Chapter 10

Product Classification and Technical Data

This chapter deals with cable types available for power distribution, including related user applications. Insulated conductors for instrumentation, communications, and protection are not described. Considerable information regarding applications, engineering design, and insulation is in previous chapters. Installation practices and connector selection are covered in Chapter 11. For ease of reference some Chapter 7 descriptions of cable types are repeated in part.

Manufacturers' catalogs should be consulted for detailed specifications, and particularly as to sizes available in each category. To save space, not all available sizes are included in the description of each classification. Omissions, however, do not imply lack of use or demand. Similarly, only a few of the available insulations are listed as a part of the description of each type of cable. Other varieties of insulation including those mentioned in Chapter 8 may be available upon inquiry.

The product classifications in this chapter follow the plan of previous chapters by proceeding from the low-voltage cables to those of high-voltage. First to be considered are the service cables.

The usual table of ampacity ratings is omitted in the descriptions of each style of conductor. Instead, reference is made to a specified vertical column of Tables 10-1, 10-7, and 10-9, in which typical ampacity ratings are listed for the applicable conductor size, insulation, and temperature.

Ampacity listings for installations to 35 kV are found in NEC Article 310, Tables 310-16 to 310-31, and except for utility installations, the NEC is the governing document. See Appendix 9A of this Handbook for discussion of ampacity ratings as listed by ICEA.

In addition, a modified type of stranding, 19 wire combination "Unilay," is now available as described in ASTM B 786 in its uninsulated form. Details of the various sizes of this conductor are listed in Table 4-26.

Service and Secondary Cables

Class 10-1

Messenger-Supported, Service-Drop and Secondary Cable (Duplex, Triplex and Quadruplex) (Figure 10-1)

This cable ordinarily is installed by the power supplier (utility) for both secondary runs and service drops. The cable construction consists of a bare neutral-messenger support member, which serves as a neutral, cables with one, two or three insulated conductors. Service-drop and secondary cable are commonly manufactured to comply with the appropriate ICEA Specification S-66-524 for crosslinked polyethylene (XLPE) insulated conductors rated at 90°C maximum; and S-61-402 for polyethylene (PE) insulated conductors rated at 75°C maximum. Cables of this type are suitable for applications where phase-to-phase voltage does not exceed 600 volts.

The following are typical sizes and insulation thicknesses for phase conductors:

<table>
<thead>
<tr>
<th>Conductor size</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>AWG or kcmil</td>
<td>mils</td>
</tr>
<tr>
<td>8 through 2</td>
<td>45</td>
</tr>
<tr>
<td>1 through 4/0</td>
<td>60</td>
</tr>
<tr>
<td>250 through 500</td>
<td>80</td>
</tr>
</tbody>
</table>

Available sizes — Generally all constructions are available in sizes No. 6 through 4/0, with large sizes through 500 kcmil available upon special inquiry.

Neutral-Messengers—Constructions are available with full or reduced sizes AAC, ACSR, ACSR/AW and Aluminum Alloy (6201) neutral-messengers.

Based on the referenced guide below Table 10-1, ampacities at a fixed condition of 40°C ambient, no wind or sun, are tabulated in Table 10-1.
covered and insulated aluminum wire and cable

<table>
<thead>
<tr>
<th>Type insulation and construction</th>
<th>Table 10-1 Col. Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyethylene</td>
<td></td>
</tr>
<tr>
<td>Duplex, Triplex</td>
<td>3</td>
</tr>
<tr>
<td>Quadruplex</td>
<td>4</td>
</tr>
<tr>
<td>Crosslinked Polyethylene</td>
<td></td>
</tr>
<tr>
<td>Duplex, Triplex</td>
<td>1</td>
</tr>
<tr>
<td>Quadruplex</td>
<td>2</td>
</tr>
</tbody>
</table>

Class 10-2
Preassembled Parallel Secondary Cable (Fig. 10-2)

This cable serves a similar purpose as Class 10-1, except it is used more for secondary runs than for service drops. The introductory comments for Class 10-1 also apply to it. The two or three insulated power conductors are laid parallel and are secured to a bare neutral messenger by means of flat aluminum-alloy binder ribbon applied helically about the assembly. The usually available insulations are cross-linked polyethylene (XLPE) rated 90°C, high density polyethylene (HDPE) and conventional polyethylene (PE) rated 75°C of the same thicknesses as listed for Class 10-1. The neutral messenger used with cables of Class 10-2 is the same as those specified for Class 10-1 cables, either full size or reduced size. Amperages are the same as those for duplex-triplex Class 10-1, according to the kind of insulation.

Class 10-3
Reverse Twist Secondary Cable (RTS) (Fig. 10-3)

This cable is similar to Class 10-1 and the introductory comments also apply. RTS cable is generally used as secondary distribution cable and occasionally used for service drops. Cable construction consists of two or three insulated phase conductors cabled about a straight neutral-messenger with direction of lay reversed at regular specified intervals throughout the length of the cable. The conductors are bound to the messenger with an aluminum flat strap binder. This cable is particularly useful in secondary distributions and where T-taps are required since “slack” can be obtained by untwisting the cable conductors. Amperages for these constructions are listed in Table 10-1.

Fig. 10-2. Preassembled parallel secondary cable.

Fig. 10-3. Preassembled reverse lay twist cable.

Class 10-4
Type SE-Style U Service Entrance Cable (Fig. 10-4)

Cable construction includes two or three insulated conductors with a bare concentric neutral considered as a conductor. Three-conductor SE-Style “U” (SEU) cable is the more widely used construction. It is employed as service entrance from the attachment point of the service drop cable down through the meter socket and then to the service panel. Three-conductor cables consist of two insulated conductors paralleled, about which is applied a bare concentric conductor. The assembly is compacted, protected and strengthened by a reinforcement tape, and an extruded polyvinyl chloride (PVC) jacket applied overall. SEU cable is manufactured to comply with the UL standard for service entrance cables (UL 854). Application is governed by local building codes which generally reference the NEC. Phase conductors in service entrance cable are usually NEC types XHHW and RHW. SE cables are recognized in Article 338 of the NEC for use as feeder and branch circuit conductors with certain limitations. Typical applications include range and dryer circuits.

Class 10-5
Type SE-Style SER Service Entrance Cable (Fig. 10-5)

SER cables meet all of the requirements of Class 10-4 above for SEU cables. Style SER cables differ from SEU in that the neutral conductor is insulated and cabled with the phase conductors. This difference produces a round configuration for three-and four-conductor cables. Available constructions are: three-conductor cable (two insulated phase conductors cabled with an insulated neutral conductor); and four-conductor cable (the same as three-conductor, plus a cabled bare equipment-grounding conductor).

SER cables are suitable for voltages not exceeding
### TABLE 10-1

Typical Ampacities for Various Sizes and Types of Stranded Conductors
in Cables of the Class

Descriptions Mentioned in the Text* (600 Volts or Less)

**NOTE:** It is suggested that this table not be used directly, but only to supply information as a supplement to the Class Descriptions which should be consulted first.

Except for Classes 10-4 , 5 , and 8 , the listed ampacities are based on 40°C ambient for cable in air or in conduits in air, and 20°C ambient for cables buried in direct earth burial, assuming 100% load factor and RHO-90 earth thermal resistivity. The listed ampacities for Classes 10-4 , 5 , and 8 are based on 30°C ambient.

<table>
<thead>
<tr>
<th>Insulated Conductors</th>
<th>Temp C</th>
<th>Col.No.</th>
<th>Duplex or Quadruplex</th>
<th>Triplex in Air</th>
<th>Triplex in Buried Duct</th>
<th>1/C in Air</th>
<th>3/C in Air</th>
<th>1/C in</th>
<th>3-1/C in</th>
<th>2/C or 3/C Concentric Neutral</th>
<th>In Plastic Duct</th>
<th>Triplex 100% LF (2/C and Neutral)</th>
<th>Ribbon</th>
<th>Portable</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>10</td>
<td>8</td>
<td>6</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>1/2</td>
<td>2/3</td>
<td>3/4</td>
<td>4/5</td>
<td>5/6</td>
<td>7/8</td>
<td>9/10</td>
<td>11/12</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>8</td>
<td>6</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>1/2</td>
<td>2/3</td>
<td>3/4</td>
<td>4/5</td>
<td>5/6</td>
<td>7/8</td>
<td>9/10</td>
<td>11/12</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>8</td>
<td>6</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>1/2</td>
<td>2/3</td>
<td>3/4</td>
<td>4/5</td>
<td>5/6</td>
<td>7/8</td>
<td>9/10</td>
<td>11/12</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>8</td>
<td>6</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>1/2</td>
<td>2/3</td>
<td>3/4</td>
<td>4/5</td>
<td>5/6</td>
<td>7/8</td>
<td>9/10</td>
<td>11/12</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>8</td>
<td>6</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>1/2</td>
<td>2/3</td>
<td>3/4</td>
<td>4/5</td>
<td>5/6</td>
<td>7/8</td>
<td>9/10</td>
<td>11/12</td>
</tr>
</tbody>
</table>

*The listed ampacities generally are from ICEA tables, and may differ from ratings in NEC 310 tables as qualified by footnotes, and after adjustment for difference of ambient temperatures. If differences occur, use adjusted NEC values when NEC conditions must be met.

Some ratings are in even figures, and others are rounded to nearest 5-ampere values. This lack of uniformity is explained by noting that ampacity ratings of successive batches may show a variation of ±2%, hence the rounding to nearest 5-ampere values is allowable. Some listings from industry sources are based on 62% IACS aluminum conductivity, but most tabulated values are based on 61% conductivity. The effect on ampacity is only 8/10 of 1% in favor of the 62% aluminum, hence the difference is ignored in the tables.

Adjustment of ampacity values for cables closely adjacent in rigid cable supports, troughs, or where there is no maintained spacing, should be made according to factors in Appendix 9A.

Ampacities are from the NEC for three-wire, single-phase residential services.
covered and insulated aluminum wire and cable

Fig. 10-4. Type SE-style U three-conductor service-entrance cable.

Fig. 10-5. Typical type SE-style SER cable.

600 volts. SER cable is primarily used in residential wiring to subfeeder distribution panels in multi-unit dwellings. The four-conductor cable provides an insulated neutral required by the NEC for feeders and branch circuits, as well as an equipment-grounding conductor. Cable is sized per NEC requirements. Where cables are used as branch circuit conductors, cable ratings are based on the type of conductor insulation within the cable — for example, XHHW for 90°C dry locations at the applicable ampacity called for in NEC tables.

Class 10-6
600-1000 Volt Power and Lighting Cable (not especially designed for direct burial) (Fig. 10-6)

Cables of the 600-volt and 1000-volt class are similar except for a slight difference of insulation thickness. NEC describes the 600-volt class completely for code applications, and its Art. 710 refers to requirements for "over 600 volts." Under NEC conditions, the 1000-volt cables mostly are applied for certain circuits related to industrial processes, motor loads, large fluorescent lighting installations, and sometimes where ungrounded neutrals are used. Some manufacturers include the 1000-volt cables in a group specified for 601-2000 volts.

Cables of the 600-volt class sometimes are referred to as building wires because of the extensive use of single conductors for interior circuits. The Aluminum Building Wire Installation Manual and Design Guide of The Aluminum Association lists sizes of the 600-volt class and NEC designations of insulation for various temperatures and environments, hence they are not repeated in this handbook. This classification includes insulated single or multiplexed cables for installation in air, duct, cable tray, metallic or non-metallic conduit, or suspended from messenger. It does not include multi-conductor cables (an assembly of several conductors under one jacket or sheath) nor cables designed especially for underground direct burial, though some cables of this class may be suitable for direct burial.

Table 10-2 shows the usual range of sizes and kinds
of insulation generally used for the 600-volt class on the basis of 100 percent insulation level, with grounded neutral. The insulation thickness for 1000 volts is slightly more than for 600 volts. If the thickness is shown as a double number, the right-hand value applies to the jacket only.

The EPM-EPDM insulation, listed in Table 10-2, represents the formulation used for 1000 volts or less of the EPR ozone-resistant insulation listed in Table 8-2.

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*product classification and technical data*

Ampacity ratings* for these conductors in air at 40°C ambient (not buried or in underground duct) are listed in the following designated columns of Table 10-1:

<table>
<thead>
<tr>
<th>Condition</th>
<th>90°C</th>
<th>75°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single conductor, in air</td>
<td>Col. 6</td>
<td>Col. 7</td>
</tr>
<tr>
<td>Each conductor of a triplexed assembly in air</td>
<td>Col. 8</td>
<td>Col. 9</td>
</tr>
<tr>
<td>Each conductor of a triplexed assembly in steel conduit in air</td>
<td>Col. 10</td>
<td>Col. 11</td>
</tr>
</tbody>
</table>

Ampacity rating of each conductor of a triplexed assembly in buried duct at 20°C ambient is listed in columns of Table 10-1 as below:

<table>
<thead>
<tr>
<th>Condition</th>
<th>90°C</th>
<th>75°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Each conductor in triplexed assembly in nonmetallic duct, buried, of two phase conductors and neutral</td>
<td>Col. 12</td>
<td>Col. 13</td>
</tr>
</tbody>
</table>

**Class 10-7
Three-Conductor Cable (600-1000 Volts) (Fig. 10-7)**

Although a triplexed cable has three conductors, it was included in Class 10-6 because essentially it is comprised of three closely spaced single conductor cables and is not designated as a multi-conductor cable.

A multi-conductor cable, on the other hand, as usually defined, has two or more phase conductors, usually cabled, and the entire assembly is enclosed in a close-fitting tubular jacket or sheath which may contain fillers to round out its circular shape. It may also have an insulating jacket under the sheath.

Sector stranded conductors are sometimes used in three-conductor cable as a means of reducing diameter. The Type SER service-entrance 600-volt cable qualifies as a three-conductor cable, but because of its special application it is listed as Class 10-5. The Types NM and NMC also are three-conductor cables, but because of availability only in small sizes for branch circuits they are separately considered as Class 10-8. It is characteristic of three-conductor cables that the outer jacket must fit closely, hence pre-assembled cables in a comparatively large duct are not included. Many portable power cables are three-conductor cables, with flexible neoprene or plastic jackets.

Armored aluminum multi-conductor power cables, Fig. 10-7, available as Type MC (metal clad) with NEC conductors No. 12 AWG and larger, have an outer protective covering of corrugated or interlocked design. A modification in branch-circuit and feeder sizes, Type AC (armor clad), has an internal bonding strip of aluminum in intimate contact with the armor for its entire length. Another style of Type MC aluminum corrugated cable has the tube formed around the assembly of insulated conductors, with the longitudinal seam closed.

* Ampacity ratings for this class are from IEC A Pub. P-46-462 (1962) as described in Chapter 9.

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Fig. 10-6. Typical 600-volt insulated power and light cables.
A—No outer covering required.
B—Comparatively thick jacket, neoprene, etc.
C—Comparatively thin jacket, nylon, etc.
D—Assembled aerial cable; phase conductors, either cabled or layed up with reverse lay twist to facilitate side taps.
<table>
<thead>
<tr>
<th>Conductor Size</th>
<th>Cross Linked Polyethylene</th>
<th>Polyvinyl Chloride</th>
<th>SBR Rubber</th>
<th>Butyl</th>
<th>EPM-EPDM Ethylene Propylene Rubber</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>90°C Dry</td>
<td>75°C Wet</td>
<td>75°C Wet</td>
<td>75°C Wet</td>
<td>90°C Dry</td>
</tr>
<tr>
<td></td>
<td>75°C Wet</td>
<td>USE-RHW-</td>
<td>THHN++</td>
<td>Wet</td>
<td>90°C Dry</td>
</tr>
<tr>
<td></td>
<td>75°C Wet</td>
<td>RHH++</td>
<td>THWN</td>
<td>Wet</td>
<td>75°C Wet</td>
</tr>
<tr>
<td></td>
<td>75°C Wet</td>
<td>RHH-USE</td>
<td>RHH-USE++</td>
<td>Wet</td>
<td>75°C Wet</td>
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<tr>
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<td>1.2-10</td>
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<td>45</td>
<td>1.14</td>
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<td></td>
<td></td>
<td>0.76</td>
<td>1.14</td>
<td>1.14</td>
<td>45-15***</td>
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<td>0.84</td>
<td>0.84</td>
<td>1.14-.38</td>
</tr>
<tr>
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<td>8-2</td>
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<td>60</td>
<td>60</td>
<td>1.52</td>
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<tr>
<td></td>
<td></td>
<td>1.14</td>
<td>1.52</td>
<td>1.52</td>
<td>45-15***</td>
</tr>
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<td></td>
<td>1.14</td>
<td>1.52</td>
<td>1.52</td>
<td>1.14-.38</td>
</tr>
<tr>
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<td>1.4/0</td>
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<td>80</td>
<td>2.03</td>
</tr>
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<td></td>
<td>1.40</td>
<td>2.03</td>
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<td>50-7</td>
</tr>
<tr>
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<td>1.27-.18</td>
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<td>1.27-.18</td>
<td>1.27-.18</td>
<td>2.03-.14</td>
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<tr>
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<td>213-500</td>
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<td>95</td>
<td>95</td>
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<td>60-8</td>
</tr>
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<td>2.41</td>
<td>1.52-.20</td>
<td>1.52-.20</td>
<td>95-65</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.41</td>
<td>1.52-.20</td>
<td>1.52-.20</td>
<td>2.16-.165</td>
</tr>
<tr>
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<td>501-1000</td>
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<td>2.79</td>
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<td>2.79</td>
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<td>1.78-.23</td>
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<td>1001-2000</td>
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<td>125</td>
<td>125</td>
<td>3.18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.41</td>
<td>3.18</td>
<td>3.18</td>
<td>110-65</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.41</td>
<td>3.18</td>
<td>3.18</td>
<td>2.79-.165</td>
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<td></td>
<td></td>
<td>2.41</td>
<td>3.18</td>
<td>3.18</td>
<td>1.78-.23</td>
</tr>
</tbody>
</table>

*100% insulation may also be used with ungrounded neutrals provided the fault-clearing devices clear the fault in less than one minute and completely de-energize the faulted section. If this condition cannot be met, it may be necessary to use insulation for 133 percent level (see manufacturer). (If thickness is shown as a double number, right-hand number indicates thickness of jacket.)

**For No. 12, values are 15-4 mils (0.38-10 mm); for No. 10, values are 20-4 mils (0.51-.10 mm); for No. 8 and No. 6, values are 30-5 mils (0.76-.13 mm); for No. 4 and No. 2, values are 40-6 mils (1.02-.15 mm).

***A 30-mil jacket is required for aerial installation.

++NEC limits wet-location rating to 75°C, but IEEA and Industry ratings allow 90°C wet or dry for cables having these insulation thicknesses.

#For sizes No. 8 and No. 7, values are 45-15 mils (1.14-.38 mm); for sizes No. 6-2, values are 45-30 mils (1.14-.76 mm).
by welding, and the corrugations roll-formed to provide flexibility.

Still another MC type is aluminum sheathed cable, formerly Type ALS. This cable has a smooth tubular aluminum sheath surrounding three or more NEC conductors of branch-circuit size with ampacity ratings from 20-amp to 90-amp. The insulation of individual conductors used in this cable type may be any listed for Class 10-6 cables. These cables are particularly useful in control circuit wiring, where provision for growth is not necessary. Its use eliminates cost of conduit installation and wire pulling.

In any of these MC types, a fourth insulated conductor can be included for three-phase, Y-connected applications.

The equivalent of a separate bare or covered grounding conductor may be included as one or more conductors in the interstices of the cable arrangement. The grounding conductors for Type MC cables are tabulated in Section 7.9 of ICEA Standard S-66-524 and Section 7.10 of S-19-81. The protective sheath or armor is not designed for use as a neutral conductor and for interlocked metal strip design is not recognized as a grounding conductor.

The exterior surface of metal clad cables must be additionally protected by a suitable jacketing material when exposed to destructive corrosive conditions. Colored PVC jackets are commonly used for this purpose.

There are moderate NEC limitations as to where Type MC and similar cables may be installed. Generally, they are placed in trays or on other rigid supports in power stations, industrial plants and commercial installations, though some types are suitable for embedded or underground use.

For calculating voltage drop in 600-volt three-conductor armored cable, the factors of Table 9-6 may be applied, using those for aluminum conduit for cables with aluminum armor, and those for steel conduit for cables with steel armor. The armor is thinner than the wall of standard conduit, but since it is closer to the conductors, its inductive effect is about the same.

The ampacity of the three-conductor unarmored or aluminum armored cables in air at 75°C with 40°C ambient is per Col. 15 of Table 10-1 and at 90°C per Col. 14. For three single-conductor cables in steel conduit, the ampacity is as shown in Col. 17 for 75°C and Col. 16 for 90°C. The range of available sizes of cables with welded-tube corrugated armor differs from that of cable with interlocked armor. For further information consult manufacturers' lists.

**Three-conductor non-metallic-jacketed cable**

This cable is similar to Type MC armored or sheathed cable except that the protective covering is a round plastic jacket instead of a metallic sheath or armor. This design is used where it is desired to maintain a fixed configuration of the conductors along with moderate protection against crushing and abrasion, such as when pulling through a duct or after installation on supports, particularly in wet locations. The insulation of the individual conductors may be any listed for Class 10-6 cables, though the conductors usually do not require additional jacketing.

In wet locations, the insulation should be selected for wet conditions. The outer jacket is usually of neoprene or polyvinyl chloride. If the cable is in air at 40°C ambient, the ampacity rating of Col. 15 for 75°C and Col. 14 for 90°C of Table 10-1 may be used. If installed in underground duct at 20°C ambient, Col. 13 for 75°C and Col. 12 for 90°C may be used.

These plastic-jacketed three-conductor cables may be installed in the same manner as single power cables (Class 10-6).

**Class 10-8**

**Types NM and NMC Nonmetallic Sheathed Cable** (Fig. 10-8)

This two-, three- or four-conductor cable is used extensively for interior wiring of branch circuits through the 75-amp ratings. It is listed by UL for sizes No. 12 through No. 2 for aluminum. The insulated conductors in the usual sizes of No. 12 and No. 10 are arranged in parallel for two-conductor cables; three and four-conductor cables are wired into a round configuration. Assemblies are enclosed in a moisture and abrasion resistant extruded PVC jacket. The three-insulated-conductor round style is suitable for 3-wire circuits with one insulated conductor serving as neutral.

NM and NMC cable is satisfactory for use in circuits not exceeding 600 volts and where conductor temperatures

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**Fig. 10-7. Typical three-conductor impervious-corrugated or interlocked, corrugated armored cable.**
covered and insulated aluminum wire and cable

Type NM (2-Cdr. with Ground, Oval Section)  
(Can be obtained without grounding conductor)

Type NM (3 Conductor, Round Section)  
(Also available with bare grounding conductor)

Fig. 10-8. Type NM branch-wiring cables.

do not exceed 60°C. Cable constructions are available with or without a bare ground conductor.

Conductors of No. 10 size or smaller are solid, and annealed for flexibility, because an advantage of this type of cable is that it readily may be bent into place. The Type NM cable is approved for installation in both exposed and concealed work in normally dry locations, but not for exposure to corrosive conditions, nor may it be run in masonry, concrete, or plaster.

Type NMC cable resembles type NM but has an integral jacket which is fungus- and corrosion-resistant. Installation in moist or corrosive locations is approved and under certain conditions it may be used where Type NM is prohibited. Neither type is approved for service-entrance use, nor for locations as limited in NEC Section 336-3. Amperages, based on 300°C ambient, are in Col. 18, Table 10-1.

Class 10-9
Secondary-Distribution Single- or Three-Conductor Cables for Underground Residential Distribution (URD) 600 Volts (Fig. 10-9)

Although these cables are usually designated as for URD, they are of course suitable for any other direct burial use within their ratings. NEC cables designated Type UF (underground feeder) are included to 4/0. Certain other conductors in Class 10-6 are also suitable for direct burial, such as USE or the combination Type USE-RHW-RHH available in several insulations. Some sizes are available in both solid and concentric-stranded aluminum conductors; the solid type is an intermediate temper.

Bare aluminum neutrals are usually not permitted for URD cables because of the possibility of corrosion in wet earth. A popular cable is a triplexed assembly of which one conductor is an insulated neutral, Fig. 10-9C.

A less frequently used form has a copper-wire neutral spiraled closely around one or two paralleled insulated conductors. (Fig. 10-9A & 9B) Copper is used for the earth contact because of its resistance to corrosion under buried conditions. Still another form is the ribbon

(A) Two-Conductor Concentric Neutral Type
(B) Three-Conductor Concentric Neutral Type
(C) Triplex Type
(D) Ribbon Type
(E) Triplexed Plastic Conduit Type

Note: A concentric-neutral cable may be used instead of the triplexed as shown for installation in plastic conduit (E).

Fig. 10-9. Typical 600-volt cables for direct burial.
### TABLE 10-3
Typical Insulation Thicknesses of Secondary Cables (600V) for Direct Burial or Underground in Duct
Thickness of Insulation in Milis (1/1000 in.), Millimeters

<table>
<thead>
<tr>
<th>Conductor Size</th>
<th>(1) Cross-Linked Polyethylene</th>
<th>(2) Concentric Neutral, or Tripled 90°C</th>
<th>(3) Parallel Ribbon Type 90°C</th>
<th>(4) Polyvinyl Chloride or Low-Density Polyethylene</th>
<th>(5) Parallel Ribbon Type 75°C</th>
<th>(6) Plastic Conduit Type 75°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>AWG-kcmil</td>
<td>Mils</td>
<td>mm</td>
<td>Mils</td>
<td>mm</td>
<td>Mils</td>
<td>mm</td>
</tr>
<tr>
<td>4-2</td>
<td>60</td>
<td>1.52</td>
<td>75</td>
<td>1.91</td>
<td>60</td>
<td>1.52</td>
</tr>
<tr>
<td>1-4/0</td>
<td>80</td>
<td>2.03</td>
<td>85</td>
<td>2.16</td>
<td>80</td>
<td>2.03</td>
</tr>
<tr>
<td>225-500</td>
<td>95</td>
<td>2.41</td>
<td>95</td>
<td>2.41</td>
<td>95</td>
<td>2.41</td>
</tr>
</tbody>
</table>

Sizes are concentric stranded conductors; for solid-conductor sizes (except for Column 5) refer to manufacturer. Special inquiry also is required for availability of sizes for Column 2 for sizes above 300 kcmil.

*The thicknesses shown include 30 mils for jacket.

cable in which two parallel insulated phase conductors have an insulated neutral between them, Fig. 10-9D. The insulation is extruded over the three conductors simultaneously so there is a thin connecting web between the conductors, or the web may be only a part of a jacket. The web is easily torn away during installation.

Available constructions include cable in a duct. This construction consists of two or more conductors pre-assembled at the factory in a plastic duct (Figure 10-9E). Use of this product provides for conductor replacement after installation. Duct sizes are compatible with existing accessories and, through supplier inquiry, may be sized to allow for some degree of enlargement on the system as installed.

The insulated conductors in any of the above-described cable assemblies can be any of the conductors of Class 10-6 listed by NEC as suitable for direct burial.

Table 10-3 shows the usual range of sizes and kinds of insulation generally used for the 600-volt cables of the types described and Table 10-1, Cols. 19 to 26 summarizes amperages that conform to ICEA requirements, and to local codes requiring that underground secondary service cables leading directly to the home be UL-listed. Care should be taken by the purchaser to assure that the product offered is UL-labeled for these applications where required.

The three-conductor URD cables for 600 volts in the arrangements shown in Fig. 10-9 are for three-wire single-phase circuits. If the cables are for three-phase (3 or 4 conductors), the amperages shown in Table 10-1 should be reduced. Consult suppliers.

Cols. 19 and 20 of Table 10-1 list amperages of 600-volt buried cables of the concentric-neutral type (having spiraled bare copper neutrals) at 200°C ambient for insulation suitable for 90°C and 75°C, respectively. The amperages of tripled buried cables are listed in Cols. 25 and 26. The ribbon type has amperages according to industry sources and tests as listed in Col. 21 for 90°C and for 75°C as in Col. 22.

In all cases of direct burial or duct installation an earth thermal resistance of RHO-90 is assumed with a load factor of 100 percent; that is, the cables will withstand these amperage ratings for continuous operation.

The amperage ratings of the cables pre-assembled in plastic ducts for the 90°C ratings are in Col. 23 and for the 75°C ratings in Col. 24.

### Class 10-10 Portable Aluminum Cables (600 Volts or less) (Fig. 10-10)

Portable aluminum cables, either single or multiple conductor, are constructed to yield a high degree of flexibility. Flexible cables usually employ an intermediate tempered aluminum conductor which is insulated with a synthetic rubber or thermoplastic material. These conductors are phase-identified for circuit applications. Two or three conductor cables, with or without equipment grounding conductors, are cable together with the necessary fillers to construct a round cable and employ an overall jacket of thermoplastic or synthetic rubber. Flat constructions are also available with conductors arranged parallel to one another and with a common overall jacket. Portable aluminum cables possess a lighter weight than other constructions, which facilitates their use. Single-conductor portable cables are available for special applications where flexibility is a requirement due to installation handling or vibration is a consideration.

Single-conductor portable cables usually are available from No. 8 to 1000 kcmil, and multiple conductor portable cables from No. 12 to 4/0 AWG. Ampacity ratings are usually approximately as follows for 75°C.
covered and insulated aluminum wire and cable

(A) Two-conductor
(B) Two-conductor With Flat Equipment-Ground Conductor
(C) Two-conductor With Stranded Equipment-Ground Conductor
(D) Three-conductor With Stranded Equipment-Ground Conductor

Fig. 10-10. Typical cross-sections of portable cables, comprising aluminum conductors, insulation, web-tape cushion, and overall jacketing.

Note: The web-tape cushion prevents longitudinal separation of insulation and jacket during bending of the cable.

operating temperatures and 400°C ambient temperatures:

<table>
<thead>
<tr>
<th>Conductors</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-conductor cables</td>
<td>Col. 3 in 10-1</td>
</tr>
<tr>
<td>Two-conductor parallel or round type</td>
<td>Col. 4 in 10-1</td>
</tr>
<tr>
<td>Three-conductor, round</td>
<td>Col. 27 in 10-1</td>
</tr>
</tbody>
</table>

Often a long portable cable is partly held on a gathering reel. The above ampacity values are reduced for such cases by multiplying by the following correction factors:

- One layer on roll: 0.85
- Two layers on roll: 0.65
- Three layers on roll: 0.45
- Four layers on roll: 0.35

Class 10-11 (Fig. 10-11)
Aluminum Control Cables (for 600 Volts or less)

Because of the wide variety of multi-conductor cables used for control and signal circuits the generally small size of the individual conductors, no detailed descriptive listing of them is attempted for this book. The individual conductors (either stranded or solid) are insulated with compounds that best meet conditions, and the whole assembly is contained within a round thick overall jacket of neoprene or thermoplastic material. Where the application environment is severe, constructions are available with reinforced overall jackets or armoring.

These control cables have wide application in utilities, industrial, municipal, and railroad installations for control and signal purposes. The automatic control of machine-tool operations is a recent application for which control cables of oil-resistant type are used. Manufacturers' lists should be consulted.

Cables For Primary Distribution Voltages

The types and voltage range of primary distribution cables with aluminum conductors were briefly described in Chapter 7. Those with rubber or thermoplastic insulations mostly are for 5-, 15-, 25-, and 35-kV all with grounded neutral. The 3-kV and 8-kV ratings sometimes are listed, but are less used because the trend is toward the next higher voltage in anticipation of load growth, even though the actual increase from the lower circuit levels may be long delayed.
Customarily, primary-distribution insulated cables are voltage-rated on the basis on the phase-to-phase voltage of a three-phase circuit of which they are a part, or would be a part if the three-phase circuit were complete. Thus, an insulated conductor of a single-phase branch circuit including a phase wire and a ground wire that is connected to the wye ground of a 25-kV three-phase wye-grounded circuit is still rated 25 kV although the actual rms kV of the single-phase circuit is only 25/√3 or 14.4 kV. This notation applies principally to the single insulated primary conductor of the two-conductor cable that supplies the single-phase transformer that feeds the secondary three-wire circuits.

Cable descriptions in this book and in the literature distinguish between the insulation thicknesses required for high-voltage cables in circuits with grounded neutral and those with ungrounded neutral, the latter requiring thicker insulation. It is recognized, however, that there are other conditions than lack of neutral ground that may make a thicker insulation desirable. To meet this condition the concept of grounded and ungrounded neutral is in the process of being eliminated as a sole criterion. Instead the insulation thicknesses are assigned based on insulation level (AEIC #5 and 1987 NEC, Table 310-13).

The selection of the cable insulation level to be used in a particular installation shall be made on the basis of the applicable phase-to-phase voltage and the general system category as outlined below:

100 Percent Level—Cables in this category may be applied where the system is provided with relay protection such that ground faults will be cleared as rapidly as possible, but in any case within one minute. While these cables are applicable to the great majority of cable installations which are on grounded systems, they may be used also on other systems for which the application of cables is acceptable provided the above clearing requirements are met in completely de-energizing the faulted section.*

133 Percent Level—This insulation level corresponds to that formerly designated for ungrounded systems. Cables in this category may be applied in situations where the clearing time requirements of the 100 percent level category cannot be met, and yet there is adequate assurance that the faulted section will be de-energized in a time not exceeding one hour. Also they may be used when additional insulation strength over the 100 percent level category is desirable.

173 Percent Level—Cables in this category should be applied on systems where the time required to de-energize a grounded section is indefinite. Their use is recommended also for resonant grounded systems. Consult the manufacturer for insulation thicknesses.

The AEIC reference to the preceding statement regarding insulation levels also includes the following:

In common with other electrical equipment, the use of cables is not recommended on systems where the ratio of zero to positive sequence reactance of the system at the point of cable application lies between 1 and 40, since excessively high voltages may be encountered in the case of ground faults.

Consideration of this requirement is in the province of the system electrical engineer.

**Tabular Voltages for Determining Insulation Thickness**

For three-phase systems with grounded or ungrounded neutral the thickness values are those given in the respective columns of Table 10-4. For three-phase delta systems where one leg may be grounded for periods of over one hour, consult the 173 percent insulation level referenced above. For single- and two-phase grounded systems, multiply the voltage to ground by 1.73 and select thickness for that voltage in the grounded neutral column. For a direct-current system up to and including 2000 volts consider it the same as a single-phase alternating-current system of the same rms voltage.

**Jacket Thickness**

The insulation of unshielded cables may be of such quality that it will withstand all environmental conditions likely to be encountered, such as moisture, oil, sunlight, and abrasion in handling. If so, no jacket has to be added. Several of the modern insulations meet this requirement, but often a slight increase in insulation thickness is used to provide for expected surface wear and to equal other advantages obtained by a jacket.

Shielded cables, on the other hand, unless protected by armor, require a jacket, not necessarily for improving surface quality, but as protection for the insulation shielding. The jacket material selected is the most suitable to meet conditions, and usually it is a different compound than that of the insulation.

The minimum thickness that qualifies a coating as a jacket on cables 2 kV and above is 30 mils, but the thickness also depends on diameter of the cable and voltage. Jacket thicknesses have substantially become standardized as shown in Tables 10-5 and 10-6. The relative suitability of jackets of various materials can be determined from Table 8-4. Jacket thicknesses generally conform to those listed in Table 10-5, based on diameter, and in Table 10-6 for single conductor cables, based on AWG-kcmil size. The individual conductors of a multi-conductor cable that has a jacket surrounding all conductors may have thinner jackets than those specified in Table 10-6, and conform to column 3 of Table 10-5. Column 4 lists thickness of the overall jacket.

It is necessary to distinguish between an overall jacket

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* Where additional insulation thickness is desired, it shall be the same as for the 133 percent insulation level.
covered and insulated aluminum wire and cable

and a band of belt insulation, as found in some kinds of cable, such as for series-lighting circuits.

Primary Unshielded Cables
3 kV and 5 kV

The 5 kV rating is the most used of this type, Fig. 10-12. If the insulation does not have a satisfactory surface for withstanding environmental conditions a jacket is added.

The usual cable construction without jacket comprises a Class-B stranded conductor (or it may be solid round in small sizes), a resistive conductor-shield and insulation of the thickness listed in Table 10-4. The insulation must be ozone and corona discharge-resistant, suitable for wet or dry locations, flame retardant, and suitable for sunlight exposure, although the latter two qualities may be obtained by jacketing, if not a characteristic of the insulation. The jacket, if used, must also be corona discharge resistant.

Primary Cables with Insulation Shielding (to 35 kV)

The conditions that require shielding at 5 kV are stated in ICEA* and pertain principally to single conductors at 133 percent insulation level or where cables are installed underground directly buried, in ducts or in wet locations. The shields are also required if the insulation or jacket is not one that protects against ozone or its effects. Insulation thicknesses are listed in Table 10-4. Generally, except for the shielding, the same construction applies as for nonshielded cables. Fig. 10-13 is typical.

Triplexed preassembled cable, or three-conductor cable, either jacketed or in metallic armor of constructions previously described is often used in the 5-kV-and-above ratings, Figs. 10-14 to -16. For ampacities see Table 10-7.

Primary Interlocked-Armor Cables (Fig. 10-16)

The description of interlocked corrugated armor used on cables for 600 volts (page 10-5) applies to cables for the primary voltages except for strand and insulation shielding requirements. However, the impervious seamless corrugated armor is not as yet available in as many voltage ratings or sizes as the interlocked armor. Three-conductor armored cables are the most used. Single-conductor cables are available for special applications with non-magnetic aluminum armor.

The cables are available both with and without an extruded outer covering under the armor. Either aluminum or steel armor is available. Voltage drop at circuit power factors less than 100 percent is increased if steel armor is used, but is negligibly affected by aluminum armor. The ampacity rating of a three-conductor cable with aluminum corrugated armor is substantially the same and may be somewhat more than that of the insulated three-conductor cable in air; the increase in area because of the corrugations and the closeness of the conductors to the armor both serve to increase the rate of heat transfer. For ampacities, see Table 10-7.

---

*ICEA S-61-402 Table 4.
### TABLE 10-4

Insulation Thickness (not including jackets) for High-Voltage Conductors in Three-Phase Systems with 100% and 133% Insulation Levels, (or Grounded Neutral and Ungrounded Neutral, respectively).

Thickness in Mils (=1/1000 in.)

Note: The values in this table are obtained from ICEA or industry designations of thickness for the insulations named. However, because of variations of dates at which the values were issued, and because of lack of uniformity of the size-steps, slight variations occur. Also some cable manufacturers issue specifications that in some respects show more favorable values. The insulations are those used for ozone-resistant conditions. In the 5000-volt class certain other insulations listed in Table 8-2 and 8-3 may be used but not necessarily at the listed thickness.

<table>
<thead>
<tr>
<th>Voltage and Size</th>
<th>XLPE or PE(1)</th>
<th>EPR</th>
<th>Butyl</th>
<th>Silicone (SA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>and AWG and kcmil</td>
<td>(2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Grounded Neutral</td>
<td>Un-Grounded Neutral</td>
<td>Grounded Neutral</td>
<td>Un-Grounded Neutral</td>
</tr>
<tr>
<td></td>
<td>mils</td>
<td>mm</td>
<td>mils</td>
<td>mm</td>
</tr>
<tr>
<td>UNSHIELDED</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2001-5000V(3)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8-4/0</td>
<td>110</td>
<td>2.79</td>
<td>110</td>
<td>2.79</td>
</tr>
<tr>
<td>225-500</td>
<td>120</td>
<td>3.05</td>
<td>120</td>
<td>3.05</td>
</tr>
<tr>
<td>525-1000</td>
<td>130</td>
<td>3.30</td>
<td>130</td>
<td>3.30</td>
</tr>
<tr>
<td>SHIELDED</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2001-5000V</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8-4/0</td>
<td>90</td>
<td>2.29</td>
<td>90</td>
<td>2.29</td>
</tr>
<tr>
<td>225-500</td>
<td>90</td>
<td>2.29</td>
<td>90</td>
<td>2.29</td>
</tr>
<tr>
<td>525-1000</td>
<td>90</td>
<td>2.29</td>
<td>90</td>
<td>2.29</td>
</tr>
<tr>
<td>6-600</td>
<td>115</td>
<td>2.92</td>
<td>140</td>
<td>3.56</td>
</tr>
<tr>
<td>525-1000</td>
<td>115</td>
<td>2.92</td>
<td>140</td>
<td>3.56</td>
</tr>
<tr>
<td>8001-15000V</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-1000</td>
<td>175</td>
<td>4.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-1000</td>
<td>215</td>
<td>5.46</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15001-25000V</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-1000</td>
<td>260</td>
<td>6.60</td>
<td>345</td>
<td>8.76</td>
</tr>
<tr>
<td>25001-28000V</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-1000</td>
<td>280</td>
<td>7.11</td>
<td>420</td>
<td>7.11</td>
</tr>
<tr>
<td>28001-35000V</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/0-1000</td>
<td>345</td>
<td>8.76</td>
<td>420</td>
<td>7.11</td>
</tr>
</tbody>
</table>

2-Conductor Concentric(4)

Helical Bare Grounded Neutral

<table>
<thead>
<tr>
<th>Voltage</th>
<th>XLPE</th>
<th>HPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 kV</td>
<td>#4-350</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>#4-350</td>
<td>175</td>
</tr>
<tr>
<td>15 kV</td>
<td></td>
<td>175</td>
</tr>
<tr>
<td>25 kV</td>
<td>#2-350</td>
<td>260</td>
</tr>
<tr>
<td>35 kV</td>
<td>1/0-350</td>
<td>345</td>
</tr>
</tbody>
</table>

NOTE: The difference of thickness between unshielded and shielded 5 kV cables using XLPE or PE insulations reflects the fact that the unshielded cable has a potential distribution not as even as that of the shielded cable. See page 10-15 for additional notes.

---

*Required by specification to have an outer jacket; maximum 3-phase voltage for 133% insulation level 3000V

<table>
<thead>
<tr>
<th>JACKET</th>
<th>THICKNESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>AWG or kcmil</td>
<td>Mils</td>
</tr>
<tr>
<td>8-6</td>
<td>30</td>
</tr>
<tr>
<td>4-2/0</td>
<td>45</td>
</tr>
<tr>
<td>3/0-1000</td>
<td>65</td>
</tr>
</tbody>
</table>

**Required by specification to have an outer jacket

<table>
<thead>
<tr>
<th>JACKET</th>
<th>THICKNESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>AWG or kcmil</td>
<td>Mils</td>
</tr>
<tr>
<td>8-1</td>
<td>45</td>
</tr>
<tr>
<td>1/0-4/0</td>
<td>65</td>
</tr>
<tr>
<td>225-750</td>
<td>65</td>
</tr>
<tr>
<td>1000</td>
<td>95</td>
</tr>
</tbody>
</table>
covered and insulated aluminum wire and cable

### TABLE 10-5
Jacket Thicknesses for Single- and Multiple-Conductor Power Cables According to Diameter Under Jacket
For all uses; Conduit, Tray, Trough, Underground Duct, Aerial, and Direct Burial† but does not include Communication or Portable Cables

<table>
<thead>
<tr>
<th>Calculated Diameter of Cable Under Jacket (inches)</th>
<th>Single-conductor Cable</th>
<th>Multiple-conductor Cables*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nonsheilded</td>
<td>Shielded**</td>
</tr>
<tr>
<td></td>
<td>mils</td>
<td>mm</td>
</tr>
<tr>
<td>0.250 or less 6.35 or less</td>
<td>15</td>
<td>0.38</td>
</tr>
<tr>
<td>0.251-0.425 6.38-10.80</td>
<td>30</td>
<td>0.76</td>
</tr>
<tr>
<td>0.426-0.700 10.82-17.78</td>
<td>45</td>
<td>1.14</td>
</tr>
<tr>
<td>0.701-1.500 17.71-38.10</td>
<td>65</td>
<td>1.65</td>
</tr>
<tr>
<td>1.501-2.500 38.13-63.50</td>
<td>95</td>
<td>2.41</td>
</tr>
<tr>
<td>2.501 and larger 63.53 and larger</td>
<td>125</td>
<td>3.18</td>
</tr>
</tbody>
</table>

* Under common jacket.
† These thicknesses apply to jackets only and do not apply to colored coatings used for the purpose of circuit identification on the individual conductors of multiple-conductor cables.
** In calculating the diameter under the jacket of single-conductor shielded conductors that are part of a multi-conductor cable, add 45 mils to the insulation thickness to allow for thickness of the insulation shield. Also add the thickness of the separator and strand tapes. Eqs. 9-3, 9-4, and 9-5 provide a means for calculation of diameter, provided D, is the inside diameter of the jacket instead of the outer sheath.
Two-conductor cables for direct burial having helical bare copper wire ground conductors have an outer protective covering of conducting material that also serves as an insulation shield. The layer is not less than 30 mils thick.
NOTE—For flat twin cable, use the calculated major core diameter under the jacket to determine the jacket thickness from Column 4.

Source: ICEA S-61-402

### TABLE 10-6
Jacket Thicknesses for Single-Conductor Power Cables, According to AWG-kcmil Sizes
For all uses: Conduit, Trays, Troughs, Underground Duct, Aerial and Direct Burial, not including Communication or Portable Cables.
It is assumed that the jacket material is compatible with the insulation for the designated kV ratings. These thicknesses also apply to single-conductor cables if they are triplexed, but they do not necessarily apply to the cables that are a part of a three-conductor cable, for which the thickness may be according to column (3) of Table 10-5

<table>
<thead>
<tr>
<th>Volts</th>
<th>Percent Insulation Level</th>
<th>Thickness of Jacket, Mil ((=1/1000) in.), (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>30 (0.76)</td>
</tr>
<tr>
<td>UNSHIELDED</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2001 - 5000</td>
<td>100 &amp; 133%</td>
<td>#8 - #6</td>
</tr>
<tr>
<td>5001 - 8000</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>8001 - 15000</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>15001 - 25000</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>25001 - 28000</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>28001 - 35000</td>
<td>100%</td>
<td></td>
</tr>
</tbody>
</table>

Shifted

|                      |                          |                  |                  |                  |                  |                  |
| 2001 - 5000         | 100 & 133%               | #8               | #6 - 2/0         | 3/0 - 1000        |                  |                  |
| 5001 - 8000         | 133%                     |                  | #6 - 2           | 3/0 - 1000        |                  |                  |
| 8001 - 15000        | 100%                     |                  |                  | #2 - 750          | 1000             |
| 15001 - 25000       | 100%                     |                  |                  | #1 - 600          | 750 - 1000       |
| 25001 - 28000       | 100%                     |                  |                  | #1 - 500          | 600 - 1000       |
| 28001 - 35000       | 100%                     |                  |                  | #1 - 350          | 400 - 1000       |

Source: ICEA S-61-402
TABLE 10-4 NOTES

(1) The characteristics for the kinds of insulation shown are listed in Tables 8-2, 8-3, and 8-4, for which also see rated temperatures.

(2) If insulation is rated according to "percent insulation level," use column "grounded neutral" for 100% level, and column for "ungrounded neutral" for 133% level.

(3) Solid dielectric insulated conductors operated above 2000 volts generally require shielding under the NEC. Conditions under which shielding is not required in the 2000-8000 volts range are detailed in NEC Section 310-6.

(4) The cables listed in the main body of the table are generally available in the sizes shown as single conductors or cable for aerial-messenger support, or in tray or duct, and with some insulations are suitable for direct burial. The two-conductor concentric-neutral cables are mostly used for direct burial, but they also may be used in duct or be aerial-supported. The insulation thickness for coaxial cables (in which the neutral is tubular) are similar.

---

**Fig. 10-14.** Typical pre-assembled triplexed 5-kV to 25-kV shielded primary cable bound to composite aluminum-steel (ACSR or ACSR/AW) or aluminum-alloy messenger with aluminum tape. A fourth insulated neutral may be included if required.

The construction of each conductor is similar to that depicted in Fig. 10-13. Also available with one, or two phase conductors.

For certain sizes reverse-lay may be obtained (see Fig. 10-3). Also for parallel lay (not triplexed) field-spinning equipment is available so that the assembly with lashing wire may be performed at the site.

Similar pre-assembled triplexed (or parallel) cables are available without insulation shielding to 5 kV.

---

**Fig. 10-15.** Typical three-conductor 5-kV to 35-kV shielded primary cable in jacket.

The construction of each conductor is similar to that depicted in Fig. 10-13. Triangular fillers in the interstices aid in forming a cylindrical exterior that will withstand bending from reel. Bare grounding conductors may be used in the interstices if required.

---

**Primary Cables for Underground Residential Distribution-URD**

Directly buried URD/UD style cables are increasingly being used as "main-line" three-phase distribution feeders.

However, by far the most used primary cables for URD are those that supply single-phase primary voltage to the single-phase transformers supplying 120-240 V three-wire circuits to the residences or other use-points in the area. These single-phase primary cables are of the two-conductor type. One conductor is an insulated phase wire. The other is either a copper-wire concentric neutral conductor of equal conductivity to that of the aluminum insulated conductor, Fig. 10-17, or a concentric flat strap neutral, Fig. 10-18, particularly adapted to conditions where substantially full metallic coverage is desired. These copper neutrals are directly in contact with the ground when buried.

The phase conductors of these cables have semi-conducting strand shielding and semi-conducting compound underneath the concentric wires or straps to serve as an insulation shield.

The insulation thickness around the phase conductor is generally the same as listed in Table 10-4. For capacities see Tables 10-9A and 10-9B.
covered and insulated aluminum wire and cable

High Voltage Primary Cables

Aluminum cables are commonly available through 115 kV levels. Advances in materials and manufacturing expertise have resulted in available cables in this and higher voltage levels. While previous cable constructions employed paper insulation, with some gas-filled designs, today’s market offers some cables of this type with solid dielectric insulations. Polyethylene and crosslinked polyethylene and similar materials are being employed in cable designs. Information concerning availability and design should be directed to individual cable manufacturers.

As typical of such construction, a 115-kV, 500-kcmil aluminum cable for direct burial, with strand and insulation shielding has 0.740 in. XLPE insulation thickness (0.525-in. for 69 kV), with a 0.140-in. thick PVC jacket, and 2.90-in. overall diameter (2.37 in. for 69-kV).

Ampacity of High Voltage Aluminum Cables

The ampacity values listed in Table 10-7A, -B, and -C for the designated cable types and installation conditions mostly are those listed in ICEA Pub. 46-426 Vol. II for aluminum, as explained in Chapter 9, applying to rubber- or thermoplastic-insulated cables. The insulation is assumed to have a power factor of 0.035, dielectric constant of 4.5, and thicknesses for the various voltages that were listed in ICEA Standards in 1962 when the ampacity values were published. Cables directly buried or in under-

Fig. 10-17. Typical 5 to 35 kV two-conductor concentric-wire neutral primary cable for direct burial, duct or aerial application.

ground ducts are assumed to be in circuits of 100% load factor and RHO-90 earth resistivity. For 75% load factor, direct burial, increase ampacity by 6%, or for duct 3%; and for 50% if by 14% and 6% respectively. Table 10-7 is based on 40°C ambient for cables in air, and 20°C ambient if underground. Adjustment factors for other mediums are in Table 10-8.

Separate tables 10-9A and 10-9B list the ampacities of concentric-neutral primary cables for direct burial in duct, at 20°C ambient, and also for installation of the cables in air, or in duct in air, at 40°C ambient, as necessary for leads into air from an underground installation. Table 10-9A also includes ampacities for 35 kV cable when buried directly or in duct.

Inasmuch as ICEA and industry standards now allow some reduction of thickness of certain kinds of insulations as compared with the values that prevailed in 1962, and also because most insulations have a lower p.f. than 0.035,
### TABLE 10-7A
Typical Amperages of 5 kV Cables with Aluminum Conductors of Various Types and for Various Installation Conditions

<table>
<thead>
<tr>
<th>Conductor Size</th>
<th>5 kV in Air 40°C Ambient Shielded Grounded Neutral</th>
<th>5 kV in Duct 20°C Ambient Shielded RHO-90 100 LF</th>
<th>5 kV Directly Buried 20°C Ambient Shielded RHO-90 100 LF</th>
</tr>
</thead>
<tbody>
<tr>
<td>AWG kcmil</td>
<td>1 in Air (1C)*</td>
<td>1 in Air (1C)*</td>
<td>1 in Air (1C)*</td>
</tr>
<tr>
<td>----------------</td>
<td>-----------------------------------------------</td>
<td>-----------------------------------------------</td>
<td>-----------------------------------------------</td>
</tr>
<tr>
<td>75°C</td>
<td>90°C</td>
<td>90°C</td>
<td>90°C</td>
</tr>
<tr>
<td>8</td>
<td>55.64</td>
<td>44.51</td>
<td>56.62</td>
</tr>
<tr>
<td>6</td>
<td>73.85</td>
<td>59.69</td>
<td>95.50</td>
</tr>
<tr>
<td>4</td>
<td>97.13</td>
<td>78.91</td>
<td>105.50</td>
</tr>
<tr>
<td>2</td>
<td>128.150</td>
<td>106.123</td>
<td>147.123</td>
</tr>
<tr>
<td>1</td>
<td>149.174</td>
<td>123.144</td>
<td>184.153</td>
</tr>
<tr>
<td>1/0</td>
<td>172.201</td>
<td>143.167</td>
<td>224.183</td>
</tr>
<tr>
<td>2/0</td>
<td>199.232</td>
<td>165.193</td>
<td>274.214</td>
</tr>
<tr>
<td>3/0</td>
<td>230.269</td>
<td>192.224</td>
<td>293.237</td>
</tr>
<tr>
<td>4/0</td>
<td>268.312</td>
<td>226.222</td>
<td>313.250</td>
</tr>
<tr>
<td>750</td>
<td>606.707</td>
<td>512.598</td>
<td>630.626</td>
</tr>
<tr>
<td>1000</td>
<td>730.853</td>
<td>612.476</td>
<td>748.514</td>
</tr>
<tr>
<td>1250</td>
<td>840.982</td>
<td>736.813</td>
<td>860.658</td>
</tr>
<tr>
<td>1500</td>
<td>944.1103</td>
<td>850.940</td>
<td>974.778</td>
</tr>
<tr>
<td>1750</td>
<td>1030.1216</td>
<td>930.1027</td>
<td>1060.892</td>
</tr>
</tbody>
</table>

Applicable notes may be found under Table 10-7C

Source: ICEA P-46-426

### TABLE 10-7B
Typical Amperages of 15 kV Cables with Aluminum Conductors of Various Types and for Various Installation Conditions

<table>
<thead>
<tr>
<th>Conductor Size</th>
<th>15 kV in Air 40°C Ambient Shielded Grounded Neutral</th>
<th>15 kV in Duct 20°C Ambient Shielded RHO-90 100 LF</th>
<th>15 kV Directly Buried 20°C Ambient Shielded RHO-90 100 LF</th>
</tr>
</thead>
<tbody>
<tr>
<td>AWG kcmil</td>
<td>1 in Air (1C)*</td>
<td>1 in Air (1C)*</td>
<td>1 in Air (1C)*</td>
</tr>
<tr>
<td>----------------</td>
<td>-----------------------------------------------</td>
<td>-----------------------------------------------</td>
<td>-----------------------------------------------</td>
</tr>
<tr>
<td>75°C</td>
<td>90°C</td>
<td>90°C</td>
<td>90°C</td>
</tr>
<tr>
<td>4</td>
<td>130.152</td>
<td>115.135</td>
<td>129.135</td>
</tr>
<tr>
<td>6</td>
<td>150.175</td>
<td>133.155</td>
<td>144.155</td>
</tr>
<tr>
<td>7</td>
<td>172.202</td>
<td>153.178</td>
<td>184.183</td>
</tr>
<tr>
<td>8</td>
<td>199.222</td>
<td>175.205</td>
<td>214.218</td>
</tr>
<tr>
<td>1/0</td>
<td>229.268</td>
<td>202.237</td>
<td>251.256</td>
</tr>
<tr>
<td>2/0</td>
<td>265.310</td>
<td>233.273</td>
<td>294.293</td>
</tr>
<tr>
<td>3/0</td>
<td>293.343</td>
<td>265.302</td>
<td>326.326</td>
</tr>
<tr>
<td>4/0</td>
<td>320.424</td>
<td>291.372</td>
<td>353.372</td>
</tr>
<tr>
<td>750</td>
<td>454.531</td>
<td>395.462</td>
<td>495.505</td>
</tr>
<tr>
<td>1000</td>
<td>587.667</td>
<td>504.591</td>
<td>677.622</td>
</tr>
<tr>
<td>1250</td>
<td>705.825</td>
<td>654.688</td>
<td>780.706</td>
</tr>
<tr>
<td>1500</td>
<td>905.905</td>
<td>804.948</td>
<td>995.975</td>
</tr>
<tr>
<td>1750</td>
<td>994.1105</td>
<td>894.1165</td>
<td>1084.1195</td>
</tr>
<tr>
<td>2000</td>
<td>1076.1263</td>
<td>945.1047</td>
<td>1154.1077</td>
</tr>
</tbody>
</table>

Applicable notes may be found under Table 10-7C

Source: ICEA P-46-426
covered and insulated aluminum wire and cable

the ampacity listings of Table 10-7 are conservative for some applications, and cable manufacturers may offer moderately larger ampcities. However, as previously stated, the 0.035 p.f. value is an IECA estimate of what the p.f. may become after many years of exposure and use.

The ampacity ratings of the types shown in Table 10-7 for 35 kV and 46 kV are practically the same as those of 25 kV for installations in air, and only up to about 2 percent less for direct burial, hence values for 35 kV and 46 kV are omitted from Table 10-7. Also inasmuch as high-voltage cables are not used in rigid conduit to the extent formerly (cables in interlocked armor have largely superseded them), ampacities for high-voltage conduit installations are not listed. Ampcacies to 35 kV conduit installations are listed in NEC Article 310 Tables, along with ampcacies for cables in free air, direct burial and underground ducts. For both underground duct and direct burial special attention must be paid to the number of circuits and/or ducts.

