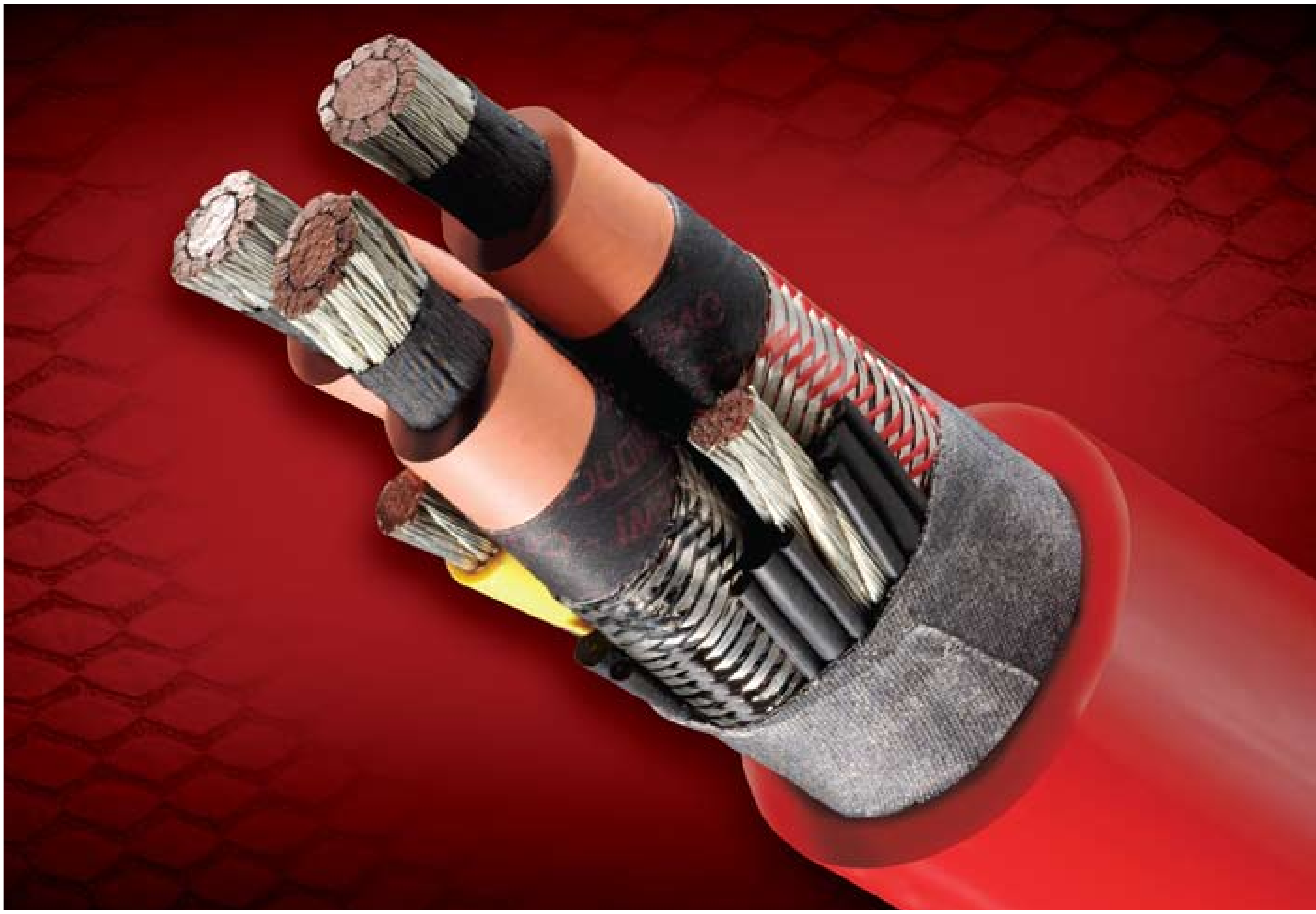
Mining Cable Engineering Handbook

2nd Edition



ANACONDA BRAND

CAROL BRAND

General Cable

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GENERAL PROPERTIES OF COPPER

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1.1 Resistance to Annealing

Both hard-drawn and medium-hard tempered wire can become annealed when used to conduct high current. Because current heating causes wire to lose tensile strength, it is imperative that hard-drawn and medium-hard tempers are designed to resist annealing.

Test values of tensile strength and elongation properties of copper wire are used to determine its final temper. See 1.1.1 Table 1 for specifics of solid wire breaking strength.

1.1.1 Table 1: Solid Wire Breaking Strength

	Approximate Tensile Strength					
	HARD-DRAWN[1]		MEDIUM-HARD[2]		ANNEALED (SOFT)[3]	
Size (AWG)	lbs	kg	lbs	kg	lbs	kg
4/0	8143	3693	6980	3166	5983	2713
3/0	6720	3048	5666	2570	4744	2151
2/0	5519	2503	4599	2086	3763	1706
1/0	4518	2049	3731	1692	2985	1354
1	3688	1672	3024	1371	2432	1103
2	3002	1361	2450	1111	1928	874
3	2439	1106	1984	899	1529	693
4	1970	893	1584	718	1213	550
5	1590	721	1265	573	961	436
6	1280	580	1010	458	762	345
7	1030	467	806	365	605	274
8	826	374	644	292	479	217
9	660	299	513	233	380	172
10	529	240	410	186	314	142
11	423	191	327	148	249	112
12	337	152	262	118	197	89
13	268	121	209	94	157	71
14	214	97	167	75	124	56
15	170	77	133	60	98	44
16	135	61	106	48	78	35

[1] **Hard-Drawn** wire has the highest tensile strength, lowest conductivity and lowest elongation of the tempers. The hot-roll rod is cold-drawn without annealing, which work-hardens the wire.

[2] **Medium-Hard** requires the hot-roll rod be briefly cold-worked to the desired diameter. The wire is then heated moderately. The tensile strength, conductivity and elongation properties are mid-way between hard-drawn and annealed.

[3] **Annealed (Soft)** wire is cold-drawn first to the desired diameter, then a high heat is applied to soften the copper. This temper has the lowest tensile strength, highest conductivity and greatest elongation of the three tempers.

1.2 Table 2: Properties of Annealed Copper Wire

Atomic Weight	63.57
Atomic Number	29
Density at 20°C	8.89 g/cm^3
Melting Point	1083°C - 1981.4°F
Boiling Point	2310°C - 4190°F
Specific Heat, 25°C	0.0918 cal per g per deg C
Latent Heat of Fusion	43.3 g-cal per gram
Linear Coefficient of Expansion	0.00001692 per deg C/0.0000094 per deg F
Electrical Resistivity at 20°C	0.15328 ohm (meter gram)
Temperature Coefficient of Resistivity at 20°C	0.00393 per deg C
Thermal Conductivity	0.93 $cal/cm^2/cm/sec/deg$ C

1.3 The AWG

AWG sizes represent the successive steps in the process of drawing wire. The AWG uses a simple mathematical law to determine size, and its numbers are retrogressive to wire size represented.

- Diameters are formed by geometrical progressions based on two diameter specifications.
- The basis of the AWG is the diameter of No. 4/0 defined as 0.0046 in. and No. 36 as 0.0050 in. The 38 sizes between these two diameters are specified by the ratio of any diameter to the diameter of the next greater number, as shown below:

$$\sqrt[39]{\frac{0.4600}{0.0050}} = \sqrt[39]{92} \qquad X = 1.1229322$$

- The square of the ratio equals 1.26010.
- The sixth power of the ratio equals 2.0050 to the next greater diameter.
- As the ratio is approximately 2, it applies a number of useful relations and short cuts in wire computations.

1.3.1 Rules of Thumb for AWG

All rules are approximate.

1. An increase of three gauge numbers doubles the area and weight and halves the dc resistance.
2. An increase of six gauge numbers doubles the diameter.
3. An increase of ten gauge numbers multiplies the area and weight by 10 and divides the resistance by 10.
4. For sizes 4/0 AWG to 29 AWG, the maximum and minimum diameters can be found by adding or subtracting 1% of the nominal diameters.
5. For sizes 30 AWG to 46 AWG, the maximum and minimum diameters can be found by adding or subtracting .0001" of the nominal diameters.
6. The weight of 2 AWG copper wire is very close to 200 lb per 1000 ft.
7. A 10 AWG wire has a diameter of approximately 0.10 in., an area of about 10,000 cir mils and a resistance of approximately 1.0 ohm per 1000 ft.

1.3.2 AWG Conversions

Copper conductor size conversion is determined by:

Circular mils = sq in. x 1,273,240 = sq mm x 1,973.5

For cross-sectional forms other than circular, where S is the cross-sectional area in square inches, the conversions are:

Ohms per 1000 feet at 20°C $= \dfrac{0.0081455}{S}$

Feet per ohm at 20°C = 122770 x S

Ohms per pound at 20°C $= \dfrac{2.1135}{S^2\ 10^6}$

Pounds per ohm at 20°C $= 473160 \times S^2$

Pounds per 1000 feet at 20°C = 3854.09 x S

Feet per pound at 20°C $= \dfrac{0.259465}{S}$

Mil is the term used to express wire diameter measurement and represents a unit of length equal to 1/1000 of an inch.

Circular mil is used to define cross-sectional areas. One circular mil equals 0.7854 square mil.

For actual wire conversions, see 1.3.2.1 Table 3.

1.3.2.1 Table 3: Wire Conversions

SIZE		CROSS-SECTIONAL AREA		WEIGHT		OVERALL DIAMETER	
AWG/ kcmil	cir mils	sq inch	sq mm	lb/1000 ft	kg/km	inch	mm
500	500000	0.3927	253.4	1513.5	2252.1	0.707	17.96
350	350000	0.2749	177.3	1059.5	1576.5	0.592	15.04
300	300000	0.2356	152.0	908.0	1351.1	0.548	13.92
250	250000	0.1963	126.7	756.6	1125.8	0.500	12.70
4/0	211600	0.1662	107.2	640.5	952.8	0.460	11.68
3/0	167800	0.1318	85.0	507.8	755.4	0.410	10.41
2/0	133100	0.1045	67.4	402.8	599.2	0.365	9.27
1/0	105600	0.0829	53.5	319.5	475.3	0.325	8.26
1	83690	0.0657	42.4	253.3	376.8	0.289	7.34
2	66360	0.0521	33.6	200.9	298.9	0.258	6.50
3	52620	0.0413	26.7	159.3	237.0	0.229	5.82
4	41740	0.0328	21.1	126.3	187.9	0.204	5.18
5	33090	0.0260	16.8	100.2	149.1	0.182	4.62
6	26240	0.0206	13.3	79.4	118.1	0.162	4.12
7	20820	0.0164	10.5	63.0	93.8	0.144	3.66
8	16510	0.0130	8.4	50.0	74.4	0.128	3.25
9	13090	0.0103	6.6	39.6	58.9	0.114	2.90
10	10380	0.0082	5.3	31.4	46.8	0.102	2.59
11	8230	0.0065	4.2	24.9	37.0	0.091	2.31
12	6530	0.0051	3.3	19.8	29.5	0.081	2.06
13	5180	0.0041	2.6	15.7	23.4	0.072	1.83
14	4110	0.0032	2.1	12.4	18.4	0.064	1.63
15	3260	0.0026	1.7	9.9	14.7	0.057	1.45
16	2580	0.0020	1.3	7.8	11.6	0.051	1.30

RESISTANCE AND RESISTIVITY 2

It is commonly held that electric current in stranded conductors is confined to individual strands and does not transfer from strand to strand parallel to the axis of the conductor. Using this reasoning, dc resistance is calculated as follows:

- Multiply the number of individual strands by the cross-section area of one wire. This product is the effective cross-sectional area of the conductor.
- Compare the length of each strand to the axial length of the conductor. Average the increased length of the strands.
- Multiply the effective cross-sectional area (the first product) by the average strand length increase to get the strand resistance.

