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ELECTRICAL CONNECTIONS FOR POWER CIRCUITS

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1. Purpose

Operating experience with high-voltage power systems has shown that defective electrical connections are involved in many circuit or equipment failures. This chapter is designed to be used as a guide in the assembly and preventive maintenance of efficient electrical connections for power circuits. An efficient connection being defined as one which exhibits minimum resistance, both at initial assembly and in the long run.

2. Scope

Data and experience gained through years of testing and actual usage on power circuits by both manufacturers and field organizations are included. The actual test and procedures are beyond the scope of this chapter, however, their results are incorporated in the recommendations. Properties of conductor metals and recommended methods of making connections are discussed to illustrate the need for the proper selection of connectors; the proper preparation of conductors; and the proper application of fusion, compression, and bolted connectors.

3. Characteristics of Conductors

3.1. PROPERTIES OF CONDUCTOR METALS.-

3.1.1 Aluminum.- Aluminum, the most abundant of all metals, is never found in its pure state because of its affinity for other elements. This affinity enables a wide range of alloying characteristics; however, it also increases refinement costs and lowers the conductivity.

Ductility: Easily worked by rolling, drawing, spinning, extruding, or forging.

Corrosion resistance: Very good except in a saline atmosphere. A tough, very hard, invisible, and high resistance oxide, which is both impermeable and protective in nature, forms quickly on exposed aluminum. Once stabilized, the oxide prevents further oxidation. For highly corrosive environments, a proper selection of alloy or anodization may be used.

Arcing effects: Aluminum resists pitting from arcs better than any other metal.

Galvanic action: Aluminum is one of the most anodic metals. When placed with copper or steel in an electrolyte (e.g., water) the potential difference between the conductors varies proportionally with the distance between them in the electrolyte series (see table 2, section 3.3.1). This difference causes a flow of electrons pitting the aluminum but leaving the cathodic material unharmed.

Insulation compatibility: Aluminum exhibits none of the sulfur combining properties of copper nor does it produce soaps by combining with oil. Usual insulating materials do not adhere to the aluminum.

Advantages: For equal ampere ratings, an aluminum conductor must have 1.66 times the cross-sectional area of a copper conductor. At this gauge, aluminum has 75 percent the tensile strength and 55 percent of the weight of copper. The larger size, in spite of its higher resistance, keeps the conductor cooler and also helps keep the corona loss down. However, its required larger size restricts its use in applications (i.e., enclosed switchgear, etc.) where there are space limitations to be considered.

3.1.2. Copper.- Copper, a reddish material, is plentiful in nature and easy to process. Because of the abundance, ease of manufacture, and, therefore, low cost, copper was once the most widely used electrical conductor. Currently copper has increased in cost considerably and its availability is limited causing aluminum to be used more readily as an electrical conductor.

Ductile: Can be cast, forged, rolled, drawn, and machined. Hardens when worked, however, annealing will restore soft state.

Corrosion resistance: Copper oxide forms immediately upon exposure to the atmosphere. Once stabilized, this oxide prevents further oxidation of the copper. When the copper is heated (e.g., by bad connection), more oxides are formed. These high-resistance oxides will continue to increase the heat until the conductor breaks. At temperatures above 88 EC (180 EF), copper oxidizes in dry air. Copper is oxidized in an ammonium environment and is also affected by sulfur dioxide.

Alloying: Manganese, nickel, zinc, tin, and aluminum harden copper and diminish its ductility. Manganese, phosphorous, and tin increase the tensile strength.

Table 1. - Properties of conductors

Properties	Pure aluminum	Pure Copper	Low-alloy steel
Electrical conductivity (by volume at 20 EC).	62 percent	100 percent	12 percent
Electrical conductivity (by mass at 20 EC).	214 percent	100 percent	–
Thermal conductivity [W/(m.K)].	218	391	59.8
Corrosion resistance.	Good[2] (depending on atmosphere and alloy).	Very good.	Poor.
Tensile strength.	89 600 MPa (13 000 lb/in^2)	172 400 MPa (25 000 lb/in^2)	517 000 to 620 500 MPa (75 000 TO 90 000 lb/in^2)
Elastic limit[1]	34 500 Mpa (5000 lb/in^2)	55 200 Mpa (8000 lb/in^2)	60 to 80 percent of maximum tensile strength.
Density (g/cm^3).	2.70	8.96	7.83
Linear density (kg/mm^2)/m.	2.70 x 10^{-3}	8.96 x 10^{-3}	7.83 x 10^{-3}
Thermal expansion coefficient.	23.6 x 10^{-6}/^{O}C	16.5 x 10^{-6}/^{O}C	11.0 x 10^{-6}/^{O}C
Resistivity, MO, M	0.28	0.17	0.7 to 1.2.
Melting point.	667 ^{O}C (1233 ^{O}F)	1084 ^{O}C (1983 ^{O}F)	1484 ^{O}C (2793 ^{O}F)

[1]Cold flow, deformation as a result of exceeding the elastic limit by either compression or elongation may occur if this stress is exceeded.

[2]Aluminum has excellent resistance to atmospheric corrosion; however, galvanic erosion is included in its resistance.

Brass: Low-conductivity, high strength alloy.

Bronze: Good conductor and atmosphere corrosion resistance.

Copper chromium: Eighty percent conductivity of pure copper; 496,000- to 552,000-MPa (72,000- to 80,000-1b/in$^{2)}$ tensile strength.