**TABLE 10-7C**

Typical Ampcacies of 25 kV Cables with Aluminum Conductors of Various Types and for Various Installation Conditions

<table>
<thead>
<tr>
<th>Conductor Size</th>
<th>25 kV in Air 40° C Ambient Shielded Grounded Neutral</th>
<th>25 kV in Duct 20°C Ambient-Shielded RHG 90° 100 LF Grounded Neutral</th>
<th>25 kV Directly Buried 20°C Ambient-Shielded RHG 90° 100 LF Grounded Neutral</th>
</tr>
</thead>
<tbody>
<tr>
<td>AWG</td>
<td>1C in Air</td>
<td>Tripleplexed 1C of 3</td>
<td>Three Cond. 1 of 3C</td>
</tr>
<tr>
<td></td>
<td>75°C</td>
<td>90°C</td>
<td>75°C</td>
</tr>
<tr>
<td>2</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1/0</td>
<td>170</td>
<td>198</td>
<td>155</td>
</tr>
<tr>
<td>2/0</td>
<td>195</td>
<td>228</td>
<td>178</td>
</tr>
<tr>
<td>3/0</td>
<td>225</td>
<td>263</td>
<td>204</td>
</tr>
<tr>
<td>4/0</td>
<td>259</td>
<td>303</td>
<td>235</td>
</tr>
<tr>
<td>5/0</td>
<td>285</td>
<td>334</td>
<td>260</td>
</tr>
<tr>
<td>6/0</td>
<td>311</td>
<td>362</td>
<td>285</td>
</tr>
<tr>
<td>7/0</td>
<td>337</td>
<td>391</td>
<td>316</td>
</tr>
<tr>
<td>8/0</td>
<td>363</td>
<td>420</td>
<td>345</td>
</tr>
<tr>
<td>9/0</td>
<td>390</td>
<td>451</td>
<td>376</td>
</tr>
</tbody>
</table>

Source: IECA P-46-426.

**FOOTNOTES FOR TABLES 10-7A, 7B, and 7C.**

Allowable ampcacies are the maximum continuous ampcacies under stated conditions. All ampcacy values, except as noted, are from IECA Publication No. P-46-426. Vol. II for the nearest comparable cables. See Table 10-9A and 9B for ampcacy values of two-conductor concentric-neutral cables for direct burial, in duct and in air. Additional ampcacy ratings and information on ampcacy calculations are available from IECA P-53-426 (NEMA WC50) and Tables in NEC Article 310.

*The Ampacity listing for single-conductor (1C) cables assumes they are spaced 7.5 in. center-to-center, or at least one cable diameter apart, surface-to-surface, that shield is grounded at only one point with negligible shield losses.*

**These values are taken from an industry source. The armor is of aluminum.**

†For ampcacy of shielded 5 kV cables refer to cable manufacturer. Shielded cables usually have slightly more ampcacy because the metallic shielding tends to increase the radial thermal heat transfer from the conductor.
TABLE 10-8
Adjustment Factors for Ampacity Values in Table 10-7 for Variations of Ambient Temperature

The following factors* may be used to adjust ampacities for various ambient temperatures:

If the ampacity is known for: | Conductor Temperature | 90°C | 75°C | 90°C | 75°C |
---|---|---|---|---|---|
Ambient Temperature | 40°C | 40°C | 20°C | 20°C |

<table>
<thead>
<tr>
<th>New Ambient Temperature</th>
<th>Multiplication Factor (MF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°C</td>
<td>1.34</td>
</tr>
<tr>
<td>10°C</td>
<td>1.26</td>
</tr>
<tr>
<td>20°C</td>
<td>1.18</td>
</tr>
<tr>
<td>30°C</td>
<td>1.09</td>
</tr>
<tr>
<td>40°C</td>
<td>1.00</td>
</tr>
<tr>
<td>50°C</td>
<td>0.89</td>
</tr>
</tbody>
</table>

For example: A cable may have a known ampacity of 100 amps when operating at a 90°C conductor temperature in a 40°C ambient. The same cable operated at 90°C conductor temperature in a 30°C has an ampacity of 109 amps; while in a 50°C ambient, 89 amps.

*Table factors are derived from the following equation:

\[
MF = \sqrt{\frac{TC-TA_2}{TC-TA_1}}
\]

\[I_2 = I_1 (MF)\]

where:
- \(I_1\) = ampacity from tables at ambient \(TA_1\)
- \(I_2\) = ampacity at desired ambient \(TA_2\)
- \(TC\) = conductor temperature in degrees C
- \(TA_1\) = ambient from tables in degrees C
- \(TA_2\) = desired ambient in degrees C
covered and insulated aluminum wire and cable

TABLE 10-9A
Ampacities of Two-Conductor Concentric-Neutral + Underground Distribution Cable for Direct Burial and for Installation in Buried Duct
(see Figs. 10-17 and 10-18)

Ambient Temperature 20°C Load Factor 100 Percent*
The 75°C ratings apply to cable with Hi-Mol Polyethylene Insulation.
The 90°C ratings apply to cables with Cross-Linked Polyethylene Insulation.

The left-hand entries of any pair are ampacities when directly buried.
The right-hand entries are ampacities when in duct.

<table>
<thead>
<tr>
<th>Conductor Size</th>
<th>5 kV</th>
<th>15 kV</th>
<th>25 kV</th>
<th>35 kV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>75°C</td>
<td>90°C</td>
<td>75°C</td>
<td>90°C</td>
</tr>
<tr>
<td>4</td>
<td>120-80</td>
<td>132-88</td>
<td>116-83</td>
<td>128-91</td>
</tr>
<tr>
<td>1</td>
<td>181-120</td>
<td>199-132</td>
<td>175-124</td>
<td>193-137</td>
</tr>
<tr>
<td>1/0</td>
<td>205-136</td>
<td>226-150</td>
<td>198-141</td>
<td>218-155</td>
</tr>
<tr>
<td>250</td>
<td>336-229</td>
<td>370-252</td>
<td>327-233</td>
<td>360-257</td>
</tr>
</tbody>
</table>

Ampacity values for 5 kV and 15 kV cables are from ICEA tables; those 25 kV and 35 kV are from other industry sources.

*Multiplying Correction Factors for Load Factors of 75 and 50 percent

<table>
<thead>
<tr>
<th>Cable Rating kV</th>
<th>75 percent Load Factor</th>
<th>50 percent Load Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cable in Buried</td>
<td>Cable in Duct</td>
</tr>
<tr>
<td>5 kV</td>
<td>1.09</td>
<td>1.04</td>
</tr>
<tr>
<td>15 kV</td>
<td>1.08</td>
<td>1.04</td>
</tr>
<tr>
<td>25 kV</td>
<td>1.08</td>
<td>1.04</td>
</tr>
</tbody>
</table>

+Refer to The Aluminum Association’s Aluminum Underground Distribution Reference Book for additional typical information.
TABLE 10-9B
Ampacities of Two-Conductor Concentric-Neutral Underground Distribution Cable when Installed in Air or in Duct in Air (usually as leads from an underground buried or duct installation) (see Figs. 10-17 and 10-18)

Ambient Temperature 40°C
The 75°C ratings apply to cable with Hi-Mol Polyethylene Insulation.
The 90°C ratings apply to cable with Cross-Linked Polyethylene Insulation.

The left-hand entries of any pair are ampacities for cable only in air.
The right-hand entries are ampacities when cable is in duct, in air.

<table>
<thead>
<tr>
<th>Cond. AWG/kcmil</th>
<th>5 kV</th>
<th>15 kV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>75°C</td>
<td>90°C</td>
</tr>
<tr>
<td>4</td>
<td>75.65</td>
<td>90.76</td>
</tr>
<tr>
<td>2</td>
<td>103.86</td>
<td>120.100</td>
</tr>
<tr>
<td>1</td>
<td>119.99</td>
<td>139.116</td>
</tr>
<tr>
<td>1/0</td>
<td>137.112</td>
<td>160.131</td>
</tr>
<tr>
<td>2/0</td>
<td>159.128</td>
<td>186.149</td>
</tr>
<tr>
<td>3/0</td>
<td>181.146</td>
<td>211.170</td>
</tr>
<tr>
<td>4/0</td>
<td>212.169</td>
<td>247.197</td>
</tr>
<tr>
<td>250</td>
<td>238.188</td>
<td>278.219</td>
</tr>
<tr>
<td>300</td>
<td>273.214</td>
<td>319.250</td>
</tr>
</tbody>
</table>

Ampacity values are from ICEA tables.
Section III  Covered and Insulated Aluminum Wire and Cable

Chapter 11

Installation Practices*

Aluminum was first used on an overhead transmission line more than 85 years ago. Today virtually all overhead transmission lines have conductors of aluminum or aluminum reinforced with steel (ACSR).

The performance record of aluminum on overhead transmission lines led to its use in conductors of other types so that today most overhead distribution, service drop, and service entrance cables are aluminum. More recently, insulated aluminum cable has come into widespread use in underground distribution and building wire applications.

Aluminum building wire installation procedures are basically the same as those for copper. However, because aluminum is a different metal with different properties, several differences in installation practices must be followed. Connectors tested and approved for aluminum conductors must be employed and equipment to which aluminum conductors are to be connected must have terminals intended for use with aluminum conductors.

Aluminum wire and cable are available in sizes to meet all needs and with the same types of insulation as copper (See Table 11-1). Connectors for all types and sizes of aluminum conductors and equipment with suitable terminals are available. Such equipment, UL-listed and designated for use with aluminum or copper conductor (AL/CU), and connectors designated “AL7CU” or “AL9CU” are available as stock merchandise in leading supply houses.

The types and electrical properties of wires and cables used in secondary distribution and interior wiring circuits are listed in previous chapters. However, the dimensions for a wide range of sizes and various types of insulation are listed, for convenience, in Table 11-1. The method of connecting** a single wire or cable (or the individual conductors of a multi-conductor cable) to other conductors or to switch-gear depends on the size of the conductor, the type of connector, and whether the components to be joined are both aluminum or one is of another metal such as copper.

Aluminum Conductor Connections

The electrical conductor has no functional value until it has been properly connected to complete the electrical circuit. Experience indicates that, apart from damage due to faulty installation or operation, most of the problems encountered in the field are at connections. Therefore, it is apparent that care taken in making a proper termination or splice is time well spent.

A similar record can be attained with insulated aluminum conductors if there is proper attention to the connecting methods. The basic function of extending the conducting path is the same whether the conductor is bare or insulated, overhead or underground, inside building walls, or in cable trays or conduit.

In the joining process, the oxide film on the contact surface of the aluminum must be ruptured to expose base metal. This fissured contact surface must be entrapped and collapsed against the adjoining contact member to establish metal-to-metal conducting areas. In addition, the joining process must protect these conducting areas against the degrading effects of service. In this respect the use of joint compound is most important. Its main function is to prevent the entry of moisture. Electrical connections are particularly vulnerable to this when the

** For further information on the installation of aluminum building wire see the AA booklet “Aluminum Building Wire Installation Manual and Design Guide.”

** For purposes of this discussion, splicing and terminating will refer to conductors in circuits above 1000 volts which require not only connecting the separate conductor elements, but also the restoration of sometimes complex installation systems over the splice or terminal and, under some circumstances, application of added protection. Splicing and terminating are described separately, page 11-11 et. seq.
covered and insulated aluminum wire and cable

TABLE 11-1
Nominal Dimensions* and Areas, Aluminum Building Wire (Taken From 1987 NEC)

<table>
<thead>
<tr>
<th>Size AWG or KCMIL</th>
<th>Number of Strands</th>
<th>Type THW</th>
<th>Type THHN</th>
<th>Type XHHW</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>7</td>
<td>.134</td>
<td>.255</td>
<td>.0510</td>
</tr>
<tr>
<td>6</td>
<td>7</td>
<td>.169</td>
<td>.290</td>
<td>.0660</td>
</tr>
<tr>
<td>4</td>
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<td>.616</td>
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</tr>
<tr>
<td>700</td>
<td>61</td>
<td>.877</td>
<td>1.110</td>
<td>.9676</td>
</tr>
<tr>
<td>750</td>
<td>61</td>
<td>.908</td>
<td>1.150</td>
<td>1.0386</td>
</tr>
<tr>
<td>1000</td>
<td>61</td>
<td>1.060</td>
<td>1.285</td>
<td>1.2968</td>
</tr>
</tbody>
</table>

*Dimensions are from industry sources.
**Compact conductor per ASTM B 400. Article 310-14 of the 1987 NEC calls for AA 8000 series electrical grade aluminum alloy conductor material.

Power is off and the conductors are cool. To the extent these are accomplished, the connection will have low and stable contact resistance during its service life. (For more information on electrical contact theory, the reader is referred to the bibliography at the end of Chapter 13.)

In this, as in preceding chapters, we will first consider conductors for secondary circuits (0 to 1000 volts) and the installation practices associated with them.

Building Wire Connectors

Only pressure-type connectors marked AL7CU or AL9CU to indicate they have been tested and are listed by UL for aluminum, copper, or aluminum to copper connections interchangeably should be used. The connectors are usually plated to avoid the formation of oxide and to resist corrosion.

Pressure connectors are of two basic types—mechanical screw type and compression type applied with a tool and die.

Both types are designed to apply sufficient pressure to shatter the brittle aluminum oxide from the strand surfaces and provide low resistance metal to metal contact.

Both basic types are suitable for use with aluminum, although many contractors believe that compression connectors are less susceptible to installation error.

UL Standard 486, covering connectors for use with aluminum wire, has been revised. A number of connectors have already been tested under the more stringent requirements of the new standard, UL 486B, and are currently available.

Installers are cautioned to avoid mechanical pressure connectors with too wide a range of wire sizes because the screw may not adequately engage the strands of the smaller conductors. Installers are also advised to contact conductor manufacturers for recommendations concerning specific connectors for use with their products.

Connectors for every conceivable need are available. Some typical connectors are shown in Fig. 11-1. Whichever type you use, follow the manufacturer’s instructions carefully.

Compression Connectors

Aluminum conductors are particularly suitable for connecting to each other or to an equipment terminal by use of solderless compression type sleeves because the conductor strands tend to weld together as a result of high compression pressure.

Compression connectors similar to those used for bare conductors (see Chapter 5) are widely used for connecting insulated conductors (Fig. 11-1). Various styles are available, along with special tools, representing the "system" of a particular manufacturer. Depending on
the size of the conductors, compression is obtained by use of hand tools or from hydraulic pressure.

**Mechanical Connectors**

Pressure connectors of the setscrew or bolted mechanical type. Fig. 11-2, also provide a rapid means of making connections particularly where space is limited and where many taps are taken from a main as in panel boards or junction boxes. Aluminum connector bodies are machined from extruded high-strength aluminum, such as 6061-T6. The setscrews are of the Allen head type and tightening of screws or bolts by wrench compresses the aluminum conductor strands against the side wall of the recess, causing the strands to intermingle. Fig. 11-1. Mechanical connectors should be tightened to manufacturer's recommended torque levels. In the absence of manufacturer's recommended torque levels, values in Table 11-2 should be followed.

**Connector Plating**

UL standards require that connectors for use with aluminum conductors be plated with tin or some other suitable contact metal and the face of any pad or lug that is plated should not be scratch-brushed but merely cleaned with a suitable solvent cleaner. Scratching the plated surface is likely to remove the plating. It should be noted that zinc plated connectors have an adverse effect on aluminum and should never be used on systems where aluminum wire is used.

**Building Wire Terminations**

UL-listed terminal lugs marked AL7CU or AL9CU are used to connect aluminum conductors to transformers, switches, bus bar, motors and other equipment. Aluminum terminals are usually plated and plated connectors should not be scratch-brushed or abraded.

Like connectors, they are of two basic types—mechanical screw type and compression type applied by tool and die. Some typical terminal lugs are shown in Fig. 11-2. They are applied to the conductor ends in the same manner as described under “Connectors.”

All equipment should be furnished with UL-listed, all aluminum terminals. Mechanical terminal lugs that are copper bonded and tin plated should not be used with aluminum conductors larger than #6 unless they have passed the 500-cycle requirements of new UL Standard 486B.

Care should be taken that the conductor temperature and ampacity ratings are compatible with the terminals and equipment to which they are to be connected.

When all components are aluminum (bus, slugs, lugs) only aluminum bolts should be used to make the connections.

The following procedures should be used:

1. Aluminum bolts should be anodized alloy 2024-T4 and conform to ANSI B18.2.1 specifications and to ASTM B 211 or B 221 chemical and mechanical property limits.
2. Nuts should be aluminum alloy 6061-T6 or 6262-T9 and conform to ANSI B18.2.2.
3. Washers should be flat aluminum alloy Alclad 2024-T4, Type A plain, standard wide series conforming to ANSI B27.2 SAE or narrow series washers should not be used.
4. Hardware should be assembled as shown in Fig. 11-3.
covered and insulated aluminum wire and cable

Fig. 11-2. Typical plated aluminum terminal lugs come in variety of styles.

### TABLE 11-2

STANDARD PRESSURE-CONNECTOR TORQUE TABLES

<table>
<thead>
<tr>
<th>Wire Size</th>
<th>Torque, Pound-Inches</th>
<th>Screw-Head Torque, Lb-Inches</th>
<th>Socket Head Torque, Lb-Inches</th>
<th>Hexagonal Head Torque, Lb-Inches</th>
</tr>
</thead>
<tbody>
<tr>
<td>18-10 AWG</td>
<td>20</td>
<td>35</td>
<td>80</td>
<td>75</td>
</tr>
<tr>
<td>8</td>
<td>25</td>
<td>40</td>
<td>80</td>
<td>75</td>
</tr>
<tr>
<td>6</td>
<td>35</td>
<td>45</td>
<td>165</td>
<td>110</td>
</tr>
<tr>
<td>4</td>
<td>40</td>
<td>50</td>
<td>165</td>
<td>110</td>
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<td>3</td>
<td>45</td>
<td>50</td>
<td>275</td>
<td>150</td>
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<td>2</td>
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<td>50</td>
<td>275</td>
<td>150</td>
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<td>1</td>
<td>50</td>
<td>50</td>
<td>275</td>
<td>150</td>
</tr>
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<td>1/2</td>
<td>50</td>
<td>50</td>
<td>385</td>
<td>180</td>
</tr>
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<td>3/4</td>
<td>50</td>
<td>50</td>
<td>385</td>
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<td>16</td>
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</tr>
<tr>
<td>18</td>
<td>50</td>
<td>50</td>
<td>500</td>
<td>250</td>
</tr>
<tr>
<td>20</td>
<td>50</td>
<td>50</td>
<td>500</td>
<td>250</td>
</tr>
</tbody>
</table>

**Note:** The torque tables presented here are taken from UL Standard 48EB, but are representative of those published in other UL Standards, in NEMA equipment installation instruction publications, and in the Canadian Electrical Code. The same values apply to pressure connectors for both copper (UL Standard 486A) and aluminum conductors.
5. All hardware should be suitably lubricated before tightening.

6. Bolts securing lugs should be tightened to the manufacturer's recommended torque. In the absence of such recommendations, torque values listed in UL 486 Standards should be used. (See Table 11-3)

If adding to an existing installation containing copper bus or studs or if it is impossible to obtain the required equipment with aluminum terminations, then a steel bolt should be used with a Belleville spring washer to allow for the differing rates of thermal expansion of the materials. The following procedures should be used:

1. The steel bolt should be plated or galvanized, medium carbon steel heat treated, quenched and tempered equal to ASTM A 325 or SAE grade 5.

2. Nuts should be heavy semi-finished hexagon, conforming to ANSI B18.2.2, threads to be unified coarse series (UNC), class 2B.

3. Flat washers should be steel, Type A plain standard wide series, conforming to ANSI B27.2. SAE or narrow series washers should not be used.

4. Belleville conical spring washers come in sizes for use with bolts ranging in sizes indicated in Table 11-4.

5. Hardware should be assembled as shown in Fig. 11-5.

6. All hardware should be suitably lubricated before tightening.

7. In the absence of specific manufacturer's instructions, bolts should be tightened sufficiently to flatten the spring washer and left in that position.

### Table 11-3

<table>
<thead>
<tr>
<th>Bolt Diameter Inch</th>
<th>Tightening Torque Pound-Feet</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/4 or less</td>
<td>6</td>
</tr>
<tr>
<td>5/16</td>
<td>11</td>
</tr>
<tr>
<td>3/8</td>
<td>19</td>
</tr>
<tr>
<td>7/16</td>
<td>30</td>
</tr>
<tr>
<td>1/2</td>
<td>40</td>
</tr>
<tr>
<td>5/8 or more</td>
<td>55</td>
</tr>
</tbody>
</table>

*From UL 486 Standards.

**NOTE:** If bolts are not lubricated with silicone spray or other suitable lubricant, torque may vary widely and result in high contact resistance at joints.

### Table 11-4

<table>
<thead>
<tr>
<th>BELLEVILLE SPRING WASHERS</th>
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</thead>
<tbody>
<tr>
<td><strong>Bolt size</strong></td>
</tr>
<tr>
<td>---------------</td>
</tr>
<tr>
<td>1/4</td>
</tr>
<tr>
<td>5/16</td>
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<tr>
<td>3/8</td>
</tr>
<tr>
<td>1/2</td>
</tr>
<tr>
<td>5/8</td>
</tr>
</tbody>
</table>

**Note:** Torque values to be used as guides only. Actual installation conditions will vary considerably. Bolt should be tightened until a sudden increase in torque is felt. In this manner, no torque wrench is required and washer will be flattened.

Material: Hardened Steel  Table Courtesy of Thomas & Betts Co.
covered and insulated aluminum wire and cable

Fig. 11-4. Gutter splice is used when terminal lugs are not removable and are approved for copper cable connection only.

Fig. 11-5. Belleville washer is used to make an aluminum-to-copper or steel joint. Note: Crown of Belleville washer should be under the nut.

Fig. 11-6. There are a number of UL-listed adaptor fittings available for use with terminals not suitable for direct connection of aluminum conductors.

With equipment having terminals that will accommodate only copper conductors, a "gutter splice" may be used to connect the aluminum conductor. The aluminum conductor is spliced to a short length of copper conductor, and the copper conductor stub is then connected to the equipment terminal (Fig. 11-4). An AL7CU or AL9CU compression type connector is used to make the splice.

Instead of a gutter splice, one of the many UL-listed AL7CU or AL9CU adaptor fittings specifically designed for this purpose may be used (Fig. 11-6).

For connecting large aluminum conductors (500 kcmil and up) to heavy equipment having copper terminal studs and/or pads, large compression type lugs, preferably with two holes, should be used in making such a connection (Fig. 5-2). With other than aluminum bolts, Belleville spring washers and heavy flat washers in consecutive arrangement as shown in Fig. 11-5 must be used. If aluminum bolts and nuts are used, only the heavy washer, bearing on the aluminum lug, is necessary.

Figures 11-7 to 11-12 show some typical connections of aluminum conductors to equipment terminals.

Because of the differing rates of thermal expansion of aluminum and other conducting or support metals, it is preferable to have all parts of the circuit, including studs and clamp bolts, of aluminum. The aluminum bolts should be of alloy 2024-T4 and the nuts compatible, though preferably not of identical alloy and temper. Bolts and nuts should be of heavy series design to reduce stress beneath the head. NC (coarse) threads are preferred for the 2024-T4 aluminum bolts. Components should be assembled as shown in Fig. 11-9. More information about aluminum bolted connections will be found in Chapter 13.

Fig. 11-7. Where possible, current transformer terminals should be replaced with compression type (B). If not possible to remove, section of copper cable should be spliced to aluminum (A).

Fig. 11-8. Power transformer terminals, if copper, must employ short copper stub spliced to aluminum cable.
Basic Installation Techniques

1. Stripping Insulation

Never use a knife or pliers to strip a conductor when stripping insulation. One way to avoid this is to use a pencil or whittle the insulation (Fig. 11-13).

Another method is to skin the insulation back from the cut end of the conductor and then cut outward (Fig. 11-14).

Several types of insulation stripper are available for quick, easy removal of insulation. One of these, useful for small size conductors, is shown in Fig. 11-15.

2. Making Connections

Preparation of aluminum conductors for connection to an equipment terminal or another conductor requires stripping of the insulation and rupture and dispersal of the nonconducting oxide film that appears quickly on a fresh aluminum surface exposed to air. Care must be taken not to nick the wires when removing insulation in order to avoid broken strands in installation or service. Several types of insulation stripper are available for quick, easy penciling or square-cut removal of insulation. One type is shown in Fig. 11-16.

Abrading the conductor strands with a wire brush or other appropriate tool will serve to clean the conductor and disperse the oxide coating prior to application of joint compound.

The conductor end is then inserted into a compression sleeve of adequate thickness or a suitable mechanical type pressure connector. If the connector does not come factory-filled with an acceptable joint compound, such paste should be applied to the conductor end before insertion into the connector. (Some manufacturers' connectors may not require the use of compound but it should be used in the absence of specific instructions to the contrary.) The compression sleeve should then be compressed with a hydraulic compression device, or the setscrew of a mechanical connector tightened, in a manner prescribed by the connector manufacturer. Excess compound should be removed from the conductor insulation, but not from the joint itself where it will serve to prevent air from entering.

Solid aluminum wires are prepared in a similar manner, and the smaller sizes may be fastened under a binding-head screw* (without joint compound) after looping in a clockwise direction.

* Note: The AL7CU or AL9CU marking is not required on equipment connectors. However the equipment to which they are installed must indicate suitability for use with aluminum and connector tightening torques.
covered and insulated aluminum wire and cable

Fig. 11-13. Never ring a cable—it may lead to a break. Insulation should be removed as one would sharpen a pencil.

Fig. 11-14. Another safe way of removing insulation from conductor is to peel the insulation back and then cut outward.

Fig. 11-15. Use wire stripper for removing insulation from smaller wire sizes. Match stripper notch to wire size.

Fig. 11-16. Penciling tool for removal of insulation in bevel configuration by rotation. Several sizes are available, which by proper selection of bushing are applicable to all usual sizes of cables. This tool is particularly suitable for primary cables, which have comparatively thick insulation.

In making connections, first strip the insulation as instructed heretofore. Then apply joint compound if it is not already contained in the connector.

If the connector is a mechanical screw type, apply the manufacturer’s recommended torque (Fig. 11-17). In absence of specific torque recommendations, use UL 468B torque values shown in Table 11-1. If a compression type, crimp it as recommended by the manufacturer (Fig. 11-18). Be sure to select the correct size die and close the tool completely for full compression. Wipe off any excess compound. Then tape the joint as instructed under Section B2 or apply the insulating enclosure that comes with some types of connectors.

3. Pulling Conductors in Conduit or Electrical Tubing

The following procedures are applicable to conduit of all types including aluminum:

a. Run a “fish” line through the conduit. This may be done by attaching the line to a piston-type device which is propelled through the conduit by compressed air. Another method is to push a round flexible speedometer type steel wire through the conduit. Polyethylene fish tapes may be used for shorter runs—up to about 100 feet.

b. Attach a clean-out brush to the fish line and behind it attach the pull line, then pull both through the conduit by means of the fish line.

c. Attach the pull line to the conductor or conductors. A basket grip over the insulation may be used for this purpose (Fig. 11-19).
d. Where conductors are pulled with a rope, stagger the conductor ends and anchor in position with tape, to provide maximum flexibility around bends (Fig. 11-20).

c. Try to feed conductors into conduit end closest to the sharpest bend, to reduce pulling tension.

e. Have pulling equipment with adequate power available to make a steady pull on the cables without “jerk”s” during the pulling operations.

f. Use pulling compound compatible with the conductor insulation as the conductors are fed into the conduit, to reduce coefficient of friction and required pulling tension.

g. For single conductors on a reel, stagger reels, one behind the other, while feeding in conduit, to maintain equal pulling tensions and prevent conductors from “crossing over” and jamming in the conduit.

h. Wherever possible, pull conductors in a downward direction, to allow gravity to assist in pulling with reduced tension.

j. When conductor ends are prepared for pulling, be sure not to nick the stranded aluminum conductor during insulation removal. Damaged strands can reduce the pulling tension capabilities of the conductor. To avoid this, pencil the insulation for removal, as described above; do not ring cut the insulation.

k. Follow all NEC requirements.

For a detailed description of calculating pulling tensions, see the example given on page 11-11 on underground installations. See Chapter 17 for a complete treatment of aluminum conductors in conduit.

4. Installation of Cables in Trays

Where aluminum cable is to be pulled in trays or cable racks, take the following precautions, plus those applicable to conduit:

a. Where pulling attachments are used on the conductors, cover them with rubber-like or plastic tapes to prevent scoring of the trays and installation sheaves during a conductor pull.

b. Use large-radius sheaves around bends and smaller sheaves on the straight sections of cable support trays to facilitate cable installations, to reduce the required pulling tensions and to prevent damage to stranded conductors or insulations.

c. Where cables are anchored on trays, be sure straps or other cable anchoring devices do not cut into the insulation.

d. Cables installed in trays should follow the requirements of NEC Article 318 for the allowable number of cables permitted in trays and their respective ampacities.
covered and insulated aluminum wire and cable

e. Straight cable tray runs may often be installed by simply laying the lightweight aluminum cables in place.

f. Be sure that supports are capable of handling maximum weight of conductors and planned conductor additions in the future.

5. Minimum Training Radii

Where permanent bends are made at terminations using aluminum building wire, Table 11-5 indicates the minimum bending radius as a multiple of the overall cable diameter. Such bends should be made before the terminal is applied to minimize electrical contact distortion.

6. Conductors in Vertical Raceways

The NEC under section 300-19 stipulates that conductors in vertical raceways shall be supported. As a general rule, one cable support shall be provided at the top of the vertical raceway or as close to the top as is practical plus an additional support for each interval of spacing as shown in Table 11-6. An exception to this rule is that if the vertical riser is less than 25% of the spacing listed in the Table, no cable support shall be required.

Installing Cable in Conduit or Duct

The procedures for inserting a “fish” line or tape through a conduit or duct, followed by a pull line and/or cable as required for the pull, are well known and established as field practice and do not need extensive description here. Aluminum conductors may be attached to pull line or cable by means of a factory-installed pulling eye, by placing a basket grip around the conductors’ insulation (Fig. 11-21), or by tying the line to a loop in the uninsulated part of the conductor (Fig. 11-20). Steel pull cables used to pull conductors around bends in aluminum conduit runs may damage the conduit at the bend. This is often avoided by using steel elbows with aluminum conduit or by use of a pull line that will not damage aluminum elbows.

Pulls should be accomplished with steady tension and pulling speeds not exceeding 50 feet per minute. Hard pulls can be eased if the reel if hand controlled and slack cable is guided into the conduit.

Pulling tensions may be reduced by lubricating the cable surface. However, some lubricating materials have been found to adversely affect cable insulations or outer jackets. In addition to cable pulling compounds, this

<table>
<thead>
<tr>
<th>TABLE 11-5</th>
<th>TRAINING RADII</th>
</tr>
</thead>
<tbody>
<tr>
<td>For 600 V Cable Not in Conduit, on Sheaves or While Under Tension</td>
<td></td>
</tr>
</tbody>
</table>

POWER CABLES WITHOUT METALLIC SHIELDING ON ARMOR.
The minimum recommended bending radii as multiples of the overall cable diameter given in the following tabulation are for both single and multi-conductor cable with or without lead sheath and without metallic shielding or armor.

<table>
<thead>
<tr>
<th>Thickness of Conductor Insulation mils</th>
<th>Minimum Training Radius as multiple of cable diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Overall Diameter of Cable—Inches</td>
</tr>
<tr>
<td></td>
<td>1.000 and Less</td>
</tr>
<tr>
<td>155 and less</td>
<td>4</td>
</tr>
<tr>
<td>170 to 310</td>
<td>5</td>
</tr>
<tr>
<td>325 and over</td>
<td>7</td>
</tr>
</tbody>
</table>

POWER CABLES WITH METALLIC SHIELDING OR ARMOR
(a) Interlocked Armored Cables
The minimum recommended bending radius for all interlocked armored cables is in accordance with table above but not less than 7 times the overall diameter of the cable, except as noted below (c) for tape shielded cable.

(b) Flat Tape and Wire Armored Cables
The minimum recommended bending radius for all flat tape armored and all wire armored cables is 12 times the overall diameter of cable.

(c) Tape Shielded Cables
For all cables having metallic shielding tape the minimum recommended bending radius is 12 times the overall diameter of the completed cable.

(d) Wire Shielded Cables
Wire Shielded Cables should have the same bending radius as power cables without metallic shielding tape.

Reprinted from NEC 5-66-524. NEwa WC-7
TABLE 11-6
SUPPORTING CONDUCTORS IN VERTICAL RACEWAYS
From 1987 NEC Table 300-19 (a)

<table>
<thead>
<tr>
<th>Conductors</th>
<th>Aluminum</th>
<th>Copper</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. 18 to No. 8</td>
<td>Not greater than 100 feet</td>
<td>100 feet</td>
</tr>
<tr>
<td>No. 6 to No. 0</td>
<td>Not greater than 200 feet</td>
<td>100 feet</td>
</tr>
<tr>
<td>No. 00 to No. 0000</td>
<td>Not greater than 180 feet</td>
<td>80 feet</td>
</tr>
<tr>
<td>211.6 kcmil to 350 kcmil</td>
<td>Not greater than 135 feet</td>
<td>60 feet</td>
</tr>
<tr>
<td>350 kcmil to 500 kcmil</td>
<td>Not greater than 120 feet</td>
<td>50 feet</td>
</tr>
<tr>
<td>500 kcmil to 750 kcmil</td>
<td>Not greater than 95 feet</td>
<td>40 feet</td>
</tr>
<tr>
<td>Above 750 kcmil</td>
<td>Not greater than 85 feet</td>
<td>35 feet</td>
</tr>
</tbody>
</table>

applies to potting and joint compounds, adhesives, tapes, etc. If in doubt, compatibility of materials foreign to the insulation should be cleared through the cable manufacturer.

A number of proprietary wire pulling lubricants and compounds are UL-listed and labeled to indicate the compound’s compatibility with conductor coverings. In all cases, the manufacturers’ instructions should be observed.

Allowable Pulling Tension

The following formulas can be used to calculate the maximum allowable tension that should be applied to the cables. Note that these allowable tensions assume the pulling eye is attached to the conductor. Where the pulling line is attached to a basket grip that surrounds the insulation, the pulling tension should not exceed 1000 lbs. It should be kept in mind that tension developed for straight runs per unit length is less than that for the portion of the cable in bends.

1. The maximum allowable pulling tension, if the pulling eye is attached to the conductor
   \[ P_m = K N A \]  
   (Eq. 11-1)
   where \( P_m \) = Maximum allowable tension, lb
   \( N \) = Number of conductors being pulled simultaneously
   \( A \) = Circular mil area of each conductor
   (If conductors are of various sizes, add the individual NA values)
   \( K \) = Conductor stress factor

2. The maximum allowable pulling tension \( (P_m) \) cannot exceed 1000 lb where cables are pulled with a basket grip, however, the tension per Eqs. 11-1 or 11-2 should not be exceeded.

3. The maximum allowable pulling tension for cable in conduit or duct bends (to prevent cable damage because of rubbing on sides of bend) must not exceed the following:
   \[ P_b = 100 \frac{r}{f} \]  
   (Eq. 11-2)
   where \( P_b \) = Maximum allowable bend tension, lb
   \( r \) = Radius of curvature of the conduit or duct bend, ft

Note: The maximum allowable tension determined from Eqs. 11-1 or 11-2 should not be exceeded.

4. For straight section of conduit or duct, the pulling tension (lb) likely to be developed can be determined as follows:
   \[ P_c = L w f \]  
   (Eq. 11-3)
   where \( P_c \) = Pulling tension in straight section, lb
   \( L \) = Length of conduit or duct straight section, ft
   \( w \) = Weight of cable (or cables), lb per ft
   \( f \) = Coefficient of friction

Note: For a well constructed conduit or duct with a lubricated cable, \( f \) approximates 0.5. For less favorable conditions or with considerable curvature, \( f \) may approximate 0.75.

5. For curved sections of conduit or duct, the pulling tension (lb) likely to be developed can be determined as follows:
   \[ P_c = P_s + P_e e^{\frac{f}{12}} \]  
   (Eq. 11-4)
   where \( P_s \) = Total pulling tension, lb
   \( P_s \) = Tension for straight section at pulling end, lb
   \( P_e \) = Tension for straight section at feeding end, lb
   \( f \) = Angle of bend in radians (1 radian = 57.3 deg)
   \( e \) = Base of Napierian logarithms (2.718)
   \( f \) = Coefficient of friction

Example: Determine the maximum pulling tension required to install three single-conductor cables in a duct, according to the arrangement in Fig. 11-22. The cable specifications are:

Three single conductor #4/0 AWG 600-volt aluminum cables with cross-linked PE insulation

Weight, 3 @ 290 lb/M ft = 0.87 lb per ft
Cable diameter, each 0.690 in.
Coefficient of friction=0.5; K value=0.008*

\*K = 0.008 for 3/4 hard aluminum conductors, or 0.004 for 1/2 or 3/4 hard aluminum.

11-11
covered and insulated aluminum wire and cable

A. Conduit or Duct Clean-out Brush
B. Kellens Grip
C. "Job Fashioned" Pulling Basket

Fig. 11-21. Pulling cable in duct. Pulling cable between junction boxes of conduit installations is similar.

Using a single pulling eye attached to the three conductors and applying Eq. 11-1, the maximum allowable pulling tension is

\[ P_m = 0.008 \times 3 \times 211,600 = 5078 \text{ lb} \]

per Eq. 11-1

For the entire run from pull-box (1) to pull box (6), the tension increments are as follows:

Eq.
11-3: At box (2) \( P_1 = L_{0+} \times w \times f = 100 \times 0.87 \times 0.5 = 43.5 \text{ lb} \)
11-4: At box (3) \( P_1 = P_2 \times e \times f = 43.5 \times 0.5 \times 1.571 = 54.1 \text{ lb} \)
11-3: At box (4) \( P_1 = 95.4 + (L_{0+} \times w \times f) = 95.4 + (50 \times 0.87 \times 0.5) = 117.2 \text{ lb} \)
11-4: At box (5) \( P_1 = 117.2 \times 0.5 \times 1.571 = 117.2 \times 2.194 = 257.1 \text{ lb} \)
11-3: At box (6) \( P_1 = 257.1 + (L_{0+} \times w \times f) = 257.1 + (15 \times 0.87 \times 0.5) = 263.7 \text{ lb} \)

The total pulling tension of 254 lb is far below the 5080 lb limitation, and the tension at each bend is far below the recommendation per Eq. 11-2 of 100 × 10, or 1000 lb. Study of such examples shows that there is an advantage in pulling cables from the pull box or manhole closest to the first bend. This aids in reducing tension on the installed cable. In this instance, if the pull started at box (6), the final tension would be about half the above-found value.

For a more complete treatment of cable pulling in conduit, the reader is referred to R.C. Rifenberg, AIEE Transactions, Dec. 1953.

Installing Directly Buried Power Cables*

If cable placement can be started before sidewalks and other obstructions are installed, the plowing-in method usually is the most economical method of burying power cable. If soil conditions are unsuitable for plowing, the

*See also Aluminum Underground Distribution Reference Book.
use of trenchers, back hoes, or manual digging is customary. If the soil is rocky, it should be screened to prevent cable damage. If it is not sufficiently fine to closely cover the cable surface, a four-inch thickness of sandy loam placed under and over the cable will improve the heat radiating quality of the soil.

Duct or conduit also should be used under streets or where access by digging to a buried cable is not practicable.

Sufficient cable slack should be provided at risers and terminals to permit earth movement that may occur because of conductor thermal expansion, frost, and also as an allowance for future repair.

Boards or slabs placed over the cable for mechanical protection should not be directly in contact with the cable but should be laid on an earth fill over the cable.

Depth of burial ranges from about 30 to 48 inches for primary cable and from about 24 to 42 inches for secondary cable when buried separately. On many systems, both primary and secondary cables are buried in the same trench with no separation. In many areas, the trenches are shared jointly with other utilities, notably communications—both telephone and television cables. Joint use of trenches requires close collaboration on installation schedules but offers substantial economies to the sharing utilities.

Initially, a separation of one foot was required between primary power and communication cables and many companies still require this separation. An amendment to the NESC, however, permits random-lay (no deliberate separation) installation of communication and power cables in the same trenches with grounded wye power systems operating at voltages not in excess of 22 kV to ground or delta systems operating at voltages not in excess of 5.3 kV phase to phase, under certain conditions described in NESC Section 35, Article 354. However, joint use with very long single-phase primary circuits is not recommended because of the inductive pickup of harmonics by the communication cables from the power cables.

Care exercised in handling the cable during installation will help to avoid trouble later, for damage sustained by the cable during installation has proved to be a major cause of subsequent cable failure.

Many of these precautions have to do with making sure there is no insulation damage. The cable is not susceptible to corrosion failure when insulation is unbroken, even where moisture has gained entry into the conductor in some manner; this fact has been determined in cable manufacturer laboratory tests and from research by utilities. Migration of moisture through damaged insulation in the presence of ac potential concentrates ions and promotes ac electrolysis.

Cable transitions between overhead and underground usually employ the conventional factory-molded pothead, of which special types are available for use in URD systems. A termination is not required, however, if the insulated aerial cable is also suitable for direct burial. Such a cable can be carried directly down the pole. Riser shields or conduit should be used to protect the cable on the riser pole to a point at least eight feet above ground level, and should extend at least 12 inches below ground. The riser shield must be solidly grounded to the system neutral, and bonded to the lightning arrester to avoid transient potentials.

Many other practices relating to buried cables and their connection to transformers, to service entrances, and to tap connections in junction boxes and vaults are described in industry manuals.* Practice is gradually becoming standardized in the direction of increasing reliability and lowering installation and maintenance costs in this most important segment of power distribution.

The following suggestions will help to avoid failures from this cause; they apply equally to cable and cable in pipe:

1. Make sure that end seals are intact both while the cable is stored and installed to avoid entrance of water into the strands.
2. If plowing is not used, cables, if at all possible, should be paid out along the side of the trench from moving reels, or carefully laid in the trench from stationary reels.
3. The trench should not be dug before final grading is determined, so cable will not be exposed or be too close to the surface.

* See also IEEE Conference Record 31C35 Special Technical Conference on Underground Distribution, Sept. 27-29, 1966.
covered and insulated aluminum wire and cable

TABLE 11-7

<table>
<thead>
<tr>
<th>ICEA MINIMUM BENDING RADIUS FOR POWER CABLES WITHOUT METALLIC SHIELDING**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Bending Radii as a Multiple of Cable Diameter</td>
</tr>
<tr>
<td>Cable OD, Inches</td>
</tr>
<tr>
<td>Thickness of Insulation, Inch</td>
</tr>
<tr>
<td>0.156 and less</td>
</tr>
<tr>
<td>0.157 to 0.312</td>
</tr>
<tr>
<td>0.313 and over</td>
</tr>
</tbody>
</table>

* Only applicable for cable training; bearing pressure limitation may require larger bending radii for cable tension.

** Data apply to single and multiple conductor cable also to wire-shielded cable. Minimum bending radius for cables with metallic shielding tape is 12 times the completed cable OD. The National Electrical Code Section 300—34 requires 8 times for non-shielded and 12 times for shielded medium voltage cable bending radii.

---

4. In rocky soil areas, use screened backfill or sand to protect direct buried cable. A 2-inch bedding is sufficient below; but there should be a minimum cover of about 4 inches. (The bedding and cover can be omitted when duct in conduit is used).

5. If boards, concrete slabs, etc., are used above the cable for mechanical protection, they should not be in direct contact, to avoid shearing action when the soil settles. Make sure boards are treated with preservatives that will not harm the cable’s insulation.

6. Check the cable visually for damage before burial or installation in duct.

7. When primaries are pulled into ducts or open trenches, the use of a pulling grip over the cable is common rather than a pulling eye or other attachment connected directly to the conductor. Duct should be carefully cleaned by pulling a plug through it to remove all burrs and obstructions. To keep the cable-pulling tension within safe limits, a lubricant approved for use with the specific insulation and insulation shield should be used.

8. When doing permanent training make sure that the minimum bending radii are observed (see Table 11-7). Make every effort to provide more radius than these values at reel payout, risers, plow guides, duct bend, etc.

9. Make sure splices and other connections are made in accordance with manufacturers’ recommendations.

10. Double check to make sure proper backfilling is done. Rock fill should be kept away from the cables to prevent damage. Compacting should be carefully done, and air spaces minimized.

11. Proof test the cable after installation to insure integrity of insulation and splices. (See Table 11-8).

12. Don’t overfuse the cable. Because of the paucity of failures, many utilities prefer to use one-shot fuses as an added protective measure for the cable.

Many of these precautions have to do with making sure there is no insulation damage. The conductor in 600 volt cables is not susceptible to corrosion failure when insulation is unbroken and moisture has not gained entry into the conductor. When moisture enters a break in insulation, however, ac electrolysis begins.

Splicing and Terminating in Underground Systems

The revolution in underground distribution system design has included the devices and methods used for making splices, connections, and terminations. The objective here has been to reduce the amount of skill and time required in the field so as to reduce the installation costs. More prefabrication is being done under factory-controlled conditions, and the need for heating and pouring of insulating compounds or extensive taping in the field has been greatly reduced.

Aluminum connectors and terminating devices should be used with aluminum conductors so as to avoid differential thermal expansion and contraction upon heating and cooling that could result from the use of connectors of dissimilar metals. Compression type connectors and lugs applied with a tool and die are widely used. It is
TABLE 11-8

ICEA RECOMMENDED dc PROOF-TEST VOLTAGES
(15 Minute Test)

<table>
<thead>
<tr>
<th>Polyethylene or Cross-Linked Polyethylene Insulated Cables</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rated Circuit Voltage</strong></td>
</tr>
<tr>
<td>---------------------------</td>
</tr>
<tr>
<td>2001 - 5000</td>
</tr>
<tr>
<td>5001 - 8000</td>
</tr>
<tr>
<td>8001 - 15000</td>
</tr>
<tr>
<td>15001 - 25000</td>
</tr>
<tr>
<td>25001 - 28000</td>
</tr>
<tr>
<td>28001 - 35000</td>
</tr>
</tbody>
</table>

important in installing these devices that a die of the correct size be used and full pressure be applied in order to obtain permanently sound connections.

600 Volt Secondary Circuits

In this regard connector manufacturers have made important advances in the design of connection devices for secondary circuits. There are far too many types to describe them all in this handbook. However, a couple of examples are given below to indicate the types of pre-molded splices and terminations that are currently available for this type of service.

(a) Underground Direct Burial Splice 600 volt insulated cable splices are available for conductor sizes #6 AWG stranded through 1000 kcmil and can be completely installed and sealed without tapping or compound filling. Typical installation procedure is (Fig. 11-23) as follows:

**Step A**
Lubricate both insulating splice caps by applying a small amount of the supplied lubricant to the inside diameter of the cap at both the housing end and also to the inside diameter of the conductor hole end. For easier assembly of the insulating caps to the conductor, it is recommended that the insulation at the end of the conductor be penciled before stripping. Then place the proper caps over each conductor end.

**Step B**
Strip correct length of conductor insulation for the splice connector being used. Place splice housing over end of conductor and assemble one cap to housing. Large end of cap should cover the knurled line of the housing body.

**Step C**
Wire brush exposed cable ends and then immediately insert cables into connector. Start crimping splice onto conductor as per manufacturer's instructions. Continue crimping to ends of splice, overlapping crimps 1/8 inch minimum. Wipe away all excess oxide inhibitor.

**Step D**
Place housing with the assembled cap over splice connection and snap remaining cap in place on housing to complete the sealed splice. When caps are correctly installed, the large ends should cover the knurled lines on both ends of the housing body.

(b) Secondary 600 V Underground Terminations. There are several different designs of connector products which are approved for use in underground 600 V electric power systems. They supply the needs of connectors required for residential or commercial use: direct burial, below grade vaults; pedestal or pad mounted equipment; bolted or compression fittings, and in any combination.

Fig. 11-24 shows a representative group of these fittings which are designed to accommodate a wide range of conductors. Their installation is straightforward and requires no field cutting or hand tapping for insulation or environmental sealing. The threaded stud connector for transformers is such that the connector can be detached from the transformer without disconnecting the conductors.

Primary Circuits

Termination of primary underground cables requires some type of stress relief. Initially, these were made up by taping a stress cone, which proved to be one of the most tedious and time-consuming jobs for the field man. Today most utilities use some form of preshaped or prefabricated stress cone, which can be installed in a fraction of the time.
Typical terminations for primary cables indicate that molded, precut tape, and porcelain types are used indoors while porcelain units are most often used outdoors. One of the most significant developments in primary cable terminations has been the introduction of plug-in connectors for joining the cables to equipment or other cables. With these devices it is almost as easy to connect a primary cable as to plug in or remove an appliance cord from a convenience outlet.

The concept of premolded stress relief takes the fabrication of a stress relief core away from the field and into the factory with its controlled environment, leaving just the assembly to the field installer. Elastomeric connections form a very convenient, inexpensive, and reliable method of connecting or terminating high voltage cables. Power cable loadbreak elbows in the 35 kV class were introduced to the industry in 1983, with designs for 15 kV and 25 kV following in 1985.
Fig. 11-24. Some typical 600 V underground termination fittings.

Through the combined efforts of the connector and apparatus manufacturers and the utilities, there is available today an array of premolded products that exhibit a high degree of safety, reliability, and flexibility.*

*See James W. Fitzhugh's paper, "Exploring the Application of Premolded Products for High Voltage Power Systems."

Some typical applications of premolded products are at pulling or junction boxes, cable to equipment connections, and cable to cable connections. All of these components are designed and tested to be in compliance with ANSI/IEEE Standard 386—1985 Separable Insulated Connectors for Power Distribution Systems above 600 Volts.
Primary Voltage Circuits

A cutaway view of an up-to-date power cable joint is shown in Fig. 11-25. The cloverleaf design allows the joint to operate at lower temperatures.

While installation of premolded devices are similar, conditions may vary depending on the device, the cable, and the manufacturer of the splice or termination. In all cases, full instructions will be provided and should be followed. Additional typical designs are shown in Fig. 11-26.

Development work in splicing, connecting, and terminating devices is still proceeding. Users thus are advised to keep posted on the latest designs being offered by the connector manufacturers in order to achieve greatest economies in making cable splices, connections, and terminations.

Though recent trends have been toward the use of premolded splicing and terminating devices, it is still necessary or desirable in some circumstances to make hand-taped joints by traditional methods. Because of this, the details of making a hand-taped, concentric neutral, straight splice are given below. Details of the joint are shown in Fig. 11-27.

The following are the instructions to be generally based in making the joint illustrated in Fig 11-27. They are for a typical hand-taped primary cable splice. All splices and terminations should be made by a qualified cable splicer in accordance with the manufacturer's instructions and recommendations.

1. Study splice drawing and instructions:
2. Train cables into final position and overlap for 18 inches to afford enough excess concentric wire for final jointing.
3. Temporarily wrap a number of turns of tape over the outer concentric wires at least 18 inches from the centerline of the splice.
4. Carefully unwrap outer concentric wires and temporarily remove them out of the splice area, being sure not to damage or kink them.

### TABLE 11-9

<table>
<thead>
<tr>
<th>Insulation Thickness</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>15kV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>.175&quot; or .220&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>One-half Connector Length</td>
<td>2&quot;</td>
<td>4 1/4&quot;</td>
<td>2A + 14 1/4&quot;</td>
<td>3 1/8&quot;</td>
<td></td>
</tr>
<tr>
<td>25kV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>.280&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>One-half Connector Length</td>
<td>2 1/2&quot;</td>
<td>5 1/4&quot;</td>
<td>2A + 17 1/4&quot;</td>
<td>7 1/16&quot;</td>
<td></td>
</tr>
<tr>
<td>35kV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>.345&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>One-half Connector Length</td>
<td>3&quot;</td>
<td>7&quot;</td>
<td>2A + 22&quot;</td>
<td>9 1/16&quot;</td>
<td></td>
</tr>
</tbody>
</table>

5. Cut off excess cable at splice centerline.
6. Remove outer semiconducting jacket for a distance of (A + 1 + B + C) inches from each cable, making sure that the insulation is not damaged during the removal operation. All traces of the semiconducting jacket must be removed by a nonconductive abrasive or rasp.
7. Remove the insulation from each conductor for a distance of (A + 1) inches, making sure that the conductor is not nicked during the removal operation.
Fig. 11-26. Some typical primary voltage premolded splicing and terminating devices.
covered and insulated aluminum wire and cable

Splicing*—15kV—25kV—35kV Primary Cables—Hand Taped Splice
Single conductor with concentric neutral, straight splice (conventional or cross-linked polyethylene insulated, solid or stranded) for grounded neutral service.

Fig. 11-27. Details of a taped primary cable joint.

Penciling tools will remove the insulation, as well as provide smooth penciled surface.

8. Apply the required compression connector on each cable, following the connector manufacturer’s recommended procedure. Note: It is recommended that a smooth surface type connector be used—not an indented type. If an indented type is used, fill the indents with a pliable insulation putty.

9. Remove all sharp edges from compressed connector, using a file or heavy abrasive cloth.

10. Pencil the ends of the polyethylene insulation for a distance of (B) inches. Be sure not to cut into the insulation or damage the conductor during the penciling procedure. Buff the insulation pencils if they are not smooth with a nonconductive abrasive or rasp. This step would be completed with a penciling tool. (See Step 7 above.)

11. Clean all exposed surfaces with a nontoxic and nonflammable solvent and allow to dry. Care must be taken in wiping the black conducting jackets, since this may smear over the insulation surface.

12. Apply one half-lapped layer of semiconducting tape (Bishop Tape No. 17 or equivalent) over the exposed conductor and connector. Tape should just contact the edge of the cable insulation and be applied with enough tension to conform to the connector.

13. Apply half-lapped layer of high voltage, self-fusing tape with manufacturer’s recommended tension, starting at connector centerline and building up to the level of the connector in areas between insulation pencil and connector by evenly wrapping tape back and forth across the connector. Apply splicing tape buildup to a thickness of “K” inches over the connector and for a longitudinal distance of “D” inches, tapering at the ends.

14. Apply one half-lapped layer of self-fusing semiconducting tape over insulating tape buildup, extending 1 inch beyond insulating tape onto the semiconducting jacket on each side of splice. The semiconducting tape should be applied with adequate tension.

15. Apply one half-lapped layer of tinned copper mesh braid over the semiconducting tape and extend 1 inch at each end of splice. The tinned copper mesh braid
should be wrapped as tight as possible, and taping should be started at the centerline of the splice, using two portions of tinned copper mesh braid.

16. Apply two solder lines 180 degrees apart for the full length of the mesh braid, making sure that the heat does not remain in one spot too long to damage the cable insulation or tapes.

17. Tie the concentric outer wires in place using wraps of No. 14 AWG tinned or bare copper wire and tack solder in place.

18. Apply two half-lapped layers of a self-fusing high voltage tape over the outer braid with minimum tension.

19. Apply one half-lapped layer of jacket tape over the mesh braid to the edge of the concentric wires at each end of the splice.

20. Twist the concentric wires together and cut off excess length. Place the formed wires into the proper sized mechanical (or compression) connector and splice in place to form low resistance joint, following the connector manufacturer’s recommended procedure.

**Terminating Detail**

The construction details of secondary or primary cable terminations depend on whether the termination is outdoor, indoor, or from underground and whether it is horizontal for connection to an equipment terminal or vertical for connection to another conductor. Truncating assemblies are also used for terminating a three-conductor cable so the uninsulated terminals are well separated (Fig. 11-28).

Terminations usually are either of the pothead type or the built-up stress-relief type. Both types provide extra insulation close to the actual termination of the conductor to provide protection against the extra voltage at these locations.

Primarily, potheads of plastic insulating materials are used with primary and secondary URD systems, although porcelain potheads and semi-assembled, built-up stress relief cones (or kits that facilitate their quick assembly) are still used for this application. (Fig. 11-16)

Stress-relief cones are also required in cable splices.

---

**Fig. 11-28. Typical terminations 5-15kV.**
where there is a change of conductor size; the variation of current density in the adjacent conductors creates dielectric stress variations that occur when a cable is terminated.

The detailed methods of terminating shielded and non-shielded cables closely resemble those used for splicing, except that the termination process requires the inclusion of a stress-relief cone or a pothead, and if the installation is outdoor and vertical the addition of a rain shield to shed water from the cable insulation is customary. Descriptive details are supplied by cable and accessory manufacturers with dimensions for various sizes and voltages. The accompanying illustrations list the successive operations. The precautionary recommendations mentioned in relation to cable splicing also apply to terminating procedure, subject to such changes as appear in manufacturer’s instructional manuals.

The cross-section of a molded terminal connector is shown in Fig. 11-29, illustrating the component part of a connector designed for conductors up to 25 kV. It is suitable for use on solid dielectric cables and can be applied directly on cables with extruded semi-conductive shields including full neutral concentric. It will accommodate aluminum conductors in the range of No. 6 to 4/0 AWG with an insulation thickness of 0.495 to 1.115 in. After proper cable preparation, the terminal connector is slid down over the bared cable insulation until it bottoms on the cable shield. No special tools or potting compounds are required for the assembly of this type of fitting.

1. TERMINAL CONNECTOR
   The universal rod connector attaches to the power source.

2. MOLDED RUBBER CAP
   Presses over top of terminator with an interference fit to provide complete water seal integrity.

