Engineering Design

This chapter describes the principal design features of bare uninsulated conductors; however much that applies to bare conductors also pertains to the metallic part of insulated or covered conductors which are considered in Section III.

Many types of bare conductors are in use depending on application requirements. They may differ in electrical and physical properties, configuration, method of assembly, and corrosion resistance. Certain general physical properties have been described in previous chapters. Detailed physical and electrical properties of the various commercial sizes of bare conductors are listed in Chapter 4.

For many years it has been the practice to employ code words to identify and precisely define specific conductor constructions and designs (conductor size, stranding, insulation type, voltage rating, neutral configuration and size, number of phase conductors, type of assembly, etc.). In our text, code words are often used, as in the example under Table 3-6 wherein the code word “Bluebell” identifies a specific cable, in this case a 1,033,500 cmil, 37 strand, bare aluminum 1350 conductor. These code words are tabulated in Aluminum Association publications “Code Words for Underground Distribution Cables” and “Code Words for Overhead Aluminum Electrical Cables.”

Symbols for types of aluminum conductors: AAC—all-aluminum conductors (of 1350 aluminum); AAAC—all-aluminum alloy-conductors (of 6201-T81); ACSR—aluminum-conductor steel-reinforced (steel wire reinforcement); ACAR—aluminum conductor aluminum alloy-reinforced (high strength 6201-T81 wire reinforcement).

Except as otherwise referenced, graphs and data in tables are taken from Alcoa Aluminum Overhead Conductor Engineering Series handbooks.

Mechanical Design of Conductors

American Wire Gage (AWG)

This wire system, formerly known as Brown & Sharpe (B&S) gage, was introduced by J. R. Brown in 1857, and is now standard for wire in the United States. Successive AWG numbered sizes represent the approximate reduction in diameter associated with each successive step of wire drawing.

Fig. 3-1 shows typical full-size cross-sections, and approximate relationships between the sizes.

For wire sizes larger than 4/0 AWG, the size is designated in circular mils. Wire sizes of 4/0 AWG and smaller also are often designated in cir mils. One cir mil is the area of a circle 1 mil (0.001 in.) diameter; that is, the area in cir mils equals diameter-in-mils squared.

As one cmil = π/4 sq mils
Area in cir mils = 1.2732 × 10^6 × area in sq. in.
Expressing diameter of wire $D$, in inches

$$D = 10^{-3} \text{ cmil}^{1/2} \text{ cmil} = 10^{6}D^2$$ (Eq. 3-2)

Thus a solid round conductor of 1,000,000 cir mils has an area of π/4 sq. in., and a diameter of 1.00 in.

Stranded Conductors

Flexibility requirements for conductors vary widely. The conductors accordingly may be either lengths of single wires or a stranded group of smaller wires arranged in

<table>
<thead>
<tr>
<th>Nominal</th>
<th>#30</th>
<th>#10</th>
<th>#1/0</th>
<th>#1/0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter, mils</td>
<td>10</td>
<td>101.9</td>
<td>324.9</td>
<td>460.0</td>
</tr>
<tr>
<td>Area, cmils</td>
<td>100</td>
<td>10,380</td>
<td>105,600</td>
<td>211,600</td>
</tr>
</tbody>
</table>

Approximate Relationships

(1) An increase of three gage numbers doubles area and weight, and halves dc resistance.

(2) An increase of six gage numbers doubles diameter.

(3) An increase of ten gage numbers multiplies area and weight by 10 and divides dc resistance by 10.

Fig. 3-1. Typical cross-sections of solid-round AWG-size wires and approximate relationships. (Actual size.)
bare aluminum wire and cable

some regular manner. In either case, the total cross-sectional area of all component conducting wires determines the AWG or cmil size of the assembled conductor.

Concentric-Lay Stranding

Most bare power conductors are in concentric-lay stranded form; that is, a single straight core wire is surrounded by one or more helically curved wires. The direction of twist of lay is usually reversed in adjacent layers. All wires of a given layer generally are of same diameter. The direction of lay is either right- or left-hand depending on whether the top wire of the helix extends to right or left as the conductor is viewed axially in the direction away from the observer. The length of lay is the axial length parallel to the center line of the assembled conductor of one turn of the helix of a single wire. Bare aluminum conductors conventionally have a right-hand lay on outside layer.

American practice (ASTM) recognizes two classes of bare concentric-lay stranded conductors, AA and A, the former usually for bare-wire overhead applications and the latter for covered overhead lines.

Still greater flexibility of stranded conductors, mostly used for insulated conductors, are those with Class B, C, D, or even finer strandings. These have more wires for a given size of conductor than used for Class AA or A stranding. Wires of softer temper than the usual hard drawn wires can be used. Added flexibility also may be obtained by using small braided wires or those in “bunched” arrangement.

The stranding arrangement of each class is also specified in ASTM Conductor Standards. Fig. 3-2 shows typical examples of concentric-lay stranded bare conductors for various degrees of flexibility.

AAC/TW is a new design of all aluminum conductor composed of shaped wires (Trapezoidal) in a compact concentric-lay-stranded configuration. The design is described in ASTM B 778, and the properties are listed in Tables 4-10 and 4-11.

![Fig. 3-2. Typical Examples of Concentric Lay Conductors. All 266.8 kcmil (Illustrations are approximately to scale.)](image)

### TABLE 3-1
<table>
<thead>
<tr>
<th>Strand Lengths vs Solid Conductor</th>
<th>Incremental Increase for Weight and dc Resistance of Stranded Over that of Solid Conductors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sizes 4,000,000 to 3,000,001 cmil</td>
<td>4%</td>
</tr>
<tr>
<td>Sizes 3,000,000 to 2,000,001 cmil</td>
<td>3%</td>
</tr>
<tr>
<td>Sizes 2,000,000 cmil or under</td>
<td>2%</td>
</tr>
</tbody>
</table>

**Differences Between Stranded and Solid Conductors**

Because of the helical path of the strand layers there is more length of metal in a given length of stranded conductor than in a solid round conductor of the same AWG size, hence both the weight and dc resistance per unit length are increased. The amount of increase for all-aluminum conductors may be computed according to a method described in ASTM B 231, or the standard increments of increase listed in Table 3-1 (also from ASTM B 231) may be used.

The tensile load on a conductor is not always equally divided among the strands. This effect can reduce the total load at which the first strand breaks as compared with that of a solid conductor of equal cross section. However, this effect is more than offset by the fact that the unit tensile strength of commercially cold-drawn wire generally increases as its diameter is reduced, as is evident by the comparison for H19 stranded conductor in Table 3-2.

According to ASTM Standards, aluminum conductors that are concentric-lay stranded of 1350 or 6201 alloys in the various tempers have their rated tensile strength (or minimum rated strength) taken as the following percentages of the sum of the minimum average tensile strengths of the component wires, multiplied by rating factors, as below:

<table>
<thead>
<tr>
<th>7 wires per conductor</th>
<th>One layer</th>
<th>96%</th>
</tr>
</thead>
<tbody>
<tr>
<td>19 wires per conductor</td>
<td>Two layers</td>
<td>93%</td>
</tr>
<tr>
<td>37 wires per conductor</td>
<td>Three layers</td>
<td>91%</td>
</tr>
<tr>
<td>61 wires per conductor</td>
<td>Four layers</td>
<td>90%</td>
</tr>
<tr>
<td>91 wires per conductor</td>
<td>Five layers</td>
<td>89%</td>
</tr>
</tbody>
</table>

(and over) (and over)

Similarly, the rated strength of ACSR is obtained by applying rating factors of 96, 93, 91, and 90 percent, respectively, to the strengths of the aluminum wires of conductors having one, two, three, or four layers of aluminum wires, and adding 96 percent of the minimum stress in the steel wires at 1.0 percent elongation for cables having one central wire or a single layer of steel wires, and adding 93 percent of the minimum stress at 1.0 percent elongation if there are two layers of steel wires.

All strengths are listed in pounds to three significant figures, and these strengths also apply to compact-round conductors.
**Special Conductor Constructions**

Large conductors requiring exceptional flexibility may be of rope-lay construction. Rope-lay stranded cables are concentric-lay stranded, utilizing component members which are themselves either concentric stranded or bunched. Bunched members are cabled with the individual components bearing no fixed geometric relationship between strands. Rope-lay stranded conductors may be stranded with subsequent layers reversing in direction, or may be unidirectional with all layers stranded in the same direction but with different lay lengths.

Some cables are designed to produce a smooth outer surface and reduced overall diameter for reducing ice loads, and under some conditions wind loading. The stranded cables are smoothed in a compacting operation so that the outer strands lose their circularity; each strand keys against its neighbor and many interstrand voids disappear. (Fig. 3-3) A similar result is commonly obtained by use of trapezoidal strands that intertw with adjacent strands to create a smooth, interlocking surface. (Fig. 3-7)

Another cable design, expanded core concentric-lay conductor, uses fibrous or other material to increase the diameter and increase the ratio of surface area to metal cross-section or weight. (Fig. 3-3) Designed to minimize corona at voltages above 300 kV, they provide a more economical balance between cable diameter and current carrying capacity.

A "bundled" conductor arrangement with two or more conductors in parallel, spaced a short distance apart, is also frequently used for HV or EHV lines. Although the ratio of radiating area to volume increases as the individual conductor size decreases, the design advantages of bundling are not wholly dependent upon ampacity. Normal radio interference, etc., and the usual controlling design characteristics are discussed elsewhere, but the current carrying capacity relationship is similar. Thus, two 795 kcmil ACSR _Drake_ under typical conditions of spacing and temperature provide 24 percent more ampacity per kcmil than a single 1780 kcmil ACSR _Chukar_.