2.1 DC Resistance of Stranded Conductors

In accordance with ASTM Specification B189-63, Tables 4 and 5 show factors for determining the dc resistance of uncoated and coated copper stranded conductors.

2.1.1 Table 4: Factors for Determining DC Resistance of Uncoated and Coated Copper Strand

	Uncoated				**Coated**									
	All Sizes				**Diameter of Individual Coated Wires, Inch**									
					0.460-0.290		0.289-0.103		0.102-0.201		0.0200-0.0111		0.0110-0.0030	
	Minimum Conductivity, Percent													
	100		98		97.66		97.16		96.16		94.16		93.15	
	Temperature, Degrees C													
Conductor	25	20	25	20	25	20	25	20	25	20	25	20	25	20
Resistance Factors — Ohms per Circular Mil *														
CONCENTRIC														
To 2000 kcmil	10786	10579	10989	10795	11045	10832	11102	10888	11217	11001	11456	11235	11579	11356
2001 to 3000	10892	10682	11097	10900	11153	10938	11210	10994	11327	11109	11568	11345	11693	11647
3001 to 3400	10998	10786	11205	11006	11261	11044	11319	11101	11437	11217	11681	11455	11806	11579
4001 to 5000	11104	10890	11313	11112	11370	11150	11428	11208	11547	11325	11793	11566	11920	11690
ROPE-LAY — Concentric-Stranded Members														
49 Wires	10892	10682	11097	10900	11153	10938	11210	10994	11327	11109	11568	11345	11693	11467
133 Wires	10998	10786	11205	11006	11261	11044	11319	11101	11437	11217	11681	11455	11806	11579
259 Wires	11051	10838	11259	11059	11315	11097	11374	11155	11492	11271	11737	11511	11863	11634
427 Wires	11104	10890	11313	11112	11370	11150	11428	11208	11547	11325	11793	11566	11920	11690
Over 427 Wires	11209	10993	11420	11199	11478	11257	11537	11315	11657	11432	11905	11676	12033	11801
ROPE-LAY — Bunch-Stranded Members														
7 Ropes	10998	10786	11205	11006	11261	11044	11319	11101	11437	11217	11681	11455	11806	11579
19, 37, 61 Ropes	11104	10890	11313	11112	11370	11150	11428	11208	11547	11325	11793	11566	11920	11690
7 x 7 Ropes	11209	10993	11420	11199	11478	11257	11537	11315	11657	11432	11905	11676	12033	11801
19 x 7, 37 x 7 or 61 x 7 Ropes	11315	11097	11528	11305	11586	11363	11646	11421	11767	11540	12018	11786	12147	11913
BUNCHED STRAND														
All sizes	10786	10579	10989	10795	11045	10832	11102	10888	11217	11001	11456	11235	11579	11356

*The direct current resistance in ohms per 1000 feet of the completed strand shall not exceed the value calculated by dividing the appropriate factor above by the nominal circular mil area of the conductor.

2.1.2 Table 5: Copper Wire DC Resistance at 20°C (68°F)

Solid Conductor Size (AWG/kcmil)	BARE HARD-DRAWN		BARE MEDIUM-HARD		BARE ANNEALED (SOFT)		TINNED ANNEALED (SOFT)	
	ohms per 1000 ft	ohms per km	ohms per 1000 ft	ohms per km	ohms per 1000 ft	ohms per km	ohms per 1000 ft	ohms per km
4/0	0.0504	0.166	0.0502	0.165	0.0490	0.161	0.0502	0.165
3/0	0.0636	0.209	0.0633	0.206	0.0618	0.203	0.0633	0.208
2/0	0.0802	0.263	0.0798	0.262	0.0779	0.256	0.0798	0.262
1/0	0.1022	0.335	0.1016	0.334	0.0983	0.322	0.1006	0.330
1	0.1289	0.423	0.1282	0.421	0.1239	0.407	0.1275	0.419
2	0.1625	0.533	0.1617	0.531	0.1563	0.513	0.1609	0.528
3	0.2050	0.672	0.2039	0.669	0.1971	0.647	0.2028	0.667
4	0.2584	0.848	0.2571	0.843	0.2485	0.815	0.2557	0.839
5	0.3260	1.070	0.3243	1.060	0.3135	1.030	0.3226	1.060
6	0.4110	1.350	0.4088	1.340	0.3952	1.300	0.4067	1.330
7	0.5180	1.700	0.5153	1.690	0.4981	1.630	0.5126	1.680
8	0.6538	2.140	0.6498	2.130	0.6281	2.060	0.6465	2.120
9	0.8241	2.700	0.8199	2.690	0.7925	2.600	0.8156	2.680
10	1.0390	3.410	1.0330	3.390	0.9988	3.280	1.0390	3.410
11	1.3100	4.300	1.3000	4.280	1.2600	4.140	1.3100	4.300
12	1.6500	5.420	1.6400	5.390	1.5900	5.210	1.6500	5.420
13	2.0800	6.840	2.0700	6.770	2.0000	6.590	2.0800	6.840
14	2.6300	8.940	2.6100	8.580	2.5200	8.270	2.6300	8.640
15	3.3140	10.900	3.2900	10.800	3.1800	10.400	3.3100	10.900
16	4.1800	13.700	4.1600	13.700	4.0200	13.100	4.1800	13.700

2.2 AC Resistance

A conductor offers a greater resistance to the flow of alternating current than it does to direct current. The magnitude of the increase is usually expressed as an "ac/dc ratio". The reasons for the increase are several: 1) skin effect, 2) proximity effect, 3) hysteresis and eddy current losses in nearby ferromagnetic materials, and 4) induced losses in short-circuited nearby non-ferromagnetic materials.

2.2.1 Skin Effect

Skin Effect describes the phenomena of alternating current flowing more densely near the surface of the conductor. The net effect is a reduction in effective area and an increase in the resistance. To calculate skin effect in tubular conductors made of solid wire to an infinitely thin tube, the curves of Ewan are used.

The parameter is:

$$X = 0.027678 \sqrt{\frac{f}{R_0}}$$

Where: **f = frequency, Hz**

R_0 = dc resistance at operating temperature, ohms per 1000 feet

When: **f = 60 H_z, the formula becomes:**

$$x = \frac{0.21439}{\sqrt{R_0}}$$

Table 6 gives the factors for skin effect ratio R/R_0 as a function of x, where R is the ac resistance and R_0 is the dc resistance.

For conductors larger than 1,500,000 circular mils, other calculation formulas must be used for accuracy.

The non-uniform cross-sectional distribution of current also affects the inductance, the value of which is less than if the current density were uniform. The table of skin effect ratios, therefore, lists the inductance ratio L/L_0 where L is the inductance due to a non-uniform current density and L_0 is the inductance assuming uniform current density.

2.2.2 Proximity Effect

Proximity Effect is the distortion of the cross-sectional current distribution of the conductor due to nearby currents. To calculate approximately the proximity effect, use the following formula:

$$\text{1-phase } f_p = 4\left(\frac{GMR}{GMD}\right)^2\left(\frac{R}{R_0}-1\right)$$

$$\text{3-phase } f_p = 6\left(\frac{GMR}{GMD}\right)^2\left(\frac{R}{R_0}-1\right)$$

Where: **f_p = the factor to account for proximity effect**

GMR = the geometric mean radius of the equal conductors

GMD = the geometric mean spacing of the conductors

R/R_0 = the skin effect ratio

The resistance of a conductor based on skin- and proximity-effect is expressed:

$$R = R_0\left(\frac{R}{R_0} + f_p\right)$$

2.3 Inter-Strand AC Resistance

The effect of inter-strand resistance is also significant to ac resistance. If the current is, or can be, confined to the individual strands, skin effect will be materially reduced below that of an effectively solid conductor. The difference may be 2 percent or more.

2.3.1 Table 6: Resistance and Inductance Ratios due to Skin Effect (when f = 60 Hz)

X	R/R_0	L/L_0	X	R/R_0	L/L_0	X	R/R_0	L/L_0	X	R/R_0	L/L_0
0.0	1.00000	1.00000	2.9	1.28644	0.86012	6.6	2.60313	0.42389	17.0	6.26817	0.16614
0.1	1.00000	1.00000	3.0	1.31809	0.84517	6.8	2.67312	0.41171	18.0	6.62129	0.15694
0.2	1.00001	1.00000	3.1	1.35102	0.82975	7.0	2.74319	0.40021	19.0	6.97446	0.14870
0.3	1.00004	0.99998	3.2	1.38504	0.81397	7.2	2.81334	0.38933	20.0	7.32767	0.14128
0.4	1.00013	0.99993	3.3	1.41999	0.79794	7.4	2.88355	0.37902	21.0	7.68091	0.13456
0.5	1.00032	0.99984	3.4	1.45570	0.78175	7.6	2.95380	0.36923	22.0	8.03418	0.12846
0.6	1.00067	0.99966	3.5	1.49202	0.76550	7.8	3.02411	0.35992	23.0	8.38748	0.12288
0.7	1.00124	0.99937	3.6	1.52879	0.74929	8.0	3.09445	0.35107	24.0	8.74079	0.11777
0.8	1.00212	0.99894	3.7	1.56587	0.73320	8.2	3.16480	0.34263	25.0	9.09412	0.11307
0.9	1.00340	0.99830	3.8	1.60314	0.71729	8.4	3.23518	0.33460	26.0	9.44748	0.10872
1.0	1.00519	0.99741	3.9	1.64051	0.70165	8.6	3.30557	0.32692	28.0	10.15422	0.10096
1.1	1.00758	0.99621	4.0	1.67787	0.68632	8.8	3.37597	0.31958	30.0	10.86101	0.09424
1.2	1.01071	0.99465	4.1	1.71516	0.67135	9.0	3.44638	0.31257	32.0	11.56785	0.08835
1.3	1.01470	0.99266	4.2	1.75233	0.65677	9.2	3.51680	0.30585	34.0	12.27471	0.08316
1.4	1.01969	0.99017	4.3	1.78933	0.64262	9.4	3.58723	0.29941	36.0	12.98160	0.07854
1.5	1.02582	0.98711	4.4	1.82614	0.62890	9.6	3.65766	0.29324	38.0	13.68852	0.07441
1.6	1.03323	0.98342	4.5	1.86275	0.61563	9.8	3.72812	0.28731	40.0	14.39545	0.07069
1.7	1.04205	0.97904	4.6	1.89914	0.60281	10.0	3.79857	0.28162	42.0	15.10240	0.06733
1.8	1.05240	0.97390	4.7	1.93533	0.59044	10.5	3.97477	0.26832	44.0	15.80936	0.06427
1.9	1.06440	0.96795	4.8	1.97131	0.57852	11.0	4.15100	0.25622	46.0	16.51634	0.06148
2.0	1.07816	0.96113	4.9	2.00710	0.56703	11.5	4.32727	0.24516	48.0	17.22333	0.05892
2.1	1.09375	0.95343	5.0	2.04272	0.55597	12.0	4.50358	0.23501	50.0	17.93032	0.05656
2.2	1.11126	0.94482	5.2	2.11353	0.53506	12.5	4.67993	0.22567	60.0	21.46541	0.04713
2.3	1.13069	0.93527	5.4	2.18389	0.51566	13.0	4.85631	0.21703	70.0	25.00063	0.04040
2.4	1.15207	0.92482	5.6	2.25393	0.49764	13.5	5.03272	0.20903	80.0	28.53593	0.03535
2.5	1.17538	0.91347	5.8	2.32380	0.48086	14.0	5.20915	0.20160	90.0	32.07127	0.03142
2.6	1.20056	0.90126	6.0	2.39359	0.46521	14.5	5.38560	0.19468	100.0	35.60666	0.02828
2.7	1.22753	0.88825	6.2	2.46338	0.45056	15.0	5.56208	0.18822	—	—	—
2.8	1.25620	0.87451	6.4	2.53321	0.43682	16.0	5.91509	0.17649	—	—	—

