause fibrillation in almost every case. Direct currents only cause fibrillation if applied during a short instance of the recovery phase of the heart muscle's contraction cycle (Cabanes, 1985; Hammer, 1989). Dalziel and Lee (1968) suggest that the threshold alternating current capable of causing fibrillation can be approximated by the formula

$$I = \frac{116 \text{ to } 185}{\sqrt{T}} \text{ mAmp rms}$$

where T is the time of contact (in seconds) with an energized conductor and I is the amount of alternating current in milliamperes.

2.5 A or more

Currents of this magnitude may stop the heart muscle all together, as opposed to causing it to fibrillate. Respiratory arrest is also common, but immediate resuscitation may succeed. Alternating currents at this level will also burn the skin and internal tissues (Hammer, 1989).

NIOSH ALERT: Request for Assistance in Preventing Fatalities of Workers Who Contact Electrical Energy

Recent incidents...have shown that electrocution victims can be revived if immediate cardiopulmonary resuscitation (CPR) or defibrillation is provided. While immediate defibrillation would be ideal, CPR given within approximately 8 minutes can be lifesaving.

*This is an excerpt; see reference materials at the end of this book for a complete copy of this Alert.

Burns

Burns, the most frequent injury associated with electric current, take several forms. Some are caused by the intense radiation of heat from an electric arc—arc burns. Others result from the flow of current through tissue—electrothermal burns. Still others, particularly in industrial settings, result from electrical malfunctions that cause hot oils or other liquids or heated metals to splash. More than one of these burn types may occur together. For example, current can flow to a body by an electric arc and cause severe skin burns. The burned skin will have a lower resistance than healthy skin, allow more current to pass directly to the internal tissues, and result in electrothermal burns. The severity of electrothermal burns is governed by Joule's law which states that the amount of energy converted to heat (W) in a time interval (t) at a constant current (I) is proportional to the square of the current.

$$W = RI^2t \text{ joules} = VIt \text{ (watt-seconds)}$$

Thus, the energy released as heat depends on voltage and current magnitudes and the total time they are applied. Note the importance of voltage in the equation; it is, in fact, high-voltage contacts that result in the most severe burns (Cabanes, 1985).

In review, the intensity of an electrical shock depends on the voltage, current magnitude, current path, current frequency, and time the current flows through a person. Many factors affect the severity and type of injury associated with a shock. For example, any current path that includes the heart (e.g., a current running from hand to hand) is more likely to result in heart fibrillation than one that doesn't.

The amount of current flow depends on the applied voltage and the resistance. For the human body, most of the resistance is provided by the skin. As Table II-2 shows, when the skin is wet there is a significant decrease in resistance. Once the resistance of the skin is overcome, the internal tissues offer very little resistance to the current (Daziel, 1972). The values contained in the table are best estimates, as individual differences and the physiological state of a person will affect actual resistance values.

Table II-2
Rough Estimates of Human Resistance to Electrical Current

Body Area	Estimated Resistance (Ohms)
Dry skin	100,000 to 600,000
Wet skin	1,000
Internal body (hand to foot)	400 to 600
Internal body (ear to ear)	(about) 100

*Adapted from Firenze and Walters, 1981.

Let's return to the case study at the beginning of this section and analyze the man's electrical shock with the information we now have. Assume a 110-volt source (i.e., 110-volt potential between each hand and ground—refer to Figure II-5), and calculate the amount of current that flows through his body when the skin is wet and when dry, using the values shown.

$V = 110 = (R_1 + R_2) * i_1 + R_3 * i_3 = (R_1 + R_2) * i_2 + R_3 * i_3$

i = branch current

$i_1 + i_2 = i_3$

$110 = (R_1 + R_2) * i_1 + R_3 * (i_1 + i_2) = (R_1 + R_2) * i_1 + R_3 * 2 * i_1$

$$i_1 = i_2 = \frac{110}{(R_1 + R_2) + (2 * R_3)}$$

So, the current in each arm is

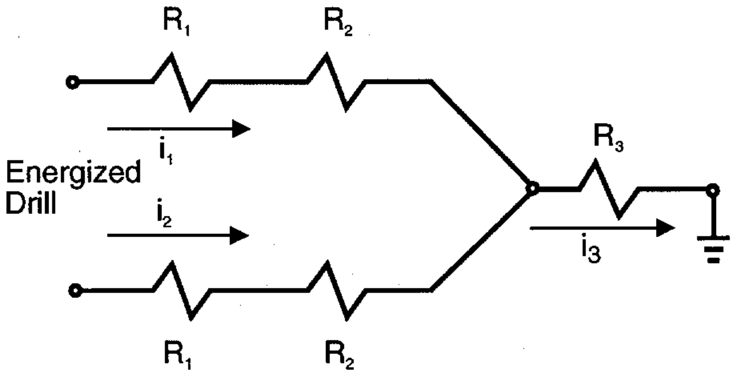
i_1 (dry skin) = i_2 (dry skin) = 0.000577 = 0.577 mAmps

i_1 (wet skin) = i_2 (wet skin) = 0.034375 = 34.375 mAmps

The total current that passed through his body is

i_3 (dry skin) = 1.154 mAmps

i_3 (wet skin) = 68.75 mAmps



R_1 = skin of hand resistance

R_2 = internal tissues resistance

R_3 = skin of back resistance

Dry skin	Wet skin
$R_1 = 90\ \text{K}\ \Omega$	$R_1 = 1000\ \Omega$
$R_2 = 500\ \Omega$	$R_2 = 500\ \Omega$
$R_3 = 50\ \text{K}\ \Omega$	$R_3 = 850\ \Omega$

Figure II-5. A schematic diagram representing the path of current and associated resistances for the man described in the electric shock case study on page II-2.

Therefore, if the man had dry skin at the time of contact, he probably would have experienced little more than a sensation of shock. Because it was a hot and humid day and his skin was wet with sweat, the skin's resistance was significantly lowered. We note from Table II-1 that 68.75 mAmps is within the current range that may cause respiratory arrest, which is consistent with the autopsy report.

SHOCK HAZARDS IN SPECIAL ENVIRONMENTS

In some environments, the hazards associated with even very low currents can be devastating to equipment and life. For example, electrostatic discharge from static electricity where silicon-based chips are manufactured or used can severely damage equipment. Electrostatic discharge has also been suggested as a cause of heart fibrillation in hospital patients with catheters or other direct paths to the heart. In fact, a hospital is a very special environment where the potential for shock must be highly controlled. Many patients have catheters that bypass the skin's relatively high resistance; some have catheters or monitoring equipment directly in contact with the heart muscle. A shock hazard that would pose little danger in a normal environment can be lethal in these situations. In certain industries or situations, therefore, special precautions, through design and procedure, are needed to minimize shock hazards.

CONTROLLING THE SHOCK HAZARD

Up to this point we've discussed the hazards that electrical shock present to personnel and equipment. Fortunately, engineers and designers have learned from past failures and applied their expertise to develop methods that eliminate or significantly reduce specific hazards. As an engineer, your responsibility will be to understand and apply known hazard controls and to develop new methods as your experience and expertise grows.

Here are some of the more common methods used to protect people from electrical shock. A system is usually designed with some combination of these features so that a failure of one method will not immediately result in a shock hazard.

Insulation

We know that a person can be fatally injured by contacting a bare energized conductor or that equipment can fail or be damaged when energized conductors contact in unintended ways. Such hazards can be significantly reduced or eliminated by insulating the conductors in a system. The hazard can be further reduced by insulating all parts and equipment that a person will contact routinely or by accident during operation or maintenance of a system. Control switches, buttons and knobs, meters, and handles are typical examples of items that should be insulated. Also recall that insulation can and does break down with time, use, system, and environmental factors. Therefore, selecting an insulation material that will retain its insulating properties during foreseeable use is critical.

Insulated conductors are marked by the manufacturer to show the maximum voltage, American Wire Gage size, the type letter of the insulation, and the manufacturer's name and location. Equipment grounding conductors are generally colored green or a green with yellow stripes. Insulation on neutral wire is generally white or natural gray color, and hot wires can be any color other than green, gray, or white (often they are colored red or black).

Personnel can also be insulated from electrical systems through the use of nonconductive floor mats (e.g., rubber) and nonconductive gloves and shoes. This is especially critical during maintenance procedures that may bypass insulation designs intended to protect an operator.

Interlocks

An interlock automatically deenergizes a system when a protective enclosure is opened. Just as opening the door to your clothes washer stops it when it is in the spin cycle, an interlock will deactivate the power to a system when someone opens the door or cover of an enclosure. Because enclosures are often used to keep personnel from accidently contacting the energized components within, an interlock still protects people if the enclosure is opened.

Isolation

Enclosures or barriers should be used to isolate unauthorized or untrained personnel from shock hazards, especially from high-voltage systems. The isolating barriers must be so designed and located to eliminate contact with energized equipment and must be available only to trained and authorized people.

Marking

Warnings posted at points of access to hazardous electrical systems should be marked with appropriate hazard information. As a designer, you should design to eliminate hazards. Some equipment is, however, inherently hazardous, especially if other hazard control methods are bypassed, as often happens during maintenance procedures. Warning information, both written and color coded, must be located so that personnel will be informed at critical points during operation, installation, or maintenance procedures.

Warning devices

Warning devices, such as a sound or light, may be connected to an electrical system to indicate when it is energized. These are especially important in complicated, multi-function systems for which an operator must monitor a number of system functions. The warning device must indicate when the particular system is actually energized. An analysis of the Three Mile Island nuclear power plant incident showed that a warning device (a light on the operators panel) indicated that a critical step in the shutdown procedure had been activated. In fact, although the system (a pump) had failed to activate, the warning device indicated it had. The warning light was wired to the switch on the operators panel, not to the actual system. Therefore, the operators assumed the system actually energized and performed its intended function when it didn't. The result was a release of nuclear material. A warning device must monitor the actual system, not the switch intended to activate the system.

Warning devices can also be used to warn operators in the event of system failure or malfunction.

Grounding

The earth can be looked at as an infinite store for electrons. Given a conductive path to earth, or "ground," a charge difference will either draw electrons from or return them to the soil (Hammer, 1989). Realistically, the idea that the earth is an infinite electrical sump is not true. All current must flow in loops; any current that enters the earth must also leave. In fact, this is often the current path in electrocution or shock incidents; the person becomes part of the circuit—a conducting path to ground. Note from Figure II-6 that the neutral wire in a circuit is also connected to ground, completing the loop.

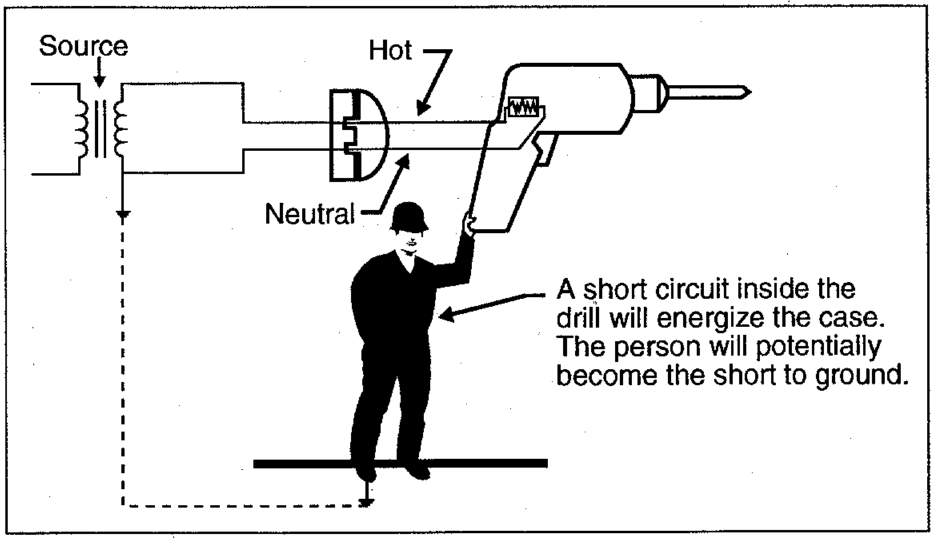


Figure II-6. In a circuit without a third wire ground, a person may become the path to ground in the event of a failure. Also note that the current completes a loop through the ground.

The idea behind grounding is to protect people and equipment from receiving a current due to a fault. Grounding provides an alternative, low-resistance, conductive path to ground. With a third wire ground system (see Figure II-7), the current resulting from a fault will flow through the ground wire rather than through the person. In contrast, when there is no third wire ground (Figure II-6), current may flow through a person (i.e., a shock) if that person provides a path to ground.

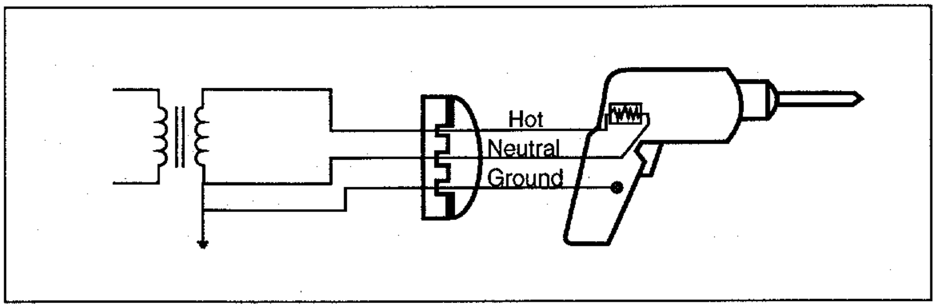


Figure II-7. Schematic of an electric drill equipped with a third-wire ground and plugged into a third wire ground receptacle.

For the three-wire grounding method to be effective, the polarity of the receptacle must be correct. That is, the "hot" wire must be connected to the "hot" wire of the electrical equipment, and similarly for the neutral and ground wires. Engineers have attempted to control this by designing a three-wire receptacle so that the connector can be plugged in only one orientation. Figure II-8 illustrates a variety of connector and receptacle designs configured so that they can only be used with specific power systems. The 15-ampere plug and receptacle is likely the most familiar because that power system is used in residential designs. Note that in all the designs the ground prong is longer than the hot and neutral prongs. This feature ensures that the ground will always beconnected before the hot and neutral energize the equipment. Thus, if there is a fault in the equipment, the ground will already be connected to safely carry the fault current to earth. Similarly, when the plug is being removed, the ground is the last connection to open.

The utility of these design features is only effective if the receptacle is correctly wired to the power system. A potential and unfortunately all too common problem is reversing wires during installation. If a fault (i.e., a short energizing the casing) occurs within a drill, the ground wire of a correctly wired system carries the current safely away from the person (Figure II-7). When wires are reversed at the receptacle, however, unexpected and possibly deadly situations may arise. Figure II-9 illustrates three possible miswired cases: reversed polarity (reversing the hot and neutral or hot and ground wires); reversing the ground and neutral; and reversing the hot and ground.

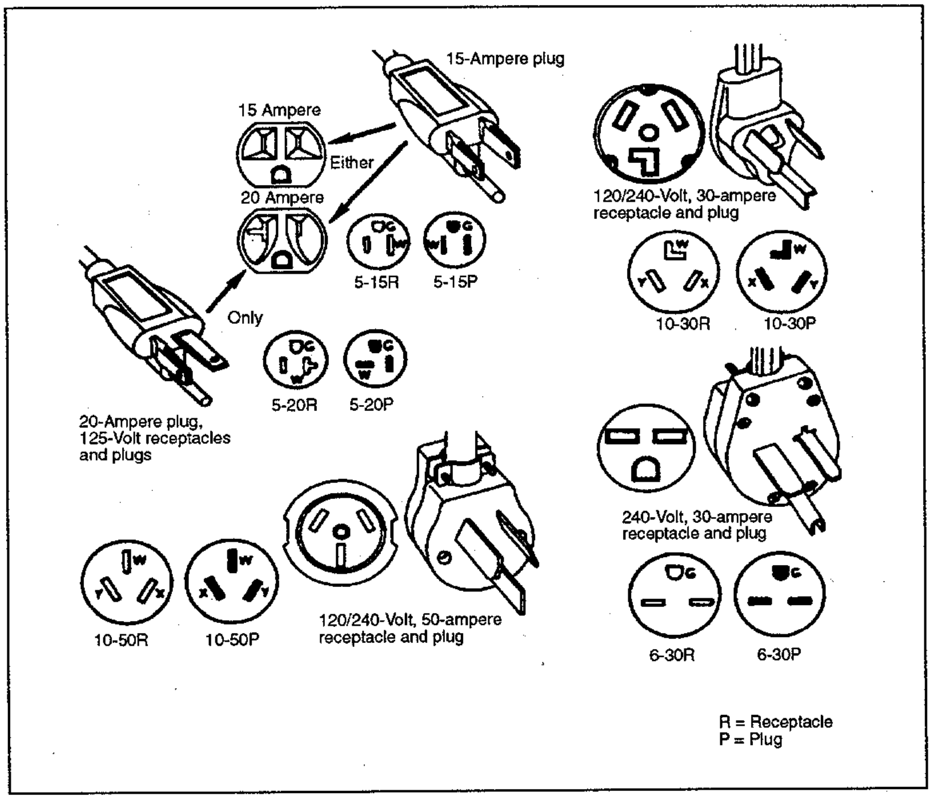


Figure II-8. Receptacles and plugs with NEMA configurations (adapted from U.S. Department of Labor, "An Illustrated Guide to Electrical Safety," Occupational Safety and Health Administration, 1981).

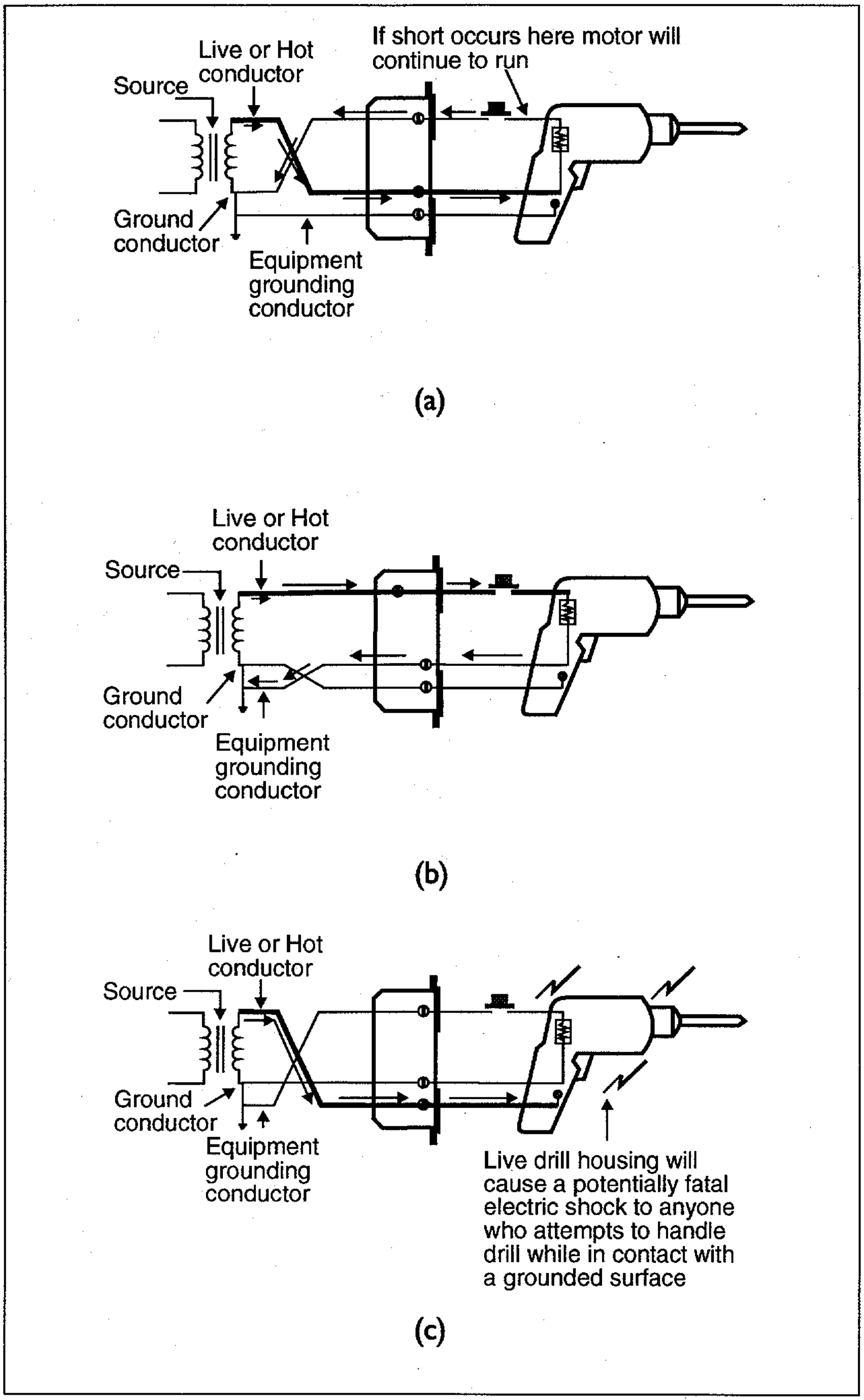


Figure II-9. Examples of incorrect wiring of receptacles (a) hot and neutral reversed; (b) ground and neutral reversed; (c) hot and ground reversed, (adapted from U.S. Department of Labor, 1981).

In the event of certain fault conditions, reversed polarity may result in internal circuits in electrical equipment being energized even if the switch is "off." Reversing the ground and neutral wires is not a hazard in itself. If such a reversal was in series with another receptacle that had reversed polarity, a hazard would exist because the neutral wire would then become hot. Reversing the hot and ground wire is the most hazardous condition shown: in this case the drill casing may become energized if a fault occurs and may cause a shock to anyone that touches it. The drill motor will not run in this situation. Figure II-10 shows a correctly wired receptacle.

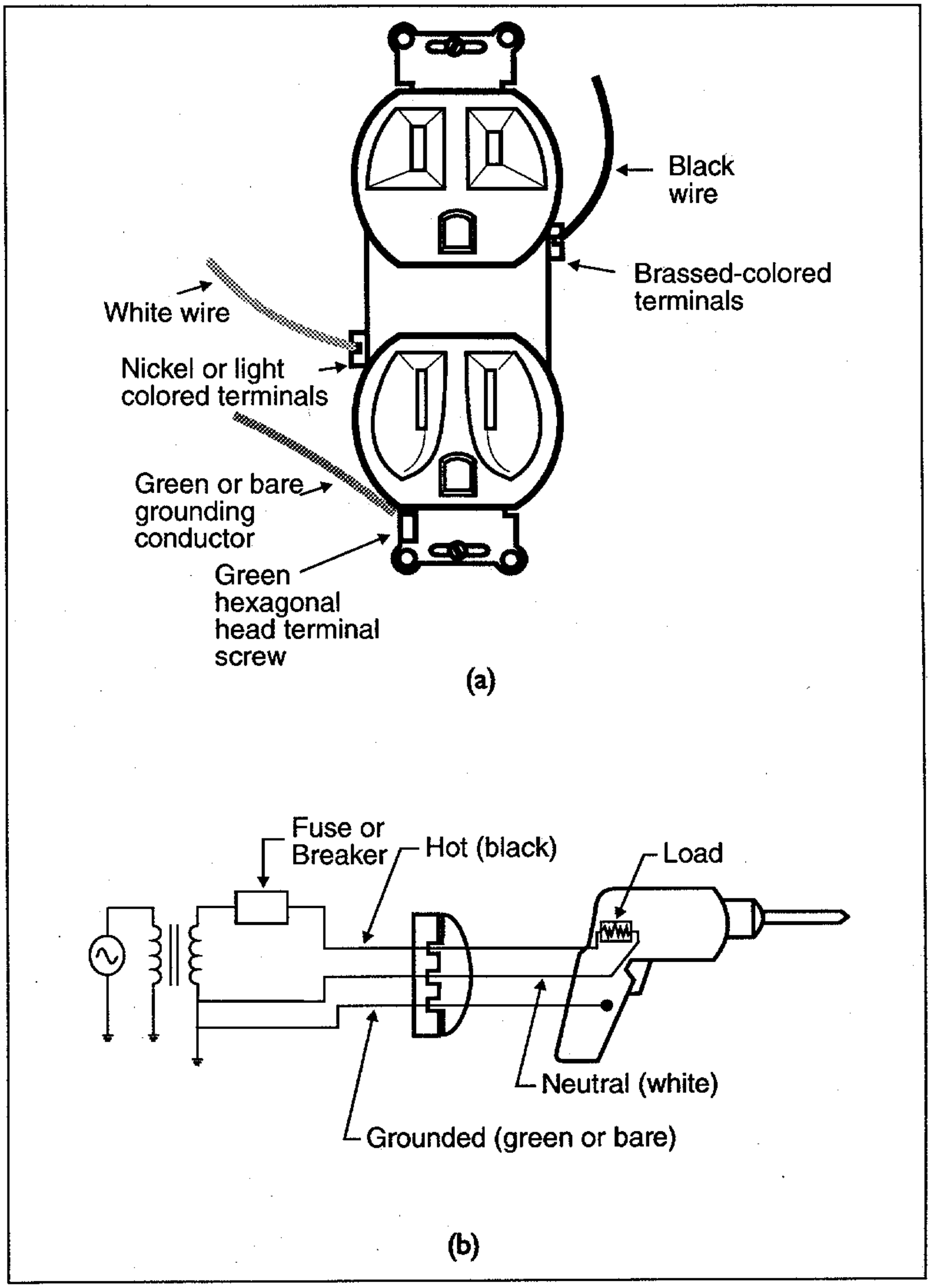


Figure II-10. (a) Duplex receptacle correctly wired to designated terminals (adapted from U.S. Department of Labor, 1981); (b) schematic of the entire, correctly wired, three-wire receptacle and circuit.

The polarity of a receptacle can be easily tested by measuring the voltage between the three terminals (V_1, V_2, and V_3), as shown in Figure II-11 (a). There are six possible fault conditions: any of the three leads may be open, and there are three ways of interchanging the connections (assuming only one fault condition at a time).