**Composite Conductors**

Composite conductors, conductors made up of strands of different alloys or different materials, are used where the required strength is greater than the strength obtainable with 1350-H19 grade aluminum strands. The principal kinds of composite conductors are (1) 1350 stranded conductors reinforced by a core of steel wires (ACSR), (2) 1350 stranded conductors reinforced by aluminum-clad steel wires which may be in the core or distributed throughout the cable (ACSR/Al), or (3) 1350 stranded conductors reinforced by wires of high-strength aluminum alloy (ACAR).

**Aluminum Conductor Steel Reinforced (ACSR) and Modifications**

ACSR has been in common use for more than half a century. It consists of a solid or stranded steel core surrounded by strands of aluminum 1350. Table 3-3 compares breaking strengths of several all-aluminum stranded conductors with ACSR and one of hard-drawn copper, all of approximately equal d-c resistance. The principal economic factors involved are weight, strength, and cost.

Historically, the amount of steel used to obtain higher strength soon increased to become a substantial portion of ACSR, but more recently as conductors became larger, the trend has been toward use of a smaller proportion of steel. To meet varying requirements, ACSR is available

---

**TABLE 3-2**

Strength of 1350-H19 Aluminum Conductors

<table>
<thead>
<tr>
<th>AWG</th>
<th>Stranding</th>
<th>Strand Diam, In.</th>
<th>Rated Strength, Lb</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Solid</td>
<td>0.2576</td>
<td>1225</td>
</tr>
<tr>
<td>2</td>
<td>7 Strand</td>
<td>0.0974</td>
<td>1350</td>
</tr>
<tr>
<td>2</td>
<td>19 Strand</td>
<td>0.0581</td>
<td>1410</td>
</tr>
</tbody>
</table>

Calculated from ASTM B 230 and B 231.
H19, although included in earlier editions of this handbook, has been deleted from this edition because it
'Abstracted from ASTM Standards and industry sources.
Resistances are based on IACS, % conductivities of 61.2% for 1350-H19; 8% for steel; 52.5% for
Typical stranding arrangements for ACSR and high-strength ACSR are depicted in Fig. 3-4. The high-strength
4517, having steel content of 26% 26%, and 31% respectively.
larger-than-AWG sizes, the most used strandings are
in a wide range of steel content—from 7% by weight
for the 36/1 stranding to 40% for the 30/7. Today, for the
larger-than-AWG sizes, the most used strandings are 18/1, 45/7, 72/7, and 84/19, comprising a range of steel content
from 11% to 18%, and for the moderately higher strength
ACSR 54/19, 54/7, and 26/7 strandings are much used, having steel content of 26%, 26% and 31%, respectively.
Typical stranding arrangements for ACSR and high-strength ACSR are depicted in Fig. 3-4. The high-strength
ACSR, 8/1, 12/7 and 16/19 strandings, are used mostly
for overhead ground wires, extra long spans, river crossings, etc. Expanded ACSR, Fig. 3-6, is a conductor the
diameter of which has been increased or expanded by
aluminum skeletal wires between the steel core and the
outer aluminum layers. This type of cable is used for lines
above 300 kV.

The inner-core wires of ACSR may be of zinc-coated (galvanized) steel, available in standard weight Class A coating or heavier coatings of Class B or Class C thicknesses. Class B coatings are about twice the thickness of Class A and Class C coatings about three times as thick as Class A. The inner cores may also be of aluminum coated (aluminized) steel or aluminum-clad steel. The latter produces a conductor designated as ACSR/AW in which the aluminum cladding comprises 25 percent of the area of the wire, with a minimum coating thickness of 10 percent of overall radius. The reinforcing wires may be in a central core or distributed throughout the cable.

Galvanized or aluminized coats are thin, and are applied to reduce corrosion of the steel wires. The conductivity of these thin-coated core wires is about 8 percent (IACS). The apparent conductivity of ACSR/AW reinforcement wire is 20.3% (IACS).

The incremental increase for dc resistance over that of solid round conductors, because of stranding of ACSR,
differs from that stated in Table 3-1, and depends on type
of stranding. The amount of increase also may be com­puted according to a method described in ASTM B232. Table V of B232 is reproduced on next page as Table 3-4A.

A description of the method of computing rated breaking strength of ACSR found in ASTM B 232 is abstracted
in right-hand column of page 3-2.

ACSR/TW is a new design of ACSR composed of shaped aluminum wires (Trapezoidal) stranded around a standard steel core. It is fully described in ASTM B 779 and Tables 4-19 to 4-22.

### Aluminum Conductor Alloy Reinforced (ACAR)

Another form of stranded composite conductor consists of 1350-H19 strands reinforced by a core or by otherwise distributed wires of higher-strength 6201-T81 alloy.

The ASTM approved method for determining ACAR rated strength is described in ASTM B 524 as follows:
(The mentioned Table 4 is that of ASTM B 524.)

*The rated strength of completed conductors shall be taken as the aggregate strength of the 1350 aluminum and aluminum alloy components calculated as follows. The strength contribution of the 1350 aluminum wires shall be taken as that percentage according to the number of layers of aluminum alloy wires, indicated in Table 4 of the sum of the strengths of the 1350-H19 wires, calculated from their specified nominal wire diameter and the appropriate specified minimum average tensile strength given in ASTM Specification B 230. The strength contribution of the aluminum alloy wires shall be taken as that percentage, according to the number of layers of aluminum alloy wires, indicated in Table 4 of the sum of the strength of the aluminum wires calculated from their specified nominal wire diameter and the minimum stress as 1 percent extension. This shall be considered to be

<table>
<thead>
<tr>
<th>Size cmil</th>
<th>Type</th>
<th>Stranding</th>
<th>Diam. in.</th>
<th>dc Resistance Ohms per 1000 ft at 20°C</th>
<th>Weight lb per 1000 ft</th>
<th>Rated Breaking Strength lb</th>
<th>Strength %</th>
<th>Conductance</th>
</tr>
</thead>
<tbody>
<tr>
<td>336,400</td>
<td>1350-H19</td>
<td>19</td>
<td>0.666</td>
<td>0.0514</td>
<td>315.6</td>
<td>6,150</td>
<td>35.6</td>
<td>102.4</td>
</tr>
<tr>
<td>394,500</td>
<td>6201-T81</td>
<td>19</td>
<td>0.721</td>
<td>0.0511</td>
<td>370.3</td>
<td>13,300</td>
<td>76.8</td>
<td>101.8</td>
</tr>
<tr>
<td>336,400</td>
<td>ACSR</td>
<td>30/7</td>
<td>0.741</td>
<td>0.0502</td>
<td>527.1</td>
<td>17,300</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td>211,600</td>
<td>HD Copper</td>
<td>7</td>
<td>0.522</td>
<td>0.0516</td>
<td>653.3</td>
<td>9,154</td>
<td>52.9</td>
<td>102.8</td>
</tr>
</tbody>
</table>

*Abstracted from ASTM Standards and industry sources. Resistances are based on IACS % conductivities of 61.2% for 1350-H19; 8% for steel; 52.5% for 6201-T81; and 97.0% for H.D. Copper. 5005-H19, although included in earlier editions of this handbook, has been deleted from this edition because it is no longer commercially available.
95 percent of the minimum average tensile strength specified for the wire diameter in Table 2 of ASTM Specification B 398. Rated strength and breaking strength values shall be rounded-off to three significant figures in the final value only..."

Because the 6201-T81 reinforcement wires in ACAR may be used in the core and/or for replacement of some of the 1350-H19 wires in the strands, almost any desired ratio of reinforcement 1350-H19 wires is achieved, thereby obtaining a range of strength-conductance properties be-

### TABLE 3-4A

<table>
<thead>
<tr>
<th>Stranding</th>
<th>% dc Resistance</th>
<th>Stranding</th>
<th>% dc Resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>6/1</td>
<td>1.5</td>
<td>42/7</td>
<td>2.5</td>
</tr>
<tr>
<td>7/1</td>
<td>1.5</td>
<td>45/7</td>
<td>2.5</td>
</tr>
<tr>
<td>8/1</td>
<td>2.0</td>
<td>48/7</td>
<td>2.5</td>
</tr>
<tr>
<td>18/1</td>
<td>2.0</td>
<td>54/7</td>
<td>2.5</td>
</tr>
<tr>
<td>36/1</td>
<td>2.0</td>
<td>72/7</td>
<td>3.0</td>
</tr>
<tr>
<td>12/7</td>
<td>2.5</td>
<td>16/19</td>
<td>2.5</td>
</tr>
<tr>
<td>24/7</td>
<td>2.5</td>
<td>30/19</td>
<td>2.75</td>
</tr>
<tr>
<td>26/7</td>
<td>2.5</td>
<td>54/19</td>
<td>3.0</td>
</tr>
<tr>
<td>30/7</td>
<td>2.75</td>
<td>76/19</td>
<td>3.0</td>
</tr>
<tr>
<td>30/7</td>
<td>2.75</td>
<td>84/19</td>
<td>3.0</td>
</tr>
</tbody>
</table>

The above resistance factors also are usually taken into account in tables of dc resistance for ACSR.

