CENGAGE

Understanding MOTOR CONTROLS

Fourth Edition

STEPHEN L. HERMAN

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FOURTH EDITION

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CENGAGE

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Preface

A Note from the Author

I have taught the subject of motor control for over 30 years. I have tried different methods and found that some are more successful than others. *Understanding Motor Controls* is the accumulation of this knowledge. I am sure other methods may work equally well, but the methods and information presented in this textbook have worked the best for me. My goal in writing this textbook is to present the subject of motor control in a way that the average student can understand. I have three main objectives:

- Teach the student how to interpret the logic of a schematic diagram.
- Teach the student how to properly connect a circuit using a schematic diagram.
- Teach the student how to troubleshoot a control circuit.

Understanding Motor Controls assumes that the student has no knowledge of motor controls. The student is expected to have knowledge of basic Ohm's law and basic circuits, such as series, parallel, and combination. The book begins with an overview of safety. A discussion of schematics (ladder diagrams) and wiring diagrams is presented early. The discussion of schematics and wiring diagrams is intended to help students understand the written language of motor controls. Standard NEMA symbols are discussed and employed throughout the book when possible. The operation of common control devices is presented to help students understand how these components function and how they are used in motor control circuits. Basic control circuits are presented in a manner that allows students to begin with simple circuit concepts and progress to more complicated circuits.

The textbook contains examples of how a schematic or ladder diagram is converted into a wiring diagram. A basic numbering system is explained and employed to aid students in making this conversion. This is the most effective method I have found of teaching a student how to make the transition from a circuit drawn on paper to properly connecting components in the field.

Understanding Motor Controls also covers solid-state controls for both DC and AC motors. Variable frequency drives and programmable logic controllers are covered in detail. I explain how to convert a ladder diagram into a program that can be loaded into a PLC. The book contains many troubleshooting problems that help the student understand the logic of a control system. Circuit design is also used to help the student develop the concepts of circuit logic.

Understanding Motor Controls contains 16 hands-on laboratory exercises that are designed to use off-the-shelf motor control components. A list of materials and suggested vendors is given for the components used in the exercises. The laboratory exercises begin with very basic concepts and connections and progress through more complicated circuits.

Supplements

An online Instructor Companion website contains an Instructor Guide with answers to end-of-chapter review questions, test banks, and Chapter presentations done in PowerPoint, and testing powered by Cognero.

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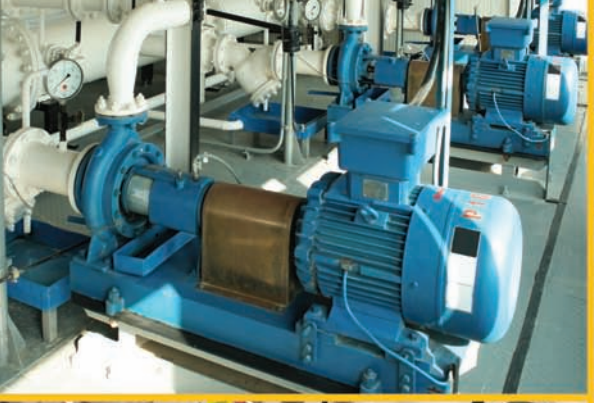
Keith Dinwiddie, Ozarks Community College

New for the Fourth Edition

Extended information for sizing overload relay heaters.
Additional review questions to selected chapters.
Upgraded and additional illustrations.
Extended explanation for how an electronic on-delay timer operates.
Extended information on float switch circuits.
Extended coverage of photodetectors.
Extended coverage of wye-delta starting.
Extended coverage of direct current motors.
The addition of electronic components and circuits frequently used in motor control applications



Safety Overview

Safety Overview

Objectives *After studying this chapter the student will be able to:*

- State basic safety rules.
- Describe the effects of electric current on the body.
- Discuss the origin and responsibilities of OSHA.
- Discuss material safety data sheets.
- Discuss lockout and tagout procedures.
- Discuss types of protective clothing.
- Explain how to properly place a straight ladder against a structure.
- Discuss different types of scaffolds.
- Discuss classes of fires.
- Discuss ground-fault circuit interrupters.
- Discuss the importance of grounding.

