Connector Theory and Application
A Guide to Connection Design and Specification

Revised 4th Edition

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Introduction

Electrical connectors, in their simplest form, join two or more conductors in a continuous, electrically conductive path.

This paper introduces various connector applications and their related conditions to consider when selecting an appropriate means of electrical connection. We recommend basing the selection of an electrical connector first on sound technical reasoning, and then from the ensuing options finalize a selection around three fundamental criteria - safety, reliability, and cost - for the specific application. It is the intent of this paper to provide the technical background enabling sound judgment when selecting an appropriate means of connection suitable for a particular application.

1.0 THEORY OF CONNECTOR TECHNOLOGY

An all-encompassing treatise on connector theory can become quite involved and confusing if not subdivided into manageable topics. Indeed, even with a topical outline, there are numerous issues that can, and will, overlap from one discussion to another. Regardless of the means of connection, its application, or its function, however, all electrical connections have one fundamental objective; to provide a path of electrical conduction between the conductors being joined. An inherent result of this objective is that an electrical connection must exhibit low bond, or contact, resistance.

Two conductor surfaces in contact (e.g., connector and cable) can never be perfectly matched. On a microscopic level, each surface resembles rough terrain with peaks and valleys. When the two surfaces come together, the peaks and valleys from one will randomly match up with those on the other surface. Where direct contact occurs, the resistance from one surface to the other is theoretically zero; i.e., there is no voltage drop across the immediate interface.

In actuality, however, there may be very few points of direct contact, also known as “A-spots,” between the two surfaces (see Figure 1.4-1). If a voltage were applied across the mating surfaces, a current will flow, but only through the contact points. The restriction of current flow to these few points constitutes the contact resistance.

For an electrical connector to achieve its objective, therefore, it must create as many contacting points as possible with the conductor. The more contact points that can be established within a given area, the lower the contact resistance. A connector’s long term performance is directly related to the contact points originally established. Not only must the connector maximize the contact points during installation, it must maintain that contact over the intended life of the connection.

Although the premise of creating an electrical connection seems simple, many factors influence a connection’s ability to first establish, and then maintain, a low contact resistance. Surface contaminants or corrosion will interfere with establishing initial contact, thermal fatigue can loosen the connector and reduce the number of contact points, and mechanical stress and long term corrosion can diminish surface contact directly or indirectly by attacking the structural integrity of the connector.

These subjects, and many others, are discussed in the balance of this treatise. By subdividing the many topics to be covered, as alluded to earlier, the main issues concerning effective electrical connection can be addressed.
connector design, specification, and installation may be more fully addressed. The subdivisions described below provide the foundation to begin our coverage of the important concepts in connector theory.

Connector application is the first categorization under which the discussion of connector theory will continue. Application is the lead topic due to when selecting a connector, the first determinable piece of information is usually the application. Application begins to differentiate connections because concerns within one application category may not be an issue within another, and vice versa. Application categorization further allows the development of the theory around the specific concerns related to each area of use. Sections 1.1 through 1.5 discuss specific application categories; (1.1) grounding and bonding, (1.2) substation, (1.3) underground distribution, (1.4) overhead, and (1.5) service entrance.

A second means for connector differentiation is function. There are three general connector functions; tap, terminal, and splice. Although some overlap can occur here, a connector will typically have a primary function that allows for distinction. Section 1.6 discusses the fundamental differences between functions and potential areas of overlap in order to provide a consistent basis to define and differentiate a connection function.

Finally, there are various means of connection that allow a connector to perform its function within an application. Section 1.7 examines the various means of connection, or connector types (mechanical, compression, wedge, fusion, etc.) in detail to provide an understanding of the theory behind the technology employed.

1.1 Grounding and Bonding

There are several main objectives for providing a well-designed ground system; safety of personnel tops the list, followed by equipment protection, signal reference quality, return path for faults and/or surges, and static dissipation. In order to meet these objectives, ground system interconnections must maintain a low contact resistance (see 1.4.1), often under adverse conditions, for the expected life of the ground system. Connections in a ground network are subject to severe corrosion, high mechanical stress due to electromagnetic forces, and rapid thermal heating (see 1.4.2) due to high current magnitudes during fault conditions.

1.1.1 Corrosion

Grounding connections have applications both above and below grade and, as such, are subject to various kinds of corrosion.

Above grade corrosion takes place mainly through galvanic action when exposed to an electrolytic source. This type of corrosion is most pronounced when the connector material differs significantly from the conductor material in nobility. In the presence of an electrolytic solution, an electrolytic cell forms allowing corrosive current to flow from the anodic material to the cathodic material. Over time, the loss of ions from the anodic material (be it the connection or the conductor) will cause a reduction in overall performance of the connection and possibly eventual failure. Like metals in direct contact are subject to minimal, if any, galvanic corrosion as an electric potential is difficult to establish.

Below grade environments will also expose a connection to conditions that cause galvanic corrosion (see Figure 1.1-1). In addition, below grade connections are subject to acidic corrosion. Soil conditions may vary greatly from one location to the next, and soil pH will vary accordingly. Acidic soils can be especially harsh on alloy materials. For example, high-zinc brasses generally perform poorly in naturally occurring acidic ground soils. Alternatively, pure copper and high copper content alloys generally perform very well in most soil conditions.
1.1.2 Fault Current

A primary task of the ground system, to safely conduct fault currents to ground, is also a leading source of stress on ground connections. Electromagnetic forces develop quickly and mechanically stress the entire ground system, including the connection points. The magnitude and direction of the mechanical force are related to the path of conduction, conductor proximity, and the fault current magnitude.

In addition to the physical strain, ground connections must also withstand high thermal shock due to the passing of fault current. Depending on how the ground system electrodes were sized, conductor temperatures may reach 250°C (maximum for copper in tension applications) to well in excess of 600°C. The connector must be capable of handling these extreme temperatures without loss of integrity.

1.1.3 Special Ground Applications

Special conditions arise in the ground system when considering all structures that require bonding to the ground network. In order to protect personnel from hazardous voltage potentials, non-circuit, conductive structures such as fences, water pipes, and structural steel need to be bonded to the ground system. These structures often require special considerations for connection due to their materials and geometric configuration.

Fence posts, gates, mesh and barbed wire often require bonding to the ground system. Post connections require connectors suitable for a pipe geometry. Connections to gates require flexibility to resist breakage during repeated open and close cycles.

Connections to pipes (including posts, water pipes, conduit, etc.) are subject to galvanic corrosion, especially when the pipes are iron derivatives. Most pipe connectors are mechanical and made of copper or copper-based alloys to ensure a long lasting connection to the ground lead. Mechanical connectors allow for connecting directly to the circumference of the pipe, although in low current applications a connection made at the pipe flange is also suitable.

In some instances, connections to pipe are made by welding. However, before welding to a pipe, it is necessary to fully understand its usage. The pipe wall or flange will be structurally weakened by the intense heat of the welding process, and could eventually lead to an operational failure. When in doubt as to the extent of damage that the weld will cause, it is best to use alternate means of connection.

Figure 1.1-1  Galvanic corrosion between steel ground rod and copper connection.

Corrosive loss of ions

ANODE

CATHODE

Ground rod - unplated steel

Connection - copper

Electrolyte

Galvanic current flow
Connecting to structural steel has similar requirements to those described for pipe including unique configuration, potential for corrosion, and structural dependence. Many structure design engineers and architects will not allow drilling or welding to the steel I-beams or rebar. As a result, alternate connection means are necessary. Figure 1.1-2 depicts a mechanical I-beam connector with compression ground rod connections used in a temporary ground application.

Corrosion protectant coatings are an important consideration when making connections to non-circuit components. Painted enclosures or epoxied surfaces must be stripped of these non-conductive coatings before connections are made. With plated surfaces such as galvanized steel, however, the plating should not be removed. Platings are specified to increase the longevity of the primary function of the item. In these cases, it may not be possible to use welding processes to make connections. The extreme heat will melt the plating and expose the base material to corrosion.

Regardless of the type of finish present, the area of contact should be cleaned and a suitable oxide inhibiting compound applied prior to making the connection. In addition, connections to the ground system should be made on both sides of non-metallic couplers; for example, those used for joining pipe sections.

A minimal requirement for ground connectors should be the ability to pass UL 467 Standard for Grounding and Bonding. By meeting the requirements in this standard, the user can be confident that the connector is greater than 80% copper (if marked “direct burial”) and has withstood a fault current test. Alternate connector testing may be substituted, but none should require less than UL 467 criteria.

IEEE Std 837 Standard for Qualifying Permanent Connections Used in Substation Grounding exceeds the requirements of all other ground connection performance standards. IEEE Std 837 testing closely simulates the application performance requirements of substation ground connections. Mechanical and electrical strength is tested with pullout and electromagnetic force tests, and longevity is proved through sequential testing on the same set of connectors and includes static heat cycling, freeze-thaw cycling, corrosion exposure (acidic or alkaline), and finally fault current. Connectors passing IEEE Std 837 are suitable for all grounding applications and require no special considerations, such as temperature de-rating.

1.2 Substation

Substations are the source of energy-supply for local area distribution, select user sites, or even a specific customer. The main function of the substation is to step down voltage from the transmission or sub-transmission level to the distribution level. In order to achieve this directive, substations employ various devices for safety, switching and voltage regulation, and measurement. Substations are usually located at or near the center of the distribution area, may be indoors or exposed outdoors, and operated manually or automatically.
1.2.1 Distribution Substations

A substation that is centrally located within the load area is called a distribution substation. Distribution substations may be as close as two miles from each other in densely populated areas. These substations may also be located near a large manufacturing facility or inside a high-rise building to supply immediate, high-load customer needs.

![Figure 1.2-1 Distribution Substation](image)

Distribution substations contain many components, a few of which are power transformers, circuit breakers, and voltage regulators. The power transformers are the heart of the distribution substation, performing the main task of stepping down sub-transmission voltages to distribution voltages (normally ranging from 4.16Y/2.4 kV to 34.5Y/19.92 kV). Circuit breakers are placed between the distribution circuits and low-voltage bus for substation protection during fault or surge conditions. Voltage regulators are installed in series on each distribution circuit if the power transformers are not equipped with automatic tap changing capabilities that enable bus voltage regulation.

1.2.2 Conductors

Bus bars (or bus) are the main current carrying conductors within a substation. Buses are constructed of either copper or aluminum, and are supplied in many configurations, including rectangular bars, round tubing, square tubing, stranded cables, and solid circular bars. They are also available both insulated and uninsulated depending on requirements.