### TABLE 3-4B

**Strength Rating Factors**

Extract from ASTM Specification B 524 for Concentric-Lay-Stranded Aluminum Conductors. Aluminum Alloy Reinforced (ACAR)

(Referenced in ASTM B 524 as Table 4)

<table>
<thead>
<tr>
<th>Stranding</th>
<th>Number of Wires</th>
<th>Number of Layers*</th>
<th>Rating Factor, per cent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1350</td>
<td>6201-T81</td>
<td>1350</td>
<td>6201-T81</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>9</td>
<td>9</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

* For purposes of determining strength rating factors, mixed layers are considered to be full layers for each material.
**Fig. 3-5.** Typical stranding arrangements of aluminum cable alloy-reinforced (ACAR). Assuming the reinforcement is 6201-T81 alloy, and that individual wires are larger than 0.150 in. diameter the strength-weight ratios are as shown: (the strengths are slightly higher if smaller wires are used). The strength/wt. ratios compare rated strength per ASTM B 524 and conductor weight in lb/ft.
between constructions of all 1350-H19 wires or those of all 6201-T81 wires. Fig. 3-5 depicts several stranding arrangements of ACAR cables of 1350-H19 and 6201-T81 wires.

The rating factors for various strandings of ACAR using 6201-T81 reinforcing wires are shown herewith as extracted from ASTM B 524. They are used as the basis for calculating the properties of ACAR listed in Chapter 4.

International Annealed Copper Standard

In 1913 the International Electro-Technical Commission established an annealed copper standard (IACS) which in terms of weight resistivity specifies the resistance of a copper wire 1 meter long that weighs one gram. Commercial hard drawn copper conductor is considered as having conductivity of 97% IACS.

Calculation of dc Resistance

USA practice is to express conductor conductivity in terms of percent International Annealed Copper Standard (IACS) instead of in mhos (the unit of conductance). Resistivity is expressed as follows:

Volume Resistivity \( \rho_v = \frac{A}{L} \) in which (Eq. 3-3)

\( A = \) Cross-sectional area

\( L = \) Length

\( R = \) Resistance

Weight Resistivity \( \rho_w = \frac{W}{2R} \) in which (Eq. 3-4)

\( W = \) Weight

These resistivity constants may be stated in whatever form is required by the units used for area, length, weight, and resistance, and if these units are used consistently \( R \) may be obtained for any \( A, L, \) or \( W, \) by inverting the equation; thus, from Eq. 3-3, \( R = \frac{L}{\rho_v A} \) or \( \frac{L^2}{\rho_w W} \) as the case may be.

For USA practice, two volume resistivity constants* are used (Table 3-5):

1. Ohm-cm/ft, representing the resistance in ohms of a round conductor 0.001 in. diameter 1 ft long.

2. Ohm-sq in./ft, representing the resistance in ohms of a conductor of 1 sq in. in cross-sectional area and 1 ft long. This constant is sometimes multiplied by 1000 which provides ohms per 1000 ft.

*The resistivity constants are based on ohms when conductor is at ASTM Standard temperature of 20°C (68 F). Some tables are based on temperature of 25°C. If so, new resistivity constants can be computed for 25°C if considerable work is to be done (see Table 3-7), or a temperature coefficient can be applied to the 20°C value of \( R_{20} \) to obtain that for 25°C, as below.

Multiply the 20°C value by

<table>
<thead>
<tr>
<th>Material</th>
<th>IACS %</th>
<th>( R_{20} ) ohms/ft</th>
<th>( R_{25} ) ohms/ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>1350-H19</td>
<td>62.0% IACS</td>
<td>1.02048</td>
<td>( 1.02048 \times 1.01734 )</td>
</tr>
<tr>
<td>1350-H19</td>
<td>61.0% IACS</td>
<td>1.02015</td>
<td>( 1.02015 \times 1.01734 )</td>
</tr>
<tr>
<td>6201-T81</td>
<td>52.5% IACS</td>
<td>1.01734</td>
<td>( 1.01734 \times 1.01734 )</td>
</tr>
</tbody>
</table>

Fig. 3-7. Composite conductors similar to ACSR also may be manufactured by using trapezoidally shaped strands as shown above for self damping conductor.
TABLE 3-5
Equivalent Direct Current (dc) Resistivity Values for Aluminum Wire Alloys at 20°C*

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Volume Conductivity percent</th>
<th>Volume Resistivity</th>
<th>Weight Resistivity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>iACS</td>
<td>Ohm-cmil per ft</td>
<td>Ohm-mm² per m</td>
</tr>
<tr>
<td>1350-H19</td>
<td>61.2</td>
<td>16.946</td>
<td>0.02817</td>
</tr>
<tr>
<td>6201-T81</td>
<td>52.5</td>
<td>18.754</td>
<td>0.03284</td>
</tr>
<tr>
<td>Alumoweld</td>
<td>20.33</td>
<td>51.01</td>
<td>0.08481</td>
</tr>
<tr>
<td>Steel</td>
<td>8.0</td>
<td>129.64</td>
<td>0.21552</td>
</tr>
<tr>
<td>HD Copper</td>
<td>97.0</td>
<td>10.692</td>
<td>0.01777</td>
</tr>
</tbody>
</table>

*Abstracted and calculated from ASTM Standards.
For stranded conductors, resistance values obtained by use of these factors are to be increased by the stranding-increment ratio, per Table 3-1 for all aluminum conductors, or per Table 3-4A for ACSR.

Example: Find dc resistance at 20°C of one mile of Bluebell cable of 1,033,500 cmil area of 1350 61.2% iACS conductivity, allowing 2% stranding increment.

Applying resistivity factor from Table 3-5, \( R = \frac{5280 \times 16.946 \times 1.02}{1,033,500} = 0.0883 \) ohms

Change of dc Resistance with Temperature
Over a moderate temperature range (0°C to 120°C) the resistance of a conductor increases linearly with increase of temperature, thus

\[ R_T = R_I [1 + \alpha_1 (T_T - T_I)] \]  

in which

- \( R_I \) = Resistance at temperature \( T_I \)
- \( R_T \) = Resistance at temperature \( T_T \)
- \( \alpha_1 \) = Temp. coefficient of resistance at \( T_I \)

Temperature-Resistance Coefficients for Various Temperatures
From Eq 3-5 it is apparent that the temperature coefficient for 20°C cannot be used when the known resistance is at some other temperature. For this condition

\[ \alpha_x = \frac{1}{\frac{1}{\alpha_{20}} + (T_x - 20)} \]  

in which \( \alpha_x \) = Temp. coefficient at \( T_x \) deg C.
- \( \alpha_{20} \) = Temperature coefficient at 20°C

Example: The 20°C temperature coefficient \( \alpha_{20} \) for 1350 (61.2% iACS) alloy is 0.00404. What is it for 50°C?

Applying Eq. 3-6

\[ \alpha_{50} = \frac{1}{\frac{1}{\alpha_{20}} + (50 - 20)} = \frac{1}{0.00404} = 0.00360 \]

For coefficients for other temperatures see Table 3-7.

Calculation of ac Resistance*

Skin effect is by convention regarded as inherent in the conductor itself; hence when the ac resistance of a conductor is stated, what is meant is the dc resistance usually in ohms, plus an increment that reflects the increased apparent resistance in the conductor caused solely by the skin-effect inequality of current density.

Skin effect results in a decrease of current density toward the center of a cylindrical conductor (the current tends to crowd to the surface).

A longitudinal element of the conductor near center is surrounded by more magnetic lines of force than is an element near the rim, hence the induced counter-emf is greater in the center element. The net driving emf at the...
### TABLE 3-6

Temperature Coefficients of dc Resistance of Wire Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Conductivity Percent IACS</th>
<th>Temperature Coefficient $\alpha_{dc}$ at 20°C per degree C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>61.2</td>
<td>0.00404</td>
</tr>
<tr>
<td>1350-H19</td>
<td>62.0</td>
<td>0.00347</td>
</tr>
<tr>
<td>Copper (h-d)</td>
<td>97.0</td>
<td>0.00381</td>
</tr>
<tr>
<td>Alumoweld</td>
<td>20.33</td>
<td>0.00360</td>
</tr>
<tr>
<td>Steel</td>
<td>9.0</td>
<td>0.00320</td>
</tr>
</tbody>
</table>

Example: The resistance of one mile of Bluebell stranded conductor of 61.2% (IACS) 1350-H19 at 20°C is 0.0883 ohms. What is $R_{50}$ at 50°C?

Applying coefficient from Table 3-6:

$$R_{50} = 0.0883 \left[1 + 0.00404 \times (50-20)\right] = 0.0990 \text{ ohms}$$

center element is thus reduced with consequent reduction of current density.

The ratio of ac resistance to dc resistance ($R_{ac}/R_{dc}$) is almost unity for small all-aluminum conductors at power frequencies, regardless of load current. It increases to about 1.04 for the 1113.5 kcmil size and to about 1.09 in the 1590 kcmil size.

The basic calculations of $R_{ac}/R_{dc}$ ratio have been made for round wires and tubes of solid material, and these values can be obtained from curves based on such calculations or tests. Fig. 3-8 shows $R_{ac}/R_{dc}$ ratios for solid round or tubular conductors, and they also may be applied for stranded conductors by treating the stranded cross-section as if it were solid.

For use of the curves of Fig. 3-8, $R_{dc}$ is first obtained and corrected for temperature. $R_{ac}$ is then obtained from the $R_{ac}/R_{dc}$ ratio read from the chart.