Copper beryllium: Forty-eight percent conductivity; (593,000-MPa (86,000-lb/in$^{2)}$ tensile strength.

Advantages: Because of copper's small size per current-carrying capacity, second to silver, copper is widely used in armor cable. Its higher tensile strength (see table 1) also makes it favorable to aluminum since it is less prone to metal deformation.

3.1.3. Steel.- For current conductors, the steel used is of the low-alloy variety. It is a low thermal and electric conductor (see table 1). It is used primarily as a strengthening agent for conductors. Some of its applications are: ACSR (aluminum cable steel reinforced), CCSR (copper cable steel reinforced, copper weld, and alumaweld.

Its main advantage is its strength.

3.1.4. Table 1 is a summary of the physical, metallurgical, and electrical properties of metals commonly used as electrical conductors.

3.2. OXIDATION OF CONDUCTORS.-High-resistance oxides form very quickly on aluminum and copper conductors expose to air. Once the oxides are stabilized, they prevent further oxidation of the parent metal; however, due to this high electrical resistance, these oxides must be broken or removed before making up connections. Oxidation-inhibiting joint compounds are used to prevent reoxidation of the metals in the connections.

3.2.1. Copper oxide.- Copper oxide is generally broken down by reasonably low values of contact pressure. Unless the copper is very badly oxidized, good contact can be obtained with minimum cleaning.

3.2.2. Silver oxide.- Silver oxide is easily broken down by contact pressure and forms less readily at elevated temperature. Thus it is good practice to silverplate copper contact surfaces that must be operated at elevated temperatures.

3.2.3. Aluminum oxide.- Aluminum oxide is a hard, high-resistance film that forms immediately on the surface of aluminum exposed to air. This tough film gives aluminum its good corrosion resistance. After a few hours, the oxide film formed is too thick to permit a low-resistance contact with cleaning. The film is so transparent that the bright and clean appearance of an aluminum conductor is no assurance of a good contact. After cleaning the oxide film from aluminum, a compound must immediately be applied to prevent the oxide from reforming (see section 4.2).

3.3. Corrosion of Conductors.- Corrosion is the electrolytic action of moisture and other elements of the atmosphere in conjunction with the metals of the connection. Corrosion is a minor factor in copper or copper alloy connections; however, it is a vital factor if aluminum is involved unless moisture can be kept away from the connection.

3.3.1. Galvanic action.- Whenever dissimilar metals are in the presence of an electrolyte, an electrical potential is developed. One metal becomes the cathode and receives a positive charge. The other becomes the anode and receives a negative charge. When these metals are in contact, an electric current will flow and this electrolytic action causes an attack on the anodic (negatively charged) metal leaving the cathodic (positively charge) metal unharmed. The extent of the attack is proportional to the strength of the electrolytic current, which in turn is proportional to the electric potential developed.

The magnitude of the electrical potential generated between two dissimilar metals can be seen by the positions of these metals in the electrolytic series shown in table 2. When two metals are in contact in an electrolyte, the higher up in the series is the anode or corroded metal while the one lower down is the cathode or protected metal. The farther apart the metals are in the series, the greater the electrolytic potential and the greater the attack upon the anodic metal.

Table 2.- Electrolytic series

Corroded end (anodic)

Magnesium.
Aluminum.
Duralumin.
Zinc.
Cadmium.
Iron.
Chromium iron (active).
Chromium-nickel-iron (active).
Soft solder.
Tin.
Lead.
Nickel.
Brasses.
Bronzes.
Monel.
Copper.
Chromium iron (passive).
Silver solder.
Silver.
Gold.
Platinum.

Protected end (cathodic)

3.3.2. Crevice corrosion.- Electrolytic attach can also occur between like metals due to a phenomenon known as oxygen concentration cell or crevice corrosion. Since oxygen is necessary for corrosive action, a variation in the concentration of oxygen where a metal is exposed to an electrolyte will generate an electrical potential and cause a corrosive attack in the oxygen starved area. Thus, since an electrolyte in a deep crevice is freely exposed to the air at the outside, the concentration of oxygen will be greatest at the mouth of the crevice. Then corrosion can be expected to occur in the crevice remote from the surface. Crevice corrosion can be prevented if the crevice is filled with a waterproof compound to exclude moisture. Thus, within the contact groove of an aluminum connector containing an aluminum conductor, there will be numerous crevices in which corrosion will take place unless a good connector compound is applied during installation. Copper, being a more noble metal, appears to be much less subject to crevice corrosion; however, a waterproof connector compound application is still justified to inhibit oxidation.

3.4. EXPANSION OF CONDUCTORS. - Aluminum, copper, and steel have vastly different coefficients of expansion and allowances for expansion must be considered when designing bus runs as well as connectors.

3.5. ANNEALING OF CONDUCTORS.- Annealing is the process of heating and slow cooling of metals. For conductors, this is an undesirable process because annealing decreases the tensile strength of the metal. Annealing is a cumulative process and is very dependent on the type of parent metal, alloys if present, and the amount of previous cold reduction.

3.6. PLATING OF CONDUCTORS.- Silver oxide is easily broken down by contact pressure and forms less readily at elevated temperatures. Therefore, silver plating is recommended for copper contact surfaces which must be operated at elevated temperatures. Tin and nickel platings are sometimes used on copper and aluminum connectors to prevent the formation of oxides. However, when wet, these plated metals can cause galvanic corrosion.