3. RETAINING WASHER
   Mechanically prevents any cable slippage within terminator.

4. TERMINATOR HOUSING
   Molded of special EPDM compounds for functional reliability and long life. Actual creep distance is 18" (45.7 cm).

5. CABLE INSULATION
   Primary insulation is provided since cable insulation carries through the terminator.

6. INTERFERENCE FIT
   Molded insulating EPDM exerts uniform concentric pressure on insulation of cable to provide required creep-path length and water seal.

7. MOLDED STRESS RELIEF

8. GROUND STRAP
   Provides a convenient point to connect a ground wire to the molded conductive shield and places the molded shield at ground potential.

Courtesy Amerace Corp., Elastimold Div.

Fig. 11-29. Typical single conductor molded pothead for cable termination.
Installing Aerial Insulated Cables

Single insulated or covered overhead primary aluminum conductors suspended from insulators sometimes are used in tree areas or similar locations. Their installation is similar to that of bare conductors, as described in Chapter 5. The span lengths usually are moderate so that sag and tension values generally are obtained from tables. However, for unusual spans, sag-tension charts can be computed or are available from conductor suppliers. For aluminum 1350 conductors or less than hard tempers, adjustment must be made for reduction of strength.

For economic reasons, however, most overhead spans of insulated power conductors are in the form of preassembled or field-assembled multi-conductor cables suspended from a bare messenger. Insulator support is not required and space is saved by using a single-multi-conductor cable. The conductors may be spiraled around the messenger or arranged parallel to it, as described in Chapter 7. Messenger supported cables are in two groups:

Preassembled aerial cables (to 35 kV)
Aerial cable assemblies (0 to 600 volts).

Primary Aerial Cables

The messenger size for primary cables is determined by the required strength, except that for single-phase primary circuits (No. 2 AWG or smaller) where the messenger also serves as a neutral conductor, the conductance of the messenger must equal that of the insulated conductor. Bare messengers not used as neutral conductors are often used also as a part of relaying circuits, as a part of the grounding circuit for the insulation shielding, and as an auxiliary to a common-neutral. For these reasons specifications for multi-conductor primary cables with bare messengers usually specify the ohmic resistance of the messenger. The combination of strength and moderate electrical resistance requirements of such non-neutral messengers has led to wide acceptance of composites of aluminum and of steel (Alumoweld) for the makeup of the messenger.

Messenger sizes are such that the normal initial sagging tension at 60°F will not exceed 30% of its rated strength, and its maximum tension will not exceed 50% of its rated strength at the fully loaded condition. Physical details of the cables used for the messengers listed in Tables 11-10 and 11-11 can be found in Tables 4-5 (1350-H19), 4-12 (6201-T81) and 4-14 (ACSR). These messenger sizes conform to the IEC recommendation that the initial sag be such that the final sag be not less than 1.667% of the span length.

Stringing sag and tension charts are supplied by cable manufacturers as an aid to circuit design for light, medium, or heavy loading conditions (NESC, see Table 5-11) for use as described in Chapter 5. However, in most instances the spans are of moderate length so suitable sag-tension values may be obtained directly or interpolated from manufacturer-supplied tables that list initial and final values for 100, 125, and 150 ft spans.

For the installer of the cable the most useful tabular values are those for initial sag and tension, usually for 60°F, but a correction factor is applied if the installation temperature differs from 60°F. The final sag and tension values for the various NESC loading districts then will meet requirements as to the percent that messenger tension bears to its ultimate breaking strength, and the manufacturer's table will confirm this if required. The messengers for preassembled primary cables are not neutral conductors, but high conductance is useful for grounding or signal purposes, hence the equivalent conductor rating is usually listed for the messenger. For this reason various combinations of steel, 1350 aluminum, and high-strength alloy aluminum are often used for primary aerial messengers.

Table 11-10 is extracted from more complete tables in order to show the form in which such tables are supplied. Although this table shows use of a combination messenger made of 1350 aluminum strands assembled with strands of aluminum-clad steel, other messengers are similarly used of high strength ACSR, as well as combinations of 6201 aluminum with steel reinforcement (AACSR).

Fig. 11-30 depicts several kinds of fittings and accessories used when installing messengers and preassembled aerial cables, some of which also apply to preassembled secondary and service-drop cables.

Neutral-Supported Secondary and Service-Drop Cables

Preassembled aluminum insulated multi-conductor cables supported by bare neutral messenger conductors have practically become standard for secondary aerial circuits and service drops. Subject to the NEC limitation of 300 volts to ground for bare neutrals, the triplex form (two insulated conductors preassembled with a bare neutral) supplies the usual single-phase three-wire circuits. Similar quadruplex cables (three insulated conductors) if connected to a three-phase Y source supplies low-voltage three-phase loads.

The neutral messengers of such cables are selected on basis of strength and conductivity; either with conductivity equal to that of a phase conductor or as a “reduced” neutral having conductivity not less than one-half that of a phase conductor, depending on service requirements. Tables in Chapter 4 show, as mentioned above, data regarding bare neutral messengers for such cables. Chapter 10 describes various types of cables. Fig. 11-31 depicts installation details for usual conditions of installation of the secondary cable and the service-drop taps extending from it. Initial sag-and-tension data for preassembled triplex aluminum cables with full- and reduced-size neutrals are in Table 11-11 for the various NESC loadings for 125 ft spans.
covered and insulated aluminum wire and cable

The notation on Table 11-11 with regard to initial sag values for other spans than 125 ft is based on Eq. 5-2, but it is only approximate; hence it is available to obtain correct values from the cable manufacturer.

The sag-tension values of Table 11-11 are for initial unloaded conditions at 60°F. The sag eventually will increase to the final value and the tension correspondingly will decrease as a result of long-time creep. When fully loaded according to NESC values the sag and tension both will increase, and as temperature drops to 0°F under Heavy-Loading conditions the sag decreases and tension increases. Thus, for 2/0—2/0 cable with aluminum-alloy messenger, the initial stringing sag-tension of 13 in.—865 lb becomes 24 in.—1955 lb (see Chapter 5).

The sag-tension values under conditions of maximum NESC loading are useful for circuit design because they indicate minimum clearances under the cable, and also verify that there is the specified margin between actual tension and the rated breaking strength of the messenger. However, tables similar to Table 11-11 for initial stringing conditions are used as a basis for installation, which is the subject considered in this chapter.

Fig. 11-30. Typical details for supporting and dead-ending cables, messengers, and guy wires on poles.
Fig. 11-31. Typical installation details for secondary triplex cables, neutral-messenger-supported, showing service-drop taps and other details.

A—Dead-end at pole, showing also application of service-drop span clamp.

B—Double service-drop taps at service-drop span clamp, and messenger suspension clamp at pole.

C—Service-drop "T" tap near pole.

D—Clevis support at pole for directional change of less than 45°.

E—Dead-end support at pole for directional change of more than 45°.

Notes: Compression connections are to be taped, even though not so shown. Poles are to be suitably guyed to resist unbalanced forces. Armor rods are used where abrasion is likely. See Chapter 5 for additional details of armor rods and the like.
covered and insulated aluminum wire and cable

TABLE 11-10

Representative Values Extracted from Tables Supplied by Cable Manufacturer for Initial Sag-and-Tension Values at 60° F, suitable for Light or Heavy NESC Districts

For Preassembled Primary Aerial 3-1/C Cables with AWAC Messenger

<table>
<thead>
<tr>
<th>Conductor Size</th>
<th>Messenger Size</th>
<th>Rated Strength (lb)</th>
<th>Cable Assembly (2)</th>
<th>Span Length in Feet</th>
</tr>
</thead>
<tbody>
<tr>
<td>AWG or Kcmil</td>
<td>Diam. in.</td>
<td>Weight lb/ft</td>
<td>100</td>
<td>125</td>
</tr>
<tr>
<td>5000 Volt Unshielded (Class B concentric stranded aluminum, cross-linked polyethylene insulation)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>#3-3/4</td>
<td>7700</td>
<td>1.251</td>
<td>0.421</td>
</tr>
<tr>
<td>1</td>
<td>&quot;</td>
<td>&quot;</td>
<td>1.575</td>
<td>0.645</td>
</tr>
<tr>
<td>2/0</td>
<td>&quot;</td>
<td>&quot;</td>
<td>1.770</td>
<td>0.827</td>
</tr>
<tr>
<td>4/0</td>
<td>&quot;</td>
<td>&quot;</td>
<td>2.007</td>
<td>1.100</td>
</tr>
<tr>
<td>350</td>
<td>&quot;</td>
<td>&quot;</td>
<td>2.374</td>
<td>1.600</td>
</tr>
<tr>
<td>500</td>
<td>#3-2/5</td>
<td>11300</td>
<td>2.693</td>
<td>2.158</td>
</tr>
<tr>
<td>750</td>
<td>#2-2/5</td>
<td>13500</td>
<td>3.215</td>
<td>3.076</td>
</tr>
<tr>
<td>1000</td>
<td>#1/0-2/5</td>
<td>19500</td>
<td>3.695</td>
<td>4.053</td>
</tr>
</tbody>
</table>

15,000 Volt Shielded, Grounded Neutral (Class B concentric stranded aluminum; semi-con tape; strand shield; 0.175 in. XLPE insulation; extruded semi-con PE, No. 22 AWG copper concentric; Mylar tape; PVC jacket)

<table>
<thead>
<tr>
<th>Conductor Size</th>
<th>Messenger Size</th>
<th>Rated Strength (lb)</th>
<th>Cable Assembly (2)</th>
<th>Span Length in Feet</th>
</tr>
</thead>
<tbody>
<tr>
<td>AWG or Kcmil</td>
<td>Diam. in.</td>
<td>Weight lb/ft</td>
<td>100</td>
<td>125</td>
</tr>
<tr>
<td>2</td>
<td>#3-3/4</td>
<td>7700</td>
<td>2.459</td>
<td>1.379</td>
</tr>
<tr>
<td>1/0</td>
<td>&quot;</td>
<td>&quot;</td>
<td>2.618</td>
<td>1.606</td>
</tr>
<tr>
<td>4/0</td>
<td>#3-2/5</td>
<td>11300</td>
<td>3.006</td>
<td>2.215</td>
</tr>
<tr>
<td>350</td>
<td>#1/0-2/5</td>
<td>19500</td>
<td>3.504</td>
<td>3.075</td>
</tr>
<tr>
<td>500</td>
<td>&quot;</td>
<td>&quot;</td>
<td>3.789</td>
<td>3.696</td>
</tr>
<tr>
<td>750</td>
<td>556,500(30/7)</td>
<td>26900</td>
<td>4.576</td>
<td>5.039</td>
</tr>
<tr>
<td>1000</td>
<td>&quot;</td>
<td>&quot;</td>
<td>5.079</td>
<td>6.390</td>
</tr>
</tbody>
</table>

1. Initial tension is such that the final tension will not exceed 25 percent of rated strength at 60° F, for Light or Heavy NESC loading districts.
2. Includes weight of messenger and binder tape.
3. Initial sag is such that final sag approximately conforms to ICEA recommendation of 1.667 percent of span length.
TABLE 11-11

Typical Initial Stringing Sag and Tension Values for
Three-Conductor Self-Supported Polyethylene Service-Drop and
Secondary Cable (Triplex), for 125 ft span at 60°F
for Various NESC Loading Districts (see Table 5-1)*

Note: For roughly approximate values for spans of 100 ft and 150 ft, multiply the initial sag values for 125 ft span by 0.64 for 100-ft span and by 1.45 for 150-ft span, retaining the initial tension values for 125 ft span. These approximations are less accurate for the Heavy Loading District. More accurate values for spans other than for 125 ft, are obtainable from cable manufacturers.

<table>
<thead>
<tr>
<th>Conductor</th>
<th>Neutral Messenger</th>
<th>NESC Light-Loading District</th>
<th>NESC Medium-Loading District</th>
<th>NESC Heavy-Loading District</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size AWG</td>
<td>Size AWG (or Equiv.)</td>
<td>Initial Sag (lb)</td>
<td>Initial Tension</td>
<td>Initial Sag (lb)</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>1760</td>
<td>8</td>
<td>467</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>2800</td>
<td>8</td>
<td>750</td>
</tr>
<tr>
<td>1/0</td>
<td>1/0</td>
<td>4460</td>
<td>8</td>
<td>1195</td>
</tr>
<tr>
<td>2/0</td>
<td>2/0</td>
<td>5390</td>
<td>8</td>
<td>1415</td>
</tr>
<tr>
<td>ALUMINUM ALLOY 6201 NEUTRAL MESSENGER</td>
<td>ALUMINUM ALLOY 6201 NEUTRAL MESSENGER</td>
<td>ALUMINUM ALLOY 6201 NEUTRAL MESSENGER</td>
<td>ALUMINUM ALLOY 6201 NEUTRAL MESSENGER</td>
<td>ALUMINUM ALLOY 6201 NEUTRAL MESSENGER</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>1190</td>
<td>10</td>
<td>290</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>1860</td>
<td>10</td>
<td>445</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>2850</td>
<td>10</td>
<td>660</td>
</tr>
<tr>
<td>1/0</td>
<td>1/0</td>
<td>4380</td>
<td>10</td>
<td>1005</td>
</tr>
<tr>
<td>2/0</td>
<td>2/0</td>
<td>5310</td>
<td>10</td>
<td>1255</td>
</tr>
<tr>
<td>ACSR NEUTRAL MESSENGER</td>
<td>ACSR NEUTRAL MESSENGER</td>
<td>ACSR NEUTRAL MESSENGER</td>
<td>ACSR NEUTRAL MESSENGER</td>
<td>ACSR NEUTRAL MESSENGER</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>1190</td>
<td>12</td>
<td>295</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>1860</td>
<td>13</td>
<td>445</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>2850</td>
<td>13</td>
<td>670</td>
</tr>
<tr>
<td>1/0</td>
<td>1/0</td>
<td>3550</td>
<td>13</td>
<td>835</td>
</tr>
<tr>
<td>REDUCED ACSR NEUTRAL MESSENGER</td>
<td>REDUCED ACSR NEUTRAL MESSENGER</td>
<td>REDUCED ACSR NEUTRAL MESSENGER</td>
<td>REDUCED ACSR NEUTRAL MESSENGER</td>
<td>REDUCED ACSR NEUTRAL MESSENGER</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>560</td>
<td>26</td>
<td>91</td>
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<tr>
<td>4</td>
<td>4</td>
<td>881</td>
<td>19</td>
<td>195</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>1350</td>
<td>17</td>
<td>385</td>
</tr>
<tr>
<td>1/0</td>
<td>1/0</td>
<td>1990</td>
<td>19</td>
<td>485</td>
</tr>
<tr>
<td>ALUMINUM NEUTRAL MESSENGER (Aluminum 1350)</td>
<td>ALUMINUM NEUTRAL MESSENGER (Aluminum 1350)</td>
<td>ALUMINUM NEUTRAL MESSENGER (Aluminum 1350)</td>
<td>ALUMINUM NEUTRAL MESSENGER (Aluminum 1350)</td>
<td>ALUMINUM NEUTRAL MESSENGER (Aluminum 1350)</td>
</tr>
</tbody>
</table>

* These initial sag-tension values are based on NESC loading limits for REA systems; that is, loaded tension is not to exceed 50% of messenger rated strength; final stringing tension is not to exceed 25% of rated strength; and initial stringing tension is not to exceed 33-1/3% of rated strength.

11-27
Chapter 12

Operation and Operating Problems

Operation of power cables under their normal conditions of intended use seldom presents major problems. Reference data in previous chapters (mostly Chapter 9) enable the designer and user to predict voltage drop as a function of load and to specify the maximum current to be carried per conductor (at 100% or reduced load factors) on a thermal limitation basis. Circuit fuses, limiters, circuit breakers, cut-outs, etc., are usually selected or adjusted to limit the current in the cable to its design short-circuit capability, and relays, regulators, and signal circuits enable the load dispatcher to maintain the load within operating limits or control its extension into the emergency load range, as required.

The basic relationship of kV, ampere, kW and kVA factors in the usual power circuit are well understood by designers and operating employees but, as a reminder, Fig. 12-1 is included. It lists equations for two-phase systems that are frequently encountered. The designation "star" is used instead of the term "Y-connected." For the probable approximate ampacity loading of branch and main circuits for residential and light industrial uses, refer to NEC Articles Nos. 220, 230 and 430.

The load factors and corresponding loss factors that apply to typical daily load curves are explained in Chapter 9. These factors are related to the heat-sink effect of the surrounding earth on conductors that are directly buried or are in underground ducts. A load factor of 100 percent is used for circuits in air or conduit in air. It is important to consider the worst case "limiting factor" when deciding the load carrying capability of a circuit.

Emergency Overloads

The conditions that permit the cable to be subjected to temporary emergency overloads, within recognized limits of good practice, were outlined in Chapter 9, and the emergency-load temperatures that the insulation can sustain are listed in Table 9-7. The load dispatcher, however, does not measure insulation temperature to indicate that the emergency-overload limit has been reached. Instead, he is supplied with the ammeter readings that correspond to the emergency-load temperatures. Precomputing of these ampacity values for the emergency-overload temperature is an operating problem solved by applying the constants from the ICEA—IEEE Ampacity Tables, described in Appendix 9A, principally Eq. 9A-1.

\[ I^* = 233 \frac{90 - 40 - 0.50}{75 - 40 - 0.50} \times \frac{228.1 + 75.0}{228.1 + 90.0} = 272 \text{ amp} \]

The Delta TD value is unchanged because it is assumed that the dielectric constant and insulation pf are the same at both temperatures.

Appendix 9A describes further adjustments of the above relationship for variations of ambient temperature, and properties of the insulation.

Short-Circuit Loading

Short circuits, either between the conductors of a power cable or from the conductors to ground or occurring in some part of the load being served by the cable, can cause a rapid rise of current values, as much as 100 times normal or more.

A discussion of short-circuit currents in aluminum conductors insulated with various materials is in Chapter 9 (see Figs. 9-5, -6, and -7). Additional information applying to bare conductors is in Chapter 6, and much of it is applicable to insulated conductors. The essential difference is that insulated conductors fail under short-circuit conditions because of loss of insulation value, whereas bare conductors fail because of loss of strength of the conductor caused by high-temperature annealing. The allowable temperatures under short-circuit conditions for insulated aluminum conductors are 150°C, 200°C, and 250°C, depending on the kind of insulation, as listed in Table 9-7.

The problem of system fault-current is beyond the scope of this publication. The reference to zero-sequence impedance of bare aluminum conductors in Chapter 3, applying to elementary circuits and to average earth resistance, may aid such calculations, but for network analysis and where terminal impedances must be considered, the method of computation is the same for aluminum as for copper, except for differences of electrical properties of the conductors.
covered and insulated aluminum wire and cable

To Find the Value

When Value Below Is Known

SYSTEM

FORMULAS

<table>
<thead>
<tr>
<th>SYSTEM</th>
<th>Direct Current</th>
<th>Single-Phase</th>
<th>Two-Phase, Four-Wire*</th>
<th>Three-Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amperes (1)</td>
<td>Horsepower (Hp)</td>
<td>I = 746 Hp/EXeff</td>
<td>I = 746 Hp/EXeffXpf</td>
<td>I = 746 Hp/1.73EEXeffXpf</td>
</tr>
<tr>
<td>Kilowatts (kW)</td>
<td></td>
<td>I = 1000 kW/E</td>
<td>I = 1000 kW/EXpf</td>
<td>I = 1000 kW/1.73EEXpf</td>
</tr>
<tr>
<td>Kilovolt-Amperes (kVAr)</td>
<td></td>
<td>I = 1000 kVAr/E</td>
<td>I = 1000 kVAr/2E</td>
<td>I = 1000 kVAr/1.73E</td>
</tr>
<tr>
<td>Kilowatts Input (kW)</td>
<td></td>
<td>kW = IXE/1000</td>
<td>kW = IXEpf/1000</td>
<td>kW = IXE2Xpf/1000</td>
</tr>
<tr>
<td>Kilovolt-Amperes (kVAR)</td>
<td></td>
<td>kVAR = IXE/1000</td>
<td>kVAR = IXE2/1000</td>
<td>kVAR = IXE1.73/1000</td>
</tr>
<tr>
<td>Horsepower Output (Hp)</td>
<td></td>
<td>Hp = IXEeff/746</td>
<td>Hp = IXEeffXpf/746</td>
<td>Hp = IXE1.73XeffXpf/746</td>
</tr>
</tbody>
</table>

I = Line Current, Amperes
E = Line-to-Line Voltage, Volts
eff = Efficiency, decimals
pf = Power Factor, decimals
Hp = Output, Horsepower
kW = Input, Kilowatts
kVAR = Input, Kilovolt-Amperes

Fig. 12-1. Diagrams and formulas showing relationships between electrical and power quantities in various types of circuits.

Some of the operating conditions that bring about short-circuits of various kinds are considered herein as a guide to what is to be avoided, if possible.

Short Circuits in Shields and Sheaths

Consideration should be given to the performance of the cable metallic shield under the influence of a line-to-ground fault.

Though several other metals are sometimes employed as sheath/shield material, (see Tables 12-4 and 12-5) copper is by far the most commonly used.

Note: The expression "decimals" refers to notation as a decimal fraction; that is, an efficiency of 85% is used in the formula as 0.85.

Cable shielded with these helically applied copper tapes or concentric servings of fine (20-24 AWG) copper wires have generally performed satisfactorily in the past because of relatively low fault currents and because these circuits were often installed in ducts in three-conductor groups with a bare ground conductor.

The increasing use of solid dielectric power cable on electric utility distribution systems with higher available fault currents underlines the importance of proper shield size for the expected fault duty.
Equation 12-1* gives the minimum effective cross-sectional area of metallic shield required for a given fault time period.

Table 12-1 shows the corresponding formulae for calculating the effective cross-sectional area of various types of sheaths/shields.

Table 12-2 shows the approximate shield normal operating temperature for various steady-state conductor operating temperatures for cables rated 5 kV through 69 kV.

---

**TABLE 12-1**

<table>
<thead>
<tr>
<th>Type of Shield or Sheath</th>
<th>Formula for Calculating A (See notes 1 and 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Wires applied either helically, as a braid or serving; or longitudinally with corrugations</td>
<td>nd$_1$</td>
</tr>
<tr>
<td>2. Helically applied tape, not overlapped</td>
<td>1.27 nw$b$</td>
</tr>
<tr>
<td>3. Helically applied flat tape, overlapped</td>
<td>$4bd_m\sqrt{\frac{100}{2(100-L)}}$ see note 3</td>
</tr>
<tr>
<td>4. Corrugated tape, longitudinally applied</td>
<td>$1.27(\pi(d_1+50)+B)$ b</td>
</tr>
<tr>
<td>5. Tubular sheath</td>
<td>$4bd_m$</td>
</tr>
</tbody>
</table>

**NOTE 1:** Meaning of Symbols
- $A$ = Effective cross-sectional area, shield or sheath.
- $B$ = Tape overlap, mils (usually 375).
- $b$ = Thickness of tape, mils.
- $d_1$ = Diameter of semiconducting insulation shield, mils.
- $d_m$ = Mean diameter of shield or sheath, mils.
- $d_w$ = Diameter of wires, mils.
- $w$ = Width of tape, mils.
- $n$ = Number of serving or braid wires or tapes.
- $L$ = Overlap of tape, percent.

**NOTE 2:** The effective area of composite shields is the sum of the effective areas of the components. For example: the effective area of a composite shield consisting of a helically applied tape and a wire serving would be the sum of the areas calculated from Formula 2 (or 3) and Formula 1.

**NOTE 3:** The effective area of thin, helically applied overlapped tapes depends also upon the degree of electrical contact resistance of the overlaps. Formula 3 may be used to calculate the effective cross-sectional area of the shield for new cable. An increase in contact resistance may occur after cable installation during service exposed to moisture and heat. Under these conditions, the contact resistance may approach infinity where Formula 2 could apply.

*From ICEA publication P-45-482, 2nd Edition, 1979. The user is cautioned to read this publication in order to fully understand the derivation and basis for this calculation and the associated parameters.

---

**TABLE 12-2**

<table>
<thead>
<tr>
<th>Rated Voltage, kV</th>
<th>Shield or Sheath Temp. °C</th>
<th>95°C</th>
<th>90°C</th>
<th>85°C</th>
<th>80°C</th>
<th>75°C</th>
<th>70°C</th>
<th>65°C</th>
<th>60°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>90</td>
<td>85</td>
<td>80</td>
<td>80</td>
<td>75</td>
<td>70</td>
<td>65</td>
<td>60</td>
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</tr>
<tr>
<td>15</td>
<td>90</td>
<td>85</td>
<td>80</td>
<td>75</td>
<td>70</td>
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<td>25</td>
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<td>45</td>
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<td>65</td>
<td>60</td>
<td>55</td>
<td>50</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**NOTE:** The maximum conductor temperature should not exceed the normal temperature rating of the insulation used.

---

Table 12-3 shows the maximum allowable transient temperature for shields in contact with various materials.

Tables 12-4 and 12-5 give the “M” values for use in Equation 12-1. As shown by the tables, the “M” values are constants and depend upon the shield material, the shield normal operating temperature and the maximum allowable transient temperature of the shield.

Example calculation: Determine the size copper wire shield required to carry a fault current of 10000 amperes for 10 cycles for a 15 kV XLP cable having a semiconducting thermoplastic insulation shield and a thermoplastic overall jacket.

**Step 1**

Determine the approximate shield operating temperature for 90°C conductor temperature (which is the maximum temperature for normal operation of XLP insulated cables). From Table 12-2:

$$T_1 = 85°C$$

**Step 2**

Determine the maximum allowable shield transient temperature for the cable materials in contact with the shield, which in this case is thermoplastic. From Table 12-3:

$$T_2 = 200°C$$

**Step 3**

Determine the “M” value for a copper shield with $T_1$ equal to 85°C and $T_2$ equal to 200°C. From Table 12-4:

$$M = 0.063$$

---

12-3
covered and insulated aluminum wire and cable

TABLE 12-3

<table>
<thead>
<tr>
<th>Cable Material in Contact with Shield or Sheath</th>
<th>T2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crosslinked (thermoset)</td>
<td>350°</td>
</tr>
<tr>
<td>Thermoplastic</td>
<td>200°</td>
</tr>
<tr>
<td>Impregnated Paper</td>
<td>200°</td>
</tr>
<tr>
<td>Varnished Cloth</td>
<td>200°</td>
</tr>
</tbody>
</table>

NOTE: The temperature of the shield or sheath shall be limited by the material in contact with it. For example, a cable having a crosslinked semi-conducting shield under the metallic shield and a crosslinked jacket over the metallic shield would have a maximum allowable shield temperature of 350° C. With a thermoplastic jacket, it would be 200° C.

*For lead sheaths this temperature is limited to 200° C.

Step 4
Calculate the required shield cross-section for a fault duration of 10 cycles (0.167) seconds. Applying Equation 12-1:

\[ A = \frac{10000 \sqrt{0.167}}{0.063} = 64866 \, \text{circular mils} \]

Step 5
Determine the number and size of the wires necessary to equal or exceed 64866 circular mils. Inspection of Table 12-1 shows that the effective cross-sectional area of a wire shield is equal to \( n d^2 \) or the number of wires multiplied by the circular mil area of each wire. The number required for any specific wire size is simply the total cross-section calculated in step 4 divided by the individual wire circular mil area and rounded up to the nearest whole number:

Number of 14 AWG wires = \( \frac{64866}{4110} = 15.8 \) or 16

Similarly, the number of any other wire size may be determined:

\[ A = \frac{1 \sqrt{t}}{M} \]  
(Eq. 12-1)

where: \( I = \) short-circuit current in shield, amperes
\( t = \) time of short-circuit, seconds
\( M = \) constant, see Tables 12-4 and 12-5

Causes of Insulation Failure
The majority of cable failures occur unexpectedly. Most often, the power dissipated in the failed area burns the insulation to the extent that the cause is destroyed.

Examination of the areas near the fault and the external appearance of the cable may also provide evidence which helps determine the apparent cause of failure. The reasons for insulation failures which are not obviously the result of physical damage may be found during laboratory investigation by electrically testing cable samples to destruction. A brief review of the most frequent causes found by this method is found in the following paragraphs.

Imperfections in extruded insulations are a major cause of failure. They are often found as voids, contaminants

---

<table>
<thead>
<tr>
<th>Shield/Sheath Material</th>
<th>Values of M for the Limiting Condition Where ( T_2 = 2000°C )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Shield/Sheath Operating Temperature (T1), °C</td>
</tr>
<tr>
<td></td>
<td>90  85  80  75  70  65  60  55  50</td>
</tr>
<tr>
<td>Aluminum</td>
<td>0.041 0.042 0.043 0.044 0.046 0.046 0.047 0.048 0.049</td>
</tr>
<tr>
<td>Commercial Bronze</td>
<td>0.045 0.046 0.047 0.048 0.049 0.050 0.051 0.052 0.053</td>
</tr>
<tr>
<td>Copper</td>
<td>0.062 0.063 0.065 0.066 0.068 0.070 0.071 0.073 0.074</td>
</tr>
<tr>
<td>Lead</td>
<td>0.012 0.012 0.012 0.012 0.013 0.013 0.014 0.014 0.014</td>
</tr>
<tr>
<td>Steel</td>
<td>0.023 0.024 0.024 0.025 0.026 0.026 0.027 0.027 0.028</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.030 0.031 0.032 0.033 0.034 0.034 0.035 0.036 0.037</td>
</tr>
<tr>
<td>Cupronickel</td>
<td>0.018 0.019 0.019 0.020 0.020 0.021 0.021 0.021 0.022</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shield/Sheath Material</th>
<th>Values of M for the Limiting Condition Where ( T_2 = 350°C )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Shield/Sheath Operating Temperature (T1), °C</td>
</tr>
<tr>
<td></td>
<td>90  85  80  75  70  65  60  55  50</td>
</tr>
<tr>
<td>Aluminum</td>
<td>0.058 0.059 0.060 0.060 0.061 0.062 0.063 0.063 0.064</td>
</tr>
<tr>
<td>Commercial Bronze</td>
<td>0.066 0.067 0.068 0.068 0.069 0.070 0.070 0.071 0.072</td>
</tr>
<tr>
<td>Copper</td>
<td>0.088 0.089 0.090 0.091 0.092 0.093 0.094 0.096 0.097</td>
</tr>
<tr>
<td>Steel</td>
<td>0.032 0.033 0.033 0.034 0.034 0.035 0.035 0.036 0.036</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.044 0.044 0.045 0.046 0.046 0.046 0.047 0.047 0.048</td>
</tr>
<tr>
<td>Cupronickel</td>
<td>0.028 0.028 0.029 0.029 0.029 0.029 0.030 0.030 0.030</td>
</tr>
</tbody>
</table>
or sharp projections into the insulation at the conductor shield or insulation shield interface. The presence of some voids is inevitable due to the chemical reaction and medium used to vulcanize insulation.

Contaminants are found in the raw materials purchased from reputable compound suppliers. To a lesser extent, they may also be introduced through inadequate quality control procedures and poor handling techniques at the cable manufacturing plant. Screens are used in the insulation extruders to help filter out solid contamination. However, some inevitably passes through into the cable insulation.

Sharp projections into the insulation may be formed as a cable is extruded. These create points of high electrical stress which can lead to premature cable failure.

In recent years, much has been learned about deterioration of insulation known as "treeing." Treeing of two types is known to occur in solid dielectric wire — water or electrochemical and electrical. Treeing sites are usually at high stress points at the insulation/shielding interface or at voids or contaminants which cause discontinuities in the insulation. Such trees can be seen by optical examination when suitably stained and magnified. If cables without a moisture-proof barrier are operated in a wet environment, water trees will likely form at high stress points in the insulation since moisture can easily penetrate the insulation. It is believed that these trees will ultimately lead to cable failure. The failure mechanism is not completely understood. Cable manufacturers have introduced compounds which retard tree growth and much research is taking place to develop improved tree-resistant insulating materials.

The major cause of failure in paper insulated cable is sheath deterioration or rupture. This permits water or other harmful liquids to penetrate the laminated insulation. Voids occur in such cable due to expansion of the cable core under electrical load. Upon cooling, the core can contract away from the sheath leaving voided areas. Ionization of the voids can polymerize the oil, forming wax. The wax may fill the voids and retard further ionization.

Surface discharge or tracking will deteriorate cable insulation. It may occur at cable terminations where the insulation is exposed. Serious discharge can also develop on non-shielded cable. In each of these instances, differences in voltage gradient on the insulation surface produces current flow. Over long periods of time, the current will erode and char the insulation, leaving tracks.

**External Causes of Cable Failure**

Failures of 600 volt cable are most often caused by mechanical damage. The cables are often directly buried at a shallow depth. Digging into the cable occurs quite frequently. Often, little attention is paid to the quality of the fill used to cover the cable. When tamped, sharp rock may pierce the insulation. Also, multiple cables may be laid across each other or in such close contact that poor heat dissipation results in insulation embrittlement.

Other trouble may occur from poor connections, inadequate short-circuit protection and contact with harmful chemicals. Occasionally, water may enter the conductor from inadequate or non-existent sealing. Conductor corrosion can result, particularly in aluminum cable.

High voltage cable is usually carefully installed and protected. Thus, mechanical damage is less prevalent. "Dig-ins" do occur, however. Cables that are plowed in are susceptible to damage unless care is taken to feed them into the equipment smoothly, without jerking. In some areas of the country, rodents attack buried high voltage cable. For these conditions, special metal protected cables are often used.

**Installation and Maintenance Proof-Testing**

Proof-testing is an accepted procedure by which higher than normal operating voltage is applied to cable. Most often this is done on high voltage cable after installation and before the cable is placed in service. The test is quick and simple, only requiring the cable to withstand the voltage for a period of minutes. However, a short time test can only detect gross defects or damage.

Normally, d-c voltage is applied because such equipment can be made lightweight and portable. Often, leakage current is read and recorded. However, the readings can vary greatly since leakage is readily influenced by the condition of the terminations. Humidity, cleanliness and the leakage distance all permit wide variations which may be mistaken for insulation deterioration. Leakage current is of value if a record is maintained over a long period of time. In this way, comparison from one year to previous years will indicate any deterioration.

Table 12-6 lists the present industry-recommended voltages after installation and for subsequent maintenance evaluation.

**Fault Location**

The necessity of developing good cable-fault locating techniques is probably more important today than ever before. The growing direct-buried residential distribution system has dramatized the need for reliable techniques to pinpoint cable faults as quickly as possible to minimize downtime and unnecessary excavating. Many power utilities are now staffed with well equipped, specialized crews, trained in the methods for locating faults.

The following material outlines in general the types of equipment commercially available for the many different kinds of fault conditions. Unfortunately, no one piece of apparatus is sufficient in itself. However, they are divided into two general categories, as follows:
**Terminal Equipment** — is employed where the entire test and determination of the fault location is made at one or more terminals of the cable.

**Tracer Equipment** — is employed where some form of electrical signal is injected into the cable at one of its terminations. The signal is traced to the fault by patrolling the cable with some form of detector used as a signal sensor.

### TABLE 12-6

<table>
<thead>
<tr>
<th>System Voltage (kV)</th>
<th>After Installation (15 minute duration)</th>
<th>During Maintenance</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>25</td>
<td>20</td>
</tr>
<tr>
<td>5.0</td>
<td>35</td>
<td>25</td>
</tr>
<tr>
<td>8.7</td>
<td>40</td>
<td>30</td>
</tr>
<tr>
<td>15</td>
<td>55</td>
<td>40</td>
</tr>
<tr>
<td>25</td>
<td>80</td>
<td>60</td>
</tr>
<tr>
<td>28</td>
<td>85</td>
<td>65</td>
</tr>
<tr>
<td>34.5</td>
<td>100</td>
<td>75</td>
</tr>
<tr>
<td>46</td>
<td>120</td>
<td>90</td>
</tr>
<tr>
<td>69</td>
<td>170</td>
<td>125</td>
</tr>
</tbody>
</table>

**NOTE:**
When equipment such as cable terminals, motors, transformers, etc. are connected to the cable circuit voltage, limitations of such equipment may require the use of lower values. In such instances, it would be advisable to contact the equipment manufacturer before testing. It is recommended the rate of increase of the voltage to the desired value be done uniformly. The voltage level should be reached within 60 seconds but not sooner than 10 seconds. The voltages in the table are 60 percent and 60 percent respectively, of the factory dc test voltages applied to the cable prior to shipment.

### Identify and Isolate

The faulted section in any branch circuit should be clearly identified, de-energized and isolated. For all of the locating techniques discussed here, it is necessary to disconnect and free all terminals. Ground connections may be left intact, if desired.

The fault resistance can be measured with an ohmmeter or megohmmeter and then classified as a parallel or grounded fault (conductor-to-conductor, conductor-to-sheath or conductor-to-ground) or a series or open fault (open circuit or excess resistance in series).

In many cases, the relative magnitude of resistance determines the type of equipment to be used to achieve good results. High resistance sometimes requires reduction of the fault resistance by "burning."  

### Location

The method of locating a fault is influenced by such variables as type of cable, fault resistance and equipment available. Having mezzed the affected circuit, several important factors are determined:

- **Parallel Fault** — Conductor-to-conductor (grounded)  Conductor-to-sheath  Conductor-to-ground
- **Series Fault** — Open circuit (open)  Open sheath

**Fault Resistance**

The types of equipment described below are among those commercially available which can, individually or in combination, locate power cable breakdowns. The Cable Radar Test, Bridge and Capacitance Instruments are classified as terminal instruments since they provide an approximate location as a percentage of circuit length. The longer the length, the greater the actual error, therefore, additional equipment is usually required to pinpoint the exact fault location.

Pulse and tone generators with companion detectors (Acoustic, Electromagnetic, Earth Gradient) are known as tracer methods and these function without knowledge of the circuit length. The tracer methods apply an input signal to either end of the faulted cable. The signal is then physically traced along the cable route until a change is detected which will reveal the location of the fault.

**Radar**

Radar transmits a series of high frequency pulses along the cable and observes the reflections from changes or discontinuities. In essence, it takes an electronic picture of the cable under test and displays it on an oscilloscope. The time required for the generated pulse to reach a discontinuity and return is measured, converted to feet and shown on a digital display. Locations better than 1 percent of the range are possible for circuits up to 80,000 feet.

For parallel faults, the fault resistance should be less than 2000 ohms. However, no limitation is placed on open circuits, loose connections or series type faults.

**Bridge**

The Murray-Loop Bridge with numerous variations has been used for many years to calculate parallel fault locations. The faulted conductor is normally joined to a similar unfaulted conductor and the bridge measurement made on the resulting loop at the opposite open end. The fault resistance should be relatively low. Higher sensitivity is possible in a high voltage adaptation of the bridge where fault resistance can be as high as 5 megohms.
A low voltage version inverted Murray-Loop Bridge having electronic null indicator can provide good results with fault resistance as high as 200 megohms. Accuracies within 0.5 percent of the loop length are possible with resolution to 0.01 percent.

**Capacitance**

A capacitance bridge is useful on very high series resistance, open-circuit faults. The capacitance of conductor-to-shield fault is measured from one end of the de-energized circuit. Knowing the capacitance per unit length, the distance to the open circuit can be calculated. This location can be verified by repeating the procedure from the remote end. Accuracies within ± 3 percent are possible.

**Impulse Generator (Thumper)**

High voltage, high energy impulses generated from a capacitor bank are applied to one end of a faulted circuit. The impulse energy in the form of a traveling wave will either dissipate noiselessly at a low resistance fault or spark-over (break down) at a high resistance fault. The spark-over results in an explosive release of sound, light and current at the fault location.

For the low resistance discharge, the location can be detected by an electromagnetic or earth gradient device. For the high resistance discharge, the location can be detected as an audible thump or an amplified thump with the aid of the acoustical detector. The electromagnetic and earth gradient devices may also be used for the high resistance discharge.

**Earth Gradient Detection**

This detector system is used to pinpoint high and low resistance faults on direct-buried non-shielded cable. A continuous d-c, interrupted d-c or audio tone is applied at one end of the faulted cable, similar to the impulse generator but is usually limited to 1000 volts. The current through the fault will travel back to the generator ground connection via the earth, thereby creating a voltage gradient. A compatible detector measures the gradient between two movable earth probes. The probes are applied as a pair over the surface route in football chain fashion. The accuracy with this method of detection is extremely high.

**Acoustic Detection**

The sharp report of the periodic discharging from a high-resistance fault reveals the location when exposed. On direct-buried cable this can be heard as a dull thump on the surface through several feet of earth; however, an acoustic pickup detector is applied along the surface to amplify a weak thump and thus locate the fault at the point of maximum intensity.

**Electromagnetic Detection**

The field generated by any transmitted impulse along a cable is sensed by means of an electromagnetic pickup coil and detector. Often, at the fault, there is a change of signal strength and if a d-c impulse is used there will be a change in the signal direction.

The electromagnetic surface coil can also be used to trace the cable route and a sheath pickup coil can be used to find faults on ducted cable.

**Audio Tone**

As a preliminary step of fault locating, a low voltage audio frequency (e.g. 1000 Hz) is sometimes matched to one end of the cable in order to transmit a signal. A selectively tuned pickup coil and amplifier is used to trace the signal which can indicate a null or peak over the cable route.

On direct-buried non-shielded cable, the same pickup coil can be used for earth gradient fault location. Some tracers also respond to energized 60 Hz current and incorporate filters for dual operations.

**Burndown**

The level of fault resistance must sometimes be reduced to enable pinpoint location with some methods. This is true for radar, Murray-Loop Bridge and some signal generators. Fault resistance may be reduced by burning the insulation at the fault with a repeated arc, or continuous ac or dc current.

A high voltage d-c, impulse or a-c resonant generator may be used to initiate the lowering of fault resistance. Ac without resonance would lose considerable effect in capacitive charging current.

**Recommendations**

Generally most faults can be detected successfully by selecting a limited number of methods and equipment.

**Recommendations:**

*High voltage, shielded conductor faults in a trench lay system —* should first be generally located with radar. An impulse generator with the appropriate detector, either electromagnetic or acoustical, can then be applied to pinpoint the exact fault location.

*High voltage, shielded conductor faults in a conduit system —* should be located with a radar set and impulse generator as with trench lay systems. However, the impulse generator with detector is usually sufficient in most instances.

*Low voltage trench lay, non-shielded, insulated neutral cable fault —* can be very successfully located with any of the voltage gradient devices available. Faults can be located quickly with excellent accuracy.

*Low voltage, non-shielded cable faults in a conduit —* can usually be located with a bridge. However, most repairs on this kind of system can be more economically performed by replacing the faulted cable section.
Chapter 13

Bus Conductor Design and Applications

The selection of material for bus conductors is usually based on a balance of mechanical and electrical characteristics, economics, and availability. The materials that have been used for bus conductors in large quantity, listed in order of volume conductivity, are: silver, copper, aluminum and iron.

Although silver has the highest volume conductivity, it was used as a bus conductor only during World War II when millions of pounds (mostly ¾" x 9" bars) were used at various aluminum smelters. The service record was excellent but costs prohibit peacetime use of silver for such applications.

Iron in various forms was also used in large volume for bus conductors during World War II. In recent years its use is primarily for power rails for rapid transit systems and overhead electrical cranes. However, even for these applications its use is declining due to the advantages of aluminum and aluminum-steel combinations (Fig. 13-5 m and n).

Copper has excellent mechanical and electrical characteristics and for many years was the metal of choice for use as bus conductor. However, the trend has been toward wider use of aluminum for all types of bus installation.

Aluminum has less than one-third the density of copper and, making allowance for conductivity, an aluminum bus bar will weigh about half as much as copper for equal conductance. For large installations requiring millions of pounds of metal, bus system designers have used the low cost of aluminum as the basis for optimum economic current density. The purpose of this chapter is to provide technical data on numerous bus conductor shapes and alloys as well as answers to basic questions on design and joining.

Typical physical properties given in figures and tables are not guaranteed and may not be exact. They are intended for general information only and should not be specified as engineering requirements. Minimum properties for various aluminum product forms, sizes and methods of manufacture are available in the Aluminum Association's Aluminum Standards and Data.

Many standard works on bus conductor are listed at the end of this chapter, and numbered references in the text relate to this bibliography.

Figures 13-1, 2, 9, 10, 11, 17, 18 and Tables 13-9, 10, 11, 12, 13, 14, 16, 23 have been reprinted with permission from the Alcoa Aluminum Bus Conductor Handbook (1957) and other Alcoa Technical Publications; Figures 13-4, 28 and Tables 13-3, 7 from the Kaiser Aluminum Bus Conductor Technical Manual.

Alloys and Tempers

Pure aluminum has a conductivity of about 65 percent of the International Annealed Copper Standard (IACS). Aluminum can be produced 99.99 percent pure; however, this purity is costly to achieve and the mechanical properties are low.

Aluminum 1350 is a commercial high-purity aluminum with 61 percent conductivity. The tensile strength of each 1350 temper is determined by the amount of work given the metal during fabrication. Today, most 1350 aluminum bus conductors are of -H111 temper for extrusions, -H112 for sawed rolled plate, and -F for cast bars.

After World War II, a new conductor alloy, 6101, was developed which had considerably higher yield strength and better creep resistance than 1350. The alloy contained magnesium and silicon for high mechanical strength without significant reduction in conductivity. The strength of this alloy (6101) is obtained by suitable heat treatments, occasionally combined with some cold work.

Alloy 6063 has been widely used for outdoor high-voltage substation buses because of its excellent mechanical and electrical properties and its availability and economy. Where high strength is desirable and conductivity requirements are lower, alloy 6061-T6 bus is used. Where high conductivity is required, with a minimum sacrifice in mechanical properties, alloy 6101 is used in a variety of shapes.

Other aluminum alloys may be used for bus conductors. However, they should be used with care since conductivity and mechanical properties can be greatly affected by small
### TABLE 13-1

**Mechanical Properties of Aluminum Bus Conductor and Related Alloys**

(The Aluminum Association; ASTM B 236, B 317, B 241, and B 429; and Manufacturer’s Listings)

<table>
<thead>
<tr>
<th>Product</th>
<th>Alloy and Temper</th>
<th>Thickness in Inches</th>
<th>Tensile Strength (ksi) at 20° C (68° F)</th>
<th>Typical Ultimate</th>
<th>Typical Yield</th>
<th>Typical Elongation (Percent — in 2 in. or 4 Dia)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Minimum Ultimate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Minimum Yield</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extruded rod, bar tube, pipe and shapes</td>
<td>1350-HIII</td>
<td>0.125-0.500</td>
<td>29.0</td>
<td>3.5</td>
<td>32.0</td>
<td>28.0</td>
</tr>
<tr>
<td></td>
<td>6101-T6</td>
<td>0.125-0.749</td>
<td>20.0</td>
<td>15.0</td>
<td>18.0</td>
<td>11.0</td>
</tr>
<tr>
<td></td>
<td>6101-T61</td>
<td>0.750-1.499</td>
<td>18.0</td>
<td>11.0</td>
<td>15.0</td>
<td>8.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.500-2.000</td>
<td>15.0</td>
<td>8.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extruded rod, pipe (c)</td>
<td>6101-T63</td>
<td>0.125-0.500</td>
<td>27.0</td>
<td>22.0</td>
<td>14.0</td>
<td>11.0</td>
</tr>
<tr>
<td></td>
<td>6101-HIII</td>
<td>0.250-2.000</td>
<td>12.0</td>
<td>8.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6101-T64</td>
<td>0.125-1.000</td>
<td>15.0</td>
<td>8.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6101-T65</td>
<td>0.125-0.749</td>
<td>25.0</td>
<td>20.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extruded pipe &amp; over</td>
<td>6061-T6</td>
<td>Pipe size 1.0</td>
<td>38.0</td>
<td>35.0</td>
<td>45.0</td>
<td>40.0</td>
</tr>
<tr>
<td></td>
<td>6063-T6</td>
<td>Pipe sizes, all</td>
<td>30.0</td>
<td>25.0</td>
<td>35.0</td>
<td>31.0</td>
</tr>
<tr>
<td>Rolled bar</td>
<td>1350-H12</td>
<td>0.125-1.000</td>
<td>12.0</td>
<td>8.0</td>
<td>14.0</td>
<td>12.0</td>
</tr>
<tr>
<td>Sawed-plate bar</td>
<td>1350-H112</td>
<td>0.125-0.499</td>
<td>11.0</td>
<td>6.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>or sheet</td>
<td></td>
<td>0.500-1.000</td>
<td>10.0</td>
<td>4.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.000-3.000</td>
<td>9.0</td>
<td>3.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rolled sheet</td>
<td>1350</td>
<td>0.020-0.249</td>
<td>8.0</td>
<td>12.0</td>
<td>4.0</td>
<td>20-30 min</td>
</tr>
<tr>
<td>(for shearing or forming)</td>
<td>1350-H12</td>
<td>0.020-0.249</td>
<td>12.0</td>
<td>14.0</td>
<td>12.0</td>
<td>4-9 min</td>
</tr>
<tr>
<td></td>
<td>1350-H14</td>
<td>0.020-0.125</td>
<td>16.0</td>
<td>18.0</td>
<td>16.0</td>
<td>4-9 min</td>
</tr>
<tr>
<td></td>
<td>1350-H16</td>
<td>0.020-0.125</td>
<td>16.0</td>
<td>18.0</td>
<td>16.0</td>
<td>2-4 min</td>
</tr>
<tr>
<td></td>
<td>1350-H18</td>
<td>0.020-0.125</td>
<td>18.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bolts (b)</td>
<td>2024-T4</td>
<td>1/2-5/8-3/4 NC</td>
<td>62.0</td>
<td>40.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cast Alloy for Bus (d)</td>
<td>1350-F</td>
<td>1 in. and up</td>
<td>8.5</td>
<td>3.5</td>
<td>35.0</td>
<td></td>
</tr>
<tr>
<td>Cast Alloy for Fittings (f)</td>
<td>A356.0-T61</td>
<td></td>
<td>37.0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(a) Elongation values apply to specimens of sizes related to product uses.
(b) Values apply to ANSI net stress area of regular or semi-finished bolts.
(c) Values apply to ASTM B 429 structural pipe and ASTM B 241 seamless pipe.
(d) The designations 1350-F and 1050 are often used in the trade for designating cast bus bars made by run-out into sand molds, or continuous run-out through an orifice.
(e) The lower elongation value applies to the thinnest sheet.
(f) Several casting alloys are suitable for aluminum sand-or die-casting of connector fittings. The most frequently used for normal conditions is A356.0-T6 (an Aluminum Association registered number), suitable both for bolted and welded connections. For special shapes and unusual conditions of installation, where considerable water may be held in the fitting and freeze, some employ a softer alloy having about 12.5 and 4.6 ksi minimum ultimate and yield strengths, respectively, and 35.0 percent or better elongation. There is no registered Association number for this alloy, but in the trade it is often referred to as A-100.
## TABLE 13-2

Physical and Electrical Properties of Aluminum Wrought Bus Conductor Alloys
(ASTM B 236, B 317, and The Aluminum Association)

Applying to all alloys and tempers of wrought alloys, typical values

<table>
<thead>
<tr>
<th>Property</th>
<th>1350</th>
<th>6101-T6</th>
<th>6101-T61</th>
<th>6101-T63</th>
<th>6101-T64</th>
<th>6101-T65</th>
<th>6061-T6 Typical</th>
<th>6063-T6 Typical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight, lb/cu in. (rounded)</td>
<td>0.098</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific heat, cal/gm°C or BTU/lb°F</td>
<td>0.214</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coefficient of thermal expansion</td>
<td>0.000023</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific gravity — 2.70</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modulus of Elasticity, Typical, psi</td>
<td>10 x 10⁶</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Note: If two values are shown, the</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>more favorable is “typical”; the</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>less favorable is designated</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>“minimum” provided a higher value is</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>favorable. Otherwise the term</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>“guaranteed” is sometimes used.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(a) Typical conductivities of 6063-T6 alloy pipe for outdoor service may be taken as 55% IACS for current ratings, per NEMA Standard.

(b) To obtain dc resistance at 20°C in microhms multiply table value by length in feet and divide by cross sectional area in sq. in.

(c) Increasing by 0.018 for each 100°C above 70°C (specific heat).

(d) The higher of a pair of coefficients corresponds to the higher value of the pair of conductivity values.
TABLE 13-3

Temperature Coefficients of Resistance (dc) for Bus-conductor Aluminum Alloys and Representative Value for Commercial Copper Bus Bar

Aluminum Alloys and Tempers, and Conductivity % (IACS) (a)

<table>
<thead>
<tr>
<th>% IACS</th>
<th>6061-T6 Typical</th>
<th>6063-T6 Typical</th>
<th>6101-T6 Minimum</th>
<th>6101-T63 Minimum</th>
<th>6101-T61 Typical</th>
<th>6101-T64 Minimum</th>
<th>1350 Minimum</th>
<th>1350 Typical</th>
<th>Representative Value Commercial Copper Bus Bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>0.00279</td>
<td>0.00377</td>
<td>0.00392</td>
<td>0.00400</td>
<td>0.00407</td>
<td>0.00415</td>
<td>0.00423</td>
<td>0.00427</td>
<td>0.00431</td>
</tr>
<tr>
<td>53% (b)</td>
<td>0.00271</td>
<td>0.00363</td>
<td>0.00377</td>
<td>0.00384</td>
<td>0.00391</td>
<td>0.00398</td>
<td>0.00406</td>
<td>0.00409</td>
<td>0.00413</td>
</tr>
<tr>
<td>55%</td>
<td>0.00264</td>
<td>0.00350</td>
<td>0.00363</td>
<td>0.00370</td>
<td>0.00377</td>
<td>0.00383</td>
<td>0.00390</td>
<td>0.00393</td>
<td>0.00396</td>
</tr>
<tr>
<td>56%</td>
<td>0.00261</td>
<td>0.00344</td>
<td>0.00357</td>
<td>0.00363</td>
<td>0.00370</td>
<td>0.00376</td>
<td>0.00382</td>
<td>0.00386</td>
<td>0.00388</td>
</tr>
<tr>
<td>57%</td>
<td>0.00257</td>
<td>0.00338</td>
<td>0.00351</td>
<td>0.00357</td>
<td>0.00363</td>
<td>0.00369</td>
<td>0.00375</td>
<td>0.00378</td>
<td>0.00381</td>
</tr>
<tr>
<td>58%</td>
<td>0.00251</td>
<td>0.00327</td>
<td>0.00339</td>
<td>0.00344</td>
<td>0.00350</td>
<td>0.00356</td>
<td>0.00362</td>
<td>0.00364</td>
<td>0.00367</td>
</tr>
<tr>
<td>59%</td>
<td>0.00245</td>
<td>0.00317</td>
<td>0.00328</td>
<td>0.00333</td>
<td>0.00338</td>
<td>0.00344</td>
<td>0.00349</td>
<td>0.00352</td>
<td>0.00354</td>
</tr>
<tr>
<td>59.5%</td>
<td>0.00239</td>
<td>0.00307</td>
<td>0.00317</td>
<td>0.00322</td>
<td>0.00327</td>
<td>0.00332</td>
<td>0.00337</td>
<td>0.00340</td>
<td>0.00342</td>
</tr>
<tr>
<td>60%</td>
<td>0.00233</td>
<td>0.00298</td>
<td>0.00307</td>
<td>0.00312</td>
<td>0.00316</td>
<td>0.00322</td>
<td>0.00326</td>
<td>0.00329</td>
<td>0.00331</td>
</tr>
<tr>
<td>70%</td>
<td>0.00228</td>
<td>0.00289</td>
<td>0.00298</td>
<td>0.00303</td>
<td>0.00307</td>
<td>0.00312</td>
<td>0.00316</td>
<td>0.00318</td>
<td>0.00320</td>
</tr>
<tr>
<td>80%</td>
<td>0.00223</td>
<td>0.00281</td>
<td>0.00290</td>
<td>0.00294</td>
<td>0.00298</td>
<td>0.00302</td>
<td>0.00306</td>
<td>0.00308</td>
<td>0.00310</td>
</tr>
<tr>
<td>100</td>
<td>0.00218</td>
<td>0.00274</td>
<td>0.00282</td>
<td>0.00285</td>
<td>0.00289</td>
<td>0.00293</td>
<td>0.00297</td>
<td>0.00299</td>
<td>0.00301</td>
</tr>
</tbody>
</table>

(a) For alloys not shown, obtain conductivities from Table 13-2, and interpolate from the listed values.

(b) Per note on Table 13-2, 55% conductivity is much used as design basis for 6063-T6 alloys for tubes, hence coefficients should be taken from the column, headed 55%.

Formula for Temperature Coefficient of Resistance:

\[ R_{T_2} = R_{T_1} \left[ 1 + \alpha R_{T_1} (T_2 - T_1) \right] \]

Example: the dc resistance of an extruded channel section of aluminum alloy 6063-T6 is 8.35 microms per foot at 20°C. Find the same channel's resistance at 30°C.

\[ R_{30°C} = (8.35) \left[ 1 + 0.0035 (30-20) \right] \]
\[ = 8.35 (1.035) \]
\[ = 8.64 \text{ microms per foot} \]
Fig. 13-1. Tensile and yield strength of 6101-T6 bus conductor at room temperature after heating.

amounts of alloying elements.

Table 13-1 lists mechanical properties and Table 13-2, the physical and electrical properties of the aluminum alloys commonly used for bus conductors. Table 13-2 gives the percent volume conductivity (IACS) and resistivity for the common bus bar alloys. It also lists their temperature coefficients of resistance for 20°C and Table 13-3 shows them for other temperatures in the range normally occurring in bus design.