Example: All-aluminum Bluebell stranded conductor of 1350-H19 (61.2% IACS) has dc resistance of 0.0188 ohms per 100 ft at 50°C. What is its approximate $R_{ac}/R_{dc}$ ratio for 60 Hz?

Substituting in equation at bottom of Fig. 3-8 on basis of ohms per mile, and $r_r=r_s=0.00$.

Abscissa parameter $= \left[50/(0.0188 \times 5.28)\right]^{\frac{1}{5}} = 24.6$ and $R_{ac}/R_{dc} = 1.031$, which compares with a value from published tables of 1.030.

**Skin Effect in Steel-Reinforced Stranded Conductors (ACSR, etc.)**

The $R_{ac}/R_{dc}$ ratio of ACSR conductors that have an even number of layers of aluminum wires (2, 4 etc.) may be estimated from the curves of Fig. 3-8, provided $r_r$ is the radius of the core and $r_s$ is the external radius. By this method, no account is taken of the current in the steel core. Some tables include the effect of core conductance, hence show a slight variation of ratio.

If the number of aluminum layers is odd (1, 3, etc.), the $R_{ac}/R_{dc}$ ratio for ACSR conductors is affected by the magnetic flux in the core, which occurs because there is an unbalance of mmf due to opposite spiraling of adjacent layers. In such conductors the core flux varies with load current, hence the $R_{ac}/R_{dc}$ ratio will vary with current. The effect is considerable in one-layer conductors, moderate in 3-layer conductors, and it may be disregarded for 5-layer conductors and more. This effect is further described and illustrated by Fig. 3-9 and Table 3-8A.

The comparison at 75% loading, shown in Table 3-8A illustrates the effect of core permeability in the one-layer ACSR whereas it has no effect in 2-layer ACSR. The one-layer ACSR may be less desirable electrically and it is used mostly where high strength is required at the sacrifice of conductance and for small sizes, 4/0 and under.

The $R_{ac}/R_{dc}$ ratios for one-layer ACSR are obtained from tables or curves that show test results at various load currents.

Three-layer ACSR, as stated, similarly has the $R_{ac}/R_{dc}$ ratio affected by load current. However, the effect may be allowed for by applying values from Fig. 3-9 which shows the correction factor to be applied to the ratio with varying load.

Example: A 54/7 ACSR conductor, Curlew of 1033.5 kcmil has an $R_{ac}/R_{dc}$ ratio of 1.025 at 25°C, 60 Hz, without regard to core-magnetic effect. What are the ratios for load currents of 200, 400, 600, 800, and 1000 amp, respectively? See also footnote under Table 3-8.

From the upper curve of Fig. 3-9, values are tabulated in col. (3), and multiplying these values by the basic ratio provides the desired ratio in col. (5) of Table 3-8.

Calculation of skin-effect ratios for composite designs in which the steel reinforcement is located wholly or partly away from the central core, or in which the steel is surrounded by a thick aluminum coating is almost impossible except for the simplest configurations. Consequently such values are taken from tables that represent test results. Accepted catalog data for most commercial designs are available.

**Proximity Effect**

When two conductors are spaced relatively close to one another and carry alternating current, their mutual inductance affects the current distribution in each conductor. However, if the distance apart of the conductors exceeds ten times the diameter of a conductor the extra I²R loss

*As $r_r/r_s$ equals ratio of diameters, it usually is more convenient to use diameters which ordinarily can be read from conductor tables, see footnote, Table 3-8.*
TABLE 3-7

Temperature Coefficients of dc Resistance of Wire Materials at Various Temperatures*

<table>
<thead>
<tr>
<th>Alloy Conductivity</th>
<th>1350-H19 61.2% IACS</th>
<th>6201-T81 52.5% IACS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp°C</td>
<td>0</td>
<td>.00440</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>.00421</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>.00404</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>.00396</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>.00389</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>.00374</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>.00361</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>.00348</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>.00336</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>.00325</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>.00315</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>.00306</td>
</tr>
</tbody>
</table>

*Calculated per NBS Handbook 109.

Example: The resistance of one mile of Bluebell stranded conductor of 1350-H19 alloy at 50°C is measured at 0.0990 ohms. What is it at 20°C?

Applying the 50°C coefficient from Table 3-7 in Eq. 3-5: 

\[
R_{20} = R_{50} \left[ 1 + 0.00361 (20 - 50) \right] = 0.0883 \text{ ohms.}
\]

TABLE 3-8

Comparison of Basic and Corrected \( R_{ac}/R_{dc} \) Curlew Conductor

<table>
<thead>
<tr>
<th>(1) Load amp</th>
<th>(2) Amps per cmil x 10^6</th>
<th>(3) Resistance multiplier Fig. 3-7</th>
<th>(4)* Basic ( R_{ac}/R_{dc} ) Ratio</th>
<th>(5) Corrected Ratio (3) x (4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>194</td>
<td>1.007</td>
<td>1.025</td>
<td>1.032</td>
</tr>
<tr>
<td>400</td>
<td>388</td>
<td>1.013</td>
<td>1.025</td>
<td>1.038</td>
</tr>
<tr>
<td>600</td>
<td>581</td>
<td>1.018</td>
<td>1.025</td>
<td>1.044</td>
</tr>
<tr>
<td>800</td>
<td>775</td>
<td>1.022</td>
<td>1.025</td>
<td>1.048</td>
</tr>
<tr>
<td>1000</td>
<td>960</td>
<td>1.025</td>
<td>1.025</td>
<td>1.051</td>
</tr>
</tbody>
</table>

*If these current variations occur in a conductor when ambient temperature is constant, the operating temperature will increase with load, hence the basic \( R_{ac}/R_{dc} \) ratio must be adjusted to reflect the variation of \( R_{dc} \) with temperature. Constants are available from the Aluminum Association that facilitate this adjustment of \( R_{ac}/R_{dc} \) ratio.

caused by this crowding is less than 1 percent, hence ordinarily can be neglected.

**Hysteresis and Eddy Current Effects**

Hysteresis and eddy current losses in conductors and adjacent metallic parts add to the effective a-c resistance. To supply these losses, more power is required from the line. They are only important in large ampacity conductors when magnetic material is used in suspension and dead-end clamps, or similar items which are closely adjacent to the conductor.

Usual tests that determine \( R_{ac}/R_{dc} \) ratios for conductors as reported in tables of properties take into account any hysteresis or eddy-current loss that is in the conductor itself, so no separate estimate of them is ordinarily required.

The calculation of eddy-current and hysteresis loss in adjacent metallic materials, (structures, housings, etc.) or its estimate by tests is beyond the scope of this book.

**Radiation Loss**

This component of power loss in a conductor is negligi-
Fig. 3-8. Skin-effect factor for solid-round or tubular conductor at 60 Hz.

bare aluminum wire and cable

TABLE 3-8A
Comparison of \( R_{ac}/R_{dc} \) Ratios for All-Aluminum and ASCR, 266.8 kcmil, Single-Layer Conductors, and Equivalent 2-Layer Conductor

<table>
<thead>
<tr>
<th>Conductor</th>
<th>Stranding</th>
<th>Resistance at 25°C</th>
<th>( R_{ac}/R_{dc} ) Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>( \text{dc} )</td>
<td>( 60 \text{ Hz} )</td>
</tr>
<tr>
<td>1350-H19, 61.2% IACS</td>
<td>7</td>
<td>0.349</td>
<td>0.350</td>
</tr>
<tr>
<td>ACSR (1 layer)</td>
<td>6/7</td>
<td>0.349</td>
<td>0.350</td>
</tr>
<tr>
<td>ACSR (2 layer)</td>
<td>26/7</td>
<td>0.349</td>
<td>0.349</td>
</tr>
</tbody>
</table>

Resistance value in ohms per mile

Table 3-8A compares the \( R_{ac}/R_{dc} \) ratios for all-aluminum and ASCR, 266.8 kcmil, single-layer conductors, and equivalent 2-layer conductor. The table lists the resistance values at light load at 25°C (75% load at 50°C) in ohms per mile, along with the \( R_{ac}/R_{dc} \) ratio under each condition. The table indicates that the ratio of AC resistance to DC resistance is important in power systems, and the table provides a comparison of the ratios for different conductor types.

Inductive and Capacitive Reactance

Variable current flow in an electrical conductor, either as alternating current or as a transient of any kind, gives rise to the parameters of inductance (usually expressed in millihenrys) and capacitance (usually expressed in microfarads) and their related properties of inductive and capacitive reactance, usually expressed as ohms per mile and megohm-miles, respectively. No energy loss is associated directly with these parameters, but the 90° out-of-phase voltage and current must be supplied to sustain the magnetic and electric fields created, so a slight increase of AC resistance in the conductors occurs because of them.

Corona

Corona occurs when the potential of the conductor is such that the dielectric strength of the surrounding air is exceeded. The air becomes ionized and bluish illuminated gaseous tufts or streamers appear around the conductor, being more pronounced where there are irregularities of the conductor surface. The discharge is accompanied by the odor of ozone, and there may be a hissing sound.

Corona discharge from a bare conductor power line may interfere with radio and TV reception, or adjacent carrier and signal circuits.

Bundled conductors are frequently used to obtain lower voltage stress on the air insulation for voltages above 350 kV.

Inductive Reactance

The inductance \( L \) of a circuit is a measure of the number of interlinkages of unit electric current with lines of magnetic flux produced by the current, both expressed in absolute units. \( L \) also is defined by \( e = L (di/dt) \) in which \( di/dt \) indicates the rate of change of current with time. \( L \) is the coefficient of proportionality, and \( e \) is the momentary induced voltage.