3.7. ANODIZING OF ALUMINUM.- Anodizing is an electrolytic process which increases the corrosion and abrasion resistance of aluminum (primarily bolts). The aluminum is made anodic with respect to a dilute acid which causes an additional porous oxide layer to form on the aluminum. This layer can be dyed and/or coated.

4. Preparation of Conductors

4.1. CLEANING CONDUCTORS.- Surface contamination, specially surface oxide, must be expected on all conductors. These surface oxide films are insulators and must be broken down to achieve the metal-to-metal contact required for efficient electrical connections. Aluminum oxide, in particular, forms very rapidly; therefore, aluminum conductors must be thoroughly cleaned by use of an emery cloth or a rag immediately prior to making the connection. In addition to cleaning, the surface should be covered with a good joint compound to exclude moisture, thus preventing the oxide from reforming. Somewhat better results may be obtained by abrading the aluminum (not copper) surface through the joint compound. When joining or terminating insulated conductors, the insulation should be removed from the contact area by "pencilling" rather than by "ringing" with a sharp tool. This will limit conductor damage and facilitate application of insulating tape and/or compound.

4.2. JOINT COMPOUNDS.- Joint compounds are used when making electrical connections to (1) prevent formation of oxides on the cleaned metal surfaces and (2) to prevent moisture from entering tile connection thus reducing the chances of corrosion. Several widely used compounds and their specific applications are discussed below.

4.2.1. Petrolatum.- Petrolatum (trade name Vaseline) is perhaps the first- used joint compound. It aids in preventing oxidation and aids in excluding moisture from connections. It is still useful in making copper and plated copper connections.

4.2.2. NO-OX-ID.- This grade "A special" is a petroleum base compound with higher melting point, higher oxidation resistance, and better weathering characteristics than petrolatum. It is widely used for copper-to-copper or bronze-to-bronze bus connections.

4.2.3. Alcoa No. 2 EJC.- Alcoa No. 2 EJC, electrical joint compound, is a patented compound of an active chemical in a grease-type sealer. It penetrates oxide film by chemical action and is recommended for aluminum- to-aluminum connections, particularly bolted aluminum cable connectors on weathered aluminum cable. Alcoa No. 2 EJC is corrosive to steel and tinned copper fitting and it should not be used on flat-pad bus connections in substations.

4.2.4. Alcoa filler compound.- Alcoa filler compound has a fine grit of alumina suspended in it and is used for transmission line compression dead- end, splice, and terminal joints on aluminum or ACSR conductors.

4.2.5. Pentox "A" (Burndy) and Alnox (Alcoa).- These are electrical joint compounds used for aluminum-to-aluminum and aluminum-to-copper connections, particularly of the bolted flat-pad type. Pentox "A" consists of a suspension of zinc granules in a paste carrier which is workable over a wide temperature. The zinc granules tend to embed into the contact surface, penetrating the oxide coating and providing additional current paths between contact surfaces. The paste inhibits corrosion from reforming by keeping moisture and air from entering the voids between joining surfaces. Alnox is similar in composition and recommended application to Pentrox "A." Alcan universal jointing compound, containing titanium dioxide, may also be used in these applications.

5. Connections

5.1. GENERAL- Electrical connections between conductors are made by fusion or pressure. Fusion involves joining by melting of the two parent metals or a third metal as in soldering and brazing. Pressure connections are made by physical contact between coincident peaks in the parent metals. With suitable pressure, as from a connector, the peaks are deformed creating a greater contact and conducting area. Because of unequal expansions of different conductors and/or connectors, voids may be reformed between conductor and connector. If the connection is not airtight, the voids provide a place for oxides to form.

5.2. FUSION CONNECTIONS.-

5.2.1. Soldering.- Soldering is one of the oldest means of joining electrical connections. A well-made soldered joint is a good joint but the quality is directly dependent on skill and inspection is nearly impossible. Soldering increases the probability of corrosion by the introduction of different metals and flux. Also, soldering may weaken the conductor by annealing and the heat may damage adjacent cable insulation. The low melting point of solder may permit a joint failure under overload conditions.

5.2.2. Brazing.- Brazing makes an excellent connection with properly done. It is essentially a soldering process with a high-temperature solder such as silversolder. Its high temperature requirement of 650 to 700EC (1,200 to 1,300 EF) may damage insulation and anneal the conductor.

5.2.3. Welding.- One of the best electrical connections is that made by a perfect weld. Welding fuses the parent metals of the two conductors being joined and theoretically produces a perfect joint. Because of the special skill required, welding has not been widely used as a field method of making connections. However, the widespread use of aluminum pipe bus has brought about a limited application for welding since soldering or brazing aluminum is difficult to control.

a. The process used in welding aluminum is the inert gas shielded electric arc method using helium or argon to shield the arc to prevent oxidation of the aluminum. In a welded joint, it is the welding bead that carries the current between conductors. Therefore, this bead must be made with great care and skill, and must have a cross-sectional are equal to that of the conductors being joined.

b. The Thermit welding process, such as the Burndy "Thermoweld," long used in steel construction, has been adapted for joining copper conductors. The process uses finely divided metallic aluminum as the reducing agent with copper oxide to cause molten copper to flow into a mold containing the conductors. The Thermit process is often used in connecting the conductors of the grounding grid in switchyards.

c. Other forms of welding such as cold welding, flash welding, spot welding, friction welding, electron-beam welding, laser welding, and percussion welding are used essentially in the manufacturing process rather than in the field to make electrical connections.