1.2.3 Substation Connector Design

The challenge for substation connector designs is to meet both the dimensional and electrical constraints. Mechanical connectors are often used for substation connections due to their adaptability to sizing. With these connectors, fastening hardware is usually located as close to and on opposing sides of the conductor to provide uniform clamping forces. (See Figure 1.2-2)

![Figure 1.2-2 Mechanical Substation Connector](image)

As aforementioned, transformers are the main pieces of equipment within the distribution system. Many types of transformers exist (pole, vault, pad-mount, submersible, direct-buried, etc.) however, the methods of connecting to them are generally similar. Each transformer will provide primary (high-voltage) and secondary (low-voltage) bushings.

Proper connector selection is crucial for providing efficient, long-term performance of the equipment/conductor connection. One type of connection used successfully on the primary bushings is a pin terminal to an eye-and-basket connection. The pin terminal is crimped to the wire conductor and then inserted into the eye-and-basket tap, which is then torqued to the manufacturer’s recommended value.
The secondary bushings may be fitted with a secondary bus, allowing connections to multi-wire services via bus clamps and supports. Other terminations allowed include multi-tap terminal adapters, stacking (spacer) adapters, and threaded spade/stud terminals.

All connections made to the distribution transformer must be capable of withstanding the rigors of the environment. Outdoor distribution equipment is exposed to winds, rain, extreme temperature variations, and ice. Indoor equipment (e.g. unheated buildings, man holes, and vaults) is subject to moisture, flooding, extreme temperatures, crowded space, and corrosion.

1.3 Underground Distribution

Nowhere in the distribution of electric power are the problems of installing, connecting and protecting conductors and equipment as complex as in underground systems. It is for this reason that there are special designs for devices used in underground distribution systems.

There are generally two types of underground distribution systems; radial (Figure 1.3-1) and network (Figure 1.3-2). The radial system is analogous to a wheel with spokes emanating out from the center. Main power is delivered to a central point, and from there is divided on series branch circuits to supply services to individual customers. The network system is much like a paralleled grid and, due to its reliability, has become the standard for underground distribution systems where load density is high.

Over time, improved methods have been developed to reduce the cost of installation and maintenance for each of these underground systems.

1.3.1 Design Objectives

While specific types of equipment designs meet particular service requirements, all have several basic objectives in common.

Reliability: Underground networks typically serve high load density areas. As a result, an uncontrolled failure in one area could affect the service to many customers. The need for reliability becomes obvious in this situation.

Installation: Working on underground networks will mean working in confined spaces, such as manholes and transformer vaults. Devices made for underground networks must be simple to install with minimum space requirements.
Economy: By minimizing the complications of installation and maximizing their reliability, devices used for underground systems become economical.

Versatility: Always remember that, like other distribution circuits, underground networks continually change and expand. Devices used in underground networks must allow for easily adapting the network to present and future needs.

Safety: Safety must be a consideration in all design objectives. Safety in design includes providing for forgiving design tolerances, making installation easy and relatively error free, and allowing for operation under non-ideal conditions.

1.3.2 Underground Secondary Networks

Underground secondary networks (see Figure 1.3-2) provide a means to distribute electric service to customers in congested areas. In the network, more than one transformer source supplies the secondary feeds. When placed in parallel, the secondary feeders form a grid in which the end customer receives service, in essence, from more than one source. Each crossing point of the grid typically requires one, or more, junction connections with appropriate circuit protection. This arrangement provides the reliable service for which underground networks are noted.

The whole underground network starts with the primary feeders and switches. Voltages are stepped down for distribution by the network transformers, which are protected by relays and backed up by network protectors. The secondary cables (primarily copper) feed into the secondary network through connector banks, and are typically protected by limiters. At various locations within the network, service cables tap off the secondary cables for providing individual services.

Smaller versions of underground networks, called “spot” networks, exist to service an individual concentrated load such as an office building. Although not as expansive, the spot network would have the same components as the underground network described above.

1.3.3 Special Considerations

Underground cables, connections and equipment are subject to continual or sporadic high moisture conditions. It is, therefore, necessary for all underground system components to be completely watertight, yet be capable of maintaining their long-term mechanical, electrical, and dielectric properties. When moisture is not of concern, such as in a ground level vault, the watertight properties are not necessary. However, watertight covering should still be considered if there is a reasonable chance of flooding or high humidity conditions to occur.

1.3.4 Network Protection

Due to the limited access of underground cable, faults on underground systems pose a threat to system safety and long term reliability if not properly protected. Therefore, the main purpose of network protection devices is to protect the weakest link in the system, the cable insulation.

Network protection devices, commonly known as limiters, interrupt fault conditions while allowing temporary overload situations to occur. The two types of faults cleared by limiters are sustained faults (fault conductors solidly in contact causing high current flow) and arcing faults (intermittent contact causing a “slow roast” of conductor insulation). Temporary overload conditions are expected on networks and limiter time-current characteristics are appropriately designed to prevent nuisance blowing.

Normal system protection design methods should be followed for coordinating the limiters with other circuit protection devices, including circuit relays, fuses, and breakers. Appropriate locations must also be selected for network protection to localize the fault and prevent unnecessary outages.
Limiters protect a variety of copper cable insulation types. Table 1.3-1 provides a listing of some of the most common underground cable types protected by limiters.

<table>
<thead>
<tr>
<th>Insulation</th>
<th>Jacket</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mineral base rubber compound or poly</td>
<td>Lead-sheath</td>
</tr>
<tr>
<td>Mineral base rubber compound or poly</td>
<td>Non-leaded braid covered</td>
</tr>
<tr>
<td>Mineral base rubber compound or poly</td>
<td>Non-leaded neoprene</td>
</tr>
<tr>
<td>Paper insulated</td>
<td>Lead-sheath</td>
</tr>
<tr>
<td>Varnished cambric</td>
<td>Lead-sheath</td>
</tr>
</tbody>
</table>

1.4 Overhead

Transmission voltages are stepped down at the substation for distribution to the local area. Each substation supplies its local area through distribution feeders operating at voltages from 2.4 kV up to as much as 64 kV. Pole transformers in the overhead network step down the distribution voltages to 120/240 V for the secondary feeds to the customer.

Selection of connectors for use on overhead applications is dependent on the type of conductor being used (aluminum, ACSR, copper, etc.), operational voltages, environmental considerations, whether the system remains energized or not, and the means of access (pole, ladder, bucket, etc.).

A good electrical connection requires three basic elements: the proper connector, suitable cable preparation, and correct installation procedures. In addition, field related conditions such as temperature, environment, and condition of the conductor are not controllable and will obstruct attempts at producing a suitable electrical connection. Therefore, the connector design must be able to compensate for these varying field conditions.

1.4.1 Thermal Expansion and Contraction

Normal operating conditions in overhead distribution will include periods of high load. Under these conditions, it is very reasonable to assume a conductor can reach operating temperatures in excess of 150°F (66°C). At this temperature, an aluminum conductor mechanically loaded under 18 000 lb/in² will move approximately 0.01 inches per inch per hour. A copper conductor under similar conditions will creep only 0.000003 inches per inch per hour.

Therefore, when designing and selecting connectors for aluminum conductor, the contact area must be large in order to minimize the applied pressure. Lower mechanical loading will keep the creep rate under control.

When connecting dissimilar metals, the different expansion rates must be taken into account. Deep cup Belleville washers are typically used in mechanical connections to maintain retention of force between the mating surfaces over wide operating temperature variations. Clamp type connectors for tap connections employ appreciably longer contact areas than that of standard compression connectors, thereby minimizing the effect of creep in both the conductor and the connector. Copper compression connectors must never be used for connecting to aluminum conductor. The high expansion rate of aluminum compared to copper will eventually loosen the connection and cause a failure.

Copper conductors, as previously seen, have considerably less creep than aluminum conductors. Thus, when making connections to copper conductors, creep is generally not a concern. What is important to consider, however, is the I2R heat generation and the connection's ability to dissipate thermal energy. If high contact resistance results from low applied forces or alloy metals are used in the connector, then the connector must be made with adequate mass to dissipate the heat.
1.4.2 Mechanical Integrity

How secure must a connection be is the key question to mechanical integrity. For the overhead distribution system, connections will require a full range of mechanical secureness; from full tension applications (95% of the ASTM rated breaking strength of the conductor) to strain relieved applications where little mechanical stress or vibration will occur.

Pullout tests and secureness tests are used to determine the adequacy of a connector’s mechanical integrity. Pullout testing is used to establish the connector’s minimum performance level for overhead lines in tension. Secureness tests involve rotating a hanging weight from the conductor held by the connector to simulate mechanical disturbances. Vibration testing is also necessary for checking for metal fatigue over the spectrum of oscillations anticipated in service.

An additional requirement for mechanical connectors is the ability to withstand approximately 50% more than the recommended torque. These connectors are tested in this manner to account for error in installation.

1.4.3 Dielectric Fundamentals

High voltage connector applications require special considerations due to high voltage stress concentrations. Sharp edges and non-smooth conductive surfaces produce concentrated voltage gradients that can become sources of corona (ionization of air due to voltage stress). Connectors for high voltage applications are available in uninsulated and preinsulated forms. Uninsulated connectors for high voltage applications are designed with smooth, tapered surfaces. The smooth design reduces the likelihood of voltage stress and facilitates the use of semi-conductive tape to further reduce voltage stress. Field covering may also be used for dielectric insulation or as a shield in preventing excessive voltage stresses. Preinsulated, high-voltage connectors are designed to minimize corona that deteriorates insulation.

1.4.4 Corrosion

There are two general types of corrosion that are of concern in overhead distribution connections. Oxidation and galvanic corrosion affect both the initial contact and the long-term performance of an electrical connection.

Oxidation can develop on both the connector and the conductor to be joined. Copper oxide forms on copper and copper alloy surfaces and is low in conductivity. Evidence of copper oxide can be seen as a black or green surface discoloration. Copper oxide layers will reduce the number of contacting points in a connection, thus increasing the contact resistance. The conductors should be cleaned prior to making a connection.

Aluminum oxide, however, is a fast forming, hard, non-conductive coating that develops on the surface of aluminum conductors exposed to air. Unlike copper oxides, aluminum oxide is not visually obvious and should be assumed to exist in all cases of bare aluminum. Aluminum oxide must be removed from a conductor’s surface prior to making a connection. Wire brushing and the immediate application of an oxide inhibitor are recommended to prevent the reformation of the non-conductive coating prior to connector installation. (See section 2.1.1.1 Contact Surface Preparation for further details on preparing conductor surfaces for connection.) An alternate method that is used to achieve low contact resistance is for the connection methodology to physically break through the aluminum oxide layer as the connection is being made. Even with these types of connections, however, cleaning is still recommended prior to installation.

An additional problem with aluminum cable is the oxide layers that develop on each inner strand of a cable. These layers can cause high inter-strand resistance and are not easily removed. This problem is accentuated in compact conductor that restricts the movement of the strands during the application of force applied during connector installation. In these cases, the use of a contact aid with particle additives helps in breaking
through inter-strand oxidation layers and in establishing the required contact spots.