The quantity \( X = 2\pi f L \), in which \( f \) is frequency in Hz, is the inductive reactance, expressed in ohms, but in phasor notation the inductive-reactance drop is perpendicular to the resistance drop; that is, the current \( I \) in a conductor having both resistance and inductive reactance, but negligible capacitance, and at unity power factor is

\[
I = \frac{E}{(R + jX)} \text{ in which } j = \text{Vector operator (-1)}^{1/2}
\]

(Eq. 3-7)

\( E = \text{Emf, volts, to neutral} \)

\( I = \text{Current in conductor, amp} \)

\( X = \text{Inductive reactance, ohms} \)

For further information regarding corona, see Standard Handbook for Electrical Engineers, McGraw-Hill Company, Sec. 14 which also contains references to the various research papers. An excellent text on corona and EHV line design is the EPRI Transmission Line Reference Book, 345 kV and above.

3-12
Resistance multiplying factors for three-layer ACSR for aluminum conductivity of 62%. Without significant error, these factors also may be used for aluminum of 61.2% IACS conductivity. These data are used to reflect the increase in resistance due to magnetizing effects of the core.

Numerically \( (R + jX) = (R^2 + X^2)^{1/2} \) and is designated impedance, also expressed in ohms.

Normally, computations of \( R \) and \( X \) for transmission lines are made, for convenience, on the basis of unit lengths, usually one mile. Tables are set up in this manner.

The inductive reactance discussed herein and listed in tables of conductor properties are suitable for calculations of either positive- or negative-sequence reactance, as employed for usual transmission and distribution circuits. Zero-sequence values, as required for unbalanced conditions or fault-currents, may be obtained by methods later described. Inasmuch as zero-sequence inductive reactance is the principal factor that limits phase-to-ground fault currents, its value is important in conductor selection.

Simplifying of reactance calculations is effected if the reactance is considered to be split into two terms *(1) that due to flux within a radius of 1 ft \((X_a)\) including the internal reactance within the conductor, and (2) that due to the flux between 1 ft radius and the center of the equivalent return conductor—\(X_a\). A further simplifying convention is that the tabulation of the latter distance is the distance between centers of the two conductors instead of the distance from one-foot radius of one conductor to the surface of the adjacent one; thus, there will be minus \(X_a\) values tabulated for distance between conductors that are less than 1 ft apart.

Conductor spacing \(D\) for 3-phase circuits is the geometric mean distance (GMD) as later defined.

The sum of the two terms \((X_a + X_a)\) is the required inductive reactance of the conductor \(X\) under usual load conditions. The values also are useful as a basis for calculating impedance under fault conditions (zero-sequence). It is to be noted that \(X_a\) is an inherent conductor electrical property, taking into account the reactance due to the flux out to a distance of 1 ft from center of the conductor, and is so tabulated for round, stranded, and composite conductors, usually as ohms per mile. The values of \(X_a\), however, depend on spacing of the conductors, and are unrelated to size of an individual conductor. Table 3-9 lists values of \(X_a\) at 60 Hz based on separation distance between centers of the conductors, in ohms per mile. The value for any other frequency is directly proportional; thus, for 25 Hz it is 25/60 of the 60-Hz value.

The conductor spacing for other than a simple two-conductor circuit is its geometric mean distance (GMD) in ft. A few of the usual arrangements and their GMD’s are shown in Table 3-10. If the spacing is unequal, the GMD is a geometric average value which, however, usually is satisfactory for preliminary calculations. Thus, in a flat
bare aluminum wire and cable

<table>
<thead>
<tr>
<th>Inches</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>feet</td>
<td>0</td>
<td>0.0097</td>
<td>0.0187</td>
<td>0.0271</td>
<td>0.0349</td>
<td>0.0423</td>
<td>0.0492</td>
<td>0.0558</td>
<td>0.0620</td>
<td>0.0679</td>
<td>0.0735</td>
<td>0.0789</td>
</tr>
<tr>
<td>1</td>
<td>0.0841</td>
<td>0.0938</td>
<td>0.1028</td>
<td>0.1107</td>
<td>0.1186</td>
<td>0.1152</td>
<td>0.1189</td>
<td>0.1227</td>
<td>0.1264</td>
<td>0.1299</td>
<td>0.1335</td>
<td>0.1370</td>
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<tr>
<td>2</td>
<td>0.1333</td>
<td>0.1399</td>
<td>0.1461</td>
<td>0.1491</td>
<td>0.1520</td>
<td>0.1549</td>
<td>0.1577</td>
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<td>0.1631</td>
<td>0.1657</td>
<td>0.1683</td>
<td>0.1709</td>
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<td>3</td>
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<td>0.1779</td>
<td>0.1802</td>
<td>0.1825</td>
<td>0.1847</td>
<td>0.1869</td>
<td>0.1891</td>
<td>0.1912</td>
<td>0.1933</td>
<td>0.1954</td>
<td>0.1975</td>
</tr>
<tr>
<td>4</td>
<td>0.1953</td>
<td>0.1993</td>
<td>0.2012</td>
<td>0.2031</td>
<td>0.2050</td>
<td>0.2069</td>
<td>0.2087</td>
<td>0.2105</td>
<td>0.2123</td>
<td>0.2140</td>
<td>0.2157</td>
<td>0.2174</td>
</tr>
<tr>
<td>5</td>
<td>0.2174</td>
<td>0.2207</td>
<td>0.2240</td>
<td>0.2256</td>
<td>0.2271</td>
<td>0.2287</td>
<td>0.2302</td>
<td>0.2317</td>
<td>0.2332</td>
<td>0.2347</td>
<td>0.2361</td>
<td>0.2376</td>
</tr>
<tr>
<td>6</td>
<td>0.2361</td>
<td>0.2390</td>
<td>0.2404</td>
<td>0.2418</td>
<td>0.2431</td>
<td>0.2445</td>
<td>0.2458</td>
<td>0.2472</td>
<td>0.2485</td>
<td>0.2498</td>
<td>0.2511</td>
<td>0.2523</td>
</tr>
</tbody>
</table>


(1) From formula: at 60 Hz

$$X_d = 0.2794 \cdot \log_{10} \frac{d}{GMR}$$

where

- $$d$$ = separation in feet

3-phase arrangement of conductors A, B, and C with 5 ft between A and B, 7 ft between B and C, and 12 ft between A and C, the reactance voltage drop from any conductor to neutral does not vary more than 2.2% from the voltage based on average $$D (A \times B \times C)^{\frac{1}{3}}$$, or 7.5 ft.

**$$X_a$$ and Geometric Mean Radius (GMR)**

The calculation of inductive reactance to a radius of 1 ft ($$X_a$$) is aided by the factor GMR, which represents the radius of an infinitely thin tube the inductance of which under the same current loading equals that of the conductor. For non-magnetic materials,

$$X_a = 0.2794 \cdot \frac{1}{\log_{10} \frac{GMR}{60}}$$

in which

- $$X_a$$ = Inductive reactance to 1 ft radius, ohms/mile
- $$f$$ = Frequency, Hz
- GMR = Geometric mean radius, ft

The GMR of a single solid round conductor is 0.7788$$r$$, in which $$r$$ is radius of conductor in ft. Fig. 3-10 is a curve showing GMR for an annular ring.

The GMR of a stranded conductor without steel reinforcement or center voids is obtained by using the concept of concentric rings of solid round wires, each ring being a specified GMD apart.*

The GMR of a stranded multi-layer ACSR or an expanded all-aluminum conductor with hollow center is

*For methods of calculation see ref. at bottom of page 3-13.
similarly based on the assumption of a hollow tube of aluminum wires.

The GMR values (in ft) for the various kinds of conductors are listed as an electrical property of the conductor in the conductor tables herein.

The GMR values for single-layer ACSR are not constant because the $X_s$ is affected by the cyclic magnetic flux which is dependent on current and temperature. The $X_s$ values for these conductors are experimentally determined and made available in tables or curves for various currents and temperatures.

The $X_s$ values for 3-layer ACSR is so little affected by the variable core magnetization that it is customary to ignore it, hence the GMR values for 3-layer ACSR are included in tables of conductor properties in the same manner as are those of other multi-layer conductors.

The following examples show the application of some of the previous equations and the comparative magnitude of some of the relationships.

**Bluebell** 1033.5 kcmil stranded aluminum cable (overall diam. 1.170 in.) is listed with GMR as 0.0373 ft and $X_s$ as 0.399 ohms per mile at 60 Hz. Check the $X_s$ value, and how much it differs from that of a solid round conductor of the same diameter.
bare aluminum wire and cable

Check of $X_a$

$X_a = 0.2794 \log_{10} \frac{1}{0.0373} = 0.399$ which checks table.

Comparison with solid round

$GMR = 0.7788 \times \frac{1.170}{2 \times 12} = 0.0380$

$X_a = 0.2794 \times \log_{10} \frac{1}{0.0380} = 0.397$

A corresponding size of ACSR, Curlew, diam. 1.246 in. is listed with $X_a$ of 0.385 and $GMR$ of 0.0420 ft, thereby showing the reduction of $X_a$ because of the hollow-tube effect and increased diameter, as per Eq. 3-8.