5.3. PRESSURE CONNECTIONS.- Because of their reliability, convenience, and economy, pressure connectors have become widely accepted as the most suitable method of making electrical connections in the field. Pressure connectors apply and maintain pressure between the contact surfaces by means of a clamp-type or compression-type fitting.

5.3.1. Clamp-type connectors.- Clamp-type connectors apply and maintain pressure by means of clamping bolts, wedges, springs, or a combination of these.

5.3.2. Compression-type connectors.- Compression connectors apply and maintain pressure by compressing the connector about the conductor by means of suitable tools.

5.3.3. Powder-actuated connectors.- A line of connectors utilizing a powder charge to facilitate installation is produced by AMP Special Industries. These connectors fall into two basic groups:

a. Wedge-type connectors (for taps, jumpers, etc.) installed by a special tool which utilizes a powder cartridge to supply the wedging force, and

b. Internally fired connectors (terminal lugs, dead ends, and line splices) which utilize internal wedges actuated by powder charges fired by impact or an external electrical circuit.

5.4. SELECTION OF CONNECTORS. - Manufacturers and utility companies have done a great deal of corrosion testing of connectors and a considerable area of agreement has been reached in spite of minor differences in recommended practices. Proper selection of connectors as shown in table 3, will reduce the effects of corrosion.

5.4.1. Aluminum-to-aluminum connections.- For joining aluminum-to-aluminum conductors, there is little disagreement that an aluminum-bodied conductor is the proper choice, since this obviously eliminates the galvanic corrosion of dissimilar metals. However, even for this case, care must be taken to prevent crevice corrosion and to select an alloy of aluminum for the connector body that is free from cracking due to stress corrosion.

5.4.2. Aluminum-to-copper connections.- Similarly, for joining aluminum to copper conductors, an aluminum bodied connector is the best choice since it prevents galvanic corrosion of the aluminum conductor, the most vulnerable element to attack in the connection.

5.4,3. Massive anode principle.- By making the aluminum connector massive in comparison to the copper conductor, where the copper conductor emerges from the connector, the electrolytic current density over the exposed face of the aluminum connector is greatly reduced. This is schematically represented in figure 1. Since the rate of corrosion is directly related to the current density on the surface of the anodic material, the relatively large face of the aluminum connector will suffer only minor attack.

In addition, because the aluminum connector body is massive in the region where the corrosion occurs, the small loss of metal caused by corrosion is insignificant even after long periods of service. Furthermore, the connector design should be such that clamping bolts (if used) and areas of high stress which provide structural strength are not in the regions subject to galvanic attack.

Table 3. - Recommended electrical connectors

Connection	Connector bodv	Bolt material and washer
Aluminum to aluminum.	Aluminum.	Aluminum with lockwasher.
Aluminum to tinned aluminum	Aluminum.	Aluminum with lockwasher.
Aluminum to tinned copper.	Aluminum.	Aluminum with lockwasher.
Copper to tinned aluminum.	Bronze.	Bronze or steel with lockwasher.
Copper to tinned copper,	Copper or bronze.	Bronze with bronze lockwasher.
Copper to copper or bronze to bronze,	Copper or bronze.	Bronze with bronze lockwasher.
Tinned copper to tinned aluminum,	Aluminum or bronze.	Aluminum, bronze, or steel with Belleville washer.

NOTE: (a) Nuts, flat washers, and lockwashers (if used) must be of the same material as the bolt. (b) Bronze is silicone bronze. Steel bolts may be zinc or cadmium plated or stainless steel. (c) When steel bolts are used for bolting flat aluminum bus bar or aluminum to copper, the use of Belleville washers in place of flat washers to compensate for the differences in expansion of steel, aluminum, and copper is recommended.

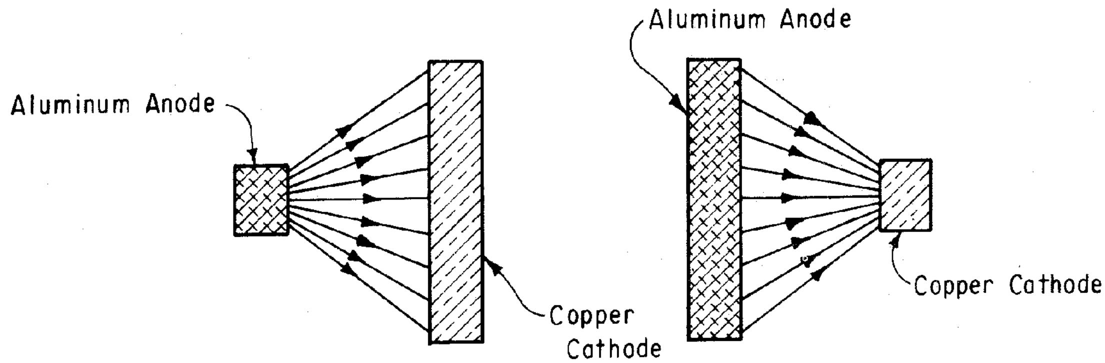

Figure 1. - Electrolytic current density diagram.

5.4.4. Position of conductor.- A properly designed aluminum connector for joining aluminum to copper must provide adequate separation between the conductors to prevent electrolytic attack on the aluminum conductor. Even then, it is good practice to install the aluminum conductor above the copper conductor if possible. This will prevent pitting of the aluminum conductor due to copper salts being washed over the aluminum.