R/R_0 = Resistance ratio due to skin effect
L/L_0 = Inductance ratio due to skin effect

$$X = \sqrt{\frac{0.21439}{R_0}}$$

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AMPACITY

3

3.1 Method of Calculations

Ampacity (current-carrying capacity) calculation should take into account natural variables such as solar warming, wind and air density, viscosity, and thermal conductivity. Ampacity is a temperature rating; mining cables insulated with ethylene propylene are rated to operate continuously at 90°C. Commonly used ICEA ratings (Publication No. S-75-381/NEMA WC 58) are for cables isolated in still air of 40°C with a conductor temperature of 90°C.

To calculate ampacity, a two-part relationship is used:

$$I^2 R_{ac} = Q_C - Q_S$$

Where: Q_C = **heat dissipated through conduction, convection and radiation**

Q_S = **heat absorbed from solar radiation**

$$\Delta T = I^2 R_{ac} R_{th}$$

Where: R_{th} = **thermal resistance of the insulation**

R_{ac} = **effective electrical resistance**

I = **current**

ΔT = **temperature difference of conductor and jacket surface**

When the two equations are solved simultaneously, it defines the ampacity for a set of given parameters. See 3.1.1 and 3.1.2 Tables 7 and 8.

3.1.1 Table 7: Ampacities for Portable Power Cables with 90°C Insulation, Amperes per Conductor

Power Conductor Size (AWG or kcmil)	Single Conductor				Two Conductor Round and Flat	Three Conductor Round and Flat	Three Conductor Round			Four Conductor	Five Conductor	Six Conductor
	0-2000 Volts Nonshielded	2001-8000 Volts* Shielded	8001-15000 Volts* Shielded	15001-25000 Volts* Shielded	0-2000 Volts	0-5000 Volts Nonshielded	0-8000 Volts* Shielded	8001-15000 Volts* Shielded	15001-25000 Volts* Shielded	0-2000 Volts	0-2000 Volts	0-2000 Volts
8	83	—	—	—	72	59	—	—	—	54	50	48
6	109	112	—	—	95	79	93	—	—	72	68	64
4	145	148	—	—	127	104	122	—	—	93	88	83
3	167	171	—	—	145	120	140	—	—	106	100	95
2	192	195	195	—	167	138	159	164	178	122	116	110
1	223	225	225	222	191	161	184	187	191	143	136	129
1/0	258	260	259	255	217	186	211	215	218	165	—	—
2/0	298	299	298	293	250	215	243	246	249	192	—	—
3/0	345	345	343	337	286	249	279	283	286	221	—	—
4/0	400	400	397	389	328	287	321	325	327	255	—	—
250	445	444	440	430	363	320	355	359	360	280	—	—
300	500	496	491	480	400	357	398	—	—	310	—	—
350	552	549	543	529	436	394	435	—	—	335	—	—
400	600	596	590	572	470	430	470	—	—	356	—	—
450	650	640	633	615	497	460	503	—	—	377	—	—
500	695	688	678	659	524	487	536	—	—	395	—	—
550	737	732	—	—	—	—	—	—	—	—	—	—
600	780	779	—	—	—	—	—	—	—	—	—	—
650	820	817	—	—	—	—	—	—	—	—	—	—
700	855	845	—	—	—	—	—	—	—	—	—	—
750	898	889	—	—	—	—	—	—	—	—	—	—
800	925	925	—	—	—	—	—	—	—	—	—	—
900	1010	998	—	—	—	—	—	—	—	—	—	—
1000	1076	1061	—	—	—	—	—	—	—	—	—	—

*These ampacities are based on single isolated cable in air operated with open-circuited shield.
NOTE — these ampacities are based on a conductor temperature of 90°C and an ambient air temperature of 40°C.
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3.1.2 Table 8: Ampacities for Mine Power Feeder Cables with 90°C Insulation, Three Conductor

5000 to 25,000 Volts Copper			
Conductor Size (AWG or kcmil)	Ampacities*		
	5000 & 8000 Volts	15000 Volts	25000 Volts
6	93	—	—
4	122	125	—
2	159	164	—
1	184	187	189
1/0	211	215	216
2/0	243	246	247
3/0	279	283	284
4/0	321	325	325
250	355	359	359
300	398	401	401
350	435	438	438
400	470	473	473
500	536	536	536

*These ampacities are based on single isolated cable in air operated with open-circuited shield.

NOTE — these ampacities are based on a conductor temperature of 90°C and an ambient air temperature of 40°C.

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3.1.3 Table 9: Approximate Ampacity Correction Factors for Cables of all Voltages

Correction factors are listed below for various ambient temperatures.

Ambient Temperature	Correction Factors for Insulations Rated At:	
°C	90°C	75°C
10	1.26	1.36
20	1.18	1.25
30	1.10	1.13
40	1.00	1.00
50	0.90	0.85

When cables are used with one or more layers wound on a reel, the ampacities should be derated as follows:

No. of Layers	Multiply Ampacities By:
1	0.85
2	0.65
3	0.45
4	0.35

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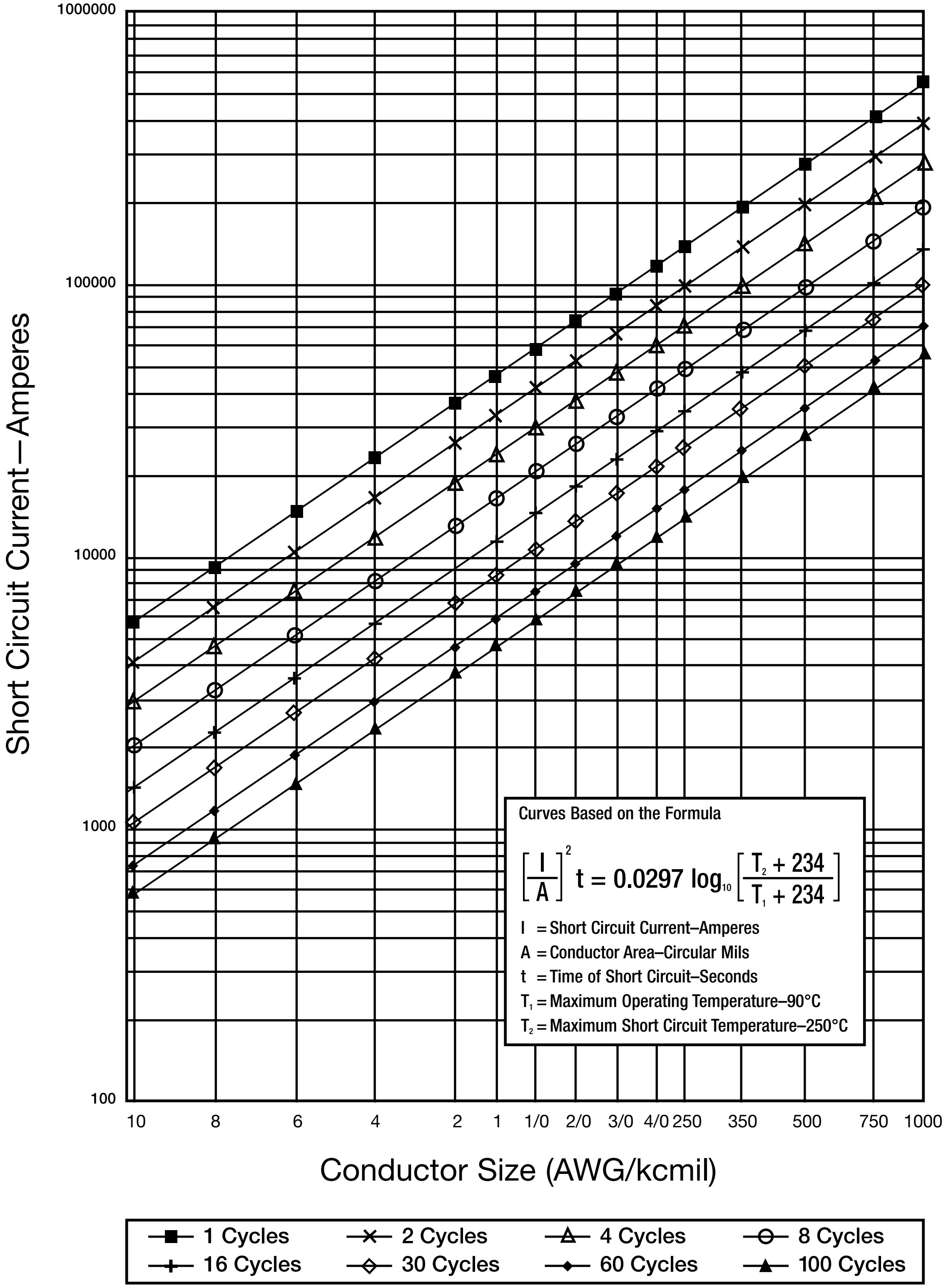
3.1.4 **Table 10: Allowable Short Circuit Currents for Insulated Copper Conductors**

Allowable Short Circuit Currents for Insulated Copper Conductors
Rated for 90°C Continuous Operation



Reprinted with permission from ICEA P-32-382 Short Circuit characteristics of Insulated Conductors, Copyright 2006, Insulated Cable Engineers Association, Carrollton, GA 30112. This reprint is not the referenced subject, which is represented only by the standard in its entirety.

3.2 Warning: Hot Conductors

A primary goal in the development of rubber or plastic compounds for cable insulations and jackets is to obtain physical and electrical characteristics that are stable at elevated temperatures in either wet or dry environments. From an engineering and design viewpoint, high temperature resistance is highly desirable and increases the safety factor during periods of emergency. Insulation stability during an emergency overload is of extreme importance. As noted in ICEA Standards covering emergency overload ratings, "Operation at these emergency overload temperatures shall not exceed 100 hrs. per year. Such 100-hr. overload periods shall not exceed five over the life of the cable."