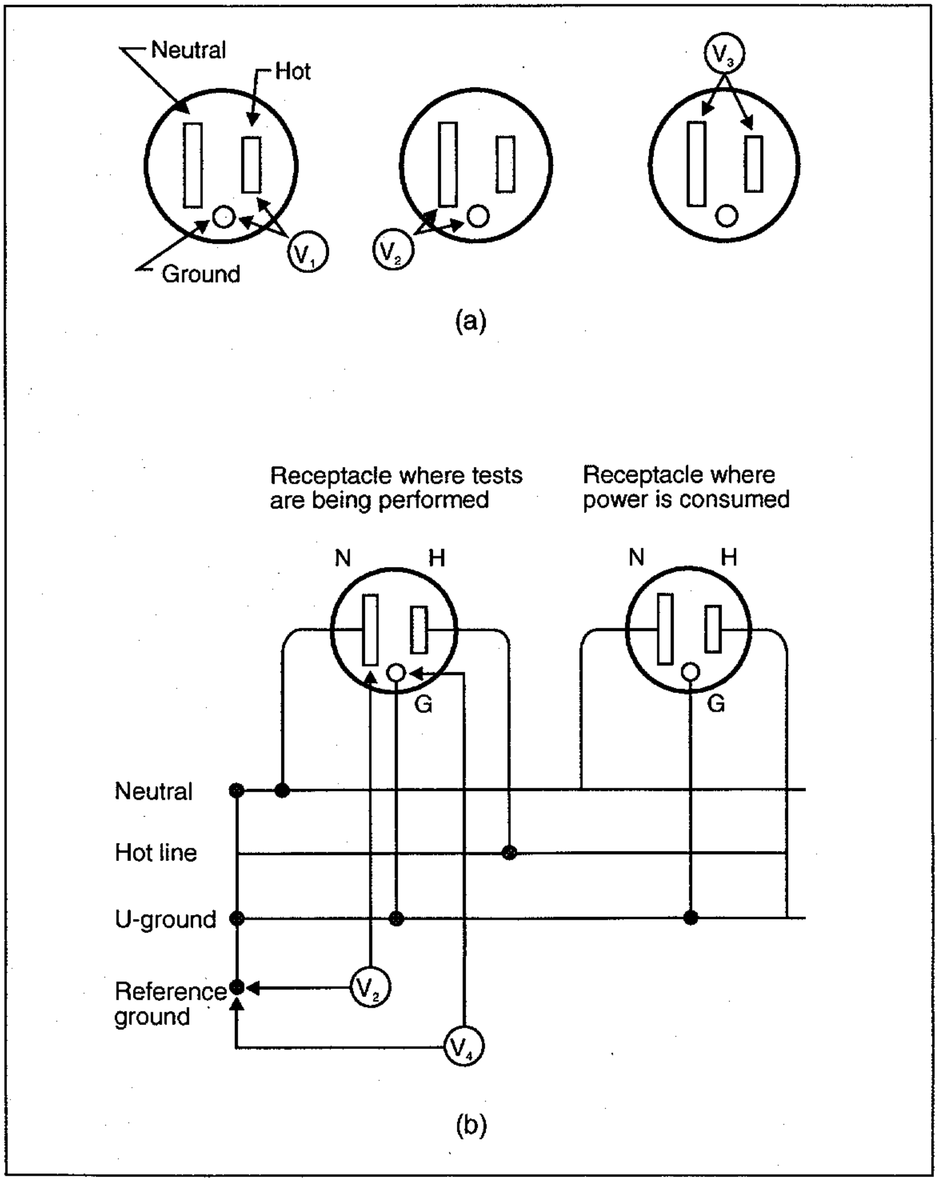


Figure II-11. Detecting improper wiring in receptacles: (a) measuring V_1, V_2, and V_3 can detect improper wiring conditions (H, N, or G not connected or N-H or H-G reversed); (b) method used to detect reversed N-G (adapted from Bahill, 1981).

If a receptacle is correctly wired, V_1 and V_3 ($V_2 = 0$) will register the same voltage. If the hot and neutral are reversed (reversed polarity), V_2 and V_3 ($V_1 = 0$) will register the same voltage. If the hot is open, all votages will be zero. If the ground is open, only V_3 will register. If the neutral is open, only V_1 will register.

If the ground and neutral are reversed, only the method pictured in figure 2.11 (b) will accurately reveal the error. This test is performed by applying a load to a nearby receptacle on the same circuit and measuring the voltages shown with an oscilloscope. When properly wired, current will flow only through the hot and neutral wires. The U-ground line will only carry a small leakage current. If the ground and neutral were reversed, the ground would carry a larger current than the neutral (i.e., $V_4 > V_2$). Commercial devices designed to test receptacle wiring are available.

> **NIOSH ALERT: Request for Assistance in Preventing Electrocutions Due to Damaged Receptacles and Connectors**
>
> *...Results of ... investigations indicate that periodic inspection, recognition of hazards, and proper use of receptacles and connectors, and prompt repair of damaged connectors and receptacles, could prevent [electrocutions]...*

*This is an excerpt; see reference materials at the end of this book for a complete copy of this Alert.

Bonding

Bonding is a form of grounding in which all major parts of a system or pieces of equipment are linked with an effective conductor to provide a continuous path to ground. A bond is a mechanical connection between physically separated parts that provides a path of low resistance for current flow between the parts and to the ground. Bonding is also an important concept for flammable liquid transfer systems and procedures, which will be covered in depth later in this text. Briefly, fluid flow can create opposing electrostatic charge buildup between containers when transferring liquids. Without bonding, which provides a conductive path between containers that will neutralize the opposing charge build-up, the charge difference may result in a spark between containers. This spark may have sufficient energy to ignite the flammable liquid or vapors.

Ground-fault circuit interrupter (GFCI)

A GFCI monitors the current flow in both the hot wire and the grounded neutral wire. For example, a current flows into a toaster through the hot wire and returns via the grounded neutral wire. Even though energy is lost in the form of heat, the current leaving the toaster will be equal to that entering.

Frustrated and hungry, a person attempts to free a piece of toast by inserting a knife into the slot and contacts the energized elements. If that person offers a path to ground (e.g., by being in contact with a grounded kitchen appliance), a portion of the current will pass through the person and to the ground. The GFCI will sense the difference in current levels between the hot and grounded neutral wires—a difference indicating a ground fault (i.e., that current is flowing in an unintended path to ground, a person in this case). When the current differences reach some predetermined level (frequently 5 milliamps) the GFCI will automatically cut power to the system, in as little as 25 milliseconds and protect the person from further shock hazards. See Figure II-12.

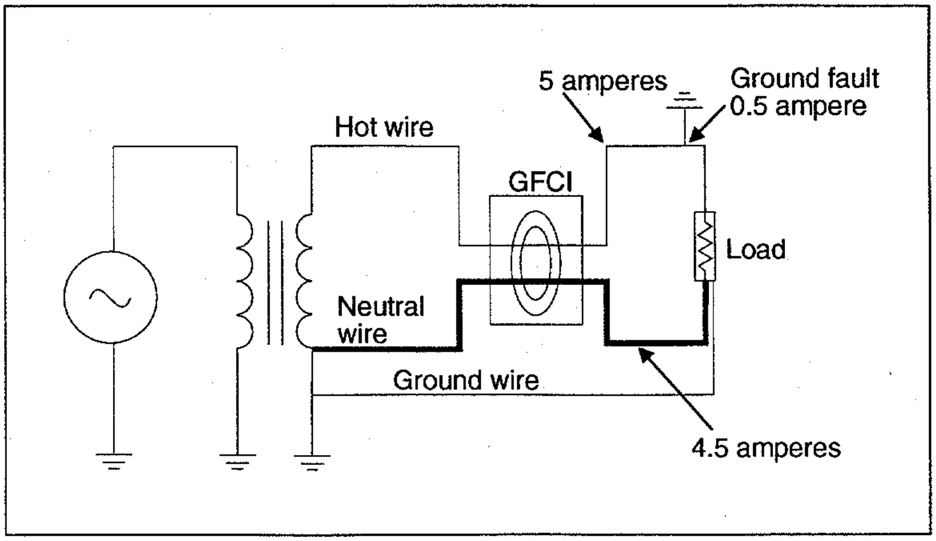


Figure II-12. A 0.5 milliampere ground fault causes a current flow imbalance between the hot and neutral wires. Sensing the imbalance, the ground-fault circuit interrupter (GFCI) breaks the circuit.

Figure II-13 illustrates a familiar receptacle-type GFCI commonly used in bathrooms. Because of the expected presence of water in a bathroom and the likelihood that water could provide a conductive path to ground, GFCI's are an important protection against shock in such environments. The National Electric Code mandates the use of GFCI systems for all bathroom, some kitchen, all basement and below-grade locations. Note also that monthly testing is recommended for all GFCIs and that test buttons are provided for this purpose.

Note also that fuses and circuit breakers do not protect people from shock. In the home situation, for example, a person could be killed long before a 15 ampere fuse blows.

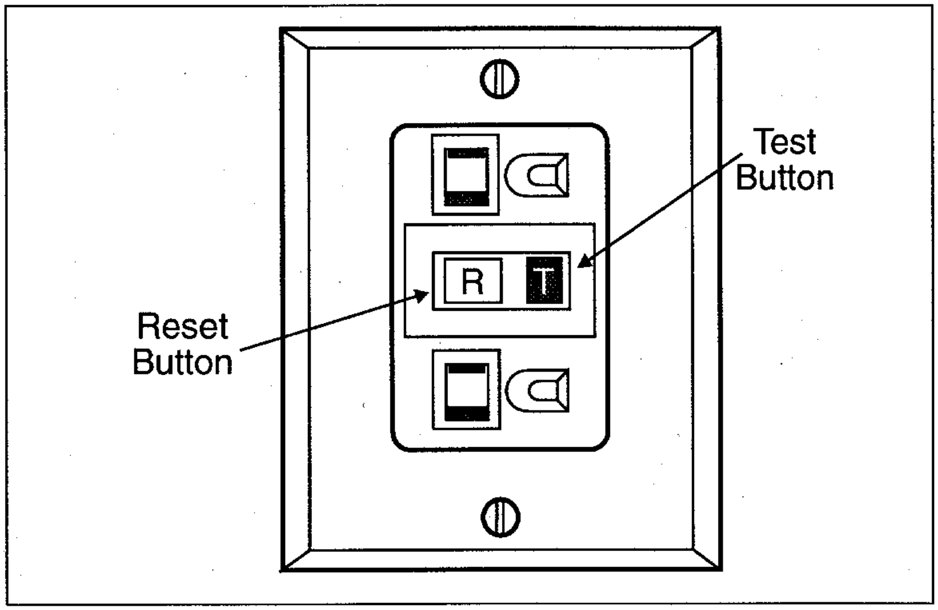


Figure II-13. Receptacle-type ground-fault circuit interrupter (GFCI) (adapted from U.S. Department of Labor, 1981).

Double insulation

In previous ground fault examples, we have used a drill as an illustration. That is, a fault (short circuit) within the drill resulted in an energized case, which then was a potential source of shock to a person. Most new hand tools, however, are double insulated. As the name implies, double insulating involves enclosing the electrical components of equipment in a layer of insulation, and then enclosing that within a case made of nonconducting material. Any shafts or components that pass through the insulation must also be made of nonconducting materials. When the insulation is intact, there is no path to the case or to a person and thus no shock. See Figure II-14 for a schematic representation of a double-insulated drill.

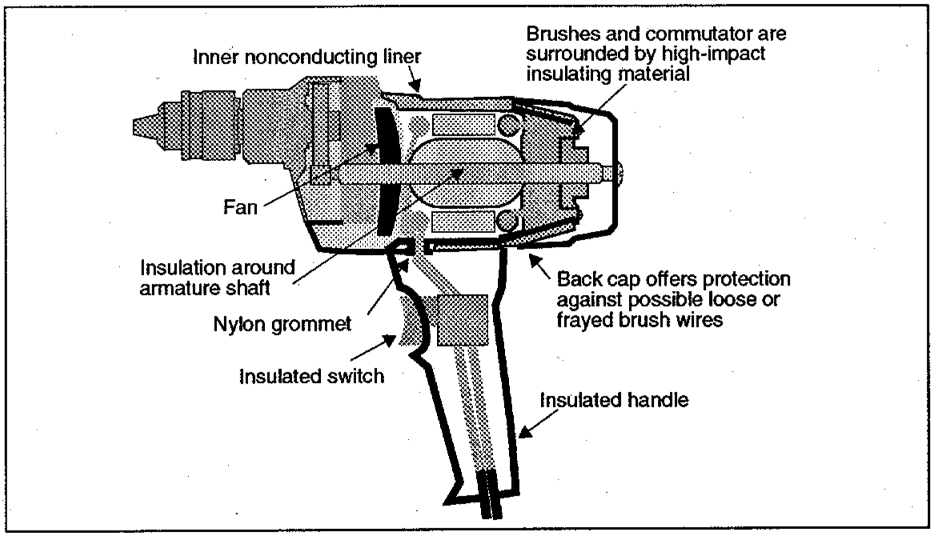


Figure II-14. On a double-insulated, shock-proof electric tool, an internal layer of protective insulation completely isolates the electrical components from the outer metal housing.

CONCLUSIONS REGARDING SHOCKS

This has been a brief review of electrical shock hazards and of some of the controls available to reduce or eliminate the hazards. When you begin designing, maintaining, or operating electrical equipment or systems, or when you are responsible for others performing such duties in your career, you must study, understand, and implement these controls to eliminate shock hazards whenever possible. When it is impossible to eliminate hazards by design, every attempt must be made to reduce the hazard to an acceptably safe level. Later in this text, we will introduce standards and regulations that address these concepts and will assist you in making your designs and procedures safe.

INADVERTENT ACTIVATION OF EQUIPMENT

Inadvertent activation of electrically powered equipment frequently causes death, injury, and equipment damage. Examples where a worker was inside a large piece of industrial equipment performing maintenance or cleaning procedures when the machine was activated are not uncommon, and the outcome is often fatal. In other cases, workers may be struck and injured by moving parts when equipment powers-up without warning or operates differently than expected. Severed fingers, hands, and limbs are not uncommon in these situations. A combination of safety designs and operating procedures are often used to minimize this hazard.

Case study

Before a worker inspected and maintained a large industrial fan, he turned off all the power at the main control panel. Normally an operator controls and monitors the equipment from this control panel. The worker assumed the operator had gone to lunch and decided he could complete his work before the operator returned. He entered the fan housing to inspect the blades, which measure some 20 feet in length. Meanwhile, the machine operator returned to his station to find the fan not running. He immediately switched all the power on to test the fan. The maintenance worker was killed within seconds, unbeknownst to the operator.

Lockout/tagout procedures

This event could have been avoided by using a number of safety designs and procedures, including locking and tagging out the control panel. Lockout/tagout procedures would have been the responsibility of the maintenance worker. Had they been a part of the company procedures, he would have physically locked the power controls in the off position and placed tags describing the work being done, the person's name, and the department involved. He would then keep the only key to that lock with him (typically, the supervisor keeps a master key to the lock in his office). These procedures should be normal in every industry. All personnel should be trained to follow and understand their use. When they are followed and assuming no other system faults, the risk of injury due to unexpected activation is significantly reduced.

No matter what method is used to lock electrical switches off, the procedures must be constantly supervised and employees thoroughly trained and required to follow them. Here is one minimally acceptable lockout program for maintenance procedures (a more detailed plan can be found in the reference materials):

1. Alert the operator that maintenance is to be performed.
2. Before beginning work, make sure that no part of the system or machine can be activated or set in motion without permission from the maintenance worker.

3. Place a personal padlock and tag on the master control switch, lever, valve, or local disconnect. This should be done even if another lock is already in place (for large operations, others may also be performing maintenance in other areas). A worker can only be protected by using his own padlock.
4. When work is complete, remove the lock and tag. Only the worker performing the work should remove the lock. Before the machine is activated, make sure no other person is in danger before activating the equipment.
5. Provide each maintenance worker with his/her own locks with unique keys. Only the worker and the supervisor should have copies of the keys. Lost keys should be reported immediately and new locks issued.

Interlock

Unfortunately, sometimes a worker will forget to follow procedures or take a short-cut. Therefore, additional safety measures should be designed into the system to further reduce the risk of injury. In the case study, an interlock would have been an additional safety measure that would have eliminated the electrical contact. An interlock is designed to disconnect all power to a system when a protective enclosure has been opened.

In other cases of inadvertant activation, a person may bump a power switch on a piece of equipment and unexpectedly activate the power, or release mechanical energy, or both. Locating the controls at a distance from moving or energized parts will preclude injury should they be accidently activated. Other methods include the use of multiple controls and actions to activate a machine. For example, power presses, such as those that stamp metal parts using huge descending weights require three separate actions to activate the press. Before each cycle, a supervisor must use a key to set the machine for operation. The operator then must activate a preset button before being able to activate the punch with dual hand buttons located a safe distance from the machine. The dual hand buttons are designed to keep both hands occupied during the machine cycle and thus keep them clear of the danger area. All buttons are guarded to minimize the possibility of accidental depression. In some cases, the machines are equipped with powerful brakes that will stop the punch from descending if the operator removes a hand or hands from the buttons. Although this system sounds fool proof, adverse events still occur because of design, manufacturing, or installation errors or because operators devise ways to bypass the safety features.

The punch press example illustrates the difficulty engineers have in trying to design a safe product. Not only will people using our designs make mistakes (we all make mistakes; we all know mistakes happen), but they may intentionally bypass safety designs to make their task easier or to reduce the time necessary to complete it. A design that is both safe and efficient is an effective design.

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SAMPLE QUIZ QUESTIONS

1. a) In the case study at the beginning of this course module, the man held the drill with both hands and leaned against a metal pole with his shoulder. Now assume that he held the drill in his left hand and grasped the metal pole with his right hand (no shoulder contact). Calculate the current that would have flowed through his body if he had dry hands and if he had wet hands. Use the following data and assume a 110 V source.

Dry Skin	**Wet Skin**
R(right hand) = 60K Ω	R(right hand) = 1K Ω
R(left hand) = 20K Ω	R(left hand) = 1K Ω
R(internal tissues) = 400 Ω	R(internal tissues) = 400 Ω

   b) Describe the potential consequences of the shock for each case. What effect does the length of time he was exposed to the current have to do with the severity of his shock (i.e, what if current only passed through him for 1 second as opposed to 10 seconds)?

2. What conditions are necessary for a person to be shocked? Briefly describe the principal ways people experience electric shock, and provide your own example for each. For example, lightning strike is one way that people are exposed to electric shock. One example might be that of a woman being severely shocked when she was struck by lightning while stranded on a golf course during an electrical storm.
3. a) Briefly describe basic ways in which the insulation covering an energized conductor might become damaged.

   b) What effect might moisture have on insulation, particularly when the insulation is already deteriorated to some extent?
4. Find a real world example of an insulated conductor that might be exposed to most or all of the factors you discussed in problem (3), and hypothetically describe how and why it might deteriorate over time.
5. What is a short circuit? What can cause a short circuit?
6. What is an open circuit? What can cause an open circuit?
7. What are the potential hazards associated with: a) a short circuit; b) an open circuit?
8. Describe two situations where a relatively minor shock from static electricity may result in severe or even fatal injuries.
9. What is a "let-go" threshold current? What are the implications to the severity of a shock when a person is exposed to a current greater than or equal to the let-go threshold?
10. If a person was exposed to a current of 50 milliamperes for 10 seconds, would the person be in danger of having heart fibrillation? What is heart fibrillation?
11. Imagine your is job to control the hazards associated with a high-voltage device to be located outdoors in a residential neighborhood. What methods would you use to minimize the potential of someone being exposed to the hazard of electric shock?
12. Briefly describe the concept of "grounding." How does grounding equipment protect people from electric shock?
13. How would grounding have protected the man in the case study at the beginning of this unit? Describe the grounding method you would recommend.
14. Describe situations in which an installation or wiring error, even with a three-wire receptacle, can still result in an energized power tool (or any other electrical device) and the potential for electric shock.
15. What is a GFCI? How does one work?
16. What is "double-insulation"? How might it have protected the man in the case study?

Unit III

IGNITION OF FLAMMABLE AND COMBUSTIBLE MATERIALS AND EXPLOSIVES

PURPOSE:

To introduce students to the consequences of electricity acting as an ignition source.

OBJECTIVE:

To acquaint the student with:

1. The basic characteristics of fires, combustions, and explosions
2. Electricity as an ignition source
3. Methods to control ignition hazards
4. Consequences of electrical overheating
5. Chararcteristics of static electricity

SPECIAL TERMS:

1. Combustible
2. Flammable
3. Deflagration
4. Detonation
5. Electrical overloading
6. Spark
7. Arc
8. Corona
9. Intrinsically safe
10. Encapsulation
11. Embedment
12. Hermetic sealing
13. Explosion-proof
14. Pressurization
15. Fuses
16. Circuit breakers
17. Static electricity

INTRODUCTION

Unexpected behavior or operating characteristics physically inherent to some electrical equipment may release energy at levels sufficient to ignite flammable materials or fuel-air mixtures. Indeed, 22 percent of 25,000 fires studied by Factory Mutual Engineering Corporation between 1968 and 1977 were caused by electrical ignition sources—the leading cause of fire in industry (National Safety Council, 1988). The Fire Protection Association (FPA), the British equivalent to the National Fire Protection Association (NFPA) in the United States, also ranks "electrical installations and apparatus" as the most common cause of "major" fires.

The occurrence of residential and commercial fires may seem rather low, but the loss of life and property when it does happen is quite disturbing. All reasonably practicable steps to eliminate the potential for a fire or explosion must be taken, or the owner, insurance carrier, and regulatory agencies must agree to reduce the hazard to some minimally acceptable probability.

In this course unit, we will begin by exploring the mechanics of fire and explosions. A complete understanding of this science, which is well beyond the scope of this course, draws heavily on the field of chemistry. What we present here, however, is enough to familiarize you with some of the terms and concepts you will be exposed to in the future. Of the greatest importance is the potential contribution of electrical equipment as an ignition source and the methods you can use to control the hazards of fire and explosion. When you are faced with design or operations, however, consultation with experts in fire prevention and control helps minimize the potential for fire and explosion hazards.

MECHANICS OF FIRE

Fire, or the process of combustion, is a complex mix of heat, fuel, oxygen, and chemical chain reactions. The "fire triangle" (Figure III-1 (a)) is a convenient way to remember the basic elements (Ridley, 1986). The "fire pyramid" (Figure III-1 (b)), symbolizes the entire process of combustion by including "chain reactions" (National Safety Council, 1988).

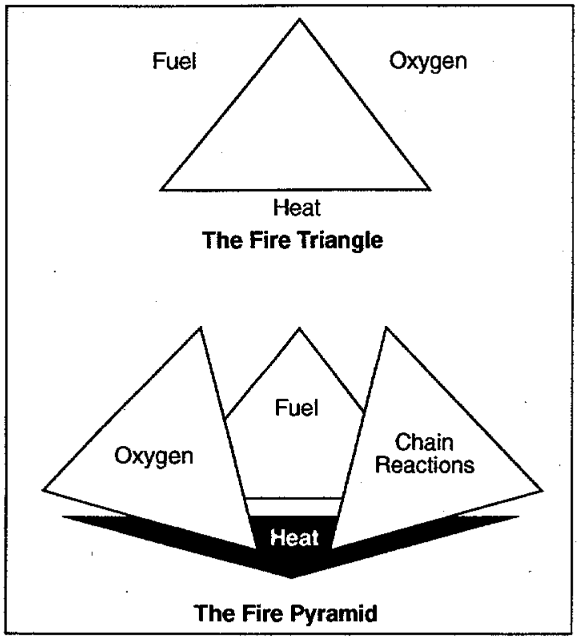


Figure III-1. (a) The fire triangle; (b) the fire pyramid.

Fire is actually an example of a more general exothermic chemical reaction called oxidation. Just as iron "rusts" because of chemical oxidation reactions, combustion is an oxidation reaction between a fuel and oxygen. The obvious difference between rusting iron and combustion is the speed and amount of heat the respective oxidation reactions involve. The speed of the reaction depends on many factors such as the mixing and the physical state of the reactants. For exothermic reactions, though, increasing the temperature generally speeds the reaction. A fire, then, is a fast, exothermic, chemical oxidation reaction involving oxygen and a fuel. You'll note from the fire triangle and pyramid figures that heat, or some form of initiation energy, is necessary to start the reaction. In the case of combustion, once ignition has occurred, the reaction will continue until at least one of the reactants has been controlled or exhausted. If the combustion process is confined so that pressure can increase, an explosion may result (National Safety Council, 1988).

When extinguishing a fire, one of the basic elements (heat, oxygen, fuel, or chemical chain reactions) must be removed or controlled. For example, fire fighters spray water on certain types of fires to lower the heat (evaporation is an endothermic, or cooling, process) and quench the flames. Since water is conductive, however, it isn't appropriate for electrical equipment fires. Electrical fires are best controlled by nonconducting chemical agents such as carbon dioxide, which may act to smother the fire, (1) removing oxygen from the reaction or (2) by chemically inhibiting the chain reactions. Class C portable fire extinguishers contain nonconducting agents meant specifically for use on fires involving electrical wiring and equipment. The type of agent used to control a fire depends on the fuel being burned. Figure III-2 describes the classification scheme for portable fire extinguishers set forth by the NFPA.