Safety is the job of each individual. You should be concerned not only with your own safety but with the safety of others around you. This is especially true for persons employed in the electrical field. Some general rules should be followed when working with electric equipment or circuits.

General Safety Rules

Never Work on an Energized Circuit If the Power Can Be Disconnected

When possible, use the following three-step check to make certain that power is turned off.

1. Test the **meter** on a known live circuit to make sure the meter is operating.
2. Test the circuit that is to become the **de-energized circuit** with the meter.
3. Test the meter on the known live circuit again to make certain the meter is still operating.

Install a warning tag at the point of **disconnection** so people will not restore power to the circuit. If possible, use a lock to prevent anyone from turning the power back on.

Think

Of all the rules concerning safety, this one is probably the most important. No amount of safeguarding or **idiot proofing** a piece of equipment can protect a person as well as taking time to think before acting. Many technicians have been killed by supposedly "dead" circuits. Do not depend on circuit breakers, fuses, or someone else to open a circuit. Test it yourself before you touch it. If you are working on high-voltage equipment, use insulated gloves and meter probes to measure the voltage being tested. *Think* before you touch something that could cost you your life.

Avoid Horseplay

Jokes and **horseplay** have a time and place but not when someone is working on an electric circuit or a piece of moving machinery. Do not be the cause of someone's being injured or killed and do not let someone else be the cause of your being injured or killed.

Do Not Work Alone

This is especially true when working in a hazardous location or on a live circuit. Have someone with you who can turn off the power or give **artificial respiration** and/or **cardiopulmonary resuscitation (CPR).** Several electric shocks can cause breathing difficulties and can cause the heart to go into fibrillation.

Work with One Hand When Possible

The worst kind of electric shock occurs when the current path is from one hand to the other, which permits the current to pass directly through the heart. A person can

survive a severe shock between the hand and foot but it would cause death if the current path was from one hand to the other.

Learn First Aid

Anyone working on electric equipment, especially those working with voltages greater than 50 volts, should make an effort to learn first aid. A knowledge of first aid, especially CPR, may save your own or someone else's life.

Avoid Alcohol and Drugs

The use of alcohol and drugs has no place on a work site. Alcohol and drugs are not only dangerous to users and those who work around them; they also cost industry millions of dollars a year. Alcohol and drug abusers kill thousands of people on the highways each year and are just as dangerous on a work site as they are behind the wheel of a vehicle. Many industries have instituted testing policies to screen for alcohol and drugs. A person who tests positive generally receives a warning the first time and is fired the second time.

Effects of Electric Current on the Body

Most people have heard that it is not the voltage that kills but the current. This is true, but do not be misled into thinking that voltage cannot harm you. Voltage is the force that pushes the current though the circuit. It can be compared to the pressure that pushes water through a pipe. The more pressure available, the greater the volume of water flowing through the pipe. Students often ask how much current will flow through the body at a particular voltage. There is no easy answer to this question. The amount of current that can flow at a particular voltage is determined by the resistance of the current path. Different people have different resistances. A body has less resistance on a hot day when sweating, because salt water is a very good conductor. What one eats and drinks for lunch can have an effect on the body's resistance as can the length of the current path. Is the current path between two hands or from one hand to one foot? All of these factors affect body resistance.

Figure S–1 illustrates the effects of different amounts of current on the body. This chart is general—some people may have less tolerance to electricity and others may have a greater tolerance.