The major cause of long term, overhead connector deterioration is galvanic corrosion. (See section 1.1.1 Grounding and Bonding Corrosion for further details on the principles of galvanic corrosion.) Both aluminum and copper conductors are used in the overhead distribution system. This use of dissimilar metals can lead to problems of galvanic corrosion if no preventative action is taken. Aluminum is the anode in the galvanic cell that is formed when in contact with copper, and is therefore the material that undergoes the corrosion. For applications that bring aluminum in to direct contact with copper, the aluminum is intentionally made to be massive in comparison to the copper. This “mass anode” principle relies on the creation of many paths of corrosion such that the corrosive current flow is minimized and insignificant amounts of the connector body are sacrificed over time.

Plating of aluminum connectors has been used to reduce the potential of the galvanic cell when applied to copper. In order to tin plate an aluminum connector, however, a copper or nickel flash must be applied first. If a scratch were to occur to the plating, a concentrated region of galvanic corrosion will develop and can result in deep pitting of the connector. This pitting may eventually lead to a failure in mechanical integrity of the connector. Due to the likelihood of concentrated corrosion to occur in this manner, and the added expense, tin plated aluminum connectors are usually not recommended for overhead applications. Plating of the cathodic material, in reverse, can be used effectively to prevent galvanic corrosion.

Finally, aluminum conductors should be installed above copper conductors. Moisture forming on copper conductors (rain or condensation) will pick up copper ions. If this moisture then drops onto aluminum conductors below, the copper salts will cause the aluminum conductor to corrode.

1.4.5 Performance Testing
(ANSI C119.4)

Initially developed under the direction of the Edison Electric Institute (EEI) in 1958, the ANSI C119.4 standard has evolved through experience and extensive trials into its present day form. An independent committee comprised of government agencies, autonomous electrical associations, and manufacturers continues to review and update this standard to relate it to modern test technology.

ANSI C119.4 specifies current cycle and mechanical tests for establishing a basis of performance for electrical connectors used to join aluminum-to-aluminum or aluminum-to-copper bare overhead conductors. This standard provides well-defined, reproducible requirements for electrical connectors and assures the user that connectors meeting these requirements will perform in a satisfactory manner when properly installed.

Current cycle testing consists of a current-ON and a current-OFF period; heating and cooling the test assembly. Resistance and temperature measurements taken at specified intervals provide the pass/fail criteria of the test. The number of cycles performed determines the current class of the connector: heavy duty (Class A) = 500 cycles, medium duty (Class B) = 250 cycles, and light duty (Class C) = 125 cycles.

Mechanical testing consists of pullout strength tests to compare the connector’s results with the rated conductor strength per the applicable ASTM conductor standards. Three classifications result from the mechanical testing: (1) Class 1, full tension = 95% of the rated conductor strength of the conductor being joined, (2) Class 2, partial tension = 40% of the rated conductor strength of the conductor being joined, and (3) Class 3, minimum tension = 5% of the rated conductor strength of the conductor being joined.

Reference the latest revision of ANSI C119.4 for actual test values and requirements.
1.5 **Service Entrance**

The point where low-voltage lines, or services, connect the secondary main conductors to the customer's building is called the service entrance. Services may be either overhead or underground and usually depend on the type of distribution system from which they originate. However, underground services are frequently installed even from an overhead secondary main in order to eliminate aerial wires from crossing the customer's property.

The size of the service wire used is determined by the size of the anticipated electrical load. Underground services require large enough conductors to avoid replacement if the customer's load increases. Overhead services can be matched to the customer's present needs as they are readily accessible for replacement, and close matching reduces the initial investment.

### 1.5.1 Secondary Conductor

Economy and appearance dictate the use of several separate wires twisted into a cable for use as secondary mains and for service connections to buildings. These twisted wires, called "triplex," consist of two insulated phase wires and a bare, uninsulated neutral conductor that may also act as the supporting wire for the bundle. The twisted combination is strung from pole-to-pole as a secondary main or from pole-to-building as a service drop connection. Other bundle combinations exist; for example two wire bundles (duplex), and four wire bundles (quadruplex). The individual wires are usually aluminum or ACSR, sized from #6 AWG to as large as 336.4 kcmil depending on service requirements.

### 1.5.2 Service Connectors

Service entrance applications require a relatively small number of connector types. The connectors most often required are splices and parallel taps, which are available in both insulated and uninsulated, mechanical and compression forms.

When connecting insulated conductor, only insulated splices and taps should be used. Insulated connectors are designed to seal out contaminants and moisture to minimize the effects of galvanic corrosion. When connecting to the uninsulated neutral conductor, however, only uninsulated connectors should be used. The absence of insulation on the neutral wire prevents an insulated connector from fully sealing out moisture. Premature failure can result from corrosion as a direct result of captured moisture within the connector's insulation.

Covers are often provided for service connectors and should not be confused with insulation. Covers are intended to protect against brush contact, and normally will have holes to allow moisture to drain, preventing premature failure due to corrosion.

Regardless of the type of connector used, one of the most important features of the service connector is easy installation. In many cases, the installer will be on a ladder and/or in an awkward situation. Ease of installation reduces the chance of injury by minimizing time spent in a precarious position. In the case of the service compression splice, specific mechanical compression tools are available to assist the installer with the connection installation. New battery powered tool technology can further support ease and reliability of installation.

### 1.6 Function

The three fundamental connector functions are tap, terminal, and splice. In order to categorize connectors based on function, a clear understanding of these terms is necessary. The definitions and examples that follow will begin to differentiate the three main functions.

#### 1.6.1 Tap

Electrical tap: an electrical connection to a main, continuous-run conductor for supplying electrical energy to a branch application(s) from the main run's principal load. Figure 1.6-1 illustrates the tap configuration.
1.6.2 Terminal

Electrical terminal: a connection used to join two different forms of conductor, often incorporating more than one means of connection methodology.

1.6.3 Splice

Electrical splice: a connection that joins two (or more) similar but non-continuous conductors into one continuous run; or that joins together two unconnected continuous runs. Figure 1.6-3 depicts several typical splice configurations.

1.7 Types of Connectors

The types of connectors developed over many years generally fall into three broad categories: mechanical, compression, and fusion. Mechanical connections employ hardware or similar mechanical means to create contact points and to maintain the connection integrity. Compression connections use engineered tooling to crimp the connector to the conductor with high force, creating a permanent electrical joint. Fusion connections are made primarily by welding, soldering or brazing. The following sections discuss the properties of each of these connector design categories, or specific connections contained therein.

1.7.1 Mechanical Connectors

Basic contact theory describes how electrical contact is established between conductors by the application of mechanical force. Even when the applied force is low, the resistance at a contact point is, in theory, zero (in practice, resistance is extremely low; typically in the micro-ohm range or lower).

However, there are many factors other than contact resistance to consider.

The mechanical connectors developed over the past few decades overcome many of the installation complications ascribed to fusion connection methods, such as soldering and welding. Today’s mechanical connection is designed to accommodate the current carrying
capacity of the conductor and provide ease of installation, resulting in a safe, reliable electrical connection.

1.7.1.1 Connector Material

Generally the alloy and hardware used for a mechanical connector depends on whether the connector is for a strain or current carrying application, and if the intended conductor is aluminum, copper, or other materials. Particular alloys and hardware are selected for strength, conductivity, durability, ductility, and resistance to corrosion.

In a mechanical copper connector, high strength alloys are used for clamping elements, and high conductivity alloys for current carrying parts. A popular choice for mechanical, copper-alloy connector hardware is silicon bronze (DURIUM™) due to its high strength and resistance to corrosion.

Mechanical aluminum connectors must be made from alloys impervious to stress corrosion. In their heat treated state, aluminum alloys have high strength and may be used for both current carrying and clamping elements. Anodized aluminum alloy bolts are typically used for mechanical aluminum connectors. Bolts made from these materials provide the best combination of strength and resistance to galling and corrosion. In addition, their thermal coefficient of expansion is most suitable for aluminum.

1.7.1.2 The Clamping Element

The clamping element of a mechanical connector provides the mechanical strength, as well as the current paths, of the connection. The following general rules are basic to the design of the clamping element, regardless of material used for construction:

1. Minimize conductor distortion and abrasion in order to prevent conductor fatigue (especially in applications where vibration or stress concentration is present). Screws that apply direct pressure to the conductor are not advised. Connectors that use direct pressure screws must be designed to minimize distortion or damage to the conductor. If a compact connector requires a single bolt to accommodate the conductor, a pressure bar is recommended, unless the connector is used in a light duty application.

2. The National Electric Manufacturers Association (NEMA) has adopted suggested standards to guide mechanical connector design. NEMA differentiates between classes in terms of the minimum number and size of bolts. The size of the bolt is determined by the clamping pressure needed to drop the resistance to a value low enough to provide a highly conductive, stable joint. The bolts used in mechanical connectors are not only the means of fastening parts of the connectors together, but more important, they are the means of establishing contact points along the connector and conductor surfaces.

Stainless steel bolts are recommended for application in highly corrosive environments and must be used in conjunction with proper selection of the connector.

The addition of Belleville spring washers is generally recommended in place of flat washers when using different connection material combinations. Belleville washers enhance the connection resilience to different thermal expansion and contraction (aluminum has twice the coefficient of expansion as steel!). Note, however, that Belleville washers cannot completely compensate for inadequate contact area, incorrect torque, or poor design. (See section 2.1.1.4 Hardware for specific recommendations.)

3. Place the bolts as close to the conductor as possible to reduce the effective length of the moment arm. Reduction in moment reduces stress within the connector. High internal stress can lead to cracking and will thus require larger connector elements than is otherwise necessary.
4. Accessibility with one wrench installation and suitable wrench clearance. Mechanical connectors often allow for one wrench installation to facilitate hot-line work and to simplify the installation process. In addition, bolt heads are all placed on the same side of the connector to allow for accessibility.

5. Employ sufficient wrap-around to contact all conductor outer strands. Establishing contact with all of the outer strands of a conductor is essential for current equalization and overall thermal performance.

6. Employ material in a manner that will make best use of its properties. The clamping element design should resist penetration of galvanic or atmospheric corrosion. Also, when considering copper mechanical connectors, thinner sections are possible because the material will yield to form around the conductor, and thereby shortening the moment arm and reducing stress. However, an aluminum mechanical connector must have a sufficient cross section to prevent deflection due to lack of conformance and brittleness inherent in the material.

1.7.1.3 Advantages of Mechanical Connectors

Mechanical connectors generally have an advantage over other types of connectors (e.g. compression) in the degree of inherent resilience of the connector components. Resilience permits follow-up of creep and reduces the stresses due to thermal expansion that tend to cause excessive creep. The components of a properly designed mechanical connector supply the desired resilience.