Operating temperatures must be kept in the correct, and safe, perspective. As the current load increases, the following phenomena occur:

- Conductor resistance increases
- Voltage drop increases and causes conductor inefficiency
- Increased conductor temperature becomes an electric furnace
- Degradation of insulations and coverings is accelerated

IMPEDANCE 4

4.1 Impedance Terms and Calculations

Impedance (Z) of a circuit to a specified periodic current, and potential difference, is the ratio of effective value of the potential difference between terminals to the effective value of the current, there being no source of power in the portion of circuit under consideration, is expressed:

$$Z = \frac{E}{I} \text{ (ohms) or}$$

$$Z = \sqrt{R^2 + X^2} \text{ (ohms)}$$

Admittance (Y) is the reciprocal of impedance.

Ohm's Law applies to all metallic circuits and to others containing electrolytic resistance. It states that current in a circuit is directly proportional to the electromotive force in the circuit. In a direct-current circuit:

$$I = \frac{E}{R} = \frac{\text{Electromotive Force (volts)}}{\text{Resistance (ohms)}} \text{ (amperes)}$$

In an alternating current circuit:

$$R_{eff} = R_{dc} \times R_{ac}/R_{dc}$$

Where: R_{ac}/R_{dc} = ratio of alternating-current resistance to direct-current resistance of the circuit conductor

For resistance and reactance of portable power and feeder cables, see 4.1.1 and 4.1.2 Tables 11 and 12.

4.2 Reactance Terms and Calculations

Reactance of a portion of a circuit for a sinusoidal current, and potential difference of the same frequency, is the product of the sine of the angular phase difference between the current and potential difference times the ratio of the effective potential difference to the effective current, when there is no source of power in the portion of the circuit under consideration.

Inductive Reactance (X_L) is calculated from the relationship:

$$X_L = 2\pi f L \text{ (ohms)}$$

Where: L = inductance (henries)
f = frequency (Hertz)

Also from the above formula:

$$X_L = 0.05292 \log_{10} \frac{GMR}{GMD} \text{ (ohms to neutral per 1000 feet at 60 Hz)}$$

For other frequencies, multiply X_L by: $\frac{f}{60}$

Capacitive Reactance (X_C) is calculated from:

$$X_C = -\frac{1}{2\pi f C} \text{ (ohms)}$$

Where: C = capacitance (farads)

Total Reactance (X) of a circuit is the sum of the inductive and capacitive reactance:

$$X = 2\pi f L + \left(-\frac{1}{2\pi f C}\right) = X_L + X_C$$

- If there is no capacitance in the circuit, the total reactance is equal to the inductive reactance.
- If there is no inductance in the circuit, the total reactance is equal to the capacitance reactance.

4.2.1 **Table 11: Resistance and Reactance of Portable Power Cables**

Conductor Size (AWG or kcmil)	R[*ac*][1] Ohms/1000 Ft.		X_L [60*Hz*][2] Ohms/1000 Ft.					
	75°C	90°C	2 kV[3] G-GC, G + GC	2 kV[3] SHD-GC	5 kV SHD-GC	8 kV SHD-GC	15 kV SHD-GC	25 kV SHD-GC
8	.838	.878	.034	—	—	—	—	—
7	.665	.696	.033	—	—	—	—	—
6	.528	.552	.032	.038	.043	—	—	—
5	.418	.438	.031	.036	.042	—	—	—
4	.332	.347	.031	.035	.040	.043	—	—
3	.263	.275	.031	.034	.039	.042	—	—
2	.209	.218	.029	.033	.038	.040	.044	—
1	.165	.173	.030[3]	.033	.036	.039	.042	.046
1/0	.128	.134	.029	.032	.035	.037	.040	.044
2/0	.102	.107	.029	.031	.034	.036	.039	.043
3/0	.081	.085	.028	.030	.033	.035	.038	.041
4/0	.065	.068	.027	.029	.032	.034	.036	.040
250	.055	.057	.028[3]	.030[3]	.031	.033	.036	.039
300	.046	.048	.027	.029	.031	.032	.035	.038
350	.039	.041	.027	.029	.030	.032	.034	.037
400	.035	.036	.027	.028	.030	.031	.033	.036
500	.028	.029	.026	.028	.029	.030	.032	.035
600	.023	.024	.026	.027	.028	.030	.032	.034
700	.020	.021	.026	.027	.028	.029	.031	.033
800	.018	.019	.025	.026	.028	.029	.030	.033
900	.016	.017	.025	.026	.027	.028	.030	.032
1000	.014	.015	.025	.026	.027	.028	.030	.032

[1] a. Sizes 8 AWG - 1 AWG based on tinned copper 94.16% conductivity.
b. Sizes 1/0 AWG and larger based on tinned copper 96.16% conductivity.
c. Resistance increased per ASTM B-172, Note 7, to compensate for stranding factor.
d. Skin effect calculated according to Arnold's Table, National Bureau of Standards.
e. Nominal cross-sectional areas.

[2] a. Based on conductor dimensions given for Class H Rope Lay conductors in ICEA S-75-381/NEMA WC 58.
b. Extruded strand thickness .015".
c. Insulation thickness according to nominals given in ICEA S-75-381/NEMA WC 58.

[3] a. Deviations from normal progression due to changes in insulation thickness for same voltage rating.

4.2.2 **Table 12: Resistance and Reactance of Mine Power Feeder Cables**

Conductor Size (AWG or kcmil)	R[*ac*][1] Ohms/1000 Ft.	X_L [60*Hz*][2] Ohms/1000 Ft.			
	90°C	5 kV MP-GC	8 kV MP-GC	15 kV MP-GC	25 kV MP-GC
6	.510	.041	.044	—	—
5	.404	.040	.042	—	—
4	.321	.038	.041	—	—
3	.254	.037	.039	—	—
2	.201	.036	.038	.042	—
1	.160	.035	.037	.041	.044
1/0	.127	.034	.035	.039	.043
2/0	.101	.033	.034	.038	.042
3/0	.080	.032	.033	.036	.040
4/0	.063	.031	.032	.035	.039
250	.054	.030	.031	.034	.038
300	.045	.029	.031	.034	.037
350	.039	.029	.030	.033	.036
400	.034	.029	.030	.032	.035
500	.027	.028	.029	.031	.034
600	.023	.028	.029	.031	.033
700	.020	.027	.028	.030	.032
800	.017	.027	.028	.030	.031
900	.016	.027	.027	.029	.031
1000	.014	.026	.027	.029	—

[1] a. Based on bare copper 100% conductivity.
b. Nominal cross-sectional areas.
c. Resistance increased by increments per ASTM B-8 to compensate for stranding factor.
d. Skin effect calculated according to Arnold's Table, National Bureau of Standards.

[2] a. Based on conductor dimensions given for Class B Concentric Stranded conductors in ICEA S-75-381/NEMA WC 58.
b. Extruded strand shield thickness .015".
c. Insulation thickness according to nominals given in ICEA S-75-381/NEMA WC 58.

4.3 Voltage Drop

Load current, power factor and impedance of the conductor all affect voltage drop. Generally, capacitance can be neglected in distribution circuits because its effect on voltage drop is negligible for the circuit lengths and operating voltages used. A major point in circuit design is to determine the proper size of conductor that will carry the current load without exceeding a specified voltage drop.

In a balanced 3-phase circuit, the drop in phase voltage is 1.73 times the drop in each conductor when they are treated as a single-phase circuit with no return wire.

$$\text{V drop} = 1.73\, IZ \cos(\Phi - \Theta)$$

Where: **I = amperes in each conductor**

Z = ohmic impedance of one conductor

Φ = impedance angle

Θ = power factor angle

See 4.2.1 Table 13.

4.3.1 Table 13: Approximate Voltage Drop Factors at 90°C and 75°C Conductor Temperatures

Three Conductor Cables at 90°C Conductor Temperature **60 Hertz Phase-To-Phase Voltage Drop Per Ampere Per 1000 ft at Power Factors of:**			
Conductor Size (AWG/kcmil)	**80%**	**90%**	**100%**
6	0.82	0.90	0.95
4	0.54	0.58	0.60
2	0.35	0.38	0.38
1	0.29	0.31	0.30
1/0	0.24	0.25	0.24
2/0	0.20	0.20	0.19
3/0	0.16	0.17	0.15
4/0	0.14	0.14	0.12
250	0.12	0.12	0.10
300	0.11	0.11	0.08
350	0.10	0.09	0.07
400	0.09	0.08	0.06
500	0.08	0.07	0.05
Three Conductor Cables at 75°C Conductor Temperature **60 Hertz Phase-To-Phase Voltage Drop Per Ampere Per 1000 ft at Power Factors of:**			
Conductor Size (AWG/kcmil)	**80%**	**90%**	**100%**
6	0.76	0.83	0.85
4	0.50	0.54	0.55
2	0.33	0.35	0.35
1	0.27	0.28	0.28
1/0	0.22	0.23	0.22
2/0	0.18	0.19	0.17
3/0	0.15	0.15	0.14
4/0	0.13	0.13	0.11
250	0.11	0.11	0.09
300	0.10	0.09	0.08
350	0.09	0.08	0.07
400	0.08	0.08	0.06
500	0.07	0.06	0.05

4.4 Voltage Regulation

Voltage regulations are expressed as follows:

$$VR = \frac{E_s - E_r}{E_r} \times 100\text{, percent}$$

Where: **VR = voltage regulation in percent**

E_S = sending-end voltage to neutral in volts

E_r = receiving-end voltage to neutral in volts

The relationship between E_s and E_r is expressed by:

$E_S = E_r + I_rZ$ (vectorially)

E_S = as above

E_r = as above

I_r = receiving-end current per conductor, amperes

Z = total series impedance per conductor, ohms

The permissible variation in voltage depends to a considerable extent on the kind of service being supplied. It must be kept within practical limits in order to obtain proper candle power and life from lamps and proper efficiency, torque, power factor, etc., from motor loads. Voltage regulation may usually be kept within desirable limits normally not over 5 percent by insuring low resistance and reactance of the lines and feeders. If this is impractical, special apparatus must be installed to regulate voltage.

The National Electrical Code (NEC) recommends maximum voltage drops of 3% for power loads and 1% for lighting loads.

4.5 Improving Voltage Regulation

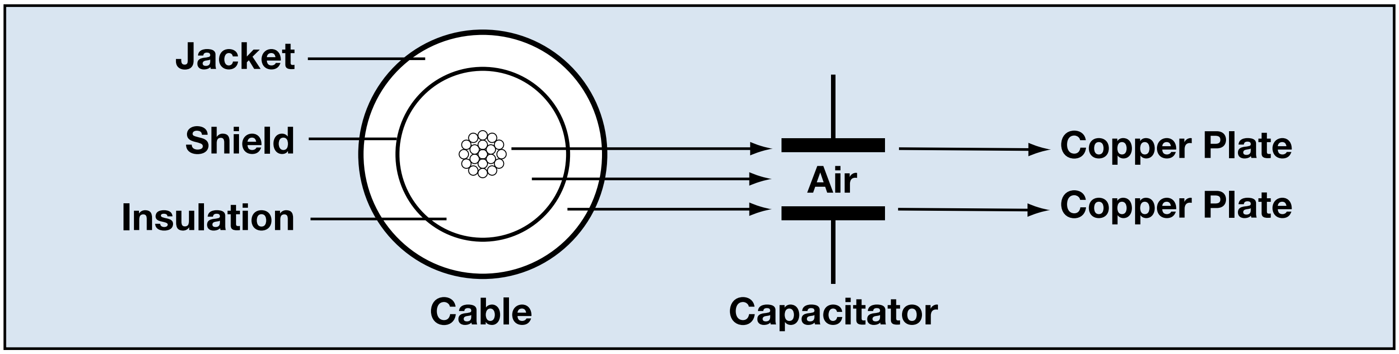
- Use a larger conductor size
- Reduce conductor spacing
- Paralleling circuits
- Improve power factor

SHIELDING 5

5.1 Cable as a Capacitor

A capacitor is an electrical device consisting of two conducting surfaces separated by insulating material (dielectric) such as air, paper, oil or rubber. A shielded cable operates as a capacitor with the insulation as the dielectric and the shield as the other conducting surface. This must be taken into consideration during cable design and application.