A current of 2 to 3 **milliamperes (mA)** (0.002 to 0.003 amperes) usually causes a slight tingling sensation, which increases as current increases and becomes very noticeable at about 10 milliamperes (0.010 amperes). The tingling sensation is very painful at about 20 milliamperes. Currents between 20 and 30 milliamperes cause a person to seize the line and be unable to let go of the circuit. Currents between 30 and 40 milliamperes cause muscular paralysis, and those between 40 and 60 milliamperes cause breathing difficulty. When the current increases to about 100 milliamperes, breathing is extremely difficult. Currents from 100 to 200 milliamperes generally cause death because the heart usually goes into **fibrillation,** a condition in which the heart begins to "quiver" and the pumping action stops. Currents above 200 milliamperes cause the heart to squeeze shut. When the current is removed, the heart usually returns to a normal pumping action. This is the operating principle of a defibrillator. The voltage considered to be the most dangerous to work with is 120 volts, because that generally causes a current flow of between 100 and 200 milliamperes through most people's bodies. Large amounts of current

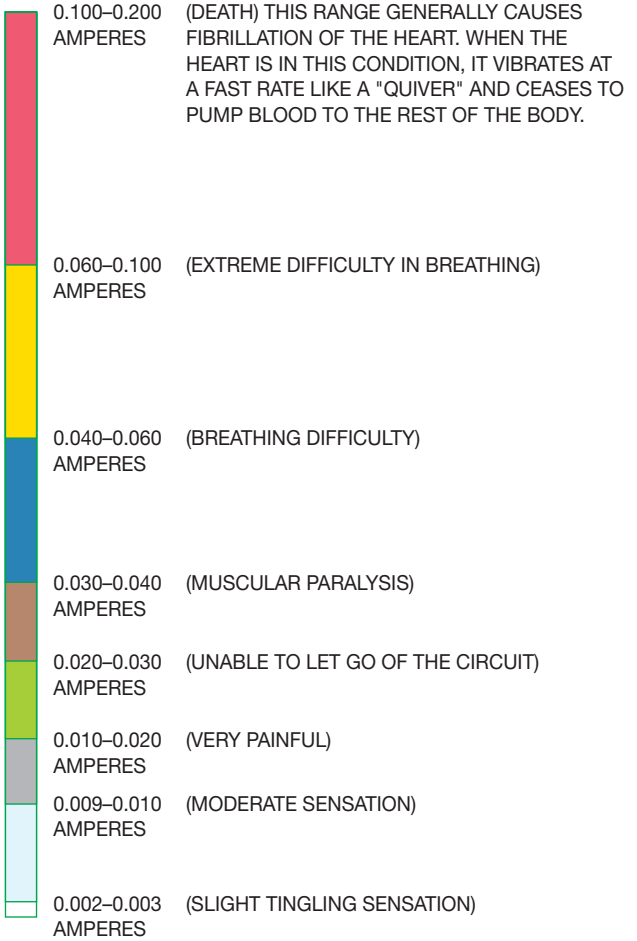


Figure S–1 The effects of electric current on the body.

can cause severe electric burns that are often very serious because they occur on the inside of the body. The exterior of the body may not look seriously burned, but the inside may be severely burned.

On the Job

OSHA

OSHA is an acronym for Occupational Safety and Health Administration, U.S. Department of Labor. Created by Congress in 1971, its mission is to ensure safe and healthful workplaces in the United States. Since its creation, workplace fatalities have been cut in half, and occupational injury and illness rates have declined by 40%. Enforcement of OHSA regulations is the responsibility of the Secretary of Labor.

OSHA standards cover many areas, such as the handling of hazardous materials, fall protection, protective clothing, and hearing and eye protection. Part 1910 Subpart S deals mainly with the regulations concerning electrical safety. These regulations are available in books and can be accessed at the OSHA website at www.osha.org.

Hazardous Materials

It may become necessary to deal with some type of hazardous material. A hazardous material or substance is any substance that if exposed to may result in adverse effects on the health or safety of employees. Hazardous materials may be chemical, biological, or nuclear. OSHA sets standards for dealing with many types of hazardous materials. The required response is determined by the type of hazard associated with the material. Hazardous materials are required to be listed as such. Much information concerning hazardous materials is generally found on **material safety data sheets (MSDS).** (A sample MSDS is shown in Table S-1 at the end of this unit) If you are working in an area that contains hazardous substances, always read any information concerning the handling of the material and any safety precautions that should be observed. After a problem exists is not the time to start looking for information on what to do.