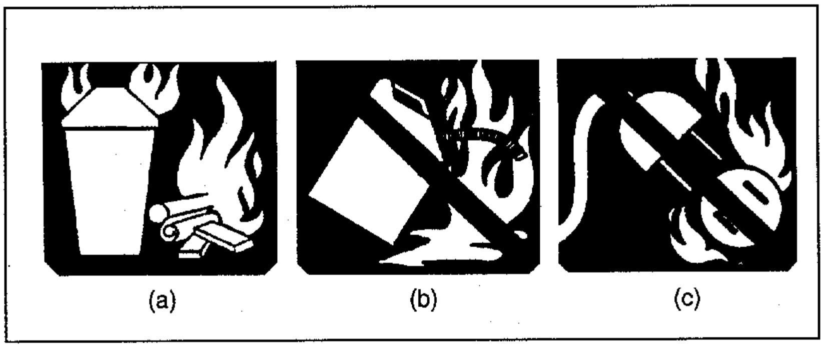
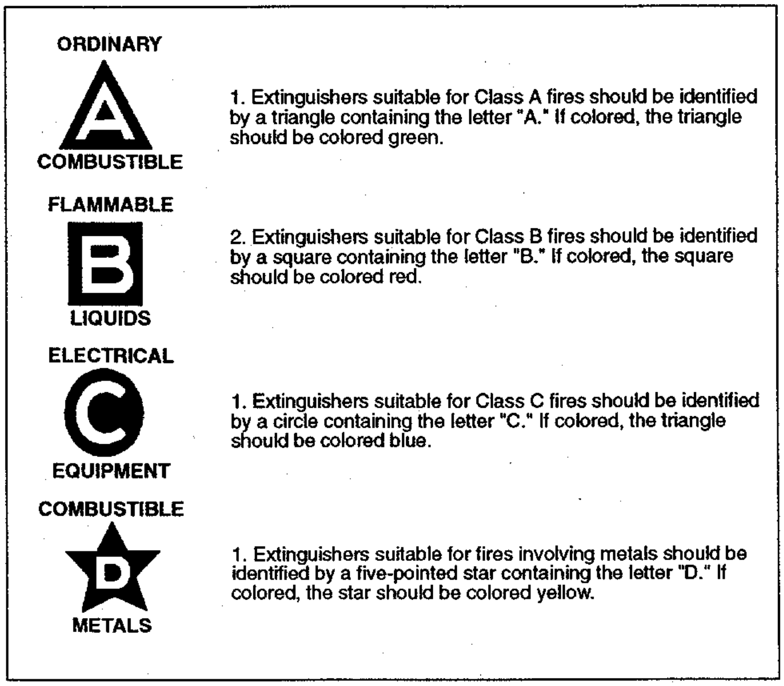


Figure III-2. Picture-symbol labels promulgated by the National Association of Fire Equipment Distributors.

These symbols are used on a Class A extinguisher (for extinguishing fires in trash, wood, or paper). The background symbol at left (a) is blue. Since a Class A extinguisher is not recommended for use on Class B or C fires, the background of (b) and (c) are in black, with a diagonal red line through each. For use on a Class A/B extinguisher, illustrations (a) and (b) would be in blue, and (c) would be in black with red diagonal. For use on Class B/C, the last two ([b] and [c]) would be in blue. On a Class A/B/C, all three would be in blue.



1. Extinguishers suitable for Class A fires should be identified by a triangle containing the letter "A." If colored, the triangle should be colored green.

2. Extinguishers suitable for Class B fires should be identified by a square containing the letter "B." If colored, the square should be colored red.

1. Extinguishers suitable for Class C fires should be identified by a circle containing the letter "C." If colored, the triangle should be colored blue.

1. Extinguishers suitable for fires involving metals should be identified by a five-pointed star containing the letter "D." If colored, the star should be colored yellow.

Figure III-3. The portable fire extinguisher marking scheme defined in NFPA Standard No. 10.

Fuel

Any combustible substance can be considered a fuel. All organic chemicals or compounds are combustibles. Examples include oil, natural gas, plastics, wood, and even living tissue (see Table III-1 for additional examples of organic compounds). Some combustibles will burn more easily than others, but all will burn under the right conditions. Most, but not all, inorganic chemicals are noncombustible. Examples of combustible inorganic chemicals include hydrogen, sulphur, phosphorus, and some metals such as magnesium, aluminum, and titanium.

Oxygen

There are only three sources of oxygen for combustion. (1) the atmospheric environment, which may be air (21% oxygen) or a controlled atmosphere containing more or less oxygen, (2) substances known as oxidizing agents, and (3) the combustible material itself.

Air is the most common source of oxygen for a fire, and its gaseous state is most efficient for combustion. Certain industrial processes and medical environments may involve oxygen-enriched atmospheres: these require special precautions to control fire hazards. Originally, carrying an atmosphere containing 79 percent of apparently useless nitrogen in space vehicles was believed uneconomical and it was, therefore, replaced by pure oxygen. After three astronauts were killed in their Apollo command module in 1967, the designers wisely reconsidered the contents of the atmosphere (Hirst, 1989). The fatal fire was ignited by a short circuit within an electronic component. Below are some example settings where oxygen-enriched atmospheres are present (Hirst, 1989).

Table III-1. The Main Groups of Organic Compounds, with Examples and Their Use*

Group	Example	Use
Aliphatic hydrocarbons	Methane Butane	Natural gas petroleum gas
Aromatic hydrocarbons	Benzene Toluene	Solvent (toxic) Solvent
Halocarbons	Bromomethane Trichloroethane	Fumigant Solvent
Alcohols	Ethanol Glycerol	"Alcohol" Glycerine
Carbonyl compounds	Formaldehyde (methanol) Benzaldehyde acetone	Fumigant Manufacturing solvent
Ethers	Ethyl ether Dioxan	Anaesthetic Solvent
Amines	Methelamine Aniline	Manufacturing
	Ethanoic acid Phthalic acid	Acetic acid manufacturing
Esters	Ethyl acetate	Solvent
Amides	Acetamide Urea	Manufacturing By-product

*Adapted from Ridley 1986.

Hyperbaric chambers, including decompression chambers, diving bells, and underwater tunnels.

Hospitals, where oxygen-enriched atmospheres are needed for some medical treatments and where oxygen supplies, which may leak, are located throughout the building.

Cutting and welding, operations that use bottled oxygen, can be very hazardous should the container begin to leak oxygen.

Aircraft with emergency oxygen supplies that can leak and create a hazardous oxygen-enriched atmosphere should ignition occur.

Industry where oxygen is needed in a variety of industrial processes. For example, huge quantities are required for the Bessemer process in steel making. Even when a process does not use oxygen, a hazard may develop. For example, liquid nitrogen has a boiling point of -196 degrees Celsius; that of liquid oxygen is a bit higher at -183 degrees Celsius. When liquid nitrogen is used to cool materials for processing, oxygen can condense from the air to create an enriched area.

Transportation where large quantities of oxygen are transported to supply industry. A spill can cause a wide area of oxygen-enriched atmosphere.

An oxidizing agent is any substance that releases gaseous oxygen when exposed to heat. Examples are hydrogen peroxide, sodium chlorate, nitric acid, and organic peroxides. Ammonium nitrate is an example of a substance that is both an oxidizing agent and a combustible, thus reacting with itself after ignition.

Ignition

An ignition source is any supply of energy that will push the reactants over the initiation energy barrier. Heat, a frequent energy source, may arise from a flame (e.g., a match or pilot light), friction (e.g., machine parts such as dry bearings or brake drums), or most important for our purposes, electrically produced energy. The energy produced, for instance, by a light bulb, an electrical heating appliance, or an overloaded circuit may provide enough heat to ignite combustible materials or flammable fuel/air mixtures under the right circumstances. Electrical discharges (e.g., arcs, sparks, coronas) may also provide sufficient energy to ignite combustibles. These events may occur under normal operating conditions, such as an arc produced when a switch breaks contact between conductors or when the brush of an electric motor spins. Static electricity, lightning, or abnormal electrical discharge in circuits and electrical systems are also potential sources of ignition.

CHARACTERISTICS OF COMBUSTION

Three measures of initiation energy are used to characterize ignition energies of substances: flash point, fire point, and spontaneous ignition temperature.

Flash point, which pertains to liquids only, is the minimum temperature at which a liquid will release enough vapor to form a mixture with air that will ignite under prescribed test conditions. The Able and Pensky-Martins tests are commonly used to test and report flash points for different substances. Flash points are sensitive to atmospheric pressure, decreasing with decreasing pressure (Ridley, 1986).

Fire point, which also pertains only to liquids, is the lowest temperature at which a burning vapor will produce sufficient heat to continue vaporizing the liquid and sustain combustion (Ridley, 1986).

Spontaneous ignition temperature is the lowest temperature at which a substance in either liquid or gas phase will ignite spontaneously. Some organic substances undergo slow partial oxidation at room temperature. The exothermic reactions cause the temperature to rise, and if the excess heat is not dissipated quickly enough, the substance or reactants may spontaneously ignite (Ridley, 1986). This condition is only reached when there is sufficient air for oxidation but not enough ventilation to carry away the heat as fast as it is generated (National Safety Council, 1988).

Upper and lower flammable limits (explosive limits) are used to describe the concentration of a gas or vapor mixture of substances that is capable of ignition and subsequent flame-propagation when mixed with air under prescribed test conditions.

The lower flammable (explosive) limit is defined as the smallest concentration of gas or vapor capable of ignition and subsequent flame propagation under test conditions.

Upper flammable (explosive) limit is defined as the greatest concentration of gas or vapor that will meet those conditions. Thus, the upper and lower limits describe the flammable range. The flammable range is sensitive to ambient temperature and pressure. In particular, increasing the ambient temperature widens the flammable range by reducing the lower limit and increasing the upper limit.

When considering the ability of an electrical discharge to ignite flammable materials, it is useful to consider ignition energies in relation to concentrations for a gas/air mixture. Figure III-4 shows a typical curve for a given substance relating ignition energies over the range of upper and lower explosive limits. Table III-2 lists minimum spark ignition energies for various fuels.

EXPLOSIONS

An explosion is generally defined as a sudden and violent release of large amounts of gas. This definition includes rupture of high pressure vessels, such as a boiler, and chemical reactions. Here we are concerned with chemical reactions, which can be either a deflagration or a detonation.

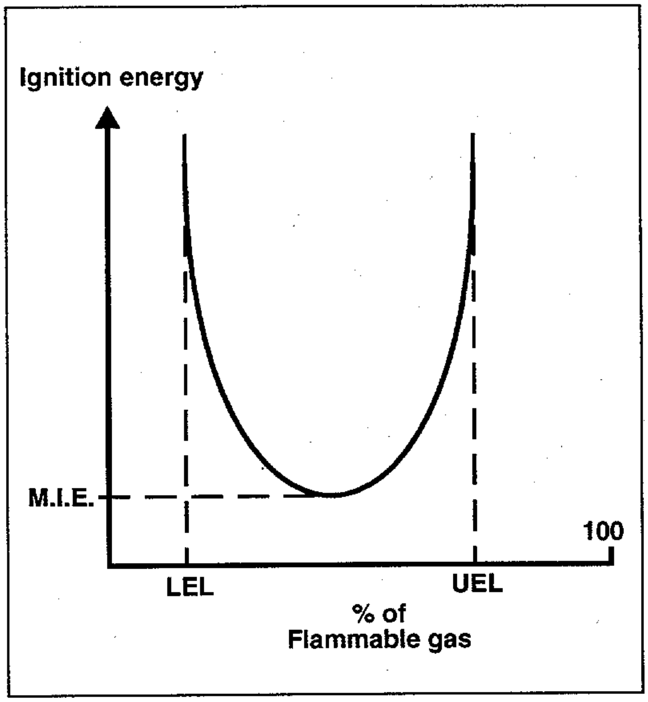


Figure III-4. Typical curve relating ignition energy to concentration for a gas/air mixture, where MIE is the minimum ignition energy and LEL is lower explosive limit and UEL is the upper explosive limit.

Table III-2. Minimum Spark Ignition Energies for Various Fuels*

Fuel	Minimum Ignition Energy (10^{-4} Joules)
Acetylene	0.2
Hydrogen	0.2
Ethylene	0.96
Methanol	2.15
Furan	2.25
Propylene	2.82
Ethane	2.85
Propane	3.05
Methane	4.7
Isobutane	5.2
Cyclohexene	5.25
Benzene	5.5
Isopropyl alcohol	6.5
Vinyl acetate	7.0
Acetone	11.5

*Adapted from Risinger, 1985.

A *deflagration* consists of a rapid reaction that progressively transfers heat from the reacting materials to neighboring materials that then react because of the increased heat, thus propagating the reaction. Although the *deflagration* rate is high, it is less than the speed of sound and will not create a shock wave unless it is in a confined space, such as a room or building.

If the velocity of a reaction through the reacting materials is greater than the speed of sound, the explosion is called a *detonation.* The reaction will create a shock wave even if the reaction is not confined (Hammer, 1989).

Some materials are specifically classified as explosives because of their fast reaction rates. Explosives, however, need not be present for an explosion to occur. In fact, many explosion disasters have occurred in the absence of any classified explosive materials.

EXPLOSIVE ATMOSPHERES

In 1937, a school in New London, Texas, was destroyed by an explosion that killed 413 students and 14 teachers. In 1944, in Cleveland, Ohio, a tank containing 80 million cubic feet of natural gas failed, leaking its contents over the surrounding area and into the storm sewers. When the vapors ignited, the liquified gas vaporized rapidly and burned in the open air. The gas that had leaked into the confined space of storm sewers, however, exploded, causing widespread damage and 135 deaths. In 1947, the French ship "SS Grandchamp" exploded at the pier in Texas City, Texas, destroying the city and killing 561 people. In 1974, a Flixborough, England, chemical plant exploded, devastating the town and killing 29 people and injuring 100. More recently, the U.S. space shuttle "Challenger" exploded during its ascent, killing all aboard. These are only a few of the more notable examples of catastrophic explosions, but all share a common thread: no classified explosives were present. Under the right conditions, seemingly benign substances and mixtures can explode when ignited (Hammer, 1989).

Dust explosions may occur wherever material that will burn is present in powder form. Examples are coal, wood, agricultural products, and certain synthetic resins present in plastic industry. Figure III-5 shows the frequency distribution of dust types involved in 357 dust explosions that occurred between 1965 and 1980.

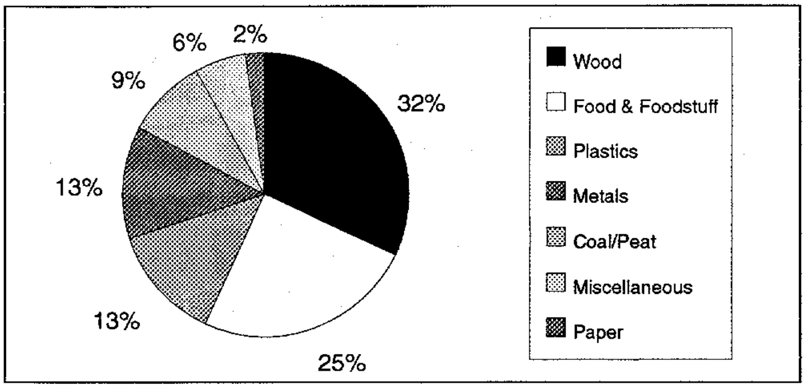


Figure III-5. Frequency distribution of the types of dust involved in 357 dust explosions between 1965 and 1980 (adapted from Bartknecht, 1989).

Industries take special precautions to minimize dust concentration, such as ventilating, enclosing dust producing processes, or applying dust arresting substances to keep the dust from mixing to dangerous concentrations in the air. As a last resort, some high-risk industries design buildings or enclosures with "blow out" walls and vents to minimize the devastating pressure should an explosion occur.

Gases and vapors that can produce flammable mixtures with air are commonly found in industrial settings. Precautions are needed to prevent explosions. Example gases include hydrogen, acetylene, propane, LP-gas, methane, and natural gas.

In industry, some commonly used liquids that emit flammable vapors include gasoline, benzene, naphtha, and methyl alcohol.

From a safety standpoint, every effort must be made to eliminate a hazard at its source. Refer to the fire triangle or pyramid; controlling a fire hazard could involve controlling the fuel, heat or ignition energy, oxygen, or chain reactions. Controlling the availability of oxygen can be done by making the atmosphere inert in certain situations. Controlling the availability of a fuel and heat or initiation energy can be done in a number of ways. Although removing and controlling flammable materials from and in an environment by ventilation, enclosure, choosing nonflammable materials for processes, etc., are necessary defenses, such controls are rarely sufficient to control hazards to an acceptable level. Even if a hazard has been controlled (which is often not possible), a failure of the controlling safety system may create a dangerous situation. Therefore, the hazard must also be controlled by eliminating potential ignition sources.

Electrical phenomena are a common source of ignition, and we now turn our attention to electrical events that create a fire or explosion hazard and to methods to control those hazards.

ELECTRICAL PHENOMENA AS AN IGNITION SOURCE

The three principal ways in which electrical installations may cause fires are electrical overloading; electrical discharges in the form of sparks, arcs, or coronas; and electrical heating appliances. All are potential ignition sources for combustible materials and atmospheres. Lightning and static electricity (forms of electrical discharge) will be discussed separately (Hammer, 1989; Cooper, 1986).

Electrical overloading

Electrical overloading exists where the electrical power supplied to a circuit exceeds its designed levels and this results in excess heat and/or in damage to components. The increased temperatures may ignite flammable material in the vicinity, including some electrical insulating materials. A severe overload may result in a sudden and immediate fire hazard as the overloaded components release heat or experience failure causing electrical discharges. Less severe or intermittent overloading may cause material changes and degrade insulation properties to a point where failure does occur. The property changes and insulation failure may result in excess heat and undesirable electrical discharge events.

Short circuits may be the result of overload or may cause overloads. Short circuits occur when an energized conductor contacts an unintended conductor not in the circuit design. Generally, short circuits occur when insulation is damaged and the energized conductor is exposed. Contact may occur with conductors that were not intended to be energized to create both a shock hazard and a potential overload situation. Similarly contact may occur with other circuit components to energize them beyond their design capabilities and cause failure or abnormal electrical discharge. This, in turn, may ignite flammable materials or fuel/air mixtures.

Sparks, arcs, and coronas

Sparks, arcs, or coronas are common precursors to fires caused by electrical systems, and they may ignite flammable solids, liquids, vapors, dusts, or powders.

A *spark* is a rapid, heavy discharge of electrons. A spark will occur any time an ionized path develops in the dielectric medium separating two conductors or a conductor and ground. A spark may be a single event that completely exhausts the electrical energy in a system, or it may repeat each time the energy is replenished.

An *arc* is a sustained stream of electrons flowing across a gap between conductors that initially were in contact or in proximity but separate while current is flowing. An arc will continue until the voltage is no longer adequate to sustain it; this may occur by lowering the system voltage, or by further separating the conducting surfaces, or by lengthening the arc until it can no longer sustain itself. Unlike a spark, an arc will not reform unless the conductors are brought back in contact, or the voltage across the gap exceeds the dielectric breakdown potential.

A *corona,* or the *corona effect,* occurs in high-voltage systems when the dielectric medium separating conductors partially breaks down. The potential difference reaches a level necessary to ionize gas in the dielectric medium but not enough to produce sparking. Ions form a cloud that drifts, typically from the negative to positive electrode, to create a low-grade continuous flow. If the medium breaks down further, a spark may occur. The corona effect may be visible as a faint glow in the dark, and it may produce a hissing sound and electromagnetic interference. The glow has been referred to as "St. Elmo's Fire."

Arcs, sparks, and coronas can all cause insulating materials to degrade and lose their nonconducting properties, thus creating additional hazards. They may also cause electrical noise, which may interfere with the intended operation of electrical equipment. The worst effect, however, is the potential these events have as ignition sources for flammable materials and atmospheres. Even a spark caused by the discharge of static electricity can cause fires in certain environments (Hammer, 1989).

Electrical heating equipment

Electrical heating appliances are commonplace in the home and workplace. Certainly, such equipment is not appropriate in areas where flammable materials or atmospheres are expected. Generally, heating appliances should be equipped with temperature limiting devices to ensure that the surface temperatures of the heating elements or guards do not reach a level that may potentially ignite combustibles or cause burns to persons that may contact the equipment. Choosing the right equipment for an application is of the utmost importance, but maintaining it and the environment is equally necessary. Too often poor housekeeping or work practices contribute to fires.

For example, periodically bumping and kicking a space heater under a desk can eventually cause an electrical failure. Another example is when papers, rags, solvents, etc., are accidentally left near a heating appliance; a slow buildup of heat can cause an eventual fire. So, as in all hazard control strategies, a combination of design features, maintenance procedures, and work or use practices all contribute to the ultimate goal of minimizing or eliminating a hazard.

METHODS TO CONTROL IGNITION HAZARDS

The best way to stop electrical energy from igniting is to stop using electric equipment in hazardous areas. Unfortunately, this is not always possible. Therefore, when electrical equipment must be located in hazardous areas, special precautions must be taken to eliminate the hazard of fire or explosion.

Whenever and wherever possible, hazards should be completely eliminated. If, however, hazardous areas and processes are necessary, great care must be taken to control them. The cost of designing to eliminate or control a hazard is usually far less than the cost (in both life and property) of an accident (National Safety Council, 1988).

The National Electric Code (NEC) is one source that must be consulted during the design or operation of any industrial plant or process. These codes should become part of your library. The NEC regulations will be discussed in more depth in a future unit; here we'll discuss Article 500, which classifies hazardous locations.

Defining hazardous locations

Hazardous locations are areas in which explosive, or flammable gases, or vapors; combustible dust; or ignitable fibers are present or likely to become present. Hazardous locations are classified as Class I, Class II, or Class III, with the classification depending on the physical properties of the combustible substance that might be present. These classes are subdivided into Divisions 1 and 2, depending on the degree of likelihood that an ignitable atmosphere might be present. The assessment of combustible substances into one of seven groups (A through G) depends on the nature of the substance's behavior on contact with an ignition source.

Class I locations are those in which flammable gases or vapors are or may be present in the air in quantities sufficient to produce explosive or ignitible mixtures.

Class II locations are those that are hazardous because of the presence of combustible dust.

Class III locations are those that are hazardous because of the presence of easily ignitable fibers or flyings; such fibers or flyings are not, however, likely to be suspended in the air in quantities sufficient to produce ignitable mixtures.

Division 1 conditions are those where an ignitable atmosphere is expected to prevail at any time during the course of normal operations. This represents the worst case.

Division 2 conditions are those where no ignitable atmosphere exists under normal operating conditions, but where abnormal circumstances such as equipment malfunction or operator error might create a hazardous environment.

To determine whether a location is considered hazardous, ask yourself the following questions. A "yes" answer to any question within a class indicates that the location is considered hazardous. (These questions and their assignments are adapted from NSC's "Accident Prevention Manual for Industrial Operations, Administration, and Programs," 1988).

Class I:

—Are flammable liquids, vapors, or gases likely to be present?
—Are liquids having flash points at or above 100 degrees Fahrenheit likely to be handled, processed, or stored at temperatures above their flash points?

Class II:

—Are combustible dusts likely to be present?
—Are combustible dusts likely to ignite as a result of storage, handling, or other causes?

Class III:

—Are easily ignitable fibers or flyings present but not likely to be in suspension in the air in sufficient quantities to produce an ignitable mixture in the atmosphere?

Each of the classes above have been further subdivided into two divisions (Division 1 and Division 2) depending on the likelihood that an ignitable atmosphere might be present. To determine those conditions that should be assigned to Division 1, ask yourself the following questions. Again, a "yes" answer indicates that an ignitable atmosphere might be present .

Class I, Division 1:

—Is a flammable mixture likely to be present under normal operating conditions?
—Is a flammable mixture likely to be present frequently because of repair, maintenance, or leaks?
—Would a failure of process, storage, handling, or other equipment be likely to cause an electrical failure coinciding with the release of flammable gas or liquid?
—Is the flammable liquid, vapor, or gas piping system in an inadequately ventilated location, and does the piping system contain valves, meters, or screwed or flanged fittings that are likely to leak?

—Is the zone below the surrounding elevation or grade such that the flammable liquids or vapors may accumulate?

Class II, Division 1:

—Is a combustible dust likely to exist in suspension in air, under normal operating conditions, in sufficient quantities to produce explosive or ignitable mixtures?

—Is combustible dust likely to exist in suspension in the air because of maintenance or repair operations, in sufficient quantities to cause explosive or ignitable mixtures?

—Would failure of equipment be likely to cause an electrical system failure coinciding with the release of combustible dust in the air?

—Is combustible dust of an electrically conductive nature likely to be present?

Class III, Division 1:

—Are easily ignitable fibers or materials producing combustible flyings handled, manufactured, or used?

Or, should the atmosphere be considered that of a Division 2—one where no ignitable atmosphere exists but where abnormal circumstances might create a hazardous environment? A "yes" answer indicates a Division 2 classification.

Class I, Division 2:

—Is the flammable liquid, vapor, or gas piping system in an inadequately ventilated location but one not likely to leak?

—Is the flammable liquid, vapor, or gas handled in an adequately ventilated location and can the flammable substance escape only in the course of some abnormality, such as failure of a gasket or packing?

—Is the location adjacent to a Division 1 location or can the flammable substance be conducted to the location through trenches, pipes, or ducts?

—If positive mechanical ventilation is used, could failure or improper operation of ventilating equipment permit mixtures to build up to flammable concentrations?

Class II, Division 2:

—Is the combustible dust likely to exist in suspension in air only under abnormal conditions but can accumulations of dust be ignited by heat developed by electrical equipment or by arcs, sparks, or burning materials expelled from electrical equipment?

—Are dangerous concentrations of ignitable dusts normally prevented by reliable dust-control equipment such as fans or filters?

—Is the location adjacent to a Division 1 location and not separated by a fire wall?

—Are dust-producing materials stored or handled only in bags or containers and only stored—not used—in the area?

Class III, Division 2:

—Are easily ignitable fibers or flyings only handled and stored and not processed?

—Is the location adjacent to a Class III, Division 1 location?

Because ignition and explosion characteristics vary widely depending on what substance is present in an area, hazardous atmospheres are categorized into seven groups. Class I locations fall into Groups A through D, and Groups E, F, and G pertain to Class II hazardous locations. Table III-3 provides example materials for each group and industries where they might be found.

Table III-3. Example NEC Class and Group Distinctions

Class	Group	Description	Examples	Industries
I	A	Highly flammable gases and vapors	Acetylene	Welding fuel generators
I	B	Highly flammable gases and some liquids	Hydrogen Butadiene	Chemicals and plastics
I	C	Highly flammable chemicals	Diethyl ether Acetyaldehyde	Hospitals, chemical plants
I	D	Flammable fuels, chemicals	Gasoline Ammonia Acetone	Refineries, chemical plants, paint spray areas
II	E	Metal dusts	Magnesium	Chemical plants
II	F	Carbon,coke, coal dust	Carbon black Charcoal	Mines, steel mills, power plants
II	G	Grain dust	Flour, starch dust	Grain mills and elevators

Determining whether a hazardous area exists and then classifying it is generally straightforward in most industries. Defining the limits of the of the hazardous location, however, can be difficult. The NEC provides guidelines for certain circumstances. For circumstances not covered by the NEC, a general rule can be applied: the limits of a hazardous location are those mutually agreed upon by the owner, the owner's insurance carrier, and the authority enforcing the code.