**Mechanical Properties**

The mechanical properties of the different aluminum alloys and tempers commonly used for bus conductors are shown in Table 13-1. The designer is offered a broad range of properties from which to select the alloy and temper best suited for his particular application. For example, high electrical conductivity alloys are the best choice for heavy duty buses for the electrochemical industry where cost of power is an important consideration. For outdoor high voltage substation buses, mechanical considerations rather than electrical, govern the selection. Where bending and forming characteristics are important, it is desirable to have a generous spread between yield strength and tensile strength (see Bending and Forming, page 13-7).

**Effects of Heating**

The generally accepted maximum continuous operating temperature (see UL 857) for open electrical buses is 70°C (30° rise over 40°C ambient) to prevent heat flowing from bus to connected apparatus which is generally limited to 70°C at terminals. Temperatures of 90°C (50°C rise over 40°C ambient) are acceptable for switchgear assemblies and metal-enclosed bus. The effects of these temperatures on the mechanical properties of aluminum bus conductors are negligible. However, short circuits or prolonged overloads may generate temperatures high enough to require consideration of the effects of heating on the bus properties. The effect of heating up to 200°C for as long as 10,000 hours on the tensile and yield strength is shown in Fig. 13-2 for Aluminum 1350-H12; Fig. 13-1 for Alloy 6101-T6.

**Stress-strain and Creep Factors**

Fig. 13-3 depicts stress-strain curves for the listed alloys and tempers, based on minimum values from Table 13-1. The intersection of the 0.002 in./in. strain line that is
Fig. 13-2. Typical tensile and yield strengths of aluminum 1350-H12 at room temperatures after heating.
parallel to the initial straight diagonal line denotes the yield strength (YS) of the alloy, according to ASTM designation. The elastic limit (EL) of an alloy is represented as the stress value of the point of tangency of the curved part of the stress-strain line and the straight part of the line.

Creep resistance and compressive yield strength are both important factors to be considered in the design of bolted joints, especially if thermal cycling as the result of variations in electrical loading is involved. Table 13-4 lists 10-year estimated creep factors for various bus conductor alloys.

**Bending and Forming**

Aluminum bus conductors can be formed by the same procedures and practices that are used for other metals. The most important factors governing the bending of bus conductors are: (1) the ductility of the conductor, (2) the size and shape of the conductor, (3) the method of bending, and (4) the bending equipment used.

A metal must be ductile enough to permit both stretching and compression to take place. However, elongation alone is not a complete criterion for ductility. The ratio of yield strength to tensile strength must also be taken into account. A combination of a high elongation value and a low ratio of yield strength to tensile strength provides the most satisfactory ductility.

Another factor that governs bending is the size and shape of the bus conductor. For example, in the case of a tube, the sharpness of a bend depends not only on the diameter of the tube, but also on the ratio of wall thickness to diameter. In the case of edgewise bends of rectangular

---

**TABLE 13-4**

Creep Factors for Aluminum Bus Conductors

(Average stress required during a 10-year period to produce 1.0% creep at 100°C, assuming well-designed bolted connections."

<table>
<thead>
<tr>
<th>Alloy and Temper</th>
<th>Estimated Average Stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>1350-H111</td>
<td>2,500</td>
</tr>
<tr>
<td>1350-H12</td>
<td>5,000</td>
</tr>
<tr>
<td>1350-H17 and 6101-T61</td>
<td>6,500</td>
</tr>
<tr>
<td>6101-T6</td>
<td>18,000</td>
</tr>
<tr>
<td>6063-T6</td>
<td>24,000</td>
</tr>
<tr>
<td>6061-T6</td>
<td>25,000</td>
</tr>
</tbody>
</table>

---

**Fig. 13-3.** Approximate tension stress-strain curves at 70°C on guaranteed minimum basis for aluminum bus conductor alloys—½ in. thickness bus bars and ½ in. diam. 2024-T4 bolts. Yield strength (YS) is arbitrary at 0.2% offset per ASTM Standard. Elastic limit is estimated as point of tangency (EL).

*Note: The shape of the curve between EL and YS is not always consistent, but the EL values are believed to be conservative.*
### TABLE 13-5

<table>
<thead>
<tr>
<th>TYPE OF BAR</th>
<th>ALLOY AND TEMPER</th>
<th>THICKNESS in.</th>
<th>RADIUS min. □</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extruded</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6101-H11</td>
<td>0.250-0.750</td>
<td>1 x thickness</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.751-1.000</td>
<td>2 x thickness</td>
</tr>
<tr>
<td></td>
<td>6101-T6</td>
<td>0.125-0.375</td>
<td>2 x thickness</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.376-0.500</td>
<td>2 1/2 x thickness</td>
</tr>
<tr>
<td></td>
<td>6101-T61</td>
<td>0.125-0.500</td>
<td>1 x thickness</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.501-0.749</td>
<td>2 x thickness</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.750-1.000</td>
<td>3 x thickness</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.001-1.625</td>
<td>4 x thickness</td>
</tr>
<tr>
<td>Rolled</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6101-T63</td>
<td>0.125-0.375</td>
<td>1 x thickness</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.376-0.500</td>
<td>1 1/2 x thickness</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.501-1.000</td>
<td>2 x thickness</td>
</tr>
<tr>
<td></td>
<td>6101-T64</td>
<td>0.125-0.750</td>
<td>1 x thickness</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.751-1.000</td>
<td>2 x thickness</td>
</tr>
<tr>
<td></td>
<td>6101-T65</td>
<td>0.125-0.500</td>
<td>1 x thickness</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.501-0.749</td>
<td>2 x thickness</td>
</tr>
<tr>
<td></td>
<td>1350-H12</td>
<td>All</td>
<td>1 x thickness</td>
</tr>
<tr>
<td>Sawed plate</td>
<td>1350-H112</td>
<td>All</td>
<td>1 x thickness</td>
</tr>
</tbody>
</table>

□ Applicable to widths up through 6 inches in the T6, T61, T63 and T65 tempers and to widths up through 12 inches for all other listed tempers. Bend radii for greater widths are subject to inquiry.

### TABLE 13-6

<table>
<thead>
<tr>
<th>WIDTH OF BAR in.</th>
<th>MANDREL RADIUS in.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Up thru 0.500</td>
<td>1/2</td>
</tr>
<tr>
<td>0.501-1.000</td>
<td>1</td>
</tr>
<tr>
<td>1.001-1.500</td>
<td>1 1/2</td>
</tr>
<tr>
<td>1.501-2.000</td>
<td>2</td>
</tr>
<tr>
<td>2.001-2.500</td>
<td>2 1/2</td>
</tr>
<tr>
<td>2.501-3.000</td>
<td>3</td>
</tr>
<tr>
<td>3.001-3.500</td>
<td>3 1/2</td>
</tr>
<tr>
<td>3.501-4.000</td>
<td>4</td>
</tr>
</tbody>
</table>

Bend Properties of Bus Bar

Extruded, rolled, and sawed-plated bus bars are capable of being bent flatwise at room temperature through an angle of 90 degrees to minimum inside radii as shown in Table 13-5. Edgewise bending radii are shown in Table 13-6.

Bending Tubular Conductors

Tubular conductors, alloys 6063-T6 and 6061-T6, are often bent to form turns and offsets. For installations where considerable bending is required, the supplier should be advised and specifications written to require seamless pipe made by the hollow ingot process (ASTM B241). For best forming capability, the ratio of tensile yield to tensile ultimate should not be greater than about .85. Producers do not normally control such ratios so it is important to specify that critical, severe forming will be encountered and optimum heat treatments are required.

For substation construction, inside radii of five to seven times the nominal pipe size for ASA schedules 40 and 80 pipe of alloys 6063-T6 and 6061-T6 should prove satisfactory with most types of conventional bending tools. More generous radii may be used for appearance.

For the occasional problem job where material of high yield to tensile strength ratio is used, it may be necessary to apply heat. This can be done readily by applying a torch for short time to the opposite sides. When doing this, care must be taken to avoid overheating. A calibrated crayon type indicator is recommended. Heating to 200°C (392°F) will cause little loss of strength.

For shop work, a forming-roll bender should be considered. Benders having formed hubs and/or followers provide minimum bending radius for 6063-T6, 6061-T6, and 6101-T6 tubes, Fig. 13-4.

Lubrication

The need for lubrication depends on the bending method and technique used. Lubrication is seldom required when bending with roll or ram type benders. However, lubrication is essential in fully tooled draw-bending operations, as well as in some compression and stretch-bending techniques. Best results are obtained if lubrication is provided wherever a relative motion or sliding action occurs between the work and the tools.

Resistance to Corrosion

Aluminum bus is highly resistant to corrosion. Its uses are, therefore, particularly widespread in applications where strong atmospheric corrosive factors are at work, as in industrial and chemical plants and seacoast environments.

Bus Conductor Shapes and Shape Selection

Choice of a bus conductor shape for a given installation is dependent on a number of factors, including operating voltage, ampacity requirements, available short circuit cur-
rents, available space, mechanical strength requirements, ambient conditions of sun, wind, ice, etc. The following review of the most common shapes and their typical characteristics is intended as a guide to bus shape selection and an introduction to bus system design.

Rectangular Bar

The most common form of bus conductor is bar stock of rectangular cross section. (Fig. 13-5a) This shape is inherently easy to fabricate, store, handle and erect. A relatively large surface area can be provided for the dissipation of heat by the use of multiple-bar buses. Joints and taps are readily made by either bolting or welding. Off-sets and 90-degree bends are easily made.

For direct current, as well as for alternating current up to certain limits, the capacity of a bus constructed of flat bar can be controlled by merely varying the size of bars or number of bars in parallel. For high-amperage alternating current, however, special arrangements of laminations are used (See ac Applications, page 13-12).

Because bars are more rigid in the direction of the large cross-sectional axis, supports must be more closely spaced to resist load and short-circuit forces that are applied perpendicular to the wider surface.

Tubular Conductors

Round tubular bus conductors (Fig. 13-5h) are used primarily for outdoor substations and switching structures where long spans between supports are required. The inherent rigidity of a tubular shape in all directions resists wind and ice loads, as well as the forces of short circuits. Since strength is a primary requirement of tubular bus, the higher-strength aluminum alloys are used.

6063-T6 alloy in ANSI Schedule 40 pipe is used widely for outdoor tubular buses because of excellent mechanical and electrical properties and availability. 6061-T6 tubular conductors are used where particularly high strength is desired and conductivity requirements are lower.

For maximum uniformity of mechanical properties at all points of the circumference, tubes are produced from hollow ingot and extruded by use of the die and mandrel method (ASTM B241). If requirements are less severe, "structural" tubes made by the bridge-die process are often used (ASTM B429). Where tubular bus is to be used for high voltage circuits (230 kV and higher), the smooth surface finish (industry class IV) should be specified, to reduce corona and radio-TV interference.

The round tubular bus is the most efficient electrical shape for an a-c bus conductor because it has the lowest skin-effect ratio of the commonly used types. The current rating is limited, however, as compared with that of flat bar, because of the smaller ratio of heat-dissipating surface area to volume. (See "Skin Effect," page 13-12, for optimum wall thickness.) Internal cooling of the tube by forced air or circulating coolants overcomes this handicap, but is not often commercially practical except for electric furnaces.

The electrical characteristics of round tubular bus have led to its use for heavy-duty generator and switching buses in central stations. Since the design of modern isolated phase buses is such that short circuit forces are not a problem, Aluminum 1350 is preferred because of its high conductivity.

Square tubular bus (Fig. 13-5e) has low skin-effect ratio, similar to that of round tubes, and has the advantage of requiring comparatively simple adapter plates for mounting the bus on pedestal insulators and the other flat sides facilitate attaching pads for taps. For this reason it is used for generator-phase and station bus, often in protective enclosures. 6101-T61 and 6063-T6 alloys are principally used, and staggered ventilation holes often are provided in top and bottom surfaces.

Integral Web Channel Bus (IWCB)

The integral web channel bus conductor (Fig. 13-5f and g) is extruded in the form of two channel-shaped condu-
Fig. 13-5. Typical bus conductor shapes.

Notes: (1) If extruded, slightly indented grooves can be extruded horizontally along the outer surface to provide centers for drilling or punching holes for attachment of supports or take-offs. (2) Shapes such as b and d may have equal thickness along any element of the section, or if rolled as a structural shape the thickness will vary to correspond to the slight bevel of structural I-beams and L's. (3) Lugs that facilitate attachments as well as add conductivity may be included as an integral part of the extrusion. (4) Flat bars may have squared corners (up to 1/32 in. radius for thicknesses to 1 in.), rounded corners (1/16 in. radius, nominal for 0.189 to 1.000 in. thickness), or full rounded edge.
tors held together by a ventilated web. The continuous web eliminates the need for spacer clamps or welded tie-bars that are normally required across the two channels between conductor supports. IWCB combines some of the advantages of the double-channel bus and the square tubular bus. Convection air flow is less than that of the face-to-face channel arrangement, but the transverse strength is greater. These buses have narrow shallow grooves extruded on the surfaces for convenience in locating centers of drilled or punched holes for attachment of taps and base plates. The shape is used for station bus, open or enclosed, and for the high-current buses of outdoor substations for distribution voltages, and also for 600-volt bus for industrial plants.

Channels - Structural Shape and Uniform Thickness

Structural shape aluminum channels consist of a pair of channels forming a hollow, ventilated square. Such a conductor is very efficient and practical for high-amperage direct or alternating current, especially above 2,000 amperes per circuit.

For d-c circuits where skin effect is not a factor, aluminum channels are sometimes placed back-to-back—that is, with flanges pointing outward—to form a conductor. Such an arrangement may be more convenient to support than a hollow square. Additional capacity is readily obtained by merely adding one or more flat bars, properly spaced, between the webs of the two channels.

Channel shapes of uniform thickness (Fig. 13-5b) may be desirable for enclosed station buses where the space occupied by the conductor is critical. This type of channel has a small inside radius and provides the maximum flat surface inside for connections. Approaching the electrical efficiency of a split tube, this bus has the added convenience of flat surfaces for making taps and connections.

Angles

The face-to-face paired angles (Fig. 13-5c and d) provide excellent transverse rigidity and ampacity, but require special spacer fittings. Angles are commonly used as singles.

Structural shape angles with slightly beveled legs, similar to the type used for steel structural shapes are sometimes used. Their use has largely been supplanted by the uniform thickness angle.

Uniform thickness angle (Fig. 13-5m), commonly called UABC (Universal Angle Bus Conductor) is a bus form used for moderate-size outdoor substations at distribution voltages. Center-line grooves facilitate location of bolt holes, and since both legs are of equal thickness at all points, the bus may be mounted directly on insulator caps. An adaptor plate is sometimes used for expansion mountings and to accommodate various bolt-circle diameters. Direct application of pads and connector plates is aided by the uniform thickness of the legs. The semi-channel form (Fig. 13-5k) has more transverse strength, and the upper flange does not extend far enough to interfere with hole drilling. 6101-T6 alloy is principally used for these angle shapes.

Round Rod

Some installations, especially in the high-voltage field, may require round rod bus conductors. This type of conductor, however, is not recommended for large alternating current because of the tendency of the current to flow only near the "skin" (outer surface) of the rod. This results in uneconomical use of the metal in the central portion of the conductor. Fittings used are similar to those on tubular buses.

Special Shapes

The extrusion process provides the designer of aluminum bus conductors with the means of making special shapes when none of the previously described shapes is wholly suitable.

Crane-runway bus shapes (Fig. 13-5n and p) are illustrative of how low-cost extrusions can be produced for special needs. The aluminum body of these bus conductors is shaped to combine ampacity and structural adequacy. In some applications, steel facing is fitted to the aluminum bar against which the collector shoe slides.

Factors Affecting Bus Design

It is important to start with a tabulation of the factors that may affect bus design, such as: d-c or a-c current, frequency, ampacity required, allowable voltage drop, operating voltage, maximum possible short circuit currents, space available, taps and connections required. Where large currents are involved the factors that affect the economic current density should also be tabulated. For outdoor substations, other factors should be tabulated, such as: maximum anticipated wind speeds, maximum expected icing conditions, corona, etc.

For industrial bus the decisive factors are generally: (1) ampacity for allowable temperature rise, (2) voltage drop, (3) power loss economics. Because of the various bus shapes available to the designer and their possible physical arrangement, the design problem may result in successive calculations involving all the factors affecting the design. A flow diagram illustrative of this iterative design process for outdoor substation bus is shown in IEEE "Guide for Design of Substation Rigid-Bus Structures" (1).*

Temperature Rise

Effect of Conductivity

The ratio of currents that will produce the same

*Numbered references in the text relate to bibliography at the end of this chapter.
temperature rise in aluminum and commercial copper bars of same size and same surface conditions can be determined from the following formulas:

\[ I^2R_{al} = I^2R_{cu} \quad \text{(Eq. 13-1)} \]

\[
\frac{I_{al}}{I_{cu}} = \sqrt{\frac{61.0}{98.0}} = 78.9 \text{ percent for 1350 alloy}
\]

\[
\frac{1}{\sqrt{\frac{57}{98}}} = 76.26 \text{ percent for 6101-T61 alloy}
\]

**Effect of Dimensions**

Tests show that for practical purposes, copper bus bar sizes can be converted to aluminum sizes for equal temperature rise by either of the following two methods:

1. Increase the width of the aluminum bar 27 percent. For example, a 5\" x ¼\" aluminum bar is equivalent to a 4\" x ¼\" copper bar.
2. Increase the thickness of the aluminum bar about 50 percent. A 4\" x 3/8\" aluminum bar is equivalent to a 4\" x ¼\" copper bar.

Increasing the cross-sectional area by increasing the width not only reduces the resistance heating but also substantially increases the area for heat dissipation. A change in thickness of a rectangular bar does not appreciably affect the amount of exposed surface area. For example, increasing the area of a ¼-in. bar by changing the width from 4 in. to 8 in. increases the capacity by about 87 percent, but increasing the thickness of a 4-in. bar from ¼-in. to ½-in. increases the capacity by only about 45 percent.

**Temperature Rise - Ampacity Tables**

The ampacity for popular shapes and sizes is shown in Tables 13-25 through 13-32 for 30°C rise over 40°C ambient or a maximum of 70°C. Experience has shown that designs using these temperatures have good service records. Although aluminum conductors may be operated at 90°C continuously, such use is generally limited to switchgear assemblies and metal enclosed bus (IEEE Standard No. 27, ASA C37.20). Operation at 100°C for emergency conditions causes very little loss of strength for alloys 6101, 6063 and 6061. However, it becomes progressively more difficult to maintain good bolted joints as the temperature increases. Also, the designer should not overlook the fact that the I²R losses are higher for the higher temperatures. In some cases the user may pay for these losses twice; once to produce the heat and again for air conditioning to remove the heat.

**Energy Loss (2,61,62)**

The cost of energy lost through resistance is important in the case of bus installations where heavy currents are used as, for instance, in the electrochemical industry. In such cases, it may pay to use larger conductors than those used in the ampacity tables. Energy savings due to lower current densities are, of course, equally applicable to all conductor materials. Designers of heavy-current bus systems are advised to factor in the cost of energy, I²R losses associated with bus-size choices, and the probable “pay-back” time for the additional expense of larger conductors. Many industrial and utility bus systems are designed according to this practice.

**ac Applications**

In addition to the factors that affect the design of a dc bus, the design of an ac bus is also influenced by such factors as skin effect, proximity effect, induced circulating currents, hysteresis losses, and mutual heating effect.

**Skin Effect**

The ratio of effective ac resistance of an isolated conductor to its dc resistance is called “skin-effect ratio.”

The 60 Hz \( R_{ac}/R_{dc} \) ratios at 70°C for the commonly used shapes are shown in Tables 13-25 through 13-32. The skin effect ratio depends not only on the size, shape and configuration of the conductor, but also on frequency of the current and the resistance and magnetic properties of the material.

Skin effect takes place not only in single conductors, but also in buses made of several bars. Flat bars can be arranged to minimize skin effect to some extent by the use of hollow square and modified hollow square arrangements. Interlacing of the bars or the paired-phase arrangement offers an excellent solution to the unequal distribution of alternating current in low voltage bus systems.

Considerable work, both of an experimental and a theoretical nature has been done on skin effect of conductors (3,4). Perhaps the most useful work for an engineer are the curves developed by Dwight as shown in Figs. 13-6, 13-7, 13-8. Lewis developed formulas applicable for computer studies (5).

Fig. 13-6 applies to a single rectangular bar per circuit. For two bars in parallel, separated by an air space, the skin effect ratio is approximately the same as would apply for a single bar equal in size to the two bars plus air space but of \( R_{dc} \) the same as that of the two bars. For three or more bars in parallel, the skin effect ratio may be taken from the curve \( t/d = 0.50 \) in Fig. 13-8 (4).

Fig. 13-7 applies to square tubular conductor, to squares made up of two channels in box form, to squares made up of four bars, and to squares made up of angles.
Fig. 13-6. Curves for skin effect of isolated flat rectangular conductors.
Fig. 13-7. Curves for skin effect of isolated square rod and square tubular conductors.

Fig. 13-8. Curves for skin effect of isolated round rod and tubular conductors.
Fig. 13-8 applies to isolated tubular conductors. The magnitude of skin effect increases with wall thickness. Curves plotted for a-c ampacity (I_{ac}) and R_{ac} at 70°C versus wall thickness (all sizes of tube) show that R_{ac} will be a minimum and I_{ac} a maximum at about 0.7 inch for Aluminum 1350 and about 0.8 inch for 6101 alloy.

Proximity Effect (4, 6, 7)

When conductors are close together, a distortion of current density results from the interaction of the magnetic fields of the conductors. This distortion of current distribution, known as “proximity effect,” causes an increase in the effective resistance. The amount of distortion depends on a number of factors—the spacing and arrangement of conductors, conductor shape, cross-section dimensions, frequency of current and dc resistance.

The usual frequency found in industrial work in North America is 60 Hz. Here, the proximity-effect factor will not be more than 1.20 of ac resistance, when isolated, for round tubes whose distance between centers is twice their diameters. With spacings of about five times the diameter, the increase is negligible. As a rule, proximity effects are negligible for phase spacings of more than three or four times the largest dimension of the cross-section. For frequencies higher than 50 or 60 Hz, the approximations should not be used. More accurate proximity effect calculations are available (4,6,7).

Interlaced and Paired Phase Arrangements

The interlacing of bars and paired phase arrangements (Fig. 13-9) offer an excellent solution to the unequal distribution of currents in low voltage systems. These arrangements have low reactance and greatly reduced skin effect and proximity effect. Dwight (4) states that the skin-effect ratio is very low for interlaced construction where bars are close together in parallel planes and where neighboring bars have currents that are always either 180° or 120° out of phase. The essence of paired-phase performance is that the currents in each closely spaced pairs of bars are essentially equal and opposite (8). This makes for an efficient use of bus bar material in that the ac ampacity approaches the dc ampacity.

The paired-phase arrangements (8) are widely used by

---

![Diagram of paired phase arrangement](image)

**Note cross ties from**

A to A,
B to B, and
C to C

**Fig. 13-9.** Paired-phase feeder busway (left) showing end-connections for AB AC BC arrangement. The proximity of A-A and C-C bars serves to reduce crowding of current into the middle pair of bars (A-C). There are several other paired-phase arrangements in common use.
manufacturers of prefabricated bus systems. Interlaced arrangements are used primarily in high current electric furnace installations (9).

Transposition

High current a-c buses, such as "side bars" for carbon baking furnaces, are sometimes designed so that the bus assembly is divided into several sections where the individual conductors, insulated from each other, are transposed so that each individual conductor runs for an equal distance in each of the available positions thereby making the mutually induced voltages equal. By this means, each individual conductor of the bus assembly can be made to share the current equally. Aluminum channel and IWCB shapes provide structural stiffness needed for the portable single-phase bus assembly. Welded connections are preferred for both mechanical and electrical reasons.

Mutual Heating (10)

Mutual heating is due to the interference of one conductor on the heat dissipation of the other. The mutual heating varies with bar spacing, vertical or horizontal arrangement, and open or enclosed bus. The designer should check the notes of the ampacity tables to ensure that the values given apply to his design conditions. Mutual heating occurs for both ac and dc current flow.

Heating Due to Magnetic Materials Near the Buses (11)

A bus carrying high current creates a magnetic field of considerable magnitude. If there are steel members in the field of an ac bus, such pieces will be heated not only by the current induced in them but also by hysteresis. In the case of dc buses, there is no loss in the steel since the magnetic field for a non-pulsating dc bus is static.

The frame in the wall of a building for the passage of the bus should either be of non-magnetic materials throughout or constructed so there is no complete magnetic ring. Even though all of the three phase conductors pass through the same opening, the magnetic fields of the flat bus arrangement do not cancel out and undue heating results unless preventative measures are taken.

Induced Circulating Currents (12,13)

Induced circulating currents in nearby metal items require energy which must be supplied from the inducing circuit. The effect is an increase of the $R_{ac}$ for the circuit. The magnitude of the loss is a function of the amount of induced current, the conductance of the metal item, and the distance of the bus to the metal item. This problem is encountered chiefly in the design of switchgear isolated phase bus.

Calculation of ac Resistance

The calculation of ac resistance is based on the assumption the $R_{ac}$ is affected only by skin effect and possibly proximity effect, e.g., no magnetic losses or induced current losses. To find the ac resistance, it is first necessary to determine the $R_{dc}$ at the design temperature. The magnitude of the skin-effect ratio can be conveniently determined from the tables for electrical characteristics of commonly used shapes or from Dwight's curves, Figs. 13-6, 13-7, 13-8. Where proximity-effect may be a factor, formulas for calculation have been developed for conductors of simple shapes (6). Having determined the skin-effect ratio and the proximity-effect ratio, then $R_{ac} = R_{dc} \times \text{skin-effect ratio} \times \text{proximity-effect ratio}$.

Temperature Rise - Ampacity Tables

The a-c ratings of commonly used shapes included in Tables 13-25 through -32 have been determined for $30^\circ$C rise over $40^\circ$C ambient in still but unconfined air, and at spacings where proximity effect is negligible. Allowance must be made for proximity effect where applicable, other temperatures, other surface finish, resistance for other alloys and tempers, other air conditions, altitude, and sun effect for outdoor installations.

Reactance (4,14,15)

Maxwell, Schurig, Arnold, Dwight, Higgins, Lewis and others have developed equations, tables and charts for the determination of reactance for many conductor shapes and arrangements. Because the physical shapes of bus conductors do not lend themselves to simple formulas, the basic calculation of reactance is a complex mathematical problem.

In order to simplify the problem, Lewis suggested breaking the total reactance of conductors into two parts so they could be tabulated as a convenience to engineers (16).

The total reactance in microhms per ft. at 60 Hz is expressed:

$$X = X_a + X_d \quad \text{(Eq. 13-2)}$$

$X_a$ values are given in Tables 13-25 and 13-27 through 13-32, together with other characteristics such as resistance, current capacity and weight, for conductors that are normally used as a unit. Although $X_d$ is actually based on the GMD between the conductors, a sufficiently accurate approximation for heavy-current conductors can usually be made if GMD is taken as the distance between center lines of the conductors. Values of $X_d$ which are functions of GMD for various distances are given in Table 13-7. For close spacings, relative to the size of the bus bars, corrections for GMD must be taken into account.

Example: Assume a three-phase symmetrical flat bus arrangement in which each conductor comprises a pair of 8-in. x 8-in. x 0.375-in. face-to-face equal thickness channels spaced 36-in. apart (center-to-center). The equivalent GMD spacing is 1.26 x 36 = 45.3-in. The inductive reactance per pair at 60 Hz is as follows:
TABLE 13-7
Inductive Reactance Spacing Factors $X_d^*$
Microhms per foot at 60 Hz for 1-in. to 107-in. GMD Spacing

<table>
<thead>
<tr>
<th>Feet</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1.84</td>
<td>3.54</td>
<td>5.13</td>
<td>6.61</td>
<td>8.00</td>
<td>9.32</td>
<td>10.56</td>
<td>11.74</td>
<td>12.86</td>
<td>13.93</td>
<td>14.95</td>
</tr>
<tr>
<td>2</td>
<td>15.93</td>
<td>16.87</td>
<td>17.77</td>
<td>18.64</td>
<td>19.47</td>
<td>20.28</td>
<td>21.06</td>
<td>21.81</td>
<td>22.54</td>
<td>23.25</td>
<td>23.93</td>
<td>24.60</td>
</tr>
<tr>
<td>4</td>
<td>31.86</td>
<td>32.33</td>
<td>32.80</td>
<td>33.25</td>
<td>33.70</td>
<td>34.14</td>
<td>34.57</td>
<td>34.99</td>
<td>35.40</td>
<td>35.81</td>
<td>36.21</td>
<td>36.60</td>
</tr>
<tr>
<td>5</td>
<td>36.99</td>
<td>37.37</td>
<td>37.74</td>
<td>38.11</td>
<td>38.47</td>
<td>38.83</td>
<td>39.18</td>
<td>39.52</td>
<td>39.86</td>
<td>40.20</td>
<td>40.55</td>
<td>40.86</td>
</tr>
<tr>
<td>6</td>
<td>41.18</td>
<td>41.49</td>
<td>41.81</td>
<td>42.12</td>
<td>42.42</td>
<td>42.72</td>
<td>43.02</td>
<td>43.31</td>
<td>43.60</td>
<td>43.88</td>
<td>44.17</td>
<td>44.44</td>
</tr>
<tr>
<td>7</td>
<td>44.72</td>
<td>44.99</td>
<td>45.26</td>
<td>45.53</td>
<td>45.79</td>
<td>46.05</td>
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<td>46.56</td>
<td>46.81</td>
<td>47.06</td>
<td>47.30</td>
<td>47.55</td>
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<tr>
<td>8</td>
<td>47.79</td>
<td>48.03</td>
<td>48.26</td>
<td>48.50</td>
<td>48.73</td>
<td>48.96</td>
<td>49.18</td>
<td>49.41</td>
<td>49.63</td>
<td>49.85</td>
<td>50.07</td>
<td>50.28</td>
</tr>
</tbody>
</table>

*The inductive reactance spacing factor (also called separation component) $X_d$ from the above table represents the inductance of a conductor at 60 Hz caused by flux that is more than 1-ft distant from the conductor. Spacings less than 12-in. have minus signs as these represent deductions from the $X_a$ (1 ft radius value) obtained from tables of conductor properties.

For usual single-phase bus circuits the spacing to be used is the center-to-center distance between conductors. For 3-phase circuits the spacing is the GMD distance.

For voltage drop calculations the $X_a$ plus $X_d$ values are per conductor, and the associated voltage is that to neutral. For other than 60 Hz, the values are in proportion to Hz; that is, for 50 Hz, the value is 50/60 of the value of 60 Hz.
Fig. 13-10. Current capacity not increased proportionately to number of bars in parallel.

\[ X_a \text{ (from Table 13-30)} = 22.0 \text{ microhm/s per ft} \]
\[ X_d \text{ (from Table 13-7)} = 30.4 \text{ microhm/s per ft} \]
\[ \text{Total reactance } X = 52.4 \text{ microhm/s per ft} \]

Consolidation of Multiple Bars — Reactance

When there are two or more closely spaced bars per phase, such as bars with separation equal to the bar thickness, the group may be replaced, for rough calculations, by a single solid bar occupying the space taken up by the group (15).

Corona and Radio-Influence Voltage (RIV)

Corona forms when the voltage gradient at the surface of a conductor exceeds the dielectric strength of the surrounding air and ionizes the air molecules. RIV is caused exclusively by corona. Corona usually is not a factor in rigid-bus design at 115 kV, and lower.

The shape of the bus conductor is probably the most critical factor in reducing corona. Circular shapes will generally give the best performance. The four basic factors that determine voltage gradient are: (1) conductor diameter (or shape), (2) distance from ground, (3) phase spacing, and (4) voltage. A smooth surface condition may be important if operating near the critical voltage gradient.

To avoid corona and RIV, bus shapes and fittings should have corners rounded to at least 1/16 in. radius at 69 kV, and to larger radii at higher voltages. Corona rings are also used to shield fittings and flexible connections.

Ampacity of Aluminum Bus Conductors

The subject of ampacity or “current carrying capacity” has intrigued engineers from the beginning of electrical power usage. Carlson and Van Nostrand made an extensive search of the literature and found more than 1500 titles, but only about 25 proved of interest to their study (17). With little to guide them, early engineers tended to use the “rule-of-thumb” of 1000 amperes per square inch for copper and 600 amperes per square inch for aluminum for any conductor shape, size or arrangement.

The industry’s need for scientific ampacity information led to the first extensive tests toward developing ampacity data and formulas for calculating ampacity for both copper and aluminum bus conductors by Melson and Booth, British National Physical Laboratory (18). Their report gave the first experimentally determined formulas for calculating the ampacity of bus conductors based on temperature rise. Although this work was a big step forward, the limitations of the formulas led to many specific tests.

The next extensive experimental work leading to formulas for calculating ampacity was done under Dwight and covered multiple bars, square tubes and round tubes (4). Dwight’s formulas give values for a single bar with a dull paint surface that closely approximates Melson and Booth’s values. Dwight’s work was another big step forward in that the scope of conductors tested was expanded and also gave engineers formulas that check test results closely for the range of conductor sizes tested. However, for large buses, particularly buses composed of a large number of bars (Fig. 13-29), the equations tend to be on the conservative side.

The most recent extensive test work that led to general equations for calculating bus ampacity is by House and Tuttle. Although the published work is for current carrying capacity of ACSR, additional work was done on bus conductors using the same fundamental heat balance equations (19).
## TABLE 13-8

Heat Loss Equations — Indoor Bus

<table>
<thead>
<tr>
<th>Bus Shape</th>
<th>Flat Bar</th>
<th>IWCB or Hollow Square Channel</th>
<th>Round Tubular</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Configuration</strong></td>
<td><img src="image" alt="Flat Bar Diagram" /></td>
<td><img src="image" alt="IWCB Diagram" /></td>
<td><img src="image" alt="Round Tubular Diagram" /></td>
</tr>
</tbody>
</table>

### Convected Heat Loss

<table>
<thead>
<tr>
<th>( W_c )</th>
<th>( W_{r} )</th>
<th>Round Tubular</th>
</tr>
</thead>
<tbody>
<tr>
<td>Convected Heat Loss — Watt/ft</td>
<td>Radiated Heat Loss — Watt/ft</td>
<td>( \frac{0.072D^{0.75} \cdot (t_c - t_a)^{1.25}}{2(L+w)} )</td>
</tr>
</tbody>
</table>

\[
W_c = 0.0275 \frac{P_c}{P_c} \left( \frac{\Delta t}{L} \right)^{0.25} \cdot \Delta t
\]

\[
P_c = 2N \left( L+w \right)
\]

\[
W_r = 0.0439 \frac{P_r \cdot e}{P_r} \left[ \left( \frac{K_c}{100} \right)^4 - \left( \frac{K_a}{100} \right)^4 \right]
\]

\[
P_r = 2 \left( L + NW \right) \text{ (Bars) } (e = 0.35)
\]

\[
P_r = 2 \left( N - 1 \right) W \text{ (Spaces) } (e = 0.95)
\]

**Notes:**
- \( t_c \) = Conductor temperature \(^\circ\)C
- \( t_a \) = Ambient temperature \(^\circ\)C
- \( \Delta t = t_c - t_a \)
- \( K_c \) = Conductor temperature \(^\circ\)K
- \( K_a \) = Ambient temperature \(^\circ\)K
- \( e \) = Emissivity (see Table 13-9)
- \( M = \frac{L \times w}{L + w} \)

*Equation must be modified if \( \frac{L}{w} < 12/1 \)
Heat-Balance Equation of Electrical Conductors (General) (20)

Under steady-state conditions of wind velocity, ambient and conductor temperature, solar radiation and electric current, the following general equation is valid.

\[ I^2R_{\text{eff}} + W_s = W_c + W_r + W_{\text{cond}} \]  \hspace{1cm} (Eq. 13-3)

\[ I = \frac{\sqrt{W_c + W_r + W_{\text{cond}} - W_s}}{R_{\text{eff}}} \]

Where:

- \( W_c \) = Convected heat loss, Watts/ft
- \( W_r \) = Radiated heat loss, Watts/ft
- \( W_{\text{cond}} \) = Conductive heat loss, Watts/ft
- \( W_s \) = Solar heat gain, Watts/ft
- \( R_{\text{eff}} \) = Effective resistance
- \( I \) = Current, amperes

For indoor locations where \( W_s = 0 \) and \( W_{\text{cond}} = 0 \):

\[ I = \frac{\sqrt{W_c + W_r}}{R_{\text{eff}}} \]

Equations for use in calculating convection and radiation heat losses have been developed by House and Tuttle and are summarized in Table 13-8.

Ampacity (Vertical Bars)

The ampacity values for standard sizes of bar and commonly used bar arrangements are shown in Table 13-26 for ac and dc current, using 30°C rise over 40°C ambient in still air.

Multiple Bar Arrangements

For direct current the capacity of a bus constructed of rectangular bar can be controlled by merely varying the size or number of laminations in parallel. However, the efficient use of flat bars for ac buses (60 Hz) in conventional same plane arrangement is limited to about four ½ in. aluminum bars per phase.

Fig. 13-10 illustrates the decrease in value for each bar added from 1 to 12 bars (3 x ½ in. cu., 3/8 in. apart, 60 Hz) for the same plane arrangement. The curve shows that four bars will carry about 70 percent as much current as 12 bars. Papst conducted a great number of tests on various arrangements of bars in efforts to find the most economical ones (18).

One arrangement, the hollow square arrangement, has a low skin effect ratio similar to a square tubular conductor. However, the supports are more costly and must be spaced closer together than for square tubing or box channel shapes.

Ampacity (IWCB)

The ampacity values for standard sizes of IWCB are shown in Table 13-32 for dc and ac current, using 30°C rise over 40°C ambient in still air.

Ampacity (Round Tubular Bar)

The ampacity values of the most commonly used large tube conductors are shown in Table 13-28 for a-c current, using 30°C rise over 40°C ambient in still air.

Ampacity for Outdoors Bus Conductors

The most extensive tests of tubular bus conductors for outdoor service were done by Schurig and Frick in 1930 (21). Since then, several investigators have conducted tests on a limited scale. However, the same rigorous combination of tests and theoretical study that was done on standard conductors by House and Tuttle (19) has not been done for tubular bus and shape conductors outdoors. The closest agreement of theoretical work with tests for pipe sizes shown in the tables appears to be the formulas listed in the House and Tuttle paper (using McAdams formula for convection for Reynolds numbers 1000 to 50,000) and the formulas given in a paper by Prager, Pemberton, Craig and Bleshman (22). The formulas and computation methods used are similar to indoor, taking into account different coefficients for outdoor convection losses and including solar heat gain.

Emissivity and Absorptivity

Emissivity (heat radiating characteristic) and absorptivity are not precisely the same since they apply to different energy spectra, but the difference is so small that for ordinary calculations they may be taken as equal.

The emissivity coefficient varies with the surface condition of the conductor. Table 13-9 lists approximate emissivity constants for typical conditions.

Effect of Painting

The ampacity of bus conductors can be increased for a given temperature rise indoors by painting with a dull finish paint of non-metallic pigment. The ampacity of a single conductor can be increased by 15 to 25 percent for the same temperature rise (18,23). For example, the effect of painting a single 1” x 10” bar is to increase the ampacity about 15 percent. As multiple bars are added, the percentage drops off since the effect of improved emissivity applies only to the outside surfaces. This leads one to consider that it is more desirable to paint the outside bars of multiple ac bus bars than dc buses since the outer bars in an ac system tend to run hotter than the inner bars because of skin effect. Painting of the outer bars very closely equalizes the temperature differential for four bar ac buses.
TABLE 13-9
Radiation Emissivity
Aluminum and Copper Surfaces

<table>
<thead>
<tr>
<th>1350 Aluminum Surface</th>
<th>Radiation Emissivity Coefficient</th>
<th>Copper Surface</th>
<th>Radiation Emissivity Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>New Bar—Extruded</td>
<td>0.05–0.15</td>
<td>Polished</td>
<td>0.03</td>
</tr>
<tr>
<td>New Bar—Cold Rolled</td>
<td>0.05–0.20</td>
<td>Shiny</td>
<td>0.07</td>
</tr>
<tr>
<td>New Bar—Hot Rolled</td>
<td>0.10–0.20</td>
<td>Slightly</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Oxidized</td>
<td></td>
</tr>
<tr>
<td>Old Bar—2 Year Indoors</td>
<td>0.24–0.45</td>
<td>Normally</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Oxidized</td>
<td></td>
</tr>
<tr>
<td>Old Bar—2 Year Outdoors</td>
<td>0.50–0.90</td>
<td>Heavily</td>
<td>0.70–0.85</td>
</tr>
<tr>
<td>Flat Paint (non-metallic base)</td>
<td>0.90–0.95</td>
<td>Flat Paint</td>
<td>0.95</td>
</tr>
</tbody>
</table>

For calculations, the following emissivity values are assumed to be representative:

- New Bus: 0.10
- Indoor current ratings (partially oxidized surface): 0.35
- Outdoor current ratings (normally oxidized surface): 0.50
- Painted surfaces (dull finish): 0.90
- Openings between members of built-up bars: 0.95

Isolated phase bus, because of space limitations and high heat concentrations, is a particularly good application for painted conductors. The conductors, usually tubes or structural shapes, are painted for maximum emissivity, the inside of the enclosure is painted for absorptivity, the metal of the enclosure is chosen for heat conductivity, the outside of the enclosure is painted for maximum emissivity.

**Ampacity Tables**

The ampacities shown in the tables are based on calculations using modern heat transfer technology. Agreement within the range of test accuracy has been obtained between test values and calculated values. Unavoidable variations show up in test values because of the physical impossibility of exactly duplicating every test condition. When calculating temperature rise, it is necessary to use the proper value of emissivity for the conductor. The heat loss will vary considerably with various surface conditions. An exception is the table on flat arrangement of bars which is based on limited test data. This arrangement has not been given the rigorous study that vertical bar arrangements have received. The designer should remember that ampacity tables are based on thermal conditions for the conductor and may not represent the most economical overall design. Craig, in comments on Carlson and Van-Norstrand’s paper, states that with today’s emphasis on energy conservation the economic effect of losses in any conductor system should be carefully considered (17).

**Current vs. Temperature Rise**

Fugill (24) derived the formula which shows that the temperature rise varies as the 1.7 power of the current:

$$\frac{T_1}{T_2} = \left(\frac{I_1}{I_2}\right)^{1.7}$$  \hspace{1cm} (Eq. 13-4)

where \(I\) = amperes

- \(T = \) Temperature Rise
  - in °C

Papst (17) also found that when the hot-spot
temperatures of test bars vs. test current were plotted on log-log paper that the curves were straight lines having the same positive slope of 1.7. Calculations based on Dwight's work (4) show essentially the same relationship. Fig. 13-11 shows the relationship in terms of load ratio in amperes to temperature rise as a convenient means of estimating current for a different temperature rise than that shown in the ampacity tables (indoors) for various conductor shapes.

Enclosed Bus Conductors

The design of enclosed bus conductors is considerably more complicated than open buses. Space limitations mean closer bus arrangements where proximity effect is a factor. Additional I²R losses, as a result of induced currents in the metal enclosure may be encountered as well as hysteresis losses in frame of enclosure. In addition, other factors such as dimensions, shape and arrangement of conductors, finish of conductors, finish of housing all have their effects on ampacity of enclosed buses. These effects are such that calculation is impossible except from test data on prototypes. Such proprietary data rarely is reported in the literature. However, some general comments may be helpful.

The greatest reduction in ampacity occurs with enclosed buses that depend mainly on free circulation of air for cooling. when such buses are enclosed in reasonably large nonmagnetic enclosures, the ampacity rating may be reduced to between 55 and 60 percent of open-air rating.

The current-carrying capacity of single tubes and bars is
least affected by enclosure. The ratings of enclosed buses of this type may be reduced to between 70 and 75 percent of the ratings in still but confined air for standard temperature rises (24).

Isolated Phase Bus

Isolated phase bus, because of its use in connecting the output of generators to step-up transformers, is a key element in a power station and therefore deserves special attention by utility engineers. Power losses in the bus system are covered in detail in IEEE Guide For Calculating Losses in Isolated Phase Bus (25). Swerdlow and Buchta (11) give data for estimating temperature rise due to hysteresis and eddy currents in steel members in proximity to unenclosed buses carrying large currents and include rules for application to isolated phase buses. Continuity of service is of primary importance for isolated phase generator buses. The design of modern isolated phase bus with its dust-tight and weather-tight aluminum covers has already reduced the frequency of periodic inspections. By using welded aluminum conductors, the inspection period may be spread over a longer interval.

Short-Circuit Conditions

The electromagnetic forces between conductors are pro-
TABLE 13-10

Maximum Instantaneous Electromagnetic Forces Between ac Bus Conductors

<table>
<thead>
<tr>
<th>Type of Fault</th>
<th>Conductor Arrangement</th>
<th>Instantaneous Maximum Force on Conductor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Phase</td>
<td>A [\rightarrow d \rightarrow B]</td>
<td>A or B [\rightarrow] [F = \frac{10.8 I^2}{10^6 d}]</td>
</tr>
<tr>
<td>Symmetrical</td>
<td>A [\rightarrow d \rightarrow B]</td>
<td>A or B [\rightarrow] [F = \frac{43.2 I^2}{10^6 d}]</td>
</tr>
<tr>
<td>Single Phase</td>
<td>A [\rightarrow d \rightarrow B]</td>
<td>A or B [\rightarrow] [F = \frac{37.4 I^2}{10^6 d}]</td>
</tr>
<tr>
<td>Asymmetrical</td>
<td>A [\rightarrow d \rightarrow B]</td>
<td>A or B [\rightarrow] [F = \frac{34.9 I^2}{10^6 d}]</td>
</tr>
<tr>
<td>Three Phase</td>
<td>A [\rightarrow d \rightarrow B]</td>
<td>A, B or C [\rightarrow] [F = \frac{37.4 I^2}{10^6 d}]</td>
</tr>
<tr>
<td>Asymmetrical</td>
<td>A [\rightarrow d \rightarrow B]</td>
<td>A, B or C [\rightarrow] [F = \frac{34.9 I^2}{10^6 d}]</td>
</tr>
</tbody>
</table>

\(\text{Eq. 13-5}\)

The current \(I\) is in terms of RMS Symmetrical.

\(F = \text{lb/ft of conductor}\)

\(d = \text{conductor spacing in inches}\)

\(\text{Note: In computing short-circuit currents in networks, the subtransient reactance of rotating machinery is used.}\)

Portional to the currents flowing in the conductors, and inversely proportional to the distance between them. The instantaneous force between two long, straight, parallel, round conductors can be found from the classic equation (4):

\[F = 5.4 \frac{i_1 i_2}{d} \times 10^{-7} \text{ pounds per foot}\]  

where \(i_1\) and \(i_2\) are instantaneous currents in amperes, and \(d\) is the distance between conductors in inches.

If the two currents flow in the same direction, the force will be one of attraction. If they flow in opposite directions, a force of repulsion is created.

**Direct Current**

For direct current, the repulsive force between positive and negative buses may be expressed as follows:

\[F = K5.4 \frac{i^2}{d} \times 10^{-7} \text{ pounds per foot}\]  

where \(K\) is the shape correction factor (Fig. 13-12).

**Application of Formulas (28,29,30)**

The use of the formulas in Table 13-10 results in values of maximum possible instantaneous magnetic force between conductors. Conductors subjected to such forces, and supporting insulators and structures, form dynamic systems that contain mass, elasticity and damping. Such
### TABLE 13-11

**Components of Electromagnetic Force**

<table>
<thead>
<tr>
<th>Current</th>
<th>Direct Component (^{(1)})</th>
<th>First Harmonic</th>
<th>Second Harmonic</th>
<th>Instantaneous Maximum Electromagnetic Force (^{(2)})</th>
<th>Ratio of Average to Instantaneous Maximum Force (^{(3)})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symmetrical Sine Current</td>
<td>0.333</td>
<td>0.0</td>
<td>0.333</td>
<td>0.667</td>
<td>0.500</td>
</tr>
<tr>
<td>Totally Displaced Sine Current</td>
<td>1.000</td>
<td>1.333</td>
<td>0.333</td>
<td>2.667</td>
<td>0.370</td>
</tr>
</tbody>
</table>

\(^{(1)}\) Average value of total electromagnetic force.
\(^{(2)}\) See Table 13-10 for values of maximum instantaneous force.

**Note:** Comparison of electromagnetic-force components for fully displaced and for symmetrical short-circuit currents, for two-wire short circuit.

The ac component of the fully displaced short-circuit current has the same amplitude as the symmetrical current. Wave-shape sinusoidal in both cases. Current decrement neglected.

### TABLE 13-12

**Deflection and Stress Formulas**

<table>
<thead>
<tr>
<th>Bus Conductors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple Beam</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>Maximum Deflection (D)</td>
</tr>
<tr>
<td>Maximum Moment (M)</td>
</tr>
<tr>
<td>Fiber Stress (f')</td>
</tr>
<tr>
<td>Maximum Load (W)</td>
</tr>
<tr>
<td>Maximum Span (l)</td>
</tr>
</tbody>
</table>

**Formulas:**
- \(D\) = deflection in inches
- \(w\) = load in lb/in. of length \((\text{Lbs per ft})\)
- \(E\) = modulus of elasticity, lb/sq in.
- \(f\) = maximum allowable fiber stress in lb/sq in.
- \(I\) = moment of inertia, inches\(^4\)
- \(M\) = bending moment in pound-inches
- \(S\) = section modulus, inches\(^3\)
- \(S\) = total uniform load in pounds (w)
- \(I\) = span in inches
- \(E\) = modulus of elasticity, lb/sq in.

**Notes:**
- Maximum deflection occurs in the end spans and is only slightly more than that for a continuous beam of 2 spans.
- Maximum moment and fiber stress for simple beams occur at the center of the span.
- Maximum moment and fiber stress for beams fixed at both ends occur at the points of support.
- Maximum moment and fiber stress for continuous beams occur at the second support from each end.
Direct Current Buses

Short circuit forces can be appreciable for large dc bus systems. A knowledge of the short circuit characteristics of the power rectifier is essential for the design of the dc bus.

Mercury arc rectifiers, once in common use in the electro-chemical industry, were subject to failure of the rectifying action of the tube. This type of rectifier failure, known as "backfire," acts as a fault to the rectifier transformer and to the dc bus. The rates of current rise through a rectifier and its transformer windings for a large system could be as high as three to six million amperes per second. High speed breakers are used to limit current to mercury arc rectifiers and protect connected equipment.

The probability of damage from a short-circuit in solid-state rectifiers is much less than for mercury arc rectifiers. However, damaging short-circuits have occurred and cannot be ignored. ANSI Standards specify that the diode-diode fuse coordination be capable of interrupting a diode failure if the fault is fed from its own rectifier transformer. The standard does not require the diode or diode fuse to be designed to withstand a positive to negative fault. The bus designer may wish to consult with the supplier of the rectifier equipment regarding a comprehensive study of regulation curves and current transients during dc fault since a system analysis is quite complicated.

Low-voltage Alternating Current Buses (31)

Predictions of possible short-circuit currents for high-voltage circuits, where arcs are of a sustained character, can be made fairly accurately. However, in ac circuits operating at low voltages (440 volts or less), the effect of fault resistance and circuit reactance is such that the actual current resulting from a fault is usually much smaller than that calculated, even though the power source is large. If this difference is not recognized, needlessly high expenses for bus structures may be incurred.

Low-voltage buses with short spans and relatively rigid supports may have natural frequencies that coincide with the natural frequency of the current. In such cases, resonant vibration can occur. The stresses resulting therefrom could be several times greater than those calculated on the basis of the maximum force applied to a static system (32,33). (See page 13-28).

High-voltage Substations

The IEEE "Guide for Design of Substation Rigid Bus Structures" (1) suggests that the interrupting capability of the substation equipment be considered as the maximum symmetrical RMS short-circuit current. The Guide recognizes the presence of reactance in the system and suggests using a value of 1.6 as the current offset. The classical general equation then becomes:

\[ F = \frac{5.4 \sqrt{1.6} I^2 \cdot 10^{-7}}{d} \]

\[ = \frac{27.6 I^2 \cdot 10^{-7}}{d} \text{ pounds per foot} \]  

(Eq. 13-6)

If a system's maximum current offset is less than the assumed value of 1.6, the force F can be further reduced.

Because of flexibility, the bus structure and support stands are capable of absorbing kinetic energy during a fault. Depending on the type of support structures and their height, the short-circuit forces can be further reduced as follows:

\[ F = k_s \frac{27.6 I^2 \cdot 10^{-7}}{d} \]  

(Eq. 13-7)

Values of \( k_s \) are given in Fig. 13-13. \( k_s \) is usually assumed to be unity for three-phase bus supports.

Longitudinal Forces

Longitudinal forces may be encountered during short-circuit for long span flexible conductors. The greater the lateral deflection of the bus during short-circuit, the greater will be this force tending to pull the insulator supports together (34).

Torsional Forces

Torsional forces are encountered in the end support of a bus, being more pronounced for flexible conductors where lateral movement is greater than for stiffer conductors (34).

Stresses Caused by Short-circuit Currents

The forces acting on a conductor that carries current are uniformly distributed along the length of the conductor. The conductor may be analyzed as a uniformly loaded beam.

Heating Caused by Short-circuit Currents

The time during which a short-circuit current flows is usually so short that for all practical purposes it can be assumed that no heat loss occurs by convection and radiation. The temperature rise is then determined by only the specific heat of the metal, the size of the conductor and the heat input. The following formula should be sufficiently
accurate for practical (1). Increase in resistance with temperature rise has been taken into consideration.

For aluminum conductors (40 to 64 percent IACS conductivity),

\[
I_{SC} = 0.144 \times 10^6 A \left( \frac{1}{t} \log_{10} \frac{T_f - 20 + (15150/G)}{T_i - 20 + (15150/G)} \right)^{1/2}
\]  

(Eq. 13-8)

where:

- \(I_{SC}\) = the rms value of fault current (amperes)
- \(A\) = conductor cross-sectional area (sq. in.)
- \(G\) = conductivity, % IACS
- \(t\) = duration of fault (seconds)
- \(T_f\) = allowable final conductor temperature (C)
- \(T_i\) = conductor temperature at fault initiation (C)

**Mechanical Design**

A bus installation must be designed as a structure with enough stiffness and strength to support its own weight without excessive sag and to withstand those external forces, such as short circuits, wind and ice loads, which may act upon it. The spans should be checked for susceptibility to electromagnetic and aeolian vibration.

High voltage buses have relatively large spacing and usually relatively low currents. Thus, the mechanical design will generally be determined by the total mechanical load, e.g. weight of conductor, ice, damping material, and any concentrated loads. Short-circuit forces and electromagnetic vibration are usually not a major factor in design. However, aeolian vibration should receive careful consideration for outdoor buses.

Low voltage buses, for the same power, have higher currents and generally smaller spacings. Here, short-circuit forces are more likely to be a major factor in the mechanical design. Also, electromagnetic vibration should receive careful study since buses with short spans and relatively rigid supports may have natural frequencies that coincide with the natural frequency or a harmonic of the current.

The mechanical design of outdoor buses is covered in considerable detail in IEEE “Guide for Design of Substation Rigid Bus Structures” (1).

After the minimum size that will satisfy the current-carrying requirements has been determined, the maximum span may be calculated from the conventional formulas in Table 13-12 or the formulas for particular end conditions as shown in IEEE Guide. Tables 13-13 and 13-14 are useful in selecting pipe size conductors.