5.1.1 Figure 1: Cable as a Capacitor



The following characteristics of a capacitor are related to shielded cable:

- **A capacitor stores electrical energy.** The SIC (specific inductive capacity) of insulation is determined by comparing the amount of energy an insulated cable (capacitor) can store to the amount of energy stored by a capacitor using air (in a vacuum) as the insulator.

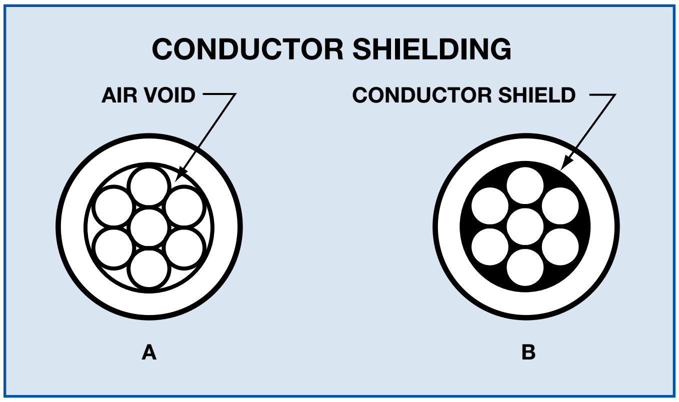
  For example, if a certain air capacitor has a measured capacitance of one µF (microfarad), but the measured capacitance is 3 µF when the air is replaced with insulation, then the insulating material has a SIC of about 3. SIC is also referred to as dielectric constant and permittivity. For a capacitor designed to store energy, a high SIC is desirable. For a cable that transports electricity, a low SIC is needed. For 600 Volt cables, the SIC is generally kept below 7. For 15kV cable, the SIC should be below 4. Cable above 15kV should have the SIC value kept as low as possible.

- **A capacitor permits the flow of alternating current.** The amount of ac flow is dependent on the SIC of the insulation and the frequency of the current. In cable design, ac flow should be kept in mind when determining whether or not to shield, the type of grounding method, the cable size, the conductor spacing and the geometry of cable.

5.2 Shielding and Stress Relief in Insulated Cable

Conductor stress relief (conductor shielding) functions to eliminate stress between the conductor and the insulation. To be effective, the conducting layer must adhere to, or remain in intimate contact with, the insulation. 5.2.1 Figure 2A shows an air gap between the conductor and the insulation. The voltage stress across the air gap can cause ionization of the air and result in deterioration of the insulation. 5.2.1 Figure 2B shows extruded shielding around the conductor. This layer presents a smooth round electrode (precluding excessive gradients due to physical irregularities) that has the same electrical potential as the conductor and is bonded to the insulation so there is no ionization within the cable.

5.2.1 Figure 2: Conductor Shielding



5.3 Functions of Insulation Shielding Systems

Shielding systems work to confine the dielectric field to the insulation. Without proper shielding, the electrical stress can cause deterioration of the insulation and danger of electrical shock.

There are three principal functions of a shielding system:

5.3.1 To Eliminate Non-Symmetrical Electrical Stresses

Power cables are subjected to radial tangential or longitudinal voltage stresses. Radial stresses are always present in cable insulation when the cable is energized. Insulation is most efficient when the electrical field is uniformly distributed around the conductor and within the envelope of the cable insulation. Non-uniform distribution of the dielectric field results in increased radial stress in portions of the insulation and less efficient usage of the insulation as a whole.

Shielding systems applied over the insulation of the individual conductors remove the fillers from the dielectric field, leaving a symmetrically distributed radial stress. This utilizes the insulation to its greatest efficiency and in the direction of its greatest strength.

One of the basic laws of electric fields states that voltage applied across dielectrics in series will divide in inverse proportion to the dielectric constant on the material. Thus, when an air gap is in series with the cable insulation, a portion of the voltage will appear across the gap. The surface of the insulation or cable will then have a voltage to ground equal to the voltage across the gap. This voltage can approach the full conductor potential when the air gap is large and will approach ground potential when the surface is in contact with a grounded surface. This phenomenon gives rise to tangential and longitudinal stresses.

Tangential stresses are always associated with non-uniform radial stress. They occur in multi-conductor cables when the individual conductors are not shielded and in all single conductor non-shielded cables installed so that non-symmetrical relations exist between conductor and adjacent grounded surfaces.

Longitudinal stresses are not necessarily associated with non-uniform radial stress but are always apparent with radial stresses of different magnitude along the length of the cable. These stresses occur in non-shielded cable installed so that intermittent contacts or variable spacings exist between the cable surface and grounded objects. Examples include metal conduits, steel supports or cable brackets, local conducting areas and wet spots in ducts.

The proper application of an external shielding system will eliminate tangential and longitudinal stresses by bringing the entire surface to ground potential.

5.3.2 To Provide a Definite Capacitance to Ground for the Insulated Conductor

Cables which are laid in ducts or directly in the earth will often run through sections of dry and wet soil or ducts having varying electrical characteristics. This results in varying electrostatic capacity to ground, hence a change in the surge impedance of the cable. In addition, cables entering metallic ducts or risers will have a change in impedance due to varying capacitance to ground.

In cables connected to overhead lines, traveling waves caused by lightning or induction from charged clouds or fog drifts will be partially reflected at points of change in the surge impedance. This will result in further build-up of the surge voltage in the cable, which may cause breakdown of the insulation. In some cases where cables run through very dry ground, traveling waves may be induced by direct induction from the clouds.

The application of a shielding system over the insulation of individual conductors or the assembly of a multi-conductor cable reduces these surge potentials. A shield over the insulation of individual conductors functions by:

a. creating a uniform capacitance from conductor to ground, resulting in a uniform surge impedance along the cable, thus preventing partial reflections and the consequent build-up of the surge voltages within the cable.

b. providing maximum capacitance from conductor to ground, thereby effecting the maximum reduction of the incoming surge potential.

c. absorbing surge energy in the same manner as the conductor by reason of the current induced magnetically in the shield.

d. reducing stress on the insulation under many circuit arrangements, because surge potential will momentarily exist on both conductors and shield.

A shielding system applied over the multi-conductor cable assembly is somewhat less effective with respect to points (a) and (c). Although it does not provide the maximum capacitance (b), it is an improvement upon non-shielded, non-metallic-covered cables and is probably equal to individual shield for (d).

5.3.3 To Reduce the Hazard of Both Shock and Danger to Life and Property

As explained in 5.3.2, when the outer surface of the insulation or covering of insulated cables is not in contact with ground throughout the entire length of the cable, a considerable potential difference may exist between the covering and the ground. This may create a hazard for the following reasons:

a. Contact with the covering may induce panic or fear, resulting in hazards to life such as falls, or other secondary factors, even though the electrical shock may not be lethal.

b. Contact with the covering under unusual conditions may be a hazard to life by electrical shock if the charging current from a considerable length of cable is carried by the covering to the point of contact. This might occur, for instance, with a heavily contaminated damp cable surface.

c. The potential difference may cause sparking, which could result in the ignition of explosive gas mixtures in tunnels or duct systems.

A properly grounded shielding system will confine the dielectric field to the insulation and eliminate these hazards. To obtain full benefit, the shield should be applied over the insulation of individual conductors. An additional safety factor is derived from shielding by providing a path to ground; this reduces the hazard to workmen who may accidently drive a pick or other tool into the energized conductor of the cable.

See 5.11.1 Table 14 for different types of shielding systems.

5.4 Insulation Stress Relief (Insulation Shielding)

Shielding systems consist of a semi-conducting layer or an extruded layer of electrically conducting material over the insulation in conjunction with a metallic, non-magnetic tape, wire, or braid. The stress-relief portion (inner layer) of the system must adhere to the insulation under all conditions. It and the metallic portion serve as a current-carrying medium for charging and leakage currents.

The shielding system should operate at or near ground potential at all times. Shielding which does not have adequate ground connection is more hazardous from a safety standpoint than non-shielded cable. An under-grounded or “floating” shield can cause electrical failure of the cable, and if the potential on such a shield penetrates the outer jacket, the resultant discharge can result in an extreme shock hazard. To minimize the possibility of open sections in the shielding system, use a trailing cable design that has the grounding conductor laid in intimate contact with the insulation shielding throughout the length of the cable.

5.5 Stress-Relief Cones

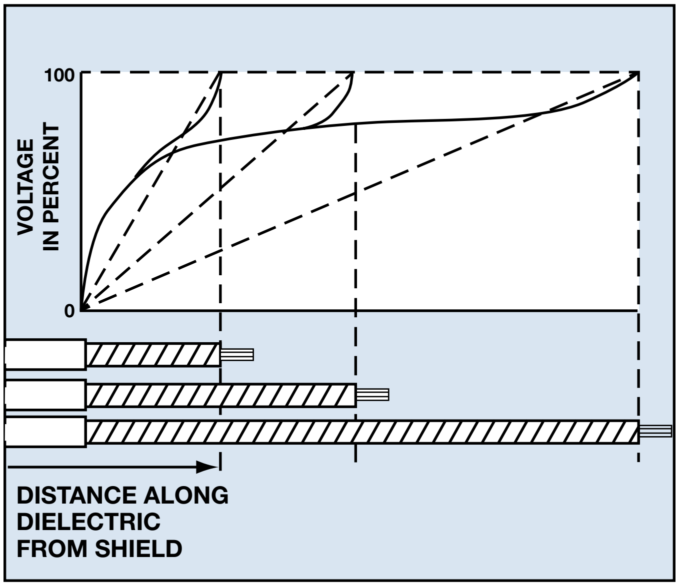
A stress-relief cone is important in relieving the area of concentrated stress at the end of a grounded shield. This stress occurs because of the potential difference between the surface of the insulation without shielding and the surface, which is still shielded.

A stress-relief cone relieves the stress, but it does not **eliminate** it. Even a well-designed stress cone has areas of stress concentration, but the conditions will be tolerable.

The shielding system must be removed completely and proper stress-relief cones made at all shield terminations. If all elements of the shield are not removed, excessive leakage current, tracking and flashover may result.

When determining the removal distance of grounded external shielding, remember that the voltage gradient between the end of the conductor and the shield terminus is extremely non-linear. The longitudinal and radial stress concentration at the edge of the shield diminishes only slightly as the axial length of shielding system removal is increased. 5.5.1 Figure 3 clearly illustrates that the voltage gradient at the shield edge is the same (for graphing purposes) for three terminations with different removal distances.