The variation of $X_a$ for different cable constructions of the same size, according to standard tables of electrical properties, is shown below for 266.8 kcmil conductors:

<table>
<thead>
<tr>
<th>Kind of Cable</th>
<th>Code</th>
<th>Stranding</th>
<th>Overall diameter</th>
<th>$X_a$ ohms per Mile</th>
</tr>
</thead>
<tbody>
<tr>
<td>All-aluminum</td>
<td>Daisy</td>
<td>1</td>
<td>0.586 in.</td>
<td>0.489</td>
</tr>
<tr>
<td>AAC</td>
<td>Owl</td>
<td>6/7</td>
<td>0.633</td>
<td>0.3635 @ 400 amps</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.50 @ 200 amps</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.48 @ 0 amps</td>
</tr>
<tr>
<td>ACSR one-layer</td>
<td>Partridge</td>
<td>26/7</td>
<td>0.642</td>
<td>0.465</td>
</tr>
</tbody>
</table>

The increased diameter of Partridge as compared with that of Daisy shows that $X_a$ is reduced 5%, but the one-layer Owl has 18% greater $X_a$ when fully loaded.

Inductive Reactance of Bundled Conductors

For increasing load stability and power capability in high-voltage lines, each of the individual phase lines is sometimes subdivided into 2, 3, or 4 subconductors but the distance between the conductors of a phase group is small compared with the distance between centers of the groups. The design of such a bundled-conductor circuit is beyond the scope of this book. However, for any such arrangement, the inductive reactances may be found as per the following example, provided the individual conductors are the same size, the same group arrangement is used for all phases, and skin and proximity effects are negligible.*

Example: Consider the arrangement below in which each conductor is ACSR 795 kcmil, Code Drake, 26/7 stranding, 60-Hz.

![Diagram of bundled conductors](attachment:image)

$X_a$ of Drake is 0.399 ohms per mile

The average $X_a$ of a phase is $1/3 (0.0492 + 0.0492 + 0.0492) = 0.0492$ ohms per mile, in which $X_a$ for 1.5 ft is 0.0492 ohms per mile (see Table 3-9).

The reactance to 1 ft radius $X_b^a$ for any group of 2 or 3 subconductors is $[(1/m) X_a - (m-1) X_a]$ where $m$ is the number of subconductors in each group.

For 4 subconductors, $X_b^a$ is $[(1/m) X_a - (m-1) X_a]$ + $X_a$ = 0.0105

Hence, for 3 subconductors $X_b^a = [(1/3)(0.399 - 2(0.0492))] = 0.1002$ ohms per mile.

As the distance between groups is comparatively large, an approximation for $X_b^a$ for a single group is made by considering the inter-conductor distances $d$ as 20 ft, 20 ft, and 40 ft, respectively, whence from Table 3-9,

$X_b^a = \frac{1}{3} \left( \frac{X_d^b}{2} + \frac{X_d^b}{2} + \frac{X_d^b}{3} \right) = 0.1002 + 0.3915 = 0.4917$ ohms per mile.

If a more accurate value of $X_d^b$ is desired (usually when distances within a group are not small as compared with phase distances), an average of all $X_a$ values for all distances between individual conductors is obtained. Thus, in the example there are 27 such distances. An $X_a$ value from Table 3-9 is obtained for each of these distances, then totaled, and divided by 27 to obtain an average $X_d^b$.

Zero-Sequence Resistance and Inductive Reactance

Zero-sequence currents ($I_o$) that occur under fault conditions are all equal and in phase. Hence they move out simultaneously through the phase conductors and return either through the earth or a combination of earth and ground-wire return paths. Zero-sequence currents are the three components of unbalanced phase currents that are equal in magnitude and common in phase. Note that $I_o$ flows in each phase conductor, and 3 $I_o$ flows to ground.

The influence of the earth return can be given by two additional terms, an earth resistance and reactance, as follows:

$R_e = 0.2858 \left( \frac{f}{60} \right)$ in ohms per mile (Eq. 3-9)

and

$X_e = 0.4191 \left( \frac{f}{60} \right) \log_{10} 77,760 \left( \frac{f}{60} \right)$ $\mu_f =$

approx 2.888 ohms per mile at 60 Hz, if $\mu_f$ is taken at 100

(see Table 3-11)

(Eq. 3-10)

* See also AIEE papers 58-41 and 59-897, *ibid.* p. 3-8 footnote.
TABLE 3-11
Zero-Sequence Resistance and Inductive Reactance Factors ($R_a$ and $X_e$)\(^\circ\)
<table>
<thead>
<tr>
<th>Frequency (f)</th>
<th>60Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistivity ($\rho_e$)</td>
<td>ohms per conductor per mile</td>
</tr>
<tr>
<td>All values</td>
<td>$R_a$</td>
</tr>
<tr>
<td>1</td>
<td>2.050</td>
</tr>
<tr>
<td>5</td>
<td>2.343</td>
</tr>
<tr>
<td>10</td>
<td>2.469</td>
</tr>
<tr>
<td>50</td>
<td>2.762</td>
</tr>
<tr>
<td>100*</td>
<td>2.888</td>
</tr>
<tr>
<td>500</td>
<td>3.181</td>
</tr>
<tr>
<td>1,000</td>
<td>3.307</td>
</tr>
<tr>
<td>5,000</td>
<td>3.600</td>
</tr>
<tr>
<td>10,000</td>
<td>3.726</td>
</tr>
</tbody>
</table>

\(^\circ\) From formulas:

\[
R_a = 0.2858 \frac{f}{60} \log \frac{77,760}{f} \rho_e
\]

where $f$ = frequency

$\rho_e$ = resistivity (ohm-meter)

* This is an average value which may be used in the absence of definite information.

in which $\rho_e$ = ac resistivity of the earth return path in ohm-meters (the resistance between the faces of a one-meter cube of earth). This value depends on quality of the earth, and is in the range shown in Table 3-11, but an average value of 100 may be used in the absence of definite information.

$R_a = 0.2858$ ohms per mile

\[
X_e = 2.888\text{ ohms per mile for 60 Hz}
\]

Substituting in Eq. 3-11 for impedance $Z_e$:

\[
Z_e = R_a + R_e + j(X_e + X_a - 2X_d) \quad (\text{Eq. 3-11})
\]

in which $R_{ac}$ = ac resistance in ohms per phase per mile

$R_a$ and $X_a$ are given by Eqs. 3-9 and 3-10 above

$X_e$ and $X_d$ are inductive reactances in ohms per mile

Example: Consider the arrangement below in which conductor is ACSR 795 kcmil, Drake, 60 Hz.

![Diagram](image)

From Eq. 3-9 $R_a = 0.2858$, and $X_e = 2.888$, ohms per mile

From tables, $R_{ac} = 0.1370$ ohms per mile at 75°C

$X_a = 0.399$ ohms per mile

$X_d = \frac{1}{3} (0.3286 + 0.3286 + 0.4127) = 0.3566$ ohms per mile in which $X_e$ at 15 ft is 0.3286 and at 30 ft is 0.4127

Substituting in Eq. 3-11 for impedance $Z_e$:

\[
Z_e = 0.1370 + 0.2858 + j (2.888 + 0.399 - 2(0.3566)) \text{ ohms/mile}
\]

\[
= 0.4228 + j 2.5738 \text{ ohms/mile} = 2.608 \text{angle} 80.67^\circ.
\]

Shunt Capacitive Reactance

In long high-voltage transmission lines the distributed capacitance caused by the electric field between and surrounding the conductors can attain high values which markedly affect circuit properties; among them voltage distribution, regulation, system stability, corona, lightning performance, and transients set up by faulting or line switching.

The shunt capacitive reactance of a conductor system is

\[
X' = \frac{1}{2\pi f C} \text{ ohms} \quad (\text{Eq. 3-12})
\]

in which if $C$ is in farads; $f$ is frequency Hz.

It is customary in engineering work to express shunt capacitance in microfarads per mile and $X'$, the corresponding reactance in megohm-miles, usually for 60 Hz. The prime (') is affixed to the $X'$ to prevent confusion with $X$-values that represent inductive reactance.

To obtain the megohms of shunt capacitive reactance that controls charging current of a line longer than one mile, the listed megohm-miles value is to be divided by length of line in miles; that is, for 100 miles of a line using 795 kcmil 54/7 ACSR at a phase spacing of 20 ft, the megohms of shunt capacitive reactance which determines the charging current will be the listed 0.1805 megohm-miles divided by 100 or 0.001805 megohms (1805 ohms).

Similar to the use of $X_a$ to represent inductive reactance to radius of 1 ft and $X_d$ to represent inductive reactance in the remaining space up to an adjacent conductor, the total capacitive reactance similarly may be divided into components as follows:
TABLE 3-12
Separation Component \(X'_d\) of Capacitive Reactance at 60 Hz \(^{(1)}\) Megohm-Miles Per Conductor

<table>
<thead>
<tr>
<th>Separation of Conductors</th>
<th>inches</th>
</tr>
</thead>
<tbody>
<tr>
<td>feet</td>
<td>0</td>
</tr>
<tr>
<td>--------------------------</td>
<td>--------</td>
</tr>
<tr>
<td>0</td>
<td>-0.0737</td>
</tr>
<tr>
<td>1</td>
<td>0.0024</td>
</tr>
<tr>
<td>2</td>
<td>0.0206</td>
</tr>
<tr>
<td>3</td>
<td>0.0326</td>
</tr>
<tr>
<td>4</td>
<td>0.0411</td>
</tr>
<tr>
<td>5</td>
<td>0.0478</td>
</tr>
<tr>
<td>6</td>
<td>0.0532</td>
</tr>
<tr>
<td>7</td>
<td>0.0577</td>
</tr>
</tbody>
</table>


From formula: for 60 Hz

\[
X'_d = 0.0683 \log_{10} d + 0.0683 \log_{10} d_{eb}
\]

in which

\[
X'_c = \text{Capacitive reactance in megohm-miles per conductor}
\]

\[
r_n = \text{Overall radius of conductor, ft}
\]

\[
d_{eb} = \text{Separation distance to return conductor, ft}
\]

\[
f = \text{Frequency, Hz}
\]

The left-hand term of the above two-term equation represents \(X'_a\), the capacitive reactance for 1 ft spacing (to 1-ft radius); the right-hand term represents \(X'_d\), the separation component; both are in terms of megohm-miles. These two values have been tabulated for 60 Hz. Those for \(X'_n\) are listed in the tables of electrical properties of conductors and those for \(X'_a\) are in Table 3-12.