Figure 1.7-1 Simple Mechanical Tap and Splice Connector

Mechanical connectors also install with basic tools, i.e. socket or open end wrenches, screwdrivers, etc. These connectors are simple to use and often require minimal training to install properly. Physical exertion is typically not excessive, although installing many connectors and/or clamping hardware per connector can require some endurance. Mechanical connectors also have the advantage of being removable, and may be reusable if in good condition (check with the manufacturer for their recommendations on reuse). When conditions warrant, mechanical connectors disassemble without damage to the connection components.

Electrical performance of mechanical connectors meets or exceeds the industry requirements for which they are designed. Hence, performance is not compromised when using mechanical connectors in tested applications.

1.7.1.4 Disadvantages of Mechanical Connectors

Although mechanical connectors offer versatility and ease of installation, among other attributes, there are some drawbacks and concerns that must be addressed.

Specific torque requirements must be followed to provide the proper clamping force needed for a sound electrical connection. Installers rarely use calibrated torque wrenches to tighten the nuts and bolts on mechanical connectors. Thus, the consistency of forces applied over identical mechanical installations is not generally repeatable.
The general nature of a mechanical connection does not allow for high mechanical holding strength. Hence, mechanical connectors are not used as full tension connections. Similarly, the use of mechanical connectors in areas of high vibration may require more maintenance and periodic inspection. Finally, if an insulated connection is required, mechanical connectors are usually difficult and awkward to adequately cover due to their geometry.

### 1.7.2 Wedge

Wedge connectors are in actuality a unique category of mechanical connectors, and sufficiently distinct enough to address separately. The wedge connector incorporates a wedge component and a tapered, C-shaped spring body (or C-body). During installation the wedge is driven between two conductors into the ‘C,’ spreading the C-body which in turn places high forces on the conductors for a reliable, stable connection. (See Figure 1.7-2.)

![Figure 1.7-2 Wedge Connector Components](image)

There are two basic means by which the wedge is driven into the ‘C’ member: (a) a specially designed tool system that fires a cartridge to propel the wedge at high velocity (powder actuated), and (b) a mechanical drive bolt which, when tightened, drives the wedge between the conductors. (Refer to Section 2.1.2 for further installation details.)

The wedge connector is primarily used in tap applications, although other functions are possible. Wedge connectors are capable of making connections between combinations of aluminum, copper, and ACSR conductors.

#### 1.7.2.1 Advantages of Wedge Connectors

Powder actuated wedge connectors provide consistent, uniform performance. Repeatable installation forces from one connection to the next are assured by selecting the proper booster. The rapid mechanical wiping action as the wedge is driven between the conductors breaks down surface oxides and generates superior contact points which together reduce overall contact resistance.

Powder actuated wedge connectors are installed with lightweight, portable tooling that feature simplified loading and engaging mechanisms in order to speed up the installation process (especially when compared to manual hydraulic crimping tools). The powder actuated system requires low physical exertion from an operator to complete a connection. (Mechanical wedge connections are installed with a basic wrench, requiring more physical exertion for installation.)

The spring effect of the ‘C’ body (especially on the powder actuated types) maintains constant pressure throughout the life of the connection for reliability under severe load and climatic conditions. Constructed with a large mass, wedge connectors dissipate heat well and utilize the mass-anode principle to reduce the effects of galvanic corrosion.

Finally, the electrical performance of fired-on wedge connectors has been shown to be excellent. The large mass, along with the low contact resistance developed during installation, result in a connection that passes the ANSI C119.4 standard mechanical and electrical test requirements.

#### 1.7.2.2 Disadvantages of Wedge Connectors

Although powder actuated wedge connections provide numerous benefits, it is a dedicated system requiring full support from the user on training, maintenance, and service. Precautions are required to ensure a safe and proper installation. Installers must be provided with
special training in order to be qualified for installing wedge connections.

Mechanical wedge connectors installed with wrenches exhibit more inconsistent performance than their powder actuated cousins. Discrepancies in the mechanical installation process are caused by contaminants on the hardware and wide tolerances of shear-off bolts. Further, mechanical wedge spring bodies are typically manufactured by casting which produces much less spring action to maintain the connection.

All wedge connections are basically restricted to non-tension, outdoor applications. For example, no in-line splice connection is available in a wedge configuration. Other connection methods are still needed for complete coverage of all potential applications.

Each wedge connector is suited only for a limited range of conductors. Conductor size must be carefully matched to the wedge connector to guarantee an appropriate connection. And, although special covers are available for contact protection, the wedge connector geometry makes full insulation difficult.

1.7.3   Automatic Connectors

Automatic line connectors are a unique subset of mechanical connectors. Automatics provide a permanent splice connection in spans where the installed tension exceeds 15 percent of the rated breaking strength of the conductor. These connectors are used almost exclusively in distribution applications and are one of the fastest methods of splicing two overhead conductors.

The “automatic” principle utilizes tapered serrated jaws inside the connector sleeve which grip the conductor when tension is applied. When an attempt is made to withdraw the conductor, the jaws clamp further down on the conductor due to the taper in the connector. This wedge action increases with the pull applied to the conductor. Obviously, automatic connections must be used only where the wires are maintained in tension. These connectors are made from aluminum, copper, and steel alloys for use on aluminum, ACSR, copper and steel conductors.

1.7.3.1   Advantages of Automatic Connectors

The primary advantage of automatic connectors is their ease of installation. No tools are necessary to make an effective installation, and the skill level required is minimal. As a result of the simple installation, the installed cost of automatics is kept low.

Automatic connections also comply with ANSI specifications for performance and are rated for full-tension applications.

1.7.3.2   Disadvantages of Automatic Connectors

The major disadvantage to automatic connections is their limited application. As they depend on tension (a minimum of 15% of the conductor's rated breaking strength) they can only be used in suspension applications for splicing. Consequently, these connectors would not be applicable for tap and other non-tension applications.

Although the actual installation is relatively simple, care must be taken to properly prepare the conductor for the resulting connection. Cable ends must be squared and surfaces thoroughly cleaned by wire brushing prior to installation. These connectors are also extremely sensitive to dirt and other contaminants getting into the contact area, even after installation.

As discussed in section 1.4, electrical resistance will vary with contact pressure. For automatic connectors, this fact becomes very important. It is critical that there is constant tension on automatic connections. Line sag and wind vibration may adversely affect contact resistance, and ultimately the integrity of the connection, over time.
1.7.4 Insulation Piercing Connectors (IPC)

Insulation piercing connectors are another particular subset of mechanical connectors. These connectors are designed for indoor and outdoor non-tension tap and splice applications on insulated secondary distribution lines. IPCs are recommended for use on combinations of insulated copper and aluminum conductors.

![Figure 1.7-3 Installing an Insulation Piercing Connector](image)

1.7.4.1 Advantages of Insulation Piercing Connectors

Insulation piercing connectors (IPC) are designed with lower installation costs in mind. No special tooling is required as they install with a basic wrench. When making connections to insulated conductors (their principal use), no insulation stripping or application of oxide inhibitor is required. IPCs incorporate contact teeth designed to penetrate conductor insulation and make electrical contact, and are pre-filled with an oxide inhibiting compound to fill voids where contamination may enter.

Insulation piercing connectors are themselves insulated, thus, no tape or special cover is required after the connection is made. Installations on energized conductors can be easily made and are relatively safe.

1.7.4.2 Disadvantages of Insulation Piercing Connectors

Insulation piercing connectors are limited in their scope of application. Specifically, they are recommended for low voltage (600 V and below) secondary distribution applications where insulated conductors are employed. The nature of the connection device limits these connectors to function mainly as taps, although some parallel splices can also be made. IPCs are for use in non-tension applications only.

With the many forms of conductors and insulations that are available today, always check the connector specifications for compatibility with the conductors being joined. IPCs may not be suitable for conductors with very thick, very thin, or very hard insulation materials as they could damage the conductor or not make electrical contact at all. Never use an IPC on bare conductor.

1.7.5 Compression Connectors

Compression connectors are part of a connection system that utilizes specific installation tools and dies for installing permanent, high quality connections. The versatility of a compression system ensures that all connector functions (tap, terminal, and splice) are attainable in numerous forms. In addition, compression connectors are available for aluminum, copper, and steel conductors and combinations thereof.

![Figure 7.1-4 Compression Connector for Structural Steel](image)
1.7.5.1 Advantages of Compression Connectors

The low cost of a compression connection compared to other methods cannot be overlooked, particularly where distribution is concerned. Performance wise, compression connectors will normally operate better than mechanical connectors, and at worse, just as well. The nature of their construction allows for a better degree of conductor encirclement that retains the oxide inhibiting compound and protects the contact area from the atmosphere, thereby providing a maintenance free connection.

The focused, consistent forces imparted in a compression connector by the installation tool results in an electrically and mechanically sound connection. High forces break down the oxides and establish contact points (A-spots) for reduced contact resistance. The compression connector itself is made from a material that is soft relative to the conductor so that it does not spring back and cause contact separation.

Requirements for full-tension applications are stated in ANSI C119.4 and, for the most part, are accommodated by compression connectors. Compression connectors are most suitable in areas of wind, vibration, ice build-up and other stresses associated with tension applications. Compression connections have also proven themselves in rigorous grounding applications above and below grade. Compression grounding connectors are available that withstand the rigors of UL467 and IEEE Std 837 testing.

A very important advantage for compression connectors is the removal of the human element during installation with the use of recommended tools and/or dies. Consistent and repeatable forces are imparted with each and every crimp. The compression system may have color coded dies to match the color coding on the connector. If color is not present, an index number is included with the stamped markings on the connector, and should match the die index number. Some dies will also emboss their index number on the completed crimp, resulting in a combination that is nearly foolproof for inspectability. To further simplify the compression process, dieless installation tools do not require die selection and insertion.

Due to their geometry, compression connectors are considerably easier to insulate or tape than mechanical connectors.

1.7.5.2 Disadvantages of Compression Connectors

Although an installed compression connection is typically lower in cost than alternative connector types, obtaining the proper installation tooling for a compression system program involves potentially high capital investments.

In addition, there are many different types of compression tooling to select from, making initial decisions difficult and costly if changes are made later on to the program. Compression installation tools have developed over many years to accommodate many different customer requirements (i.e. conductor sizes or ease of handling). Hence, a typical compression splice connector could potentially have a multitude of tools and dies recommended for installation.

Due to the need for specific tools and dies to install a compression connection, installers must be trained on the proper techniques and maintenance of these tools. Accurate die and tool selection is a must for proper installation of a compression connection.