**Vibration**

*Electro-magnetic (Resonance) (32,33)*

A bus conductor installation will have a frequency of vibration depending upon the span length, rigidity of supports, degree of damping and flexibility of the conductor
### TABLE 13-13

Deflection Values
Schedule 40 Aluminum Pipe

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Nominal Pipe Size in.</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
<th>30</th>
<th>35</th>
<th>40</th>
<th>45</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare</td>
<td>1/2</td>
<td>0.39</td>
<td>1.96</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1/4</td>
<td>0.24</td>
<td>1.20</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>0.15</td>
<td>0.76</td>
<td>2.39</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 1/4</td>
<td>0.09</td>
<td>0.46</td>
<td>1.45</td>
<td>3.55</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 1/2</td>
<td>0.07</td>
<td>0.35</td>
<td>1.09</td>
<td>2.67</td>
<td>3.46</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.06</td>
<td>0.21</td>
<td>0.97</td>
<td>1.65</td>
<td>3.46</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 1/4</td>
<td>0.03</td>
<td>0.15</td>
<td>0.47</td>
<td>1.15</td>
<td>2.38</td>
<td>4.22</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.02</td>
<td>0.10</td>
<td>0.31</td>
<td>0.76</td>
<td>1.58</td>
<td>2.93</td>
<td>5.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3 1/2</td>
<td>0.02</td>
<td>0.08</td>
<td>0.24</td>
<td>0.58</td>
<td>1.20</td>
<td>2.21</td>
<td>3.78</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.01</td>
<td>0.06</td>
<td>0.19</td>
<td>0.45</td>
<td>0.94</td>
<td>1.74</td>
<td>2.96</td>
<td>4.76</td>
<td>7.26</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.01</td>
<td>0.04</td>
<td>0.12</td>
<td>0.29</td>
<td>0.61</td>
<td>1.12</td>
<td>1.91</td>
<td>3.08</td>
<td>4.69</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.01</td>
<td>0.03</td>
<td>0.08</td>
<td>0.20</td>
<td>0.42</td>
<td>0.79</td>
<td>1.34</td>
<td>2.15</td>
<td>3.28</td>
</tr>
<tr>
<td>1/2 in. Ice</td>
<td>1/2</td>
<td>1.48</td>
<td>7.51</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2.20</td>
<td>4.12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 1/4</td>
<td>0.24</td>
<td>1.23</td>
<td>3.89</td>
<td>9.62</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 1/2</td>
<td>0.17</td>
<td>0.88</td>
<td>2.80</td>
<td>6.83</td>
<td>8.36</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.10</td>
<td>0.52</td>
<td>1.63</td>
<td>4.00</td>
<td>8.36</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 1/4</td>
<td>0.06</td>
<td>0.30</td>
<td>0.96</td>
<td>2.30</td>
<td>4.89</td>
<td>9.05</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.04</td>
<td>0.19</td>
<td>0.60</td>
<td>1.47</td>
<td>3.06</td>
<td>5.72</td>
<td>9.75</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3 1/2</td>
<td>0.03</td>
<td>0.14</td>
<td>0.44</td>
<td>1.08</td>
<td>2.24</td>
<td>4.16</td>
<td>7.16</td>
<td>11.46</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.02</td>
<td>0.11</td>
<td>0.34</td>
<td>0.83</td>
<td>1.71</td>
<td>3.17</td>
<td>5.42</td>
<td>8.73</td>
<td>13.31</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.01</td>
<td>0.07</td>
<td>0.21</td>
<td>0.51</td>
<td>1.05</td>
<td>1.98</td>
<td>3.34</td>
<td>5.37</td>
<td>8.19</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.01</td>
<td>0.04</td>
<td>0.14</td>
<td>0.34</td>
<td>0.71</td>
<td>1.32</td>
<td>2.25</td>
<td>3.60</td>
<td>5.49</td>
</tr>
<tr>
<td>1/2 in. Ice,</td>
<td>1/2</td>
<td>2.10</td>
<td>10.62</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>1</td>
<td>1.12</td>
<td>5.63</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>4 lb Wind</td>
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<td>2.85</td>
<td>9.02</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1/2</td>
<td>0.30</td>
<td>1.33</td>
<td>4.84</td>
<td>11.81</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>0.12</td>
<td>0.61</td>
<td>1.93</td>
<td>4.70</td>
<td>9.75</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plus Constant</td>
<td>1/2</td>
<td>0.02</td>
<td>0.07</td>
<td>0.21</td>
<td>0.67</td>
<td>1.64</td>
<td>3.40</td>
<td>6.30</td>
<td>10.76</td>
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</tr>
<tr>
<td></td>
<td>1</td>
<td>0.01</td>
<td>0.05</td>
<td>0.15</td>
<td>0.34</td>
<td>0.75</td>
<td>1.39</td>
<td>2.37</td>
<td>3.80</td>
<td>5.79</td>
</tr>
<tr>
<td>1 in. Ice</td>
<td>1/2</td>
<td>3.40</td>
<td>17.20</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>1.76</td>
<td>8.92</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1/2</td>
<td>0.88</td>
<td>4.44</td>
<td>14.03</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1/4</td>
<td>0.47</td>
<td>2.37</td>
<td>7.47</td>
<td>18.49</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>0.34</td>
<td>1.69</td>
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<td>2</td>
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<td>0.92</td>
<td>2.91</td>
<td>7.09</td>
<td>14.95</td>
<td></td>
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<td></td>
<td></td>
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<td></td>
<td>2 1/2</td>
<td>0.10</td>
<td>0.50</td>
<td>1.59</td>
<td>3.87</td>
<td>8.03</td>
<td>15.06</td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.08</td>
<td>0.31</td>
<td>0.97</td>
<td>2.37</td>
<td>4.91</td>
<td>9.20</td>
<td>15.69</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3 1/2</td>
<td>0.05</td>
<td>0.22</td>
<td>0.70</td>
<td>1.70</td>
<td>3.53</td>
<td>6.52</td>
<td>11.14</td>
<td>18.06</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.03</td>
<td>0.16</td>
<td>0.52</td>
<td>1.27</td>
<td>2.63</td>
<td>4.88</td>
<td>8.32</td>
<td>13.49</td>
<td>20.56</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.02</td>
<td>0.10</td>
<td>0.31</td>
<td>0.76</td>
<td>1.57</td>
<td>2.91</td>
<td>4.97</td>
<td>8.05</td>
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</tr>
<tr>
<td></td>
<td>6</td>
<td>0.01</td>
<td>0.06</td>
<td>0.21</td>
<td>0.50</td>
<td>1.04</td>
<td>1.92</td>
<td>3.28</td>
<td>5.26</td>
<td>8.02</td>
</tr>
</tbody>
</table>

Note: These are maximum deflection values in inches for a simple beam with uniformly distributed load. For beams fixed at both ends the deflection will be one-fifth of the values given.

Deflection $d$, for any other span $L$, may be obtained from the relation: $d = d_e \left(\frac{L^2}{L}\right)$. 

13-29
## TABLE 13-14

**Deflection Values**

**Schedule 80 Aluminum Pipe**

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Nominal Pipe Size in.</th>
<th>Span in Feet</th>
<th>Deflection in Inches</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>Bare</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$1/2$</td>
<td>0.42</td>
<td>2.13</td>
<td></td>
</tr>
<tr>
<td>$3/4$</td>
<td>0.25</td>
<td>1.29</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.16</td>
<td>0.81</td>
<td>2.56</td>
</tr>
<tr>
<td>$11/4$</td>
<td>0.10</td>
<td>0.49</td>
<td>1.54</td>
</tr>
<tr>
<td>$11/2$</td>
<td>0.07</td>
<td>0.36</td>
<td>1.15</td>
</tr>
<tr>
<td>2</td>
<td>0.04</td>
<td>0.23</td>
<td>0.72</td>
</tr>
<tr>
<td>$23/4$</td>
<td>0.03</td>
<td>0.16</td>
<td>0.49</td>
</tr>
<tr>
<td>3</td>
<td>0.02</td>
<td>0.10</td>
<td>0.33</td>
</tr>
<tr>
<td>$33/4$</td>
<td>0.01</td>
<td>0.08</td>
<td>0.25</td>
</tr>
<tr>
<td>4</td>
<td>0.01</td>
<td>0.06</td>
<td>0.19</td>
</tr>
<tr>
<td>5</td>
<td>0.01</td>
<td>0.04</td>
<td>0.12</td>
</tr>
<tr>
<td>6</td>
<td>0.01</td>
<td>0.03</td>
<td>0.09</td>
</tr>
<tr>
<td>$11/2$</td>
<td>1.35</td>
<td>6.85</td>
<td></td>
</tr>
<tr>
<td>$3/4$</td>
<td>0.73</td>
<td>3.75</td>
<td></td>
</tr>
<tr>
<td>1</td>
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<tr>
<td>2</td>
<td>0.09</td>
<td>0.46</td>
<td>1.45</td>
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<tr>
<td>$23/4$</td>
<td>0.05</td>
<td>0.28</td>
<td>0.88</td>
</tr>
<tr>
<td>3</td>
<td>0.03</td>
<td>0.17</td>
<td>0.55</td>
</tr>
<tr>
<td>$33/4$</td>
<td>0.02</td>
<td>0.13</td>
<td>0.40</td>
</tr>
<tr>
<td>4</td>
<td>0.02</td>
<td>0.10</td>
<td>0.31</td>
</tr>
<tr>
<td>5</td>
<td>0.01</td>
<td>0.06</td>
<td>0.19</td>
</tr>
<tr>
<td>6</td>
<td>0.01</td>
<td>0.04</td>
<td>0.13</td>
</tr>
<tr>
<td>$11/2$</td>
<td>1.86</td>
<td>9.44</td>
<td></td>
</tr>
<tr>
<td>$3/4$</td>
<td>0.97</td>
<td>4.92</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.50</td>
<td>2.53</td>
<td>7.99</td>
</tr>
<tr>
<td>$11/4$</td>
<td>0.27</td>
<td>1.34</td>
<td>4.24</td>
</tr>
<tr>
<td>$11/2$</td>
<td>0.19</td>
<td>0.94</td>
<td>2.97</td>
</tr>
<tr>
<td>2</td>
<td>0.10</td>
<td>0.53</td>
<td>1.66</td>
</tr>
<tr>
<td>$23/4$</td>
<td>0.06</td>
<td>0.31</td>
<td>0.98</td>
</tr>
<tr>
<td>3</td>
<td>0.04</td>
<td>0.19</td>
<td>0.60</td>
</tr>
<tr>
<td>$33/4$</td>
<td>0.03</td>
<td>0.14</td>
<td>0.44</td>
</tr>
<tr>
<td>4</td>
<td>0.02</td>
<td>0.10</td>
<td>0.33</td>
</tr>
<tr>
<td>5</td>
<td>0.01</td>
<td>0.06</td>
<td>0.20</td>
</tr>
<tr>
<td>6</td>
<td>0.01</td>
<td>0.04</td>
<td>0.13</td>
</tr>
<tr>
<td>$11/2$</td>
<td>2.98</td>
<td>15.10</td>
<td></td>
</tr>
<tr>
<td>$3/4$</td>
<td>1.51</td>
<td>7.67</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.76</td>
<td>3.86</td>
<td>12.21</td>
</tr>
<tr>
<td>$11/4$</td>
<td>0.40</td>
<td>2.02</td>
<td>6.39</td>
</tr>
<tr>
<td>$11/2$</td>
<td>0.28</td>
<td>1.40</td>
<td>4.42</td>
</tr>
<tr>
<td>2</td>
<td>0.15</td>
<td>0.77</td>
<td>2.43</td>
</tr>
<tr>
<td>$23/4$</td>
<td>0.09</td>
<td>0.44</td>
<td>1.38</td>
</tr>
<tr>
<td>3</td>
<td>0.05</td>
<td>0.26</td>
<td>0.84</td>
</tr>
<tr>
<td>$33/4$</td>
<td>0.04</td>
<td>0.19</td>
<td>0.60</td>
</tr>
<tr>
<td>4</td>
<td>0.03</td>
<td>0.14</td>
<td>0.45</td>
</tr>
<tr>
<td>5</td>
<td>0.02</td>
<td>0.08</td>
<td>0.26</td>
</tr>
<tr>
<td>6</td>
<td>0.01</td>
<td>0.05</td>
<td>0.17</td>
</tr>
</tbody>
</table>

**Note:** These are maximum deflection values in inches for a simple beam with uniformly distributed load. For beams fixed at both ends the deflection will be one-fifth of the values given.

**Deflection $d_i$ for any other span $L$ may be obtained from the relation:**

$$d_i = \left( \frac{L}{L_i} \right) d_i$$
### TABLE 13-15

**Maximum Vibration-Free Span Length**

<table>
<thead>
<tr>
<th>Tubular Bus</th>
<th>Universal Angle Bus Conductor</th>
<th>Integral Web Channel Bus</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5(^{\prime}) – 0(^{\prime})</td>
<td>3 1/4 x 3 1/4 x 1/4</td>
</tr>
<tr>
<td>1 1/4</td>
<td>6(^{\prime}) – 3(^{\prime})</td>
<td>4 x 4 x 1/4</td>
</tr>
<tr>
<td>1 1/2</td>
<td>7(^{\prime}) – 0(^{\prime})</td>
<td>4 x 4 x 3/8</td>
</tr>
<tr>
<td>2</td>
<td>9(^{\prime}) – 0(^{\prime})</td>
<td>4 1/2 x 4 1/2 x 3/8</td>
</tr>
<tr>
<td>2 1/2</td>
<td>10(^{\prime}) – 9(^{\prime})</td>
<td>5 x 5 x 3/8</td>
</tr>
<tr>
<td>3</td>
<td>13(^{\prime}) – 3(^{\prime})</td>
<td></td>
</tr>
<tr>
<td>3 1/2</td>
<td>15(^{\prime}) – 3(^{\prime})</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>19(^{\prime}) – 0(^{\prime})</td>
<td></td>
</tr>
<tr>
<td>4 1/2</td>
<td>19(^{\prime}) – 0(^{\prime})</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>21(^{\prime}) – 3(^{\prime})</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>25(^{\prime}) – 3(^{\prime})</td>
<td></td>
</tr>
</tbody>
</table>

(1) Lengths based on one loop of vibration.
(2) Lengths can be increased approximately 20 percent with reasonable certainty there will be no vibration.
(3) Does not apply for double angles in back-to-back configurations.
(4) Lengths apply to both Schedule 40 and Schedule 80 tubular bus.

---

### TABLE 13-16

**Recommended Sizes of ACSR to Be Inserted in Tubular Bus to Prevent Vibration**

Based on No Energy Absorption by Supports

<table>
<thead>
<tr>
<th>Nominal Pipe Size Inches</th>
<th>Recommended Min. Size of ACSR cmil</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>266,800</td>
</tr>
<tr>
<td>2 1/2</td>
<td>266,800</td>
</tr>
<tr>
<td>3</td>
<td>266,800</td>
</tr>
<tr>
<td>3 1/2</td>
<td>397,500</td>
</tr>
<tr>
<td>4</td>
<td>795,000</td>
</tr>
<tr>
<td>5</td>
<td>1,431,000</td>
</tr>
<tr>
<td>6</td>
<td>1,590,000</td>
</tr>
</tbody>
</table>

Notes:

(1) ACSR should have a multi-strand core.
(2) Since any bus system has some damping capacity, similar sizes of ACSR may be used depending upon the damping characteristics of the particular installation. The design factors, installation, and cost favor consideration of dampers.

in the plane of vibration.

The general formula (33) for "clamped-clamped" (rigid support) uniform beam vibration in the transverse or bending mode is as follows for single loop:

\[
f = \frac{22.0}{2\pi(L^2)} \left( \frac{EI}{N} \right)\]  

(Eq. 13-9)

where:

- \(f\) = frequency in cycles per second
- \(L\) = span length in inches
- \(E\) = modulus of elasticity \((10^7\) for aluminum), psi
- \(I\) = moment of inertia of conductor in plane of vibration, in.\(^4\)
- \(N\) = \(\frac{W}{g} = \frac{lb/in.}{386}\) for conductor

Electro-magnetic vibration has been observed chiefly on buses for electric furnaces. Here, the buses experience the equivalent of a short-circuit repeatedly in normal operation. Fatigue breaks have occurred. Curves, based on Eq. 13-9, are shown in Fig. 13-14 as a guide to avoid critical lengths for bars. The span and depth in the plane of vibration are the major factors in determining the frequency.
Fig. 13-14. Resonant frequencies — rectangular aluminum bars clamped at each end.
The width of the bar in the commonly used sizes has little
effect on $I_{y-y}$ and on the natural frequency.

For reasons of clearance and economy, high voltage
substations are generally designed with relatively long
spans, pedestal-type insulators, and relatively flexible
structures. Such high-voltage “bus systems” (which in-
clude bus, supports and structures) have a marked degree
of flexibility. As a result, the natural frequencies of such
high-voltage bus systems are normally much lower than the
frequency of the current in the bus. A short circuit normally
could not excite a long span bus system with flexible sup-
ports in one of its natural frequencies.

**Aeolian Vibration**

Bus vibration is caused by a low steady wind blowing
across the bus at approximately right angles to the span.
Under certain low velocity wind conditions, eddies will
break off alternately from the top and bottom surfaces
causig the bus to vibrate in a vertical plane. The bus will
vibrate at its natural frequency provided that this frequen-
cy is within the range that can be excited by the wind. The
classical formula for frequency of vibration of round con-
ductors by wind is as follows:

$$f = \frac{3.26V}{d} \quad \text{(Eq. 13-10)}$$

where:

$\begin{align*}
  f & = \text{aeolian vibration frequency in cps.} \\
  V & = \text{wind velocity (miles per hour)} \\
  d & = \text{conductor diameter (inches)}
\end{align*}$

Tests by Alcoa on tubular conductors of various
diameters, wall thicknesses and alloys showed that internal
damping of the conductor itself caused only minor devia-
tions from the theoretical formula. The conductors were
suspended on piano wires to eliminate damping effect of
supports (Table 13-15).

Winds causing vibration are low steady winds under 15
mph; winds over 15 mph are generally too turbulent to in-
duce vibration. A span that is “sheltered” from the wind
will not be as prone to vibrate as an exposed span. This
shelter can be caused by trees around the station, equip-
ment in the station or by the location of the station, as in
a valley.

Tests and experience show that all shapes of bus will
vibrate provided the following conditions are present: (1)
suitable winds are present, (2) span lengths are long
enough to vibrate and (3) support losses are less than input
by wind.

There are too many variables involved to definitely state
that a given span will vibrate; only that due to the fact of
its length it has the potential to vibrate. The possibility of
vibration should be considered if the span lengths are
greater than lengths listed in Table 13-15.

Until recently, the most commonly used damping
method was by inserting flexible cable in the bus. The size
and type of cable was determined by trial and error for
each installation and there was little consistency (Table
13-16).

In recent years, specially designed bus dampers have
found increasing use for vibration protection. Specific
sizes of flexible conductor, particularly in the short lengths
required for damping purposes, are not always available or
practical to acquire. Furthermore, dampers may be install-
ed in an existing station where vibration problems have oc-
curred.

**Expansion Joints for Bus Conductors**

When the temperature of a bus conductor changes, there
is a change in length due to thermal expansion.

Long, continuous buses should be provided with expan-
sion joints at intervals. Expansion calculations are covered
in detail in the IEE Guide (1) and are applicable to both in-
door and outdoor bus.

**Rectangular Bars**

For flat-bar construction where the continuous length of
bus is not more than 50 to 75 ft, and where the bus is sub-
ject to only normal variations in temperature, it is common
practice to neglect any special consideration of expansion.
Support clamps are installed tight, and the small change in
length of bus is absorbed by the lateral flexibility of the flat
bars.

**Structural Shape**

Buses designed with structural shape conductors should
be allowed freedom of longitudinal movement except at
anchor points; otherwise, the force exerted on the in-
sulating supports may be higher than advisable. This is
necessary, because structural shapes have much greater
lateral stiffness than flat bars, and changes in length are
not so easily absorbed by lateral bowing of the conductor.

**Tubular**

Runs of considerable length require expansion joints,
particularly if the tube terminates at both ends in electrical
equipment that should not be highly stressed. At section
points either an expansion connector can be used, or the
section is anchored at a central point of a long run, with
slip-supports on far distant insulators. Usually the max-
imum slip on such a support is about one inch, which limits
the run to about 100 ft. each way from a mid-anchor point
for usual temperature variation. A favored expansion con-
nection is the straddle-type (Fig. 13-16) that is mounted on
an insulator cap.

13-33
Positioning Expansion Joints — Continuous Spans

The following are some common arrangements for placing expansion and slide supports in continuous bus spans, designed to accommodate bus expansion without placing undue stress on fixed supports or other components under various installation conditions (35).

Fixed Supports in Center Only

Fixed Supports at One End Only

Fixed Supports at Both Ends

Fixed Supports at Intermediate Points

Fixed Supports at Center and Both Ends

Expansion Joint Types

There are many variations in the design of expansion joints. They generally consist of terminal lugs joined by flexible thin sheet of 1350 aluminum laminations or rope lay cable welded or compressed to the lugs at each end. The gauge of aluminum sheets is 0.010 in. to 0.016 in. thick and for heavy, stiff buses, thicker laminations may be used. If greater flexibility is required woven braid is suitable. The latter type, however, makes the assembly somewhat bulky because of the large number of fine strands that may be needed. Copper braids should not be used for outdoor service on aluminum since copper salts from weathering of copper are corrosive to aluminum. Typical expansion joints for different kinds of aluminum buses are illustrated in Fig. 13-16.

Bus Supports

Bus supports should have a cantilever strength equal to or greater than the strength of the NEMA station post insulators used with the supports. High strength aluminum alloy bodies with aluminum alloy bolts (never bronze) is the best combination of materials. Slip-fit supports that have a rocker pin may be a problem for spans prone to aeolian vibration. ANSI C119.3 lists industry standards for heights of supports.

Standard supports are satisfactory for cables, flat bar and flexible tubes since the movement of the conductors largely absorbs suddenly developed forces of short-circuit currents. However, channel conductors, stiff tubes and flat bars mounted edgewise to the direction of force convey the total impact to the support. Papst (36) conducted extensive tests that showed when the bus is used with spring-mounted supports the reduction in stress is substantial. The springs may be mounted between the bus and its insulator or between the insulator and its supporting structure.

Rigid bus swing-suspended from insulators is sometimes used where short-circuit forces are high, Fig. 13-15. Shock stress from short circuits is partly absorbed by the inertial swing of the bus and, for a sustained short circuit, the bus swing stops at such a position that the balance of forces, including tension in the insulator links, offsets the short-circuit force. Support bumpers sometimes are provided into which the bus enters at full swing, thereby reducing tension on the insulator. This swing principle also sometimes is employed for indoor bus in industrial plants where short-circuit forces otherwise would make it necessary to provide more supports (37).

Clearances and Phase Spacings

There are no industry standards for all aspects of clearances and phase spacings. However, many are covered by National Electrical Code and the various

Fig. 13-15. Swinging suspension for high-current bus.
Fig. 13-16. Typical expansion connectors.
TABLE 13-17
Minimum Spacing Between Bare Metal Parts
(NEC Table 384-26)

<table>
<thead>
<tr>
<th>Opposite Polarity</th>
<th>Opposite Polarity</th>
<th>Live Parts* to Ground</th>
</tr>
</thead>
<tbody>
<tr>
<td>Where Mounted On the</td>
<td>Where Held Free in</td>
<td>1/2 inch</td>
</tr>
<tr>
<td>Same Surface</td>
<td>Air</td>
<td>1/2 inch</td>
</tr>
<tr>
<td>Not over 125 volts,</td>
<td>3/4 inch</td>
<td>1/2 inch</td>
</tr>
<tr>
<td>nominal</td>
<td>1 1/2 inch</td>
<td>1/2 inch</td>
</tr>
<tr>
<td>Not over 250 volts,</td>
<td>2 inches</td>
<td>1 inch</td>
</tr>
<tr>
<td>nominal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Not over 600 volts,</td>
<td></td>
<td></td>
</tr>
<tr>
<td>nominal</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For SI units: one inch = 25.4 millimeters.
*For spacing between live parts and doors of cabinets, see Section 373-11(a) (1), (2), and (3).

Minimum Spacing Between Bottom of Enclosure and Bus Bars, Their Supports, or Other Obstructions (Inches)
(NEC Sect. 384-10)

<table>
<thead>
<tr>
<th>Conductor</th>
<th>Inches</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insulated bus bars, their supports, or other obstructions</td>
<td>8 (203 mm)</td>
</tr>
<tr>
<td>Non-insulated bus bars</td>
<td>10 (254 mm)</td>
</tr>
</tbody>
</table>

manufacturers have their own standards (Tables 13-17, 13-18 and 13-19).

Jointing and Connecting

Properly designed bolted, clamp-fitted, or welded bus bar connections provide equally satisfactory service. Welding is generally preferred for permanent connections and bolting is used where connections may be periodically broken. Bolting and clamping are also used where welding equipment and trained welders are not available.

Nature of Contact Interface

There are similarities in the contact interfaces between any two conductors. The surface of a piece of metal — no matter how well polished — consists of innumerable microscopic hills and valleys. Theoretically, the initial contact of two mating surfaces occurs at only three points. When increasing pressure is applied, the initial points are broken down and multiple points of contact are established.

The natural oxide films on both copper and aluminum, particularly aluminum, are poor electrical conductors. They must be ruptured or otherwise penetrated to bring about the required conducting path. The quality of conducting path across the contact interface must approach that of the continuous conductor if significant resistance concentrations are to be avoided.

Photomicrographs of contact surfaces have shown how metal is extruded into the fissures in the oxide surface during interfacial collapse to provide the bridges by which current can traverse the interface. Resistance measurements of completed connections reveal the degree to which these bridges are effective in providing a low resistance path (38).

The installing force on a connection disrupts the natural oxide film on the contact surface, allowing metal-to-metal contact for low contact resistance. Contact resistance may be sensitive to subsequent micro-movement from creep or differential thermal expansion. If the increase in joint resistance causes a significant increase in temperature the deterioration may be cumulative until the circuit opens or high temperature provides more conducting areas at the in-
### TABLE 13-18
Minimum Clearance of Live Parts\(^{(1)}\)
(NEC Table 710-33)

<table>
<thead>
<tr>
<th>Nominal Voltage Rating ( kV )</th>
<th>Impulse Withstand, ( B.I.L. )</th>
<th>Minimum Clearance of Live Parts in Inches</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Indoons</td>
<td>Outdoors</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>95</td>
</tr>
<tr>
<td></td>
<td>75</td>
<td>95</td>
</tr>
<tr>
<td>13.8</td>
<td>95</td>
<td>110</td>
</tr>
<tr>
<td>14.4</td>
<td>110</td>
<td>110</td>
</tr>
<tr>
<td>23.0</td>
<td>125</td>
<td>150</td>
</tr>
<tr>
<td>34.5</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>46.0</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>69.0</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>115.0</td>
<td>250</td>
<td>21</td>
</tr>
<tr>
<td>138.0</td>
<td>250</td>
<td>21</td>
</tr>
<tr>
<td>161.0</td>
<td>350</td>
<td>31</td>
</tr>
<tr>
<td>230.0</td>
<td>550</td>
<td>53</td>
</tr>
<tr>
<td></td>
<td>550</td>
<td>53</td>
</tr>
<tr>
<td></td>
<td>650</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td>650</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td>750</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>750</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>1050</td>
<td>89</td>
</tr>
<tr>
<td></td>
<td></td>
<td>105</td>
</tr>
</tbody>
</table>

For SI units: one inch = 25.4 millimeters.

(1) The values given are the minimum clearance for rigid parts and bare conductors under favorable service conditions. They shall be increased for conductor movement or under unfavorable service conditions, or wherever space limitations permit. The selection of the associated impulse withstand voltage for a particular system voltage is determined by the characteristics of the surge protective equipment. These values shall not apply to interior portions or exterior terminals of equipment designed, manufactured, and tested in accordance with accepted national standards.

(2) ANSI C 37.46 lists 6 in. for 8.25 kV.

---

interface. Al-Cu bolted interfaces between flat bus may exhibit this characteristic (39).

Contact resistance of two metallic surfaces appears to consist of two parts: (1) the constriction resistance caused by non-uniform flow of current in the body of the conductors as the result of the constrictive nature of the small metal extrusion contacts at points of oxide fracture, and (2) film resistance caused by random areas of less perfect contact.

Although the contact resistance consists of film resistance in parallel with the constriction resistance, the latter is by far the most important.

**Constriction Resistance**

The distribution of dc current in a long thin rod is uniform. The resistance of such rod can be calculated by
### TABLE 13-19
Electrical Clearances
Outdoor Substations — Basic Parameters

(From Table 1, NEMA STD SG 6)

<table>
<thead>
<tr>
<th>Line No.</th>
<th>Rated Max. Volt kV rms</th>
<th>Rated Impulse 1.2 x 50 μs Wave kV Crest</th>
<th>60 Hz kV rms Wet 10 Seconds</th>
<th>Minimum Metal-to-Metal Distance Between Rigidly Supported Energized Conductors Inches (Meters)</th>
<th>Ground Clearance Inches (Meters)</th>
<th>Recommended Minimum Clearance Center to Center Inches (Meters)</th>
<th>Recommended Phase Spacing Horizontal Break Disc Switches</th>
<th>Bus Supports, Vertical Birk Disc Switches</th>
<th>Power Fuses Non-expulsion Type Rigid Conductors</th>
<th>Recommended Minimum Clearance Between Overhead Conductor and Ground for Personal Safety Feet (Meters)</th>
<th>Withstand S, S, Crest kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.25</td>
<td>95</td>
<td>30</td>
<td></td>
<td>7 (.18)</td>
<td>7-1/2 (.19)</td>
<td>6 (.15)</td>
<td>36 (.91)</td>
<td>30 (.76)</td>
<td>18 (.46)</td>
<td>8 (2.44)</td>
</tr>
<tr>
<td>2</td>
<td>15.5</td>
<td>110</td>
<td>45</td>
<td></td>
<td>12 (.30)</td>
<td>10 (.26)</td>
<td>7 (.18)</td>
<td>36 (.91)</td>
<td>30 (.76)</td>
<td>24 (.61)</td>
<td>9 (2.74)</td>
</tr>
<tr>
<td>3</td>
<td>25.8</td>
<td>150</td>
<td>60</td>
<td></td>
<td>15 (.38)</td>
<td>12 (.30)</td>
<td>10 (.25)</td>
<td>48 (1.22)</td>
<td>36 (.91)</td>
<td>30 (.76)</td>
<td>10 (3.05)</td>
</tr>
<tr>
<td>4</td>
<td>38.0</td>
<td>200</td>
<td>80</td>
<td></td>
<td>18 (.46)</td>
<td>15 (.38)</td>
<td>13 (.33)</td>
<td>60 (1.52)</td>
<td>48 (1.22)</td>
<td>36 (.91)</td>
<td>10 (3.05)</td>
</tr>
<tr>
<td>5</td>
<td>48.3</td>
<td>250</td>
<td>100</td>
<td></td>
<td>21 (.53)</td>
<td>18 (.46)</td>
<td>17 (.43)</td>
<td>72 (1.83)</td>
<td>69 (1.75)</td>
<td>48 (1.22)</td>
<td>10 (3.05)</td>
</tr>
<tr>
<td>6</td>
<td>72.5</td>
<td>350</td>
<td>145</td>
<td></td>
<td>31 (.79)</td>
<td>29 (.74)</td>
<td>28 (.71)</td>
<td>96 (2.43)</td>
<td>96 (2.43)</td>
<td>66 (1.68)</td>
<td>11 (2.83)</td>
</tr>
<tr>
<td>7</td>
<td>121</td>
<td>550</td>
<td>220</td>
<td></td>
<td>53 (.13)</td>
<td>47 (1.24)</td>
<td>42 (1.07)</td>
<td>120 (3.05)</td>
<td>94 (2.39)</td>
<td>84 (2.13)</td>
<td>12 (3.05)</td>
</tr>
<tr>
<td>8</td>
<td>145</td>
<td>650</td>
<td>275</td>
<td></td>
<td>69 (.17)</td>
<td>52-1/2 (1.33)</td>
<td>59 (.15)</td>
<td>144 (3.66)</td>
<td>132 (3.35)</td>
<td>84 (2.13)</td>
<td>12 (3.05)</td>
</tr>
<tr>
<td>9</td>
<td>169</td>
<td>750</td>
<td>315</td>
<td></td>
<td>72 (1.83)</td>
<td>61-1/2 (1.56)</td>
<td>58 (.14)</td>
<td>168 (4.27)</td>
<td>156 (3.96)</td>
<td>108 (2.74)</td>
<td>13 (3.35)</td>
</tr>
<tr>
<td>10</td>
<td>242</td>
<td>900</td>
<td>385</td>
<td></td>
<td>89 (2.26)</td>
<td>76 (1.93)</td>
<td>71 (1.80)</td>
<td>192 (4.88)</td>
<td>192 (4.88)</td>
<td>132 (3.35)</td>
<td>13 (3.35)</td>
</tr>
<tr>
<td>11</td>
<td>242</td>
<td>1050</td>
<td>455</td>
<td></td>
<td>105 (2.67)</td>
<td>90-1/2 (2.30)</td>
<td>83 (2.11)</td>
<td>216 (5.49)</td>
<td>216 (5.49)</td>
<td>156 (3.96)</td>
<td>14 (4.37)</td>
</tr>
<tr>
<td>12</td>
<td>362</td>
<td>1050</td>
<td>455</td>
<td></td>
<td>119 (3.02)</td>
<td>106 (2.66)</td>
<td>84 (2.13)</td>
<td>240 (6.10)</td>
<td>192 (4.88)</td>
<td>156 (3.96)</td>
<td>15 (4.67)</td>
</tr>
<tr>
<td>13</td>
<td>362</td>
<td>1300</td>
<td>525</td>
<td></td>
<td>104 (2.64)</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>18 (4.64)</td>
<td>650</td>
</tr>
<tr>
<td>14</td>
<td>550</td>
<td>1500</td>
<td>620</td>
<td></td>
<td>124 (3.15)</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>759</td>
</tr>
<tr>
<td>15</td>
<td>550</td>
<td>1800</td>
<td>710</td>
<td></td>
<td>144 (3.66)</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>898</td>
</tr>
<tr>
<td>16</td>
<td>800</td>
<td>2050</td>
<td>850</td>
<td></td>
<td>168 (4.29)</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>982</td>
</tr>
</tbody>
</table>

Note—For insulator data, see the NEMA Standards Publication for High Voltage Insulators, Pub. No. HV 1-1973.

*Ground clearance for voltages 362 kV and above are selected on the premise that at this level, selection of the insulation depends on switching surge levels of the system. The values were selected from Table 1 of IEEE Transactions paper T-72-151-6 (Vol. No. 5, page 1924) which is a report of the Transmission Substation Subcommittee. For additional switching surge values refer to the above noted paper.*
R = ρL/A, where ρ is the resistivity, L is the length and A the cross-sectional area. When a constriction (Fig. 13-17) is interposed in such rod or strip, the current flow is no longer uniform. The distortion of the lines of current flow results in an increase in resistance, called "constriction resistance."

Greenwood (40) showed mathematically that, with a large number of small contacts, the self-resistance term in the constriction resistance at asperities becomes very small. Thus with a large number of small paths through a surface film, the total resistance may be almost as low as with no film.
**Film Resistance**

The natural oxide film, in air, may be said to have a thickness ranging from 10 to 100Å (one angstrom unit = 1 x 10^-7 mm). Thick films (multimolecular) without fissures, such as oxides, sulfides and others, can as a rule be regarded as insulating. Thick films in the order of 20Å may be regarded as barrier films. Thin films pass electric current practically without perceptible resistance (41).

According to Mott’s application of quantum mechanics (42), conduction through very thin films depends upon the fact that electrons in the metal can penetrate a distance of a few angstrom units into an insulating layer without receiving energy of excitation.

**Design Factors Of Bolted And Clamped Joints**

Research on the nature of the contact interface points out the importance of those combination of connection elements—contact members, contact surfaces, and means of assembly—that minimize differential thermal expansion, creep, relaxation, and other stress changes. Therefore, in the design of bolted connections, consideration should be given to: (1) contact area, (2) contact pressure, (3) contact surface preparation, (4) characteristics of the metals involved (both mechanical and relative thermal expansion), (5) jointing hardware, (6) sealing the joint against possible oxidizing or corrosive agents, (7) operating temperature and (8) possible hot spots due to short-circuit currents.

**Contact Surface Area (Overlap)**

Melsom and Booth (43) in their extensive work in 1922 presented practical recommendations regarding size of overlap, surface preparation, and use of petroleum jelly as a valuable guide for both aluminum and copper conductors.

Experience has shown that good performance is obtained if the current density for bare contact surface is in the order of 90 to 100 amperes per square inch, calculated on the basis of total area of overlap, when the overlap equals the width of the bar for field fabricated bus. For factory fabricated apparatus, such as busways, switchgear, and isolated phase bus, where joints are electro-plated and tested, a current density of 200 amp. sq. in. is permissible (UL 857).

**Contact Resistance—Clamping Force**

The initial contact resistance in clean contacts depends on (1) the resistivity of the contact members, and (2) the area and distribution of the conducting spots in the interface between the contact members. The area and distribution of the conducting spots are generally determined by the magnitude of the clamping force and the manner in which it is applied. For example, Fig. 13-18 shows the relative change of resistance with increasing and decreasing...
pressure.

For practical purposes, the problem of adequate clamping force for a joint of satisfactorily low initial resistance can be simplified by considering the clamping force as uniformly distributed over the apparent contact area. In this way, rule-of-thumb limits of unit pressure can be applied to serve as guides when making joints. A practical design range for average clamping pressures is 800 to 1200 psi for 1350 alloy conductors. Higher average clamping pressures may be used for 6101 and other strong alloy conductors.

**Contact Surface Preparation**

A flat, unplated, aluminum contact surface for a bolted connection requires some treatment prior to assembly to reduce the contact surface resistance. The most effective treatment is to abrade the aluminum to disrupt the oxide film and immediately coat with an electrical joint compound containing an active chemical that attacks and disperses the oxide film on the aluminum. The chemical action not only reduces the thickness of the film, but also improves lubricity which assists in the seating of the contact members.

Plated bus is normally used in industrial equipment to avoid the necessity of field joint preparation. Plating is required where plug-in contacts are used. UL specifications permit 15°C higher temperature rating, hence increased ampacity, where plated connections are used, or an allowable temperature rise of 55°C above 30°C ambient. Silver plating was once generally specific but tin plating has largely taken its place.

**Characteristics of Dissimilar Metal Interfaces**

Different contact materials have different capabilities for maintaining interfacial fixity—lack of relative movement—against nonplated aluminum.

Bolted Al-Cu connections, installed with joint compound in accordance with instructions, have given satisfactory performance under normal operating conditions. Where operating temperatures have been high, generally in excess of 100°C, resistance increases have been experienced in certain connections. Such increases are greatest where the Al is soft and the Al contact surface is not severely deformed. Although these increases are frequently attributed to a lack of spring follow-up in the fastening system, data indicate that interfacial shear strain—strain resulting from the shear component of contact force—is by far the more important cause (38). One solution is to interpose a bi-metal wafer (Al-Cu) to establish Al-Al and Cu-Cu contact surfaces.

An area of more concern is the problem of bolting nonplated aluminum to silver or tin plated surfaces. Bond's tests (44,45) show that heavier silver and tin plated surfaces had poor capability for interfacial fixity while nickel was quite good.

With increased plating thickness the creep and expansion properties of the plated contact surface become more like those of the plating material than the substrate. Therefore, plating thickness is a factor in determining whether or not fixity will be maintained.

Plating thicknesses in excess of 0.2 mil have shown significant resistance increases in joints with nonplated soft Al. With harder Al or thinner plating, the resistance is more stable. Therefore, 0.2 mil has been considered the limit of plating thickness below which special precautions are not required in properly designed connections to nonplated Al.

If one has a thick-plate silver or tin contact member that must be electrically connected to nonplated aluminum by bolting, the possibility of trouble can be reduced by interposing a bi-metal wafer. The connection would then be installed in accordance with standard recommendations. Another method is to plate the aluminum contact surface.

**Bolted Joints and Jointing Hardware**

When the electric load on a bus increases in the course of normal load cycles, the joints are heated, the aluminum tends to expand more than the steel bolts and looseness of the joint may result for certain conditions.

Reasonably constant clamping force can be maintained with any one, or a combination, of the following methods: (1) use of aluminum alloy bolts; (2) use of Belleville spring washers with quality steel bolts; (3) use of clamps with built-in elasticity; (4) use of thick flat washers in conjunction with steel bolts designed to operate as elastic members.

**Bolts—Size and Number**

The size and number of bolts in electric joints are of particular importance, since the bolting pressure must be adequate to establish a high initial joint efficiency without subjecting the bolts to stresses beyond their yield strengths. The work of Shand and Valentine (46) on the effects resulting from the use of different quantities and sizes of bolts and of different thicknesses of bars disclosed some interesting facts:

1. Thickness of Bar—Provided that surface preparation, overlap and bolting remain the same, the different thicknesses of material commonly used do not appreciably affect the joint efficiency.

2. Bolt Size—For a given thickness of material, where joint surface preparation and the number of bolts remain constant, the joint resistance for bolt sizes between 3/8 in. and 3/4 in. diameter may be lower for the larger bolts.

3. Number of Bolts—As the number of bolts is increased, the joint resistance is definitely decreased. Joint efficiency increases most sharply as the number of bolts is increased from one to four. When five or six bolts are used, however, the additional increase in joint efficiency is
### TABLE 13-20

**Bolting Schedule for Field Erected Buses**

<table>
<thead>
<tr>
<th>Bar Width, Inches</th>
<th>Arrangement</th>
<th>Bolt Spacing, Inches</th>
<th>No. of Bolts</th>
<th>Bolt Size</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>C</td>
<td>D</td>
<td>E</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>1/2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>1 1/2</td>
<td>1/2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>1/2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
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<td>2</td>
</tr>
<tr>
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</tr>
<tr>
<td>3</td>
<td>3</td>
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<td>1 1/2</td>
<td>3</td>
</tr>
<tr>
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<td>3</td>
</tr>
<tr>
<td>5</td>
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<td>3</td>
</tr>
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<td>2</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
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<td>2</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>8</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>8</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>8</td>
<td>6</td>
<td>3</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>3</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

### Tangent or Right-Angle Joints

<table>
<thead>
<tr>
<th>Bar Width, Inches</th>
<th>Arrangement</th>
<th>Bolt Spacing, Inches</th>
<th>No. of Bolts</th>
<th>Bolt Size</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>C</td>
<td>D</td>
<td>E</td>
</tr>
<tr>
<td>8</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>5</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>6</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

### Bolts

<table>
<thead>
<tr>
<th></th>
<th>Aluminum</th>
<th>Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANSI B18-2 heavy finished hexagon nut and bolt, No-Ox-id coated.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ASTM—A325 steel bolt.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heavy gauge flat steel washer.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum flat washers.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Belleville spring washer.*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Locknut or Flanut, if service conditions require.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
small.

Donati's work (62) shows that, for bolted joints using multiple through bolts inline with the axis of the bus, the current will traverse the contact surface only in the vicinity of the two outer bolts, while the intermediate ones have no practical influence on the current distribution over the contact. It is, therefore, of little electrical value to use the intermediate bolts.

The use of thick, wide-series flat washers under the bolt heads, nuts and Belleville washers, serves to distribute the high contact pressures over a larger area. Most of the current transfer occurs in the area of high pressure under the bolt heads (Fig. 13-19).

The series of designs of bolted joints for bars, shown in Table 13-20, is offered as a guide for heavy-duty service.

Bolts—Torque vs. Clamping Pressure

The relation between tightening torque and clamping pressure in a bolted joint is greatly dependent on the finish and lubrication of the threads and other bearing surfaces. The average relation between tightening torque and clamping forces for specified conditions is shown in Fig. 13-20.

Many factors are relevant to the performance of bolted overlap bus joints involving aluminum and other metals. However, the greatest single concern should be relative movement at the film-coated surface of the aluminum. Whether this movement is caused by differential thermal expansion, elastic deformation, or permanent deformation (creep, etc.), if it shears the current-carrying spots by which the current traverses the interface, the contact resistance is increased.

Aluminum Alloy Bolts

Aluminum bolts have the same thermal expansion as the aluminum bus, therefore loosening of the joint because of temperature cycling will never result from thermal expansion.

Aluminum alloy 2024-T4 bolts have the tensile strength of mild steel. Hence, the same clamping force can be achieved with the same size bolt. Aluminum alloy bolts, however, are somewhat lower in torsional strength than mild steel. To offset the lower torsional strength, alloy bolts 1/8-inch larger than the equivalent steel bolts are sometimes used.

Since the compressive stress in a bolted joint is concentrated under the head and nut of the bolt, flat washers are recommended to increase the bearing area. The larger bearing area is helpful in reducing stress concentrations and in increasing effective contact area. Aluminum alloy bolts are non-magnetic and, therefore, not subject to heating due to hysteresis losses in ac fields.

Table 13-21 shows dimensions of heavy-series aluminum bolts, and Table 13-22 lists the recommended loadings of the usual sizes of aluminum 2024-T4 bolts for bus connections together with the resulting stresses in shank, in root area, and under the bolt head. The torque necessary to produce these bolt loadings is also shown, assuming suitable lubrication on threads, under bolt and nut bearing surfaces.

Steel Bolts and Belleville Spring Washers (47)

Another method of avoiding a potential problem as a result of differential expansion of bolts and conductors is the use of Belleville washers under the nut of a steel bolt. Experience over many years in North America and France has shown that very satisfactory results can be obtained by using Belleville spring washers. A flat washer should be used under the Belleville. The flat washer should be larger than the spring washer, and the nut should be tightened until the spring washer is in a completely flattened position. In the absence of specific instructions to the contrary, it should be left in flattened position and the normal relaxation of the metals will restore some crown to the washer (See Chapter 11).

Steel Bolts and Pressure Plates

Stainless steel pressure plates have been used successful-
ly for bolted joints. These plates, drilled to conform to the bolting layout, expand the pressure area around the bolts.

**Steel Bolts and Standard Flat Washers**

The higher yield strength and better creep characteristics of 6101 alloy make it easier to obtain stable electric joints with this alloy than with aluminum 1350. Tests and field experience show that as a rule-of-thumb Belleville spring washers are not necessary to the satisfactory performance of bolted overlap joints secured with quality steel fasteners if the tensile strength of the aluminum bus is in excess of 20 ksi and provided the contact surfaces have been properly prepared. Dimensions of flat washers are shown in Table 13-23.

---

**TABLE 13-21**

Dimensions of Heavy-Series Aluminum Bolts 2024-T4
Aluminum Alloy, (N.C.) National Coarse Thread
(Dimensions in inches: \( F \) and \( G \) are maximum; \( H \) is nominal)

<table>
<thead>
<tr>
<th>Threads Per In.</th>
<th>D Nominal Diam.</th>
<th>F Across Flats</th>
<th>G Across Corners</th>
<th>H Unfinished Head</th>
<th>H Finished Head</th>
<th>J Pitch Diam.</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>( \frac{1}{2} )</td>
<td>( \frac{7}{6} )</td>
<td>1.010</td>
<td>( \frac{7}{16} )</td>
<td>( \frac{13}{32} )</td>
<td>0.4500</td>
</tr>
<tr>
<td>11</td>
<td>( \frac{5}{8} )</td>
<td>( \frac{11}{16} )</td>
<td>1.227</td>
<td>( \frac{17}{32} )</td>
<td>( \frac{1}{2} )</td>
<td>0.5660</td>
</tr>
<tr>
<td>10</td>
<td>( \frac{3}{4} )</td>
<td>( \frac{1}{2} )</td>
<td>1.443</td>
<td>( \frac{5}{8} )</td>
<td>( \frac{19}{32} )</td>
<td>0.6850</td>
</tr>
</tbody>
</table>

*Note:*
The unthreaded shank length and overall length of the bolt should be selected so that there is little excess of thread length above nut thickness. If the bolts have rolled threads, the shank diameter \( D \) closely equals pitch diameter \( J \). Bolts should be anodized with adequate thickness and seal to impart suitable corrosion resistance for the application. It is recommended that unanodized nuts of 6061-T6 or 6262-T9 alloy be used. The corrosion resistance of these unanodized nuts is compatible with that of anodized 2024-T4 bolts.
TABLE 13-22

<table>
<thead>
<tr>
<th>Nominal Bolt Size</th>
<th>1/2'-13</th>
<th>5/16'-11</th>
<th>3/8'-10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net stress area under thread*</td>
<td>0.1416</td>
<td>0.2256</td>
<td>0.3340</td>
</tr>
<tr>
<td>Shank area, sq. in.</td>
<td>0.196</td>
<td>0.307</td>
<td>0.442</td>
</tr>
<tr>
<td>Area under regular bolt head and nut (semi-finished)**</td>
<td>0.164</td>
<td>0.273</td>
<td>0.412</td>
</tr>
<tr>
<td>Same, but for heavy-series bolt, min.</td>
<td>0.318</td>
<td>0.462</td>
<td>0.637</td>
</tr>
</tbody>
</table>

A. Torque and stress under average conditions—with stresses suitable for optimum creep conditions. Recommended for connecting aluminum bus bars with either regular or heavy series aluminum bolts.

<table>
<thead>
<tr>
<th>Torque, lb-ft (approx.)***</th>
<th>5,500</th>
<th>8,800</th>
<th>13,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load on bolt, lb (probable)</td>
<td>38,800</td>
<td>39,000</td>
<td>39,000</td>
</tr>
<tr>
<td>Stress in shank, psi</td>
<td>28,100</td>
<td>28,600</td>
<td>29,400</td>
</tr>
<tr>
<td>Stress under regular head, psi**</td>
<td>33,500</td>
<td>32,200</td>
<td>31,500</td>
</tr>
<tr>
<td>Stress under heavy-series head, psi</td>
<td>17,300</td>
<td>19,100</td>
<td>20,400</td>
</tr>
</tbody>
</table>

* In accordance with ANSI Standard, the net stress area is slightly larger than the area of a circle of same diameter as thread root, thereby allowing for the slight spiral stress transfer that is characteristic of ANSI threads.

** Stresses under bolt heads in this table are computed on the basis of minimum width across flat of a semi-finished bolt, and that nut area is same as head area.

*** IEEE paper 63-280, Use of Aluminum in Substation Buses, a report of Working Group 57.1, Substation Committee, Power Division, recommends 25 lb-ft as torque for 1/2-13 NC bolts, and 40 lb-ft for 5/8-11 NC bolts, which is same as NEMA Std. CCI Table 4-2 for aluminum bolts that fasten connectors to flat conducting surfaces.

Quality Steel Bolts

Bolts, unless purchased to a specification, vary widely in mechanical properties. For bus bar joints, it is desirable to use bolts that have a known elastic proof load, such as those meeting ASTM A 325. High-strength bolts such as SAE Grades 7 or 8 (ASTM A 354, Grade BD) are recommended for thick packs of bars where it is customary to use fewer bolts and larger Belleville washers.

Special Clamps

Fairly uniform pressure may be obtained over a wide range of operating temperatures by the use of special clamps. The "curved back" clamp, designed so that the convex face will be parallel when the bolts are drawn down to the rated capacity of the clamp, have given satisfactory service. Assembly of bus using clamp joints is relatively simple because pre-drilling and aligning of bolt holes is not required.

Aluminum-To-Copper Connection

Aluminum and copper are both ideally suited for use as electrical conductors, not only because of their conductivity, but also because both metals have an excellent inherent resistance to atmospheric weathering. Because these two metals are almost exclusively used as electrical conductors,

TABLE 13-23

<table>
<thead>
<tr>
<th>Outside Diameter &amp; Thickness of Flat Washers—Inches</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bolt Size</td>
</tr>
<tr>
<td>Diam.</td>
</tr>
<tr>
<td>--------</td>
</tr>
<tr>
<td>1/2 in.</td>
</tr>
<tr>
<td>1/2 in.</td>
</tr>
<tr>
<td>1/2 in.</td>
</tr>
<tr>
<td>1/4 in.</td>
</tr>
</tbody>
</table>

*Medium" washers are specified in NEMA SG1.4.10 for joining power connectors to flat contact surfaces.

*Extra-thick washers of Heavy or Extra-Heavy series of aluminum often are available on special order, and larger outside diameters similarly are usually obtainable. Generally, the thickness of a washer should be increased with increased washer diameter.

Note: As bolt holes usually are 1/16 in. larger in diameter than the nominal bolt size, the bearing area of the washer, in sq. in., is 0.7854 (O.D.^2 — (Size + 0.0025)^2)

The rim effect of washers applied to aluminum that is not stressed above its elastic limit is sometimes taken into account, if "medium" washers are used, by assuming that the effective bearing area under the washer is the same as that of an area the diameter of which equals the outside diameter of the washer plus twice the washer thickness.

13-45
connections between the two metals have to be made frequently. Such joints, when properly made with well-designed fittings of good quality, have given satisfactory outdoor service for many years. It must be remembered, however, that because of the electrochemical relation of the two metals, aluminum is anodic to copper. As a consequence, the joint in the presence of an electrolyte will be susceptible to galvanic corrosion. The accumulation of films or corrosion products on the contact surfaces may adversely affect the electrical resistance of the joint.

The factors that influence the degree or the severity of the galvanic action are numerous and complex. They are covered in Chapter 2. For protection of installations in environments that are known or expected to have severe galvanic action, the joint should be thoroughly sealed with a suitable grease-type compound to prevent the entrance of moisture into the contact surfaces. Such compounds are also used to minimize the formation of oxide films on the contact surfaces. If possible, the copper side of the joint should be placed on the bottom for outdoor applications to prevent copper salts washing over the aluminum.

For ordinary applications (normal conductor temperatures of 70°C), both outdoor and indoors, protective grease-type compounds are effective and suitable for controlling corrosion and maintaining low resistance in direct aluminum-to-copper electric connections.

**Welded Aluminum-to-Aluminum Connections**

Welding of aluminum in electrical construction offers a superior and economical means of joining conductors. Electric arc welding using an inert gas shield produces mechanically and electrically sound joints requiring no flux or special surface preparation other than the cleaning of the surface to be welded.

A welded connection that is mechanically satisfactory is also electrically satisfactory. With welded connections, there is an essentially homogeneous union that gives a permanent stable connection. It is not necessary to try to produce a connection with the same resistance as bus itself in order to have a stable permanent joint. This can be observed from Fig. 13-17.

There are bus connections where it is important to insure a resistance ratio of unity with the conductor itself. Small differences in resistance can affect the current distribution in some bus systems. Some bus systems require equalization bars. Welded connections are an ideal solution to both problems. Such connections can be made by following procedures outlined in The American Welding Society Handbook “Welding Aluminum”. When the bead is not ground off, the result is a welded joint that usually has a lower resistance than an equal length of conductor for the recommended filler metal.

For outdoor substation applications, the criterion of “mechanically satisfactory” means “electrically satisfactory” is applicable.

There are a number of excellent papers on designs using welded aluminum bus for outdoor substations. Some of the earlier papers (48,49,50) give considerable data on design features and test information. Substations using these design features have given trouble-free service for over 25 years.

**Welding Processes**

The most used welding processes for joining bus are the gas tungsten-arc welding method (GTAW) which employs a non-consumable tungsten electrode with filler metal fed by hand or automatically, and the gas metal-arc welding method (GMAW) in which the filler wire is power-fed continuously through the torch, thereby constituting a consumable electrode.

Both GTAW and GMAW processes employ inert gas shielding (argon, helium, or a mixture of these) that keeps air away from the arc and the molten weld pool, thereby eliminating need for welding flux.

Basic joint designs and welding procedures are shown in “Welding Aluminum”. Details of GMAW and GTAW welding as to shaping of the edges to be welded, current density, size and kind of filler wire, speed of welding, and manipulation of the torch are described in specialized publications of aluminum producers and welding equipment manufacturers. For bus work 4043 and 1100 alloy filler wires are commonly used with GMAW, however alloy 4043 is easier and faster to use.

**Strength of Aluminum in Weld-Heat Zone**

Bolted joints lose strength because of bolt holes. Properly made GMAW and GTAW welded joints also lose strength in the heat-affected zone that extends about two or three times the metal’s thickness from the center of the weld. Average strength values are shown in Table 13-24.

The value for 6101-T6 is about the same as for 6063-T6. If the weld bead is left on, the average yield strength in the

---

**TABLE 13-24**

Typical Alloy Strength Values As Welded

<table>
<thead>
<tr>
<th>Alloy and Temper</th>
<th>Minimum Yield Strength of Parent Metal</th>
<th>Typical Yield Strength Fully Annealed &quot;O&quot; Temper</th>
<th>Filler Metal</th>
<th>Minimum Expected Tensile Yield Strength As Welded ksi</th>
</tr>
</thead>
<tbody>
<tr>
<td>1350-H111</td>
<td>3.4 ksi</td>
<td>4.0 ksi</td>
<td>4043</td>
<td>4.5</td>
</tr>
<tr>
<td>6063-T6</td>
<td>25.0 ksi</td>
<td>7.0 ksi</td>
<td>4043</td>
<td>11.0</td>
</tr>
<tr>
<td>6061-T6</td>
<td>35.0 ksi</td>
<td>8.0 ksi</td>
<td>4043</td>
<td>15.0</td>
</tr>
</tbody>
</table>
Welded Straight Connector

Slotted insert tube next smaller pipe size. Locate slot in region of lowest tensile stress of conductor tube.

Insert tube held by plug welds provides back-up for the butt weld and also reinforces tube strength.

Welded Branch for Bottom of A-Frame Assembly

Direct weld after upper tube is cut to shape by means of special cutting template.

Welding to Intermediate Aluminum Connector Fitting

Usually one of these welds may be a shop weld at reduced cost.

Fig. 13-21. Typical welded tubular bus connections.

heat-affected zone is about 75 percent of minimum yield strength of the parent metal. Locating the weld in the region of moderate stress is a usual method of offsetting the effect of partial weld annealing. For situations where locating the weld in a region of moderate stress is not practical for tubular conductors, reinforcing inserts (Fig. 13-21) may be used. Static bending tests of such joints show developed stresses as high as 28,000 to 32,500 psi without failure for 6063-T6 tubing. (See ref. 48 and 50).

Other Welding and Bonding Methods

Other less often used welding and bonding techniques for joining aluminum bus are available for special circumstances and applications. Among these methods are: GMAW spot welding, gas welding, resistance (flash) butt welding, resistance spot welding, capacitor discharge welding, pressure welding, ultrasonic welding, exothermic welding, explosion welding, diffusion bonding, brazing and soldering.

To cover all these methods in detail is beyond the scope of this chapter and the reader is advised to consult the American Welding Society's Welding Handbook for further information.

Bus Installations

The descriptions of bus installations in this section are only sufficient to enable recognition of the various types, with emphasis on the conductors, and with supports and protective housings only incidentally described. The various types of installations are considered in the order in which they occur as the energy is generated, transmitted, distributed and utilized.

Generator and Station Bus

The generator in a large power station will generally be rated at 23 kV or higher with current rating up to 40,000 amperes, three phase, 60 (N. American std.) or 50 Hz. The bus runs from the generator terminals to the main transformer terminals are generally metal enclosed buses of the isolated phase bus construction. In cases where lower current ratings are involved, the bus may be of segregated or non-segregated phase construction.

ANSI Standard C37.20 contains the following definitions for various types of bus construction.

Non-Segregated Phase Bus - One in which all phase conductors are in a common metal enclosure without barriers between the phases (Fig. 13-22a). Another configuration has triangular bus arrangement in a circular enclosure.

Segregated Phase Bus - One in which all phases are in a common metal enclosure, but are segregated by metal barriers between phases (Fig. 13-22b).