Example: For 795 kcmil Drake, Radius of conductor 0.0461 ft, 60 Hz, 20 ft spacing.

Substituting in the terms of Eq. 3-13

\[
X'_a = 0.0683 \log_{10} \frac{1}{0.0461} = 0.0683 \times 1.3365 = 0.0913 \text{megohm-miles}
\]

\[
X'_c = 0.0683 \log_{10} 20 = 0.0683 \times 1.3010 = 0.0889 \text{megohm-miles}
\]

\[
X'_e = 0.0913 + 0.0889 = 0.1802 \text{megohm-miles}
\]

Zero-Sequence Capacitive Reactance

An added term \(E'_e\) that affects zero-sequence capacitive reactance depends on distance above ground. It is represented by

\[
X'_e = 0.0205 \frac{60}{f} \log_{10} 2h \quad \text{in which } h \text{ is height of conductor above ground, ft}
\]

\[(\text{Eq. 3-14})\]
The zero-sequence capacitive reactance of one 3-phase circuit without ground wires in terms of megohm-miles per conductor is

\[ X'_o = X'_a + X'_d - 2X'_e \]  
(Eq. 3-15)
in which the terms have previously been defined.

**Capacitive Reactance of Bundled Conductors**

The shunt capacitive reactance of bundled conductors can be found from equations identical with those used in the numerical example relating to inductive reactance of bundled conductors (page 3-17), except a prime is added to each \( X \). Thus \((X'_a)^b\) and \((X'_b)^b\) may then be used in place of \( X'_a \) and \( X'_d \) in the corresponding equations for positive- or zero-sequence inductive reactance.

**Ampacity of Bare Conductors**

The major considerations involving the current-carrying capacity (ampacity) of overhead transmission conductors are the effect of conductor heating by the current and the consequent reduction of tensile strength. Most aluminum transmission conductors are hard-drawn and operate over predetermined ranges of maximum sags and tensions. Heating to relatively high temperatures for appreciable time periods anneals the metal, thus reducing the yield strength and increasing elongation. Hence the ampacity of such conductors is generally stated to be the current under the assumed conditions of operation which will not produce sufficient heating to affect significantly the tensile properties of the conductor.

Basic to the calculation is the establishment of an ambient temperature level. Obviously the ampacity is related to temperature rise, and the amount of the latter depends on temperature of the outside air.

Usual practice is to assume an ambient temperature of 40°C for overhead conductors, and the tables and charts herein are on that basis. However, lower ambient will be found in some applications, and the temperature rise for a given operating temperature must be altered accordingly.

The usual maximum operating temperature for tensioned bare conductors is 70° to 85°C, with 100°C and over permissible only in limited emergencies.

**Heat Balance:**

Temperature rise in a conductor depends on the balance between heat input (IR loss plus heat received from sunshine) and heat output (due to radiation from the conductor surface, and transfer because of convection of air currents). The heat loss arising from metallic conduction to supports is negligible, so is ignored. When the temperature of the conductor rises to the point where heat output equals heat input the temperature remains steady, and the current for such condition is the ampacity for that temperature under the stated conditions.

The factors of importance that affect ampacity for a given temperature are wind velocity, conductor surface emissivity, atmospheric pressure (which affects ampacity at high altitudes), and of course the ambient temperature.

Neglecting sunshine heat input, the heat balance may be expressed as

\[ I^2R_{eff} = (W_c + W_r)A, \]
both terms in watts/linear ft. 
(Eq. 3-16)
and in which
\[ W_c = \text{Convection loss, watts/sq in. of conductor surface} \]
\[ W_r = \text{Radiation loss, watts/sq in. of conductor surface} \]
\[ A = \text{Surface area of conductor per ft of length, sq in.} \]
\[ R_{eff} = \text{Total effective resistance per ft of conductor, ohms, including the resistance-equivalent of pertinent components of loss under a-c conditions. (Skin and proximity effects, reactance components, etc.)} \]

which reduces to

\[ I = \frac{37.7 X d (W_c + W_r)}{R_{eff}} \]
(Eq. 3-16a)
in which \( d \) = Outside diameter of conductor, in.
\[ I = \text{Current for balanced condition (the ampacity), amp} \]

The convection heat loss \( W_c \) depends on wind velocity, temperature rise, and atmospheric pressure (altitude). The radiation heat loss \( W_r \) is considered to depend on temperature rise and an emissivity constant \( \epsilon \) that expresses the ability of the conductor to radiate internal heat.

A perfect non-radiative surface would have \( \epsilon = 0 \), and a body that radiates all heat would have \( \epsilon = 1 \). The emissivity factor \( \epsilon \) for aluminum conductor surfaces depends on the degree of oxidation and discoloration of surface, its roughness, and the stranding. Newly installed conductors may have \( \epsilon \) as low as 0.23, and may be 0.90 after being well-blackened after years of service. A value of \( \epsilon = 0.5 \) provides a safety factor for the majority of exposed conductors which have been installed for several years. This value (\( \epsilon = 0.5 \)) is used for the tables and curves herein, which also show values based on a cross-wind of 2 ft per sec (1.36 miles per hr) as well as for still but unconfined air (Figs. 3-11 et seq).

The effect of sunlight and altitude as well as of variations of emissivity constants are shown by small auxiliary curves of Fig. 3-15.

The various factors entering the heat balance equations have been summarized by one conductor engineering group into the following:

1. Convection Heat Loss (\( W_c \)) for 2 ft/sec wind, at sea level for 60°C rise above 40°C ambient.
### TABLE 3-13
Current Ratings for High-Strength ACSR with Single Layer of Aluminum Strands 40°C ambient $\epsilon_0 = 0.5$ emissivity; no sun.

<table>
<thead>
<tr>
<th>Code Name</th>
<th>Size (cmils)</th>
<th>Stranding</th>
<th>Wind Condition</th>
<th>Temp Rise 10°C</th>
<th>Temp Rise 30°C</th>
<th>Temp Rise 60°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grouse</td>
<td>80,000</td>
<td>8AI- 1 St.</td>
<td>2 ft per sec</td>
<td>106</td>
<td>175</td>
<td>236</td>
</tr>
<tr>
<td></td>
<td>80,000</td>
<td>8AI- 1 St.</td>
<td>Still Air</td>
<td>62</td>
<td>113</td>
<td>166</td>
</tr>
<tr>
<td>Petrel</td>
<td>101,800</td>
<td>12AI- 7 St.</td>
<td>2 ft per sec</td>
<td>125</td>
<td>204</td>
<td>263</td>
</tr>
<tr>
<td></td>
<td>101,800</td>
<td>12AI- 7 St.</td>
<td>Still Air</td>
<td>75</td>
<td>133</td>
<td>190</td>
</tr>
<tr>
<td>Minorca</td>
<td>110,800</td>
<td>12AI- 7 St.</td>
<td>2 ft per sec</td>
<td>132</td>
<td>211</td>
<td>277</td>
</tr>
<tr>
<td></td>
<td>110,800</td>
<td>12AI- 7 St.</td>
<td>Still Air</td>
<td>79</td>
<td>142</td>
<td>201</td>
</tr>
<tr>
<td>Leghorn</td>
<td>134,600</td>
<td>12AI- 7 St.</td>
<td>2 ft per sec</td>
<td>149</td>
<td>239</td>
<td>314</td>
</tr>
<tr>
<td></td>
<td>134,600</td>
<td>12AI- 7 St.</td>
<td>Still Air</td>
<td>92</td>
<td>162</td>
<td>231</td>
</tr>
<tr>
<td>Guinea</td>
<td>159,000</td>
<td>12AI- 7 St.</td>
<td>2 ft per sec</td>
<td>166</td>
<td>266</td>
<td>352</td>
</tr>
<tr>
<td></td>
<td>159,000</td>
<td>12AI- 7 St.</td>
<td>Still Air</td>
<td>104</td>
<td>182</td>
<td>262</td>
</tr>
<tr>
<td>Dotterel</td>
<td>176,900</td>
<td>12AI- 7 St.</td>
<td>2 ft per sec</td>
<td>178</td>
<td>285</td>
<td>374</td>
</tr>
<tr>
<td></td>
<td>176,900</td>
<td>12AI- 7 St.</td>
<td>Still Air</td>
<td>111</td>
<td>196</td>
<td>280</td>
</tr>
<tr>
<td>Dorking</td>
<td>190,800</td>
<td>12AI- 7 St.</td>
<td>2 ft per sec</td>
<td>187</td>
<td>300</td>
<td>394</td>
</tr>
<tr>
<td></td>
<td>190,800</td>
<td>12AI- 7 St.</td>
<td>Still Air</td>
<td>117</td>
<td>208</td>
<td>296</td>
</tr>
<tr>
<td>Cochin</td>
<td>211,300</td>
<td>12AI- 7 St.</td>
<td>2 ft per sec</td>
<td>199</td>
<td>319</td>
<td>422</td>
</tr>
<tr>
<td></td>
<td>211,300</td>
<td>12AI- 7 St.</td>
<td>Still Air</td>
<td>126</td>
<td>223</td>
<td>318</td>
</tr>
<tr>
<td>Brahma</td>
<td>203,200</td>
<td>16AI-19 St.</td>
<td>2 ft per sec</td>
<td>188</td>
<td>301</td>
<td>389</td>
</tr>
<tr>
<td></td>
<td>203,200</td>
<td>16AI-19 St.</td>
<td>Still Air</td>
<td>120</td>
<td>210</td>
<td>296</td>
</tr>
</tbody>
</table>

If the ambient temperature is less than 40°C, a small change in ampacity for a given temperature rise may be obtained because the resistance of the conductor is less (because of its reduced temperature). However, at the lower ambient and the same temperature rise, the radiated heat loss is less. The net result is that the current for a given temperature is little changed over a considerable range of ambient temperature.