6. Procedure for Making Connections

6.1. ALUMINUM-TO-ALUMINUM BUS.-

6.1.1. Clean contact surfaces immediately prior to making connections. Use a rag or emery cloth to remove direct, black deposits, and any old joint compound.

6.1.2. Completely coat the contact surfaces with a liberal amount of Pentrox "A" or Alnox joint compound.

6.1.3. Abrade the contact surfaces through the joint compound with a wire brush. Aluminum oxide forms immediately upon exposure; therefore, do not remove joint compound during brushing.

6.1.4. Add more joint compound to contact surfaces and prepare to make the connection.

6.1.5. Bolted bus connection:

a. Lubricate bolts with a nongrit joint compound (NO-OX-ID or Alcoa No. 2 EJC).

b. Torque all bolts in accordance with manufacturer's instructions or, in the absence of these, in accordance with table 4 in section 6.5.

c. Remove excess joint compound but leave a bead around joint to prevent entrance of moisture and dirt.

6.2. ALUMINUM-TO-COPPER OR - BRONZE (Tinned or Untinned) BUS.-

6.2.1. Whenever possible, place the aluminum member above the tinned copper member to prevent copper salts from washing into the joint which may result in galvanic corrosion.

a. Clean aluminum as described in section 6.1.1.

b. Clean the tinned copper or bronze surface by a few light rubs with fine steel wool.

c. Clean untinned copper or bronze surface to bright metal with emery cloth. Remove ridges or nicks by filling. Wipe off copper particles before coating. Do not abrade or wire brush either tinned or untinned copper or bronze surfaces, as this may result in galvanic corrosion.

6.2.3. Coat the contact surfaces with Pentrox "A" or Alnox joint compound as described in section 6.1.2.

6.2.4. Abrade the aluminum contact surface through the joint compound as described in section 6.1.3.

6.2.5. Add more joint compound to contact surfaces.

6.2.6. Bolt the bus connection as described in section 6.1.5.

6.3. COPPER-TO-COPPER OR BRONZE-TO-BRONZE CONNECTIONS (Tinned or Untinned).-

6.3.1. Clean the contact surfaces immediately prior to making tile connection to remove dirt deposits and any old joint compound.

a. Prepare tinned contact surfaces by rubbing with fine steel wool.

b. Prepare untinned contact surfaces by cleaning to bright metal with emery cloth. Remove nicks and ridges by filling. Wipe off all copper particles.

6.3.2. Coat the contact surfaces with a "nongrit" joint compound such as NO-OX-ID "A-Special." Use of Pentrox "A" or Alnox which contain the embedded zinc particles will cause a poorer connection due to the lower conductivity of zinc.

6.3.3. Do not abrade the copper contact surfaces through the joint compound, as this will roughen the contact surface and damage plated surfaces. Smooth surfaces have much higher incidences of microscopic point-to-point contacts, and thus exhibit much lower contact resistances.

6.3.4. Bolt the bus connection as described in section 6.1.5.

6.4. ALUMINUM CABLE TO CONNECTOR JOINTS.-

6.4.1. Use UL-approved aluminum-bodied connectors for aluminum cable, as these will expand and contract at the same rate as the cable; i.e., thereby main-raining contact pressure.

6.4.2. "Pencil" the insulation from aluminum conductor. Never "ring" the insulation. Avoid nicks and cuts in the conductor.

6.4.3. Coat the conductor and connector with electrical joint compound (Pentrox "A" or Alnox). Alcoa No. 2 EJC may be used on unplated aluminum connectors. Cables under No. 8 AWG are usually not coated.

6.4.4. Immediately prior to installing the connector, wire brush the cable and connector contact surfaces through the joint compound. Do not abrade plated connectors as the plating will be damaged.

6.4.5. Add more joint compound to conductor.

6.4.6. Push prepared conductor all the way into the connector. Make sure all insulation is tripped from the contact area. 'Fasten connector to the cable:

a. For bolted mechanical connectors, tighten and torque bolts in accordance with section 6.6. and table 4.

b. For compression connections, select the proper die and work tile tool completely to obtain the proper pressure. Refer to connector manufacturer's instructions on the proper selection of dies and tools.

6.4.7. Prepare the joint between the cable connector and the bus as previously described for various types of bus connections.

6.5. CABLE JOINTS.- The basic requirements of any cable joint and/or connection are that it must assume the mechanical and electrical strength of the cable(s) with which it is used. The workmanship and materials used should be of the highest quality, so that good electrical/mechanical contact and insulation (if required) will be ensured. The insulation materials must be equivalent in insulation properties to that of the insulated cable itself.

6.5.1. Prepare the contact surface(s) according to the appropriate preceding section(s), i.e., 4.1., 6.1., 6.2., 6.3., and 6.4.

6.5.2. The specific procedure(s) and materials to be used in the installation of the large variety of connectors and insulation materials currently available are beyond the scope of this bulletin. Therefore, refer to the connector/cable manufacturers' instructions for the proper procedure(s) and materials to be employed. In the absence of these specific instructions, refer to a reputable electrician's handbook for general instructions,

6.6. TORQUE MOMENTS AND PROCEDURES FOR BOLTED CONNECTIONS.-

6.6.1. Torque moments.- All bolts in bolted connectors should be tightened with a torque wrench to the torque value recommended by the connector manufacturer. In the absence

Table 4. - Recommended tightening torque on aluminum and silicon bronze bolts [Torque moments in newton meters (foot pounds) for lubricated bolts]

Bolt size/ thread	Silicon bronze	Aluminum
1/4 inch - 20.	8.1 (6)	
5/16 inch -18.	13.6 (10)	10.8 (8)
3/8 inch- 16.	23.0 (17)	14.9 (11)
1/2 inch -13.	47.5 (35)	31.2 (23)
5/8 inch -11.	67.8 (50)	54.2 (40)
3/4 inch- 10.	88.1 (65)	74.6 (55)

NOTE: If steel bolts are used, the torque moment will depend on the compression of the Belleville washer (which should always be used with steel bolts). Care must be taken to avoid overcompression (flattening) of the Belleville washer.