Isolated Phase Bus - One in which each phase conductor is enclosed by an individual metal housing separated from adjacent conductor housings by an air space (Fig. 13-23).
Distribution switchyards that serve local areas at moderate voltages also use rigid bus for principal circuits. Fig. 13-26 is typical for 13.8 kV distribution. Round tubular bus also may be mounted on inverted insulators, and the take-offs are similarly tubular, though connections between the low-voltage breakers and the disconnects may be of flexible cable. Angle bus and double-channel web bus, Figs. 13-5k, -f, and -g, also are widely used in distribution switchyards because the flat surfaces aid the connecting of side taps and reduce fitting costs.

Detailed information on design of moderate voltage substations using UABC and 1WBC are given in a number of technical papers (56, 57).

High voltage substations require special care in regard to corona. The supplier should be advised when tubular bus conductors, 3 in. nps and larger, are to be used in substations over 230 kV so that “High Voltage Finish” can be supplied, i.e. special attention given to the exterior surface finish to avoid sharp protrusions.

The maximum allowable height of a sharp protrusion is controlled to some extent by operating voltage. High voltages require better surface conditions, as shown:

<table>
<thead>
<tr>
<th>Operating Voltage</th>
<th>Maximum Height</th>
<th>Finish Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>230 kV or lower</td>
<td>1.5 mm (0.062)</td>
<td>Standard Mill</td>
</tr>
<tr>
<td>230 kV to 345 kV</td>
<td>1.2 mm (0.047)</td>
<td>High Voltage</td>
</tr>
<tr>
<td>345 kV to 500 kV</td>
<td>0.6 mm (0.025)</td>
<td>High Voltage</td>
</tr>
<tr>
<td>500 kV</td>
<td>0.1 mm (0.004)</td>
<td>High Voltage</td>
</tr>
</tbody>
</table>

Defects should be smoothed to a height not exceeding the appropriate value based on the operating voltage. Complete removal is not necessary, but repaired area should be blended into the remaining surface and should not exceed 250 micro-inch (AA).

Gas Insulated Bus (58)

Compressed gas insulated bus is becoming popular for switchyard installations where space is at a premium.

Busways

Often called “bus duct,” busways are enclosed, sectionalized, prefabricated bus-bar assemblies with associated fittings for distribution of ac or dc power at 600 volts or less in ratings of 100 amp or more. They are used for transmitting power in industrial and commercial buildings where concealment of circuits is not necessary. They are particularly advantageous for vertical risers of large buildings, and in machine shops where current-using equipment is likely to be relocated with process changes.

Feeder busways supply power to a distribution center. Plug-in busways are similar, but provide for plug-in attachment of power takeoffs at spaced intervals by insertion of grip contacts or “stabs”. Protective or indicating
Fig. 13-23. Isolated phase bus — typical support arrangement.
Fig. 13-24. Typical isolated-phase bus commonly used in generating station.

Fig. 13-25. Schematic of ground-type outdoor switchyard for high-voltage transmission. A switchyard for distribution voltage may be on same level and supplied through transformers from the high voltage main bus.
Fig. 13-27. Section through fully insulated feeder busway—cooled by conduction only.

The aluminum phase and neutral bars are solidly encased in laminated insulation, and the assembly housed in an all-aluminum weathertight enclosure, which is held between top and bottom steel channels. Weep holes in bottom channel prevent water accumulation.

Another much-used form of feeder bus provides air ventilation between the vertical bars.

Fig. 13-26. Typical switchyard for 14.4 kV substation. The bus conductors are Types k and m of Fig. 13-3 either single or back-to-back. Types f and g, or other flat-face types are equally suitable.

Fig. 13-28. Typical plug-in busway. The molded plastic plug-in blocks open alternately on opposite sides so connection can be made to any pair. The bars are immersion insulated between plug-in blocks and terminals. They are paired to reduce reactance AB BC CA. The arrangement shown is suitable for three-phase delta. By adding a neutral bar three-phase wye loads can be supplied. There are many varieties of plug-in busways for each of which advantages are claimed.
Fig. 13-29. Multi-bar stepped parallel arrangement for large dc bus for electrolytic supply. Aluminum bars are welded as an assembly by means of top and bottom cross members.

Bus conductors

Devices also may be plugged in or permanently connected. Feeder busways often have bars paired or interlaced to reduce reactance. However, some are purposely designed for high reactance to reduce short-circuit currents.

Busway bars may be arranged flat or on edge; they may be unplated between contact areas but must be suitably plated at bolted joints or at plug-ins. The housings may be ventilated or fully enclosed, and also are available in weather-resistant construction for outdoor runs. Standard operating temperature for plated busways is 55°C rise above 30°C ambient, with 85°C hot-spot temperature. A few designs are shown in Figs. 13-9, -27, and -28, but others having important and valuable features also are available from manufacturers literature.

Industry standards applying to busways are NEC Art. 364, NEMA BU-1 and UL 857.

Switchgear

Rectangular bar is the most commonly used shape for switchgear bus because this shape is inherently easy to fabricate and lends itself to connector and space requirements of switchgear. Capacity can readily be varied by multiple bar arrangements. Switchgear standards are covered by NEMA No. SG5 and ANSI C37.20.

The major switchgear manufacturers use aluminum bus as a standard conductor material. Some designs use silver or tin plated joints while other designs utilize welded joints. The bus system is phase isolated/insulated to preclude accidental contact with live bus.

Buses for the Chlor-Alkali Industry (59)

In large chlor-alkali plants, the bus amperages involved are such that the $I^2R$ losses in the bus system can amount to an appreciable cost. Designers of bus systems for such plants should consider an economic design based on a balance of cost of power losses with bus investment (1). Although the total bus current may be quite large, connection requirements usually require moderate size bars of extruded 1350-H111 or sawed plate, 1350-H112. The type of cell and the plant layout are major factors influencing the bus design. In the stepped-paralleled design Fig. 13-29 the individual bars extend far enough to reach the cell group they supply.

Buses for the Aluminum Industry (60)

Although aluminum smelters vary in type of installation and size, some of the larger installations use from 15 to 22 million pounds of aluminum bus. The buses for these large installations may carry as much as 225,000 amperes. The larger installations use primarily very large thick cast bars of 1350 aluminum and some sawed plate. Sawed plate or extruded bar, mostly 1350 aluminum, are used for connections. Welded joints are used wherever possible.

Buses for the Magnesium Industry

Buses for the magnesium industry, like the aluminum industry, optimize the conductor cross section on the basis of economics. Aluminum "log" bus (rectangles in the order of 14" x 16") 1350 aluminum appears to be the favorite bus shape (61).

Buses for Electric Furnaces (9,62)

Buses for electric furnaces present a different problem from buses for electrolytic installations since alternating current is involved and reactance of the bus system must be kept low. Bars are interlaced to obtain low reactance (Fig. 13-9). Aluminum, sawed plate and extruded bar in relatively thin wide sizes are used. Here the change in cross section from copper to larger cross section for aluminum should always be in the width dimension to gain the added benefit of lower reactance.
### TABLE 13-25

**Aluminum Rectangular Square-Corner Bus Bars Physical and Electrical Properties**

6101-T61 Alloy 57% IACS Min.

<table>
<thead>
<tr>
<th>Size in.</th>
<th>Area Sq. in.</th>
<th>Wt lb/ft</th>
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(Continued)
### TABLE 13-25 (Continued)

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<td>1.13</td>
<td>1.96</td>
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</table>

(1) Structural properties (moment of inertia, etc.) are also suitable for bars having rounded edge within accuracy limits that are regarded as satisfactory for bus-conductor applications.

(2) dc resistance at 20°C is based on minimum conductivity of 57% IACS for 6101-T61 alloys.

Note: See also pages 13-63 to 13-67 for additional information regarding Tables 13-25 through 13-32.
<table>
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<th>Size (Inches)</th>
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<th>1 Bar ac</th>
<th>2 Bars dc</th>
<th>2 Bars ac</th>
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<th>3 Bars ac</th>
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<td>833</td>
<td>817</td>
<td>1235</td>
<td>1194</td>
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<td>2000</td>
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<td>2530</td>
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<td>4284</td>
<td>7514</td>
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<td>2393</td>
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<td>9531</td>
<td>6246</td>
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<td>4779</td>
<td>8763</td>
<td>6256</td>
<td>11493</td>
<td>7579</td>
</tr>
</tbody>
</table>

1. Ratings based on 30°C rise over 40°C ambient in still but unconfin ed air (e = 0.35), corresponding to usual indoor temperature. For other temperature rise values see Fig. 13-11. Vertical bar ampacity based on work by House and Tuttle. Horizontal bar ampacity from industry sources.

2. Space between bars is assumed equal to bar thickness.

3. For a-c phase spacings less than 18-in, an allowance for proximity effect must be made.

4. Ratings are based on horizontal mounting, in air with no attachments.

5. For dc ratings of other alloys, multiply by:
   For 1350, 1.035; 6101-T6, 0.982; 6101-T63, 0.992; 6101-T64, 1.02; 6101-T65, 0.996.
   For 60 Hz, the use of these multipliers is conservative.
### TABLE 13-27
Physical and Electrical Properties of Aluminum Standard Pipe-Size Conductors at Typical Conductivities

<table>
<thead>
<tr>
<th>Outside Wall Thickness (in.)</th>
<th>Nominal Size (in.)</th>
<th>1 E10 ft/milft</th>
<th>60 Hz X-Sectional Area (sq. in.)</th>
<th>Weight (lb/ft)</th>
<th>Inductive Reactance at 60 Hz</th>
<th>Resistance at 60 Hz</th>
<th>Area Weight (lb/sq. ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/2</td>
<td>1/4</td>
<td>0.173</td>
<td>0.026</td>
<td>0.068</td>
<td>0.044</td>
<td>0.0032</td>
<td>0.0002</td>
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<tr>
<td>3/4</td>
<td>3/8</td>
<td>0.353</td>
<td>0.051</td>
<td>0.211</td>
<td>0.080</td>
<td>0.0064</td>
<td>0.0004</td>
</tr>
<tr>
<td>5/8</td>
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<td>0.136</td>
<td>0.350</td>
<td>0.160</td>
<td>0.0120</td>
<td>0.0006</td>
</tr>
<tr>
<td>7/16</td>
<td>7/32</td>
<td>0.876</td>
<td>0.205</td>
<td>0.490</td>
<td>0.240</td>
<td>0.0159</td>
<td>0.0009</td>
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</table>

**Notes:**
1. Current ratings listed in the tables are based on 30°C temperature rise over conductor heat by supporting structures and flanges.
2. Conductor ratings outdoors with a 2.5-kilowatt crossover. Nominal oxidized surface (e = 0.50).
<table>
<thead>
<tr>
<th>Outside diam. in.</th>
<th>Wall thickness in.</th>
<th>Area sq. in.</th>
<th>Weight lb/ft</th>
<th>Moment of Inertia 1 in.⁴</th>
<th>Inductive Reactance 1 ft spacing 60 Hz—Xₐ microhms/ft</th>
<th>dc Resistance at 20°C microhms/ft</th>
<th>Rₑₑ/Rₑₑ at 70°C</th>
<th>ac Resistance at 70°C 60 Hz microhms/ft</th>
<th>Current Rating 60 Hz Amp</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
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<td></td>
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<td>1.831</td>
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<td>17.55</td>
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1. Current ratings are on same basis as per Notes 1, 2, and 3 of Table 13-27.
### Table 13-29

Physical and Electrical Properties of Square Aluminum Tubular Conductors 6101-T61 Alloy
57% IACS Conductivity (minimum)

Tabulated values apply to unvented tubes. Vented tubes have about 8 percent less weight. Add 15 percent to current ratings of ventilated tubes having staggered ventilating holes spaced 4-in. apart longitudinally with hole diameters as follows: For 3-in. tube, 1¾ in.; for 4-in. tube, 1½ in.; for 5-in. tube, 1¾ in.; for 6-in tube, 1¾ in.

<table>
<thead>
<tr>
<th>Inches (a) Square Size</th>
<th>(b) Outside Corner Radius</th>
<th>Area sq. in.</th>
<th>Weight lb/ft</th>
<th>Moment of Inertia 1 in.³</th>
<th>Inductive Reactance 1 ft spacing 60 Hz—Xₚ microhms/ft</th>
<th>dc Resistance at 20°C microhms/ft</th>
<th>Rₑₑₑ/ₚₑₑₑ at 70°C 60 Hz</th>
<th>ac Resistance of 70°C 60 Hz microhms/ft</th>
<th>e = 0.35</th>
<th>e = 0.90</th>
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<tr>
<td>3 ⅛ ¾ ¼</td>
<td>2.643</td>
<td>3.108</td>
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<td>45.5</td>
<td>5.407</td>
<td>1.04</td>
<td>6.683</td>
<td>1880</td>
<td>2300</td>
<td></td>
</tr>
<tr>
<td>3 ⅓ ½ ½</td>
<td>4.571</td>
<td>4.975</td>
<td>4.815</td>
<td>46.9</td>
<td>3.825</td>
<td>1.09</td>
<td>4.954</td>
<td>2170</td>
<td>2640</td>
<td></td>
</tr>
<tr>
<td>4 ½ ⅞ ¼</td>
<td>3.589</td>
<td>4.221</td>
<td>8.215</td>
<td>38.7</td>
<td>3.825</td>
<td>1.05</td>
<td>4.968</td>
<td>2450</td>
<td>3020</td>
<td></td>
</tr>
<tr>
<td>4 ⅔ ⅞ ½</td>
<td>5.236</td>
<td>6.158</td>
<td>11.30</td>
<td>39.0</td>
<td>2.729</td>
<td>1.11</td>
<td>3.600</td>
<td>2880</td>
<td>3550</td>
<td></td>
</tr>
<tr>
<td>5 ¾ ⅗ ¼</td>
<td>6.571</td>
<td>7.727</td>
<td>13.06</td>
<td>39.6</td>
<td>2.175</td>
<td>1.21</td>
<td>3.127</td>
<td>3040</td>
<td>3760</td>
<td></td>
</tr>
<tr>
<td>5 ⅘ ⅗ ½</td>
<td>8.571</td>
<td>10.08</td>
<td>16.26</td>
<td>33.5</td>
<td>3.189</td>
<td>1.06</td>
<td>4.016</td>
<td>2980</td>
<td>3700</td>
<td></td>
</tr>
<tr>
<td>6 ⅝ ¾ ¼</td>
<td>5.482</td>
<td>6.447</td>
<td>29.36</td>
<td>29.1</td>
<td>2.607</td>
<td>1.08</td>
<td>3.346</td>
<td>3540</td>
<td>4420</td>
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</tr>
<tr>
<td>6 ⅞ ¾ ½</td>
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<td>1.770</td>
<td>1.15</td>
<td>2.418</td>
<td>4170</td>
<td>5200</td>
<td></td>
</tr>
</tbody>
</table>

1. Current ratings are based on 30°C rise over 40°C ambient, conductors horizontally mounted and spaced sufficiently to eliminate proximity effects. For temperature rise of 50°C above 40°C ambient, increase ratings by about 30 percent. (See Fig. 13-11). The e = 0.35 rating applies to tubes in still but unconfined air (usual indoor condition) with normal oxidized surface. The e = 0.90 rating applies similarly but with surface painted with flat nonmetallic paint.
### TABLE 13-30

Properties of Uniform Thickness Aluminum Channel Bus Conductors

Physical properties are for single channels; electrical properties are for two channels in face-to-face arrangement. 6101-T61 alloy 57.0% IACS Conductivity (minimum)

<table>
<thead>
<tr>
<th>Dimensions in. see sketch</th>
<th>Area Wt.</th>
<th>Moment of Inertia in</th>
<th>Distance to Neutral</th>
<th>Inductive Reactance 1 ft spacing 60 Hz–Xa microhms/ft</th>
<th>dc Resistance at 20°C microhms/ft</th>
<th>R_s/R_o at 70°C 60 Hz microhms/ft</th>
<th>ac Resistance at 70°C 60 Hz microhms/ft</th>
<th>ac Current Ratings 60 Hz Amp</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A</strong></td>
<td><strong>B</strong></td>
<td><strong>T</strong></td>
<td><strong>W</strong></td>
<td><strong>Section</strong></td>
<td><strong>lb/ft</strong></td>
<td><strong>I-x</strong></td>
<td><strong>I-y</strong></td>
<td><strong>X in.</strong></td>
</tr>
<tr>
<td>3</td>
<td>1.312</td>
<td>0.25</td>
<td>3.933</td>
<td>1.23</td>
<td>1.44</td>
<td>1.49</td>
<td>0.18</td>
<td>0.397</td>
</tr>
<tr>
<td>4</td>
<td>1.75</td>
<td>0.25</td>
<td>4.188</td>
<td>1.70</td>
<td>1.99</td>
<td>3.79</td>
<td>0.46</td>
<td>0.500</td>
</tr>
<tr>
<td>5</td>
<td>1.75</td>
<td>0.625</td>
<td>4.375</td>
<td>3.67</td>
<td>4.30</td>
<td>6.72</td>
<td>0.74</td>
<td>0.627</td>
</tr>
<tr>
<td>6</td>
<td>2.187</td>
<td>0.625</td>
<td>5.</td>
<td>4.84</td>
<td>5.68</td>
<td>13.5</td>
<td>1.60</td>
<td>0.750</td>
</tr>
<tr>
<td>7</td>
<td>2.687</td>
<td>0.437</td>
<td>6.</td>
<td>4.46</td>
<td>5.23</td>
<td>21.3</td>
<td>2.83</td>
<td>0.794</td>
</tr>
<tr>
<td>8</td>
<td>3.187</td>
<td>0.375</td>
<td>7.</td>
<td>4.63</td>
<td>5.43</td>
<td>33.7</td>
<td>4.33</td>
<td>0.893</td>
</tr>
<tr>
<td>9</td>
<td>3.187</td>
<td>0.562</td>
<td>7.</td>
<td>6.69</td>
<td>7.87</td>
<td>44.4</td>
<td>6.15</td>
<td>0.935</td>
</tr>
<tr>
<td>10</td>
<td>3.187</td>
<td>0.625</td>
<td>7.</td>
<td>7.34</td>
<td>8.61</td>
<td>47.7</td>
<td>6.72</td>
<td>0.989</td>
</tr>
<tr>
<td>11</td>
<td>3.687</td>
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<td>8.</td>
<td>5.38</td>
<td>6.31</td>
<td>49.9</td>
<td>6.91</td>
<td>1.02</td>
</tr>
<tr>
<td>12</td>
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<td>0.500</td>
<td>8.</td>
<td>7.03</td>
<td>8.33</td>
<td>63.4</td>
<td>8.64</td>
<td>1.07</td>
</tr>
<tr>
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<td>8.</td>
<td>8.59</td>
<td>10.07</td>
<td>74.9</td>
<td>11.1</td>
<td>1.10</td>
</tr>
<tr>
<td>14</td>
<td>4.125</td>
<td>0.625</td>
<td>9.</td>
<td>9.77</td>
<td>11.44</td>
<td>109.2</td>
<td>14.9</td>
<td>1.21</td>
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<tr>
<td>15</td>
<td>5.312</td>
<td>0.250</td>
<td>11.</td>
<td>5.23</td>
<td>6.13</td>
<td>91.8</td>
<td>14.4</td>
<td>1.40</td>
</tr>
<tr>
<td>16</td>
<td>5.312</td>
<td>0.312</td>
<td>11.</td>
<td>6.49</td>
<td>7.60</td>
<td>118.5</td>
<td>17.7</td>
<td>1.42</td>
</tr>
<tr>
<td>17</td>
<td>5.312</td>
<td>0.562</td>
<td>11.</td>
<td>11.32</td>
<td>13.27</td>
<td>198.5</td>
<td>29.8</td>
<td>1.51</td>
</tr>
<tr>
<td>18</td>
<td>5.812</td>
<td>0.25</td>
<td>12.</td>
<td>5.73</td>
<td>6.71</td>
<td>128.5</td>
<td>19.0</td>
<td>1.53</td>
</tr>
<tr>
<td>19</td>
<td>5.812</td>
<td>0.315</td>
<td>12.</td>
<td>7.11</td>
<td>8.40</td>
<td>186.0</td>
<td>27.5</td>
<td>1.57</td>
</tr>
<tr>
<td>20</td>
<td>5.812</td>
<td>0.625</td>
<td>12.</td>
<td>13.75</td>
<td>16.11</td>
<td>288.5</td>
<td>45.3</td>
<td>1.67</td>
</tr>
</tbody>
</table>

1. Ratings are based on 30°C rise over 40°C ambient temperature in still but unconfined air for usual indoor conditions (e = 0.35), and for 2 ft/sec cross wind for usual outdoor conditions (e = 0.50).
2. For temperature rise of 50°C above 40°C ambient, an increase of about 30 percent of current rating indoors is generally in accordance with tests. (See Fig. 13-11.)

13-60
### TABLE 13-31

Properties of Uniform Thickness Angle Bus Conductors
6101-T6 Alloy 55.0% IACS Conductivity (minimum)\(^\text{(4)}\)

<table>
<thead>
<tr>
<th>W in.</th>
<th>T in.</th>
<th>Area Sq. in.</th>
<th>Wt lb/ft</th>
<th>(2) Moment of Inertia in.(^4)</th>
<th>(2) Moment of Inertia about Neutral Axis</th>
<th>Minimum Distance to Neutral Axis</th>
<th>Inductive Reactance 1 ft spacing 60 Hz—X, microhms/ft</th>
<th>dc Resistance at 70°C microhms/ft</th>
<th>R(<em>{ac})/R(</em>{dc}) at 70°C 60 Hz</th>
<th>ac Resistance at 70°C microhms/ft</th>
<th>ac (1) Current Ratings Amp—60 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>3(\frac{1}{4})</td>
<td>1/8</td>
<td>1.56</td>
<td>1.83</td>
<td>1.60</td>
<td>0.65</td>
<td>0.91</td>
<td>1.28</td>
<td>51.41</td>
<td>11.23</td>
<td>1.024</td>
<td>11.50</td>
</tr>
<tr>
<td>4</td>
<td>1/4</td>
<td>1.93</td>
<td>2.27</td>
<td>3.04</td>
<td>1.22</td>
<td>1.09</td>
<td>1.55</td>
<td>46.60</td>
<td>9.06</td>
<td>1.045</td>
<td>9.46</td>
</tr>
<tr>
<td>4(\frac{5}{8})</td>
<td>3/16</td>
<td>2.85</td>
<td>3.36</td>
<td>4.36</td>
<td>1.77</td>
<td>1.14</td>
<td>1.61</td>
<td>46.62</td>
<td>6.13</td>
<td>1.115</td>
<td>6.84</td>
</tr>
<tr>
<td>4(\frac{1}{2})</td>
<td>1/8</td>
<td>3.23</td>
<td>3.80</td>
<td>6.30</td>
<td>2.55</td>
<td>1.26</td>
<td>1.79</td>
<td>43.93</td>
<td>5.42</td>
<td>1.145</td>
<td>6.20</td>
</tr>
<tr>
<td>5</td>
<td>3/16</td>
<td>3.60</td>
<td>4.24</td>
<td>8.74</td>
<td>3.54</td>
<td>1.39</td>
<td>1.96</td>
<td>41.52</td>
<td>4.86</td>
<td>1.175</td>
<td>5.70</td>
</tr>
</tbody>
</table>

1. Indoor current ratings are based on 30°C rise over 40°C ambient in still but unconfined air, normally oxidized surface (\(e = 0.35\)). Outdoor ratings are based similarly, but with 2 ft/sec crosswind (\(e = 0.50\)). Horizontal mounting is assumed with spacing sufficient to eliminate proximity effects, generally assumed to be 18-in. or over. Indoor ratings based on work by House and Tuttle. Outdoor ratings from IEEE paper by Prager, Pemberton, Craig, Bleshman (22).

2. Back-to-back angles are to be considered as separate members; not as a composite.

3. Alignment grooves are extruded to facilitate centering of holes according to NEMA standard spacings.

4. A modification of this design (see Fig. 13-5k) has a lug at top that does not interfere with bolting, yet it strengthens the shape against tendency to roll-over to the z-z axis in long spans subjected to large lateral short circuit forces. For equal weight of shape, the z-z radius of gyration is increased 20 percent. The stress that causes roll-over is thereby increased about 40 percent.

5. See page 13-66 for additional information regarding this table.

---

### Notching Dimensions

<table>
<thead>
<tr>
<th>Angle</th>
<th>Notching</th>
<th>Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>3(\frac{1}{4}) (\times) 1/4</td>
<td>A</td>
<td>1.50</td>
</tr>
<tr>
<td>4 (\times) 1/4</td>
<td></td>
<td>1.875</td>
</tr>
<tr>
<td>4 (\times) 3/8</td>
<td></td>
<td>1.875</td>
</tr>
<tr>
<td>4(\frac{1}{2}) (\times) 3/8</td>
<td></td>
<td>2.187</td>
</tr>
<tr>
<td>5 (\times) 3/8</td>
<td></td>
<td>2.313</td>
</tr>
</tbody>
</table>

---

**Diagram:**

- Notch Detail
- Some Notching on Other Leg
- 0.02 IN.
- 0.06 IN.
- Notch
- A
- W
- X
- Y
- Z
- B
- C
- D

---

13-61
### TABLE 13-32

Properties of Integral-Web Channel Bus Conductors

6101-T61 Alloy (IACS 58% typical)

<table>
<thead>
<tr>
<th>Size (See Sketch)</th>
<th>Wall Thickness</th>
<th>Area sq. in.</th>
<th>Wt lb/ft</th>
<th>Moment of Inertia, in.²</th>
<th>dc Resistance Rₙₚ=70°C microhms per ft</th>
<th>Current Rating dc Rₘₚ=70°C e = 0.35 Indoors</th>
<th>Inductive Reactance 1 ft spacing 60 Hz = Xₙ=70°C microhms per ft</th>
<th>ac 60 Hz Resistance Rₙₚ=70°C microhms per ft</th>
<th>Current Rating ac—60 Hz Indoor e = 0.35 Outdoor e = 0.50</th>
</tr>
</thead>
<tbody>
<tr>
<td>A in.</td>
<td>B in.</td>
<td>4</td>
<td>4</td>
<td>0.156</td>
<td>2.439</td>
<td>2.87</td>
<td>3.876</td>
<td>6.213</td>
<td>6.88</td>
</tr>
<tr>
<td>T in.</td>
<td>4</td>
<td>0.250</td>
<td>3.781</td>
<td>4.45</td>
<td>5.788</td>
<td>9.216</td>
<td>4.42</td>
<td>2810</td>
<td>39.76</td>
</tr>
<tr>
<td>4</td>
<td>0.312</td>
<td>4.46</td>
<td>5.25</td>
<td>6.892</td>
<td>10.94</td>
<td>3.75</td>
<td>3050</td>
<td>40.8</td>
<td>1.05</td>
</tr>
<tr>
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<td>0.250</td>
<td>4.78</td>
<td>5.62</td>
<td>16.35</td>
<td>12.74</td>
<td>3.50</td>
<td>3480</td>
<td>34.8</td>
</tr>
<tr>
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<td>4</td>
<td>0.375</td>
<td>6.02</td>
<td>7.08</td>
<td>14.5</td>
<td>14.0</td>
<td>2.78</td>
<td>3900</td>
<td>36.6</td>
</tr>
<tr>
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<td>4</td>
<td>0.375</td>
<td>6.95</td>
<td>8.17</td>
<td>22.91</td>
<td>17.45</td>
<td>2.41</td>
<td>4200</td>
<td>—</td>
</tr>
<tr>
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<td>8.94</td>
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<td>29.78</td>
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<td>29.73</td>
<td>45.98</td>
<td>1.95</td>
<td>5020</td>
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<td>5730</td>
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<td>7</td>
<td>7</td>
<td>0.500</td>
<td>12.84</td>
<td>15.10</td>
<td>64.83</td>
<td>95.87</td>
<td>1.30</td>
<td>6530</td>
<td>27.6</td>
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<tr>
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<td>5350</td>
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<td>11.75</td>
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<td>68.84</td>
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<td>1.42</td>
<td>6090</td>
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<td>5</td>
<td>0.500</td>
<td>16.12</td>
<td>18.96</td>
<td>103.5</td>
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<td>9</td>
<td>0.625</td>
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<td>23.57</td>
<td>162.3</td>
<td>240.1</td>
<td>0.84</td>
<td>9060</td>
<td>21.6</td>
</tr>
<tr>
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<td>10</td>
<td>0.625</td>
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<td>27.64</td>
<td>255.6</td>
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<td>0.71</td>
<td>10260</td>
<td>19.1</td>
</tr>
<tr>
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<td>11</td>
<td>0.625</td>
<td>26.16</td>
<td>30.76</td>
<td>281.7</td>
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<td>11260</td>
<td>16.9</td>
</tr>
<tr>
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<td>12</td>
<td>0.625</td>
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<td>312.0</td>
<td>653.0</td>
<td>0.52</td>
<td>12980</td>
<td>15.8</td>
</tr>
</tbody>
</table>

1. Current ratings are based on 6101-T61 alloy with standard vent-holes in web. For 6101-T6 reduce rating by 2 percent. Indoor ratings are based on 30°C rise over 40°C ambient in still but unconfined air, normally oxidized surface (e = 0.35) and similarly for outdoor ratings, except 2 ft/sec cross wind (e = 0.50). Horizontal mounting is assumed with spacing sufficient to eliminate proximity effects, generally assumed to be 18-in. or over. For temperature rise of 50°C above 40°C ambient, the indoor ratings for 30°C rise may be increased about 30 percent. (See Fig. 13-11.)

Indoor ratings (dc and ac) calculated by computer and verified by tests, rounded. Outdoor ratings are calculations only. More test work is needed for outdoor.

2. The sketch only approximates a typical outline. For vent and notch arrangements consult supplier. The interior perimeter varies according to the washer diameters that are to be accommodated, and as to their location per NEMA spacing. The 12 in. x 12 in. size is a composite of two symmetric extrusions bolted together.

See also page 13-67 for additional information regarding this table.

For standard vent diameter and spacing, and notch-groove arrangements, consult suppliers.
APPENDIX 13A

Notes To Tables 13-25 Through 13-32

General

1. Aluminum weights are computed on basis of 0.098 lb. per cu. in.
2. Elements of sections for rectangles, tubes and equal angles calculated from following relationships.

### RECTANGLE

<table>
<thead>
<tr>
<th>A</th>
<th>( \frac{bd}{2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>( \frac{d}{2} )</td>
</tr>
<tr>
<td>( l_{i-1} )</td>
<td>( \frac{bd}{12} )</td>
</tr>
<tr>
<td>( s_{i-1} )</td>
<td>( \frac{bd}{6} )</td>
</tr>
<tr>
<td>( r_{i-1} )</td>
<td>( \frac{d}{\sqrt{12}} )</td>
</tr>
</tbody>
</table>

### CIRCLE

\[ A = \frac{\pi d^2}{4} = 0.785398 d^2 \]

### EQUAL ANGLE

\[ A = \frac{t(b+c)}{2} \]

\[ x = \frac{b^2 + ec}{2(b + c)} \]

\[ y = x \]

\[ a = 45^\circ \]

\[ I_{i-1} = \frac{1}{3} \left( b - x \right)^2 + \frac{1}{3} \left( b - x \right)^2 \]

\[ I_{i-2} = \frac{1}{3} \left( b - x \right)^2 \]

\[ I_{i-1} = \frac{1}{2} \left( b - x \right)^2 + \frac{1}{3} \left( b - x \right)^2 + \frac{1}{4} \left( b - x \right)^2 + \frac{1}{6} \left( b - x \right)^2 \]

\[ e = 0.35, \; T_a = 40^\circ C, \; T_c = 70^\circ C, \; R\text{dc} \text{ at } 70^\circ C = 4.245 \times 10^{-6} \text{ ohms} \]

\[ W_c = 0.0275 P_c \left( \frac{t_c - t_a}{L} \right)^{0.25} \]

where \( P_c = 4 \times 8.5 = 34 \text{ in.} \)

\[ L = 4 \text{ in.} \]

\[ = 0.0275 \times 34 \left( \frac{30}{4} \right)^{0.25} \]

\[ = 46.419 \text{ watt/ft.} \]
bus conductors

\[ W_{rm} = 0.0439 \, P_{rm} \cdot e \left[ \left( \frac{K_C}{100} \right)^4 - \left( \frac{K_A}{100} \right)^4 \right] \]

where \( P_{rm} = 10 \) in.

\( e = 0.35 \) bars

\( = 0.95 \) openings

\[ = 0.0439 \times 10 \times 0.35 \left[ \frac{343}{100} \right]^4 - \left( \frac{313}{100} \right)^4 \]

\[ = 6.520 \text{ watt/ft. for metal surfaces} \]

\[ W_{ri} = 0.0439 \, P_{ri} \cdot e \left[ \left( \frac{K_C}{100} \right)^4 - \left( \frac{K_A}{100} \right)^4 \right] \]

where \( P_{ri} = 2 \times 3 \times 0.25 = 1.5 \) in.

\[ = 0.0439 \times 1.5 \times 0.95 \times (42.33) = 2.655 \text{ watt/ft. for open bar spacing} \]

\[ W = 46.419 + 6.520 + 2.655 = 55.594 \]

\[ I = \left( \frac{\Sigma W}{R_{dc \text{ at } 70^\circ C}} \right)^{\frac{1}{2}} = \left( \frac{55.594}{4.245 \times 10^{-6}} \right)^{\frac{1}{2}} \]

\[ = 3,619 \text{ amperes} \]

**Table 13-27**

*Physical and Electrical Properties of Aluminum Standard Pipe Size Conductors at Typical Conductivities*

1. Ampacity values calculated from House-Tuttle formulas

2. Example (Refer to Ampacity discussion):
   - 4 in. Schd. 40 6063-T6 Pipe Conductor Outdoor Services, \( e = 0.5 \), wind 2 ft/sec, no sun.

\[ W_c = 0.1695 \left( \frac{D_{pf} V}{\mu f} \right)^{0.6} K_f (t_c - t_a) \]

where \( D = 4.5 \) in.

\( pf = 0.0672 \) (from Table 13A-1)

\( V = 2 \times 3600 \) (for 2 ft/sec wind)

\( \mu f = 0.0478 \) (from Table 13A-1)

\( K_f = 0.00864 \) (from Table 13A-1)

\( t_c = 70^\circ C \)

\( t_a = 40^\circ C \)

\[ W_c = 0.1695 \left( \frac{4.5 \times 0.0672 \times 7200}{0.0478} \right)^{0.6} \times 0.00864 \times (70-40) \]

\[ = (4.5)^{0.6} 11.1165 \]

\[ = 27.409 \text{ watts/ft.} \]

\[ W_r = 0.138 \, D \, e \left[ \left( \frac{K_C}{100} \right)^4 - \left( \frac{K_A}{100} \right)^4 \right] \]

where \( D = 4.5'' \)

\( e = 0.5 \)

values of \( K \) from Table 13A-1.

\[ W_r = 0.138 \times 4.5 \times 0.5 [138.41 - 95.98] \]

\[ = 13.1745 \]

\[ \Sigma W = 27.409 + 13.1745 = 40.5835 \]

\[ I_{ac} = \left( \frac{\Sigma W}{R_{dc \text{ at } 70^\circ C}} \right)^{0.5} \]

\[ = \left( \frac{40.5835}{5.717 \times 10^{-6}} \right)^{0.5} \]

\[ = 2,664 \text{ amperes} \]
TABLE 13A-1
Viscosity, Density at Sea Level to 15,000 Ft, and Thermal Conductivity of Air

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Absolute Viscosity, ( \mu_t )</th>
<th>Density, ( \rho_t )</th>
<th>Thermal Conductivity ( k_t )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( F^\circ )</td>
<td>( C )</td>
<td>( K )</td>
<td>( \left( \frac{K}{100} \right)^4 )</td>
</tr>
<tr>
<td>32</td>
<td>0</td>
<td>273</td>
<td>55.55</td>
</tr>
<tr>
<td>41</td>
<td>5</td>
<td>278</td>
<td>59.73</td>
</tr>
<tr>
<td>50</td>
<td>10</td>
<td>283</td>
<td>64.14</td>
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<tr>
<td>59</td>
<td>15</td>
<td>288</td>
<td>68.80</td>
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<tr>
<td>68</td>
<td>20</td>
<td>293</td>
<td>73.70</td>
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<tr>
<td>77</td>
<td>25</td>
<td>298</td>
<td>78.86</td>
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<td>66</td>
<td>30</td>
<td>303</td>
<td>84.29</td>
</tr>
<tr>
<td>95</td>
<td>35</td>
<td>308</td>
<td>89.99</td>
</tr>
<tr>
<td>104</td>
<td>40</td>
<td>313</td>
<td>95.98</td>
</tr>
<tr>
<td>113</td>
<td>45</td>
<td>318</td>
<td>102.26</td>
</tr>
<tr>
<td>122</td>
<td>50</td>
<td>323</td>
<td>108.85</td>
</tr>
<tr>
<td>131</td>
<td>55</td>
<td>328</td>
<td>115.74</td>
</tr>
<tr>
<td>140</td>
<td>60</td>
<td>333</td>
<td>122.96</td>
</tr>
<tr>
<td>149</td>
<td>65</td>
<td>338</td>
<td>130.52</td>
</tr>
<tr>
<td>158</td>
<td>70</td>
<td>343</td>
<td>138.41</td>
</tr>
<tr>
<td>167</td>
<td>75</td>
<td>348</td>
<td>146.66</td>
</tr>
<tr>
<td>176</td>
<td>80</td>
<td>353</td>
<td>155.27</td>
</tr>
<tr>
<td>185</td>
<td>85</td>
<td>358</td>
<td>164.26</td>
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<tr>
<td>194</td>
<td>90</td>
<td>363</td>
<td>173.63</td>
</tr>
<tr>
<td>203</td>
<td>95</td>
<td>368</td>
<td>183.40</td>
</tr>
<tr>
<td>212</td>
<td>100</td>
<td>373</td>
<td>193.57</td>
</tr>
</tbody>
</table>

*Degrees Fahrenheit.

\( \mu_t \) = absolute viscosity, lb/(hr)(ft).

\( \rho_t \) = density, lb of air/ft².

\( k_t \) = thermal conductivity of air, watts/(sq ft)(C) at \( t_a = (t_c + t_f)/2 \).

\( t_a \) = ambient temperature °C.

\( t_c \) = conductor temperature °C.

bus conductors

Table 13-28

Physical and Electrical Properties of Large Diameter Round-Tube Bus Conductors, 6101-T61

1. Ampacity values calculated from House-Tuttle formulas.
2. Example (Refer to Ampacity discussion)
   8 in. O.D. by 0.500 in. wall, 6101-T61 indoor service, e = .35

\[ W_c = 0.072 \times D^{0.75} \times (t_c - t_a)^{1.25} \]

where \( D = 8 \text{ in.}, t_c = 70^\circ C, t_a = 40^\circ C \)

\[ W_c = 0.072 \times (8)^{0.75} \times (70 - 40)^{1.25} = 24.046 \]

\[ W_r = 0.138 \times D \times e \left( \frac{K_c}{100} \right)^4 - \left( \frac{K_a}{100} \right)^4 \]

where \( D = 8 \text{ in.}, K_c = 343^\circ K, K_a = 313^\circ K, e = 0.35 \)

\[ W_r = 0.138 \times 8 \times .35 [138.41 - 95.98] = 16.395 \]

\[
\frac{1}{L} = \frac{1}{LV_1 + LV_2} + \frac{1}{LH_1 + LH_2} = 1.685
\]

\[ \Delta t = 30 \]

\[ t_c = 70^\circ C \]

\[ t_a = 40^\circ C \]

\[ W_c = 0.027 \times 6.75 \times \left( \frac{30}{1.685} \right)^{0.25} \times (70-40) = 11.23 \text{ watts/ft.} \]

\[ W_r = 0.0439 \times P_r \left( \frac{K_c}{100} \right)^4 - \left( \frac{K_a}{100} \right)^4 \]

\[ P_r = \text{total exposed perimeter (13 in.)} \]

\[ W_r = 0.0439 \times 13 \times .35 [138.41 - 95.98] = 8.48 \text{ watts/ft.} \]

\[ \Sigma W = 11.23 + 8.48 = 19.71 \]

\[
I = \left( \frac{\Sigma W}{R_{ac \text{ at } 70^\circ C}} \right)^{1/2} = \left( \frac{19.71}{11.47 \times 10^{-6}} \right)^{1/2} = 1,311 \text{ rounded to } 1,300 \]

Table 13-31

1. \( X_a \) values from work by W.A. Lewis for Alcoa.
2. Outdoor ampacity from IEEE paper by Prager, Pemberton, Craig, Bleshman (22)
3. Indoor ampacity based on formulas developed by House-Tuttle and verified by extensive tests.

Example:
3-1/4 in. x 3-1/4 in. x 1/4 in. UABC, 6101-T6
Indoor service, e = .35, \( R_{ac} \) at 70\(^\circ\)C = 11.47
Table 13-32

Properties of Integral - Web Channel Bus Conductors

1. $X_a$ values from work by W.A. Lewis for Alcoa

2. Ampacity based on formulas developed by House-Tuttle. Indoor values based on tests data. Typical conductivity used because of better correlation with test points. Test work needed for outdoor values since it is not known how wind would affect this shape. However, it appears from theoretical studies that the results may have an accuracy of ±10%.

Example:

6 in. x 6 in. x .0550 in., ventilated, 30°C rise over 40°C

Radiated Heat

$$W_r = 0.0439 P_r e \left[ \left( \frac{K_c}{100} \right)^4 - \left( \frac{K_a}{100} \right)^4 \right]$$

where: $P_r$ = exposed perimeter in inches

$$= (2 \times \text{heights} + 2 \times \text{width})$$

$e$ = emissivity

Test showed value of 0.47, combination of surface and slots for new bus.

0.35 is conservative.

$$W_r = 0.0439 \times 24 \times .35 \left[ \left( \frac{343}{100} \right)^4 - \left( \frac{313}{100} \right)^4 \right]$$

$$= 15.65 \text{ watts/ft.}$$

Convection Loss (Free Air)

$$W_c = 0.026 P_c \left( \frac{\Delta t}{L} \right)^{0.25} (t_c - t_a)$$

$\Delta t = t_c - t_a$ in degrees C = 70 - 40 = 30

$$\frac{1}{L} = \frac{1}{\text{height}} + \frac{1}{\text{width}}$$

$$L = \frac{H \times W}{H + W} = \frac{36}{12} = 3.00$$

$$W_c = 0.026 \times 24 \left( \frac{30}{3.00} \right)^{0.25} \times (30)$$

where $P_c$ = nominal perimeter-inches

$$= 33.29 \text{ watts/ft.}$$

$$I = \left( \frac{\sum W}{R_{ac \ at \ 70°C}} \right)^{1/2}$$

where $R_{ac \ at \ 70°C} = 1.82$, typical

$$I = \left( \frac{15.65 + 33.29}{1.82 \times 10^{-6}} \right)^{1/2}$$

$$= 5,186 \text{ rounded to 5,190 amperes}$$


bus conductor design and applications


40. J.R. Greenwood, “Area of Contact Between Rough Surfaces and Faults.”


47. Stewart, H.J., "Belleville Spring Washers," Fasteners, Vol. 9, No. 5


51. ANSI Standard C37.23


59. Hagemoen, S.W., "Improving the Capacity of a High Current D-C Bus," Ref: IEEE PCI-76-52, Conference Record 76CH1109 8-1A.


Chapter 14

Aluminum Magnet Conductor

During the 1950-1960 period when aluminum conductors began to displace copper in overhead transmission and distribution and a large effort was started to evaluate aluminum in the insulated cable field, some attention was also directed to aluminum magnet wire. These early efforts were confined to round 1350 aluminum wire in the fully annealed or partly annealed condition using conventional and new magnet wire insulations. Results from an economic viewpoint were only moderately successful and, in order to achieve better space factors, an anodized film was used as turn insulation. However, at almost this same time it became apparent that thin aluminum strip conductor in the form of anodized foil or foil interleaved with a suitable insulating film would eliminate many of the magnet wire problems previously experienced. The subsequent development of aluminum foil or strip magnet conductor has successfully achieved a new order of improvement in electromagnetic coil design.

In transformer practice, aluminum conductors have lower stray losses than copper conductors for a given size. This is because the eddy current losses are an inverse function of resistivity of the conductor. This advantage for aluminum is offset by the fact that larger conductor sizes are needed for equal resistances. On balance, aluminum windings, with resistances equal to copper windings of similar design, have about 3% lower stray losses.

Aluminum Magnet Wire (Round, Square, Rectangular)

As previously indicated, the first use of aluminum magnet wire was as a film-insulated round wire. This type of conductor is now available in virtually all AWG sizes as it is for copper magnet wire (No. 4 through No. 26 or finer AWG) and with all conventional insulation including class 105, class 130, class 155 and class 200.

Certain small, fractional horsepower motors, mainly in the washer and dryer appliance field, are designed now exclusively with round aluminum insulated wire. However, the greatest increase in growth has been in the use of rectangular and square aluminum magnet wire in distribution, small power and dry type transformers, both bare and tape insulated with Aramid, thermally upgraded paper and crepe paper. Tape-insulated aluminum, in comparison to film-insulated aluminum of the same temper, size and shape, usually has a higher tensile strength due to the tape. Film-insulated conductors must be processed through a curing oven which results in total or partial anneal of the wire. Therefore, taped conductor can have a higher temper which results in much higher tensile and yield strengths. Taped conductors also have greater resistance to mechanical stresses and abuse, making them easier to wind and more resistant to the effects of electrical short circuit forces at elevated temperatures. Many of these applications can be served by 1350 aluminum, but there is a substantial demand for commercially available alloys possessing higher yield strength while maintaining conductivity of 61 percent as a minimum.

Since annealed 1350 aluminum has a tensile strength of 12,000 psi as compared to 35,000 psi for annealed copper, coil winding operations must be modified somewhat but once the necessary adjustments have been made aluminum magnet wire may be handled readily and rapidly.

Conventional aluminum magnet wire possesses a number of advantages over copper in both economic and technical aspects.

Light Weight

Aluminum, with a density of 2.703 grams per cubic centimeter at 20°C has less than one-third the density of copper and weighs one-half as much as a copper conductor of equal resistance and equal length.

The lighter-weight conductor is of advantage in most electrical equipment for transformers, especially coils, and motors in portable equipment or in air-borne, missile, or space-vehicle applications where reduced component weight allows vital additional payload.

Generally superior performance can be expected when aluminum magnet wire is used for rotating and other moving windings. The lower mass of aluminum designs results in lower inertia—improving performance of a wide variety of equipment.

In rotary equipment, low mass simplifies dynamic balancing. Because vibration from dynamic imbalance is
TABLE 14-1
Springback Comparison Chart

<table>
<thead>
<tr>
<th>Wire Size (AWG)</th>
<th>Degree of Angular Springback* (Typical figures)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Copper</td>
<td>Aluminum</td>
<td></td>
</tr>
<tr>
<td>AWG 18</td>
<td>54°</td>
<td>38°</td>
<td></td>
</tr>
<tr>
<td>AWG 16</td>
<td>46°</td>
<td>32°</td>
<td></td>
</tr>
<tr>
<td>AWG 14</td>
<td>38°</td>
<td>26°</td>
<td></td>
</tr>
</tbody>
</table>

* In “degrees per turn” when tested per NEMA publication MW-1000/1967 Part 3, Par. 2.2.5.

reduced, aluminum construction contributes to longer operating life of rotary apparatus.

Lower mass also results in higher sensitivity and response in moving coil applications. Manufacturers can take advantage of this characteristic in the design of electrical instruments and acoustical devices.

Significant weight reductions of coils can also lower shipping and handling costs. Dramatically lower spool weights reduce operator fatigue by making it easier to load the winding machines.

Windability

Because annealed aluminum magnet wire has a low yield strength (approximately 4000 psi), little strain energy is required to conform it to an arbor. This quality is noticeable in practice: rectangular coil sides have less bow than similar copper coils; end turns on a motor stator are shorter; all coils are more compact; and operator fatigue is reduced in hand winding operations. The most striking aspect of this lower springback is reduction in winding tension. Even though aluminum wire may be two gauges larger than copper, machines run faster, and they readily handle aluminum wire four sizes larger than the largest copper gauge they can handle. Operators have no problem threading machines or advancing the wire. Table 14-1 presents some comparative springback data provided by a manufacturer of magnet wire.

Thermal Characteristics

Tests indicate that insulations applied to aluminum can be expected to operate one IEEE temperature classification* higher than the same insulation applied to copper, and still have equal life; for example, a class 105 insulation for copper can be used as class 130 insulation for aluminum.

Insulations applied to aluminum have longer life at the same operating temperature than the same insulation applied to copper. The mechanical properties of insulation on thermally aged magnet wire show a marked advantage for aluminum. In certain applications, where electrical losses are not a problem, designers have used these advantages (higher temperature operation and good mechanical properties after aging) for both economic and space reasons by using aluminum magnet wire only one or one-and-a-half sizes larger than copper, rather than the rule-of-the-thumb two sizes.

Fig. 14-1 was provided by a manufacturer of aluminum magnet wire and gives data on the aging of aluminum vs. copper magnet wire insulated with a variety of materials.

Economic Factors

Through lower initial cost and other savings due to aluminum's advantages, manufacturers can realize significant improvements in product cost control.

In the size range No. 8 AWG through No. 24 AWG, aluminum film-insulated round magnet wire costs less per unit of length than its equivalent copper conductor. These savings run from 15 to 25 percent and more in the heavy gauges.

Coil Design

Engineering with aluminum magnet wire is not different fundamentally from engineering with copper wire, but some allowances do have to be made. Because aluminum has a lower conductivity than copper, designers often must find space to increase the wire gauge by two sizes. In changing from copper to aluminum, some engineers may prefer to develop an entirely new coil design. Sometimes modification of existing designs will be sufficient. Sometimes, it is discovered that an existing unit allows sufficient space to accommodate the larger aluminum coil without major revisions. Usually, however, for optimum results it is necessary to redesign the unit (e.g., distribution transformer primaries).

Apparatus with Stamped Laminations: When there is insufficient space for an easy substitution of aluminum for copper, redesign of transformers and similar apparatus using scrapless laminations will usually involve one or two kinds of changes. It may be necessary to increase stack height to accommodate an aluminum coil of fewer turns of large wire, or a different lamination may be necessary. If the designer must change lamination size, he has, in effect, developed an entirely new design.

Apparatus with Wound Cores: For apparatus using wound cores the procedure is nearly the same as for scrapless lamination. However, considering the moderate increase in cost for special core designs, this family of electrical devices yields the greatest return when completely new designs are used.

Optimum designs for aluminum wire require different
core dimensions than are used with copper. A typical copper design has a window area one-half of its central core area, stack height 1½ times core width, and a window length 1½ times window width. In the finished product, coil weight is about 33% of the total. Such a design probably is very close to minimum material costs.

But for aluminum, the window area is approximately 75% greater than core area, stack height 2 to 2½ times core width and the window length 2 to 2½ times window width. In the finished product, aluminum-coil weight would be approximately 40% of the total. Such a design, which constitutes a complete departure from standard practice, is most practical with tape-wound cores.

**Motors:** Many classes of motors lend themselves readily to redesign with aluminum magnet wire. In particular, shaded-pole types often have sufficient space for an easy substitution of aluminum. Induction motors may have space for a change in wire size of one or one-and-a-half gauges. This change together with shortened end turns may be sufficient for a simple substitution. As with transformers, stack length can be increased or a larger lamination can be used.

**Other Devices:** In general, the same information applies to all other magnetic devices which a designer wishes to convert to aluminum windings. If the necessary extra space does not already exist, it must be provided by modification or redesign on the entire device.

**Means of Minimizing Coil Size:** In copper-wound electromagnets, the design flux density of the pole piece is often conservative, and the pole-piece diameter can safely be reduced by 10 to 15 percent. This approach of reducing the inside diameter of the coil is better than increasing the outside coil diameter because it lowers the mean turn length while it provides the extra space required for larger gauge wire.

There are various measures available for minimizing size of wound coils. Coils can be precision wound instead of random wound. Bobbins can be made smaller—sometimes they can be eliminated altogether. Coil operating temperatures can be raised—with moderate temperature increases, aluminum coils still have longer life than copper coils. Finally, as a result of a thoroughgoing redesign particularly of an older item in a product line, the new device and its aluminum coil may operate cooler.

Often overlooked are the opportunities to modify existing windings, if only slightly, to take advantage of aluminum magnet wire’s economic benefits. Through close attention to coil configuration, the designer can employ previously wasted space to accommodate windings even though it may alter the basic shape of the coil. Sometimes, only one additional turn per layer or special contouring of the winding to fit special cavities will use a space for maxi-
electromagnetic and other electrical applications of aluminum

Since cases of redesign for aluminum wire are highly individual, some manufacturers maintain a coil-prototype laboratory to help customers with aluminum application designs by winding experimental coils and demonstrating techniques of joining.

**Coil Connections**

Joining aluminum coils to lead wires is not a laboratory curiosity; it is done in everyday production. The joining and termination of insulated aluminum wire—which has been a source of concern to many coil makers—can be easily done with mechanical connectors.

**Mechanical Termination:** Mechanical termination and splicing methods have been developed which are highly effective and low in cost. These methods employ machine-applied compression terminals with serrated barrels, such as those shown in Fig. 14-2.

This mechanical connection has numerous features that make it more efficient and more economical than conventional joining and termination methods. A one-step, machine-applied process combines low labor costs with high production speeds of up to 4000 terminations per hour. Top quality terminations and splices are exceptionally reproducible—and the resulting low rejection rate helps increase output while reducing scrap costs.

A considerable number of environmental tests, developed by the manufacturers, have proved this method to be highly reliable. Millivolt drops and temperature rise are essentially the same as the best of connections made carefully by other methods. There’s no damage to insulation from heat, stripper residues, or soldering fluxes.

**Soldering:** A secondary method of splicing and terminating is by soldering. Aluminum can be soldered using the same tools and techniques as copper, but requires special procedures and solder and flux. Information about procedures for soldering aluminum is available from various manufacturers on request.

**Aluminum Strip Magnet Conductor**

Strip conductor by definition is a flat, flexible metal strip usually produced by slitting a supply roll of proper gage metal into required widths for the finished product. The resulting conductor has a rectangular cross-section with a large width to thickness ratio; a broad range of widths and thicknesses are available.

Aluminum strip magnet conductor is usually made from either 1350 grade aluminum or 1235 aluminum alloy. Although 1350 grade metal will be principally discussed in what follows, technical data are included for both alloys and are compared to electrolytic copper.

**Strip Magnet Conductor Insulation**

Aluminum strip magnet conductor may be insulated by extremely thin, high dielectric strength anodized films; by interleaved (wider) films of a variety of high grade insulating materials; or by the deposition and bonding of insulating coatings. All of these methods require some special treatment of the strip surfaces and edges.

**Anodized Films:** Early developments by the aluminum industry clearly recognized the possibilities of using anodic films for the electrical insulation of aluminum conductors. Aluminum oxide exists to some extent on all aluminum in the form of a microscopically thin layer and provides aluminum with its excellent corrosion resistance. By the use of anodizing techniques, this thin layer can be expanded into a hard, inelastic and highly insulating film in the order of three ten-thousandths of an inch thick. This anodic film is desirable in many applications because of its hardness, abrasion resistance and high breakdown potential for a given thickness and high temperature rating.

Early work was directed at anodizing round aluminum conductors. A satisfactory film was obtained on straight conductor but bending sometimes resulted in crazing at
the outside radius of the bend and an actual extrusion of metal through similar cracks on the inside radius. Developments were directed toward anodizing a relatively wide and thin strip of aluminum having the same cross-sectional area as the round conductor. The bending problem was overcome by going to a strip, but the edges were almost impossible to anodize. By utilizing a chemical and mechanical treatment of the ragged, non-uniform edges, a surface that could be anodized adequately was obtained. The results of the fabrication process for anodized strip are considerably improved insulation efficiency and overall strength.

*Interleaved Insulation:* The thermal, mechanical, chemical and electrical requirements must be defined before an interleaving material can be selected.

Paper and polyester interleave as thin as .0005 inch have been used as turn insulation in electromagnetic coils wound with edge-conditioned strip conductor.

The width of the interleave is usually about 0.125 inch wider than the strip. Of course, this dimension may vary considerably—depending on the interleaving material, the coil and the equipment used to wind the coil.

Paper: Paper has a thermal rating of 90°C (Class O) and 105°C (Class A) or better when submerged in oil or impregnated. Because it is able to withstand large compressive forces and has good dielectric strength, it is usually the interleaving material used in oil-filled transformers and in coils that do not operate above 105°C.

Polyester: Polyester interleaving materials have a thermal rating of approximately 150°C which is between Class B, 130°C and Class F, 155°C. They have excellent dielectric strength, resistance to most chemicals and solvents and very high tensile strength. Polyester films are not compatible with some varnishes and are not generally recommended for use in oil-filled equipment. Under certain electrostatic conditions they have a tendency to attract foreign matter while being wound.

Aramid: Polyamide, such as DuPont "Nomex," has a thermal rating of 200°C (Class K). It is available in thicknesses of 2 mils and over. It has good abrasion resistance and can be wound on automatic equipment.

Asbestos: Asbestos treated with silicone or other high temperature varnish has a thermal rating of 220°C (Class H). It acts as a positive spacer and varnish absorbent. Silicone, polyester, epoxy and other varnishes are generally used to treat the asbestos fibers. (Lower thermal varnishes like epoxy bring the thermal rating down.) The use of this interleaving material is limited because it is a bulky insulation.