**Ampacity of 1350-H19 All-Aluminum Conductor and Standard-Strength ACSR Conductors**

Ampacity graphs for 1350 all-aluminum conductors, and Standard-Strength ACSR are shown in Figs. 3-11, 12, 13, and 14 for still air and for 2fps wind at 40°C ambient for $\epsilon_0 = 0.50$ and 62% 1ACS aluminum without sunlight effect. For 61.2% 1ACS multiply by 0.994. Small graphs of multiplying factors for sunlight, altitude, and emissivity corrections are shown in Fig. 3-15. The $W_c$ and $W_v$ values for 60°C rise are from Eqs. 3-17, -18, and -20. The slope of the lines from the 60°C values is based on experimental data.

---

$W_c = 0.5388 (1.01 + 43.22 d^{0.02})$ watts per ft of length for $d$ up to 1.6 in. diameter (Eq. 3-17)

$W_c = 22.15 d^{0.6}$ watts per ft of length for $d$ 1.6 in. diameter and over (Eq. 3-18)

2. Convection Heat Loss ($W_c$) for still air, at sea level:

$W_c (\text{still}) = 0.072 d^{0.75} \Delta t_0^{0.35}$ watts per ft of length in which $\Delta t_0$ is temperature rise above ambient (Eq. 3-19)

3. Radiation Heat Loss ($W_r$) for 60°C rise above 40°C ambient:

$W_r = 6.73 d$ watts per ft of length for $\epsilon = 0.5$ (an average emissivity for weathered conductors) (Eq. 3-20)

4. Sun Heat Gain ($W_s$)—to be subtracted from ($W_c + W_r$) in the above equations:

$W_s = 3.0 d$ watts per ft of length for mid latitudes (Eq. 3-21)
Ampacity of Single-Layer High-Strength ACSR Conductors

Table 3-13 can be used for ampacity values for high-strength ACSR in larger-than-AWG sizes for 10°, 30°, and 60°C rise. Values for intermediate temperatures may be obtained by plotting these values on log-log paper similar to that used for Figs. 3-13 and 3-14.

Ampacity of 6201-T81 and ACAR Conductors

Inasmuch as heat loss for a given temperature rise is proportional to conductor surface (or diameter) and heat input is proportional to FR, the ampacity of any conductor of conductivity other than 62% IACS is found closely per the following example:

Find ampacity in still air for 30°C rise of 394.5 kemil (0.684 in. diam.) cable of 6201-T81 of 52.5% IACS conductivity.

By interpolating in Fig. 3-11, the ampacity of 62% IACS 1350 conductor of same diameter (if it could be obtained) would be 320 amp. Hence, the ampacity at 52.5% IACS is 320 × (52.5/62.0)½; or 294 amp.*

For ACAR which has wires of two conductivities, the equivalent conductivity value is used; thus, for 42/19 ACAR (1350 and 6201-T81) of 1.165 in. outside diameter, the % IACS conductivity of the ACAR conductor, if the 1350 wires are 61.2% IACS, is

\[ (42 \times 61.2 + 19 \times 52.5) / 61 = 58.5\% \text{ IACS} \]

Examples of Ampacity Values Obtained from Figs. 3-11 to 15 incl.

The following typical examples illustrate the use of the various graphs:

1. Cable size 795 kemil ACSR 26/7 stranding, \( \epsilon = 0.50 \), diam. 1.1 in. approx., wind of 2 ft per sec. What is ampacity for 35°C rise, or 75°C operating temperature?

At top of Graph Fig. 3-14 note the diagonal line that extends downward from the designated size. It intersects the 35°C rise horizontal at 835 amp, which is the ampacity for the stated conditions.

2. For the cable of Example 1, what is ampacity if altitude is 10,000 ft with sun, and with emissivity factor reduced to 0.23?

Note: The multiplying factors of Fig. 3-15 are to be used. These strictly are applicable only for 100°C operating temperature, but inasmuch as the ampacity diagonals on Fig. 3-13 are almost straight lines, it is satisfactory to apply the multiplying factors directly to the 35°C rise ampacity of 835 amp.

The altitude factor with sun is taken from the left-hand diagram of Fig. 3-15D as being 0.83 (approx) for 1.1 in. diam., and the emissivity factor taken from the right-hand diagram with sun for \( \epsilon = 0.23 \) is 0.90. The desired ampacity is 835 × 0.83 × 0.90 = 630 amp.

Note: If the multiplying factors are applied to the 60° Rise ampacity, for conditions stated in Example 1, the unadjusted ampacity is 1050 amperes. After applying the multiplying factors, this reduces to 1050 × 0.83 × 0.90 = 785 amp. Entering Fig. 3-14 at intersection of 60°C rise and 785 amp, and following down an imaginary diagonal that is parallel to an adjacent diagonal, it is noted that this intersects the 35°C line at 630 amp, the same value as previously obtained.

Emissivity Limitations for Figs. 3-11 to 3-14

An emissivity of \( \epsilon = 0.5 \) is the maximum assumed for weathering conditions at high altitudes (10,000 ft). The maximum assumed emissivity for a fully weathered conductor in normal altitude is 0.91.

Conductor Economics

The high cost of energy and generation facilities has made it very important that power losses be evaluated when selecting the correct conductor size to be used in a given project. Construction and energy costs have increased dramatically during the past decade, and this trend seems likely to continue. The Aluminum Association publication, "The Evaluation of Losses in Conductors," provides details on how such an economic analysis could be done.
Fig. 3-11. Current-Temperature-Rise Graph for Ampacity of Bare Aluminum Cable Stranded 1350-H19 62% IACS Still Air, Ambient Temperature 40°C Emissivity (ε) 0.5. For 61.2% IACS, multiply values by 0.994. No Sun–Sea Level.

For multiplying factors for various sun and emissivities, and for high altitudes, see Fig. 3-15, Chart A.
Fig. 3-12. Current-Temperature-Rise Graph for Ampacity of Bare Aluminum Cable Stranded 1350-H19 62% IACS Still Wind 2 fps, Ambient Temperature 40øC Emissivity (E) 0.5. For 61.2% IACS multiply values by 0.994. No Sun-Sea Level. For multiplying factors for various sun and emissivities and for high altitudes, see Fig. 3-15, Chart B.
Fig. 3-13. Current-Temperature-Rise Graph for Ampacity of Bare ASCR 62% IACS Still Air, Ambient Temperature 40°C Emissivity (ε) 0.5. For 61.2% IACS, multiply values by 0.994. No Sun-Sea Level.

For multiplying factors for various sun and emissivities, and for high altitudes, see Fig. 3-15, Chart C.
Fig. 3-14. Current-Temperature Rise Graph for Ampacity of Bare ACSR 62% IACS Wind 2 fps, Ambient Temperature 40°C.

Emissivity (ε) 0.5. For 61.2% IACS multiply values by 0.994. No Sun-Sea Level.

For multiplying factors for various sun and emissivities and for high altitudes see Fig. 3-15. Chart D.
bare aluminum wire and cable

**Chart A**

- a. Altitude Effect 10,000 feet
- b. Emissivity Effect no sun
- c. Emissivity Effect with sun

**Chart B**

- a. Altitude Effect 10,000 feet
- b. Emissivity Effect no sun
- c. Emissivity Effect with sun

**Chart C**

- a. Altitude Effect 10,000 feet
- b. Emissivity Effect no sun
- c. Emissivity Effect with sun

**Chart D**

- a. Altitude Effect 10,000 feet
- b. Emissivity Effect no sun
- c. Emissivity Effect with sun

*A—For stranded 1350 in still air. Fig. 3-11.*  
*B—For stranded 1350-wind 2 fps. Fig. 3-12.*  
*C—For stranded ACSR in still air. Fig. 3-13.*  
*D—For stranded ACSR-wind 2 fps. Fig. 3-14.*

Fig. 3-15 (A, B, C, and D)—Multiplying factor for various conditions of emissivity ($e$), sun, and altitude.  
Multiply the ampacity value obtained from Figs. 3-11 to 3-14 for 60°C rise inclusive by the applicable factor at bottom of diagram corresponding to the associated ampacity curve.