The selection of electrical equipment that must be located in an area classified as hazardous depends on the Class, Division, and Group. Often, equipment manufacturers can aid in the selection of appropriate equipment. For example, the selection of explosion-proof equipment (discussed below) depends on the combustion characteristics of the specific atmosphere in which the fixture will operate. In essence, equipment must be customized to the specific hazardous environment where it will be used.

The more common techniques and equipment used in hazardous locations are briefly described below. The NEC provides guidance for minimizing or eliminating electrical ignition sources from hazardous areas. As always, keep in mind that although these methods of control offer a necessary and significant degree of protection, they are subject to failure and, therefore, do not ever completely eliminate the risk of an adverse event.

Intrinsically safe designs

An intrinsically safe design (sometimes called an inherently safe design) is one that is not capable of igniting because its operating energies are less than the energy required to ignite the known flammable materials or mixtures in the area. An inherently safe design could be one that employs miniaturized equipment utilizing components that operate with far less current and voltage than those that would present an ignition hazard for flammable mixtures.

To say a design is "intrinsically (inherently) safe," however, may lead to a false sense of security. No design can be totally fail proof. Certainly, we can minimize the likelihood of failure to an almost negligible level but never to zero. Many of the failures that have led to ignitions in the past were never imagined before they happened.

Encapsulation and embedment

Embedment and encapsulation are methods designed to separate the potential electrical ignition sources from a flammable environment. The materials used are nonflammable, sufficiently thick to prevent sparks from reaching flammable mixtures, and thermally nonconductive so the outer surfaces are kept well below ignition temperatures for the known flammable environment.

Hermetic sealing

Similar to encapsulation, hermetic sealing was originally developed to protect electrical equipment from moisture and environmental contaminants. As the name implies, hermetic sealing completely separates the components by containing them within a tightly sealed enclosure. The container can be filled with liquid or gas and is designed to dissipate heat at levels safely below ignition temperatures for flammable mixtures.

Liquid filling

Liquid-filled containers surrounding electrical equipment, such as transformers and circuit breakers, have been used for some time as a way to cool and protect components. Liquids can be chosen that can also eliminate sparking and arcing that otherwise could ignite a flammable or explosive atmosphere. The enclosure and liquid filling separate the flammable atmosphere from the potential electrical ignition source. A disadvantage with liquid filling is that some of the most effective liquids are also very hazardous to humans (e.g., PCB's). This has presented problems for maintenance people who may be unaware of the hazards and for people and fire fighters exposed to these chemicals during fires or when such equipment explodes (for instance, a transformer overloaded by a power surge from a lightning strike may explode).

Explosion-proof equipment

The idea behind explosion-proof equipment is to enclose electrical components in a way that allows access of flammable atmospheres and yet contains any resultant explosion without igniting the surrounding atmosphere. Design regulations are largely concerned with the strength of the enclosure; details of the joints between removeable covers and the main housing; and the design of any other necessary apparatuses in the housing, such as shaft exits (Bass, 1984). Because of the mechanisms of explosions and flame-propagation, explosion-proof enclosures are only appropriate for small components, such as switches. For larger enclosures, a small explosion-proof apparatus prevents external gases or vapors from igniting by cooling an escaping gas flow. This is done through conduction of heat by the gas flow; either the enclosure material conducts the heat or the escaping gas expands and mixes with the external atmosphere. Figure III-6 illustrates the idea behind explosion-proof equipment.

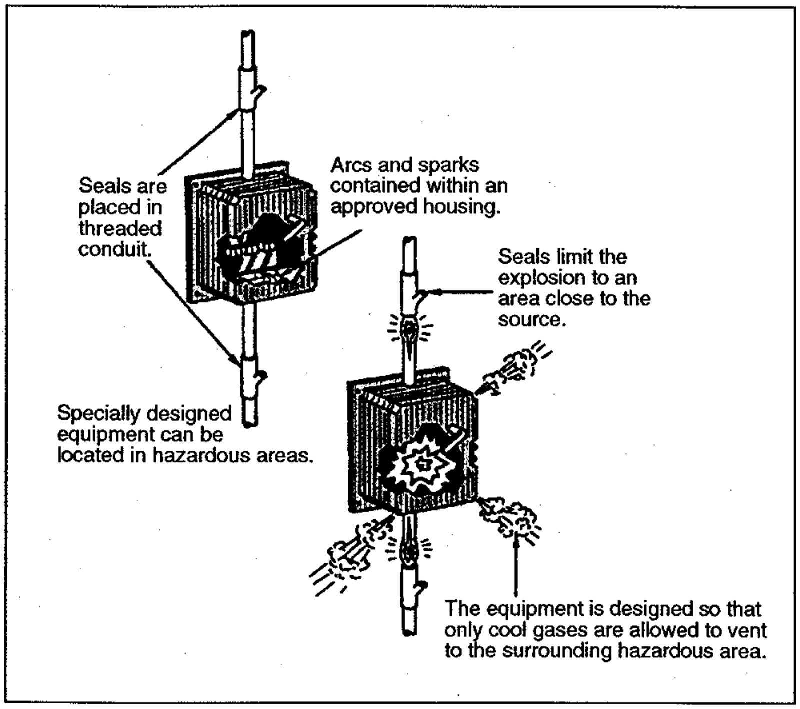


Figure III-6. When sparks or arcs ignite flammable gases, vapors, or liquids, explosion-proof equipment contains the explosion and vents only cool gases into the surrounding hazardous atmosphere (adapted from U.S. Department of Labor, 1981).

When explosion-proof equipment generates sufficient heat to increase the potential of ignition, that equipment must be cooled so that the casing does not reach temperatures that may contribute to an external atmosphere explosion.

Pressurization

If appropriate explosion-proof equipment is not available or feasible, pressurization systems may be possible alternatives for electrical equipment located in hazardous areas. Explosion-proof equipment is generally most appropriate and economical for individual units. Pressurization may be suitable when a large unit or area or a number of units are to be contained in one enclosure. Pressurization may also be advisable or necessary for some types of equipment operating in high altitude. Because the lower pressure reduces the dielectric effects of air, electrical discharges may occur at lower operating energies than those at sea level.

Pressurization is accomplished by providing a constant flow of air or inert gas to the inside of the enclosure so that the internal pressure is higher than that of the surrounding atmosphere. The increased, positive pressure prevents the flammable atmosphere from entering the enclosure where it might be ignited by the electrical equipment. The constant flow also clears the enclosure of any contaminants that may enter. Using an inert gas has an added advantage in that it contains no oxidizing agents, a necessary element for fire or explosion. Because a failure could be very hazardous, the enclosures are designed with a pressure-sensing switch that prevents activation or halts operations if the pressurization fails.

Isolation

Isolation is a desirable approach to reduce fire and explosion hazards because it completely removes either the flammable mixtures or the electrical ignition source. Isolation is not fool-proof, however, because the enclosure or physical partitions between the elements may fail.

Isolating an ignition source from a flammable or explosive atmosphere can be done in two ways: all electrical ignition sources can be sealed off from the hazardous environment; or the hazardous environment can be enclosed and sealed from any electrical ignition sources.

OVERHEATING, DAMAGE TO EQUIPMENT, ELECTRICAL EXPLOSIONS

Equipment failures, malfunctions, damage to equipment, or tampering with intended protection devices can lead to hazardous situations for any electrical component or system. The hazard may be an increased risk of shock, a fire or explosion hazard, the hazard of equipment activating unexpectedly or operating in an unexpected way, or any number of dangerous scenarios. The results may be injury or death to people, damage to equipment and facilities, or both.

In this section, we will focus on the hazardous effects of electrical equipment overheating and the conditions that lead to it and some methods to control the hazard. In previous sections we discussed the mechanics of fires and explosions and accentuated the hazard of electrical discharge (sparks, arcs, and coronas) as an ignition source. Here, we continue with electrical overheating as an additional source of ignition and suggest you review the section on fire mechanics where needed.

Reasons for overheating

All energized conductors release energy in the form of heat. (The only exception to this rule would be a super conductor, which at the time of this writing is an intriguing area of research but one not likely to reach widespread commercial application in the near future. A super conductor offers virtually no resistance to the flow of electrons and, therefore, loses no energy.) In general, the electrical energy converted to heat is equal to the current (I) squared multiplied by the resistance (R), or

$$\text{Electrical energy converted to heat} = I^2R$$

This expression is sometimes referred to as the Joule heat equation.

When designing a circuit, an engineer considers that heat will be generated in the conductors. Appropriately specified materials are chosen so that the expected operating energies, with a safety factor, will not generate too much heat to damage the conductors or insulating materials. Without circuit protection (sometimes even with circuit protection, which we discuss below), a circuit may experience over currents or over voltages, generally referred to as overloads, above those designed for. If this occurs, the conductors may heat to temperatures sufficient to increase fire hazards or even be the ignition source for a fire or explosion. Even if the generated heat is not a fire hazard in itself, this condition can deteriorate properties of the conductor or insulator, which, in turn, may cause immediate or eventual failure or malfunction. In some cases, the temperature may rise so quickly that the component itself explodes.

A circuit can receive over currents or excess voltage in many ways. Some may seem rather unlikely; the fact is they do occur, and the consequences may be catastrophic. Some of the more common causes of circuit overloading are short circuits, current surges, transient surges during startups, and lightning strikes (discussed in the next section). Circuit protection methods often will minimize the associated hazards, but in some cases, they may not be able to react quickly enough, or may not be designed to sense the particular overload condition. We will briefly discuss situations that can overload a circuit; recognize that some of the concepts may be beyond your current level of training in electrical engineering.

When a switch is closed to energize a system, the sudden input of energy may for a brief period produce a current or voltage spike larger than that expected. An individual spike of this type is generally not a problem, but repeated exposure to small spikes may lead to failure over the long term. Such failure may contribute to a short circuit, spark, arc, or corona, which would increase shock and fire hazards.

A short circuit between elements in a circuit, or an unintended open circuit in a parallel element, can cause greater current to flow in a conductor or circuit component.

Lightning sometimes strikes power lines and sends voltage spikes through the lines and to customer installations. Lightning can also induce current in conductors that are parallel to its path. In either case, the resulting overload conditions can be sufficient to severely damage equipment and cause fires or explosions.

These more common situations lead to overloaded circuits and equipment. Be assured that many other scenarios may unexpectedly increase the energy supplied to a circuit, such as induced currents and resonance occurring in complicated electronic systems.

Effects of electrical overheating

Electrically produced heat can contribute to a fire hazard by:

— increasing the temperature of a flammable mixture to a point where it easily ignites;

— raising a flammable mixture to its ignition temperature, and then igniting it;

— causing damage to insulating material, possibly igniting some;

— causing organic solids to melt, char, or burn;

— contributing to rapid evaporation of liquids to a point where flammable concentrations exist; and

— breaking down otherwise noncombustible materials to a combustible form.

Overheating can also cause equipment to burn out by raising its temperature so high that it fails or ignites itself. The damage to equipment depends to some extent on how fast the overheating occurs. There are forms of circuit protection designed to deenergize a circuit if the current increases at a certain rate. Conditions exist, however, where the circuit can be overloaded at a rate faster than the protection device can react and result in equipment failure. Systems can also overheat when operating at normal energies, such as when a cooling system fails.

Overheated equipment can also be a burn hazard by heating surfaces to temperatures capable of causing skin burns if a person touches them. Operating temperatures should be determined in the design of a system, and appropriate measures should be taken to cool or isolate equipment as a protective measure.

Electrical explosions

A conductor may experience rapid electrical loading and, due to its size and/or composition, explode. When exposed to overcurrents, rapid overheating may occur in switches, fuses, or circuit breakers and cause them to melt and vaporize very quickly. This effect is sometimes used purposefully (see discussion of fuse below), but when it occurs unexpectedly, it can be very hazardous, especially if it occurs in an explosive or flammable atmosphere. We will discuss methods to control such hazards at the end of this unit.

Electrical explosions can also occur when contaminants (water, for example) are present in equipment such as oil-filled breakers or transformers. Electrical heating can cause the contaminants to vaporize and thus create high pressure in the sealed enclosure, that would cause it to rupture.

Capacitors may explode if exposed to excessive currents. Some capacitors, as well as batteries, are sensitive to polarity and may explode if the they are subjected to the wrong polarity of current and voltage. This can occur if the component is installed incorrectly or if the leads are reversed in a direct current system.

Methods to protect circuits from overheating

Guarding circuits from overload and its potential overheating and explosive effects is done by devices that sense specific overload conditions and deenergize the circuit by interrupting the flow of current. We will briefly describe the most common of these devices.

Fuses

Fuses are devices placed at strategic locations in electrical circuits and systems; they conduct rated currents without overheating but melt when exposed to currents in excess of designed loads. You are probably familiar with fuses if you own a stereo system or an automobile, for example. Occassionally a fuse will "blow;" this may seem like an inconvenience until you realize that that blown fuse may have protected your equipment from major damage due to overcurrents. If a system repeatedly blows fuses, it indicates that a more severe problem exists and repair is in order. People sometimes short circuit a fuse when this happens, which is, almost literally, "playing with fire."

Circuit breakers

Circuit breakers, located at specific points in an electrical system or circuit, also react to overloads by breaking the flow of current. Three types of circuit breakers are in general use: magnetic, thermal, or a combination of both. The magnetic type utilizes a wire coiled around a plunger, which is attached to a switch. When the current exceeds the designed level, the magnetic field moves the plunger and opens the switch, stopping current flow. Magnetic breakers will stop the flow of current any time the current reaches a preset limit.

Thermal breakers utilize material properties of bimetallic conductors. As the conductor heats in proportion to electrically produced heat, it bends. When the current exceeds the rated current of the breaker, the conductor bends to a point where it will activate a switch, cutting the flow of current. A thermal breaker reacts to prolonged overloads, but is generally not affected by minor short-lived current surges.

Some circuit breakers are designed with magnetic and thermal elements placed in series. The magnetic element protects the circuit from heavy overloads and short circuits, and the thermal element protects against lighter, but sustained, overloads.

Controlling electrical equipment explosion hazards

When electrical equipment or components are located in flammable or explosive environments, we must expect the unexpected. That is, even though the circuitry has been designed to minimize the possibility of overload or electrical discharges (sparks, arcs, coronas), we must assume that they will nevertheless occur. Through lessons from past accidents, designers have learned that special precautions must be taken for electrical equipment operating in environments where flammable gases or vapors are or may be expected. One such design precaution is the use of explosion-proof equipment, which was previously discussed. Refer to previous sections describing methods to control ignition hazards.

Static electricity

We're all familiar with static electricity: a shock when you touch a door knob—your hair standing on end after pulling a sweater over your head—the "static cling" of your clothing. In every day life, static electricity manifests itself more as an annoyance than as a hazard. Under some conditions, though, the electrical discharge may be enough to ignite a flammable atmosphere. Lightning, a more violent form of static discharge than we typically experience, is also a significant shock and fire ignition hazard. First we'll discuss the nature of static electricity and present some methods to control its associated hazards; a discussion of lightning and controlling its hazards will follow.

Any time two dissimilar materials are in contact, static charges are formed. Loosely held electrons may drift from one material to another to create a negative charge on one surface and a corresponding positive charge on the other. Depending on the conductivity of the materials, separating them may cause equal but opposite charges to remain. Before materials that are good conductors are fully separated, the charge separation will neutralize as the electrons flow freely between the surfaces. If the materials are poor conductors, however, the charge difference will remain as the surfaces are separated. Since the potential to develop a static charge is inversely related to the conductivity of the materials, the presence of water or humidity (high conductivity) will reduce the potential for static charge accumulation. Depending on the materials involved and environmental conditions, voltages between 1 volt and 1 kilovolt can result from simple separation (Hammer, 1989; Hirst, 1989).

Bringing a charged body near a second with no initial charge can induce a charge on the second. If the materials are conductors, the charge will move to the outside of the bodies. If the body with an induced charge (with an unlike charge equal and opposite to the charged body) is momentarily grounded, the like charge disappears but the unlike (equal and opposite) remains (Figure III-7). Separating the bodies then leaves the equal and opposite induced charge on the second body, until either a static discharge or grounding releases the potential difference between the body and ground (Hirst, 1989; Wright, 1985).

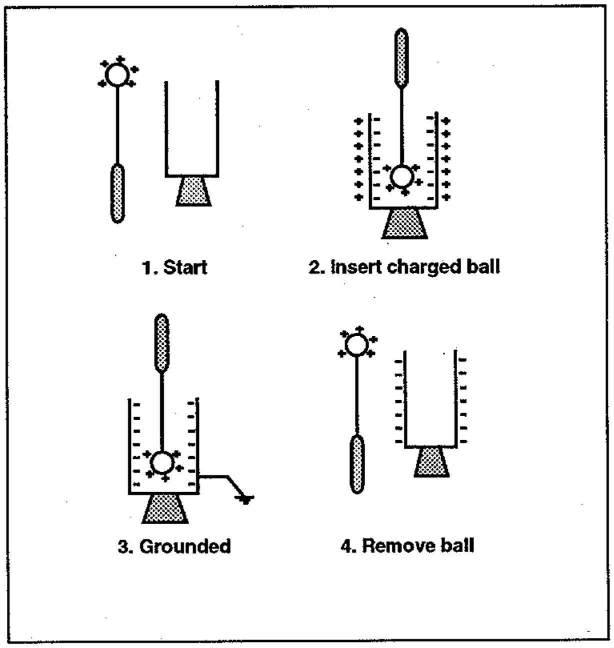


Figure III-7. Static charged by induction. The shaded areas represent insulation (adapted from Wright, 1985).

This type of static charge buildup is probably not surprising to you. What does come as a surprise to many, however, is that one material flowing through or over another can develop high static charges. Flow constitutes a continuous separation condition and can occur between a liquid and solid, two liquids, a gas and a solid, a gas and a liquid, or two solids. Flow over protrusions or rough surfaces increases the generation of charge. Table III-4 contains some examples for each of these situations. Figure III-8 illustrates a static charge accumulation caused by a fluid flow through a pipe and through a filter (Hirst, 1989).

Table III-4. Examples of Static Charge Generation Between Flowing Materials*

Media	Flow
Liquid/solid Flow	Liquid flowing through a pipe Liquid passing through a filter Splash filling a tank
Liquid/liquid	Drops of one liquid settling through another Stirring immiscible liquids
Gas/solid	Filling a container with powder Dust filter Discharge of carbon dioxide (or any other nonconducting gas)
Gas/liquid	Liquid spray (even water) Discharge of wet steam
Solid/solid	Reeling or unreeling of plastic or paper sheets Conveyor belt passing over a pulley/roller Movement of the human body

*Adapted from Hirst, 1989.

A low conducting liquid flowing through a pipe can generate a continuous leakage current (resulting from continuous static charge accumulation) of between 0.001 and 1 microampere. Powder being discharged from a grinding mill can produce currents of 0.1 microampere. Such low currents are generally not a problem. If static charge cannot leak away, however, and it thus accumulates a high voltage, a significant hazard exists (Hirst, 1989).

Once a static charge has accumulated on a body, it will either discharge as a capacitor would or slowly leak away. Relaxation time is a term used to describe the time, or time constant, it takes to leak away 63 percent of the original charge. This time varies from material to material depending on conductivity and with environmental conditions such as humidity.

For instance, if a container that is insulated from ground (i.e., no path to ground to leak the charge) is being filled with a liquid and gaining a charge at 1.0 kilovolt per second, 10 seconds of filling would result in a static charge of 10 kilovolts. The charge may slowly dissipate by leaking to ground, or it may discharge as a spark to ground (directly or via a person or other object). The high voltage makes it possible that a subsequent spark would be of sufficient length and energy to ignite a variety of flammable atmospheres. A person can develop a potential difference as high as 10 kilovolts between his body and ground simply by briskly scuffing one's shoes across a wool or nylon carpet. This is enough voltage to produce an arc in a 1/8-inch gap through air (Hammer, 1989).

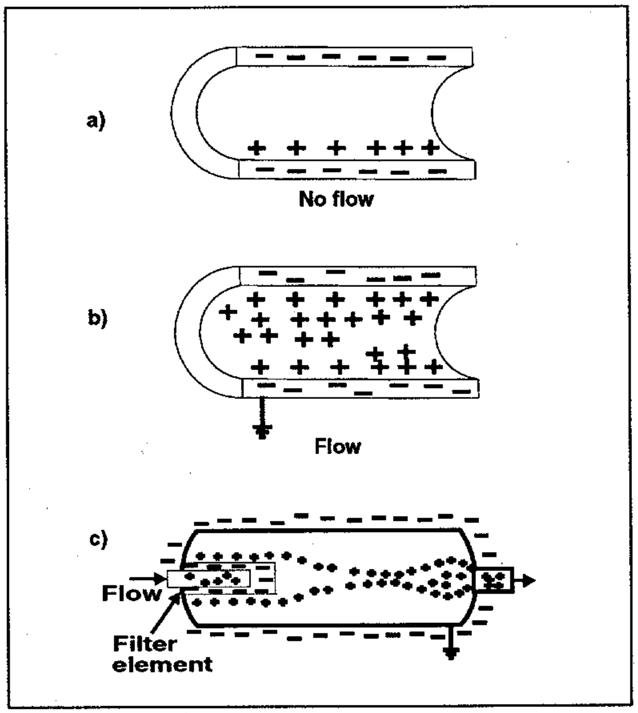


Figure III-8. (a) Equal and opposite charge separation between a low conduction fluid and a pipe without flow; (b) when fluid flows in the pipe, the charges begin to accumulate and move with the fluid ("streaming current"); (c) charge separation in a filter (adapted from Hammer, 1989).

The ability to store electric charge is known as capacitance. When a static charge discharges as a capacitor, static electricity is a hazard. If a charge leaks away over time, the energy released is not enough to constitute a fire or explosion hazard. A capacitive discharge, however, may release sufficient energy to ignite a variety of flammable mixtures. The energy in a capacitor, and thus a static charge insulated from ground or other conductor, is

$$E = \frac{CV^2}{2}$$

where E is energy in joules, C is capacitance in farads, and V is voltage (Howard, 1985).

When this energy is released, there is, indeed, a concern wherever flammable environments could be present, as the following case histories illustrate.

A fatality occured in a hospital operating room when a static discharge ignited ether vapor, which was being used as an anaesthetic.

A large underground gasoline storage area used a carbon dioxide total flooding system as a fire suppression system. During a system demonstration at the opening ceremonies, a static discharge apparently caused by the flowing carbon dioxide ignited gasoline vapors. The resulting explosion killed a number of people.

Similarly, a damaged tanker vessel that had carried a flammable liquid was being prepared for cutting. Because of concern that the sparks and heat created by the cutting tool could ignite vapors, it was decided to create an inert atmosphere inside the vessel by discharging a number of carbon dioxide extinguishers. A static discharge caused an explosion, and a number of fatalities resulted.

In a hairdressing salon, a static discharge created by brushing a client's hair ignited the vapor of a flammable hair spray being used on another customer; a fatality resulted.

In 1964, a discharge of static electricity while a plastic cover was being removed from the third stage of a NASA Delta rocket ignited the fuel; two people were killed and three others were critically injured (Hammer, 1989).

A man was cleaning a container with toluene. As he swirled the liquid around the container, a static discharge ignited the toluene vapor.

Figure III-9 shows a hypothetical (but very potentially real occurrence) life history of a bulk static electrical charge that could result in two separate fire incidents. A flammable liquid becomes charged by flowing through a tap; an equal and opposite charge is left behind, (a). The charged liquid induces equal and opposite charges on the walls of the bucket in which it is collected, (b). The bucket is grounded by placing it on the ground and loses its outer charge; although both the bucket and the liquid are charged, they are now neutral as a whole, (c). The liquid and its charge are poured into a basin, and the process of the inducing charge is repeated; the exterior charge in the bucket is left behind, (d). A man in rubber soled shoes shares the charge with the bucket and a spark passes from his hand to a grounded fuel tap to cause a fire, (e). Another man without rubber-soled shoes (and thus grounded) puts his hand near the surface of the charged liquid and a spark passes to cause another fire, (f). This scenario has, in fact, caused many such incidents, and grounding the basin makes very little difference.

These examples illustrate that static electricity fire hazards exist across many industries and tasks. They share three things in common, however: the generation of static charges; the storage of static charges and associated energy; and the release of that energy to ignite a fuel. Using such information from past events is very helpful in taking measures to avoid future disasters.

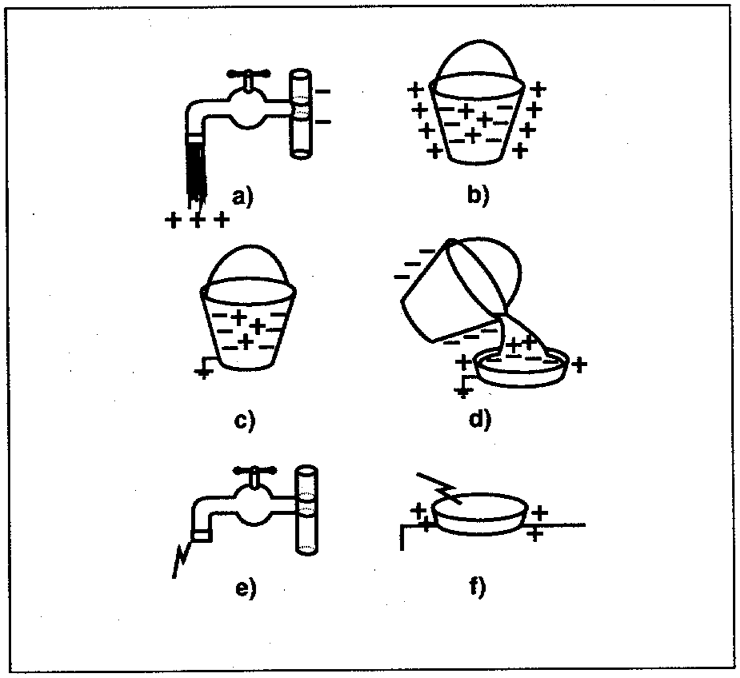


Figure III-9. A hypothetical life history of a bulk static electrical charge (adapted from Cooper, 1986).