Teflon: Teflon has a thermal rating of 200°C per MIL-W-16878. (Teflon backed up by glass cloth to prevent cut-through has a much higher rating than 200°C.) It is very resistant to abrasion and has good chemical resistance and good dielectric strength. Teflon is more expensive than most other interleaving materials which limits its major application to aircraft and missile work.

Mica: Mica has a thermal rating of 220°C (Class C). It is sometimes used without a binder, but normally it is impregnated with silicone or other resins which may limit the temperature classification. Mica has good electrical properties but its tensile strength is low and it is bulky.

Glass: Glass has a thermal rating of 220°C (Class C). It also depends on binder thermal rating for its rating. It has excellent thermal endurance, acts as a positive spacer and is able to withstand the elements that deteriorate other insulations. It is used where dependability is an important factor. The major limitation is its poor space factor. Glass is sometimes used as a backing for other interleaving materials to provide tensile strength.

Coated Strip: Coated aluminum strip has also been developed for use in commercially available distribution transformers. Epoxy (Class B, 135°C), polyvinyl formal (Class A, 105°C), polyesters (Class F, 155°C), and the amide-imide polymer enamel coatings (200°C +) are used. Epoxy and polyamide-imide appear to be growing in favor.

Fig. 14-3: An aluminum to copper transition piece may be used to make aluminum to aluminum connection at the strip and to make a copper connection to a lead or terminal. The transition pieces are usually made by cold or flash welding.
Coil Design with Aluminum Strip Magnet Conductor

Aluminum strip magnet conductor can be designed into most electromagnetic devices when all of the parameters of the device as well as the characteristics of aluminum are taken into consideration.

Strip made of electrical conductor grade aluminum 1350 has a guaranteed conductivity from 61 to 62 percent IACS. 1350 aluminum strip conductors are designed for equal direct current (DC) resistance compared to a copper conductor must, therefore, have a larger cross-section area.

This means that the aluminum strip conductor will require about 60 percent more space than is needed for an equivalent copper conductor. Therefore, space conservation must be employed in designs where dimensions are critical. Because of its geometric shape, the aluminum strip conductor will utilize more of the allocated coil space than the equivalent round wire. This is graphically shown in Fig. 14-4. It is noted that for the same coil "window" opening the utilization of space by the conductor is much greater in the foil or strip form than for the usual insulated round shape. This, in large part, is due to the elimination of need for the wire insulation.

In addition to better space utilization, strip conductor offers the following advantages:

1. More rigid construction results in greater strength. No side supports are necessary for the strip wound coil.
2. Better heat dissipation—each turn is exposed to the outside and in flat surface contact with insulation of the next turn.
3. Lower voltage stress between turns—turn voltage gradient is layer voltage gradient.
4. Easier winding—no traverse guiding necessary.
5. Less supplementary insulation necessary.
7. Better short-circuit performance in transformer since each turn is centered in the magnetic field.
Winding Design Techniques With Strip Magnet Conductors

Many techniques can be employed to adapt strip conductor to coils previously wound only with round insulated wire. Coils for field windings of rotating equipment, for example, previously considered only for winding with round wire because of shape, are now wound with strip conductor and used in many different types and sizes of motors and generators.

This ability to post-form coils after winding allows the designer more flexibility. Coils can be wound on a round mandrel then formed into rectangular shape. This is advantageous because round coils are more easily adapted to winding on automatic high speed machines than are rectangular coils.

The per unit cost of conductor increases as the size decreases. It is, therefore, advantageous to control the amount of smaller conductor used on a coil assembly. A transformer is an assembly where this design technique can be utilized. The smaller winding of the primary containing many turns can be located next to the core where the mean turn length will be minimized. The amount of smaller conductor is kept to a minimum and the larger conductor of the secondary, which is the lower cost, is placed to the outside of the coil.

Coils containing two or more windings that must be balanced in impedance can be wound bifilar; that is, with the conductors of each winding physically paralleled and wound together with proper insulation between. The close coupling of the flat conductors results in the best possible balance in impedance between these windings.

The higher cost thin gauge conductors can sometimes be economically replaced by strip of heavier gauge and narrower width. This approach also decreases the amount of insulation required. The narrower coils can be wound and placed side by side on the core to utilize the available space. The cores can then be electrically paralleled with the same results as obtained with a coil of thinner, wider strip conductor.

These are but a few techniques the designer has at his disposal to arrive at the proper coil design.

Determination of Foil Size and Coil Characteristics

Direct current (dc) resistance of the aluminum strip magnet conductor coil can be determined by using the following formula:

\[
R_w = \frac{\rho \times 12(MLT)N \times 10^{-6}}{A} \text{ ohms at } 20^\circ C \quad (Eq. 14-1)
\]

Where:  
\( \rho \) = microhm-inches resistivity of 1350  
\( \rho = 1.09483 \) microhm-inches at 20°C  
MLT = mean length turn in feet  
N = number of turns  
A = cross sectional area of strip in square inches = W x t (width times thickness)

Then the winding resistance is:

<table>
<thead>
<tr>
<th>TABLE 14-2</th>
<th>Formulas For Calculating Weights And Resistances at 20°C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Aluminum*</td>
</tr>
<tr>
<td>Weight, lb per 1000 ft</td>
<td>1173 X A</td>
</tr>
<tr>
<td>Length, ft per lb</td>
<td>0.85336</td>
</tr>
<tr>
<td>dc resistance, ohms per 1000 ft</td>
<td>13.138 X 10^{-3} A</td>
</tr>
<tr>
<td>dc resistance, ohms per lb</td>
<td>11.212 X 10^{-6} A</td>
</tr>
</tbody>
</table>

*Based on aluminum at 62% conductivity where: A = nominal cross-sectional area of the wire in square inches.

\[
R_w = \frac{13.138(MLT)N \times 10^{-6}}{W x t} \text{ ohms at } 20^\circ C \quad (Eq. 14-2)
\]

Ohms per 1000 feet is calculated as:

\[
R_{1000} = \frac{13.138 x 10^{-3}}{W x t} \text{ ohms/1000 ft at } 20^\circ C \quad (Eq. 14-3)
\]

Inductance values for strip magnet conductor coils can be determined approximately by using conventional formulae for round wire wound coils. Tests performed to date indicate that inductance values for coils of the same number of turns and of the same shape and size will be approximately equal regardless of conductor shape.

Bunet* gives formulae for round and rectangular shaped coils of round wire which are beyond the scope of this work. These formulae generally yield accuracies between -4% and +4.7% depending on the coil dimensions. Since they are for approximation of inductance, they suffice for engineering needs and can be used for strip wound coils as mentioned above.

If the round copper wire size used in a coil is known, the conversion to aluminum strip conductor for an approximate equivalent coil is simple. The cross sectional area of the round copper conductor is increased by 64% to obtain the required cross sectional area of aluminum for equal dc resistance in a coil having equal length. This area of aluminum conductor is then dimensioned to obtain the required thickness and width. Fig. 14-5 provides a ready means for determining strip dimensions and also the corresponding dc resistance per 1000 ft. at 20°C.

The following example illustrates the ease with which aluminum strip conductor can be sized for an equivalent round copper wire wound coil:

Fig. 14-5. Aluminum strip conductor application. (Notes and data on Fig. 14-5 may be found on page following.)
Strip Conductor Equivalents

(Notes and data on Fig. 14-5 preceding)

The computation chart is used for obtaining approximate data useful in coil design.

Since the electrical conductivity of 1350 aluminum in this chart is 61% of copper, approximately 64% more aluminum by volume is required. A useful rule of thumb is: for equal conductivity—use 2 wire sizes larger than round copper, and 3 wire sizes larger than square copper.

Example:

A small solenoid coil is wound with 100 turns of No. 19 AWG enamelled round copper on a coil width of ½ inch. Aluminum Strip, electrically equivalent to No. 19 AWG copper, must have an area of .00167 sq. inches (approximately No. 17 AWG). From the chart a strip width of ½ inch requires a .0033 thickness. Slight adjustments may be necessary for choosing exact dimensions.

Resistance is determined by intersection of the .00167 area line and the appropriate resistance line. This resistance is found to be 7.8 ohms per 1000 ft. Weight calculated by formula 2 is found to be 2 lbs per 1000 ft.

FORMULAS FOR STRIP WOUND COILS

1. Resistivity

\[
 r = \frac{0.13138}{A}
\]

(Example continued from page 14-7)

A coil is wound with 100 turns of No. 1/0 AWG* square copper wire (.1022 sq. in.) and is 3 inches wide. Based on an aluminum conductivity of 62 percent IACS, the equivalent aluminum strip conductor will have an area of 1648 square inch (.1022/.62). From the Fig. 14-5 computation chart, the intersection of the lines corresponding to a 3-inch width and a .1648 square inch area gives a thickness of .055 inch. The resistivity is found to be .08 ohms per 1000 feet by locating the intersection of the .1648 sq. in. area line and the resistivity line.

Tables 14-2, -3, -4 and -5 provide additional data and formulas which are useful in strip conductor winding coil design calculations.

Dielectric and Thermal Advantages of Strip Magnet Conductor

Since a strip wound coil consists of a number of turns of film-insulated aluminum strip or strip interleaved with thin layers of strip insulation, the number of layers is equal to the number of turns and the layer to layer voltage is equal to the turn to turn voltage. This eliminates the high layer to layer voltage common on copper magnet wire coils and the expensive layer insulation normally used. The result is a compact coil with no air voids and a minimum of insulation.

The system is flexible since many arrangements of strip width and thicknesses may be used. Two or more strips multiple wound may result in lower cost coils, since the lower cost of thicker strips and the elimination of almost 50% of the insulation may more than offset the slitting costs and the additional labor to handle two coils.

The excellent heat transfer characteristics of strip wound coils result in lower average operating temperatures and in much lower hot-spot temperatures. Fig. 14-6 showing temperatures vs. conductor location for an actual case amply demonstrates this principle. As noted, average operating temperature is reduced in this instance about 120° C and hot-spot temperatures are reduced approximately 40° C. These reductions may be significant when the choice of insulating materials is considered. Cooling ducts may be eliminated under certain conditions with significant cost savings.

Joining

Electrical connection of an aluminum strip wound coil to external circuits requires that a suitable lead be attached to the strip which can then be soldered or bolted into the external circuit. These leads usually are round copper wire or flat copper strip. Common methods of joining such leads to the aluminum strip and for making aluminum to aluminum splices are:

Coldwelding: Pressure welding at room temperature is an accepted method of joining aluminum strip conductor

* See ASTM-B324 for additional information on rectangular and square wires of aluminum.
to aluminum or copper in production. Cold-welding anodized aluminum to anodized aluminum, bare aluminum or copper requires no wire brushing of the aluminum surface. Tests have proven that the joints formed by this method have high conductance and high strength. Commercial equipment is available for joining a wide range of thicknesses and widths of strip conductor.

Mechanical Joints: Use of mechanical joints in aluminum and copper has been successful when joints have been properly designed. Riveted joints have been successfully used for years in the small strip conductor wound horn coil and the larger welder reactor coils. Mechanical connectors are available for joining solid or stranded wire leads to strip conductor.

Fold Out Parent Metal: The end of the strip may be slit or folded by various techniques and brought out at 90° to form a narrow laminated lead. A flexible lead can then be attached by welding, by mechanical connectors, or by bolted connections. In Fig. 14-7, C is a strip slit in four equal widths folded out individually—one on top of the other.

Shielded Inert Arc Welding: All types of inert gas shielded arc welding which do not require a flux are acceptable for joining aluminum to aluminum. Two methods are most commonly used:

1. A tungsten electrode with the filler rod being fed by hand as in gas welding. (TIG)

2. A consumable electrode of aluminum welding wire fed through the inert gas envelope. This is a particularly fast method and is used for automatic set-ups. The weld has 80-90% of the original strength of the parent metal. (MIG)

High Temperature Solder: Effective solder joints can be made without the use of corrosive fluxes. Abrasive means must be employed in pre-tinning the surfaces of the metals for subsequent soldering without fluxes.

Ultra-Sonic Welding: Lap joints may be made between aluminum to aluminum and to copper by a vibrating technique to result in a metallurgical bond without the application of heat.

Transition Pieces: An aluminum to copper transition piece (Fig. 14-3) may be used to make aluminum to aluminum connection at the strip and to make a copper connection to a lead or terminal. The transition pieces are usually made by cold or flash welding.

Strip Magnet Conductor Types

Magnet strip is available in gauges ranging from .001 inches to .0959 inches. It is supplied bare for use with interleaving materials, or coated with conventional film insulations and special high temperature types including anodized strip.

Magnet strip conductor from .008 inch and heavier can be supplied with a fully contoured round edge, both bare and insulated. Magnet strip conductor is supplied insu-
### TABLE 14-3

Comparative Cross Section Area—Equal Volume Conductance

<table>
<thead>
<tr>
<th>AWG WIRE SIZE</th>
<th>SQ. IN. COPPER 100% IACS</th>
<th>ALUMINUM EQUIVALENT 1350–0 62% IACS</th>
<th>ALUMINUM EQUIVALENT 1235–0 61% IACS</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>.02062</td>
<td>.03325</td>
<td>.03380</td>
</tr>
<tr>
<td>7</td>
<td>.01635</td>
<td>.02637</td>
<td>.02680</td>
</tr>
<tr>
<td>8</td>
<td>.01297</td>
<td>.02091</td>
<td>.02126</td>
</tr>
<tr>
<td>9</td>
<td>.01028</td>
<td>.01659</td>
<td>.01686</td>
</tr>
<tr>
<td>10</td>
<td>.008155</td>
<td>.01315</td>
<td>.01337</td>
</tr>
<tr>
<td>11</td>
<td>.00647</td>
<td>.01043</td>
<td>.01060</td>
</tr>
<tr>
<td>12</td>
<td>.00513</td>
<td>.00827</td>
<td>.00841</td>
</tr>
<tr>
<td>13</td>
<td>.00407</td>
<td>.00656</td>
<td>.00667</td>
</tr>
<tr>
<td>14</td>
<td>.00323</td>
<td>.00521</td>
<td>.00529</td>
</tr>
<tr>
<td>15</td>
<td>.00256</td>
<td>.00413</td>
<td>.00419</td>
</tr>
<tr>
<td>16</td>
<td>.00203</td>
<td>.00327</td>
<td>.00333</td>
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<tr>
<td>17</td>
<td>.00161</td>
<td>.00259</td>
<td>.00264</td>
</tr>
<tr>
<td>18</td>
<td>.00128</td>
<td>.00206</td>
<td>.00208</td>
</tr>
<tr>
<td>19</td>
<td>.00101</td>
<td>.00163</td>
<td>.00166</td>
</tr>
<tr>
<td>20</td>
<td>.000802</td>
<td>.00129</td>
<td>.00132</td>
</tr>
<tr>
<td>21</td>
<td>.000636</td>
<td>.00103</td>
<td>.00104</td>
</tr>
<tr>
<td>22</td>
<td>.000505</td>
<td>.000814</td>
<td>.000827</td>
</tr>
<tr>
<td>23</td>
<td>.000400</td>
<td>.000645</td>
<td>.000656</td>
</tr>
<tr>
<td>24</td>
<td>.000317</td>
<td>.000512</td>
<td>.000520</td>
</tr>
<tr>
<td>25</td>
<td>.000252</td>
<td>.000406</td>
<td>.000413</td>
</tr>
<tr>
<td>26</td>
<td>.000200</td>
<td>.000322</td>
<td>.000327</td>
</tr>
</tbody>
</table>

### TABLE 14-4

Useful Formulas for Aluminum Strip Wound Coils

<table>
<thead>
<tr>
<th>Area</th>
<th>A = W X T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance @ 20°C</td>
<td>R = .013138 L/1000A</td>
</tr>
<tr>
<td>Weight</td>
<td>M = 1.172 X L X A</td>
</tr>
<tr>
<td>Length</td>
<td>L = N X MLT</td>
</tr>
<tr>
<td>Mean Length Turn</td>
<td>MLT = P + π D/12</td>
</tr>
<tr>
<td>Winding Depth</td>
<td>D = N(T + t) / .975</td>
</tr>
</tbody>
</table>

\[ W = \text{Strip width in inches} \]
\[ T = \text{Strip thickness in inches} \]
\[ t = \text{Interleave thickness in inches} \]
\[ N = \text{Number of turns} \]
\[ P = \text{Perimeter of core insulation in feet} \]

Some Basic Considerations Relating to Aluminum Magnetic Wire

When a current passes through a loop or turn of the electrical conductor, a magnetic field is set up within and around the turn. The magnetic field increases and decreases directly as the current varies. Adding turns also increases the magnetic field. The reverse of this process is that when a magnetic field varies within a turn or turns
electromagnetic and other electrical applications of aluminum

A. Mechanical joints. Use of mechanical joints in aluminum and copper has been successful when joints have been properly designed. Riveted joints have been successfully used for years in the small strip conductor wound horn coil and the larger welder reactor coils. Mechanical connectors are available for joining solid or stranded wire leads to strip conductor.

B. Coldwelding. Pressure welding at room temperature is an accepted method of joining aluminum strip conductor to aluminum or copper in production. Coldwelding anodized aluminum to anodized aluminum, bare aluminum or copper requires no wire brushing of the aluminum surface. Tests have proven that the joints formed by this method have high conductance and high strength. Commercial equipment is available for joining a wide range of thickness and widths of strip conductor.

C. Fold out parent metal. The end of the strip may be slit or folded by various techniques and brought out at 90° to form a narrow laminated lead. A flexible lead can then be attached by welding, by mechanical connectors, or by bolted connections. Shown is a strip slit in four equal widths folded out individually—one on top of the other.

of an electrical conductor, there is induced in the conductor an electromagnetic force which will cause current to flow if the turn is connected to a load. This action forms the basis of a fundamental law of electricity, the application of which underlies the design and operation of most electrical apparatus and circuitry.

Electrical energy may be transformed from one circuit to another with possible change of voltage and isolation of the two circuits by sharing of a magnetic field in which one component forms the magnetic field (must be alternating) and the other has induced in it the electromagnetic force from the changing magnetic field. This is known as mutual coupling.

A second method of transforming energy is by direct coupling—the sharing of a resistor, inductor or capacitor.

The magnitude of the induced emf (e) depends on two fundamental factors, as follows:

\[
e = N \frac{\Delta \phi}{\Delta t}
\]  \hspace{1cm} (Eq. 14-4)

where:
- \(N\) = number of turns
- \(\frac{\Delta \phi}{\Delta t}\) = time rate of change of flux (the magnetic field)

and

\[
e = L \frac{\Delta i}{\Delta t}
\]  \hspace{1cm} (Eq. 14-5)

where:
- \(L\) = coefficient of self inductance
- \(\frac{\Delta i}{\Delta t}\) = time rate of change of current

From (4) and (5) it is seen that:

\[
\phi = \frac{LI}{N} \quad \text{(for a non-magnetic core coil)}
\]  \hspace{1cm} (Eq. 14-6)
TABLE 14-5
Strip Conductor Alloys — Physical Constants at 20°C

<table>
<thead>
<tr>
<th></th>
<th>Aluminum 1350–0</th>
<th>Aluminum 1235–0</th>
<th>Copper Electrolytic</th>
</tr>
</thead>
</table>
| Volume electrical conductivity
  minimum percent IACS    | 62              | 61              | 100                 |
| Density lb./in.³        | 0.09765         | 0.09765         | 0.32117             |
| Volume resistivity microhm - in. | 1.09482        | 1.11277         | 0.67879             |
| Weight resistivity microhm -lb./ft.² | 15.40          | 15.65           | 31.39               |
| Temperature co-efficient of resistance ohm/°C | 0.00410      | 0.00403         | 0.00393             |
| Specific heat cal/gram/°C | 0.214           | 0.225           | 0.092               |
| Co-efficient of thermal conductivity cal/sec/
  CM²/CM/°C               | 0.57            | 0.55            | 0.934               |
| Co-efficient of linear expansion per °C | $23.8 \times 10^{-6}$ | $23.6 \times 10^{-6}$ | $16.8 \times 10^{-6}$ |

Where: \( \phi = \) flux or field
\( I = \) current in conductor

For a coil with a magnetic core (iron) with permeability \( \mu \) and reluctance \( R \):

\[
\phi = \frac{N}{R} I \quad \text{(Eq. 14-7)}
\]

and

\[
R = \frac{1}{\mu A} \quad \text{(Eq. 14-8)}
\]

Therefore:

\[
\phi = \frac{N I}{\mu A} \quad \text{(Eq. 14-9)}
\]

Where: \( A = \) area of flux path in iron
\( l = \) length of flux path in iron

To achieve a coil with high magnetic field capability and low cost, size, weight, and energy consumption has been the goal of designers since the time of Faraday who did fundamental work in the area of electromagnetic induction in the last century.

Electromagnetic coils consist of coils of many turns of magnet wire (insulated conductor) wound around soft iron cores whose ends are connected in loops, if design permits. Improvements over the years have been (1) lamination of the iron to reduce losses, (2) increasing the permeability of the iron, (3) reducing the thickness of the magnet wire insulation and layer insulation to permit more turns per unit space, (4) improving the thermal stability of the magnet wire insulation to allow more current to flow at higher temperatures, (5) use of rectangular wire and strip (interleaved) to gain in space factor, (6) improved thermal dissipation for cooler operation.

Other more recent advances in rapid-chilled iron with amorphous internal structure (glass-like) promise a drastic reduction in iron losses for next generation coils and transformers.

14-13
Chapter 15

Capacitor Foil

Capacitors both fixed and variable are used today in almost every electrical system. From great power generating and distributing networks to electric organs, including telephone and radio systems, computers and motors, elevators and X-ray apparatus and so on, the use of a capacitor almost always is a fundamental necessity.

Any arrangement of electrodes whatsoever upon which electric charges accumulate or move will exhibit the incidence of capacitance. Where the electrode geometry is extensive in space such as a wire or cable, the charges are distributed likewise and we speak of such a structure as being a distributed capacitance. When the electrodes are deliberately concentrated in space, the charges are concentrated and this is termed a lumped capacitance. All electrical components used specifically as capacitors are looked upon as providing lumped capacitance.

Aluminum has been and is the preferred metal for capacitor electrodes whether used in rigid plate form or in varying thicknesses of foil for d-c, a-c low voltage, high voltage, high frequency, high or low power, impulse discharge, etc.

Capacitor Design Considerations

Under given conditions of electrical, physical and environmental factors, a capacitor may be called upon to provide a precise amount of capacitance, a required time constant of charge and discharge (with proper circuit resistance) or a specified impulse release of stored energy. The selection of electrode and insulation materials and the design of their electrical and mechanical arrangements can be optimized to produce an economical capacitor that will perform properly in its intended service.

In Section III, Chapter 8, the general conditions governing the relation of potential and charge to capacitance were discussed as well as the influence of the dielectric medium. The equations for capacitance relating to a wide variety of electrode geometries were given and the nature of the dielectric polarization of the insulation discussed. All of this is applicable to capacitor design.

A common economic consideration in capacitor design is to obtain the largest amount of capacitance per unit volume of material used. This is, of course, obtained by using the thinnest electrodes and the thinnest insulating material possessing the highest dielectric constant. How far one can go in these directions depends upon the circuit voltage to be withstood, the conductance and/or dielectric loss that can be tolerated and the stability of the assembly under the operating conditions.

Equivalent Network of a Capacitor

All capacitors possess a certain amount of series resistance and inductance as well as shunt capacitance and conductance. Fig. 15-1 shows a simple, unrolled foil capacitor and its equivalent electrical circuits. The series impedance \((r + j\omega L)\) is made up of the resistance and inductance of the capacitor leads plus those inherent in the electrode material, shape and extent. Usually the inductance is negligibly small as compared to the other factors. Actually, the inductance is approximately the same as a wire loop equal in area to that formed by the two leads and the capacitor unit itself. The foil electrodes appear as a uniformly distributed series resistance.

The overall impedance of the equivalent network shown in Fig. 15-1(c) is:

\[
Z = r + \frac{g}{g^2 + \omega^2 C^2} - j\frac{\omega C}{g^2 + \omega^2 C^2} + j\omega L
\]  
(Eq. 15-1)

where:

- \(\omega = 2\pi f\)  
- \(f\) in Hz  
- \(g\) in mhos  
- \(C\) in farads  
- \(L\) in henrys  
- \(r\) in ohms

or since \(g^2\) is usually very small compared to \(\omega^2 C^2\),

\[
Z \approx (r + \frac{g}{\omega^2 C^2}) + \frac{j(\omega^2 CL - 1)}{\omega C}
\]  
(Eq. 15-2)
From the above it is obvious that the effective capacitance seen across the terminals of a capacitor is \( \frac{C}{\omega^2CL-1} \) and that this will vary with frequency. For low frequencies it will be equal to C; as frequency increases, the effect of the inductance increasingly reduces the capacitance and the capacitive reactance. At a frequency where resonance occurs (usually very high), the overall impedance is entirely made up of the effective resistance of the leads and the foil electrodes at that frequency. Above the resonant frequency, the capacitor acts as an inductance coil with some series capacitance. Although theoretically every practical capacitor will exhibit resonance at some high frequency, it is always possible to arrange the electrode and terminal wires to obtain the effect of a low impedance, long transmission line free of apparent resonance over a wide high-frequency band. Fig. 15-2 shows the reactance vs. frequency effect for a waxed paper insulated capacitor designed for audio frequency circuits.

Effective Resistance and Loss of a Capacitor: At frequencies below which parasitic inductance becomes significant, the dissipated watt loss in a capacitor is occasioned by both the ohmic loss in the foils and leads and the dielectric loss in the insulating material. However, as the ohmic loss is almost always insignificant it is usually ignored in commercial practice and power loss is computed with the following formula:

\[
W = E^2\omega C \tan \delta \quad \text{(Eq. 15-3)}
\]

Where: 
- \( E \) = volts
- \( \omega = 2\pi f \) (frequency in Hz)
- \( \tan \delta \) = dissipation factor
- \( \delta \) = loss angle

Reduction of losses in a capacitor is quite important from the standpoints of both adequate performance and stable life. In capacitors carrying heavy currents, the energy loss is a source of heating which, if not adequately reduced or carried off by thermal conduction, can cause rapid deterioration and failure of the insulation. Control of heat loss enters into the design and use of capacitors for low frequency operation in connection with power factor correction and, at high frequencies, in radio transmitting capacitors. In radio frequency circuits, effective resistance becomes important in series coil and capacitor combinations required to have low impedance at the resonance frequencies or parallel combinations required to have high impedance at the anti-resonance frequency. This is because resistance may add appreciably to the desired low impedance at the resonance frequency or reduce the desired high impedance at the anti-resonant frequency.

In electric wave filters intended to pass a single band of frequencies and suppress others, the transmission loss is ideally zero over the pass-band and rises sharply beyond the edge or edges. Parasitic loss in the reactive elements is unwanted loss which varies over the pass-band and reaches a maximum at the edges resulting in distorted transmission. This source of loss is generally objectionable, for example, in carrier-telephone systems where the cumulative loss of many filters in tandem may result in considerable distortion which must be compensated for by means of attenuation-equalizing networks.

In his efforts to limit the losses in capacitors required to pass alternating current in telephone and electronic circuits, the capacitor engineer is usually primarily concerned with the effect of frequency on series and shunt resistance.
This is because the effective resistance undergoes large changes with changing frequency and because of the wide frequency-range which circuits are often required to cover.

Loss in Foil and Leads: At a first approximation, the effective impedance of the foil and leads of a capacitor appears as a straight-line factor over a wide range of frequency. At higher frequencies, impedance increases due to eddy-current and other losses including skin effect where only the outer portion of the metallic components carry the current.

From the watt loss (Eq. 15-3) above, it is seen that the heat loss in the foil and leads increases as the square of the frequency for constant applied voltage. In general, this condition applies over the operating frequency-range of many capacitors.

Effective Resistance of Foil Electrodes

In the case of wound paper capacitors, there is a simple relationship between the effective resistance of the foil electrodes and their d-c resistance. With reference to Fig. 15-1, it is clear that alternating current entering the foil electrodes at the lead-in wires decreases as it spreads or distributes along the foil, and the current flowing at points remote from the lead-in wires may be only a small fraction of the entering current. It may be shown theoretically and demonstrated experimentally that for the long, narrow electrodes of wound paper capacitors the effective foil resistance is approximately equal to 1/3 of the loop d-c resistance obtained by adding the d-c resistance values of the two foils. In other words, due to current attenuation along the foils only 33 percent of the total d-c foil resistance is effective with respect to alternating current. Fig. 15-3 shows the effect of several laid-in terminals in reducing effective foil resistance especially at the higher frequencies.

Where, as is more usual in practice, the terminals are laid-in at approximately the middle of the foil electrodes, the current spreads in opposite directions along the foils. The effective resistance of the loop in each direction is then R/6 and, since the two loops are in parallel, the total effective resistance becomes R/12. When "n" terminals are laid-in on a foil of length "L", it may be shown that the lowest resistance is obtained by spacing the terminals at intervals of L/n, with each end terminal located L/2n from the end of the foil. With this arrangement, the effective resistance is inversely proportional to the square of the number of terminals.

In the limiting case, the edge of the foil is connected together along its entire length. This, known as "extended foil" or "overlapped foil" construction, gives the lowest attainable effective foil resistance for a foil of given material and dimensions. In addition, by providing an efficient

---

**Fig. 15-2. Impedance versus frequency of paper capacitors at audio frequencies.**

15-3
Electromagnetic and other applications of aluminum

![Impedance graph](image)

Fig. 15-3. Impedance at high frequency is reduced by adding terminals.

Conduction path for heat from the inside to the outside of the unit, extended foil construction is advantageous in high-power capacitors having large heat dissipation. Fig. 15-5 illustrates the relation between heat loss and frequency in a waxed paper capacitor.

**Electrolytic Capacitors**

The electrolytic capacitor provides the most capacitance in a given space at the lowest cost per microfarad. Primarily a filtering capacitor, this type is largely used in connection with dc circuits at working voltages less than 500 volts. For example, at low voltage, several thousand microfarads may be contained in a one cubic inch electrolytic capacitor using etched aluminum foil electrodes. Fig. 15-4 shows a typical electrolytic capacitor design.

The high capacitance per unit volume of electrolytic capacitors comes from the extreme thinness of the dielectric which is an anodic oxide film previously built up by an electrolytic process on one of the foil electrodes, known as the anode (capacitance per cubic inch is inversely proportional to the thickness of the dielectric). The thickness of this insulating film is but a few millionths of an inch and the working voltage gradient can be of the order of 10 million volts per inch. Etching the anode increases the effective area so as to increase the capacitance as much as 7 to 30 times.

With the voltage applied in one direction, the film has a high resistance to the flow of current and behaves like a dielectric. With the voltage reversed, the film behaves like a relatively low resistance and, if the voltage is high enough, it passes large currents, heats up and soon breaks down. Because of this unidirectional property, the film is suitable only for direct voltage in a single direction and the anode terminal is usually marked "positive" to indicate in which direction the voltage shall be applied.

Electrolytic capacitors are used extensively in low voltage ac applications. One type consists virtually of two capacitors with their cathodes connected together so that the two capacitors operate in series but in opposite directions. One capacitor absorbs the applied voltage on one half of the ac cycle and the other capacitor comes into

![Cross-sectional view](image)

Fig. 15-4. Cross-sectional view of a typical capacitor.
play during the succeeding half-cycle when the voltage reverses. The most common type is a capacitor wound as a non-polar capacitor utilizing two anodes instead of an anode and a cathode. Such capacitors are used extensively on low ac voltages; for example, as motor-starting capacitors when the full voltage is of short duration. Where the voltage is very low, they can be used continuously; for example, to filter audio frequencies in radio sets. In general, they are limited on ac with respect to voltage because of the high power factor.

Improvements made in the design and manufacture of aluminum electrolytic capacitors allow for use in a wide variety of commercial and industrial precision circuit applications. Common usage today is in the telecommunications industries. The highest aluminum purities, for example 1199, allow for the manufacture of high reliability capacitors with extended life and temperature characteristics and long, stable storage life.

**Capacitor Foil Availability**

Precise capacitor design begins with high-purity aluminum capacitor foil of precise thickness and desired surface and edge treatment. High purity aluminum capacitor foil is produced by a number of manufacturers and is available in a wide range of thicknesses, widths and alloys. Precision processing assures control of impurities, foil uniformity and continuity, freedom of sticking during unwinding, excellent gauge control, perfectly slit burr-free edges, and tightly wound compact coils. A full range of purities are available—from 99.35% to 99.99% pure aluminum.

Foil is produced either in the dry condition, or with a so-called slick finish, or etched and anodized.

**Dry Foil**: Specialized annealing technique provides a surface free from residual oil contamination. A thoroughly wet surface will show no droplet formations indicative of oil residue.

**Slick Foil**: A slightly lubricated surface developed in combination with annealing practices overcomes friction generated by winding equipment, but will not contaminate the dielectric.

---

Fig. 15-5. Heat loss versus frequency at constant current in paper capacitor
Anodized Foil: High purity aluminum foil is specially treated to provide a very thin oxide film on its surface. This film acts as a dielectric and results in high capacitance as compared to paper capacitors. It can be etched to increase the surface area 7 to 30 times thereby providing even greater capacitance in a given volume.

A typical group of product data tables of one aluminum foil manufacturer is reproduced here.

Table 15-1 gives chemical composition of the aluminum alloys most used in condenser foil production. It is to be recalled, in this connection, that the addition of other metals to aluminum usually lowers its electrical conductivity. Also that heat treatment putting other metals in solid solution with the aluminum also lowers conductivity.

Table 15-2 gives typical properties.
Table 15-3 gives thickness and width limitations.
Table 15-4 gives weight-area conversion factors.
Table 15-5 gives typical splice data.
Table 15-6 gives foil roll sizes and weights.
### TABLE 15-2
Typical Physical Properties—O Temper

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Gauge</th>
<th>Tensile-psi</th>
<th>% Elongation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1199</td>
<td>.003&quot;</td>
<td>5,000</td>
<td>3.2</td>
</tr>
<tr>
<td>1193</td>
<td>.003&quot;</td>
<td>8,100</td>
<td>6.6</td>
</tr>
<tr>
<td>1188</td>
<td>.003&quot;</td>
<td>6,300</td>
<td>5.7</td>
</tr>
<tr>
<td>1180</td>
<td>.003&quot;</td>
<td>6,500</td>
<td>6.0</td>
</tr>
<tr>
<td>1145</td>
<td>.003&quot;</td>
<td>10,000</td>
<td>7.0</td>
</tr>
<tr>
<td>1235</td>
<td>.003&quot;</td>
<td>10,500</td>
<td>8.1</td>
</tr>
</tbody>
</table>

### TABLE 15-3
Thickness And Width Limitations

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Gauge</th>
<th>Finish*</th>
<th>Widths</th>
</tr>
</thead>
<tbody>
<tr>
<td>1235; 1145</td>
<td>.00017&quot;-.0002&quot;</td>
<td>MIS</td>
<td>3/8&quot;-.26&quot;</td>
</tr>
<tr>
<td>1235; 1145</td>
<td>.0002&quot;-.00023&quot;</td>
<td>MIS</td>
<td>3/8&quot;-.31&quot;</td>
</tr>
<tr>
<td>1235; 1145</td>
<td>.00025&quot;</td>
<td>MIS</td>
<td>3/8&quot;-.43&quot;</td>
</tr>
<tr>
<td>1235; 1145</td>
<td>.0003&quot;</td>
<td>MIS</td>
<td>3/8&quot;-.50&quot;</td>
</tr>
<tr>
<td>1235; 1145</td>
<td>.00035&quot;-.0004&quot;</td>
<td>MIS</td>
<td>3/8&quot;-.64&quot;</td>
</tr>
<tr>
<td>1235; 1145</td>
<td>.00045&quot;-.001&quot;</td>
<td>MIS</td>
<td>3/8&quot;-.72&quot;</td>
</tr>
<tr>
<td>1235; 1145</td>
<td>.0015&quot;-.0059&quot;</td>
<td>MIS, 2SB</td>
<td>1/4&quot;-.72&quot;</td>
</tr>
<tr>
<td>1235; 1145</td>
<td>.002&quot;-.0059&quot;</td>
<td>2SB</td>
<td>1/4&quot;-.52&quot;</td>
</tr>
<tr>
<td>1180; 1188</td>
<td>.0004&quot;-.0015&quot;</td>
<td>MIS</td>
<td>3/8&quot;-.36&quot;</td>
</tr>
<tr>
<td>1180; 1188</td>
<td>.002&quot;-.0059&quot;</td>
<td>2SB</td>
<td>1/4&quot;-.36&quot;</td>
</tr>
<tr>
<td>1193; 1199</td>
<td>.001&quot;-.0015&quot;</td>
<td>MIS</td>
<td>3/8&quot;-.36&quot;</td>
</tr>
<tr>
<td>1193; 1199</td>
<td>.002&quot;-.0059&quot;</td>
<td>2SB</td>
<td>1/4&quot;-.36&quot;</td>
</tr>
</tbody>
</table>

*MIS designates Matte one side.
2SB designates Two sides bright.

### TABLE 15-4
Weight-Area Conversion Factors

<table>
<thead>
<tr>
<th>Thickness (in.)</th>
<th>Sq In./Lb</th>
<th>Sq Ft/Lb</th>
<th>Lb/432,000 Sq In.*</th>
</tr>
</thead>
<tbody>
<tr>
<td>.00017</td>
<td>60,300</td>
<td>418.75</td>
<td>7.16</td>
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<tr>
<td>.0002</td>
<td>51,300</td>
<td>356.25</td>
<td>8.42</td>
</tr>
<tr>
<td>.00023</td>
<td>44,600</td>
<td>309.72</td>
<td>9.69</td>
</tr>
<tr>
<td>.00025</td>
<td>41,000</td>
<td>284.72</td>
<td>10.54</td>
</tr>
<tr>
<td>.00030</td>
<td>34,200</td>
<td>237.50</td>
<td>12.63</td>
</tr>
<tr>
<td>.00035</td>
<td>29,300</td>
<td>203.47</td>
<td>14.74</td>
</tr>
<tr>
<td>.00040</td>
<td>25,600</td>
<td>177.78</td>
<td>16.88</td>
</tr>
<tr>
<td>.00045</td>
<td>22,800</td>
<td>158.33</td>
<td>18.95</td>
</tr>
<tr>
<td>.00050</td>
<td>20,500</td>
<td>142.36</td>
<td>21.07</td>
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<tr>
<td>.00055</td>
<td>18,600</td>
<td>129.17</td>
<td>23.23</td>
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<td>.00060</td>
<td>17,100</td>
<td>118.75</td>
<td>25.26</td>
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<tr>
<td>.00065</td>
<td>15,800</td>
<td>109.72</td>
<td>27.34</td>
</tr>
<tr>
<td>.0007</td>
<td>14,600</td>
<td>101.39</td>
<td>29.59</td>
</tr>
<tr>
<td>.00075</td>
<td>13,667</td>
<td>94.91</td>
<td>31.61</td>
</tr>
<tr>
<td>.00080</td>
<td>12,800</td>
<td>88.89</td>
<td>33.75</td>
</tr>
<tr>
<td>.00085</td>
<td>12,058</td>
<td>83.74</td>
<td>35.83</td>
</tr>
<tr>
<td>.00090</td>
<td>11,400</td>
<td>79.17</td>
<td>37.89</td>
</tr>
<tr>
<td>.00095</td>
<td>10,789</td>
<td>74.92</td>
<td>40.04</td>
</tr>
<tr>
<td>.0010</td>
<td>10,250</td>
<td>71.18</td>
<td>42.15</td>
</tr>
<tr>
<td>.0015</td>
<td>6,830</td>
<td>47.43</td>
<td>63.25</td>
</tr>
<tr>
<td>.0020</td>
<td>5,130</td>
<td>35.63</td>
<td>84.21</td>
</tr>
<tr>
<td>.0025</td>
<td>4,100</td>
<td>28.47</td>
<td>105.37</td>
</tr>
<tr>
<td>.0030</td>
<td>3,420</td>
<td>23.75</td>
<td>128.32</td>
</tr>
<tr>
<td>.0035</td>
<td>2,930</td>
<td>20.35</td>
<td>147.44</td>
</tr>
<tr>
<td>.0040</td>
<td>2,560</td>
<td>17.78</td>
<td>168.75</td>
</tr>
<tr>
<td>.0045</td>
<td>2,280</td>
<td>15.83</td>
<td>189.47</td>
</tr>
<tr>
<td>.0050</td>
<td>2,050</td>
<td>14.24</td>
<td>210.73</td>
</tr>
<tr>
<td>.0055</td>
<td>1,860</td>
<td>12.92</td>
<td>232.26</td>
</tr>
</tbody>
</table>

*432,000 sq. in. signifies one ream (500 sheets) of 24 in. x 36 in. sheets.

### TABLE 15-5
Splices (Annealed Foil—Dry or Slick)

<table>
<thead>
<tr>
<th>Gauge</th>
<th>Width</th>
<th>Splice</th>
</tr>
</thead>
<tbody>
<tr>
<td>.00017&quot;-.0004&quot;</td>
<td>23&quot; Maximum</td>
<td>Knurl</td>
</tr>
<tr>
<td>.00017&quot;-.0015&quot;</td>
<td>All Widths</td>
<td>Foil Tape</td>
</tr>
<tr>
<td>.002&quot;-.005&quot;</td>
<td>All Widths</td>
<td>(Electric Weld)</td>
</tr>
<tr>
<td>(Electrolytic Foil)</td>
<td></td>
<td>(Ultrasonic Splice)</td>
</tr>
</tbody>
</table>
### TABLE 15-6(a)
**Roll Size**

<table>
<thead>
<tr>
<th>Width</th>
<th>Type of Core</th>
<th>Maximum OD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/4&quot;-3&quot;</td>
<td>1 5/16&quot; Aluminum</td>
<td>6&quot;</td>
</tr>
<tr>
<td>3&quot;-31&quot;</td>
<td>1 5/16&quot; Aluminum</td>
<td>12&quot;</td>
</tr>
<tr>
<td>1/4&quot;-3&quot;</td>
<td>3&quot; Aluminum</td>
<td>8&quot;</td>
</tr>
<tr>
<td>3&quot;-72&quot;</td>
<td>3&quot; Aluminum</td>
<td>13&quot;</td>
</tr>
<tr>
<td>17&quot;-72&quot;</td>
<td>3&quot; Iron</td>
<td>30&quot;</td>
</tr>
</tbody>
</table>

### TABLE 15-6(b)
**Roll Weight Data—Unmounted Foil**

<table>
<thead>
<tr>
<th>SPOOLED ROLL</th>
<th>WEIGHT OF FOIL PER INCH OF WIDTH—(POUNDS)</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Outside Diameter (Inches)</td>
<td>ALUMINUM CORE</td>
<td>1D-3 5/16&quot;</td>
<td>ID-3&quot;</td>
<td>1D-2 1/2&quot;</td>
<td>ID-3&quot;</td>
</tr>
<tr>
<td></td>
<td>OD-1-1/2&quot;</td>
<td>OD-3-3/16&quot;</td>
<td>OD-3&quot;</td>
<td>OD-3-1/4&quot;</td>
<td>OD-3&quot;</td>
</tr>
<tr>
<td>2&quot;</td>
<td>0.3 lb</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>2¼&quot;</td>
<td>0.3</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>3&quot;</td>
<td>0.5</td>
<td>0.2 lb</td>
<td>0.3 lb</td>
<td>0.2 lb</td>
<td>--</td>
</tr>
<tr>
<td>3½&quot;</td>
<td>1.0</td>
<td>0.4</td>
<td>0.5</td>
<td>0.4</td>
<td>--</td>
</tr>
<tr>
<td>4&quot;</td>
<td>1.3</td>
<td>0.7</td>
<td>0.8</td>
<td>0.7</td>
<td>--</td>
</tr>
<tr>
<td>4½&quot;</td>
<td>1.7</td>
<td>1.1</td>
<td>1.2</td>
<td>1.1</td>
<td>--</td>
</tr>
<tr>
<td>5&quot;</td>
<td>2.1</td>
<td>1.5</td>
<td>1.6</td>
<td>1.5</td>
<td>--</td>
</tr>
<tr>
<td>5½&quot;</td>
<td>2.6</td>
<td>2.0</td>
<td>2.1</td>
<td>2.0</td>
<td>--</td>
</tr>
<tr>
<td>6&quot;</td>
<td>3.1</td>
<td>2.5</td>
<td>2.6</td>
<td>2.5</td>
<td>--</td>
</tr>
<tr>
<td>6½&quot;</td>
<td>3.6</td>
<td>3.0</td>
<td>3.1</td>
<td>3.0</td>
<td>--</td>
</tr>
<tr>
<td>7&quot;</td>
<td>4.1</td>
<td>3.5</td>
<td>3.6</td>
<td>3.5</td>
<td>--</td>
</tr>
<tr>
<td>7½&quot;</td>
<td>4.7</td>
<td>4.1</td>
<td>4.2</td>
<td>4.1</td>
<td>--</td>
</tr>
<tr>
<td>8&quot;</td>
<td>5.3</td>
<td>4.7</td>
<td>4.8</td>
<td>4.7</td>
<td>--</td>
</tr>
<tr>
<td>8½&quot;</td>
<td>6.0</td>
<td>5.4</td>
<td>5.5</td>
<td>5.4</td>
<td>--</td>
</tr>
<tr>
<td>9&quot;</td>
<td>6.7</td>
<td>6.1</td>
<td>6.2</td>
<td>6.1</td>
<td>--</td>
</tr>
<tr>
<td>9½&quot;</td>
<td>7.5</td>
<td>6.9</td>
<td>7.0</td>
<td>6.9</td>
<td>--</td>
</tr>
<tr>
<td>10&quot;</td>
<td>8.3</td>
<td>7.7</td>
<td>7.8</td>
<td>7.7</td>
<td>--</td>
</tr>
<tr>
<td>10¼&quot;</td>
<td>9.1</td>
<td>8.5</td>
<td>8.6</td>
<td>8.5</td>
<td>--</td>
</tr>
<tr>
<td>11&quot;</td>
<td>10.0</td>
<td>9.3</td>
<td>9.4</td>
<td>9.3</td>
<td>--</td>
</tr>
<tr>
<td>12&quot;</td>
<td>10.9</td>
<td>10.2</td>
<td>10.3</td>
<td>10.2</td>
<td>--</td>
</tr>
<tr>
<td>12½&quot;</td>
<td>11.8</td>
<td>11.2</td>
<td>11.3</td>
<td>11.2</td>
<td>--</td>
</tr>
<tr>
<td>13&quot;</td>
<td>12.8</td>
<td>12.2</td>
<td>12.3</td>
<td>12.2</td>
<td>--</td>
</tr>
<tr>
<td>13½&quot;</td>
<td>13.8</td>
<td>13.2</td>
<td>13.3</td>
<td>13.2</td>
<td>--</td>
</tr>
<tr>
<td>14&quot;</td>
<td>14.8</td>
<td>14.2</td>
<td>14.3</td>
<td>14.2</td>
<td>--</td>
</tr>
<tr>
<td>14½&quot;</td>
<td>15.9</td>
<td>15.3</td>
<td>15.4</td>
<td>15.3</td>
<td>--</td>
</tr>
<tr>
<td>15&quot;</td>
<td>17.0</td>
<td>16.4</td>
<td>16.5</td>
<td>16.4</td>
<td>--</td>
</tr>
<tr>
<td>15½&quot;</td>
<td>18.2</td>
<td>17.6</td>
<td>17.7</td>
<td>17.6</td>
<td>--</td>
</tr>
</tbody>
</table>

**NOTES:**
- ID and OD dimensions represent the Inside and Outside Diameter, respectively, of the metal core.
- The above figures are approximate and do not include core weight.
- For approximate net weight of Foil per roll, exclusive of core weight, multiply the figure under the applicable roll OD and type of core by the inches of roll width.
Chapter 16

Cast Aluminum Rotors and Switchgear

Squirrel cage induction motors are the most popular form of motor design for both household appliances and heavy industrial equipment.

Before the advent of present aluminum die casting techniques, rotors for squirrel cage motors were built up in a step by step fashion using iron laminations and wound copper wire conductors or conducting rods of copper or bronze alloys welded to end-rings of copper or bronze.

Experimental work with aluminum castings conducted in the 1930's focused serious attention on the lower cost and engineering advantages of making an integrally cast aluminum/iron lamination squirrel cage rotor.

The Cast Rotor

The cast rotor has two essential components. These are the punched iron disks or laminations containing the holes for the conducting bars, the shaft, and any cooling holes or vents, and the aluminum which is used in integrally casting the conductor bars and collector rings. A stack of laminations is assembled for a particular rotor, the diameter and height of which are determined by the motor design. The laminations may have either open or closed slots (See Fig. 16-1, A and B), however in recent years, the closed-slot design is much more commonly used.

The stack of laminations is placed in a permanent mold or die-casting die containing a space at the top and bottom for the simultaneous casting of end-rings. These end-rings serve to connect electrically all of the rotor bars. The mold is clamped together and the selected molten aluminum alloy is poured or forced into the mold. The resultant cast rotor is shown in Fig. 16-2. The particular rotor shown is of the open-slot type. If this particular rotor were of the closed-slot type, the flash would not be in evidence.

The rotor shaft may or may not be inserted in the rotor bore at this point, depending on the succeeding finishing steps required and the particular manufacturing process being used.

Fig. 16-3 shows a typical cast rotor from which all of the iron laminations have been eaten away by acid in order to reveal the interior construction.

Comparative Performance of Cast Aluminum Rotors

Casting rotors in aluminum makes it possible to fill all the conductor bar slots, bind the entire assembly together, and produce the end-rings and cooling fan vanes in a single economical operation. The resultant assembly is sturdier and less noisy than a copper-cage rotor. It gives motor designers greater latitude and makes better use of the slots by filling them completely. Because of this, a cast rotor should maintain its balance indefinitely whereas a welded, brazed or wound cage, in which the conductors do not fill the slots completely, may lose its balance in time.

Electrical Conductivity: In an induction motor, the higher the electrical conductivity of the rotor, the greater the efficiency of the motor under normal load. On the other hand, the lower the conductivity the higher the starting torque and the lower the starting current. The use to which the motor will be subjected determines motor design and selection of alloy for a desired conductivity. Since, on a volume basis, aluminum has lower conductivity than copper, the required conductivity in a cast aluminum rotor is achieved simply by increasing the size of the slots and of the end rings over that required by an equivalent copper-cage. The overall dimensions remain approximately the same.

Weight: Because of the relative densities of the two metals the weight of an aluminum conductor is half that of an equivalent copper conductor. This means that an aluminum rotor is subject to less stress from centrifugal forces, less starting inertia, less vibration while running and is more portable than an equivalent copper rotor.

Heat Capacity: Temperature rise is one of the limiting factors in motor design. The greater the heat capacity of the rotor the cooler it remains during temporary overloads. Pound for pound aluminum has more than twice the heat capacity of copper but, since its weight in a rotor is about half that of an equivalent copper-cage, heat capacity remains on an equivalent basis.

Thermal Conductivity: The higher the thermal conduc-
tivity the greater the ability of the rotor to dissipate
heat. Aluminum has half the thermal conductivity of
copper. On the other hand an equivalent aluminum cage
has a relatively larger volume and better heat transmission
conditions between conductor and core. In this respect,
therefore, equivalent performance is attained.

Alloy Selection

Rotor casting demands relatively high conductivity for
most applications, exceptionally clean metal that will
completely fill the conductor-bar slots and form sound
end-rings and fan vanes around the assembled core of
steel laminations. The aluminum must solidify without
cracks or excessive porosity to provide the necessary elec-
ctrical circuits, and develop adequate strength to bind the
entire unit together.

The important factors, therefore, in cast rotor alloy se-
lection are: conductivity, castability, cleanliness and
strength. Unfortunately not all of these factors are opti-
mized by the same alloy composition. For most appli-
cations rotor manufacturers strive for maximum conductivity
but as the size and complexity of the rotor increases some
sacrifice is unavoidable if the needed castability and
strength are to be secured.

Manufacturers generally provide several recommended
aluminum rotor alloys whose use depends upon the size
of the rotor. For smaller rotor sizes the aluminum content
is higher and the conductivity approaches 59 to 60%
IACS. For larger rotors a greater amount of alloyed silicon
and iron is provided so that the conductivity may be from
54 to 57% IACS. The higher alloy content is controlled
carefully and provides greater castability, greater freedom
from hot cracking and shrinkage during casting. Manufac-
turers recommend the use of the higher iron/silicon alloy
when one or more dimensions of the rotor is greater than
five inches.

For a listing of rotor alloys and their chemical compo-
sitions, see Table 16-1 on page 16-5.

Conductivity from Composition: Conductivity meas-
urements on the ingot itself are not a reliable measure of
the conductivity of conductor bars and collector rings be-
cause rotor casting processes affect such conductivity
measurements. Yet rotor manufacturers need a means for
identifying consistent electrical characteristics in the rotor
metal they purchase. This is accomplished by specifying
the chemical composition limits and a range or the mini-
num electrical conductivity of the ingot.

Rotor Ingot: Manufacturers of aluminum rotor alloys
supply such metal in ingot form to specifications for com-
position and conductivity. The rotor alloys are particu-
larly free from non-metallic and harmful oxide inclusions
resulting in better fluidity and improved castability than
commercial grades of unalloyed aluminum.

Manufacture of Cast Aluminum Rotors

Melting and Metal Preparation Equipment

Fuel fired, induction and electric resistance furnaces are
used to melt and hold aluminum for the casting of motor
rotors. The choice of melting equipment will depend on
the type and volume of rotors to be cast and on the cost of
fuel for any given locality.

The following types of furnace equipment can be used
to melt and hold aluminum for motor rotors:

Crucible Furnaces: Underfired crucible furnaces are
available with capacities that range from just a few pounds
to 1500 pounds. Although it is possible to use the same
crucible furnace for both the melting and casting
processes, it is preferable to melt and flux in one unit
and transfer the molten metal to a second furnace for
casting. The use of a single furnace for melting and
casting does not provide good temperature control since
ingot and gates charged into the melt drop the temperature
of the metal making it impossible to maintain a uniform
pouring or casting temperature. A single furnace for melting and holding also complicates the fluxing of the melt for cleaning the metal.

The use of a refractory crucible such as silicon carbide or clay graphite is recommended as iron pickup can result from the use of cast iron crucibles. Where cast iron crucibles are employed, they must be kept coated with a refractory pot wash to minimize iron pickup since iron is readily soluble in molten aluminum and reduces the electrical conductivity of aluminum. Proprietary salt fluxes are used to dry the surface skim on the melt and remove build-up from crucibles.

**Reverberatory Furnaces:** Reverberatory furnaces may be built in sizes varying from about 1000 pounds capacity to as high as 100,000 pounds. The reverberatory furnace is usually employed as a “breakdown” furnace with the molten metal transferred to crucible type or induction holding furnaces at the casting machine. Reverberatory furnaces with a dipping well or wells are also employed as combination melt and hold furnaces. The advantage of the dip well type of furnace is in the elimination of molten metal transfer and a low cost for melting and holding. The principal disadvantage of this type of furnace, aside from its higher original cost, is that salt fluxing and cleaning of the furnace is more difficult than with the crucible type. In all rotor casting work, the degree of cleanliness of the melting and holding furnaces is an important factor in preventing low or variable conductivity and casting problems due to the occurrence of oxide inclusions in the rotor castings. The combination of rotor grades of ingot and clean furnaces provides optimum metal quality.

**Induction Furnaces:** Electric induction furnaces are employed by a number of motor rotor manufacturers for the melting and holding of aluminum. Induction furnaces provide a high quality melt with uniform composition and excellent temperature control; however, where ingot and scrap are charged into a single chamber induction furnace, some variation in metal temperature and oxide content can be expected.

Successful operation of core-type induction furnaces requires regular maintenance of the inductor channels. These channels usually require “rodging out” at regular intervals to prevent the channel from plugging up. The non-metallic deposit in the channels of an induction furnace consists of the oxides and nitrides of aluminum and other elements which are formed during continuous melting and holding. The non-metallics are concentrated in the channels by the electromagnetic field and form a hard deposit. Complex intermetallic compounds of iron and impurities may also settle in the furnace channels if the original rotor alloy is contaminated with impurity elements.

The proprietary fluxing compounds required to clean crucible and reverberatory furnaces in induction furnaces have been shown to promote channel plugging. The metal salts in fluxing compounds form oxides which are deposited on the walls of the inductor channels. Where fluxing is deemed necessary, a degassing flux of the hexachloroethane type or chlorine-nitrogen gas mixture is recommended. With rotor grade ingots, it is not necessary to flux the melt when 100% ingot is charged. The charging of gates and the biscuits from the shot chamber may necessitate fluxing of the melt at times to cleanse the metal and the channels.

**Casting Methods Employed for Aluminum Rotors**

The horizontal cold chamber die-casting method is recommended for high volume production of fractional horsepower motor rotors. The die casting process provides a good quality rotor casting at a low unit cost. The process lends itself to automation providing further production economics. Multiple cavity dies are usually employed to cast several rotors of the same or different design at one time. In volume production the high original investment cost of the die casting machine, dies and suitable metal melting and holding equipment is justified. In the die-casting process, the steel lamination stack is usually loaded into the die without preheating. Conventional die casting practices are used to produce rotors.