5.5.1 Figure 3: Voltage Gradient vs. Distance along Dielectric from Shield

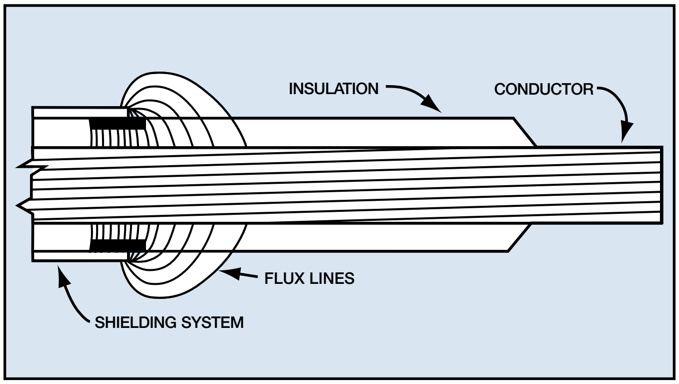


5.6 Concentrated Stresses

The voltage gradient between the end of the conductor and the edge of the shielding system is non-linear and, for all practical purposes, independent of removal distance. One of the primary purposes of shielding in cables is to achieve uniform radial stress distribution so that all flux lines extend from the conductor to the grounded metallic shield.

5.6.1 Figure 4 shows the stress distribution at the edge of the shielding. For the portion of the conductor beyond the edge of the shield, the shielding tape is still the nearest component at ground potential, and all electrical flux lines concentrate at this shield edge. Under such conditions, this is the weakest point in the cable circuit and electrical failure can result either radially or longitudinally at this location unless measures are taken to reduce these electrical stresses.

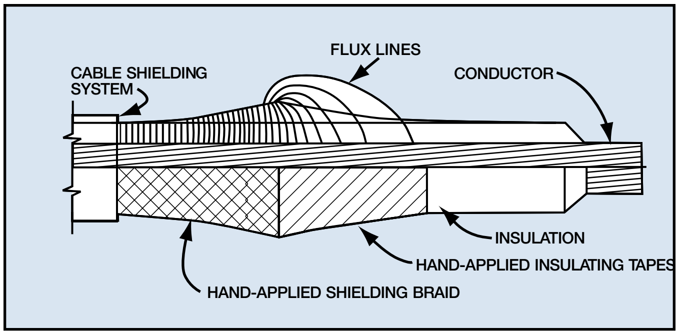
5.6.1 Figure 4: Stress Distribution at Edge of the Shielding System



5.7 Stress-Relief Mechanism

5.7.1 Figure 5 illustrates a conventional stress-relief cone made of hand-applied insulating tapes and shielding braid. This simple mechanism relieves the high concentration of stress at the cable shield terminus by providing a gradual transition. The cone does not completely eliminate the stress but reduces it below the limits of trouble-free cable operation.

5.7.1 Figure 5: Conductor Stresses



5.8 Extruded Stress-Relief Layer

The use of conducting extruded layer as part of the shielding system has gained acceptance through three contributing factors:

1. Cable Acceptance

   Extruded conducting compounds used over the insulation have proved to have distinct advantages over tape bedding. Conducting compounds are not susceptible to the deterioration of fabric tapes and are not limited to the decreased physical protection of tape. Conducting compounds have also had an excellent performance record over a wide range of cable environments and locations.

2. Rigorous Requirements for Corona Levels

   Corona level testing determines voids in conductor/insulation interface and insulation surface/shielding system interface. Because fabric tapes have a wide range of limitations in conductivity, splices, fiber ends, uneven tensions and tape laps, there is a difficulty in obtaining a consistent, smooth interface which reduces voids. Conducting compounds suffer from none of these variables and have proven to be far less likely to develop voids.

3. Intimate Contact With Insulation Surface

   Conducting insulation shield or extruded stress-relief layers provide smooth round electrodes and intimate contact with the insulation. It is able to match the expansion characteristics of the insulation, which prevents the formation of voids.

   Extruded conducting compounds are available in thermoplastic and thermosetting types. The choice is dependent on cable type, thermal rating, emergency and short-circuit ratings.

Following are some factors that characterize both types:

Thermoplastic Conducting Compounds

- Deforms at elevated temperatures
- Sharp increase in resistance at higher temperatures
- Not inherently flame resistant
- Does not subject insulation to vulcanization or cross-linking
- Adhesion control is possible for easy stripping
- Good performance record in a variety of applications

Thermosetting Conducting Compounds

- Excellent deformation characteristics
- Consistent in resistant characteristics over temperature range
- Not inherently flame resistant
- Requires heat for cross-linking, can cause conductor drift and very tight bond with insulation

5.9 Applications of Shields

Association of Edison Illuminating Companies (AEIC) and Insulated Cable Engineers Association (ICEA) offer shielding guidelines and recommendations. It may be difficult to determine when a shield is absolutely required, but a properly installed shielded cable will always offer the maximum in safety and reliability. The shielding system must always operate at or near ground potential.

5.10 Effects of Shield Loss on Ampacity

The purpose of a cable insulation shield is to confine electrostatic stresses to a definite pattern and provide a fixed path of grounding for cable charging and leakage currents. When a cable carries current, there is an electrostatic and a magnetic field. The cable shield confines the electrostatic field but **not** the magnetic field.

The magnetic field affects the current density in adjacent conductors and induces voltage in nearby metallic objects. If metallic circuits in the cable, or metal nearby, form a closed electrical path, there will be I^2R losses. The losses that occur in these "external" circuits are felt in the electrical characteristics of the cable, particularly if the object is made of magnetic material which will increase power loss by hysteresis effects.

Three single conductor cables laid in an equilateral triangular configuration will experience losses based on this formula:

$$X_m = 52.92 \text{ Log } \frac{S}{r}$$

Where: **X_m = micro-ohms per foot of cable**
S = spacing between centers of cables in inches
r = radius of cable shield in inches

If the cable shields are open circuited (i.e., they are grounded at only one place and they are not in contact with each other at any one point), the voltage induced in one of them is:

$$V_s = IX_m$$

Where: **V_s = micro-volts per foot, to neutral**
I = current in conductor, amperes
X_m = micro-ohms per foot of cable

If cable shields are grounded at both ends, the electrical circuit is complete, and a current flows as a result of V_S. The power loss due to this current is:

$$W_s = I^2R_s \quad \frac{X_m{}^2}{R_s{}^2/X_m{}^2}$$

Where: **W_s = micro-watts per foot per cable**
R_s = shield resistance in micro-ohms per foot
I = current in conductor, amperes
X_m = micro-ohms per foot of cable

On a three-phase system, the total shield loss is approximately three times the above value.

Inductive losses make the use of large single conductor leaded or armored cables impractical. The low resistance of these coverings causes excessive losses that reflect back to the conductor as an increase in impedance. This results in an excessive voltage drop in the cable circuit.

One advantage of a three conductor cable is the 120-degree phase difference between the conductor currents, which results in a partial cancellation of the magnetic field around the three conductor cable. This reduces the losses in the shield to a tolerable level. The impedance of a three conductor cable is less than the impedance of three single conductor cables of a corresponding size.

5.11 Dielectric Constant

The Dielectric Constant of a material is defined as the ratio of the amount of energy that a given capacitor with insulating material between its plates can store to the amount of energy that the same capacitor can store when it has air between its plates. In the cable industry, the Dielectric Constant of a material is referred to as Specific Inductive Capacity (SIC).

If one plate of a capacitor is bent into a circle and the other plate is stretched and then wrapped concentrically around the first, it is a capacitor and the cross-section of a shielded cable. Obviously, whenever a shielded cable is made, a capacitor is also made.

In the case of a shielded, single conductor cable, the size of this capacitor is:

$$C = \frac{7.354Le}{Log\,(D/d)}$$

Where: **C = picofarads**
L = length of cable in feet
e = SIC of insulation
D = outside diameter of insulation
d = inside diameter of insulation

Whenever an ac voltage is applied across a capacitor, a current will flow. In a power cable, this is referred to as the charging current. The magnitude of this current per thousand feet of cable is:

$$I = \frac{2{,}772.46\,(kV)e}{1{,}000{,}000\,Log\,(D/d)}$$

Where: **I = amperes**
kV = kilovolts between conductor and shield
e = SIC of insulation
D = outside diameter of insulation
d = inside diameter of insulation

There are two sources of current in the shield of a cable: 1) the current that is due to the inductive coupling with the conductor and is a function of the conductor current, and 2) the current which results from the capacitive coupling between the conductor and the shield, which is dependent upon the voltage that exists between the conductor and the shield.

The current flowing in the shield and the shield resistance losses show up as heat, similar to losses and heat due to current in the phase conductor.

The ampacity of a cable is dependent on the amount of heat generated in a cable and the dissipation rate of the heat to the cable surroundings. Once the surroundings have been chosen, the amount of heat dissipation is fixed, as is the amount that the cable can be allowed to generate. Any heat that the shield generates must be subtracted from the amount that would otherwise be allotted to the phase conductor. This reduces ampacity.

The greater the shield losses, the higher the economic loss. In essence, excessive shield loss translates into **paying a premium to obtain less cable capacity.**

5.11.1 Table 14: Shielding Systems

Solid Dielectric Cables		
Shielding System	**Advantages**	**Disadvantages**
Non-Magnetic Copper Tape Shield	(1) Effective electrostatic shield (2) Consistent and controlled electrical properties (3) Universally accepted – reliable standard for comparison	(1) Difficult to apply tapes without wrinkling (2) Requires semi-con bedding layer to insure intimate contact and high corona resistance (3) Vulnerable to damage during installation (4) Relatively high cost (5) Cutting of tapes during splicing and termination requires considerable skill and careful handling
Semi-Conducting Extruded Layer With Concentric Metallic Drain	(1) Effective electrostatic shield (2) Combination of semi-con layer with drain wires insures both intimate contact with insulation and controllable electrical properties (3) Easy to add capacity with extra or larger wires	(1) Requires caution during installation to prevent displacement of wires (2) Should not be used in contact with oil (3) External wires vulnerable to corrosion (4) Design balance to control shield losses critical for top efficiency in three-phase operation
Flexible Nylon/Copper Braid Over Semi-Conducting Tape	(1) Effective electrostatic shield (2) Provides additional grounding conductor capacity in type SHD cables (3) Good shock hazard protection	(1) Extensive flexing lowers corona extinction levels (2) Shield losses relatively high
Flexible Full Copper Braid Over Semi-Conducting Tape	(1) Effective electrostatic shield (2) Provides additional grounding conductor capacity in type SHD cables (3) Good shock hazard protection	(1) Extensive flexing lowers corona extinction levels (2) Shield losses higher than nylon/copper (3) Broken shield wires button-hook, producing possible insulation penetration

INSULATION AND JACKET STABILITY 6

6.1 Partial Discharge Resistance

Partial discharge is the name given to the corona phenomenon by power cable engineers. Corona, or partial discharge, is a very complicated phenomenon and not easily defined. Below are a few accepted facts that outline the characteristics of partial discharge:

- Ozone resistance is not synonymous with partial discharge resistance; they are separate phenomena.
- Extinction level is the voltage point where partial discharge disappears.
- Voids within the insulation, between insulation and the conductor shield, or between insulation and the insulation shield can cause partial discharges.
- Extruded strand shields with smooth surfaces and a bond to the insulation will virtually eliminate partial discharge at the interface.
- Keeping insulation voids to a minimum will drastically reduce partial discharge.
- Intimate contact between the outer surface of the insulation and the shielding system will reduce partial discharges.