Controlling static electricity fire hazards

When determining appropriate controls for a hazard, first determine what constitutes the hazard. Drawing on the above discussion, the fire hazard associated with static charge involves two basic elements: (1) static electricity with sufficient potential energy to ignite (2) a flammable atmosphere. The most effective hazard reduction strategy would involve controlling both of these elements.

Controlling the flammable atmosphere may include choosing alternative materials, or processes, or both that do not use flammable materials (or the use of less hazardous materials); ventilation; or other means of minimizing flammable fuel-air mixtures, etc., as discussed in other sections of this course.

The most effective method of controlling the static charge would be to hinder the generation, accumulation, and discharge of stored energy. It would be wrong, however, to believe that generation of static electricity could be completely eliminated without eliminating all movement and the presence of other charged bodies. We can, however, reduce the generation and increase the rate of leakage to a level that does not constitute a hazard in a given environment (Wright, 1985).

Choosing materials that are good conductors or coating nonconducting bodies with conducting materials will minimize potential static charge accumulations. Since the presence of water (a good conductor) reduces static accumulations, humidifying the atmosphere might also be a reasonable and effective method to reduce charge accumulation.

Grounding and bonding are also effective ways to eliminate potential differences (voltage) between two conducting bodies or a body and a ground. Recall that it is the voltage and capacitance that determine the energy released in a discharge of static charge. By bonding two conducting bodies together and grounding the system, the voltage between neighboring bodies can be nearly eliminated. Bonding decreases the potential difference between conducting bodies, and grounding the system decreases the potential between the conducting bodies and the ground.

For some applications, electrostatic neutralizers may be appropriate. There are three major types of charge neutralizers: radioactive, high-voltage, and, induction. The radioactive source emits alpha particles with two positive unit charges that act to neutralize the net negative charge on a material. Because radioactivity may be harmful to human tissue, this type of neutralizer should be used only when humans will be protected from harm (Hammer, 1989).

High-voltage neutralizers produce a high potential in the air near the surface of the material of concern. This type of device ionizes the air by producing both positively and negatively charged particles that act to neutralize any charges that may develop on the nearby material. These high-voltage devices may, however, create their own fire hazard where flammable atmospheres are a concern and may present a shock hazard to personnel as well (Hammer, 1989).

Induction neutralizers produce opposite polarity to that causing static charge generation and accumulation and, thus, neutralize any potential difference (Hammer, 1989).

Some industries are particularly prone to hazards related to electrostatic discharge and have developed specific safeguards and procedures over the years. Hydrocarbon industries and industries handling or producing dusts and powders are worth special mention, and the general concepts should be extended to other industries as well.

Control of static hazards in hydrocarbon industries

Because of the flammable characteristics of many hydrocarbon products (e.g., oils, gasoline, etc.), it is not surprising that this industry has experienced many ignitions blamed on static electricity. Liquid transfer often presents the greatest hazard. Fluid movement may cause flammable vapors, and the flow through pipes, filters, spraying the product through air, and impurities present in the product can all generate static charges. In particular, the following operations have been identified as static charge hazards when handling dry refined oils such as gasoline, kerosene, and jet fuels:

— flow through a pipe,
— agitation by propeller mixing or a centrifugal pump,
— overhead splash filling of tanks,
— settling of water or other contaminants through an oil,
— filtering, and
— rapid evaporation.

Experiments have shown that oils generally need a resistivity greater than 10^{10} Ω-centimeters to generate appreciable static charge accumulations and that charge generation increases with the velocity of flow. Although heavy oils are good generators of static charge, alone they are generally not a hazard because of their low volatility. They have contributed to many fires and explosions, however, when they are loaded into a vessel that previously contained a lighter fuel such as gasoline. If residual vapors from the previous fuel reach a flammable mixture, a static discharge from the loading process will result in explosion or fire. Protection against this hazard usually involves making the vessel atmosphere inert or purging the atmosphere during the loading process (Howard, 1985).

Several general approaches to controlling static hazards during loading and unloading tasks are worth mentioning here, but you should, of course, consult specific texts, standards, and experts should your responsibilities ever include such activities.

As always, controlling the potential for a flammable atmosphere is the first step; however, the nature of hydrocarbon products makes this difficult in some cases (inerting the atmosphere or purging are possible methods). Controlling the generation, accumulation, and discharge of static electricity is done in several ways.

One important control of static charge generation in all applications is minimizing or eliminating water from settling through an oil. Keeping water from a tank and keeping any water that does enter from being agitated are necessary procedures. Limiting the velocity of flow in pipes, reducing splashing, and minimizing contaminants are all common ways to reduce generation of static charges.

Bonding and grounding can control accumulation of charges. Pipes carrying the liquids should be of conducting materials, and all flanges and connections should be bonded if not of conducting material. For example, loading fuel into a tank truck would involve making an effective conducting bond between the loading hose and the tank and ground. This does not, however, eliminate charge accumulations on the surface of the fluid in the tank nor is there an effective method to do this. That is, although the potential difference between the hose and ground are minimized, a potential difference between the fluid surface and the inner walls of the tank is still present, and sparking over the oil surface can occur. Sometimes the only way to control the sparking-over hazard is to minimize charge generation; this, however, depends on the type of tank and process. With stationary tanks, a floating roof can be used to eliminate sparking over the fluid surface. The potential for static discharge can be reduced by minimizing protruding surfaces inside the tank (see Figure III-10).

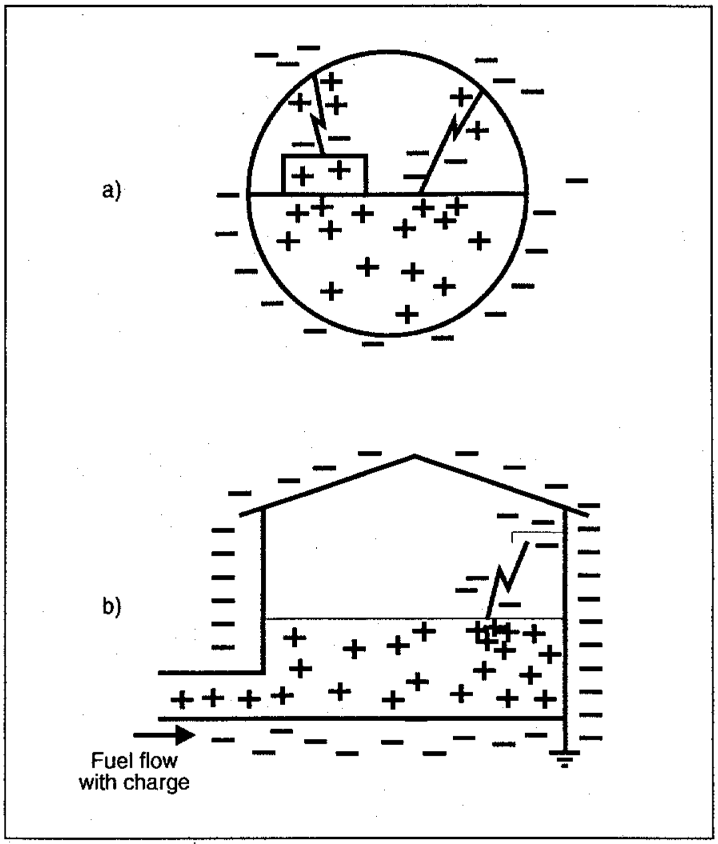


Figure III-10. Examples of tanks with interior surface projections: (a) spark discharges can occur between the fluid surface and tank walls or between an object floating on the surface and the tank wall; (b) charged fluid entering a tank; discharge can occur between fluid surface and projections inside the tank (adapted from Hammer, 1989).

Control of static hazards in industries handling or producing dusts or powders

Electrostatic discharge was traced as the ignition source in 9 percent of 357 dust explosions studied between 1965 and 1980. Just as flowing fluids or solids generate static charges, so do dusts or powders flowing through ducts or shifting in piles and in storage tanks.

The first step in minimizing the explosive hazard is to eliminate or reduce dust air mixtures to a level that is below the lower minimum ignition energy for the specific mixture. When this is not possible, control the hazard by controlling the generation, accumulation, and discharge of static electricity (this logic should be quite familiar by now).

As with fluid flow through pipes, ducts handling moving dust should be constructed of conducting materials and all equipment should be effectively bonded and grounded. Limiting flow velocities and feed rates into vessels such as silos will also limit charge generation.

Where controls cannot satisfactorily reduce static accumulations and the hazardous dust/air mixtures that are expected, making the atmosphere inert is an effective means of reducing ignition hazards (Bartknecht, 1989).

A relatively new method of controlling dust explosions involves infrared detectors to locate "hot spots" in product flowing through ducts. When particles reach potentially hazardous temperatures, the device will trigger a suppression system and stop the process before an explosion can occur (Field, 1989).

Humans and static electricity

Humans can generate static charge by body movements, especially when wearing nonconducting clothing containing synthetic fibers. Movement of the body over other nonconducting surfaces, such as walking on synthetic carpet in low humidity conditions, also generates static charges. When accumulated charges cannot leak away because of nonconducting footwear or an insulated floor, the resulting charge buildup can produce sufficient energy to ignite certain flammable fuel/air mixtures.

A person can also accept a charge from another charged body. The charge may be transferred by current during contact or may be in the form of a spark discharge of, potentially, enough energy to ignite flammable atmospheres. An induced charge may develop as electrons move over the surface of the body if a person is merely near a charged body. Again, once a body is charged, the charge can be discharged either to another conducting body or to ground with sufficient energy to ignite certain flammable atmospheres.

Only by eliminating people from an area can the static charge on their bodies be avoided. Charge accumulation can, however, be minimized by providing conductive floors (that are effectively grounded) and conductive paths to the floor from the body. For example, looping a conductive material in contact with clothing and the body around the bottom of the foot would provide a path to a conductive floor. This is especially critical in flammable atmospheres were people are expected to be present (Hirst, 1989).

Hospitals are an especially hazardous environment requiring extensive measures to minimize static hazards. Hospitals may have oxygen-rich atmospheres (due to oxygen being administered to patients) in combination with flammable gases used as anesthetics, and patients may have catheters or other invasive devices that bypass the relatively high resistance of the skin or that may even be in direct contact with the heart. During surgery, the body is directly open to the environment and contact with the attending medical personnel. A static discharge could result in explosion or may produce enough current to cause heart fibrillation (irregular and ineffective heart beat). For these reasons, very innovative methods are used to bond and ground equipment and personnel in the hospital environment.

To summarize, static electricity is a significant hazard in any industry or task that is likely to have flammable fuel/air mixtures. Any time there is movement between materials (solids, liquids, gases, or dusts), static charges will be generated. Static charges can be transferred to other materials by sparking or current during contact, and a charge can be induced on nearby materials from another charged material. Accumulation of static charge depends on the conductivity of the materials involved: conductors will leak away charges if they have a path to ground or have enough time to safely relax a charge through poor conducting materials. Poor conductors will readily accumulate and hold static charges. Humidity will reduce the accumulation of charge.

Controlling the potential for flammable atmospheres, charge generation, and accumulation are the most effective methods to minimize static discharge as an ignition source.

Lightning

Lightning is a massive discharge of static charge involving very high potentials and currents (Hammer, 1989). In electrical storms, clouds gradually accumulate static charges until the voltage is high enough to cause a discharge through a lightning stroke. As a cloud accumulates charge, an equal and opposite charge is induced on the ground (or structures) beneath it, as illustrated in figure III-11. Because of this equal and opposite charge, lightning will sometimes travel upwards rather than downwards. The induced charge on structures may also, under certain atmospheric conditions, result in corona discharge (a glow, sometimes accompanied by a hissing sound, "St. Elmo's Fire") capable of igniting flammable atmospheres.

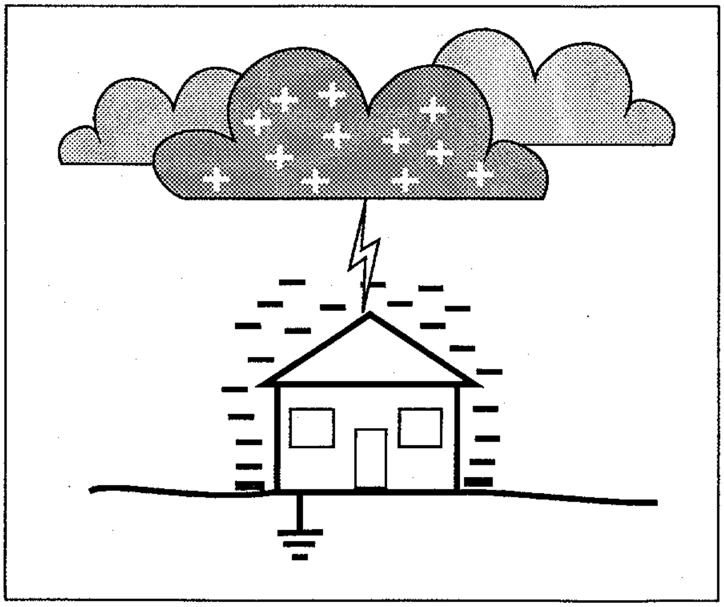


Figure III-11. When a cloud becomes charged due to atmospheric flow, an equal and opposite charge develops on the ground. The charge on the ground may accumulate the most on projections (such as the house pictured).

Lightning will follow the path of least resistance, often striking a conducting structure that protrudes above the ground (Hammer, 1989). Lightning may also travel from one cloud to another. When this happens, the sudden release of the induced charge on the ground may cause hazardous sparking among structures such as tanks if they are not properly bonded.

The voltage necessary to cause a lightning strike to ground exceeds 100 megavolts, with resulting current flows between 3 and 200 kiloamperes. Such high current flows can cause appreciable current to flow in conductors that are parallel to a lightning strike. For low resistance conductors, the temperature increase may be only about 1 degree Celsius because of the short duration of a strike, perhaps only 0.1 millisecond. If lightning strikes objects of high resistance, the temperature increase can be quite substantial. For example, when lightning strikes a tree (trees are poor conductors), the water in the trunk can flash into steam, which can create pressures that blow the tree apart, possibly igniting fragments. In fact, many forest fires are started by lightning striking trees.

Controlling lightning hazards

The need for and the lengths taken in the design of lightning protection systems is a function of the frequency that lightning occurs in a given location and the consequences of strike for a given structure, system, or process. If lightning is rare in a location, and the hazards associated with a strike are low as well, the lengths and expenses taken to provide protection probably do not need to be overly elaborate. If, however, lightning strikes are of low probability yet the consequences of a strike could be catastrophic, it is probably best to design for the worst case. Company officials, insurance carriers, and local regulatory authorities should work together to determine the type and extent of protections necessary for a given facility.

Probably the most familiar lightning protection is the lightning rod. A conducting rod placed atop a structure that provides an effective conducting path to ground "entices" any discharge that may occur in that vicinity to strike the rod and shunts the current to ground. The structure is, we hope, protected (although, power surges in parallel conductors may still create shock, fire, and equipment hazards).

For high-hazard industries and structures, a variation of the lightning rod concept may be used. For example, protecting an explosives manufacturing facility or storage area may, in part, be done by suspending a series of horizontal conductors over the structure, suporting them with effectively grounded conducting masts.

Since lightning strikes can cause power surges even when lightning rod concepts are used, another measure of protection is surge arrestors located at the service entrance to buildings and on individual pieces of equipment. These devices act to minimize voltage spikes and, hence, protect circuits from overloading conditions and associated shock and fire hazards. Surge protectors are also valuable for protecting sensitive electronic equipment, such as computers. Be aware that the protective capability of these devices may be limited.

Again, certain industries and situations present greater hazards than others. A storage tank holding flammable liquids presents one type of situation that has experienced many lightning-related fires in the past. Investigate each specific situation, and when necessary, implement minimum protective schemes. These frequently involve effectively bonding and grounding all conducting parts in and around a tank.

Specific precautions beyond the general scope of this material must be taken to protect high-voltage power lines and transformers from the hazards of lightning. Power lines are a relatively common target for lightning, and the associated power surges can cause severe damage to equipment (transformers have been known to explode under such conditions). An elaborate combination of grounding strategies and surge protection is required to reduce these hazards.

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SAMPLE QUIZ QUESTIONS

1. Briefly describe the mechanics of fire.
2. (a) What is a "Class C" fire extinguisher?
   (b) What type of fire extinguisher should be used to extinguish an electrical equipment fire? Why?
3. (a) Discuss the sources of oxygen in a fire.
   (b) Is there a way to control the source of oxygen as a method to minimize a fire hazard? Explain.
4. Two liquids, A and B, have the same boiling point (the temperature at which a liquid will begin to boil). When both are spilled onto a surface of that temperature, however, only liquid A will ignite. Why might this occur?
5 What distinguishes a fire from an explosion? Explain.
6. What is a "short-circuit"? Why is a short-circuit an undesirable event?
7. What is an "open circuit?" Why is an open circuit an undesirable event?
8. What is the difference between a "spark" and an "arc"?
9. The "corona effect" has been called "St. Elmo's Fire." Describe a corona, and postulate why it may have acquired the nick-name of "St. Elmo's Fire."
10. What does "NEC" stand for?
11. What NEC Hazardous Class, Division, and Group would you assign to the following area: 50 pound bags of flour are stored in a room. The flour dust is normally not in suspension in the air, except when a bag is accidently damaged. Ignitable dust concentrations are controlled by a reliable ventilation system.
12. What is the principle behind "intrinsically safe designs"?
13. What is the principle behind "explosion-proof equipment"?
14. What is the principle behind "pressurization"?
15. Describe three situations that can lead to an overloaded circuit.
16. How could an overloaded circuit contribute to a fire hazard?
17. In addition to the fire hazards that an overloaded circuit presents, what other hazards to people might an overloaded circuit present? Explain.
18. Describe a device that takes advantage of the fact that specific materials can be designed to rapidly heat and melt. What are such devices used for?
19. If you were designing a capacitor, why might you design it so that it can be installed in only one orientation with respect to polarity?
20. What does the conductivity of a material have to do with its ability to accumulate a static charge?
21. How and why does the presence of water affect a material's ability to accumulate a static charge?
22. Describe how one charged body can induce a charge on another body.
23. Once a body has accumulated a static change, how can the charge be dissipated?
24. Assume your skin has a capacitance of about 200 pico-farads (200 × 10-12 farads). Now assume that you have just walked across the office carpeting and entered an area that has a dangerous fuel/air mixture of ethylene due to an accidental spill. As you walked across the carpet, you developed a static charge resulting in a 1 kilovolt potential difference between your body and a grounded appliance. As you reach for the appliance, the charge dissipates as a capacitor. Is the energy released sufficient to ignite the ethylene/air mixture?
25. How and why could water settling through a tank of flammable liquid create a fire hazard?
26. What can be done to minimize the generation and accumulation of static charges on the human body?
27. Why are special precautions taken to minimize the generation and accumulation of static charges in a hospital environment?
28. People who have survived lightning strikes often report a strong feeling of static charge immediately preceding the strike. What would you expect this to be caused by?
29. Describe the different ways that lightning can contribute to a fire hazard.

Unit IV

SAFETY STANDARDS, ORGANIZATIONS PROMULGATING STANDARDS, AND PROFESSIONAL LIABILITY

PURPOSE:

To introduce the student to pertinent electrical safety standards, the organizations which produce them, and professional liability for not applying the standards in one's work practices.

OBJECTIVE:

To acquaint the student with:
1. The different types of safety standards
2. The organizations which develop electrical safety standards
3. The concept of professional liability for not following these standards

SPECIAL TERMS:

1. Standard
2. Code
3. Recommended practice
4. Voluntary standard
5. Mandatory standard
6. Consensus standard
7. Horizontal standard
8. Vertical standard
9. Specification standard
10. Performance standard
11. Liability
12. Negligence
13. Strict liability
14. Warranty

HAMMURABI'S CODE (approximately 1750 B.C.)

> "If a builder constructs a house for a man and does not make it firm and the house collapses and causes the death of its owner, the builder shall be put to death."

Hammurabi's Code contains what may be the first written statements regarding responsibilities of a party in accident prevention. Since 1750 B.C., the penalties have softened, but the volume of standards, codes, and other written safety documents has proliferated in step with technological advances over the 3700 years (Hammer, 1989).

Debate over the language contained in standards, and whether the standards should be enforced by a government or be voluntary, probably began when Hammurabi's law was pressed in cuneiform wedges and baked; certainly the debate continues today. There is no arguing, however, the valuable role of standards in making products, homes, and workplaces safer than they would without such guidance.

THE ROLE OF SAFETY STANDARDS

Safety, in part, depends on the development and use of safety documents summarizing previous knowledge designed to protect individuals in a society. As engineers, we rarely design every aspect of a product or process from scratch. By using standards, we are free to spend more time and energy on the new and unique aspects of a design.

Ideally, the standards we refer to and depend on would incorporate all the lessons learned by those that passed before us, including the successes and the failures. Realistically, though, safety standards generally provide only minimum guidelines. The safety of our designs should never be limited by merely satisfying some minimally acceptable requirements of applicable standards. Wherever possible, we must exceed those safety requirements. It is our moral obligation (and often legal obligation, as well) to provide products and systems that can be used safely by the general public (Bass, 1986).

In this course unit, we will discuss the nature of standards and some of the standard-producing organizations you should be familiar with. We will conclude with some thoughts on what can happen if we are derelict in exercising our professional responsibilities as engineers..

A few definitions

A *standard* is a set of rules, requirements, or principles.

A *code* is a collection of laws, standards, or criteria relating to a particular subject.

A *recommended practice* is a series of recommended methods, rules, or designs.

A *test method* defines such things as specimen selection, testing procedures, sampling, and analysis methods to determine the properties, composition, or performance of materials or products.

A *definition* explains standardized meaning of terms as applied to materials, products, systems, and methods.

Except where otherwise indicated, we will use "standard" as a generic descriptor for standards, codes, criteria, recommended practice, or any other safety-related document.

Voluntary versus mandatory

Standards may be applied voluntarily, or they may be mandated by some federal, state, or local regulatory agency. Voluntary standards may be those developed and followed by a single company (i.e., "in-house"), or they may be consensus standards decided on by a group of representatives for a given industry. For example, the National Electric Code (NEC) is a consensus standard developed and agreed upon by interested member organizations and citizens. The NEC is not mandatory; it is not a law. It is, however, often adapted and mandated by regulatory agencies.

Consensus

Consensus implies more than simple majority approval, but it does not necessarily mean unanimity. Unanimous agreement usually cannot be achieved without compromising the effectiveness of the standard (Bass, 1986). Some contend that the effectiveness of consensus standards is still compromised by attempting to reach near unanimous agreement on language. They contend further, that members of the sponsoring organizations are not bound to adhere to the standards and, therefore, might not do so. They believe that, at a minimum, government's role should be to ensure that all segments of an industry adhere to a given standard.

Mandatory standards, codes, practices, etc., are those that have passed into law, such as the laws under the jurisdiction of the Occupational Safety and Health Administration (OSHA). OSHA standards are mandatory; they are law. The OSHA standards are, for the most part, standards that were once voluntary consensus standards that have since been adopted and enforced under the OSHAct. We will discuss the OSHA in detail later in this unit.

Government involvement in safety standard activities is not without critics. Among other arguments, the critics believe that by mandating (by law, with penalties for noncompliance) standards, which most agree are <u>minimum</u> safety requirements, regulatory agencies actually stifle progress toward more effective safety policies.

Horizontal versus vertical

Standards can be classified as horizontal or vertical.

A **horizontal standard** is one that is applicable across all industries—one that is generalized by a particular hazard type, regardless of the industry.

A **vertical standard** is one that applies to one type of industry only.

Because of the huge variety of industries under the jurisdiction of OSHA, most of their regulations are horizontal, although vertical standards are included where appropriate. For instance, OSHA standard 1910.106 is basically a horizontal standard pertaining to flammable and combustible liquids. Section 1910.106(i), however, within the same standard, contains a vertical portion entitled "Refineries, chemical plants, and distilleries."

Specification versus performance

A standard may also be classified as being a specification or a performance standard. A **specification standard** is one that describes exact details of what and how something must be done. For example, Article 200 of the NEC, "Use and Identification of Grounded Conductors," provides specific requirements for (1) identification of terminals; (2) grounded conductors in premises wiring systems; (3) identification of grounded conductors. Example specification language from this section includes:

> "200-6. Means of Identifying Grounded Conductors.
>
> "(a) Sizes No. 6 or Smaller. An insulated grounded conductor of No. 6 or smaller shall be identified by a continuous white or natural gray outer finish along its entire length." [Exceptions listed.]

Although specification standards may be difficult to develop, they are easy to implement and enforce. Specification standards emphasize the methods necessary to satisfy the given code.

Performance standards emphasize the results that should be realized to satisfy the code without specifically stating the methods to do so. Performance standards allow the user more leeway and creativity in devising methods to eliminate or reduce hazards. An example of a performance standard taken from the NEC states the following.

> "Article 230-41. Insulation of Service-Entrance Conductors.
>
> "Service-entrance conductors shall normally withstand exposure to atmospheric and other conditions of use without detrimental leakage of current. Service-entrance conductors entering or on the exterior of buildings or other structures shall be insulated." [Exceptions listed.]

This passage states only that the specified conductors *shall normally withstand exposure to ... shall be insulated [on exterior buildings or structures].* It does not specify the materials, design, or methods to accomplish the goal; it is thus a performance standard.

Performance standards are relatively easy to develop but more difficult to enforce.

Classifying most standards as solely performance or specification is difficult, but a rough distinction can usually be made as to one or the other. Industries tend to prefer performance standards because they can then customize for their particular needs. Performance standards also allow innovative hazard control techniques to be implemented by incorporating new ideas and new technology.

Some performance standards, intentionally designed to stimulate new technology, set performance goals that are currently not feasible. For example, setting a pollution emission level for an industry below the currently feasible levels will, in theory, stimulate research and product development which will meet the new performance levels.

ORGANIZATIONS PROMULGATING STANDARDS

Throughout your career you will probably sift through thousands of pages of standards from a variety of organizations and agencies. Some organizations that you are or should become familiar with, include the Occupational Safety and Health Administration (OSHA), the American National Standards Institute (ANSI), the National Fire Protection Association (NFPA), Underwriter's Laboratories (UL), the Institute of Electrical and Electronics Engineers (IEEE), and the professional societies in your field. A brief description of each of these organizations and their purpose follows.