When using manually operated tools, it must be realized that some compression connections require greater physical exertion to install. When installing numerous connections, installers can become fatigued and possibly not complete the specified number of crimps.
1.7.6  Welded Connections

Welded connections are used primarily in substation applications, and particularly for aluminum conductors. Once the substation is designed, various connection interfaces will require a connection methodology to be selected. As discussed earlier, in many cases a mechanical means will be chosen. However, welded connections provide a viable alternative for certain connections.

1.7.6.1  Advantages of Welded Connections

Welded connections can provide an economical means only when making many connections within a substation area. Large quantity of connections results in a lower cost per weld due to the availability of needed materials and skilled, qualified labor. A properly welded joint can create a continuous conductor that is highly reliable. Allowing for the conductivity of the filler material, the essentially homogenous union created by a weld provides a resistance ratio less than unity.

1.7.6.2  Disadvantages of Welded Connections

When upgrading or making additions requiring few connections, welding is not a cost effective connection methodology. Low quantities of welded joints result in high installation costs.

Additionally, the skill level required to produce a reliable weld is very high. The welding process requires the materials being joined to be free of all contaminants. Any surface impurities, such as grease or dirt, will contaminate the joint and result in low electrical conductivity and/or insufficient mechanical strength. Contaminants may also cause premature corrosion of the welded connection. Cleaning conductor surfaces may be adequately performed with solvents, but mechanical cleaning methods may also be necessary. As a consequence, installation costs may rise on account of the increased time needed to properly prepare the conductor and due to the high skill level of personnel needed to perform welding operations.

1.7.7  Exothermic Connections

Exothermic welding is a process in which an electrical connection is made by pouring superheated, molten copper alloy on and around the conductors to be joined. The molten copper alloy, contained and controlled within a semi-permanent graphite mold, causes the conductors to melt. When cooled, the conductors are joined in a fusion weld.

The superheated, molten metal is created by a chemical reaction between aluminum and copper oxide. The process uses finely divided aluminum particles as the reducing agent with copper oxide to produce the following chemical reaction:

\[ 2Al + 3CuO \rightarrow 3Cu + O3 \]

This reaction generates a tremendous amount of heat, i.e. is exothermic in nature, with the molten metals reaching temperatures of approximately 4000°F.

1.7.7.1  Advantages of Exothermic Connections

When installed properly under favorable conditions, exothermic connections exhibit sound electrical properties. Similar to welded connections, the material costs of an exothermic connection are low when compared to other connection means.

1.7.7.2  Disadvantages of Exothermic Connections

Cost advantages are not realized when installing numerous exothermic connections. In most cases, the installed cost of exothermic connections is greater than other comparable connection means due to the lengthy process, numerous mold requirements, and potential down-time caused by inclement weather or wet conditions. The repeatability of the process can
not be easily determined, as the inspection of completed connections is extremely difficult, especially under field conditions.

The extreme heat generated during the reaction presents several problems. First and foremost are the inherent safety risks to personnel and equipment. Wet molds can produce an explosive reaction from the rapid vaporization of the moisture. Hot molds are also fire hazards, and are hazardous around volatile fumes. Further, the intense heat damages both the conductor and its insulation (if present). Due to the annealing of the conductor, exothermic connections can not be used in tension applications.

Other disadvantages relate to the tooling required to complete an exothermic weld. Mold life is shortened by use of larger powder cartridge sizes and is extremely sensitive to improper storage and mishandling. Range taking is not possible due to the need for close tolerances at conductor openings to contain the molten metal. Finally, the resultant weld material exhibits lower conductivity and physical properties than the conductor, being similar to cast copper.

1.7.8 Split Solder Sleeves

Split solder sleeves are used primarily for fusion type splices in the underground distribution network. These connectors simply provide a holding sleeve for inserting the conductors to be joined. Once inserted, the wall split along the entire length of the connector allows for wetting of the conductors during the soldering process.

1.7.8.1 Advantages of Split Solder Sleeves

When installed properly, the split solder sleeve provides an excellent electrical connection. Open split solder sleeves have been developed recently to allow easier access of the solder to the conductors, eliminating the possibility of solder voids within the connector.

1.7.8.2 Disadvantages of Split Solder Sleeves

The fabrication of a split solder joint requires a high level of training, high amounts of heat, and can lead to health risks. To form an acceptable solder joint, the conductors being joined must be preheated to allow wetting. When working with large conductors, heating entails the use of torches which may be unsafe for confined areas. Fluxes used to clean the conductor and the solder itself vaporize during the solder process, and in the confines of underground installations, can lead to solder asthma with prolonged exposure.

Further, solder materials will typically have low melting temperatures, especially when compared to the conductor material. The reduced temperature capacity of the soldered connection, therefore, reduces the overall maximum operating temperature of the circuit. The reduced operating temperature may have significant consequences on how overload and fault conditions are specified and handled.

2.0 PRACTICAL CONNECTOR CONCEPTS

In all electrical connector applications, there are issues other than theory to consider when making connection decisions. There may be several types of connection methodologies suitable for any given application.

In this section (Practical Connector Concepts, 2.0) additional information is provided for making final connection selections. The information provided in this section covers three important aspects that relate to final selection; installation, infrastructure, and safety.

Means of installation, discussed in section 2.1, are very important for proper connector operation. Tooling, training, and proper application are just a few of the issues when considering installation. Without installation being performed correctly, the theoretical behavior of the connector is no longer valid.
A company’s infrastructure (section 2.2) becomes very important when making connection selection decisions. The infrastructure referred to here includes the tooling already purchased and in place, training programs, and economic impact of final selections. Infrastructure parameters are essential in the connector decision process and will lead to superior results.

Finally, safety (section 2.3) must be considered throughout the entire connector selection program. Safety issues are involved from design through to installation and long-term performance.

2.1  Installation

Conductor joints and interconnections are part of every electrical circuit. There is utmost importance that electrical connections be properly made. The basic requirement of any electrical connection is that it maintains both structural and electrical integrity throughout its expected life span. High quality materials and workmanship (in both the connector and during installation) are essential to ensure the basic connector requirements are achieved.

2.1.1  General Practice

Regardless of the connection methodology employed, there are many general practices that help ensure a good electrical connection. These practices result from many years of experience and testing, and must be considered for every connector installation.

2.1.1.1  Contact Surface Preparation

Contact surface preparation is essential to ensure proper contact between connector and conductor. Surface contaminants will greatly interfere with the establishment of a sound electrical connection. The following steps must be taken to prepare a contact surface for connection:

1. Removal of all corrosion and surface oxides along contact areas. Oxides naturally form on metallic surfaces with exposure to air, and in the case of some metals such as aluminum, the formation is relatively quick and transparent to the eye. Removal of oxides, on both the connector and conductor, is performed just prior to installation and can be adequately achieved by wire brushing. Plated surfaces should not be wire brushed.

2. If a connector or conductor surface is plated, removal of contaminants should be done with an appropriate cleaning solvent or similar compound that does not disturb the integrity of the plating.

3. A select few manufacturers will chemically etch and then apply an anti-oxidant coating to all surfaces of the connector just after its fabrication. The anti-oxidant coating, in addition to oxide inhibitor compounds, acts to retard the formation of aluminum oxide on unplated aluminum. For connectors treated with an anti-oxidant coating during manufacture, contact surfaces can be relatively assured of being oxide free and ready for connection. (To determine if an anti-oxidant coating has been applied, place the connector under a black light. Anti-oxidants will appear as a “whitish” coating when exposed to black light.) Connectors not treated with an anti-oxidant should be cleaned prior to installation.

4. Surface preparation also includes the removal of other contaminants from contact surfaces. Types of contaminants that may be present on a conductor surface are insulation particles, adhesives, oils, dirt, and moisture. Regardless of the contaminant, removal is essential for proper electrical contact. Once again, contaminant removal should be performed without disturbing plated surfaces.

2.1.2  Insulation Removal

Conductor coverings and insulations protect the conductor from corrosion and mechanical damage, as well as provide electrical separation between conductive layers and/or from external contact. When installing a connector, the covering must be removed completely without damaging...
the underlying conductor. The exposed conductor region must be of sufficient length to accommodate the entire contact surface(s) of the connector.

Depending on the type of conductor, the removal of insulation (and reinsulation of the finished connection) can be quite complicated. Whether working with intricate conductors that have multiple layers of insulating and covering materials, or just simple jacketed cables, there exist some basic rules for insulation removal.

1. The insulation must be removed for a length just greater than the contact length of the connector to be installed. In the case of compression connections, the strip length must include additional length to compensate for the connector’s extrusion during crimping.

2. Regardless of the method used, the underlying conductor must not be damaged by cutting or nicking during the insulation removal process. Cut or nicked strands reduce the cross sectional area of the conductor and may result in an eventual failure.

3. After the conductor is stripped and all insulation is removed, follow the guidelines for contact surface preparation and, when necessary, oxide inhibitor application.

2.1.1.3 Oxide Inhibitors

Whether making mechanical or compression connections, it is generally a recommended practice to coat contact surfaces with an oxide inhibiting compound. These compounds have many attributes that ensure good contact and enhance the longevity of the connection. Although discussed in numerous sections within this paper, a compiled list of benefits of using oxide inhibitors is presented below.

- Penetration of oxide layers helps produce low initial contact resistance, resulting in improved connection conductivity.
- Prevention of oxidation and other corrosion by sealing the joint from air and contaminants.
- Assistance in increasing pullout strength of the connection, when needed.
- Continuance of properties to maintain connection integrity over wide temperature ranges.
- Compatibility with cable insulation.

In many cases, the connector manufacturer will predetermine the appropriate oxide inhibitor and supply the connector pre-filled with that compound. Where the connector is not pre-filled, two general types of compounds are available, dependent on whether copper or aluminum is to be joined. Both types are suitable for pad-to-pad and contact groove-to-conductor connections.

2.1.1.4 Hardware

All clamp type connections, including the pad-to-pad applications, depend on the force developed by fastening hardware to provide a stable electrical connection. For hardware to adequately perform this task, it must (a) be strong enough to withstand the torque requirements recommended by the connector manufacturer, (b) develop the correct pressure for the recommended installation torque, and (c) must remain reliable for the entire expected service life of the connection.