A few factors can minimize partial discharge. Consider these when specifying insulated cable:

- Choose insulation with a high degree of resistance to partial discharge.
- Design the cable to incorporate features that facilitate the partial discharge extinction level.
- Use processing techniques that minimize voids.

6.2 The Major Prerequisite of Insulated Cables

An insulated cable has one purpose – to transmit power. To achieve this at the highest possible levels, the characteristics of the insulated cable must remain stable and predictable. The environments that affect performance levels can be divided into four areas:

- **Physical environment** affects cable installation and its actual operation. Severe bending, compression, cutting abrasion, and excessive tension can all contribute to damage which reduces the reliability of a cable installation.
- **Chemical environment** affects the cable components. Chemical environments such as free chlorine, oil, ozone, etc., can influence the choice of materials for insulations and jackets.
- **Thermal environment** can affect the degradation of insulation and jackets at elevated levels since the speed of a chemical reaction is doubled with a 10°C rise in temperature.
- **Electrical environment** that causes magnetic and static fields can result in data logging control cable interference.

The environments should be taken into consideration whenever specifying material and cable design. Thought-out choices allow a balance between economy and sound engineering.

6.3 Ozone Resistance

Similar to an oxygen molecule (O_2) in chemical structure but containing one more atom of oxygen (O_3), ozone is a gas with a pungent characteristic odor. Ozone can be produced anywhere a combination of air and an electrical discharge is present and is usually encountered in diluted form mixed with air.

Cable problems related to ozone are most likely to occur at voltages above 5kV; however, 2kV cables can also be attacked if they are in an environment where ozone is being generated. Ozone and cable coverings share an interesting history. The chemical nature of ozone is such that it is capable of deteriorating virtually every extruded type of cable covering used in the industry. For many years, the most practical method of obtaining some degree of ozone resistance in cable insulation was to incorporate a substantial quantity of polymerized oil or factice into the compound. The disadvantage of obtaining ozone resistance in this fashion is a significant sacrifice of heat aging resistance, low-temperature flexibility and physical strength.

Ozone attack of cable covering is more easily understood if the **basic polymer** is considered as a **discrete and identifiable chemical.** The major component in polymers is a chain of carbon atoms. How these carbon atoms are linked is the determining factor in predicting ozone resistance.

In some polymers like polyethylene and the ethylene-propylene types, the carbon-to-carbon link or bond in the main chain looks something like the following:

(-C-C-C-C-)

This arrangement provides excellent ozone resistance.

Many polymers like SBR, Neoprene and natural rubber have a carbon-to-carbon linkage or bond that looks like this:

(-C-C = C-C-)

Notice there is a double bond between two of the carbons. This is the location where ozone attacks and reacts, splitting the carbon chain and resulting in radial cracks in the cable covering. The more of these double bonds present, the more quickly the deterioration in the presence of ozone, limiting polymers of this type to 600 Volt service.

EPR and XLPE are the leaders in medium-voltage insulations with inherent or built-in ozone resistance. EPR and XLPE contain a limited number of double bonds, virtually all of which are used up in the vulcanizing process. The resulting compound has a high degree of ozone resistance without sacrificing important properties.

General Cable's Technology Center monitors polymer innovations and the development of built-in ozone resistance. Some of the better ozone-resistant jackets on the market include CSPE and CPE.

6.4 Jacket — Physical Toughness

For most industrial power cables, the durability of protective sheaths or jackets is secondary to electrical stability but still an important part of a cable system. However, for mining cables, the jacket durability is more important than electrical stability. Over 90% of cable failure can be traced to physical damage to the cable in handling, installation or service. Cable is laboratory- and field-tested for the following factors of physical toughness:

- **Compression-cut** is the result of a crushing load that ruptures the insulation and/or jacket. The conductor can act as a cutting tool.
- **Impact damage** occurs upon impingement. The degree of damage is dependent upon the foot-pounds of force and the size of the area impinged.
- **Tearing** is caused in cables that are pulled over rough terrain having sharp rocks or other obstructions.
- **Abrasion** is rare in industrial power cables but occurs readily in mining applications.
- **Deformation** is caused by excessive shearing stress and will be accelerated by high temperatures. Cable used in fill with large rocks is subject to the natural shearing stress of the earth's movements.

6.5 Jacket — Hardness

The hardness of the cable jacket can be indicative of the health of the insulation and jacket. Hardness is usually measured with a Shore Durometer; for example, a mining-grade synthetic rubber jacket in good condition would show a Shore A hardness of 65-75. If the jacket goes to 90, it's a good indication that it has been exposed to elevated temperatures and is becoming brittle.

Elevated temperatures or a loss of plasticizer increase hardness, while a decrease in hardness signals cable deterioration. An excessive hardness increase or decrease is a sign that a problem is occurring.

6.6 Thermal Stability and Heat Resistance

Heat resistance is a major component of thermal stability, cable longevity and reliability. By reviewing the properties of insulation that affect heat resistance, it is easier to make cable specifications that will offer true thermal stability and facilitate service life predictions.

- **Heat aging** is tested by exposing insulation to air oven, oxygen bomb and air pressure heat test (APHT). Noting whether a material gets brittle or softens during these tests gives good insight to polymer choice and compounding ingredient control.
- **Deformation** of the insulation under stress or high loads should not occur to an excessive degree. In general, thermoplastic insulations deform more readily than thermosetting compounds at high temperatures. At temperatures over 100°C, even thermosetting compounds will show differing degrees of deformation. The polymer insulation that shows the least deformation should be considered the most stable.
- **Creep** is the dimensional change of a material under load over a given time. In vertical riser cable and terminations, creep could be a very serious problem. Insulation with zero creep is considered to be extremely stable.
- **Thermal expansion** is the fractional change in length or volume of a material related to a unit change in temperature. Cables used for alternating heavy and light current loads will be subject to expansion and contraction. If the expansion is excessive, the integrity of the overall design can be disrupted, and cable failure is accelerated. Thermal expansion stability is measured by cyclic aging tests.
- **Physical properties** of insulation, such as tensile strength and cut resistance, can be reduced dramatically by repeated exposure to elevated temperatures. The insulating compound that retains the greatest degree of its properties after high temperature aging should be considered the most stable.

- **Electrical EP rubber properties** are also affected by high temperatures. However, most insulations are designed to remain stable through a variety of temperatures.

6.7 Moisture Penetration

Cables absorb water at a rate determined by the ambient water temperature, conductor temperature, cable insulation temperature, and the permeabilities of the cable jacket and insulation. The usual method for determining moisture resistance properties is a gravimetric measurement of the moisture absorbed by an insulation after seven days in hot water. The value is reported in mg/in^2.

While gravimetric measurements show the amount of moisture absorbed, there is only one factor when determining the correct insulation for wet environments. Some insulations, such as EPR, will show a high moisture gain but actually have a higher probability of wet environment survival when voltage is applied.

Measurements of the maximum flow rate into unloaded 15kV cables in various water temperatures are shown below:

6.7.1 Table 15: Moisture Transmission

Milligrams Per Foot Per Day			
Insulation	**50°C**	**75°C**	**90°C**
PE	3	10	42
XLPE	6	14	63
EPR	11	25	110

The best insulation in a wet environment is the one that demonstrates intrinsic resistance to moisture-induced deterioration, as does EPR insulation in the Electrical Moisture Absorption test. In this test, insulated conductors are immersed in a 90°C water bath with continuous voltage stress applied. The cables are tested until dielectric breakdown occurs. In this test, which more closely resembles actual field service, EPR outlasts polyethylenes by a wide margin.

6.8 Sunlight Resistance of Cable Coverings

The continuous exposure of cable to weather is a major concern for cable engineers. All polymer-type coverings undergo degradation over time. Environment, installation and chemical composition of the polymer significantly influence longevity.

Sunlight is a serious and potent threat to wire covering. The ultraviolet band of sunlight promotes the oxidation of polymers and results in cracking, chalking and crazing. Cable coverings that incorporate 2-3% channel black dispersed in the polymer have proven to provide the best protection against sunlight deterioration.

6.9 ICEA Minimum Requirements for Mining Cable Jackets

6.9.1 Table 16: ICEA Minimum Requirements for CPE and CSPE Jackets

Physical Requirements	Heavy-Duty	Extra-Heavy-Duty
Tensile Strength, lbs. per square inch (The pull stress required to break a specimen)	1,800	2,400
Elongation, percent (The percentage increase in length of a material stressed in tension before rupture)	300	300
Tensile Stress @ 200%, psi (The tensile force needed to stretch a material to 200% of its original length)	500	700
Tear Resistance, lbs/in (The force required to initiate a tear in a material under specified conditions)	N/A	40

6.9.2 Table 17: ICEA Minimum Requirements for Thermoplastic Polyurethane Jackets

Physical Requirements	TPU
Tensile Strength, lbs. per square inch (The pull stress required to break a specimen)	3,700
Elongation, percent (The percentage increase in length of a material stressed in tension before rupture)	400
Tensile Stress @ 200%, psi (The tensile force needed to stretch a material to 200% of its original length)	800
Tear Resistance, lbs/in (The force required to initiate a tear in a material under specified conditions)	80

FLEXIBILITY AND FLEX LIFE 7

Cable flexibility is a relative term; there are no real standards of comparison. In the past, cable coverings were manufactured from natural rubber (a material that is inherently flexible) and had to be specially processed to achieve rigidity. Today, cable coverings are made of polymer compounds that are by nature semi-rigid. This major difference in cable-covering technology has led to new ways to judge cable flexibility — but the best guide is still personal judgment and choice.

The flexibility of the copper wires is often offset by the flexibility of the cable insulation and jacket. Even reducing the size of individual wires may not mean the cable becomes more flexible, especially if the cable covering is harder to bend than the wires it is protecting.

The primary advantage of a flexible cable is its ease in handling. Rarely is cable faulted because it is too flexible, so the judgment becomes how flexible does it need to be? By taking the following advantages of flexibility into consideration, you should be able to weigh that against your rigidity needs to make a sound judgment.

The more flexible the cable:

- the easier to handle during reeling and the less likely to sustain damage
- the easier to train into position, which subsequently saves space
- the easier for craftsmen to work with, which leads to timesaving and safe working practices

7.1 Low Temperature Flexibility

All polymers have a tendency to become progressively stiffer as they are cooled. Cable difficulty occurs when two conditions are reached:

- Cable coverings become too stiff to be functional.
- Cable coverings become brittle or will shatter under impact.

The ability of a cable to withstand impact at a low temperature is a prime factor to consider during application or installation in northern areas. A cable which can be bent successfully under a low temperature may shatter under impact at a significantly higher temperature.

In general, XLPE, EPR, and CPE all have excellent low-temperature resistance properties rated to -50°F. General purpose CSPE and PVC compounds have passed cold bend tests in the -22°F to -40°F range.

The overall choice for a range of temperature applications is CPE. In laboratory tests, it showed superiority in respect to physical properties at elevated, room and sub-zero temperatures.