The National Fire Protection Association (NFPA)

The NFPA is the clearinghouse for information regarding fire protection, fire prevention, and fire fighting. It is a nonprofit technical and educational organization with a membership of approximately 32,000 companies and individuals.

The NFPA is the administrative sponsor of the National Electric Code (NEC). The 1993 NEC, formally known as ANSI/NFPA 70-93SB, should become part of your personal library, and you should update it with each new edition. A brief description and history of this important document follows (National Safety Council, 1988).

The National Electric Code (NEC)

The NEC is the most widely adopted code in the world. It is, in fact, the basis for all electrical codes used in the United States and is also used extensively by other countries, especially where American-made equipment is installed.

The basis for the NEC originated from a proposal drafted at an 1881 meeting of the National Association of Fire Engineers. It covered such things as insulated conduit, the use of single disconnect units, and the identification of the white wire. The first nationally recommended electric code was published in 1895 by the American Insurance Association, known then as the National Board of Fire Underwriters. By combining the efforts of architectural, electrical, insurance, and allied interests, the National Electric Code was drafted in 1887.

In 1911, the National Fire Protection Association (NFPA) assumed sponsorship of the NEC. Since 1920, the American National Standards Institute (ANSI) (formerly known as the United States of America Standards Institute and the American Standards Association) has officially endorsed the NEC, and the NFPA has maintained its capacity as administrative sponsor.

In 1923, the NEC was rearranged and rewritten. In 1937 and 1959, it was editorially revised. Since then, new additions have been adopted, the most recent (at the time of this writing) being the 1993 edition, which superseded all previous editions. As is typical for consensus standards, each revision is the culmination of proposed amendments by members and interested citizens—amendments that must pass through committees until final language is agreed on (thus, a "consensus" is reached).

The 1993 NEC, "...is purely advisory as far as the NFPA and ANSI are concerned but is offered for use in law and for regulatory purposes in the interest of life and property protection" (National Fire Protection Association, 1993).

American National Standards Institute (ANSI)

The ANSI is an organization that issues standards (more than 8,000) on a wide variety of topics, often in conjunction with other professional organizations. For instance, the 1990 edition of the NEC, titled ANSI/NFPA 70-1990, indicates joint sponsorship and approval between the ANSI and the NFPA. All standards issued by the ANSI are consensus and thus, voluntary as evidenced by the following passage contained in their standards:

> "An American National Standard implies a consensus of those substantially concerned with its scope and provisions. A National Standard is intended as a guide to aid the manufacturer, the consumer, and the general public. The existence of an American National Standard does not in any respect preclude anyone, whether he has approved the standard or not, from manufacturing, marketing, purchasing, or using products, processes, or procedures not conforming to the standard. American National Standards are subject to periodic review and users are cautioned to obtain the latest edition."

The ANSI coordinates and administers the federated voluntary standardization system in the United States—a system that provides all segments of the economy with national consensus standards dealing with operations and protection of the consumer and industrial workers. It also represents the United States in international standardization efforts through the International Organization for Standardization (ISO), the International Electrotechnical Commission (IEC), and the Pacific Area Standards Congress (PASC).

The ANSI coordinates the standard development efforts of about 1,200 national trade, labor, professional, and consumer organizations; government agencies; and individual companies. It will approve a standard as an American National Standard if its Board of Standards Review determines that the document reflects a national consensus (National Safety Council, 1988).

In addition to joint sponsorship of the NEC with the NFPA, the ANSI also sponsors such standards as:

> Classification of Gases, Vapors and Dusts for Electrical Equipment in Hazardous (Classified) Locations, ANSI/NFPA 497M.
>
> Electrical Equipment for Use in Class I, Division 2 Hazardous (Classified) Locations, ANSI/ISA-S12.12.
>
> National Electrical Safety Code (NESC), ANSI C2.
>
> Safe Current Limits for Electromedical Apparatus, ANSI/AAMI ES1.
>
> Preparation of Test Procedures for the Thermal Evaluation for Insulation Systems for Electrical Equipment, ANSI/IEEE 99.
>
> Static Electricity, ANSI/NFPA 77.

These examples are but a few of the hundreds of standards listed in the Catalog of American National Standards that cover procedures, practices, designs, etc., that would be of interest to engineers.

American Society for Testing and Materials (ASTM)

ASTM is the world's largest source (currently over 8,000 standards) of voluntary consensus standards for materials, testing, products, systems, and services. The roughly 30,000 members draw on a broad spectrum of interests and include engineers, scientists, researchers, educators, testing experts, companies, associations, institutes, government agencies, consumers, and even libraries.

ASTM standards cover many topics of interest to electrical engineers, including, for example, material specifications and testing procedures regarding electronic equipment and protective equipment for electrical workers (National Safety Council, 1988).

Underwriter's Laboratories

Underwriter's Laboratories (UL), a not-for-profit organization, maintains laboratories where the compliance of a product, device, system, or material with specific safety standards is tested. It is not an enforcement agency, but it does issue labels certifying that UL criteria have been met.

UL publishes annual directories listing the manufacturers whose products have met the appropriate safety standard criteria and whose products are covered under the UL's Follow-Up Services program. UL inspectors make at least four unannounced follow-up site visits to companies making UL-Listed products to evaluate the effectiveness of a manufacturer's quality control for continued compliance with appropriate safety standards.

It is important to realize that UL-listed products are only tested under specific conditions set forth in particular standards. Satisfactory performance under the prescribed conditions may have no bearing on performance or other factors outside the scope of the UL investigation. That is, any use of the product outside the conditions prescribed by the criteria set forth in the particular standard may present a hazard (National Safety Council, 1988).

The Institute of Electrical and Electronics Engineers (IEEE)

The IEEE is the world's largest technical professional society. Founded in 1884 by a handful of practitioners of the new electrical engineering discipline, today's Institute is composed of over 52,000 students and 320,000 members who conduct and participate in its activities in more than 130 countries.

In addition to its standard activities, the IEEE keeps its members abreast with their field through numerous conferences, journal publications, and educational services. The IEEE has 35 specialized technical Societies with interests that span the many disciplines that encompass electrical, electronics, computer engineering, and computer science. IEEE is not just for electrical engineers—its publications and services span a wide variety of topics of interest and importance to engineers in general.

State and Federal Government Regulations

During the first half of the 20th century, the federal government's involvement in safety legislation was largely limited to setting safety and health standards for its contractors. The Walsh-Healy Public Contract Act of 1936 provided that contracts in excess of $10,000 entered into by an agency of the United States prohibit the use of materials "manufactured in working conditions which are unsanitary or dangerous to the health and safety of the employees" (Bloswick, 1992).

Federal legislation during the 1960's was aimed primarily at specific industries. The Construction Safety Act of 1969 required that all federal or federally financed or assisted projects in excess of $2,000 comply with established safety and health standards enforced by the U.S. Secretary of Labor. The Federal Metal and Nonmetallic Mine Safety Act of 1966 and the Federal Coal Mine Health and Safety Act of 1969 also directed attention to occupational safety and health. The Federal Mine Safety and Health Act, promulgated in 1977, established a single mine safety and health law for all mining operations enforced by the Mine Safety and Health Administration (MSHA) within the Department of Labor.

Occupational Safety and Health Act (OSHAct)

On October 29, 1970, Richard Nixon signed Public Law 91-596. This law, the Williams-Steiger Occupational Safety and Health Act of 1970 (OSHAct), became effective on April 28, 1971. Its stated purpose is:

> "To assure safe and healthful working conditions for working men and women: by authorizing enforcement of the standards developed under the Act; by assisting and encouraging the States in their efforts to assure safe and healthful working conditions; by providing for research, information, education, and training in the field of occupational safety and health; and for other purposes."

Occupational Safety and Health Administration (OSHA)

The Occupational Safety and Health Administration (OSHA) was established to enforce the OSHAct. OSHA is located within the Department of Labor. Under the provisions of the OSHAct, the National Institute for Occupational Safety and Health (NIOSH) was established within the Department of Health, Education and Welfare (currently the Department of Health and Human Services). Whereas OSHA is primarily an enforcement agency, the primary functions of NIOSH are to perform safety and health research, develop and establish recommended standards, and facilitate the education of personnel qualified to implement the provisions of the OSHAct.

The regulations relating to the OSHAct are included in Parts 1900-1927 of Title 29 of the Code of Federal Regulations (CFR) and the operation of the Occupational Safety and Health Review Commission (OSHRC) are included in Parts 2200-2499. Unless specifically excluded, the OSHAct applies to every employer who has one or more employees and who is engaged in a business affecting interstate commerce. Major examples of specific exclusions of the OSHAct are state and local government employees, self-employed persons, farms at which only immediate members of the farm employer's family are employed, and workplaces already protected by other federal agencies under other federal statutes (operators and miners covered by the Federal Mine Safety Act of 1977, for example). Employers with fewer than 10 full or part-time employees are excluded from the record keeping requirements of the OSHAct.

OSHA Standards

There are three separate sets of OSHA standards: General Industry (29 CFR 1910), Construction (29 CFR 1926), and Maritime Employment (29 CFR 1915-1919). OSHA has summarizedof major portions of the OSHA standards, and these are available in digest form. OSHA publication 2201 is a summary of the OSHA General Industry standards (OSHA, 1991a) and OSHA publication 2202 is a summary of the OSHA Construction standards (OSHA, 1991b).

To consider hazards not specifically included in OSHA standards, OSHA has turned to the provisions of Section 5(a) of the OSHAct or the "General Duty Clause" that states:

> "Each employer—
>
> (1) shall furnish to each of his employees employment and a place of employment which are free from recognized hazards that are causing or are likely to cause death or serious physical harm to his employees;
>
> (2) shall comply with occupational safety and health standards promulgated under this Act."

In summary, four governmental units have the primary responsibility to carry out the act:

1. The Occupational Safety and Health Administration (OSHA) is concerned with national, regional, and administrative programs for developing and ensuring compliance with safety and health standards. It also trains OSHA personnel. U.S. Department of Labor, Department of Labor Building, 200 Constitution Avenue, NW., Washington, D.C. 20210; (202) 523-8148.

2. The Occupational Safety and Health Review Commission OSHRC), reviews citations and proposed penalties in enforcement actions contested by employers or employees. 1825 K Street, NW., Washington D.C., 20006; (202) 634-7970.

3. The National Institute for Occupational Safety and Health (NIOSH) provides research, training, and education. U.S. Department of Health and Human Services, 1600 Clifton Road NE., Atlanta GA,30333; (404) 329-3061.

4. The Bureau of Labor Statistics (BLS) conducts statistical surveys and establishes methods for acquiring injury and illness data. U.S. Department of Labor, 200 Constitution Avenue, NW., Washington D.C. 20210; (202) 523-1092.

PROFESSIONAL LIABILITY

> "Engineers shall hold paramount the safety, health and welfare of the public in the performance of their professional duties."

This statement is the first principle listed in "The Fundamental Canons" of the "Code of Ethics of Engineers."

As engineers, we create things that have profound effects on the lives of individuals in society. Through our studies and our work, we become very familiar with new and complicated technologies. Technical concepts become intuitive to us: "... it's obvious ... everybody knows that." We tend to forget the years spent developing our expertise—years developing basic knowledge of the physical laws of our world. Can we assume, or even expect, the general public possesses the technical skills and knowledge we take for granted? Of course not.

Certainly some people understand, for instance, that submerging a hair dryer in water is hazardous. More important, however, is that many others do not realize that mixing electric appliances and water creates a very dangerous situation. A child has no concept of electricity. An adult may have an understanding of electricity, but not understand that it can dangerously energize the bathtub water. Furthermore, even if the hazard is understood, that knowledge won't help when the hair dryer accidentally falls into the bath water. We know that many people are unaware of some electrical hazards.

We know that people—even skilled people—make mistakes and that adverse events happen. If we don't make every effort to provide safe products, systems, components, homes, and workplaces, we are ignoring our ethical obligations.

This, of course, over simplifies ethical and moral dilemmas that face an engineer in the normal conduct of a career. Often it is not one engineer that makes risk-benefit decisions that affect the safety of the design or operation of products and systems. For highly complex systems, such as a nuclear reactor, the effort and compromises of a wide variety of interests and expertise decide the final course of action in design and operations. As an example, study of the Three Mile Island nuclear power plant incident highlights the difficulty in satisfying the interests of all parties involved in a project, and the incident exemplifies the hazardous outcome when those involved have not held paramount the safety, health, and welfare of the public in the performance of their professional duties.

You are encouraged to do additional readings regarding your responsibilities and your rights as an engineer.

When accidental injury or death does occur, who was at fault? If an injury occurs in the workplace, workers' compensation laws generally provide limited compensation to an injured employee, and the employer is exempt from civil lawsuit. Designers, manufacturers, and distributors, however, are subject to civil lawsuits whether an injury or death was work related or not. In some instances, individual engineers can be held civilly or even criminally liable.

The basis on which parties named in a products liability suit are judged is called the **standard of responsibility**. The legal standards used to test liability are the theories of negligence, strict liability, warranty, and misrepresentation.

Negligence focuses on conduct and asks whether the manufacturer acted reasonably. Under this theory, the standard of responsibility is the duty to exercise due care in providing a reasonably safe product.

Under the theory of **strict liability** the standard of responsibility is to provide a product free of defects. A product may be deemed defective if a reasonably prudent manufacturer or seller, knowing of the risk which the product presented, would have put the product into the stream of commerce. Under strict liability theory, even if a manufacturer did not know of a defect, it can be held liable if expert testimony reveals a defect.

A **warranty** is a promise made by a seller that a product possesses certain performance, safety, or quality characteristics. Under warranty, the standard of responsibility is whether the capabilities of the actual product differ from the expressed capabilities. Within this theory, a seller may be found liable under express warranty or implied warranty. An express warranty is breached when the product cannot safely be used for purposes portrayed in statements, pictures, or advertisements. Implied warranty may be defined as a promise that the goods are fit for the ordinary purposes for which such goods are used.

Any party along the stream of commerce (design through sales) may be liable for **misrepresentation** of fact, intentional or not, if the public relies on such information and consequently suffers harm. That is, even if a product is manufactured with the highest standards and is free of defects, any misrepresentation concerning the product that contributed to an injury may make the defendant(s) liable.

In many product liability lawsuits, more than one of these theories will be tested, and most or all of the individuals, or corporations, or both involved in the design, manufacturing, and distribution of the product will be named.

CONCLUSIONS

The engineers that passed before us laid groundwork upon which we can expand. Our predecessors built foundations for greater and more complicated technologies; by analyzing their successes and unfortunate failures, we can build for those that follow us. To protect the safety, health, and welfare of the public and to speak out against abuses in those areas affecting the public interest, we must maintain [our] professional skills at a level of the state of the art and recognize the importance of current events in our work (excerpted from the IEEE Code of Ethics).

Our responsibilities include being familiar with the standards promulgated by our professional societies, standard organizations, trade associations, and regulatory agencies. Wherever necessary, we must adhere to those standards and, whenever possible, expand on them, as they usually serve as the minimum means of protection. These standards, which are the compilation of the lessons previously learned, become increasingly necessary to study as we push technology to even more complicated and potentially hazardous limits.

If we fail to uphold our professional responsibilities, we have failed as engineers and as members of society. Individuals that experience injury or hardship because of our failures have legal recourse through the civil court system under products liability theory. Although none of us are completely immune from becoming involved in such lawsuits, our best protection is to keep our education up to date and to keep the safety, health, and welfare of the public paramount in the performance of our professional duties.

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SAMPLE QUIZ QUESTIONS

1. How do a standard, a code, and a recommended practice differ? Explain.
2. When an engineer is working on a new or unique design or process, reviewing existing standards that deal with conceptually similar products or systems is very helpful. Assume you are working on a new product idea and you correctly determine that some initial research into similar types of products is necessary. Describe your new product idea, and explain what types of similar products you would study to help guide you in your design.
3. In the library, locate some or all of the standards you can that relate to your product design in problem (2). Explain how they would help you in your new product design, particularly concerning safety.
4. Do safety standards, codes, etc., represent the "state-of-the-art" in safety for a given product or process? Discuss.
5. Briefly discuss how consensus standards are developed.
6. Briefly discuss how mandatory standards are developed.
7. Discuss the difference between mandatory and consensus standards.
8. Discuss the difference between a horizontal standard and a vertical standard.
9. Discuss the difference between a specification standard and a performance standard.
10. In the library, find a safety standard pertaining to a subject that interests you. Classify the standard as horizontal or vertical, specification or performance. You may find that different parts of a given standard can be classified differently. Justify your classifications.
11. What is the NFPA, and what do they have to do with electrical safety?
12. What is ANSI, and what does ANSI do?
13. What role does UL play in product safety?
14. Why is it in an engineer's best interest to belong to a professional society? What benefits do professional societies offer their members?
15. What is the "General Duty Clause?" Discuss.
16. What is the BLS? How could information compiled by the BLS help you in making a product or process safer?
17. The Three Mile Island nuclear power plant accident, the space shuttle Challenger explosion, and the Ford Pinto rear-end collision explosions are examples of well-publicized cases involving safety issues and engineering ethics. Each has been written on extensively. Choose one of these, and do a case study of the event and the aftermath. Note the errors that led to the accident(s) and how they might have been avoided. Discuss the ethical dilemmas faced by the engineers involved in the case.

Unit V
SYSTEMS SAFETY ANALYSIS

PURPOSE:

To introduce the student to the importance of systems safety analysis in the design of electrical systems

OBJECTIVE:

To acquaint the student with:

1. Inductive methods of systems safety analysis
2. Deductive methods of systems safety analysis

SPECIAL TERMS:

1. Preliminary Hazard Analysis (PHA)
2. Job Safety Analysis (JSA)
3. Failure Mode and Effect Analysis (FMEA)
4. Systems Hazard Analysis (SHA)
5. Fault Tree Analysis (FTA)
6. Management Oversight and Risk Tree analysis (MORT)
7. Sneak circuit analysis

The general area of system safety analysis may be defined as a directed or systematic process for the acquisition, review, and analysis of specific information relevant to a particular system. This process is methodical, careful, and purposeful. The purpose is to provide information for informed management decisions. System safety analysis techniques can be categorized as either inductive or deductive.

INDUCTIVE METHODS OF SYSTEMS SAFETY ANALYSIS

Inductive methods use observable data to predict what *can* happen. These techniques consider systems from the standpoint of the component parts and determine how a particular mode of failure of component parts will affect the performance of the system. Major inductive methods are Preliminary Hazard Analysis (PHA), Job Safety Analysis (JSA), Failure Modes and Effects Analysis (FMEA), and Systems Hazard Analysis (SHA).

Preliminary Hazard Analysis (PHA)

Preliminary Hazard Analysis is a qualitative study conducted during the conceptual or early developmental phases of a system's life. Its objectives are to:

1. identify known hazardous conditions and potential failures,
2. determine the cause(s) of these conditions and potential failures,
3. determine the potential effect of these conditions and potential failures on personnel, equipment, facilities, and operations,
4. determine the probability of each failure, and
5. establish initial design and procedural requirements to eliminate or control these hazardous conditions and potential failures.

In some cases an additional step, the estimation of the probability of an adverse event due to the hazard, is performed between steps 3 and 4 above.

Table V-1 illustrates an amusing but instructive PHA of the feathers, flax, and beeswax wings that Daedalus and Icarus, in Greek mythology, used.

The PHA is often based on a limited number of hazards determined as soon as initial facts about the system are known. These basic hazards must be dealt with even though many different circumstances might lead to the different hazards. The design process may be monitored to determine whether these hazards have been reduced or eliminated and, if not, whether the effects can be controlled.

Table V-1. Preliminary Hazard Analysis of Flight of Daedalus and Icarus*

PRELIMINARY HAZARD ANALYSIS

IDENTIFICATION Mark I Flight System SUBSYSTEM Wings DESIGNER Daedalus

Hazard	Cause	Effect	Probability of Accident Due to Hazard	Corrective or Preventive Measures
Thermal radiation from sun.	Flying too high in presence of strong solar radiation.	Heat may melt beeswax holding feathers together. Separation and loss of feathers will cause loss of aerodynamic lift. Aeronaut may then plunge to his death in the sea.	Reasonably probable.	Make flight at night or at time of day when sun is not very high and hot. Provide warning against flying too high and too close to sun. Maintain close supervision over aeronauts. Use buddy system. Provide leash of flax between the two aeronauts to prevent a young, impetuous one from flying too high. Restrict area of aerodynamic surface to prevent flying too high.
Moisture.	Flying too close to water surface or from rain.	Feathers may absorb moisture, causing them to increase in weight and to flag. Limited propulsive power may not be adequate to compensate for increased weight so that the aeronaut will gradually sink into the sea. Result: loss of function and flight system. Possible drowning of aeronaut if survival gear is not provided.	Reasonably probable.	Caution aeronaut to fly through middle air where sun will keep wings dry or where accumulation rate of moisture is acceptable for time of mission.
Inflight encounter.	a. Collision with bird.	Injury to aeronaut.	Remote probability.	a. Select flight time when bird activity is low. Give birds right-of-way.
	b. Attack by vicious bird.	Injury to aeronaut.	Remote probability.	b. Avoid areas inhabited by vicious birds. Carry weapon for defense.
Hit by lignting bolt.	Bolt thrown by Zeus angered by hubris displayed by aeronaut who can fly.	Death of aeronaut.	Happens occasionally.	Aeronaut should not show excessive pride in being able to perform godlike activity (keep a low profile).

*Adapted, with permission from Hammer, W., p. 553.

Job Safety Analysis (JSA)

Job Safety Analysis is a written procedure designed to review job methods, uncover hazards, and recommend safe job procedures. The following four basic steps are included in making a JSA:

1. Select the job, usually basing selection on potential hazards or high incidence rates.
2. Break the job down into a sequence of steps. Job steps are recorded in their normal order of occurrence. Steps are described in terms of *what* is done ("lift," "attach," "remove") not *how* it is done.
3. Identify the potential hazards. To determine what events can happen one should: observe the job, discuss the job with the operator, and check accident records.
4. Recommend safe job procedures to avoid the potential incident or injury.

A basic JSA form should include the job steps, the hazards associated with these steps, and recommended safe procedures. The form may be altered if needed to meet specific organizational needs by including such information as the name of the person performing the analysis, name of the operator and supervisor, or the name of reviewers or approvers of the analysis.

Failure Mode and Effect Analysis (FMEA)

Failure Mode and Effect Analysis is both a system safety and reliability analysis used to identify critical failure modes that seriously affect the safe and successful life of the system or failure modes that could prevent a system from accomplishing its intended mission. This technique permits system change to reduce the severity of failure effects. FMEA is organized around the basic question "What if?" The areas covered and the questions asked move logically from cause to effect.

1. Component—What individual components make up the system?
2. Failure Mode—What could go wrong with each component in the system?
3. System Causes—What would cause component failure or malfunction?
4. System Effects—What would be the effect of such a failure on the system and how would this failure affect other components in the system?
5. Severity Index—Consequences are often placed into one of four reliability categories:

   1—Catastrophic—may cause multiple injuries, fatalities, or loss of a facility.

   2—Critical—may cause severe injury, severe occupational illness, or major property damage.

   3—Marginal—may cause minor injury or minor occupational illness resulting in lost workday(s) or minor property damage.

   4—Negligible—probably would not affect the safety or health of personnel but is still in violation of a safety or health standard.

6. Probability Index—How likely is the event to occur under the circumstances described and given the required precursor events? These probabilities are based on such factors as accident experience, test results from component manufacturers, comparison with similar equipment, or engineering data. Probability categories, which may be developed by individual companies or analysts, are sometimes classified as:

   1—probable (likely to occur immediately or within a short period of time),

   2—reasonably probable (probably will occur in time),

   3—remote (possible to occur in time), or

   4—extremely remote (unlikely to occur).

7. Action or Modification—After the failure modes, causes and effects, severity, and probability have been established, the system must be modified to prevent or control the failure.

The severity index, probability index, and a third index relating to personnel exposure may be used to determine the overall risk. A review of the above steps makes the objectives of FMEA clear. FMEA is intended to rank failures by risk (severity and probability) so that potentially serious hazards can be corrected.

When the analysis includes the severity, probability, and criticality indices, it is sometimes called a Failure Mode, Effect, and Criticality Analysis (FMECA). A failure modes effects (and criticality) analysis of a drill is shown on Table V-2. In this case, the criticality index is the sum of the severity and probability indices and represents a measure of the overall risk associated with each combination of severity and probability.

Table V-2. Failure Mode and Effect Analysis* of an Electric Drill

Component	Failure Mode	System Causes	System Effects	Severity Index	Probability Index	Criticality Index	Action or Modification
On-off switch	Fails open	Normal wear	Drill disabled	4	2	6	None
	Fails closed	Normal wear	Drill continues to run	4	2	6	None
Reduction gear train	Functional disability	Normal wear overload, lack of lubrication	Drill disabled	3	4	7	Preventive maintenance, avoid overload
Commutator	Functional disability	Normal wear, broken spring	Drill disabled	3	3	6	None
	Fault to case	Carbon buildup across insulating block	Fatality, if operator is grounded at a remote extremity	1	1	2	Ground the case or go to double insulated construction
Windings	Burnout	Overload, plus fuse failure to open	Drill disabled	3	2	5	Check fuse, avoid overload
	Fault to case	Insulation failure	Fatality, if operator is grounded at a remote extremity	1	2	3	Ground the case or go to double insulated construction

*The analysis of this drill system includes a criticality index (in this case, the sum of the severity and probability indices); therefore, it can be called a Failure Mode, Effect and Criticality Analysis.

For example, if the commutator were to fault to the case of the drill (see Unit II), the potential injury severity is very high (death due to shock). The probability is also relatively high. This leads to a high criticality index. In this case, the hazard can be very significantly reduced by grounding the case of the drill or using double insulation. (Both of these measures were discussed in the module dealing with shock.)

Systems Hazards Analysis (SHA)

Systems Hazards Analysis includes the human component (a strength of Job Safety Analysis) and the hardware component (a strength of Failure Mode and Effects Analysis).

SHA concentrates on the worker/machine interface. What process is being performed on what equipment? What major operations are required to complete the process? What tasks or activities are required to complete an operation? The thesis of SHA is that failures (undesired events) may be eliminated by systematically tracking through the system, looking for hazards that may result in a failure situation.