To achieve optimum efficiency, the bolt/nut/washer combination must be appropriately selected for the conductors being joined. There are two distinct groupings of hardware for making electrical connections:

1. Hardware supplied with the connector assembly. Most mechanical connectors are supplied with appropriate hardware to complete an electrical connection. The hardware supplied is best suited for both the intended application and the connector material. Copper alloy connectors will normally be supplied with silicon bronze, or DURIUM™ hardware. Aluminum connectors are generally assembled with aluminum alloy hardware. Aluminum alloy hardware components are lubricated to prevent galling and to provide consistent clamping force.
Table 2.1-1  Bolted Joints

<table>
<thead>
<tr>
<th>Materials Being Joined</th>
<th>Bolt</th>
<th>Nut</th>
<th>Flat Washer</th>
<th>Lock Washer</th>
<th>Belleville Washer</th>
<th>Reference</th>
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<td>SB</td>
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<td>SB</td>
<td>SB</td>
<td>NR</td>
<td>Figure 2.1-1</td>
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<td>SB*</td>
<td>NR</td>
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<td>NR</td>
<td>SS**</td>
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<td>SB</td>
<td>SS**</td>
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<td>GS</td>
<td>GS</td>
<td>NR</td>
<td>(a)</td>
</tr>
<tr>
<td>Aluminum to Steel</td>
<td>SB*</td>
<td>SB*</td>
<td>SB*</td>
<td>NR</td>
<td>SS</td>
<td>(b)</td>
</tr>
<tr>
<td></td>
<td>SS</td>
<td>SS</td>
<td>SS</td>
<td>NR</td>
<td>SS</td>
<td>(b)</td>
</tr>
<tr>
<td></td>
<td>GS</td>
<td>GS</td>
<td>GS</td>
<td>NR</td>
<td>SS</td>
<td>(b)</td>
</tr>
</tbody>
</table>

Key:

NR  Not Required
SB  Silicon Bronze
SS  Stainless Steel
AL  Aluminum
GS  Galvanized Steel
*B  Tin Plated
** Alternate recommendation in place of lock washer.
A critical aspect when installing hardware is the torque used to tighten the components. Every field termination, from a low voltage screw terminal to the largest lug, has an optimum value of torque that produces the most reliable, low resistance joint.

Torque is the result of a force applied to a lever arm multiplied by the distance measured from the pivot point to the point along the arm where the force is applied \((F \times d)\). In the English system of units, where force is in pounds and distance is in inches, torque has the units of pound-inches, or \(\text{lb-in}\).

Some years ago the electrical industry established optimum torque values for the most common materials and sizes of hardware used for electrical connections. Table 2.1-2 lists the results of this work.

It is often asked whether bolted connections require periodic retightening. The simple answer is NO. Once the connector is installed with the proper torque, repeated tightening could actually damage the connector and/or the conductor and eventually lead to a failure.

Figure 2.1-2 illustrates how tightening of a bolt affects contact resistance. When the bolt is torqued to produce a contact force of \(F_1\), the contact resistance is brought down to \(R_1\). Through creep and temperature cycling, the connection materials may undergo relaxation resulting in a contact force of \(F_2\). As seen in Figure 2.1-2, however, the relaxation curve differs from the tightening curve. Although the materials relax to a contact force of \(F_2\), the contact resistance remains relatively constant, indicating a stable connection throughout the contact force range from \(F_1\) to \(F_2\).

Torquing the bolt beyond producing a contact force of \(F_1\) does not produce a better connection. The only effect of increasing torque is possible damage. Therefore, better practice is to initially install hardware with the recommended torque values, and then periodically check for signs of loosening or overheating before making any adjustments.

Finally, the method of installing Belleville spring washers is often misunderstood. In fact, there are...
varying opinions as to what is the “correct”
method. Among these differing views, the
following is a successful time-tested procedure.
(Refer to Figure 2.1-1 b for assembly details.)

1. A flat washer is placed between the concave
side of the Belleville washer and the surface of
the member being joined. The Belleville is
thus captured between the head of the bolt
and the large flat washer. The flat washer
should have an outside diameter greater than
the flattened Belleville’s such that no overhang
results. Select a flat washer that is twice as
thick as the Belleville for strength. (If not
available, stack two or three thinner washers
to achieve the same effect.)

2. With the Belleville washer captured between
the flat washer and the bolt head, fit the
assembly into its hole. When the washers are
fitted in position, there should be no
interference with washers of adjacent bolts
and no overhang over surface edges.

3. Tighten the nut on to the bolt (with a washer of
its own) until a sudden, noticeable increase in
torque is required to continue. The Belleville
washer is now flat. It is not necessary to “back
off” the nut after tightening to this point.

2.1.1.4.1 Terminal Hardware Considerations

Within limits, the resistance of a bolted joint will
decrease and its mechanical strength will
increase with an increase in the size and number
of bolts employed. Utilizing this fact, bolted
terminal connectors are commonly available in
one-hole, two-hole, and four-hole configurations.
A further increase in the number of bolts beyond
four produces little appreciable increase in joint
efficiency, except for very wide conductors. By
combining existing performance data and the
mechanics of bolted joints presented in earlier
sections, it is possible to generate guidelines for
selecting one-, two-, and four-hole bolted
terminations.

In the case of one-hole terminals, a single bolt is
used to make the connection. While offering the
simplicity of installation, the single bolt produces
an electrically sound, compact connection. In
static applications, the one-hole terminal will
perform very well. However, unless the connector
pad is adequately constrained to prevent rotation,
torsional movement may overcome the hardware
installation torque and loosen the connection.

Two-hole terminals have longer pads and require
two bolts for installation. The longer pad offers
increased electrical performance due to a larger
contact surface area. Also, employing two bolts in
the connection completely eliminates the problem
of rotational forces from loosening the connection.

Four-hole terminals will further increase both
mechanical and electrical performance. More
contact surface area is available with the larger
pad, and the even pressure applied by using four
bolts takes advantage of the increased surface
area for electrical conductivity.

When selecting between terminal types for
connection installation, consider the following list
of criteria:

1. Preparation of interface surfaces.
   (See 2.1.1.1)
2. Provisions for the effects of thermal expansion
   of the bus and terminal.
   (See 1.4.2 and 2.1.1.4)

(a) The cross-sectional ampacity of the materials being used.

<table>
<thead>
<tr>
<th>Material</th>
<th>Current Capacity (Amps/in²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>1000</td>
</tr>
<tr>
<td>Aluminum</td>
<td>700</td>
</tr>
</tbody>
</table>
3. Proper bolt-tightening torque.  
   (See Table 2.1-2) 
4. Current per unit of contact area for normal and short circuit conditions. 
5. Bolt spacing and current per bolt. 

Use the information provided in sections (a) and (b) below to determine items (4) and (5) above, and finalize selection between one-, two-, and four-hole terminals.

Example 1: What size copper pad is required to safely conduct 1000 Amps?

Assume a pad thickness of manageable size; 1/4 in thick. To conduct 1000 Amps, we have

\[
1000A = \left( \frac{1000}{\text{A in}^2} \right) \times \left( \frac{1}{4} \right) \times w
\]

\[
w = \frac{4}{\text{lin}} \times \left( \frac{1000 \text{A}}{\text{lin}^2} \right) \times \left( \frac{\text{lin}^2}{1000 \text{A}} \right)
\]

\[
w = 4\text{in}
\]

Thus, a 1/4 in thick pad must be 4 in wide to safely conduct 1000 Amps.

(b) Amps per bolt.

<table>
<thead>
<tr>
<th>Bolt Diameter (inch)</th>
<th>Amps per Bolt*</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;1/2</td>
<td>225</td>
</tr>
<tr>
<td>1/2</td>
<td>300</td>
</tr>
<tr>
<td>5/8</td>
<td>375</td>
</tr>
<tr>
<td>3/4</td>
<td>450</td>
</tr>
</tbody>
</table>

*NOTE: These current values represent the current flow enabled by the bolt due to its applied contact pressure, and NOT the current capacity of the bolt itself.

Example 2: How many 1/2 inch bolts are required to secure the pad from Example 1?

Each 1/2 in bolt provides sufficient clamping force to support 300 Amps. To conduct 1000 Amps, we need

\[
\left( \frac{1000 \text{Amps}}{300 \text{Amps/bolt}} \right) = 3.3 \text{bolts}
\]

Thus to secure the 1/4” x 4” copper pad for carrying 1000 Amps, four 1/2” bolts are required.

Note: If a calculation results in a recommended quantity of bolts greater than four, an adjustment in bolt size and/or pad size is possible and desirable in order to yield a better connector design or selection.

2.1.1.5 Aluminum Above Copper

As briefly mentioned in section 1.4 Overhead, in outdoor installations where mixed metals are used, aluminum conductors must be installed above copper conductors whenever possible. Moisture on copper conductor surfaces will accumulate copper ions. If positioned above aluminum, these copper salts will wash onto the aluminum and cause galvanic corrosion.

In the event the aluminum conductor is located below the copper, a “drip loop” should be provided on the copper conductor. The drip loop redirects the copper conductor around and below the aluminum conductor for attachment. The loop formed allows corrosive moisture to drip from the copper conductor safely below the aluminum.

2.1.1.6 Plating

Various plating materials and processes are used on electrical connection products. Table 2.1-3 contains a short list of possible reasons for plating and the corresponding types of plated connectors suitable for meeting that objective.
2.1.1.7  DTS Terminals

A DTS treated compression terminal utilizes a selective application of brazing. Compression terminals are manufactured using a tube flattening process to form the pad area. As a result, a fine seam may exist down the center of the pad through which moisture or oil may seep into or from the compression barrel. The DTS terminal is brazed internally and then electro-tin plated to prevent moisture and oil from migrating through the seam. After plating, the compression barrel is pressure tested to 5 lb/in² (psi) to ensure an effective seal has been achieved.

The value of a DTS treated terminal is generally not required for use in “normal” service applications with low moisture environments and non-oil-filled cable. When using oil-filled cable, or when high moisture levels are expected, the use of DTS terminals or other means of sealing is warranted.

2.1.1.8  Standard Wall and Heavy Wall Compression Connectors

“Standard wall” and “heavy wall” are terms referring to the thickness of the material of a compression connector barrel.

Standard wall products are used to connect all covered and bare ASTM classes and strandings of copper and aluminum wire conductors (including flexible and extra-flexible) in minimum tension, UL listed (or recognized) and NEC approved applications conforming to UL486 requirements. Standard wall connectors are typically tin-plated and used in non-tension, non-exposed environments (either indoors, panel boxes, or cabinets).

Heavy wall products are suited for all covered and bare ASTM classes and strandings of copper and aluminum cable as well as bi-metallic type conductors (e.g. ACSR, Alumoweld, and Copperweld) in applications conforming to ANSI C119.4 requirements. Table 2.1-4 provides a summarization of these two types of compression barrels.

2.1.2  Wedge Installation

Wedge connectors are distinct connections which, depending on the type, may be installed with standard lineman’s hand tools or a powder actuated tool system. Wedge connectors installed with lineman’s tools are similar to mechanical connector installations and the general rules for installation should be followed. The powder actuated, or fired-on, wedge requires somewhat different installation methods. The steps below outline a general process for installing a fired-on wedge connector. Read and follow the specific instructions included with the tool and connectors for all appropriate safety and installation practices.