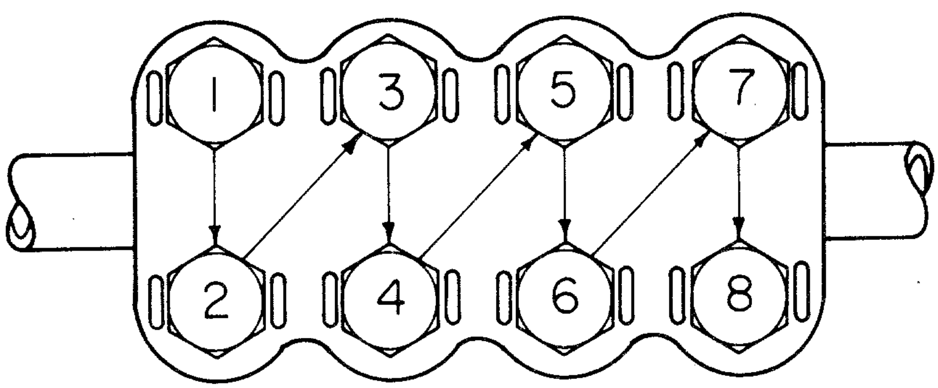

Figure 2. - Clamp tightening sequences.

of manufacturer's specific torque values, the torque values in table 4 should be used.

6.6.2. Torquing procedures.- The following procedure is recommended for installing all bolted connectors.

a. Lubricate bolt threads with a suitable nongrit joint compound.

b. Fit the connector to the conductor and tighten all nuts "finger tight."

c. With a torque wrench, tighten the nuts alternately to one-half of the recommended torque (manufacturer's recommendation or values from table 4). Figure 2 illustrates a tightening sequence:

d. Go back to nut No. 1 and tighten all bolts in sequence to the full recommended torque. This will ensure full clamping force and contact area.

Temperature Considerations

7.1. CURRENT AND TEMPERATURE LIMITATIONS.- The amount of heat generated in a conductor is proportional to its resistance and to the square of the current it carries, while the temperature rise depends on the rate at which the heat is dissipated through convection, radiation, and conduction.

7.1.1. Current-carrying capacity of a bus.- The current-carrying capacity of a bus is limited by the temperature rise produced by the current and other factors. Buses for generating stations and substations are generally rated on the basis of the temperature rise which can be permitted without danger of overheating equip-merit terminals, bus connections, and joints. ANSI C37.20C-1974 (IEEE standard 27-1974) permits a hottest spot temperature rise for plain copper buses of 30 EC (54 EF) above an ambient temperature of 40 EC (104 EF), with a hottest spot total temperature limit of 70 EC (158 EF).

The standard allows a hot spot temper-attire rise of 65 EC (117 EF) for metal-en-closed applications where silver contact surfaces are used on connections and a hot-spot temperature rise of 45 EC (81 EF) for silver-surfaces terminals of outgoing circuits. Aluminum used for bus work ordinarily has a conductivity of 63 percent, as compared to copper at 99 percent. For a given current rating and for equal limiting temperatures, the area of an aluminum bus will be about 133 percent of the area of a copper bus.

7.1.2. Allowable current density in a **bus.-** Allowable current density in a bus is the amount of current that the bus can carry per square inch or cross-sectional area without exceeding the permissible temperature rise. For both ac and dc buses, densities may var~v from values of 9.3. X 105 and 1.09 X 10~A/m^2 (600 and 700 A/in$^{2)}$ in heavy current-carrying copper buses to 1.86 X 106 and 2.17 X 106 A/m^2 (1,200 and 1,400 A/in$^{2)}$ in light buses under favorable conditions. For aluminum, densities of 75 percent of the above values are usually permitted.

7.1.3. Current-carrying capacity of conductors.- No method has been generally accepted by the industry for the calculation of the current- carrying capacity of conductors for overhead power transmission lines. However, Reclamation designs its ACSR transmission line capacity in accordance with tables, charts, and procedures in the "Aluminum Electrical Conductor Handbook," 1971 edition or specific instructions from the conductor manufacturer.

7.2. TEMPERATURE OF CONNECTIONS.- The principal function of an electrical connection is to satisfactorily carry the electrical load over its entire service life. The electrical load can be expected to have daily fluctuations from no load to full load and frequently to very heavy overloads, thus causing wide fluctuations of operating temperature. In addition, the ambient temperature can be expected to fluctuate between daily extremes and between seasonal extremes. The effect of this heat cycling on a poorly designed or improperly installed connection is frequently progressive deterioration and ultimate failure of the connection or associated equipment. Therefore, temperature rise provides an important and quite convenient method of monitoring the condition of electrical connections.

7.3. MEASUREMENT OF CONNECTION TEMPERATURE.- To evaluate the condition of an electrical connection by temperature, the conductor must be energized and carrying as near rated load as possible. Temperature measurement under these conditions, therefore, requires the use of special equipment, materials, and procedures, a few of which are described in the following paragraphs.