In the language of SHA, the terms process, operation, and task have specific meanings. Process means the combination of operations and tasks that unite physical effort and physical and human resources to accomplish a specific purpose. An operation is a major step in the overall process (e.g., drilling and countersinking stock on a drill press). A task is a particular action required to complete the operation (e.g., placing a cutting tool in a holder before sharpening the tool on the grinder).

Once the process to be analyzed has been identified, it is subdivided into its operations and tasks. To do this, the analyst must be familiar with the tasks involved in the operation and the interactions between and within the system being analyzed and associated systems and subsystems. Often a flow diagram is constructed to record what is taking place throughout the flow of operations and tasks that fulfill process demands. This enables the analyst to see the pertinent subsystems, methods, transfer operations, inspection techniques, and man/machine operations.

One type of hazard analysis process (adapted from Firenze, 1991) includes identifying and recording information relating to:

1. process (turning between centers on a machine lathe),
2. major unit operations required to complete the process (rough-turning steel stock),
3. tasks required to complete an operation (select cutting tool and place in holder),
4. variance from safe practices with the potential to cause hazards (incorrect cutting tool used),
5. hazard that has the potential to cause an injury (worker in proximity to lathe when incorrect cutting tool used),
6. triggering event causing hazards to result in incidents, brought about by human error or situational, or environmental factors (starting the lathe),

7. incident resulting from effect of triggering event on hazard (stock comes off centers when lathe is running),
8. effect indicating type of injury or damage resulting from the incident (eye injury),
9. hazard consequence classification (called the severity index in FMEA),
10. hazard probability (same as in FMEA),
11. procedural requirements to eliminate or reduce hazards in the workplace,
12. safety and personal protective equipment requirements to reduce the possibility of injuries and illnesses while performing operations and tasks, and
13. instructions/recommendations to ensure safety and health in the workplace.

DEDUCTIVE METHODS OF SYSTEMS SAFETY ANALYSIS

Inductive methods of analysis analyze the components of the system and postulate the effects of their failure on total system performance. Deductive methods of analysis move from the end event to try to determine the possible causes. They determine how a given end event *could* have happened. One widespread application of deductive systems safety analysis is Fault Tree Analysis.

Fault Tree Analysis (FTA)

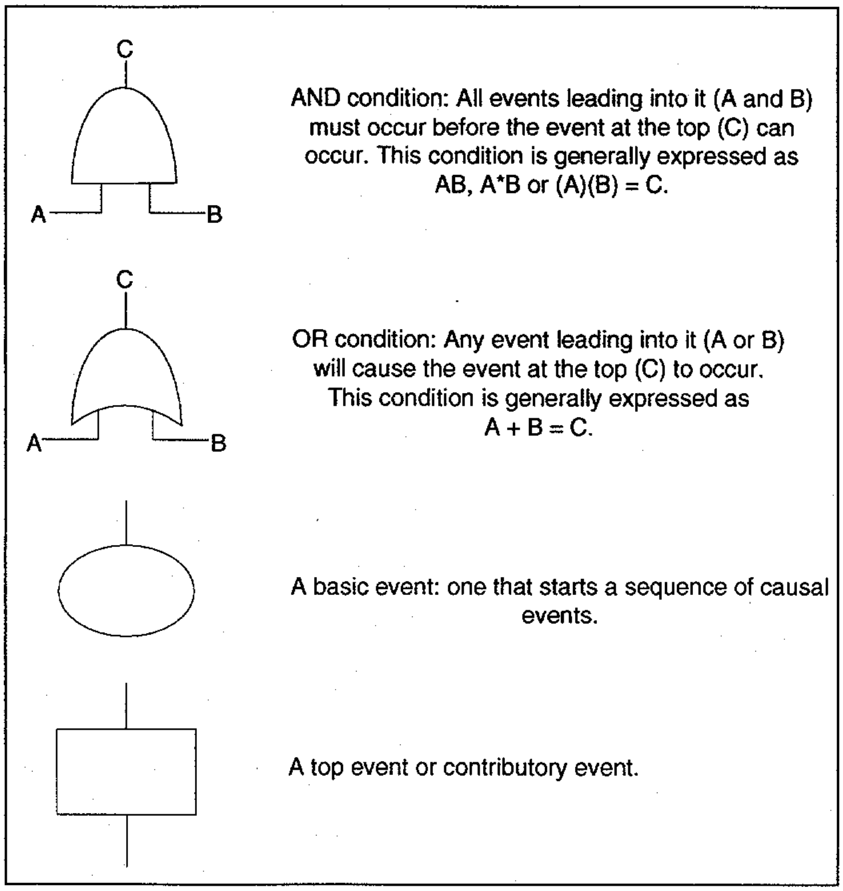
Fault Tree Analysis postulates the possible failure of a system and then identifies component states that contribute to the failure. It reasons backwards from the undesired event to identify all of the ways in which such an event could occur and, in doing so, identifies the contributory causes. The lowest levels of a fault tree involve individual components or processes and their failure modes. This level of the analysis generally corresponds to the starting point in FMEA.

FTA uses Boolean logic and algebra to represent and quantify the interactions between events. The primary Boolean operators are AND and OR gates. With an AND gate, the output of the gate, the event that is at the top of the symbol, occurs only if *all* of the conditions below the gate, and feeding into the gate, coexist. With the OR gate, the output event occurs if *any one* of the input events occur. Figure V-1 illustrates the basic gates used. Figure V-2 illustrates a simple FTA. The "basic events" in Figure V-2 are represented as rectangles rather than circles because they could possible be developed (reduced) further.

When the probabilities of initial events or conditions are known, the probabilities of succeeding events can be determined through the application of Boolean algebra. For an AND gate, the probability of the output event is the intersection of the Boolean probabilities, or the product of the probabilities of the input events, or:

$$\text{Prob (output)} = (\text{Pr Input 1}) \times (\text{Pr Input 2}) \times (\text{Pr Input 3})$$

For an OR gate, the probability of the output event is the sum of the "union" of the Boolean probabilities, or the sum of the probabilities of the input events minus all of the products.



AND condition: All events leading into it (A and B) must occur before the event at the top (C) can occur. This condition is generally expressed as AB, A*B or (A)(B) = C.

OR condition: Any event leading into it (A or B) will cause the event at the top (C) to occur. This condition is generally expressed as A + B = C.

A basic event: one that starts a sequence of causal events.

A top event or contributory event.

Figure V-1. Fault Tree Symbols.

$$\text{Prob (output)} = (\text{Pr Input 1}) + (\text{Pr Input 2}) + (\text{Pr Input 3})$$

$$- [(\text{Pr Input 1}) \times (\text{Pr Input 2}) + (\text{Pr Input 2}) \times (\text{Pr Input 3})$$

$$+ (\text{Pr Input 1}) \times (\text{Pr Input 3}) + (\text{Pr Input 1}) \times (\text{Pr Input 2}) \times (\text{Pr Input 3})]$$

Where the probabilities of the input events are small (less than 0.1, for example), the probability of the output event for an OR gate can be estimated by the sum of the probabilities of the input events or:

$$\text{Prob (output)} = (\text{Pr Input 1}) + (\text{Pr Input 2}) + (\text{Pr Input 3})$$

Assume for example, in Figure V-2, that the following probabilities exist:

Probability of power supply failing	=	.0010
Probability of switch open	=	.0030
Probability of blown fuse	=	.0020
Probability of light 1 out	=	.0300
Probability of light 2 out	=	.0400

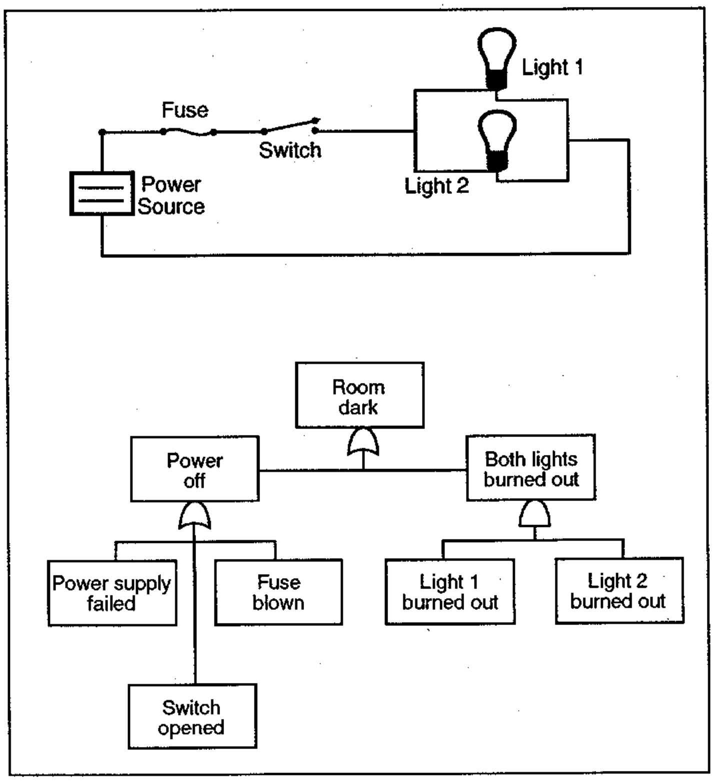


Figure V-2. Fault Tree Analysis of light bulbs (adapted from EG&G).

Since the power will be off if the the power supply fails, or, the switch is open, or the fuse is blown, the probability of the power being off is the sum of the probabilities of the power supply failing, the switch being open, and the fuse being blown or (.0010) + (.0030) + (.0020) = .0060. Both lights will be burned out if light 1 is out and light 2 is out. The probability of both lights being out is (.0300) × (.0400) or .0012. The room will be dark if the power is off or both lights are burned out which is (.0060) + (.0012) or .0072.

The concepts of "cut sets" and "path sets" are useful in the analysis of fault trees. A cut set is any group of contributing elements that, if *all* occur, will *cause* the end event to occur. A path set is any group of contributing elements that, if *none* occur, will *prevent* the occurrence of the end event.

For the example in Figure V-2, the end event will occur if:

— the power supply fails,

— the switch is open,

— the fuse is blown, or

— light 1 and light 2 are burned out.

Each of the four sets above represents a cut set since, if all of the events in any of the sets occur, the end event (room dark) will occur.

For the example in Figure V-2, the end event will not occur if no events in either of the following sets occur:

- the power supply fails, the switch is open, the fuse is blown, and light 1 is burned out, or
- the power supply fails, the switch is open, the fuse is blown, and light 2 is burned out.

Each of the two sets above represents a path set since, if none of the events in either of the sets occur, the end event (room dark) cannot occur.

Management Oversight and Risk Tree Analysis (MORT)

Management Oversight and Risk Tree Analysis is defined as a formalized, disciplined logic or decision tree to systematically relate and integrate a wide variety of safety concepts. As an incident analysis technique, it focuses on three main concerns: specific oversights and omissions, assumed risks, and general management system weaknesses (EG&G, 1984).

It is essentially a series of fault trees with three basic subsets or branches:

1. a branch that deals with specific oversights and omissions at the worksite,
2. a branch that deals with the management system that establishes policies and makes them work, and
3. an assumed risk branch that acknowledges that no activity is completely free of risk and that risk management functions must exist in any well managed organization. These assumed risks are those undesirable consequences that have been quantitatively analyzed and formally accepted by appropriate management levels within the organization.

MORT includes about 100 generic causes and thousands of criteria. The MORT diagram terminates in some 1,500 basic safety program elements needed for a successfully functioning safety program—elements that prevent the undesirable consequences indicated at the top of the tree. MORT has three primary goals:

1. to reduce safety-related oversights, errors, and omissions;
2. to allow risk quantification and the referral of residual risk to proper organizational management levels for appropriate action; and
3. to optimize the allocation of resources to the safety program and to organizational hazard control efforts.

MORT programs and their associated training courses place emphasis on constructing trees for individual program needs and on a set of readymade MORT trees that can be used for program design, program evaluation, or accident investigation.

Sneak circuit analysis

Sneak circuit analysis is a type of systems safety analysis particularly applicable to the analysis of electrical systems—a method of analyzing a circuit to determine unintended and unexpected ways in which current might flow in a circuit. It may be used to determine how equipment might operate undesirably in the *absence of component failure*. This distinguishes sneak circuit analysis from the other systems safety techniques discussed above such as FTA and FMEA. Sneak circuit analysis is also intended to help determine where current might be induced to flow when it shouldn't because of the influence of outside factors.

Sneak circuit analysis can be of several different types:

1. *Sneak Path*, determining if current may flow along an unexpected route.
2. *Sneak Timing*, determining if current may be caused to flow or prevented from flowing to activate or prevent a particular function at an unexpected *time*.
3. *Sneak Indication*, determining if an ambiguous or false *display* of the operating conditions of the system may exist at a particular time.
4. *Sneak Label*, determining if an unexpected current flow may lead to an incorrect, incomplete, or misleading *label*. The resulting misinterpretation of the function of a control might lead to improper system performance.

An example of a sneak path is shown in Figure V-3. In this case, the ignition switch of the automobile is intended to be between the battery and the radio. When the ignition switch is off, the current path to the radio and tail lights is intended to be broken. This intended path is shown by the long arrows. In certain conditions, however, the radio will play intermittently with the ignition switch off. This happens when the emergency flashers are turned on and the brake pedal is depressed. In this case, when the flashers activate, intermittent current is also sent to the radio even when the ignition is off. This unexpected current path is shown with short arrows.

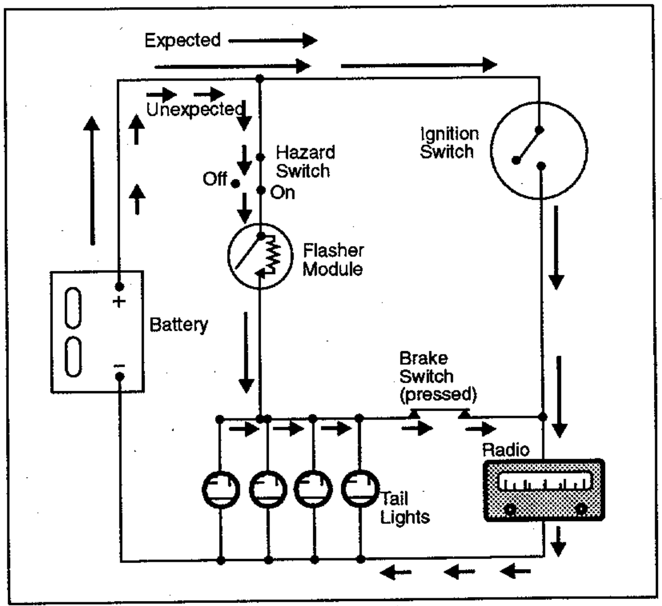


Figure 5.3. Sneak circuit analysis (used by permission, ASSE, 1987).

The application of sneak circuit analysis requires the thorough, systematic, branch-by-branch inspection of a circuit with attention to the intended function of each circuit and possible malfunctions.

Sneak circuit analysis can also be applied to systems involving hydraulic systems, pneumatic systems, mechanical systems, and computer software.

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SAMPLE QUIZ QUESTIONS

1. What is the difference between inductive and deductive systems safety analysis techniques?
2. When is the appropriate time to apply the PHA technique to a design?
3. Apply the PHA technique to an office chair with coasters, adjustable seat height and backrest, and swivel seat.
4. Perform a JSA on a household task of your choosing.
5. Perform a FMEA on a tricycle.
6. Apply fault tree analysis to the undesirable event of falling from the office chair described in problem (3). Do not assign or calculate probabilities.
7. Assign probabilities (your best estimate) to each of the bottom events in the fault tree you developed in problem (6), and calculate the probability of falling from the chair.
8. Discuss the primary goals of MORT.

APPENDIX

NIOSH *Alerts*

NIOSH

ALERT

JULY 1985

Request for Assistance in Preventing Electrocutions from Contact Between Cranes and Power Lines

U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES
PUBLIC HEALTH SERVICE
CENTERS FOR DISEASE CONTROL
NATIONAL INSTITUTE FOR OCCUPATIONAL SAFETY AND HEALTH

DISCLAIMER

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REQUEST FOR ASSISTANCE IN PREVENTING ELECTROCUTIONS FROM CONTACT BETWEEN CRANES AND POWER LINES

BACKGROUND

Contact between cranes and overhead power lines is a major cause of fatal occupational injuries in the United States. Based upon an analysis by the National Institute for Occupational Safety and Health (NIOSH) of the data from the Supplementary Data System [1] of the Bureau of Labor Statistics, there were approximately 2,300 lost workday occupational injuries in the United States in 1981 which resulted from contact with electrical current by crane booms, cables, or loads. These 2,300 injuries were extremely severe, resulting in 115 fatalities and 200 permanent total disabilities. Comparable statistics obtained in studies conducted by the National Safety Council from 1964 to 1976 produced an estimated annual average of 150 fatalities resulting from such incidents [2]. NIOSH believes that this type of event is the most common cause of fatalities associated with mobile crane operations [3] and is responsible for approximately 1.5% of all fatal work-related injuries each year.

CASE REPORTS

As part of the Fatal Accident Circumstances and Epidemiology (FACE) Project conducted by NIOSH, six fatal injuries involving crane-related electrocutions were investigated. The synopses of these cases are as follows:

Case #1:

A 28-year-old construction worker was holding on to a steel ladder being moved by a telescoping boom crane. As the crane's boom was swung in the direction of 7,200 volt power lines, the cable contacted the closest of the lines and the worker was electrocuted.

Case #2:

A co-owner of a steel erection company and three workers were using a telescoping boom crane to move a section of a steel framing member at the construction site of a commercial storage shed. As the section was moved, it came into contact with a 23,000 volt overhead power line. Two of the three workers who were in direct contact with the load were electrocuted while the third received serious electrical burns.

Case #3:

Roof materials for an addition to a commercial building were stored outside the building directly beneath a 7,200 volt power line. While hooking a load (joist angle bracing) to the crane, a worker was electrocuted when the cable came into contact with the power line as the boom swung.

Case #4:

A construction company was in the process of laying concrete water pipe with a crane. As workmen were placing support timbers beneath the crane's outrigger pads, the operator began extending the crane boom for the next lift when the boom came into contact with a 3 phase 13,800 volt overhead power line. One worker touching an outrigger of the crane was electrocuted.

Case #5:

At a highway construction site, a carpenter attached a 4' x 8' wood and metal form to a crane. While holding on to the form in attempting to guide it into place, the carpenter was electrocuted when the boom or cable came into contact with a 34,000 volt power line.

APPROPRIATE STANDARDS AND RECOMMENDED WORK PRACTICES

The Occupational Safety and Health Administration (OSHA) Safety and Health Regulations for Construction, Subpart N--Cranes, Derricks, Hoists, Elevators, and Conveyors (29 CFR 1926.550(a)(15)) contains specific requirements for the safe use of cranes proximate to overhead power lines. Electrical distribution and transmission lines are required to be de-energized and visibly grounded, moved, or separated from cranes with independent insulating barriers. The regulation states that when it is not possible to meet these requirements, cranes may operate proximate to power lines only if:

a) minimum clearance (absolute limit of approach) is maintained between the crane and the lines (10 feet for ≤50 kV and 10 feet plus 0.4 inch for each 1 kV over 50 kV, or twice the length of the line insulator but never less than 10 feet); or,

b) in transit with no load and boom lowered, minimum clearance (absolute limit of approach) is maintained (4 feet for <50 kV, 10 feet for 50 kV to 345 kV, or 16 feet for up to and including 750 kV).

Additionally, 1926.550(a)(15) requires that: a person be designated to observe the clearance of the crane when it is difficult for the crane operator to use direct observation; cage-type boom guards, insulating lines, or proximity warning devices may be used, but their use does not eliminate the need to adhere to the other parts of the regulation; any overhead wire is to be considered energized until the owner of the line or the electric utility indicates that it is not energized and that it has been visibly grounded; transmitter towers should also be de-energized or tests shall be conducted to determine if an electrical charge has been induced on the crane. Induced charges shall be dissipated by providing an electrical ground directly to the upper rotating structure supporting the boom; ground jumper cables shall be attached to materials when an electrical charge is induced; crews shall be provided with nonconductive poles to attach the ground cable to the load; combustible and flammable materials shall be removed from the immediate area prior to operations.

The Construction Safety Association of Ontario, Canada (CSA-Ontario), recommends safe work practices [4] beyond those addressed in the OSHA standard including the use of nonconductive taglines to guide loads and the use of insulating personal protective equipment by exposed workers.

APPLICATION OF EXISTING STANDARDS AND RECOMMENDED WORK PRACTICES

Table 1 presents an analysis for each of the five cases described in this alert regarding compliance with the OSHA standard or CSA-Ontario recommended work practices. In two of the cases, neither the OSHA standard nor the CSA-Ontario recommended work practices were being followed. In the remaining three cases, only one of these safe work practices (avoiding the storage of materials directly under power lines) was being followed. In each of these five cases, there was demonstrable lack of compliance with the OSHA standard.

CONCLUSION

The principal objective of the investigations undertaken by NIOSH as part of its Fatal Accident Circumstances and Epidemiology (FACE) Project is to determine what factors enabled the fatality to occur. The goal is to learn how such fatalities can be prevented. In this context, whether or not an operation was "in compliance" with existing standards is but one of many variables which may or may not have contributed to the fatality. However, in the course of the investigations reported here, it became obvious that full compliance with relevant OSHA standards and full use of the CSA-Ontario work practices would have prevented each fatality.

As an obvious first step in preventing such fatalities in the future, we conclude that all such operations should be done only in compliance with existing OSHA standards.

TABLE 1

Status of Compliance with OSHA Standards (or Use of CSA-Ontario Recommended Work Practices) in Operations Which Resulted in Six Crane-related Electrocutions

Relevant OSHA Standard (or CSA-Ontario Recommended Work Practice)	Status of Compliance by Case				
	#1	#2	#3	#4	#5
1. Move, insulate, or de-energize power line before starting work (OSHA)	No	No	No	No	No
2. Maintain recommended absolute limit of approach (minimum clearance) for specific voltage (OSHA)	No	No	No	No	No
3. Utilize a signal man (OSHA)	No	No	No	No	No
4. Utilize nonconductive taglines, rather than direct contact, to stabilize load (CSA-Ontario)	No	No	No	No	No
5. Do not store combustible materials directly beneath power lines (OSHA & CSA-Ontario)	No	Yes	No	Yes	Yes
6. Use boom guards, insulating lines, or proximity warning devices in addition to other requirements (OSHA)	No	No	No	No	No
7. Use insulating boots and gloves when workers connect loads or contact the crane while in the vicinity of overhead power lines (CSA-Ontario)	No	No	No	No	No

No = Data demonstrated lack of compliance with the OSHA standard (or lack of use of CSA-Ontario recommended work practices).

Yes = Data demonstrated compliance with the OSHA standard (or use of CSA-Ontario recommended work practices).

RECOMMENDATIONS BY NIOSH

The existing OSHA standard appears sufficient to prevent the crane-related electrocutions described in this alert as well as all others. NIOSH urges all employers who use cranes in the vicinity of overhead power lines to familiarize themselves with and implement the existing OSHA standard. NIOSH urges safety and trade associations, crane manufacturers, electric utility companies, and OSHA state consultative services to bring this standard to the attention of employers who use cranes. Implementation of the work practices described by the CSA of Ontario can provide an additional margin of safety.

Suggestions, requests for additional information on safe work practices, or questions related to this announcement should be directed to Mr. John Moran, Director, Division of Safety Research, 944 Chestnut Ridge Road, Morgantown, West Virginia 26505-2888, Telephone (304) 291-4595.

We greatly appreciate your assistance.

J. Donald Millar, M.D., D.T.P.H., (Lond.)
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NIOSH ALERT

JULY 1989

REQUEST FOR ASSISTANCE IN

Preventing Electrocutions of Workers Using Portable Metal Ladders Near Overhead Power Lines

U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES
Public Health Service
Centers for Disease Control
National Institute for Occupational Safety and Health

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ALERT

Request for Assistance in

Preventing Electrocutions of Workers Using Portable Metal Ladders Near Overhead Power Lines

WARNING!

Persons using portable metal or conductive ladders near energized overhead power lines are at risk of electrocution.

The National Institute for Occupational Safety and Health (NIOSH) is requesting assistance in preventing electrocutions that occur when portable metal ladders (including aluminum ladders) contact overhead power lines. Portable metal ladders are used widely in many industries. This *Alert* describes six deaths that occurred because portable aluminum ladders, which are electrical conductors, came in contact with energized overhead power lines. If nonconductive ladders had been used instead, or if safe working clearances had been maintained, these deaths might have been prevented.

Specific Occupational Safety and Health Administration (OSHA) regulations govern the use of portable metal ladders. These regulations should be implemented and enforced by every employer, manager, supervisor, and worker in operations that use portable metal ladders. Editors of appropriate trade journals, safety and health officials, and other persons (especially those in the building trades) are requested to bring the recommendations in this *Alert* to the attention of contractors and workers.

BACKGROUND

Contact between portable metal ladders and overhead power lines causes serious and often fatal injuries to workers in the United States. Data show that during the years 1980 through 1985, the contact of metal ladders with overhead power lines accounted for approximately 4% of all work-related electrocutions in the United States (e.g., 17 out of 382 deaths for 1985) [NIOSH 1988].

REGULATIONS

Safety regulations promulgated by the Occupational Safety and Health Administration (OSHA) establish specific requirements intended to prevent workers from positioning portable metal ladders where they might contact electrical conductors [29 CFR* 1926.450(a)(11) and 1926.951(c)(1)]. These regulations stipulate that "portable metal or conductive ladders shall not be used for electrical work or where they may contact

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*Code of Federal Regulations. See CFR in references.

electrical conductors." Other pertinent regulations require that "portable ladders in use shall be tied, blocked, or otherwise secured to prevent their being displaced" [29 CFR 1926.450(a)(10)]. Additional OSHA regulations require employers to instruct each worker to recognize and avoid unsafe conditions [29 CFR 1926.21(b)(2)], and to provide prompt medical attention in case of serious injury [29 CFR 1926.50].

CASE REPORTS

As part of the Fatal Accident Circumstances and Epidemiology (FACE) Program, NIOSH investigated five incidents (resulting in six electrocutions) that occurred between 1985 and 1987 and that involved contact between portable aluminum ladders and overhead power lines.