<table>
<thead>
<tr>
<th>Objective</th>
<th>Electro-tin</th>
<th>Hot tin dip</th>
<th>Nickel</th>
<th>Silver*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduce galvanic corrosion (bimetallic)</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Resist corrosive elements</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Increase conductivity/lower contact resistance</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>X</td>
</tr>
<tr>
<td>Provide high, continuous service temperatures (maximum)</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(650°F/343°C)</td>
<td>(500°F/260°C)</td>
</tr>
</tbody>
</table>

*Note: Never connect an aluminum surface to a silver plated surface. Aluminum in contact with silver results in a highly corrosive joint, which will further result in a high resistance connection.
1. Carefully select the proper wedge connector according to the conductor sizes being joined. Proper selection may involve either checking the catalog, the packaging, or the connector itself to see if the conductor sizes are accommodated. Computer programs can be used to obtain exact cable diameter accommodations.

2. Match the color coding on the wedge connector (red, blue, yellow) to the color of the power booster. The color marking dictates the proper power booster to choose for the wedge to be correctly installed. [Note: As an option, the correct installation power booster can be packaged with the connector for convenience.]

3. Choose the matching installation tool frame based on the wedge connector to be installed - the smaller tool frame is for red and blue connectors, and the larger tool frame is for yellow connectors.

4. Follow all applicable general installation practices for connector and conductor preparation described earlier.

5. Position the connector on the conductor. Correct positioning of the connector involves placing the conductors between the wedge and against the C-body. The tap can be above or below the run. The wedge should be positioned so that the large groove is placed against the larger conductor. This side is identified by a chamfer on the wedge.

6. Load the tool according to the manufacturer’s instructions. Follow the instructions closely to complete the installation.
After the connection is made, inspect the connection for the manufacturer’s embossment on the wedge, interlocking skive, and general soundness of the connection.

The fired-on wedge connection is an intricate system and care must be taken to follow the published installation instructions carefully and accurately to ensure both a sound electrical connection and personal safety.

2.1.3 Compression Installation

Compression connections will often require a few special considerations in addition to the general installation practices. These topics are discussed in this section and should be utilized in conjunction with the general guidelines.

2.1.3.1 Cable Insertion

In order to install a compression connector such that its performance is to specification, the conductor must be inserted for the entire length of the crimp barrel. Full insertion will result in maximum surface contact area between the connector and conductor, helping to ensure a sound electrical connection. The following installation steps will assist in meeting the full insertion requirement.

1. Pre-mark the cable: Lay the connector’s compression barrel along the end of the conductor until the inner-most crimp line is even with the conductor’s edge. Mark the conductor with a pen or tape even with the open end of the barrel. This mark will provide the installer with a visual identifier of full insertion.

2. Insertion: As the cable is inserted into the barrel, a twisting action of the connector/conductor may be necessary along with the insertion force. Twisting especially helps when the barrel is lined with an oxide inhibitor. Wipe away excess inhibitor compound as it extrudes out of barrel openings.

3. Completion: When the conductor mark (or tape) is flush with the end of the connector’s barrel, the cable is fully inserted.

4. Sector cable: Sector cable presents an additional problem when using compression connectors. Due to its triangular shape, sector cable does not insert into a round compression barrel. As a result, rounding dies were developed to shape the conductor to match the round barrel. Therefore, prior to inserting sector cable into a compression barrel, pre-round the entire insertion length using these rounding dies. Follow steps 1 through 3 above for completing the insertion process.

There is an unsanctioned field practice of adding or, even worse, removing conductor strands during the insertion process to facilitate installation. This practice is NOT recommended and could result in a dangerous situation. Changing the original conductor stranding by adding or removing strands can lead to improper compression which may adversely affect the integrity of the connection.

2.1.3.2 Bias Cuts

When using a connector that requires conductor insertion, the squareness of the cut is important. Cables that are not cut square may result in the following undesirable conditions:
• Incomplete cable insertion and compression of the full conductor at the first crimp.

• Insufficient distribution of the oxide inhibiting compound on the connector’s inner wall and around the conductor.

• Errors in determining the proper conductor strip length.

2.1.3.3 Compression Installation Tooling

Compression connectors are installed with engineered tooling. In some cases there may be several tools and corresponding dies allowed for installing a particular connector. The use of matched tool, die and connector combinations is important when installing the compression connector.

A compression tool, whether mechanical, hydraulic, or battery operated, typically can accommodate only a finite range of connectors. The connector specification sheet, catalog page, and/or packaging will list recommended installation tools. Selecting the proper tool for your application is the first step to making a sound electrical connection.

Installing the compression connector requires the correct number of crimps to be applied by the tool and die. Making too few crimps can seriously impair the long-term performance of a connection. Crimp information is in the catalog, on the specification sheet, and directly on the connector itself. Clearly marked knurls or color bands indicate both the position and the number of crimps to be applied.

Each compression connector function has general guidelines for making crimps.

Splices: Normal practice is to start the crimping from the middle, or innermost, crimp spaces. Crimping is performed on alternating sides, moving out towards the ends of the connector. This process allows the material to extrude outwards, thereby reducing electrical and mechanical stress points. (See section 2.1.3.5 Bird-caging for potential problems with this method.)

Terminals: Similar to splice connectors, crimping of terminal connectors should start from the point closest to the tongue (pad). Successive crimps are made moving towards the end of the barrel. Again, this reduces high stress points in the completed connection.

Crimp dies are designed with a particular tool/connector/conductor application in mind. Once again, the die selection is an important component in the compression installation process. The connector will normally be stamped with the die index codes to indicate suitable crimp dies. Final die selection will need to also match the installation tool chosen.
2.1.3.4 Bowing (“bananaing”)

Bowing refers to the curvature that can occur on a completed compression connection. Bowing is sometimes caused by the natural curvature of the cable conductor (caused by storage on a reel). During the compression process, the compression sleeve material enters a “plastic” state, and can be easily influenced to bend with little force. Therefore, if unopposed, the wire conductor’s tendency to curl will cause the final connection to be bowed.

There are two ways to reduce or eliminate bowing. First, when feasible, the cable conductor should be straightened as much as possible before being inserted into the connector sleeve. Straightening the cable eliminates the primary force that causes bowing. Secondly, the operator can carefully apply force by hand opposite to the bow direction to straighten the sleeve. It takes surprising little effort, while the materials are being compressed, to counter the tendency of the connector to bow.

2.1.3.5 Bird-caging

Bird-caging refers to the separation of cable conductor strands at the entrance of a compression barrel. This phenomenon occurs when two (or more) metals with different physical properties are extruded together, as in the compression connector installation process where the connector sleeve and wire conductor are not the same. Unequal plastic deformation results from the different extrusion rates, and when one material is stranded wire, the individual strands may separate.

As an example of how bird-caging can occur, take the compression splice connector. The normal installation process, as described earlier, would be to apply the first crimps at the center location, locking the conductor strands at that end. Successive crimps are made moving out to the connector ends. When the materials differ (conductor and compression sleeve), different extrusion rates are involved. Since the cable strands were locked on the first crimp, extrusion of conductor material can only occur towards the sleeve end. By the final crimp, the faster extruding conductor strands are constrained on the connector side by the crimps, and along the conductor by either the wire insulation or simply the strand twisting. With both sides thus constrained, excess material bunches in the middle causing the bird-cage effect.

Bird-caging does not have a detrimental effect on the overall connection. However, it is desirable to minimize or eliminate this condition to avoid areas that could produce corona or cause uneven current distribution outside of the connection. One method used to eliminate bird-caging is to use a compression sleeve designed to be crimped from the outer position first. This type of compression connector must have pressure relief holes located at the center of the sleeve to allow the oxide inhibitor to bleed out as crimping takes place. With this type of connector, the first crimp locks the cable strands at the edge of the connector, and extrusion takes place within the connector sleeve.
2.1.3.6  Spaced and Overlapping Crimps

Spaced crimps refers to the case where individual crimps are made in separate, distinguishable locations along the compression sleeve. Overlapped crimps are made such that one crimp is made partially (1/4 of a crimp width) on top of a preceding crimp.

Both of these methods produce functionally acceptable connections. However, overlapping crimps offer the advantage of facilitating preparation of the finished connection, especially in high voltage applications, where a relatively smooth crimp profile is desirable. Some flash may remain after overlapping crimping that can be easily removed if required.

Spaced crimps result in individual indentations in the connector sleeve between the knurl or ink marks. In most cases, especially lower voltage applications, the connection does not require post finishing procedures to remove flash.

[Note: Regardless of the method used, no crimps should be made on tapered ends or beyond the crimp lines of compression connectors, and the specified number of crimps must be completed.]

2.1.3.7  Crimp Configurations

There are several crimp configurations available for crimping compression connectors; the most popular in North America being circumferential and hex. Figure 2.1-3 depicts the die configurations that produce circumferential and hex crimps.

Circumferential dies produce circular indents on opposite sides of the compression barrel. There will normally be a thick region of flash extruded between the indents. This flash material is simply a redistribution of the connector material and must not be removed. When a circumferential crimp is to be insulated for use at higher voltage applications (above 5 kV), the gaps around the flash areas must be filled with a suitable inert material to remove air pockets and ensure dielectric integrity.

Hex dies, like circumferential dies, produce a uniform compression crimp. In the process of crimping, a thin, sharp flash may result on the completed crimp. The flash must be removed to prepare the connector for use at higher voltages due to the need for a smooth finish. Also, care must be taken to remove flash to prevent damage to applied insulation and reduce the safety risks of cut gloves or skin of personnel. Note that removing flash from the connector will result in plating removal as well, possibly requiring the application of a secondary means of corrosion protection.

Other crimp configurations available include nest and indentor (longitudinal) and dieless. Nest and indentor crimps are made with a die set consisting of the “nest” die, which cradles the tubular barrel being crimped, and the “indentor” die, which compresses and cold-works the conductor and connector into a sound crimp. Nest and indentor crimps are uniform and easily inspected, resist pullout, and provide secure connections to flexible and extra-flexible stranded conductors. However,
nest and indentor crimps require a filler in the finished crimp indentation for high-voltage installations, are not suitable for tension applications, and are not recommended for solid conductor.

Dieless installation tools are essentially self-contained crimp devices that eliminate the need for dies. The crimp geometry is very similar to the nest indentor configuration, where the head of the tool acts as the nest and the tool ram acts as the indentor. Dieless tools accept a wide range of conductor sizes (e.g. #6 AWG to 1000 kcmil), accommodates both aluminum and copper conductor, and provide for inspectability by embossing the BURNDY® logo in the crimp area. Crimps made with dieless tools have the same disadvantages as nest indentor crimps.

An extensive list of die and dieless compression crimp configurations are available other than those described above (e.g. symmetrical, “B,” “D,” two-indent, and quad or four-indent). Although very specific connections may utilize one of these configurations, their overall use and general application is limited due in large part to the performance and universality of the more popular crimp styles.