Some hazardous materials require a Hazardous Materials Response Team (HAZMAT) to handle any problems. A HAZMAT is any group of employees designated by the employer that are expected to handle and control an actual or potential leak or spill of a hazardous material. They are expected to work in close proximity to the material. A HAZMAT is not always a fire brigade, and a fire brigade may not necessarily have a HAZMAT. On the other hand, HAZMAT may be part of a fire brigade or fire department.

Employer Responsibilities

Section 5(a)1 of the Occupational Safety and Health Act basically states that employers must furnish each of their employees a place of employment that is free of recognized hazards that are likely to cause death or serious injury. This places the responsibility for compliance on employers. Employers must identify hazards or potential hazards within the work site and eliminate them, control them, or provide employees with suitable protection from them. It is the employee's responsibility to follow the safety procedures set up by the employer.

To help facilitate these safety standards and procedures, OSHA requires that an employer have a competent person oversee implementation and enforcement of these standards and procedures. This person must be able to recognize unsafe or dangerous conditions and have the authority to correct or eliminate them. This person also has the authority to stop work or shut down a work site until safety regulations are met.

MSDS

MSDS stands for material safety data sheets, which are provided with many products. They generally warn users of any hazards associated with the product. They outline the physical and chemical properties of the product; list precautions that should be taken when using the product; and list any potential health hazards, storage consideration, flammability, reactivity, and, in some instances, radioactivity. They sometimes list the name, address, and telephone number of the manufacturer; the MSDS date and emergency telephone numbers; and, usually, information on first aid procedures to use if the product is swallowed or comes in contact with the skin. Safety data sheets can be found on many home products such as cleaning products, insecticides, and flammable liquids.

Trenches

It is often necessary to dig trenches to bury conduit. Under some conditions, these trenches can be deep enough to bury a person if a cave-in occurs. Safety regulations for the shoring of trenches is found in OSHA Standard 1926 Subpart P App C titled "Timber Shoring for Trenches." These procedures and regulations are federally mandated and must be followed. Some general safety rules should be followed, such as:

1. Do not walk close to trenches unless it is necessary. This can cause the dirt to loosen and increase the possibility of a cave-in.
2. Do not jump over trenches if it is possible to walk around them.

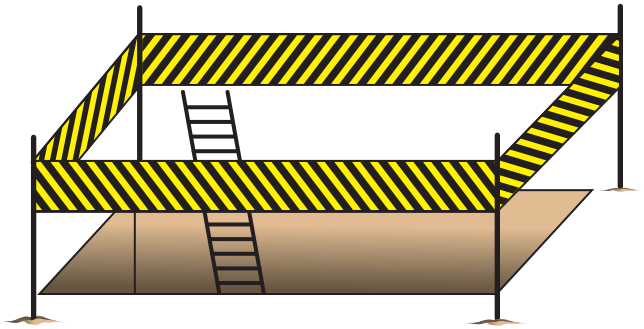


Figure S–2 Place a barricade around a trench and use a ladder to enter and exit the trench.

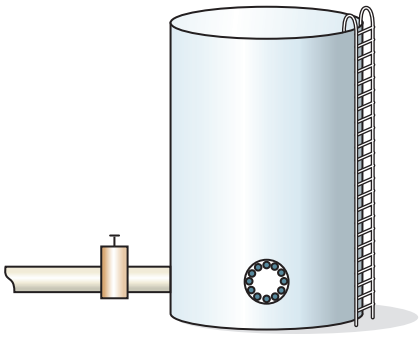


Figure S–3 A confined space is any space having a limited means of entrance or exit.