---

*Fig. 16-2. A typical die-cast rotor of the open-slot type.*

*Fig. 16-3. Iron surrounding the cast-aluminum squirrel cage has been removed to reveal construction.*
The vertical press method of pressure casting aluminum rotors has been used for many years to cast both fractional and large integral horsepower motor rotors. The original investment is lower than die casting equipment. In this process the lower platen of the press usually contains a round well or sump into which the molten metal is poured. The sump may be lined with mica and/or asbestos paper to prevent excessive metal temperature loss or is sometimes sprayed with an aqueous graphite or similar type coating to prevent the metal from sticking. The rotor mold and the lamination stack are mounted on the upper platen. The molten metal is forced by the stroke of the press through a series of small gates into the rotor die. The gates into the rotor usually consist of a number of tapered holes through the base plate of the mold into the collector ring part of the cavity. In this casting method, it is desirable to preheat the lamination stack to a temperature of from 400°-1000° F. prior to loading the stack into the casting die. The required preheat temperature of the laminations will vary depending on the size of the rotor to be cast and the size of the slots in the laminations.

Casting Problems

Problems usually show up as low conductance or high starting torque of the rotors. The major casting problem in the production of aluminum rotors is the presence of entrapped air and/or gas from the die lubricant. This type of defect manifests itself as a number of smooth rounded (or slightly elongated) gas holes within the end rings and conductor bars. This type of defect reduces the conductance of the rotor and the electrical efficiency of the motor. Some porosity of this type is experienced in varying degrees in all of the casting methods employed for rotors. This type of defect may be reduced by providing adequate venting of the die or mold during the casting cycle and by avoiding excessive use of die or mold lubricants. The rate of metal injection into the die can also influence the occurrence of this type of defect. The optimum metal injection rate must be determined by the producer as it will vary depending on the type of casting equipment, mold design and design of rotor being cast.

Other casting defects encountered in rotors are dross or oxide films, shrinkage, cracks and poor fill (usually in conductor bars). The dross defect can be the result of poor metal melting and handling practice and is discussed under the previous section on melting. Aluminum alloys undergo a 5 to 6 percent volume decrease in solidifying from the liquid state. Since it is impractical to supply molten metal to feed or make up for this volume change in most designs of cast rotors, some internal shrinkage porosity may occur, particularly in large integral rotors with heavy end rings. Cracks in the end rings or in the conductor bars are extremely detrimental to the service of the rotor. Unalloyed aluminum, 99.80 or 99.85, is more prone to cracks and shrinks than the rotor alloys. Other casting alloys such as 380.0 are prone to cracking in rotor casting because of their relatively long solidification range. In large rotors, it may be possible to provide excess metal in the form of risers to aid in overcoming the shrinkage tendency in the top ring. Careful control of the metal temperature and mold temperature is necessary in minimizing cracks and poor fill in 380.0 alloy rotors.

Loss of conductivity and poor casting characteristics may occur if the rotor alloy becomes contaminated with other metals. Iron is readily soluble in molten aluminum and iron contamination in the melt is quite often the cause of low conductivity and poor fill or cold shuts.

Steel Laminations: In the stamping of laminations the formation of burrs at the slot edges should be kept to a minimum by proper maintenance of punches and dies. Excessive burring can contribute to metallurgical bonding with the aluminum during casting, and lead to loss of motor efficiency.

To assist in the casting of sound conductor bars and end rings (whether by gravity, centrifugal or pressure die casting) it is recommended that the steel lamination stacks be preheated. This greatly facilitates metal flow and the filling of intricate passages. Preheating the laminations also oxidizes freshly sheared edges of the slots thereby reducing the tendency for metallurgical bonding to occur between the steel and aluminum. Preheating at 250-350°C for 1-2 hours is usually adequate though bulky lamination stacks may require higher temperatures for a somewhat longer period.

Casting: Casting temperatures for rotor metal may lie anywhere in the range 700-800°C (1290-1470°F) depending upon individual foundry practices. Once casting temperature is established it should be held within ± 10°C. In production, uniform casting cycles should be maintained so as to properly control die and mold temperatures. Dies should be preheated to 250-300°C (480-570°F). Cold dies are the cause of scrap which can be reduced by maintaining uniform and continuous production cycling.

In pressure die-casting an important factor in the production of sound rotors is adequate venting of the cavity. Excessive use of die lubricants can lead to venting problems. If asbestos paper is used to line the mold (vertical pressure die casting of larger rotors) it should be thoroughly furnace dried just before use to eliminate this source of gas pick-up.

Thermal Treatment: Two considerations are important for the efficient electrical operation of a squirrel cage motor. These are (1) there should be a reasonably high inter-laminar resistance and (2) there should be a high resistance between the iron laminations and the die-cast aluminum conductors and end rings. The second item is particularly important and even a partial separation of aluminum from iron immediately results in noticeably better performance.

Thermal treatment of rotor castings, 1-2 hours at 300-450°C (570-840°F), is helpful in breaking metallurgical bonds between steel laminations and the aluminum conductor bars. This is due to a large differential in thermal expansion of the two metals. For pressure die cast rotors,
TABLE 16-1
Rotor Metal Alloys

<table>
<thead>
<tr>
<th>Alloy*</th>
<th>Aluminum Grade Min. Purity*</th>
<th>Rated Conductivity % IACS — Min.</th>
</tr>
</thead>
<tbody>
<tr>
<td>100.1</td>
<td>99.00%</td>
<td>54</td>
</tr>
<tr>
<td>130.1</td>
<td>99.30%</td>
<td>55</td>
</tr>
<tr>
<td>150.1</td>
<td>99.50%</td>
<td>57</td>
</tr>
<tr>
<td>170.1</td>
<td>99.70%</td>
<td>59</td>
</tr>
</tbody>
</table>

Chemical Composition of Rotor Alloys

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Silicon</th>
<th>Iron</th>
<th>Copper</th>
<th>Manganese</th>
<th>Chromium</th>
<th>Zinc</th>
<th>Titanium</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.6—0.8</td>
<td>0.10</td>
<td>(a)</td>
<td>(a)</td>
<td>0.05</td>
<td>(a)</td>
<td>0.03 (a) 0.10</td>
</tr>
<tr>
<td>100.1</td>
<td>(b)</td>
<td>(b)</td>
<td>0.10</td>
<td>(a)</td>
<td>(a)</td>
<td>0.05</td>
<td>(a)</td>
<td>0.03 (a) 0.10</td>
</tr>
<tr>
<td>130.1</td>
<td>(c)</td>
<td>(c)</td>
<td>0.06</td>
<td>(a)</td>
<td>(a)</td>
<td>0.05</td>
<td>(a)</td>
<td>0.03 (a) 0.10</td>
</tr>
<tr>
<td>150.1</td>
<td>(d)</td>
<td>(d)</td>
<td>—</td>
<td>(a)</td>
<td>(a)</td>
<td>0.05</td>
<td>(a)</td>
<td>0.03 (a) 0.10</td>
</tr>
<tr>
<td>170.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(a) Manganese plus chromium plus titanium plus vanadium is 0.025% max.
(b) Iron to silicon ratio is 2.5 minimum.
(c) Iron to silicon ratio is 2.0 minimum.
(d) Iron to silicon ratio is 1.5 minimum.

*In judging the rotor alloy to be used, it should be noted that the highest purity alloy (170.1) is the most difficult to cast and is subject to a greater degree of shrink cracking. By contrast, the lessor purity 100.1 alloy is easier to cast with a minimum of cracks.

For high torque rotors (37% IACS — typical) the standard foundry alloy 443.0 (Nominal 5.2% Si) is applicable. Also for high torque 30% IACS conductivity, the standard foundry alloy 380.0 (Nominal 3.5% Cu, 8.5% Si) is applicable.

treatment temperatures at the lower end of the indicated range are less likely to cause blistering. The heating also tends to introduce some further oxide film between the aluminum and iron thus assisting electrical isolation further.

**Aluminum in Power Switchgear**

Aluminum and its alloys have become increasingly important in the manufacture of all types of electrical switchgear. Its applications in switchgear vary from small rivets, sheet metal enclosures and hardware to important current-carrying and structural parts.

High electrical and thermal conductivity, high strength-to-weight ratio, excellent corrosion resistance, non-magnetic properties and superb fabrication capability are some of the most important characteristics favoring the use of aluminum.

Fig. 16-4 shows an example of modern switchgear using aluminum in various forms.
electromagnetic and other electrical applications of aluminum

Figure 16-4. Modern aluminum switch gear capable of handling 50,000 ampere short circuit current.
One of the earliest, and still most effective, methods of installing concealed electrical cable within the structure of a building, in the building foundations or the subgrade is the use of rigid conduit. The many advantages rigid conduit provides include:

A very high order of mechanical and flame protection for the enclosed cables.

A high order of safety to personnel who might otherwise accidentally come in contact with the ungrounded portion of the electrical system.

An easy pulling, smooth, snag-free pathway for the cables through an otherwise intricate, many-turned run.

Pull-boxes to enable straight pulls as required.

An easy means for replacing conductors or pulling in additional ones.

Permanent, built-in cable runways in cast concrete structures.

Elements of Conduit Design

Important elements in the design of electrical conduit are related to:

Adequate strength in relation to size for self-support over reasonable lengths.

Smooth, round, burr-free interior.

Capability of being cut and threaded readily and bent smoothly (no flattening) with normal field methods and tools.

Provision and maintenance of good electrical conductivity through the conduit proper and across all threaded joints.

Development of a compatible line of accessories, such as elbows, couplings, unions, tees, pull and junction boxes.

Freedom from destructive corrosion in the working environment.

Provision for expansion fittings for long lengths operating under widely varying temperature conditions.

Installation and construction requirements for electrical conduit are set by the National Electrical Code (NEC). These include rigid aluminum, galvanized steel, IMC (intermediate metal conduit) and nonmetallic conduit, as well as conduit fittings, conduit bodies and boxes in aluminum, galvanized steel and PVC. Individual product lines must be manufactured to conform to the standards set forth by Underwriters Laboratories, in order to qualify for UL Labels.

The factors involved in NEC rigid conduit specifications relate to installation and operating requirements.

For example, the Code specifies maximum allowable fill areas for given conduit sizes. Table 17-1, abstracted from the 1987 NEC, shows the allowable fill area for each conduit trade size.* Table 17-3 gives cross-sectional areas for typical conductor sizes insulated with both thermosetting and thermoplastic materials. Table 17-4 converts these area limitations to the number of typical conductor sizes permitted in one conduit based on both thermosetting and thermoplastic insulations. Tables 17-5a and 17-5b give dimensions of rigid aluminum, galvanized steel, and IMC. Table 17-6 gives comparative weights for the three types of metallic conduit.

The NEC also recognizes the effect of the conduit or raceway on temperature rise of the encased conductor. In Chapter 9 of this book, Tables 9-3, 9-4, 9-5, 9-6 and 9-7 show characteristics of wires and feeders in magnetic and non-magnetic conduit or raceways. Metallic conduits can contribute a small amount of heating due to hysteresis (if the conduit is magnetic) and eddy current losses. Of greatest importance in its effect on ampacity, however, is the number of loaded conductors in a given conduit. The tables referenced above give ampacity data for the case of not more than three loaded conductors per conduit. When the number of conductors increases to from 4 to 6 the ampacity values are reduced to 80% of the tabulated value. If there are 7 to 24 conductors in the conduit, the allowable currents are to be reduced to 70% of the tabulated value. (The neutral conductors, since they only carry the unbalanced currents in normally balanced circuits, are not to be considered in determining

* Table 17-2 shows the maximum number of compact conductors allowable in conduit or tubing.
**TABLE 17-1**
Conduit-Allowable Fill Area
Square Inches

<table>
<thead>
<tr>
<th>Conduit Trade Size Inches</th>
<th>Total Internal Area Sq. In.</th>
<th>1-Cond. 53%</th>
<th>2-Cond. 31%</th>
<th>3 or more 40%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/4</td>
<td>.30</td>
<td>.16</td>
<td>.09</td>
<td>.12</td>
</tr>
<tr>
<td>3/8</td>
<td>.53</td>
<td>.28</td>
<td>.16</td>
<td>.21</td>
</tr>
<tr>
<td>1/2</td>
<td>.86</td>
<td>.46</td>
<td>.27</td>
<td>.34</td>
</tr>
<tr>
<td>1/4</td>
<td>1.50</td>
<td>.80</td>
<td>.47</td>
<td>.60</td>
</tr>
<tr>
<td>1/2</td>
<td>2.04</td>
<td>1.08</td>
<td>.63</td>
<td>.82</td>
</tr>
<tr>
<td>2</td>
<td>3.36</td>
<td>1.78</td>
<td>1.04</td>
<td>1.34</td>
</tr>
<tr>
<td>2 1/2</td>
<td>4.79</td>
<td>2.54</td>
<td>1.48</td>
<td>1.92</td>
</tr>
<tr>
<td>3</td>
<td>7.38</td>
<td>3.91</td>
<td>2.29</td>
<td>2.95</td>
</tr>
<tr>
<td>3 1/2</td>
<td>9.90</td>
<td>5.25</td>
<td>3.07</td>
<td>3.96</td>
</tr>
<tr>
<td>4</td>
<td>12.72</td>
<td>6.74</td>
<td>3.94</td>
<td>5.09</td>
</tr>
<tr>
<td>5</td>
<td>20.00</td>
<td>10.60</td>
<td>6.20</td>
<td>8.00</td>
</tr>
<tr>
<td>6</td>
<td>28.89</td>
<td>15.31</td>
<td>8.96</td>
<td>11.56</td>
</tr>
</tbody>
</table>

**TABLE 17-2**
Maximum Number of Compact Conductors
in Trade Sizes of Conduit or Tubing

<table>
<thead>
<tr>
<th>Conductor Size AWG or kcmil</th>
<th>Insulation Type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T</td>
</tr>
<tr>
<td></td>
<td>H</td>
</tr>
<tr>
<td>Conduit Trade Size</td>
<td>1 in.</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>1/2</td>
<td>3</td>
</tr>
<tr>
<td>2/0</td>
<td>3</td>
</tr>
<tr>
<td>3/0</td>
<td>3</td>
</tr>
<tr>
<td>4/0</td>
<td>3</td>
</tr>
<tr>
<td>250</td>
<td>3</td>
</tr>
<tr>
<td>300</td>
<td>3</td>
</tr>
<tr>
<td>350</td>
<td>3</td>
</tr>
<tr>
<td>400</td>
<td>3</td>
</tr>
<tr>
<td>500</td>
<td>4</td>
</tr>
<tr>
<td>600</td>
<td>3</td>
</tr>
<tr>
<td>700</td>
<td>3</td>
</tr>
<tr>
<td>750</td>
<td>3</td>
</tr>
<tr>
<td>1000</td>
<td>3</td>
</tr>
</tbody>
</table>
TABLE 17-3
Conductor Cross-Sectional Areas
(Based on Table 5, Chapter 9, 1987 NEC)

<table>
<thead>
<tr>
<th>WIRE SIZE AWG, kcmil</th>
<th>APPROXIMATE AREA, SQUARE INCHES</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>INSULATED CONDUCTOR</td>
</tr>
<tr>
<td></td>
<td>Types RHH &amp; RHW* Type THW Type THHN THWN Type XHHW BARE</td>
</tr>
<tr>
<td>12</td>
<td>0.38   0.025 0.012 0.017 0.005</td>
</tr>
<tr>
<td>10</td>
<td>0.46   0.031 0.018 0.022 0.008</td>
</tr>
<tr>
<td>8</td>
<td>0.85   0.060 0.037 0.046 0.017</td>
</tr>
<tr>
<td>6</td>
<td>1.24   0.082 0.052 0.062 0.027</td>
</tr>
<tr>
<td>4</td>
<td>0.161  0.109 0.084 0.084 0.042</td>
</tr>
<tr>
<td>3</td>
<td>0.182  0.126 0.099 0.099 0.053</td>
</tr>
<tr>
<td>2</td>
<td>0.207  0.147 0.118 0.118 0.067</td>
</tr>
<tr>
<td>1</td>
<td>0.272  0.203 0.159 0.159 0.087</td>
</tr>
<tr>
<td>1/0</td>
<td>0.311  0.237 0.189 0.189 0.109</td>
</tr>
<tr>
<td>1/0</td>
<td>0.358  0.278 0.226 0.226 0.137</td>
</tr>
<tr>
<td>3/0</td>
<td>0.415  0.329 0.271 0.271 0.173</td>
</tr>
<tr>
<td>4/0</td>
<td>0.484  0.390 0.328 0.328 0.219</td>
</tr>
<tr>
<td>250</td>
<td>0.592  0.488 0.403 0.403 0.260</td>
</tr>
<tr>
<td>300</td>
<td>0.684  0.558 0.467 0.467 0.312</td>
</tr>
<tr>
<td>350</td>
<td>0.762  0.629 0.531 0.531 0.364</td>
</tr>
<tr>
<td>400</td>
<td>0.836  0.697 0.593 0.593 0.416</td>
</tr>
<tr>
<td>500</td>
<td>0.983  0.832 0.716 0.716 0.520</td>
</tr>
<tr>
<td>600</td>
<td>1.194  1.026 0.879 0.904 0.626</td>
</tr>
<tr>
<td>700</td>
<td>1.336  1.158 1.001 1.030 0.730</td>
</tr>
<tr>
<td>750</td>
<td>1.408  1.225 1.062 1.094 0.782</td>
</tr>
<tr>
<td>800</td>
<td>1.478  1.291 1.123 1.150 0.833</td>
</tr>
<tr>
<td>900</td>
<td>1.617  1.421 1.245 1.267 0.933</td>
</tr>
<tr>
<td>1000</td>
<td>1.753  1.548 1.362 1.389 1.039</td>
</tr>
<tr>
<td>1250</td>
<td>2.206  1.953 1.767 1.305</td>
</tr>
<tr>
<td>1500</td>
<td>2.548  2.275 2.061 1.561</td>
</tr>
<tr>
<td>1750</td>
<td>2.890  2.693 2.378 1.829</td>
</tr>
<tr>
<td>2000</td>
<td>3.208  2.901 2.659 2.087</td>
</tr>
</tbody>
</table>

*RHH and RHW without outer covering are the same as THW.

rigid aluminum conduit

film, and excellent ductility and machinability are basic factors in its present wide acceptance. The following material examines in some detail how these plus factors compare with steel.

**Composition and Manufacture:** Rigid aluminum conduit is usually extruded from the magnesium-silicide, 6063-T1 alloy, though other alloys can be used which meet UL requirements.

Being an extrusion, aluminum conduit is completely moisture-and vapor-tight. Also, extruded pipe provides a smooth, uniform interior surface.

**Weight Comparison:** Aluminum conduit with aluminum couplings weighs approximately one-third of its galvanized steel counterpart, and one-half that of steel IMC. This difference in weight is reflected in substantially greater ease and cost savings in installation. For example, a 10-foot standard length of 4-inch steel conduit weighs over 98 pounds and requires two men or a hoist to place it. The same size aluminum conduit weighs only 34 pounds and is handled easily by one man. The larger the conduit size, the greater the savings in labor.

**Electrical Characteristics**

Aluminum conduit alloy 6063 has about 1/4 the electrical resistance of the usual galvanized mild steel conduit. In the installed condition, with couplings, elbows and boxes, a run of aluminum conduit will show about 4-1/2 times greater electrical conductivity, and if the installation is properly made will maintain its high value.

**Protective Capability:** In a conduit/cable system when a phase-to-ground fault occurs, the conduit will normally carry most of the fault current—which can be quite high in value. Usually, the wiring system neutral is grounded at one point. The conduit may be grounded at many points. In any event, the fault current flowing in the conduit raises its potential above ground by an amount equal to the impedance drop to ground. The lower the installed conduit impedance to ground the less danger there is from fault/ground shocks, and in this respect the advantage of aluminum conduit is obvious. The lower resistance of aluminum conduit also means that ground current fault relaying is more reliable.

It must be understood that rigid electrical conduit as installed per NEC requirements is normally not supposed to carry any ground currents; it is to act as a mechanical protection and carry current only in the case of a fault. The Code specifically* indicates that any neutral wires shall not be installed in electrical continuity with the conduit and, if accidental continuities are found to exist between the neutral and the conduit, such neutral faults shall be cleared. This separation of neutral ground current

*1987 National Electrical Code, Section 250-21
TABLE 17-4
Typical Number of Conductors Allowable in Trade Sizes of Conduit or Tubing

<table>
<thead>
<tr>
<th>Wire Size AWG or kcmil</th>
<th>Maximum Number of Conductors in Conduit*</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>6</td>
</tr>
<tr>
<td>12</td>
<td>4</td>
</tr>
<tr>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
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<tr>
<td>6</td>
<td>1</td>
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<td>3</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

A — THW, RHH, RHW (without outer covering).
B — THW and THHN. (XHHW in sizes #4 AWG through 500 kcmil) see NEC, Chapter 9, Table 3 for other sizes and types.

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flow from the conduit is very helpful in minimizing ac electrolytic corrosion, and interference with communication circuits.

**Short Circuit Capability:** Comparative short circuit tests* on aluminum and galvanized steel conduits have been made to determine their relative behavior under heavy fault conditions. Fig. 17-1 shows the temperature rise vs. time of 2-inch aluminum and steel conduits joined in series and subjected to a short circuit current flow of 22,200 amperes RMS. The steel conduit at the end of 10 seconds was buckling and dully glowing and its temperature rise was about 4-1/2 times as great as that of the aluminum conduit. The steel couplings all smoked profusely and showed thread damage. In contrast, the aluminum conduits still retained their gummed labels and showed no signs of the heavy current passage after the test. Thus, despite the considerably lower melt-point of aluminum conduit, its ability to carry short circuit currents is greatly superior to galvanized steel.

**Circuit Voltage Drop:** Aluminum conduit, being non-magnetic, exhibits no hysteresis losses from alternating current fields. The net effect is that voltage drop in a typical three-phase feeder or branch circuit in aluminum conduit may be from 10 percent to as much as 20 percent lower than with a corresponding steel conduit. For conductor sizes 250 kcmil and higher, this overall reduced voltage drop may permit the use of conductors one size

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or in some cases two sizes smaller — where voltage drop is the governing concern.

**Corrosion Characteristics of Rigid Aluminum Conduit**

Alloy 6063, which is commonly used for rigid aluminum conduit, has an industry maximum limit of 0.1 percent copper content and 0.35 percent for iron (Table 17-7). Aluminum conduit has been used successfully for more than 50 years in many marine and corrosive industrial installations under conditions where galvanized steel conduit should not be used.

The galvanizing on a steel conduit acts as an anodic sacrificial metal coating and is continuously “wearing out.” On the other hand, aluminum quickly builds up its refractory oxide layer which is relatively inert to most chemicals except strong alkalies and acids. This tough, protective skin automatically renews itself whenever the bare metal becomes exposed.

Aluminum’s resistance to atmospheric corrosion has been demonstrated repeatedly by tests and research studies. Some of the results:

No signs of corrosion were evident on rigid aluminum conduit when inspected 5 years after it was installed on cooling towers. Severe combinations of moisture and chemical-laden atmospheres at the installation had required frequent replacement of rigid galvanized conduit, according to Paper CP 58-1072 of the American Institute of Electrical Engineers.

Aluminum alloy 6063 was exposed to marine, industrial and rural atmospheres. After exposures of 1, 2, 3, 4 and 5 years, there appeared no significant effects on yield and tensile strengths.

Atmospheric corrosion rates of four solid metals, as determined by a 10-year study project of an ASTM committee, are shown in Table 17-8.

**Broad Industrial Application**: Installations of rigid aluminum conduit usually require no maintenance painting.
or protective treatment, as may be required on steel conduit. Because its resistance to corrosion is greater than steel’s, it is the choice for many severely corrosive industrial environments such as: sewerage plants, water treatment stations, filtration plants and chemical plants.

**Exposure to Galvanic or Electrolytic Attack**: Aluminum conduit should not be direct-buried in earth due to unpredictable soil conditions of moisture, possible presence of strong electrolytes and stray electrical currents. If it is necessary to bury aluminum conduit, in accordance with the NEC, it should be thoroughly coated with coal-tar epoxy or given a layer of half-lapped approved tape. Also, factory-applied PVC coatings are commercially available.

Galvanic attack can occur when the aluminum forms the anode of a battery created by two dissimilar metals in contact with an electrolytic medium. Stray alternating or direct currents can aggravate the galvanic action, eventually destroying the buried or embedded conduit.

**Conduit Embedded in Concrete**: In accordance with the NEC, aluminum conduit should not be embedded in concrete without approved protection because of the possibility of galvanic or electrolytic corrosion. Stray currents can aggravate the corrosion, severely damaging the conduit. If it is necessary to embed aluminum conduit in concrete, it should be given the same protection recommended for direct-earth burial.

Additionally, to mitigate the corrosion of all metallic conduit embedded in concrete:

1. The concrete should contain no extraneously added chloride. Such chlorides can originate from concrete additives (to speed setting time), use of sea or brackish water, use of unwashed beach sand or other saline aggregate and similar materials.

2. A low resistance conduit run should be maintained.

3. The circuit neutral should be grounded at one point and be insulated from and have no electrical contact with the conduit. The conduit should not carry any of the ground currents associated with normal operation.

**Hazardous Locations**: Requirements of Article 500 of the NEC covering conduit installations in hazardous locations can be easily met with properly installed rigid aluminum conduit. The characteristics of aluminum conduit facilitate the installation of a tight explosion-proof system.

**Installation of Aluminum Conduit**

Easier, safer workability adds to the many advantages of rigid aluminum conduit at every step of installation.

**Cutting**: Fast, easy cuts are handled well by standard cutting tools, which are generally used. Power saws and cutting wheels work fast and neatly on 1-1/2-inch and larger conduit; for smaller sizes (as for smaller steel conduit), an 8-tooth hacksaw is recommended for easy, neat cuts. Reaming, as required by the NEC, can be easily accomplished by conventional means.

**Threading**: Standard dies, used according to accepted good practices, thread aluminum rigid conduit faster than

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*Nominal

<table>
<thead>
<tr>
<th>Trade Size</th>
<th>Rigid Aluminum</th>
<th>Galvanized Steel</th>
<th>IMC Type I</th>
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</thead>
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<tr>
<td>1/8</td>
<td>28.1</td>
<td>80.3</td>
<td>57.0</td>
</tr>
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<td>6</td>
<td>630.4</td>
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<table>
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<tr>
<th>Percentage Limits per Industry Standards</th>
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</thead>
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<tr>
<td>Copper</td>
</tr>
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<td>0.10 max.</td>
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<tr>
<td>Silicon</td>
</tr>
<tr>
<td>0.20 to 0.6</td>
</tr>
<tr>
<td>Iron</td>
</tr>
<tr>
<td>0.35 max.</td>
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<tr>
<td>Magnesium</td>
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<td>0.45 to 0.9</td>
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<td>Manganese</td>
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<tr>
<td>0.10 max.</td>
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<td>Chromium</td>
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<td>0.10 max.</td>
</tr>
<tr>
<td>Titanium</td>
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<tr>
<td>0.10 max.</td>
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<tr>
<td>Zinc</td>
</tr>
<tr>
<td>0.10 max.</td>
</tr>
<tr>
<td>Others</td>
</tr>
<tr>
<td>0.15 max.</td>
</tr>
<tr>
<td>Aluminum</td>
</tr>
<tr>
<td>Remainder</td>
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</table>

*Alloys with up to 0.40% copper are acceptable to Underwriters’ Laboratories, Inc., for use in rigid aluminum conduit and fittings.
Fig. 17-1. Measured temperature rise vs time for aluminum and steel conduit under short circuit conditions.

Steel and with less effort. Hand threaders produce good threading on smaller sizes. Power threaders, however, can be used on all sizes and operated at maximum drive speeds. When using top drive speeds, and for longer tool life, dies with 30° to 35° rake angles should be used. Standard cutting oils of known good quality are recommended for uniform threads.

**Bending:** Sweeps, elbows, cross-overs, offsets—every type of bend is easily made in rigid aluminum conduit. Standard hand and power benders produce smooth and exact bends in all conduit sizes.

Standard EMT benders can be used on 1-inch or smaller aluminum conduit for one-shot bends. Use an EMT bender one size larger than the conduit. Mechanical or power benders can be used on all sizes, provided they have shoes and action similar to those of an EMT bender.

**Joining:** Adequate electrical conductance in a conduit system requires tight joints. To simplify field joining, both threads of every length of rigid aluminum conduit should be lubricated in the field if not lubricated at the factory. (On field-cut threads, of course, a reliable quality lubricant containing zinc or graphite should be used). Proper lubrication aids in assuming tight joints, a system that can be easily dismantled, and a permanent, low-resistant electrical ground path.

**Pulling:** Modern equipment and faster, safer techniques that work well with aluminum conduit have been introduced for fishing and pulling through all types of wireways.

**Propelled Lines:** CO$_2$ or air propelled lines of nylon or other plastic shoot through all sizes or rigid aluminum conduit.

**Small Conduit:** In sizes up to 1-1/2-inch and on shorter runs — up to 100 feet — polyethylene fish tapes can be used effectively. Also recommended are round, flexible, speedometer-type steel cables. Use of flat steel tapes should be avoided since they tend to jam in the bends or, if not used carefully, scrape and cut conduit walls.
related structural applications of aluminum

<table>
<thead>
<tr>
<th>Atmosphere</th>
<th>Location</th>
<th>Aluminum*</th>
<th>Copper</th>
<th>Zinc**</th>
<th>Lead</th>
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</thead>
<tbody>
<tr>
<td>Desert</td>
<td>Phoenix, Arizona</td>
<td>0.000</td>
<td>0.005</td>
<td>0.010</td>
<td>0.009</td>
</tr>
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<td>Rural</td>
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<td>0.020</td>
<td>0.021</td>
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<td>0.052</td>
<td>0.068</td>
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<td>0.047</td>
<td>0.190</td>
<td>0.017</td>
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<tr>
<td>Industrial</td>
<td>Altoona, Pa.</td>
<td>0.025</td>
<td>0.046</td>
<td>0.190</td>
<td>0.027</td>
</tr>
</tbody>
</table>

Corrosion rate shown in average mils per year. Table based on ASTM data (Committee report).

*Aluminum 1100. Aluminum conduit is usually made from aluminum alloy 6063, generally considered to be equivalent in corrosion resistance to aluminum 1100.

**Prime western zinc.

Larger Conduit: For pulling large conductors through larger conduit or longer runs, polypropylene rope is recommended. Steel pulling cables, especially when old or frayed, can damage steel or aluminum conduit.

Fittings for Rigid Aluminum Conduit: Although galvanized or plated steel fittings are permitted by the 1987 NEC and can be safely used with rigid aluminum conduit, good aluminum fittings result in a superior installation.

An all-aluminum conduit run has better conductivity and provides safer ground protection. And aluminum's non-magnetic property, in fittings as well as conduit, reduces ground current losses and voltage drops.

Expansion Joints: Linear expansion of rigid aluminum conduit is not a factor in most installations. If a straight run is unusually long or subjected to extremes of temperature, expansion fittings might be needed. A good general rule: use an expansion joint if the degree-feet of a run may exceed 10,000. (Degree-feet is the length of the run in feet multiplied by the temperature rise, °F.)
Chapter 18

Street-Lighting Poles, Transmission Towers, and Station Structures

This book would be incomplete without a brief mention of the specialized structures related to the everyday use of aluminum electrical conductors.

Recent years have witnessed a steady gain in the use of aluminum for many types of structures required by the electrical industry. This is based on very sound considerations. Research programs have led to the development of high strength aluminum alloys, new effective structural designs and strong, economical fastening and joining methods. These factors, coupled with aluminum’s traditionally known high resistance to corrosion, account for the wide use of aluminum structures today. We will discuss just a few of these in this chapter.

Aluminum Lighting Standards

A lighting standard is many things to many people.

It must be tall enough to cast its light from the luminaire it carries above any normal eye level and the angle of sighting along the thoroughfare.

It must be strong enough to resist high winds. On interstate highways it must be safe enough that its base breaks away when hit by a subcompact car at 20 mph.

It must be graceful in appearance and at the same time unobtrusive and uncluttered.

It must resist the effects of industrial and traffic induced corrosion for 25 years at least.

It must be designed to provide inherent concealment for transformer and wires or protective components and for easy cleaning of lenses and replacement lamps.

It must be versatile in that signs (either permanent or not) may be hung on the standard or flag poles provided at the top, or Christmas street decorations mounted from special brackets or used for a number of other accessories.

It must be low in installation and maintenance costs.

Aluminum, taking advantage of its good looks, light weight, high strength-to-weight ratio possibilities and high corrosion resistance has been accepted as an ideal material for street and highway lighting poles. This has been a steadily growing application of aluminum since the 1940’s.

Aluminum lighting standards extend their versatility into highway safety by reducing vehicular damage and driver injury in collisions either as an intrinsic aspect of their design or by the simple installation of accessory breakaway devices.

Modern aluminum lighting standards are a combination of sheet, extruded and cast alloy sections. Shafts are usually 6063-T6 or 6005-T6 extrusions or 5086-H34 sheet; luminaire arms are 6061-T6 or 6063-T6 extrusions; bases and arm holders may be 356 casting alloy (Fig. 18-1).

Aluminum lighting standards can be designed with classic simplicity so that they may complement virtually every type of architectural or landscape background. Although aluminum has a pleasing appearance in its natural state, it can be made to take on a variety of finishes applied mechanically, chemically or electrochemically. The surface can be polished, buffed or electrobrightened to give a wide range of interesting and attractive appearances. Through the anodizing process the natural surface oxide film can be deepened and strengthened to a substantial, hard refractory coating not only providing a very high degree of corrosion resistance but a surface that can also be impregnated with permanent coloring dyes.

With the high strength-to-weight ratios provided by these alloys, aluminum lighting standards form an assembly that is rugged enough for the severest service, yet light enough for installation crews to handle without special equipment.

Aluminum lighting standards are available for mounting luminaires up to 50 feet above the roadway with various arm configurations. (See Table 18-1).

Aluminum lighting standards may be of a tapered or uniform cross section. The former is fabricated by spin-tapering extruded 6063-T4 tubes about 1/8” per foot and then artificially aging to the T6 temper. The profile may also be fabricated from trapezoidal sheet sections pressformed and longitudinally welded into a tapered shaft. Uniform cross sectional lighting standards can be made in any cross sectional geometry with extrusions or press forming of sheet.
related structural applications of aluminum

![Diagram of a street lighting standard](image)

<table>
<thead>
<tr>
<th>Alloys and Temper</th>
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<tbody>
<tr>
<td>Spun Aluminum Standard</td>
<td>Welded Tapered Sheet Aluminum Standard</td>
</tr>
<tr>
<td>6063-T6, 6005-T6</td>
<td>5086-H34</td>
</tr>
</tbody>
</table>

*Fig. 18-1. Typical street lighting standard using aluminum.*
### Aluminum Transmission Towers

Use of prefabricated metal towers for 138 kV and higher transmission is widespread today. However, the traditional place held by steel in tower construction due to its high strength and relatively low cost is now being effectively challenged by selected high-strength aluminum alloys such as 6061-T6. The keys to this challenge are high strength-to-weight ratio, high corrosion resistance, multi-form shape extrudability and reasonably low, stable prices. The two factors of (1) dramatic reduction of installation costs and (2) virtual elimination of maintenance costs account in large part for the present serious consideration given to aluminum towers. Surfaces of aluminum transmission tower structures can be treated with various coatings to meet “non-glare” requirements often specified. These coatings need little or no maintenance in service.

Although aluminum cross-arms had been used in combination with steel towers for a complete transmission system before 1950, the first all-aluminum tower lines were placed into operation in 1959 by several utilities. These early aluminum towers were of the self-supporting type similar to existing steel tower designs. Structural angles in sizes from 2" x 2" x 3/16" to 10" x 10" x 1 1/4" and plates in thicknesses from 1/4" to 3/4" were employed using the excellent structural alloy 6061-T6.

Since pound for pound, aluminum represents a significantly higher metal cost than steel, it is to be expected that the shop-fabricated cost of an aluminum tower will be higher than for a comparable loading design in steel. This increase, however, can be fully offset in some cases because of lower field erection costs plus credit from much lower maintenance over the life of the structure. Also there are circumstances where interruptions of service for maintenance work cannot be tolerated; this factor alone justifies the use of aluminum.

**Weight Reduction:** Aluminum tower structures afford weight reductions of 50 to 75% from steel structures having equivalent capabilities.

This weight advantage of aluminum works as an important cost reduction factor in the construction of transmission towers. Lighter, conventional erection equipment can be used, as well as faster methods. Lightweight aluminum structural can be assembled into components or complete towers at convenient locations, then transported easily and quickly to erection sites.

Still more time can be saved by using helicopters to transport components or even fully assembled towers.

With the many advantages of aluminum’s light weight, shorter schedules are easily met when installing any type of transmission line.

**Corrosion Resistance:** Pre-painting inspections, initial painting and subsequent upkeep repaintings are unnecessary when aluminum structural is used to build transmission towers. Dangers of repainting “hot line” towers (or the expense of de-energizing to make them safe) is avoided. Even without expensive painting and repainting, however, corrosion-resistant aluminum retains its good looks and remains structurally dependable longer than any other metal.

**Extrusion Design Capabilities:** As designers and users gained experience with aluminum towers, the advantages of special component shapes over conventional structural shapes became apparent. More opportunities in design innovation and economy are made available to the designer of transmission towers by aluminum than by any other material. Thus, the unique structural shapes into which aluminum can be extruded can be designed for optimum efficiency. Extrusion dies made to design specifications add only negligible amounts to the cost of the line system. Made-to-order steel members, on the other hand, would require highly expensive rolling equipment and operations.

With extruded aluminum structural, maximum torsional rigidity and radii of gyration can be realized. And, since both assembly and erection are simpler with aluminum structural, transmission lines can be designed more
related structural applications of aluminum

easily and with less risk of problems in the field.

Aluminum Transmission Tower Designs

Guyed "V" Towers (Fig. 18-2): A guyed-V tower is basically two guy-supported vertical masts having a common footing and supporting a horizontal section for carrying electrical conductors and overhead ground wires. Design of a guyed-V tower is such that overturning moments are resisted by guy wires serving as tension members, and by latticed masts serving as compression members.

Guyed-V towers built with extruded aluminum structures average approximately 30% of the weight of self-supporting steel structures designed to the same performance specifications.

Because aluminum guy-supported line towers use guy wires as tension members, they weigh substantially less than equivalent aluminum self-supporting towers. (And the weight which has to be carried by the tower masts is reduced as the spread between the vertical masts and guy wires is increased. This spread, which represents the arm of the resisting moment, can be made as wide as the right-of-way will allow.)

Guyed "Y" Towers (Fig. 18-3): A guyed-Y transmission tower can be described as a guyed-V mounted on a guyed vertical mast. Like the V tower, the guyed-Y has 4 guy wires serving as tension members of its upper section. But is also has 4 guys stabilizing its lower, vertical section. These 4 lower, inside guys take shear from a guyed-Y tower at the junction point where the vertical mast meets the upper V section. Thus, the only shear load remaining on the tower foundation is that of the wind load on the slim vertical mast.

The guyed-Y tower, because of its unique geometry, has fewer members than a guyed-V. Further, it has less column length—and the effect of wind on a long, unsupported column varies as the square of the length of the column. For tall towers, therefore, and for towers which will have to withstand heavy wind loads, the guyed-Y design will satisfy performance requirements at considerably lower cost than a guyed-V tower.

An aluminum guyed-Y transmission tower weighs considerably less than an equivalent guyed-V tower. And a guyed-V, for reasons noted on earlier pages, weighs less than an equivalent self-supporting tower.

Guyed-Y towers built with extruded aluminum structures weigh only 25%, on an approximate average, of self-supporting steel towers designed to same performance specifications.

Guyed "Delta" Towers (Fig. 18-4): This design has all the advantages inherent in the guyed "V" and "Y". Having a single mast requiring fewer pieces, it is a very economical structure to assemble. The "Delta" configuration has an electrical and lower noise advantage over the flat and vertical configurations.

Guyed "Gull Wing" Towers (Fig. 18-5): This design is similar to the guyed "Delta" with further advantages in the unique design, increasing the spread of the guy wire attachments, minimizing the torsional forces and reducing guy tensions.

Three-Pole Guyed Towers (Fig. 18-6): Sharp angles in direction of a power transmission line pose problems best solved by the 3-pole tower. Recommended for lines having changes of direction greater than 150, the 3-pole design provides a separate pole to support each phase of the line system.

Introduction of aluminum guyed "pole" transmission towers further refined this proven design. As with other 3-pole towers, each conductor on a 3-pole guyed aluminum transmission tower traverses the angle in the line supported by its own pole. Guy wires for the poles can be placed easily at those points where they will most effectively overcome the tangential forces created by the angles in the line.
Fig. 18-4. Guyed "Delta" aluminum structure on Southwestern Electric Power Company 345 kV line.

Fig. 18-3. Guyed "Y" aluminum structure on Louisiana Power & Light Company 500 kV line.
On a guyed tower, however, easily adjusted guys serve as tension members so that anchor points and central footing are not dependent on one another. Since each can be installed with little concern for the others, time and effort are saved and costs reduced.

Three types of foundations are generally used for guyed towers—galvanized grillage, pre-cast concrete and poured-in-place concrete. Screw anchors, piles and floating bases are also used.

Guyed transmission towers require no more right-of-way than equivalent self-supporting towers, since the towers’ supporting guy wires require no greater width along the right-of-way—usually less than needed for mid-span blow-out of the conductors. This holds true with any design of guyed tower and regardless of whether the conductors are strung by V-strings or by single-string, free-swinging insulators.

An aluminum 3-pole guyed angle tower weighs approximately 20% of a self-supporting steel angle tower.

Guy-supported transmission towers have radically smaller bases than self-supporting towers. In terrain too difficult for locating conventional towers, therefore, the guyed tower—with its small footing and easily placed guy anchors—can be installed with relative ease.

Substantial savings in foundation costs are possible with guyed transmission towers. The central footing for a guyed tower need be designed for compression only; guy anchors, for uplift only. A self-supporting tower, on the other hand, requires costly multi-purpose foundations, designed for both compression and uplift.

Foundations on a self-supporting tower, in addition, are precisely interrelated—to each other and to the tower legs—and must be designed and installed with a high degree of exactness to avoid unnecessary stresses.
In H-frame towers, the economies inherent in aluminum because of its light weight and minimal maintenance needs are added to by generally lower material costs. This is especially so with line voltages through 345 kV, since tall wooden poles are continually becoming scarcer and more and more costly.

Variations of the all-aluminum H-frame include wooden poles with aluminum cross-arms and aluminum pole structures with wooden cross-arms. Two types of aluminum cross-arms are being used for this purpose: A single tube, 8 to 10 inches in diameter, 3/16 to 3/8 in. in thickness, of extruded 6061-T6 alloy makes a simple, strong, easily installed cross-arm. For the heaviest loadings, latticed cross-arms of extruded structural shapes in aluminum alloys are available.

**Conventional Self-Supporting Towers:** Overall weight reductions averaging 55 to 60 percent can be made by using extruded aluminum structural materials instead of steel in building conventional, self-supporting types of transmission towers. When the design of a system calls for self-supporting towers—either 3- or 4-legged—the light weight of aluminum provides installation advantages at any tower site, but particularly at difficult, hard-to-reach locations. Fig. 18-8 is of a typical aluminum self-supported transmission tower (also called free-standing).

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**Semi-Flexible Towers** (Fig. 18-7): The semi-flexible transmission tower reflects a unique basic tower geometry. It is built with a transverse side as slender as stresses allow, thus is able to deflect under longitudinal loads produced at the conductor and ground wire attachment levels. Such deflection allows a portion of the unbalanced load to be carried by the other conductors or ground wires.

As a structural material, aluminum has far greater elasticity and flexibility than steel. In a semi-flexible transmission tower, this permits greater movement under given loading conditions than with steel. Economies in tower weight result as well as substantial savings in erection.

**H-Frame Towers** (Fig. 18-8): The “old reliable” H-frame transmission tower takes on new usefulness when constructed with extruded aluminum structural materials. The aluminum version is similar in outline to X-braced wood pole structures but has columns and cross-arm assemblies that make maximum use of extruded shapes designed specifically for this application. It can be built not only taller than usual wooden pole H-frame towers but also stronger. Fewer towers are needed, therefore, for any given length of line. And fewer towers mean fewer sets of hardware in installation costs and fewer insulators to service and replace.

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**Fig. 18-7. Semiflexible tower of aluminum deflects under load.**

**Fig. 18-8. Helicopter leaving assembly yard with “H” frame on Public Service Company of Indiana 345 kV line.**
related structural applications of aluminum

Savings realized from aluminum's minimal need for maintenance are especially pronounced on lines using self-supporting towers.

**Single Mast Self-Supporting Towers** (Fig. 18-9): This structure, designed for simplicity and limited right-of-way widths through urban or farm areas, has all the advantages inherent in an aluminum structure. The structure is designed using a rotating crossarm. Under minimal unbalanced longitudinal loads a pattern of bolts shears, allowing the arm to rotate reducing the longitudinal and torsional load on the mast and minimizing any domino effect due to structural failure.

**Internally Guyed Self-Supporting Towers** (Fig. 18-10): This structure satisfies conditions where external guy wires cannot be used. The internal guys act as structural members, increasing transverse strength with a considerable reduction in structural members.

**Self-Supporting Composite Towers** (Fig. 18-11): The self-supporting tower of conventional design can be built with steel base and aluminum top. This composite variation minimizes the cost premium. Like an all-aluminum tower, however, it requires no maintenance in the dangerous and high-cost vicinity of the conductors.

**Helicopters and Aluminum Towers**: The transmission line industry has developed ingenious and valuable short-cuts in its use of helicopters to transport and erect lightweight aluminum transmission towers and components.

This has been most dramatic in rough country, where tower installations virtually impossible by ordinary methods have been completed with relative ease by the versatile aircraft.

In all types of country, however, helicopters have proven highly economical, and aluminum tower crews are using them in many different operations.

Components of aluminum transmission towers bundled or partly assembled can be lifted, shifted or moved by helicopter. Use of 'copters is especially helpful when running power lines through rough country. Towers assembled on pipe racks in marshaling areas reduce heavy equipment needs and dramatically increase productivity. Assembled towers can be carried by 'copter from assembly points directly to tower sites and set, no matter how inaccessible the site might be.

Aluminum towers can be assembled on the ground at installation sites and then a helicopter can be used to tilt the towers easily and quickly to vertical positions.

When guyed-Y towers are being installed, a 'copter can be used, first, to erect the vertical mast of the Y. The upper part of the Y can then be lifted by helicopter and attached with perfect alignment to the vertical mast.

Even the erection crews on tower jobs can be transported by helicopter—to and from the tower sites and from site to site—fast, efficiently in any terrain.

![Fig. 18-9. Square Butte Electric Coop., 250 ± D-C line crossing North Dakota.](image)

**Aluminum Station Structures**

Most of what has been presented above on the advantages of aluminum transmission line towers is directly applicable to aluminum supporting structures used in outdoor electrical substations. Despite a higher cost per unit weight, a comparable aluminum structure can often be completely erected at a cost equal to or somewhat less than steel. Thereafter the virtual elimination of maintenance costs for aluminum structures is an important bonus factor.

Station structures fully designed in aluminum will have the following economic and performance advantages:

**Light Weight**: The use of aluminum can mean a reduction in weight of up to 70% over a steel structure... a weight reduction without loss of structural integrity.

The weight advantage of aluminum can represent a major saving in erection costs. Aluminum allows a greater amount of sub-assembly prior to shipment and
construction site erection. More work can be done in the shop, thereby reducing the number of man hours in the field. Assembled sections that would be difficult to handle in steel are easily handled in aluminum. For example, where one man can lift an aluminum section, a similar steel section would require two or three men. The need for high cost heavy equipment also may be drastically reduced or often eliminated.

A further cost reduction is possible because aluminum's exceptionally high conductivity can simplify structural grounding and may eliminate a groundwire system.

Thus faster erection times and reduced labor, equipment and shipping costs are possible with aluminum.

Corrosion Resistance: The economy of aluminum's corrosion resistance should also be considered. Aluminum resists chemically corrosive atmospheres, salt air and industrial fumes and does not require protective coatings. And unlike steel that eventually rusts and requires painting, aluminum substations stay attractive without major maintenance.

The savings by not having to repaint the structure with attendant costly shutdowns may more than pay for the cost of the aluminum substation structure over a period of years.

Safety Factors: Safety is a very important advantage of aluminum substations. Since aluminum never requires painting, there is no need to run the risk of having painters climb or work in proximity to energized parts. Costly and inconvenient shutdowns in the interest of safety for painting purposes are unnecessary.

Appearance: Because of their excellent corrosion resistance and freedom from rust, aluminum substations remain modern looking year-in and year-out with a minimum of maintenance. Properly designed with the new, low silhouette, they offer improved appearance to metropolitan and suburban areas.

Fabrication. The relative ease of extruding aluminum makes it possible to offer special as well as standard structural shapes and sizes. This means aluminum can
Fig. 18-13. All-aluminum substation designed to operate at 750 kV.
be tailored to fit many different design requirements that utilize sizes, shapes, and lengths unobtainable with steel. As a result, a more efficient use can be made of the metal. Fig. 18-12 shows some of the structural shapes readily extruded.

In the field, when cutting and drilling operations are required, aluminum is a much easier metal to work with than steel, and it is easier to handle because of its light weight. Since there is no galvanizing, no special precautions are necessary to prevent corrosion after field cutting or drilling.

High Scrap Value: An important economic factor to consider is aluminum’s recognized high scrap value. When a structure has fulfilled its useful life, aluminum will bring a much higher scrap return than other structural materials.

Aluminum Structural Alloys: The two most commonly used aluminum substation alloys are 6061-T6 and 6063-T6. Alloy 6061-T6 is a high strength metal used for tension and compression members. Alloy 6063-T6 has less strength and finds principal use in redundant structural members.

Tables 18-2 and 18-3 contain condensed but rather complete technical and availability information on the above two structural alloys.

Structural Design: Fabricators of aluminum structural components and assemblies maintain complete engineering design information which is available on request. Structural design handbooks for aluminum have been prepared and published by several manufacturers and by the Aluminum Association, and these may be obtained by writing to them.


Fastening Methods: Bolting—Where bolting is the desired method of fastening, 5/8" and 3/4" diameter bolts are recommended. Normally, aluminum bolts of high strength alloy 2024-T4, anodized and either chromate or nickel acetate sealed, are used with recessed nuts of alloy 6061-T6 lubricated with a wax coating to prevent galling. Recessed nuts preclude the need for washers. Aluminum coated steel bolts, aluminum lock bolts, and galvanized steel bolts may have applications under certain conditions. It is accepted practice to restrict bolts to one size in a given structure.

Riveting: In substation construction alloy 6061-T6 rivets are recommended because of their high shear value. They are available in sizes ranging up to 1" shank diameter. These rivets are cold driven as received.

To avoid corrosion, the rivet alloy selected should have equal or greater corrosion resistance than the alloys being joined. The rivet alloy should also be somewhat softer.

Rivets offer the advantage of an approximate 15% shear advantage over aluminum bolts. Additionally, shop riveted sub-assemblies eliminate deflections caused by bolt slippage.

Welding: All types of inert gas shielded arc welding (not requiring a flux) are acceptable for aluminum. However, two methods are most commonly used:

1. A tungsten electrode with the filler rod being fed by hand as in gas welding. (GTAW)

2. A consumable electrode of aluminum welding wire fed through the inert gas envelope. This is a fast method and is used also for automatic set-ups. (GMAW)

The strength of the weld generally varies from 60-90 percent of the original strength of the parent metal, depending on the alloy and temper. In many cases, proper arrangement of the seams may compensate for possible loss of strength. Butt seams offer the highest efficiency.
TABLE 18-2
Alloy 6061
Minimum Mechanical Properties—Values Are Given in Units of ksi (1000 lb/in²)

<table>
<thead>
<tr>
<th>Alloy And Temper</th>
<th>Product*</th>
<th>Thickness Range* in.</th>
<th>TENSION</th>
<th>COMPRESSION</th>
<th>SHEAR</th>
<th>BEARING</th>
<th>Compressive Modulus of Elasticity† E ksi</th>
</tr>
</thead>
<tbody>
<tr>
<td>6061-T6, T651</td>
<td>Sheet &amp; Plate</td>
<td>0.010-4.000</td>
<td>42</td>
<td>35</td>
<td>35</td>
<td>27</td>
<td>20</td>
</tr>
<tr>
<td>-T6, T6510**</td>
<td>Extrusions</td>
<td>All</td>
<td>38</td>
<td>35</td>
<td>35</td>
<td>24</td>
<td>20</td>
</tr>
<tr>
<td>-T6, T651</td>
<td>Rolled Rod &amp; Bar</td>
<td>up thru 8.000</td>
<td>42</td>
<td>35</td>
<td>35</td>
<td>27</td>
<td>20</td>
</tr>
<tr>
<td>-T6</td>
<td>Drawn Tube</td>
<td>0.025-0.500</td>
<td>42</td>
<td>35</td>
<td>35</td>
<td>27</td>
<td>20</td>
</tr>
<tr>
<td>-T6</td>
<td>Pipe</td>
<td>up thru 0.999</td>
<td>38</td>
<td>35</td>
<td>35</td>
<td>24</td>
<td>20</td>
</tr>
<tr>
<td>-T6</td>
<td>Pipe</td>
<td>over 0.999</td>
<td>38</td>
<td>35</td>
<td>35</td>
<td>24</td>
<td>20</td>
</tr>
</tbody>
</table>

* Most product and thickness ranges are taken from The Aluminum Association’s “Aluminum Standards and Data.”
† $F_{tu}$ and $F_{y}$ are minimum specified values of ultimate (u) and yield (y) tensile (t) strengths. Other strength properties are corresponding minimum expected values.
‡ For deflection calculations an average modulus of elasticity is used; numerically this is 100 ksi lower than the values in this column.
** Values also apply to -T6511 temper.

Typical Characteristics and Applications

<table>
<thead>
<tr>
<th>ALLOY AND TEMPER</th>
<th>RESISTANCE TO CORROSION</th>
<th>WELDABILITY*</th>
<th>TYPICAL APPLICATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>6061-T4, T451, T4510, T4511</td>
<td>B</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>T6, T651, T652, T6510, T6511</td>
<td>B</td>
<td>B</td>
<td>B</td>
</tr>
</tbody>
</table>

1 Ratings A through E are relative ratings in decreasing order of merit, based on exposures to sodium chloride solution by intermittent spraying or immersion. Alloys with A and B ratings can be used in industrial and seacoast atmospheres without protection. Alloys with C, D and E ratings generally should be protected at least on faying surfaces.
2 Stress-corrosion cracking ratings are based on service experience and on laboratory tests of specimens exposed to the 3.5% sodium chloride alternate immersion test.
A = No known instance of failure in service or in laboratory tests.
B = No known instance of failure in service; limited failures in laboratory tests of short transverse specimens.
C = Service failures with substaned tension stress acting in short transverse direction relative to grain structure; limited failures in laboratory tests of long transverse specimens.
D = Limited service failures with sustained longitudinal or long transverse stress.
3 Ratings A through D for Workability (cold), and A through E for Machinability, are relative ratings in decreasing order of merit.
4 Ratings A through D for Weldability and Brazability are relative ratings defined as follows:
A = Generally weldable by all commercial procedures and methods.
B = Weldable with special techniques or for specific applications which justify preliminary trials or testing to develop welding procedure and weld performance.
C = Limited Weldability because of crack sensitivity or loss in resistance to corrosion and mechanical properties.
D = No commonly used welding methods have been developed.
### TABLE 18-3
**Alloy 6063**

Minimum Mechanical Properties—Values Are Given in Units of ksi (1000 lb/in²)

<table>
<thead>
<tr>
<th>Alloy And Temper</th>
<th>Product*</th>
<th>Range* Thickness</th>
<th>TENSION $F_{tu}$ $F_{ty}$ ksi</th>
<th>COMPRESSION $F_{cu}$ $F_{cy}$ ksi</th>
<th>SHEAR $F_{su}$ $F_{sy}$ ksi</th>
<th>BEARING $F_{bu}$ $F_{by}$ ksi</th>
<th>Compressive Modulus of Elasticity† $E$ ksi</th>
</tr>
</thead>
<tbody>
<tr>
<td>6063-T5</td>
<td>Extrusions</td>
<td>up thru 0.0500</td>
<td>22 16</td>
<td>16 13</td>
<td>9</td>
<td>46 26</td>
<td>10,100</td>
</tr>
<tr>
<td>-T5</td>
<td>Extrusions</td>
<td>over 0.500</td>
<td>21 15</td>
<td>15 12</td>
<td>8.5</td>
<td>44 24</td>
<td>10,100</td>
</tr>
<tr>
<td>-T6</td>
<td>Extrusions</td>
<td>All</td>
<td>30 25</td>
<td>25 19</td>
<td>14</td>
<td>63 40</td>
<td>10,100</td>
</tr>
<tr>
<td></td>
<td>Pipe</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Most product and thickness ranges are taken from The Aluminum Association's "Aluminum Standards and Data."
† $F_{tu}$ and $F_{ty}$ are minimum specified values, other strength properties are corresponding minimum expected values.
‡ For deflection calculations an average modulus of elasticity is used; numerically this is 100 ksi lower than the values in this column.

### Typical Characteristics and Applications

<table>
<thead>
<tr>
<th>ALLOY AND TEMPER</th>
<th>RESISTANCE TO CORROSION</th>
<th>WELDABILITY</th>
<th>TYPICAL APPLICATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>General1</td>
<td>Stress Corrosion2</td>
<td>Workability3</td>
</tr>
<tr>
<td>6063-T1</td>
<td>A</td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>T4</td>
<td>A</td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>T5, T52</td>
<td>A</td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>T6</td>
<td>A</td>
<td>A</td>
<td>C</td>
</tr>
<tr>
<td>T83, T831, T832</td>
<td>A</td>
<td>A</td>
<td>C</td>
</tr>
</tbody>
</table>

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