2.1.3.8 Concentric, Compressed & Compact Conductor

Today, stranded conductors are available in many forms, the three most common types being concentric (full diameter), compressed (3% reduction), and compact (10% reduction). It is often asked what compression connector is appropriate for use on these different conductors.

A compression connector that is specified for use with aluminum conductor only will functionally accept concentric, compressed, and compact aluminum of the same AWG/kcmil wire size. Similarly, a compression connector that is specified for copper conductor only will accept concentric, compressed, and compact copper of the same AWG/kcmil wire size.

When fitted in to the compression sleeve, the smaller diameter cables (compressed/compact) may appear “loose” prior to compression. This is simply due to the fact that the cable is, in effect, “precompressed” by the wire manufacturer. When the crimps are made, the same compression connection integrity will result as with larger diameter cables (of equal cross-sectional area). Connections to compressed and compact conductors have been thoroughly tested in the laboratory and in the field with successful results.

Any compression connector that accepts ACSR will not accommodate compact copper or aluminum conductor of the same nominal size. These connectors have larger barrel sizes in order to accommodate ACSR and do not work with the much smaller compact copper and aluminum conductors. However, ACSR compression connectors will accommodate compressed and compact ACSR conductor of the same cable size.
As in all connection applications, refer to the individual connector specifications to determine the conductor sizes that are accommodated.

2.2 Infrastructure

An organization’s established infrastructure is a major consideration in the overall scheme of electrical connector and electrical connection system selection. Infrastructure is defined here as the underlying policies, procedures, culture, and equipment already in place within an organization. Information regarding the organization’s infrastructure is an important component of the decision making process in implementing a connection system. Understanding infrastructure ultimately relates to the safest, most economical and reliable connector solution that is presently most suited to an organization, and can lead to an effective means of implementing new technologies as they become available.

2.2.1 Total Cost of Ownership

Total cost of ownership of an electrical connection system involves several components; up-front costs, installation costs, maintenance costs, and the cost of failure.

2.2.1.1 Up-front Costs

Up-front cost, or initial cost of acquisition, will include many or all of the following items:

- Purchasing the specific connector.
- Adapting or modifying a connector to be compatible with an existing system.
- Acquiring a connector/tool system.
- Appropriating new tool technology for existing connector selections.
- Adding relevant training for new installation and maintenance procedures.

Evaluation of a connector can not be based solely on the connector’s acquisition cost. The specific application may dictate the choices available, regardless of cost issues.

Many connection systems require the use of specialized tooling and training for successful installation. Compression connectors require a full complement of specialized tooling to install. Similarly, wedge connectors require a different set of special tools for assembly. For a company trained and equipped to install one system, the costs associated with switching to an alternative may initially seem cost prohibitive. However, an in depth cost analysis could justify a switch, or lend further support to the present system. In any case, the costs of in-house tooling must be included in the acquisition cost of each connector on a depreciated type basis. This process ties in directly to the next topic of installation cost.

2.2.1.2 Installation Costs

Installation costs are directly related to the cost of installing the connector (tooling and equipment) as well as the time to complete the installation process.

The cost of the tooling may be depreciated over the number of installations made. This consideration is often included in the original tool purchase justification. However, the tool’s cost may be factored directly into the cost per connection to accurately capture all of the costs associated with a connector installation.

The time required to complete an installation directly affects labor costs, and may indirectly affect the company’s profitability, especially when considering the costs of lost opportunity. Installation time is dependent on the connection type itself, the type of tooling (if required), the proficiency of the installer, and the environment in which the installation is being made.

Regardless of the accounting methodology used, it is important to understand how the connector selection process relates to the total installed cost. Capturing this information can affect future decisions regarding connector systems within the organization’s infrastructure. Making sound estimates of these costs and documenting the decision process helps to avoid revisiting previously made decisions.
2.2.1.3 Maintenance Costs

Specialized installation tooling requires maintenance. Calibrated tooling and equipment must be maintained to ensure proper connector installation. Generally, the company will institute a tool repair and maintenance program to maintain the satisfactory condition of installation tools. Part, or all of this program may entail utilization of the original tool manufacturer’s warranty and expertise in servicing tools. Either way, there is cost involved with any maintenance program which contributes to the total cost of connection selection and installation.

2.2.1.4 Cost of Failure

The total cost of an electrical connection failure is difficult to fully realize as the impact is usually far-reaching. Lost revenue, cost of replacement and retrofit, and other direct external damages are quantifiable. The costs of property damage claims alone can be significant in comparison to the costs of re-tooling to eliminate future failures. However, the costs of ill will, miscellaneous claims, recalls, and other internal reaction to prevent repeat failures can not be easily or accurately captured.

Therefore, the importance of selecting the proper electrical connection system for the application is critical in minimizing failure costs. Costs associated with initial installation may be higher than alternative means, but the potential cost savings can be significant if the correct connector is originally installed. The theoretical and practical knowledge relating to the various electrical connection systems cited in this paper is targeted towards assisting the connection selection process to decrease and eliminate avoidable costs.

2.3 Safety

Connection safety issues center around two main areas; installation and improper handling and use. Installation safety involves more factors than connector selection. How the connector is applied, the installation tooling and operational practices within the organization for a specific application all encompass the safety issue as a prime concern.

2.3.1 Installation Safety

By far the most important aspect of connector safety is installation practices. Anytime work is performed near (or on) energized or potentially energized conductors, an element of danger is present. Due to the hazards associated with electrical work, many industry standards have evolved for the safety of the worker. In addition, where the means of connection involves potentially hazardous installation tooling or materials, the manufacturer will include specific information for safe work practices.

2.3.1.1 Industry Standards

Many industry standards are available for reference concerning work on or near electrical equipment. These standards go into great detail for performing electrical work safely due to the hazards involved.

The federal government produces general work safety standards through the Occupational Safety and Health Administration (OSHA), which publishes the CFR 29 Federal Code of Regulations. Contained within CFR 29 are numerous references to safe electrical work practices, as well as other industry safety requirements.

IEEE (Institute of Electrical and Electronic Engineers) also publishes numerous safety work standards. The National Electrical Safety Code (NESC) specifically relates to work practices for electrical workers and utility operators. The color book series details numerous topics related to electrical safety, both in work practices and system requirements.

The National Fire Protection Association (NFPA) publishes electrical industry safety standards as well, the National Electrical Code (NEC) being the most well known. NFPA 70E Standard for
Electrical Safety Requirements for Employee Workplaces is directly related to OSHA requirements for electrical safety.

### 2.3.1.2 Manufacturer’s Guidelines

When specific connector installation methods may involve a hazard to the operator, the manufacturer will provide detailed information for safety. Operator’s manuals, instruction sheets, and labels provided with these connectors and/or tooling should be read and followed by the worker prior to performing the installation.

OSHA also regulates manufacturers for providing information on the safe storage, handling, and disposal of hazardous materials. It is important to maintain connector-related Material Safety Data Sheets (MSDS) including oxide inhibitors, welding powders, cleaning solvents and even solders to comply with these federal regulations.

Other types of safety support provided by manufacturers may include training on handling and using their products safely, as well as tool repair and replacement programs to insure tooling meets specifications.

### 2.3.1.3 Internal Safety Programs

Most utilities and companies develop their own internal safety programs to train and advise employees in proper safety procedures. These programs are very useful for initiating new employees to occupational hazards, as well as alerting long-time associates of new or forgotten procedures.

Comprehensive internal safety programs will often incorporate many or all of the safety advisory rules from OSHA, IEEE (NESC), NFPA and/or other similar organizations. Where the organization feels a high risk or unusual circumstance is involved with a particular task, the safety program can highlight this area and specify even stricter guidelines for processing.

### 2.3.2 Improper Handling and Use

The mishandling and misuse of electrical connectors and related installation tooling are also important areas of safety concern. Although closely related, mishandling topics include storage, inspection, and transportation of connector related items, where misuse refers to inappropriate tool usage and misapplication of connectors.

#### 2.3.2.1 Storage

Connectors should be stored in a clean, dry environment to prevent contaminants and corrosion from damaging contact surfaces. Tooling should be stored according to manufacturers’ recommendations. Hydraulic hoses should be cleaned prior to storing, and must never be kinked or wound too tightly to prevent damage. Powder actuated tools and boosters should be stored in clean and dry areas, and boosters should not be exposed to extreme cold, high heat or direct sunlight.

#### 2.3.2.2 Inspection

Connectors should be inspected for damage and appropriateness for the application prior to installation. Tooling and equipment should be inspected regularly for defects, wear, and signs of damage. Inspection should be and often is a significant step in equipment maintenance procedures. Tools, equipment, and/or connectors that do not meet specifications can result in safety related violations.

#### 2.3.2.3 Transportation

Manufacturers will usually take care to properly package electrical components for transit. However, since electrical connectors and installation tooling are often repackaged and transported multiple times prior to their subsequent use, care should be taken in handling these products. If connectors are too loosely packed or insufficiently protected from harsh abuse, they may become damaged. Damaged
connectors can make installation difficult, and in severe cases may affect the performance of the connection. Even more important, care must be taken to protect the installation tool from damage. Tools should always be placed inside carrying cases when provided, or otherwise secured against potential breakage during transport. A damaged connector and/or tool may not perform appropriately and increases the chance of malfunction and/or injury.

2.3.2.4 Tool Selection and Use

It is critical to select the correct installation tool for the job in any electrical connector installation. As aforementioned, some connectors may be installed with several different tools. In all instances, the tool should be used in accordance with the manufacturer’s recommended procedures and all precautions should be followed to the fullest. Safety, Operating and Maintenance Instruction manuals provide directions for the correct operation of the tool. Personnel should read and follow the instructions provided in manuals for safe tool practices. Incorrectly selecting or operating a tool may void its warranty and worse, could lead to serious injury.

2.3.2.5 Improper Application

Misapplication of an electrical connector installation involves the incorrect connector and/or the incorrect tool for the application at hand. Every effort must be made to choose the correct electrical connector for the job, and the associated recommended tool for installation. Consequences of misapplication may range from burn, down to potential injury or death.

3.0 Summary

In Section 1, Theory of Connector Technology, we discussed the design principles for specific applications and all types of connections, and the critical aspects of an electrical connection system. The range of topics was broad in nature and allows for general referencing when making connector specifications. In Section 2, Practical Connector Concepts, we stressed the importance of correct installation procedures, how infrastructure can influence connector selection, and the safety concerns for connectors and installation methodologies. The information provided between the two sections may be used together or in part for managing a comprehensive connector specification program. It is our belief that most of the concerns involved with connector design, specification, selection, installation, and performance have been touched upon, and may be utilized as is or further developed as seen fit by the end customer. •
4.0 Bibliography


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