3. Place barricades around trenches (Figure S–2).
4. Use ladders to enter and exit trenches.

Confined Spaces

Confined spaces have a limited means of entrance or exit (Figure S–3). They can be very hazardous workplaces, often containing atmospheres that are extremely harmful or deadly. Confined spaces are very difficult to ventilate because of their limited openings. It is often necessary for a worker to wear special clothing and use a separate air supply. OSHA Section 12: "Confined Space Hazards" lists rules and regulations for working in a confined space. In addition, many industries have written procedures that must be followed when working in confined spaces. Some general rules include the following:

1. Have a person stationed outside the confined space to watch the person or persons working inside. The outside person should stay in voice or visual contact with the inside workers at all times. He or she should check air sample readings and monitor oxygen and explosive gas levels.
2. The outside person should never enter the space, even in an emergency, but should contact the proper emergency personnel. If he or she enters the space and become incapacitated, no one would be available to call for help.
3. Use only electric equipment and tools that are approved for the atmosphere found inside the confined area. It may be necessary to obtain a burning permit to operate tools that have open brushes and that spark when they are operated.
4. As a general rule, a person working in a confined space should wear a harness with a lanyard that extends to the outside person, so the outside person could pull him or her to safety if necessary.

Lockout and Tagout Procedures

Lockout and tagout procedures are generally employed to prevent someone from energizing a piece of equipment by mistake. This could apply to switches, circuit breakers, or valves. Most industries have their own internal policies and procedures. Some require that a tag similar to the one shown in Figure S–4 be placed on the piece of equipment being serviced; some also require that the equipment be locked out with a padlock. The person performing the work places the lock on the equipment and keeps the key in his or her possession. A device that permits the use of multiple padlocks and a safety tag is shown in Figure S–5. This is used when more than one person is working on the same piece of equipment. Violating lockout and tagout procedures is considered an extremely serious offense in most industries and often results in immediate termination of employment. As a general rule, there are no first-time warnings.

After locking out and tagging a piece of equipment, it should be tested to make certain that it is truly de-energized before working on it. A simple three-step procedure is generally recommended for making certain that a piece of electric equipment is de-energized. A voltage tester or voltmeter that has a high enough range to safely test the voltage is employed. The procedure is as follows:

1. Test the voltage tester or voltmeter on a known **energized circuit** to make certain the tester is working properly.
2. Test the circuit you intend to work on with the voltage tester or voltmeter to make sure that it is truly de-energized.
3. Test the voltage tester or voltmeter on a known energized circuit to make sure that the tester is still working properly.

This simple procedure helps to eliminate the possibility of a faulty piece of equipment indicating that a circuit is de-energized when it is not.

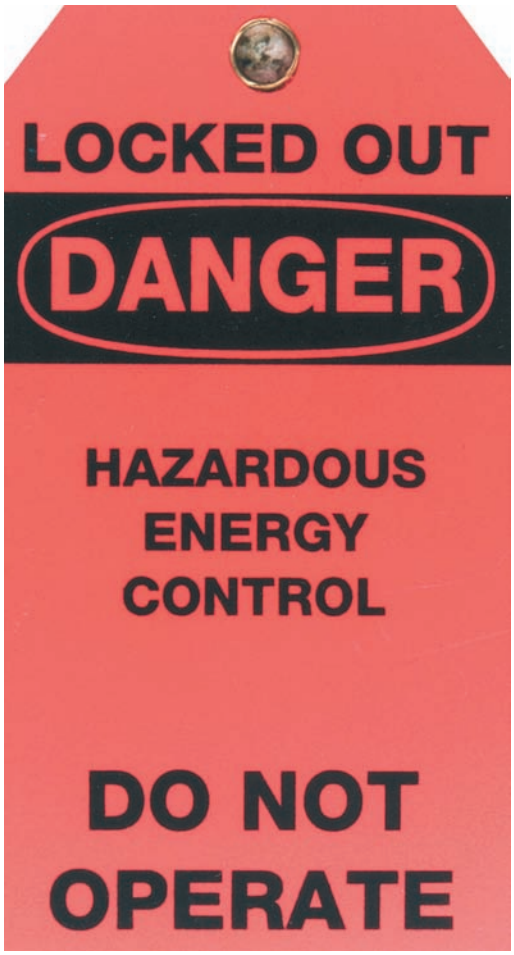


Figure S–4 Safety tag used to tagout equipment.