7.3.1. Thermometers, thermocouples, and resistance temperature detectors.- Thermometers, thermocouples, and resistance temperature detectors, designed for use with hot sticks, are commercially available. These devices are useful for determining the temperature of accessible energized connections which visual inspection indicates may be overheating.

7.3.2. Temperature sensitive paints, crayons, and adhesive labels.- These are available for use on conductors and connectors, which are not readily accessible when energized and/or at maximum temperature. These materials are particularly useful in determining the maximum temperatures of insulated connections such as in generator of motor windings, cable splices, etc. These materials are known as fusible or phase-change indicators and indicate predetermined temperature by melting or an irreversible change in color. Table 5 contains a partial list of supplier of phase-change temperature indicators.

7.3.3. Infrared thermometers.- Infrared thermometers provide instant temperature measurement of energized equipment without contact. Such devices are extremely useful in monitoring suspected hotspots in switchyard bus and equipment terminal connections and in transmission line conductor splices, jumpers, and support points. In use, the infrared device is signed on the connection in question and the temperature read on the self- contained meter in degree Celsius above ambient with an accuracy of 2 EC (4 EF) or better.

Several manufacturers market a product line of infrared thermometers with several models for specific applications such as:

a. "Raytek Raynger," marketed by Raytek Division, Optical Coating Laboratory, Inc., Mountain View, California.

b. "Heat Spy," marketed by Wahl Instruments, Inc., Culver City, California.

c. "Mikron" models 5, 10, 22, and 56, marketed by Mikron Instrument Company, Inc., Ridgewood, New Jersey.

d. "Digital Infrared Thermometer," marketed by M-C Products, Division of Material Control, Inc., Scottsdale, Arizona.

7.4. THERMOGRAPHIC (INFRARED) SURVEYS.- Sophisticated infrared equipment in vans or helicopters is now widely used throughout the electric power industry for rapid scanning of substation and switchyard bus and equipment as well as transmission lines. Available equipment can survey an average-sized switchyard in about 30 minutes. Experience in the industry has proven the technical worth and economic justification of infrared testing as a preventive maintenance tool.

Table 5. - Temperature sensitive paints, crayons, and other materials

Model	Range	Principle. comments
W. H. Brady Co.		
Thermomarker.	38 to 260 EC. (100 to 500 EF).	Press-sensitive, nonreversible temperature indicators.
CAMWIL, Inc.		
Thermtab.	38 to 232 EC. (100 to 450 EF).	Press-sensitive labels have accuracy temperature
Klinger Scientific Apparatus Corp.		
KH2004 Thermochrome	65 to 600 EC. (149 to 1112 EF).	Set of 12 crayons, color changes at temperature.
MARKAL Co.		
Thermomelt sticks.	38 to 1204 EC. (100 to 2200 EF).	5E/10E intervals to 650 EF; 20E intervals to 2200 EF.
Thermomelt liquid.	Same.	Same.
Thermomelt pellets.	Same.	Same.
Thermomelt thinner		
Paintstiks ball point marker.		For identifying and marking measurement data.
Marlin Manufacturing Co.		
Tempilstiks.	38 to 1371 EC. (100 to 2500 EF).	Indicating crayons, calibrated melting points.
Tempilaq.	38 to 1371 EC. (100 to 2500 EF).	Lacquer of calibrated melting points suspended in volatile vehicle.
Tempil pellets.	38 to 1760 EC. (100 to 3200 EF).	Indicating tablets of calibrated melting points.
Tempilabels.	38 to 260 EC. (100 to 500 EF).	Self-adhesive temperature monitors.
Omega Engineering, Inc.		
Tempilaq aerosol.	38 to 1371 EC. (100 to 2500 EF).	Temperature sensitive spray lacquer; accuracy ± 1.0 percent.
Tempilstiks.	38 to 1371 EC. (100 to 2500 EF).	Temperature indicating crayons, smooth or rough surfaces; accuracy ± 1.0 percent.
Tabs.	38 to 260 EC. (100 to 500 EF).	Self-adhesive temperature monitors; accuracy ± 1.0 percent.
Temp pellets.	38 to 1788 EC. (100 to 3250 EF).	Pellets; 20/tube; special series for reducing atmosphere; accuracy +- 1.0 percent.
Tempilaq lacquer.	38 to 1371 EC. (100 to 2500 EF).	For fabrics, rubber, plastics, smooth surfaces, etc.; accuracy ± 1.0 percent.

Table 5. - Temperature sensitive paints, crayons, and other materials

Model	Range	Principle. comments
Paper Thermometer Co.		
Sensitive paper		Thermopaper, thermolablel, thermotube-single and multiple temperatures, adhesive backing, clear plastic window.
Tempil Division, Big Three Industries, Inc.		
Tempilsticks.	38 to 1371 EC. (100 to 2500 EF).	Temperature indicating crayons in aluminum holder.
Tempilaq.	38 to 1371 EC. (100 to 2500 EF).	Temperature indicating liquids. Brush or aerosol spray application.
Tempil pellets.	38 to 1760 EC. (100 to 3200 EF).	Temperature indicating pellets. Special series for reducing atmosphere.
Tempilabels.	38 to 260 EC. (100 to 500 EF).	Self-adhesive temperature monitor tabs.
William Wahl Corp.		
Temp-Plate.	38 to 593 EC. (100 to 1100 EF).	Turns black at critical temperature; eight-position recorder (101-8) has ± 1.0 percent accuracy from 43 to 260 EC) (110 to 500 EF).