Case No. 1 - One Fatality

On May 4, 1985, a 28-year-old male worker removed the bottom of a poster on a 12-by-24-foot (-ft) billboard that was scheduled for reposting. He then removed a 24-ft aluminum hook ladder from the service truck. While the worker was positioning the ladder to reach the top section of the billboard, the ladder contacted a 7,200-volt (-V) overhead power line that was located 8 ft from the top of the billboard, and he was electrocuted [NIOSH 1985a].

Case No. 2 - One Fatality

On July 21, 1986, a 27-year-old male painter was standing on a fully extended 24-ft aluminum ladder while painting a rain gutter on an apartment building. After painting a section of the gutter, the worker descended the ladder to move it to a new location. As he was repositioning the ladder, it contacted a 7,200-V overhead power line that was located 8 ft from the gutter, and he was electrocuted [NIOSH 1987d].

Case No. 3 - Two Fatalities

On November 17, 1986, two male painters (20 and 21 years old) were using a 36-ft aluminum extension ladder to paint a 20-ft-high metal light pole. One worker was standing on the ladder painting, and his coworker was on the ground holding the ladder. The ladder slipped away from the pole and contacted a 12,460-V overhead power line that was located within 2 ft of the pole. Both painters were electrocuted [NIOSH 1987c].

Case No. 4 - One Fatality

On September 1, 1987, a 28-year-old male painter and a coworker were using an aluminum extension ladder while cleaning the outside brick wall of a three-story convalescent home before painting. After cleaning one section, the workers moved the ladder to another location. The painter held the base of the ladder as the coworker simultaneously climbed and raised the extension of the 40-ft ladder. When the ladder was extended to approximately 34 ft, it tipped backward, contacting a 7,200-V overhead power line that was located 15 ft from the structure. The coworker on the ladder received an electrical shock and fell to the ground. The painter holding the ladder provided a path to the ground for the electrical current and was electrocuted [NIOSH 1987b].

Case No. 5 - One Fatality

On September 24, 1987, an 18-year-old male construction worker and two coworkers were looking for an area on an office building roof to store shingles. The 18-year-old and a coworker were holding a fully extended, 32-ft aluminum ladder as the other coworker descended it. The ladder tipped backward, contacting a 7,200-V overhead power line that was located 6 ft from the building, electrocuting the 18-year-old worker holding the ladder, and shocking the other two coworkers [NIOSH 1987a].

APPLICATION OF EXISTING REGULATIONS

Data demonstrated that employers and workers in all five fatal incidents violated the following applicable* OSHA regulations:

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*Regulation No. 3 did not apply to Case No. 1.

1. Portable metal or conductive ladders shall not be used for electrical work or where they may contact electrical conductors [29 CFR 1926.450(a)(11) or 1926.951(c)(1)].
2. Employers shall instruct each employee in the recognition and avoidance of unsafe conditions and the regulations applicable to his work environment to control or eliminate any hazards or other exposure to illness or injury [29 CFR 1926.21(b)(2)].
3. Portable ladders in use shall be tied, blocked, or otherwise secured to prevent their being displaced [29 CFR 1926.450(a)(10)].

Compliance with these regulations might have prevented all five deaths.

CONCLUSIONS

The principal objectives of the NIOSH FACE Program are to identify potential risk factors that may contribute to traumatic worker deaths and to recommend measures that might prevent similar fatalities. Whether or not a work operation complies with existing OSHA regulations is only one variable that may contribute to a fatality. However, in the investigations reported here, full compliance with relevant OSHA regulations would probably have prevented these deaths. The lack of compliance with existing regulations in the five incidents described suggests that many employers and workers may be (1) working unaware of these OSHA regulations, (2) misinterpreting the requirements of the regulations, or (3) failing to inform their workers about the dangers of using metal ladders around overhead power lines.

RECOMMENDATIONS

The following recommendations will help prevent deaths and injuries resulting from contact between metal ladders and overhead power lines:

- NIOSH recommends that employers and workers comply with the OSHA regulation prohibiting the use of portable metal or conductive ladders for electrical work or in locations where they may contact electrical conductors. Nonconductive ladders such as those made of wood or fiber glass should be used instead.
- Employers should fully inform workers about the hazards of using portable metal (including aluminum) ladders near energized power lines.
- If portable metal ladders are used in the vicinity of energized power lines, NIOSH urges that all employers and workers strictly adhere to the OSHA safety regulations [29 CFR 1926.450 and 1926.951(c)(1)] for providing proper balancing and securing of ladders, and for maintaining safe working distances to avoid contact with electrical conductors.
- To assure proper protection for anyone working near electrical power lines, arrangements should be made with the power company to de-energize the lines or to cover the lines with insulating line hoses or blankets.
- Employers should provide workers with training in emergency medical procedures such as cardiopulmonary resuscitation. Fatalities may be prevented by prompt emergency medical care.

NIOSH also urges safety and trade associations, electrical utility companies, product manufacturers, and OSHA State consultative services to bring these recommendations to the attention of employers and workers using portable metal ladders. Further information on electrical energy hazards can be found in six previously published NIOSH *Alerts* [NIOSH 1987e, NIOSH 1986a, NIOSH 1986b, NIOSH 1986c, NIOSH 1985b, NIOSH 1984].

Suggestions, requests for additional information on safe work practices, or questions related to this announcement should be directed to Dr. Thomas R. Bender, Director, Division of Safety Research, 944 Chestnut Ridge Road, Morgantown, West Virginia 26505-2888; telephone (304) 291-4595.

We greatly appreciate your assistance.

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Request for Assistance in

Preventing Grain Auger Electrocutions

July 1986

U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES
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REQUEST FOR ASSISTANCE IN PREVENTING GRAIN AUGER ELECTROCUTIONS

WARNING!

MOVING GRAIN AUGERS IN THEIR ELEVATED POSITION MAY RESULT IN ELECTROCUTION IF THEY CONTACT OVERHEAD POWER LINES WHILE BEING MOVED. FARM OWNERS AND MANAGERS SHOULD ENSURE THAT AUGERS ARE IN THE LOWERED POSITION PRIOR TO MOVING THEM.

SUMMARY

This Alert requests the assistance of farm owners/managers, farm/agricultural workers, and farm equipment manufacturers in the prevention of electrocutions which may occur while moving metal grain augers. The grain auger is an essential piece of farm equipment which is used to move grain from one location to another. However, every year accidents occur when this piece of equipment is improperly moved in the elevated position and it comes into contact with high voltage power lines. This has resulted in one or more fatalities per incident. This Alert describes two separate incidents that resulted in five fatalities, and occurred within the same week (150 miles apart). Neither of the incidents fell under OSHA jurisdiction because both farms were family operations employing fewer than 10 workers.

July 1986

BACKGROUND

The grain auger is a portable piece of farm equipment, 50 to 60 feet long, and weighing several hundred pounds. It is used to move grain from one location to another (e.g., unloading grain from a truck or trailer and loading it into a dryer or storage bin). It is moved to a desired location on inflatable-type car tires and then raised into position by means of a hand crank attached to a steel pully system; the discharge end is elevated to the top of a dryer or bin, and the opposite end is lowered in order to pick up the grain to be moved. The auger is usually powered by connecting a universal joint to the power takeoff on a tractor or other piece of farm equipment. After transferring the grain, the auger should be lowered to a horizontal position for safe transportation to another location. However, the auger is not always lowered before being moved, and this unsafe practice could pose a life threatening hazard if the auger comes into contact with overhead electrical lines or if it were to tip over during transport.

CASE REPORTS OF TWO FATAL INCIDENTS

These case reports resulted from NIOSH investigations of the circumstances that led to the five fatalities described below. The investigations were conducted as part of the NIOSH Fatal Accident Circumstances and Epidemiology Program.

Case #1 - TWO ELECTROCUTED, THREE INJURED

During mid-morning on October 14, 1985, five farm workers were in the process of moving a portable grain auger. To move the auger from a 30-foot tall grain drying bin to another location, it was raised to approximately 35 feet (an angle of about 45 degrees) so that the top could clear the bin. The workers then pulled the grain auger machine back approximately 15 feet from the grain bin, rotated the rear of the auger 90 degrees, and began pushing the auger to the new location. As the workers pushed the auger forward, approximately 90 feet, it contacted an electrical line which was about 25 feet above the ground. Two of the workmen were electrocuted and three others were injured.

Case #2 - THREE ELECTROCUTED

During the early morning of October 18, 1985, two farm workers and the farm owner were moving a portable grain auger from a grain bin, approximately 30 feet high, to another location. The auger was first raised to 35 feet to clear the top of the grain bin and then pulled back approximately 15 feet. The workers swiveled the auger 90 degrees to allow a straight path to the truck, approximately 40 yards away, that was to be loaded with grain. As the workers pushed the auger forward, it contacted a 7200 volt electrical line which was 25 feet above the ground. The two workers and the farm owner were electrocuted.

REGULATORY STATUS

OSHA estimates that over 90% of all farms in the United States are not covered by OSHA regulations. OSHA regulations are not applicable to most farms because they employ fewer than 10 employees. However, for farms employing 11 or more workers (family members do not count in this number), OSHA jurisdiction does apply and mandatory compliance is required to 29 CFR 1928.57, Guarding of Farm Field Equipment, Farm Machinery & Farmstead, Sub Part D.

CONCLUSIONS

Based on the information collected on the two cases cited, it can be concluded that the five fatalities occurred as a result of the following:

1. The lack of hazard recognition.
2. The failure to lower the grain augers to the horizontal position before moving them to other locations.

RECOMMENDATIONS

NIOSH recommends that all farm owners/managers, farm/agricultural workers, and farm equipment manufacturers be made familiar with, and reinforce the following steps:

1. Hazard Awareness

A survey of the farm should be conducted to identify hazards posed by the locations of overhead electrical lines. When all such hazards are identified and documented for future reference, workers should be informed of their location and instructed in the steps necessary to safely move grain augers.

2. Safe Movement of Grain Augers and Other Farm Equipment

Grain augers pose a life threatening hazard when moved in an elevated position if they contact overhead electrical lines or if they tip over. Therefore, it is essential that grain augers be lowered to a horizontal position before being moved from one location to another. In addition, all other equipment to be moved should be evaluated in order to determine the most appropriate method that will ensure worker safety during its transport. Manufacturers of grain augers are urged to consider design modifications that will prevent grain augers from being moved while in an elevated position.

3. Safety Signs

It is recommended that users and manufacturers of grain augers affix safety signs onto the equipment that warn the user of the potential hazards of moving the auger in its upright position. A safety sign to draw attention to avoiding electrical hazards when moving grain augers is provided with this Alert. This sign should be placed on the grain auger in a conspicuous location so that it will alert workers of life threatening hazards.

We are requesting editors of appropriate trade and farm journals, members of farm extension associations, and those responsible for safety and health (e.g. inspectors, managers, and agricultural extension specialists) to bring these recommendations to the attention of farm workers, managers, and owners.

Requests for additional information on control practices or questions related to this announcement should be directed to Mr. John B. Moran, Director, Division of Safety Research, National Institute for Occupational Safety and Health, 944 Chestnut Ridge Road, Morgantown, West Virginia 26505, Telephone (304) 291-4595.

We greatly appreciate your assistance.

J. Donald Millar, M.D., D.T.P.H. (Lond.)
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Request for Assistance in

Preventing Fatalities of Workers Who Contact Electrical Energy

December 1986

U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES
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REQUEST FOR ASSISTANCE IN PREVENTING FATALITIES OF WORKERS WHO CONTACT ELECTRICAL ENERGY

ATTENTION!

PROMPT EMERGENCY MEDICAL CARE CAN BE LIFESAVING FOR WORKERS WHO HAVE CONTACTED EITHER LOW VOLTAGE OR HIGH VOLTAGE ELECTRICAL ENERGY. IMMEDIATE CARDIOPULMONARY RESUSCITATION (CPR) FOLLOWED BY ADVANCED CARDIAC LIFE SUPPORT (ACLS) HAS BEEN SHOWN TO SAVE LIVES.

SUMMARY

Recent incidents that have come to the attention of NIOSH have shown that electrocution victims can be revived if immediate cardiopulmonary resuscitation (CPR) or defibrillation is provided. While immediate defibrillation would be ideal, CPR given within approximately 4 minutes of the electrocution, followed by advanced cardiac life support (ACLS) measures within approximately 8 minutes, can be lifesaving. This alert describes recommendations that can be used to help save the lives of workers who contact electrical energy. Editors of appropriate trade journals, safety and health officials, and especially those who work with electrical equipment, are requested to bring these recommendations to the attention of owners, managers, and workers.

December 1986

BACKGROUND

It has been estimated that at least 700 occupational electrocutions occur each year [1]. Therefore, a primary goal of occupational safety programs must be to prevent workers from contacting electrical energy. Effective measures include safe work practices, job training, proper tools, protective equipment, and lockout/tag-out procedures.

Investigations by NIOSH, as part of its Fatal Accident Circumstances and Epidemiology (FACE) Project, also have revealed that once an electrical energy incident occurs, emergency response plans are often lacking, even in organizations which promote safety. Hence, a secondary goal of safety programs must be to provide appropriate emergency medical care to workers who contact electrical energy.

The National Electrical Code divides voltages into two categories: greater than 600 volts (high voltage) and less than or equal to 600 volts (low voltage) [2]. Momentary contact with low voltages produces no thermal injury, but may cause ventricular fibrillation (very rapid, ineffective, heartbeat) [3].

In contacts with high voltage, massive current flows may stop the heart completely. When the circuit breaks, the heart may start beating normally [3]. Supporting respiration by immediate mouth-to-mouth techniques may be required, even if heartbeat and pulse are present. If extensive burns are present, death may result from subsequent complications [4].

APPROPRIATE STANDARDS AND GUIDELINES

The revised "Standards and Guidelines for Cardiopulmonary Resuscitation (CPR) and Emergency Cardiac Care (ECC)" published in June 1986, is a product of the 1985 National Conference on CPR and ECC. There are two parts: basic cardiopulmonary resuscitation (CPR) and advanced cardiac life support (ACLS). A lay person can be trained in CPR to support circulation and ventilation of the victim of cardiac or respiratory arrest, until ACLS (provided by medical professionals using special equipment) can restore normal heart and ventilatory action [5].

Speed has been found to be critical to resuscitation: immediate defibrillation would be ideal. The highest success rate has been achieved in those patients for whom CPR followed cardiac arrest within approximately 4 minutes, and ACLS was begun within approximately 8 minutes of the arrest [5]. CPR often must be initiated immediately by lay individuals at the scene of the incident. It should be noted that CPR skills can be gained in 4-hour courses similar to those taught by the American Heart Association or the American Red Cross.

NIOSH CASE REPORTS

Case #1 - SUCCESSFUL RESUSCITATION

A 30-year-old construction worker was working on a fire escape in a building being renovated. Another worker handed the victim a metal pipe, and he was holding it with both hands when it contacted a nearby high voltage line, completing a path-to-ground. The worker instantly collapsed from this contact with electrical energy. Approximately 4 minutes after he collapsed, the fire department rescue squad arrived and began CPR. Within 6 minutes, a paramedic unit was on the scene providing defibrillation and other ACLS measures. They were able to establish a heartbeat and pulse, but the individual continued to require respiratory support during transport to the hospital. He regained consciousness and was discharged within two weeks. He did have to return for further medical care for burns he received on his hands (current entrance) and buttocks (current exit) [6].

Case #2 - UNSUCCESSFUL RESUSCITATION

An 18-year-old male restaurant worker contacted electrical energy when he kneeled to plug a portable electric toaster into a 110-120 V/20 amp floor outlet. After a scream was heard, the victim was found convulsing on the damp floor, with one hand on the plug and the other on the receptacle box. The assistant manager went to the electrical panel, but was unable to locate the appropriate circuit breaker. A coworker attempting to take the victim's pulse received an electrical shock, but was not injured. After telephoning the emergency medical service, the assistant manager returned to the panel and de-energized all of the circuits (3 to 8 minutes after the worker contacted electrical energy). The injured worker was covered with a coat to "keep him warm." After about 5 minutes, another call was placed to the emergency squad, and the assistant manager "yelled" for an off-duty employee who lived in an apartment across the lot, who came and began CPR. The emergency service was on the scene 10 minutes after receiving the first call. ACLS measures were available, but the resuscitation was unsuccessful and the worker was pronounced "dead on arrival" at the local hospital. The exact time span between the worker contacting electrical energy and the beginning of CPR is unknown, but it is reasonable to assume that it was longer than 4 to 6 minutes. Paramedics with ACLS capability arrived 10 minutes after receiving the call, but more than 10 minutes after the accident occurred [7].

CONCLUSIONS

In Case #1, basic life support was begun within 4 minutes by the fire department rescue squad who happened to be stationed nearby. They were experienced and had up-to-date knowledge in CPR techniques. In this case, CPR was begun within the 4-minute recommendation. An ambulance, equipped and staffed to provide ACLS, arrived within 6 minutes. The standards and guidelines [5] for CPR within 4 minutes, and ACLS within 8 minutes, were met and the worker did survive.

In Case #2, the worker's contact with electrical energy was prolonged and a coworker who aided him received an electrical shock, because coworkers did not know how to de-energize the circuit. The optimal times for CPR and ACLS were exceeded, and the resuscitation was unsuccessful. Providing appropriate medical care after an electrical energy incident will not guarantee success. However, as has been reported elsewhere [5] and supported in the NIOSH case reports, the chance for successful resuscitation after cardiopulmonary arrest is best when the criteria for providing emergency medical care are met.

RECOMMENDATIONS

1. PREVENTION

PREVENTION must be the primary goal of any occupational safety program. However, since contact with electrical energy occurs even in facilities which promote safety, safety programs should provide for an appropriate emergency medical response.

2. SAFE WORK PRACTICES

No one who works with electrical energy should work alone, and in many instances, a "buddy system" should be established. It may be advisable to have both members of the buddy system trained in CPR, as one cannot predict which will contact electrical energy.

Every individual who works with or around electrical energy should be familiar with emergency procedures. This should include knowing how to de-energize the electrical system before rescuing or beginning resuscitation on a worker who remains in contact with an electrical energy source.

All workers exposed to electrical hazards should be made aware that even "low" voltage circuits can be fatal, and that prompt emergency medical care can be lifesaving.

3. CPR AND ACLS PROCEDURES

CARDIOPULMONARY RESUSCITATION (CPR) and first aid should be immediately available at every worksite. This capability is necessary to provide prompt (within 4 minutes) care for victims of cardiac or respiratory arrest, from any cause.

Employers may contact the local office of the American Heart Association, the American Red Cross, or equivalent groups or agencies, to set up a course for employees.

Provision should be worked out at each worksite to provide **ADVANCED CARDIAC LIFE SUPPORT (ACLS)** within 8 minutes (if possible), usually by calling an ambulance staffed by paramedics. Signs on or near phones should give the correct emergency number for the area, and workers should be educated regarding the information to give when the call is made. For large facilities, a prearranged place should be established for company personnel to meet paramedics in an emergency.

We are requesting that employers, worker representatives, editors of appropriate trade journals, and safety and health professionals assist in disseminating these recommendations to those individuals and organizations responsible for providing a safe workplace. Suggestions or questions related to this announcement should be directed to Mr. John Moran, Director, Division of Safety Research, National Institute for Occupational Safety and Health, 944 Chestnut Ridge Road, Morgantown, West Virginia 26505-2888, telephone (304) 291-4595.

We greatly appreciate your assistance.

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Request for Assistance in

Preventing Electrocutions Due to Damaged Receptacles and Connectors

October 1986

U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES
Public Health Service
Centers for Disease Control
National Institute for Occupational Safety and Health

DISCLAIMER

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REQUEST FOR ASSISTANCE IN PREVENTING ELECTROCUTIONS DUE TO DAMAGED RECEPTACLES AND CONNECTORS

WARNING!

PERSONS USING ELECTRICAL EQUIPMENT ARE CAUTIONED THAT THE USE OF DAMAGED RECEPTACLES AND CONNECTORS CAN BE EXTREMELY DANGEROUS.

SUMMARY

The National Institute for Occupational Safety and Health (NIOSH) is requesting assistance in preventing the electrocution of workers due to the use of damaged electrical receptacles and connectors. Two recent incidents are described. Results of the investigations indicate that **periodic inspection**, **recognition of hazards**, and **proper use of receptacles and connectors**, and **prompt repair of damaged connectors and receptacles**, could prevent such incidents. Editors of appropriate trade journals, safety and health officials, and especially those who work with electrical equipment, are requested to bring these recommendations to the attention of owners, managers, and workers.

October 1986

BACKGROUND

Occupational electrocutions continue to be a serious problem throughout the United States. Data obtained from the Bureau of Labor Statistics' Annual Survey indicate that approximately 10% of all occupational fatalities are due to electrocutions. Those data, as well as other information collected by the National Institute for Occupational Safety and Health (NIOSH), demonstrate that fatalities due to electrocutions occur in a variety of ways. For example, previous NIOSH Alerts have described cases in which workers have been electrocuted as a result of contacting improperly grounded equipment, or when cranes or grain augers have contacted overhead power lines [1,2]. This Alert presents information on two fatal electrocutions that occurred as a result of using damaged receptacles and connectors.

Two investigations by NIOSH found evidence to suggest that the victims were unaware of hazards associated with the use of damaged connectors. In both cases, it was assumed that because a connector fit into a receptacle, the connection was proper and no hazard existed. The prevalence of this particular hazard is not clear. However, the cases described below point out the insidious nature of this hazard. The presence of receptacles and connectors in all workplaces, and the repetitive nature of their use (which in certain workplaces increases the possibility of damage) suggests that the potential hazard is widespread. These investigations also demonstrate that careful routine inspection and aggressive maintenance might well prevent such fatalities.

CASE REPORTS OF FATAL INCIDENTS

Case #1 - (ONE FATALITY)

On July 23, 1985, a 24-year-old employee of a textile mill was electrocuted when he **touched a loom frame** while performing his routine duties at the loom. The loom had become energized when an electrical, three-prong connector from a thread feeder machine was inserted into a damaged receptacle mounted on the loom. The damage to the receptacle permitted the ground prong of the plug to be improperly inserted into one of the phase terminals (90 degrees clockwise away from the appropriate ground terminal). This resulted in energizing the ground prong and the frame of the loom. When the worker touched the energized loom, he was electrocuted. It appeared, upon subsequent inspection, that the receptacle had been damaged because of a lack of adequate strain relief for the electrical cord from the thread feeder.

Case #2 - (ONE FATALITY)

On July 29, 1985, a 29-year-old welder was electrocuted when he inserted the "male" end of an electrical plug on a portable arc welder into a broken "female" connector of an extension cord. As in the previous case, the victim inserted the ground prong of the welder cord 90 degrees clockwise away from the appropriate ground terminal of the extension cord, and the metal casing of the welder connector became energized. It appeared that the connector on the extension cord had been damaged by everyday use or abuse (being thrown down on and dragged across concrete floors, being run over by industrial equipment, etc.).

REGULATORY STATUS

Although, in these investigations the receptacles and connectors in these investigations were listed by a nationally recognized testing laboratory, the damaged state of the receptacles negated their conformance to these listings*, to the manufacturers' specifications, and to the safety features inherent in their design. NIOSH strongly urges periodic inspection and maintenance of electrical systems to assure compliance with applicable sections of the National Electric Code, OSHA standards, and other listing requirements. Electrical components should be used only in accordance with the manufacturers' specifications, and should be tested and approved by a nationally recognized laboratory (such as Underwriters Laboratory, Factory Mutual, etc.).

CONCLUSION

The investigations by NIOSH indicate that damaged receptacles may physically permit improper electrical connections to be made, negating the intended safeguards designed into them. Furthermore, workers may not recognize a hazard of electrocution associated with the use of worn or damaged receptacles and connectors. Electrical hazards of this sort are of particular concern because of the large number of users of electrical equipment in all kinds of workplaces. Investigations of such incidents suggest failures in the areas of **PROPER UTILIZATION OF ELECTRICAL COMPONENTS**, **HAZARD RECOGNITION**, and **PERIODIC INSPECTION AND MAINTENANCE OF ELECTRICAL SYSTEMS**. These basic safety activities are potentially lifesaving in preventing such incidents.

Caution should be used around **ALL** electrical circuits and equipment. The potential for electric shock should never be underestimated. Employers and other groups should regularly emphasize the safe use of electricity in the workplace. Continuous efforts must be made to prevent electrical injuries and deaths due to damaged receptacles and connectors.

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*A listing means that the piece of equipment has met the safety criteria established by the testing laboratory.

RECOMMENDATIONS

NIOSH makes the following recommendations in these areas:

1. PROPER UTILIZATION OF ELECTRICAL SYSTEMS

All receptacles and connectors should be used only in accordance with the manufacturers' specifications, and the specific listing for the item as set forth by nationally recognized testing laboratories. Users should be advised of the importance of using receptacles and connectors only for applications for which they have been designed. When a component is selected for use, it should be evaluated to determine if it can tolerate the environment to which it will be exposed. Physical abuse and stress on these components should be minimized by the selection of a safe location and by the use of stress/strain relief devices.

2. AWARENESS AND RECOGNITION OF HAZARDS

Policies that address the proper use of receptacles and connectors should be developed and implemented by qualified safety personnel. Safety training should emphasize awareness and recognition of electrical hazards associated with receptacles and connectors (i.e., broken receptacles and connectors, improper electrical connections, damaged cords, the importance of grounding, etc.). Immediate corrective action should be taken when damaged components or safety hazards are encountered. When safety policies and procedures are developed, they should be enforced.

3. PERIODIC INSPECTION AND MAINTENANCE OF ELECTRICAL SYSTEMS

Periodic inspections should be conducted for all electrical system equipment and components in order to identify all electrical hazards present. Records should be kept of any electrical hazards identified, and appropriate corrective action should be taken immediately. These periodic inspections should be supplemented with daily inspections by the personnel using this equipment.

We urge safety and trade associations interested in job site safety to bring these recommendations to the attention of employers.

Requests for additional information, and comments or questions concerning this announcement, should be directed to Mr. John Moran, Director, Division of Safety Research, National Institute for Occupational Safety and Health, 944 Chestnut Ridge Road, Morgantown, West Virginia 26505, Telephone (304) 291-4595.

We greatly appreciate your assistance.

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