Protective Clothing

Maintenance and construction workers alike are usually required to wear certain articles of protective clothing, dictated by the environment of the work area and the job being performed.

Head Protection

Some type of head protection is required on almost any work site. A typical electrician's hard hat, made of nonconductive plastic, is shown in Figure S–6. It has a pair of safety goggles attached that can be used when desired or necessary.

Eye Protection

Eye protection is another piece of safety gear required on almost all work sites. Eye protection can come in different forms, ranging from the goggles shown in Figure S–6 to the safety glasses with side shields shown in Figure S–7. Common safety glasses may or may not be prescription glasses, but almost all provide side protection (Figure S–7). Sometimes a full face shield may be required.

Hearing Protection

Section III, Chapter 5 of the OSHA Technical Manual includes requirements concerning hearing protection. The need for hearing protection is based on the ambient sound level of the work site or the industrial location. Workers

Figure S–5 The equipment can be locked out by several different people.

Figure S–6 Typical electrician's hard hat with attached safety goggles.

Figure S–7 Safety glasses provide side protection.

are usually required to wear some type of hearing protection when working in certain areas, usually in the form of earplugs or earmuffs.

Fire-Retardant Clothing

Special clothing made of fire-retardant material is required in some areas, generally certain industries as opposed to all work sites. **Fire-retardant clothing** is often required for maintenance personnel who work with high-power sources such as transformer installations and motor-control centers. An arc flash in a motor-control center can easily catch a person's clothes on fire. The typical motor-control center can produce enough energy during an arc flash to kill a person 30 feet away.

Gloves

Another common article of safety clothing is gloves. Electricians often wear leather gloves with rubber inserts when it is necessary to work on energized circuits (Figure S–8). These gloves are usually rated for a certain amount of voltage. They should be inspected for holes or tears before they are used. Kevlar gloves (Figure S–9) help protect against cuts when stripping cable with a sharp blade.

Safety Harness

Safety harnesses provide protection from falling. They buckle around the upper body with leg, shoulder, and chest straps; and the back has a heavy metal D-ring (Figure S–10). A section of rope approximately 6 feet in length, called a lanyard, is attached to the D-ring and secured to a stable structure above the worker. If the worker falls, the lanyard

Figure S–8 Leather gloves with rubber inserts.

Figure S–9 Kevlar gloves protect against cuts.

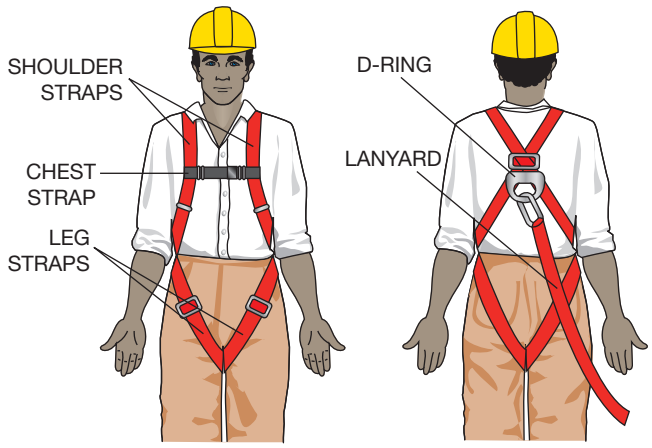


Figure S–10 Typical safety harness.

limits the distance he or she can drop. A safety harness should be worn:

1. When working more than 6 feet above the ground or floor
2. When working near a hole or drop-off
3. When working on high scaffolding

A safety harness is shown in Figure S–11.

Ladders and Scaffolds

It is often necessary to work in an elevated location. When this is the case, ladders or scaffolds are employed. **Scaffolds** generally provide the safest elevated working platforms. They are commonly assembled on the work site from standard sections (Figure S–12). The bottom sections usually contain adjustable feet that can be used to level the sections. Two end sections are connected by X braces that form a rigid work platform (Figure S–13). Sections of scaffolding are stacked on top of each other to reach the desired height.

Figure S–11 Safety harness.