7.4.1. Thermal imaging devices.-Thermal imaging devices are useful in permitting a rapid scan of switchyard buses and equipment terminals to detect temperature differences. Infrared signals from photovoltaic detectors are electronically amplified and transmitted to a small television viewing screen producing an image corresponding to the thermal patterns within the viewed scene. Temperature differences are shown in varying shades of gray or in different colors. An accessory instant camera may be used to provide a permanent record of temperature differences. Thermal imaging devices that have been used by Bureau personnel include:

a. "Thermovision" model 750, marketed by AGA Corporation, Piaya Del Rey, California.

b. "Probeye," marketed by Industrial Products Division, Hughes Aircraft Company, Carlsbad, California.

7.4.2. Thermal imaging television units. - Thermal imaging television units are sophisticated, infrared-sensitive television cameras, which display the thermal image on a television monitor or feed into an accessory video recorder for future playback. These units may be hand-held or mounted in vehicles or helicopters for rapid thermal scanning of transmission lines and switchyards. Several of these units are described below:

a. "XS-410," marketed by the XEDAR Corporation, Boulder, Colorado, is a pyroelectric vidicon camera which produces a thermal image, which is viewed on a 76-mm (3-in) integral television display, or may be fed into a video recorder.

b. "Infravision," marketed by FLIR Systems, Inc., Lake Oswego, Oregon, utilizes an MCT (mercury cadmium telluride) detector, which is cooled by compressed argon gas. This unit has several remote-controlled mounting options, which facilitate its use in vehicles or helicopters. The thermal image is displayed on a separate television monitor or may be fed into a video recorder.

c. "VideoTherm 84," marketed by LENTECH International Corporation, San Diego, California, is a pyroelectric vidicon camera, similar to the "XS- 410" above. It has a number of options which make it a quite versatile unit.

7.4,3. Scheduling of infrared surveys.- Scheduling of infrared surveys to detect hotspots in electrical connections and equipment is an important facet of an effective infrared testing program. Under such a program, each major station should be tested every 2 or 3 years, and less important stations every 3 to 4 years. Such surveys should be conducted during periods of high system loads, which circuits in a given station are sufficiently loaded to reveal existing or potential hotspots. Subsequent surveys should be scheduled to test transfer of auxiliary buses under loaded conditions. Each hotspot detected by an infrared survey should be physically inspected and evaluated. Judging the severity of a faulty connection by temperature readings alone can be misleading. A reading of 50 EC (90 EF) above ambient in one case can be as serious as one 180 EC (325 EF) above ambient, especially if the load is low in the first case. A followup inspection of suspect and/or repaired connections should be performed with a hand-held infrared thermometer, temperature-sensitive tape, or other suitable means.

7.4.4. Contracting for infrared inspection services.- Contracting for infrared inspection services is presently regarded as more feasible for Reclamation's power systems than the purchase and operation of the required sophisticated equipment. The Bonneville Power Administration, Public Service Company of Colorado, and other utilities interconnected with Federal power systems which operate thermovision equipment, have provided infrared surveys for Federal stations in their service areas at a nominal cost.

Table 6 lists a number of commercial firms which provide infrared testing services to power utilities. Transportation to and from the stations to be tested accounts for a considerable portion of the survey cost. Therefore, it is usually advantageous to schedule testing at a number of stations in a given area in cooperation with another utility in that area, to reduce overall transportation costs. Also, contracting for infrared testing on a regionwide (or several regions) basis offers some economies over such testing on a project or single-station basis. Contracts for infrared testing services should be handled in strict accordance with Federal procurement regulations.

Table 6. - Some infrared testing services

Bisbee Infrared Services, Inc.
P O Box 51
Jackson MI 49204
(517) 787-4620

Diversified Inspections of California, Inc.
12007 Palo Alto
Etiwanda CA 91739
(714) 989-1551

Independent Testing Laboratories, Inc.
P O Box 657
No. 1 Rand Street
Searcy AR 72143
(501) 268-7191

ThermoTest Inc.
3940 Geary Boulevard
San Francisco CA 94118
(415) 387-2964

Diversified Inspections, Inc.
2255 West Northern Avenue
Suite B-111
Phoenix AZ 85021
(602) 995-5800

Heliwest, Ltd.
Suite 600
300 Union Boulevard
Lakewood CO 80228
(303) 989-9310

Infrared Surveys, Inc.
Suite 609
9001 Airport Boulevard
Houston TX 77061
(713) 944-0061

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Aluminum Electrical Conductor Handbook, 1st edition, September 1971.

Alcoa Aluminum Bus Conductor Handbook, Copyright 1957.

Lineman's and Cableman's Handbook, Kurtz, 4th edition.

ANSI Standard C37.20C-1974, "Standard for Switchgear Assemblies Including Metal-Enclosed Bus."

Croft's American Electricians Handbook, Carr, 8th edition.

Burndy Basic Connection Principles, 2nd edition, September 1965.

"Making Bus Connections," Bonneville Power Administration Substation Maintenance Information, April 22, 1974.

Transmission Lines and Substations Branch Memorandum, June 25, 1974.

Live Line Barehand Manual, Colorado River Storage Project, 1974.

Standard Handbook for Electrical Engineers, A. E. Knowlton, 9th edition.