Rolling Scaffolds

Rolling scaffolds are used in areas that contain level floors, such as inside a building. The major difference between a rolling scaffold and those discussed previously is that it is equipped with wheels on the bottom section that permit it to be moved from one position to another. The wheels usually contain a mechanism that permits them to be locked after the scaffold is rolled to the desired location.

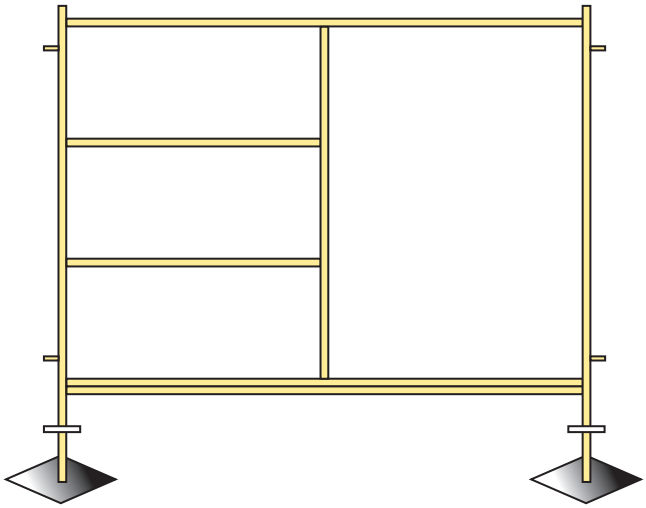


Figure S–12 Typical section of scaffolding.

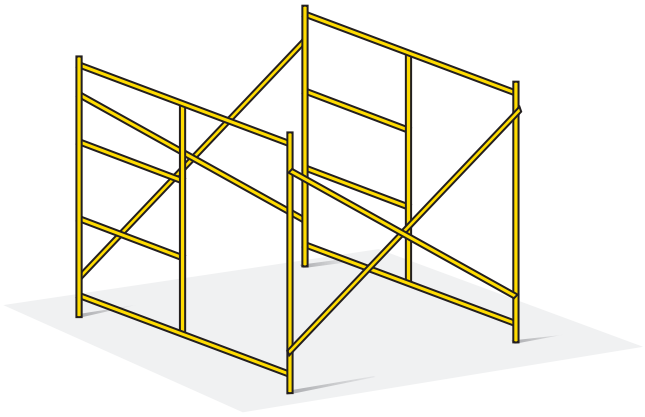


Figure S–13 X braces connect scaffolding sections together.

Hanging or Suspended Scaffolds

Hanging or suspended scaffolds are suspended by cables from a support structure. They are generally used on the sides of buildings to raise and lower workers by using hand cranks or electric motors.

Straight Ladders

Ladders can be divided into two main types, straight and step. Straight ladders are constructed by placing rungs between two parallel rails (Figure S–14). They generally contain safety feet on one end that help prevent the ladder from slipping. Ladders used for electrical work are usually wood or fiberglass; aluminum ladders are avoided because they conduct electricity. Regardless of the type of ladder used, you should check its load capacity before using it. This information is found on the side of the ladder. Load capacities of 200 pounds, 250 pounds, and 300 pounds are common. Do not use a ladder that does not have enough load capacity to support your weight plus the weight of your tools and the weight of any object you are taking up the ladder with you.

Straight ladders should be placed against the side of a building or other structure at an angle of approximately 76° (Figure S–15). This can be accomplished by moving the base of the ladder away from the structure a distance equal to one fourth the height of the ladder. If the ladder is 20 feet high, it should be placed 5 feet from the base of the structure. If the ladder is to provide access to the top of the structure, it should extend 3 feet above the structure.

Step Ladders

Step ladders are self-supporting, constructed of two sections hinged at the top (Figure S–16). The front section has two rails and steps, the rear portion two rails and braces.

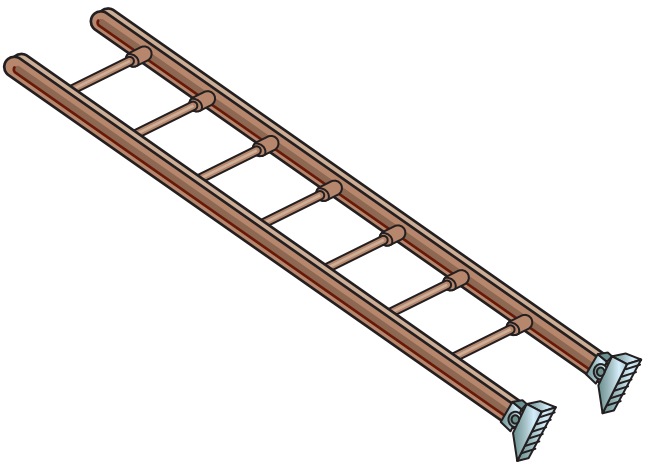


Figure S–14 Straight ladder.

Like straight ladders, step ladders are designed to withstand a certain load capacity. Always check the load capacity before using a ladder. As a general rule, ladder manufacturers recommend that the top step not be used because of the danger of becoming unbalanced and falling. Many people mistakenly think the top step is the top of the ladder, but it is actually the last step before the ladder top.

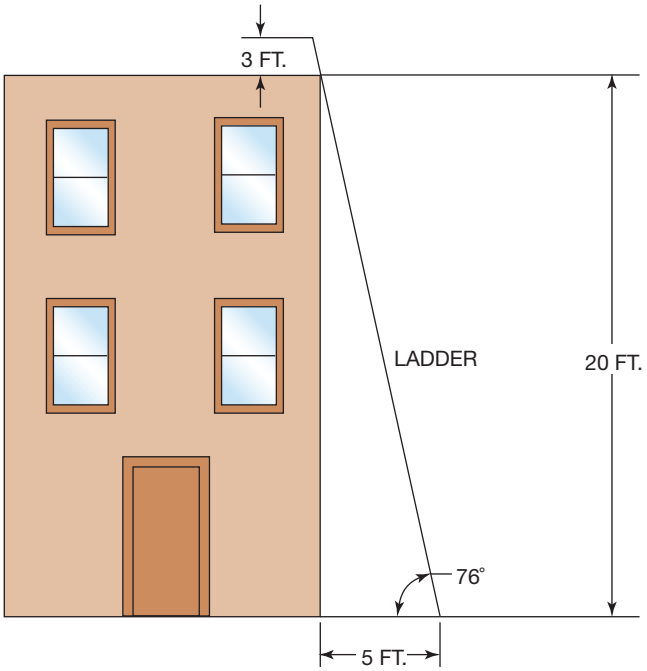


Figure S–15 A ladder should be placed at an angle of approximately 76°.

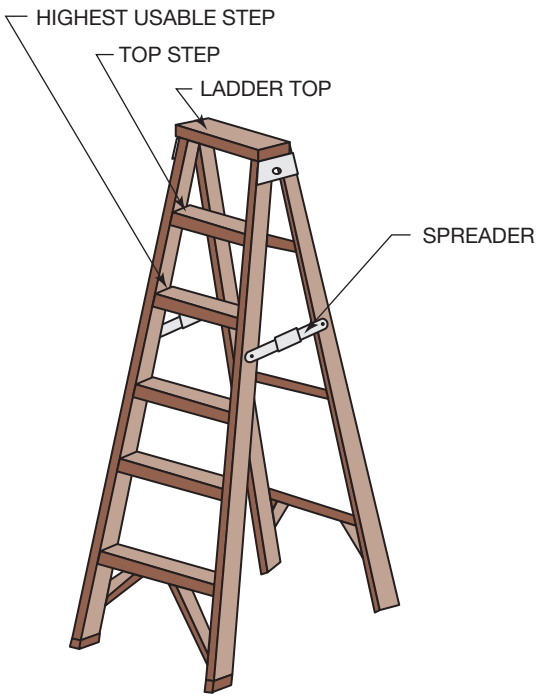


Figure S–16 Typical step ladder.