7.2 Flex Life as a Function of Stress

The elastic limit of soft copper is safely figured at 10% of its breaking strength. The magnitude of stress applied to copper above the elastic limit decreases its flex life at an exponential rate. This is the basis for manufacturers' recommendations that portable cables not be subjected to tensile stresses above this limit.

7.3 Bending Radii

Cables are exposed to both electrical and physical environments. In a physical environment, a cable can be considered a machine and amenable to the laws of mechanics. The laws of torsion, shear, tension and compression forces can all be applied to cable technology and bending radius.

Mining cable conductors are composed of many wires. The number of wires in an AWG size is dependent on the ultimate application and is usually designated as Class A, B, C, G, H, K, etc. Note that the nearer the end of the alphabet, the greater the number of wires.

The recommended bending radius for a specific cable construction is related to, and dependent upon, the length of lay of individual components making up the construction. Maximum efficiency in a conductor composed of a number of wires is obtained only when all of these wires work together during bending, flexing or tension.

ICEA minimum recommended bending radii are standardized at a level to assure that working cable will not exceed a critical level, resulting in a non-uniform distribution of individual wire stress.

In the following chart, flex life data is shown for a 4 AWG conductor utilizing one bending radius less than the critical diameter (A) and one safely above (B).

7.3.1 Table 18: Flex Life

No. of Strands	2" Sheave	4" Sheave	Ratio [A/B]
7	203	415	.489
37	726	2008	.362
133	3055	13844	.221
259	6118	47987	.127
420	13820	187237	.074
1064	20925	500778	.042

Notice that even though the ratio of A to B decreases as the number of strands increases, the flex life increases significantly with the number of strands.

7.4 ICEA Recommendations

The ICEA minimum bending radius recommendations for portable cable are:

- Braid-shielded portable cables — 8 times the cable diameter
- Non-shielded portable cables — 6 times the cable diameter
- Flat non-shielded cables — 6 times the minor dimension
- Copper tape shielded cables — 12 times the cable diameter

8.1 Table 19: Product Matrix

Product Range Portable Cables	Anaconda® Brand Lead-Cured Mining-Grade Cable Types	Carol® Brand CV-Cured Industrial-Grade Cable Types
Type W Flat	2kV	—
Type G Flat	2kV	—
Type G-GC Flat	2kV	—
Type SHD Flat	2kV	—
Type W Round	2kV	2kV
Type G Round	—	2kV
Type G-GC Round	2kV	2kV
Type G plus GC	2 & 5kV	—
Type SHD-GC	2, 5, 8, 15 & 25kV	—
Type SHD plus GC	2 & 5kV	—
Type SHD-PCG Longwall	2 & 5kV	—
Mine Power Feeder		
Type MP-GC (XLPE/PVC)	8 & 15kV	—
Type MP-GC (EPR/CPE)	5, 8, 15 & 25kV	—

8.2 Table 20: Mining Cable Product Constructions

General Cable offers the broadest line of mining- and industrial-grade flexible power cables.

Construction	Carol® Brand Industrial-Grade Cables	Anaconda® Brand Mining-Grade Cables	Features and Benefits
Conductors:			**Bare Copper Conductor** • Flexible conductor for industrial and static applications • Cost-effective conductor designs where cable is not being subjected to repetitive movement **Tinned Copper Conductor** • Enhanced flex life and increased resistance to wire breakage during repeated movement • Additional corrosion resistance adds to service life
• Fully Annealed Bare Copper	X		
• Fully Annealed Tinned Copper		X	
Type MP-GC:			
• Fully Annealed Bare Copper		X	
Insulation:			**EPR Insulation** • Outstanding dielectric properties • Long life at temperatures rated from -40˚C to +90˚C • Excellent moisture and corona resistance • Flexible for ease of handling
• Premium-Grade EPR	X	X	
Type MP-GC:			
• Premium-Grade EPR		X	
• Premium-Grade XLPE		X	
Shielding: **Type SHD-GC and SHD Plus GC:**			**Tinned Copper/Textile Composite Braid Shielding** • Provides maximum shield flex life **Copper Tape Shielding (EIS)** • 100% coverage and added corona protection (EIS - Extruded Insulation Shield)
• Copper/Textile Braid		X	
Type MP-GC:			
• EIS/Copper Tape		X	
Grounding Conductors: **Type G:**			**Bare Copper Grounding Conductor** • Flexible conductor for industrial applications • Cost-effective conductor designs where cable is not being subjected to repetitive movement **Tinned Copper Grounding Conductor** • Enhanced flex life and increased resistance to wire breakage during repeated movement • Additional corrosion resistance adds to service life
• Covered Bare Copper	X		
• Covered Tinned Copper		X (Flat)	
Type G-GC:			
• Covered Bare Copper	X		
• Covered Tinned Copper		X (Flat)	
• Tinned Copper		X	
Type W:			
• Covered Bare Copper	X		
• Covered Tinned Copper		X	
Type SHD-GC:			
• Tinned Copper		X	
Type MP-GC:			
• Tinned Copper		X	
Ground-Check Conductors:			**Ground-Check Conductor** • Provides maximum reliability of the ground-check circuit in all round constructions • Insulated with high-strength polypropylene (Anaconda)
• Insulated Bare Copper	X	X (Round)	
• Insulated Tinned Copper		X (Flat)	
Jackets: **Round Constructions:**			**Heavy-Duty, Single-Layer Jacket** • Heavy-duty construction for non-critical applications and distribution cable • Good physical characteristics with high degree of resistance to cutting, abrasion and medium-duty flexing • Excellent general purpose industrial performance **Extra-Heavy-Duty, Two-Layer Reinforced Jacket** • Increased jacket tensile strength • Increased mechanical strength for high flex applications • Maximum mechanical protection against crushing and tearing • Maximum abrasion resistance • Preferred construction for mining machines
• CV-Cured, Single-Layer, Reinforced Chlorinated Polyethylene (CPE)	X		
• Lead-Cured, Two-Layer, Reinforced Chlorinated Polyethylene (CPE)		X (Round)	
Flat Constructions:			
• Lead-Cured, Chlorinated Polyethylene (CPE)		X (Flat)	
Type MP-GC:			
• Premium-Grade PVC		X	
• Lead-Cured, Chlorinated Polyethylene (CPE)		X	

*Anaconda® Brand Flat and Type MP-GC cables have an extra-heavy-duty, single-layer jacket.

8.3 Table 21: Mining Cable Application Guide

APPLICATION	CAROL® BRAND INDUSTRIAL GRADE CABLES	ANACONDA® BRAND MINING-GRADE CABLES
UNDERGROUND MINING APPLICATIONS		
Longwall Shearers		X
Shuttle Cars		X
Bridge Conveyors		X
High-Voltage Distribution		X
Cutting Machines		X
Loading Machines		X
Continuous Miners		X
Drills		X
Roof Bolters		X
Locomotives		X
Hydraulic Pumps		X
Sectionalized Portable Power		X
Borehole Cables		X
Pumps	X	X
Accessory Equipment	X	X
Two-Conductor Welding	X	X
Belt Drives	X	X
Hydraulic Power Packs	X	X
Belt Take-Ups	X	X
Battery Changers	X	X
Conveyor Feeder/Breakers	X	X
SURFACE MINING APPLICATIONS		
Drills		X
Stripping Shovels		X
Loading Shovels		X
Drag Lines		X
Pumps	X	X
Accessory Equipment	X	X

General Cable mining cables are manufactured in accordance with:

- ICEA S-75-381 Portable and Power Feeder Cables for Use in Mines and Similar Applications.
- CAN/CSA-C22.2 No. 96 Portable Power Cables, and certified by Natural Resources Canada.
- CAN/CSA-C22.2 No 96.1 Mine Power Feeder Cables.
- Mine Safety and Health Administration flame test requirements and accepted for listing by MSHA.

9.1 Engineering Information

Working Tension

The maximum working tension per conductor should not exceed 10 percent of the rated conductor strength. To determine the approximate tensile strength of the cable, multiply the total power conductor area (in^2) by 30,000 psi.

Bending Radius

The recommended Insulated Cable Engineers Association (ICEA) minimum bending radii are as follows:

- Braid-shielded portable cables — 8 times the cable diameter
- Non-shielded portable cables — 6 times the cable diameter
- Flat non-shielded cables — 6 times the minor dimension
- Copper tape shielded cables — 12 times the cable diameter

9.1.1 Table 22: Ampacity Correction Factors

Approximate for all cable voltages

Correction factors are listed below for various ambiant temperatures.

AMBIENT TEMPERATURE	CORRECTION FACTORS FOR INSULATIONS RATED AT:
°C	90°C
10	1.26
20	1.18
30	1.10
40	1.00
50	0.90

When cables are used with one or more layers wound on a reel, the ampacities should be derated as follows:

NUMBER OF LAYERS	MULTIPLY AMPACITIES BY
1	0.85
2	0.65
3	0.45
4	0.35

9.1.2 Table 23: Voltage Drop

Approximate for all cable voltages—
Three Conductor Cables

	90°C		
	60-CYCLE PHASE-TO-PHASE VOLTAGE DROP PER AMPERE PER 1,000 FT AT POWER FACTORS OF:		
SIZE (AWG or kcmil)	**80%**	**90%**	**100%**
6	0.82	0.90	0.95
4	0.54	0.58	0.60
2	0.35	0.38	0.38
1	0.29	0.31	0.30
1/0	0.24	0.25	0.24
2/0	0.20	0.20	0.19
3/0	0.16	0.17	0.15
4/0	0.14	0.14	0.12
250	0.12	0.12	0.10
300	0.11	0.11	0.08
350	0.10	0.09	0.07
400	0.09	0.08	0.06
500	0.08	0.07	0.05

9.1.3 Table 24: AWG-to-Metric Conversion Chart

SIZE (AWG)	mm^2	SIZE (AWG or kcmil)	mm^2
18	0.82	**1/0**	53.5
16	1.31	**2/0**	64.4
14	2.08	**3/0**	85.0
12	3.31	**4/0**	107.2
10	5.26	**250**	126.7
9	6.63	**300**	152.0
8	8.37	**350**	177.3
6	13.30	**500**	253.4
4	21.15	**600**	304.0
2	33.62	**750**	380.0
1	42.40	**1000**	506.7

9.2 Why and How Mining Cables Fail

Cable breakdowns are neither mysterious nor unaccountable and almost without exception can be traced to one or more of the following causes:

1. Excessive tension
2. Mechanical damage
3. Current overload
4. Improper splicing and termination techniques

Excessive Tension

Many cable failures are the direct result of excessive tension. A cable that has been "stretched" no longer has the balanced construction that is so vital to long life. Tension on the conductors subjects the individual wires in the strand to compression and shear. These thin wires are damaged and will break more easily when bent or flexed.

Tension also elongates the conductor insulation. The elongated insulation is then vulnerable to compression cutting. It will rupture more easily when it is crushed against the stranded conductor during runovers. The insulation will also have a tendency to creep over the conductor at a splice.

Jackets under tension lose a considerable part of their resistance to mechanical damage. A jacket under tension is much more likely to be cut or torn. Stretching also causes the copper conductors to take a permanent set. Of course, the insulation and jacket are stretched as well, but they will return to their original length when the tension is removed. This difference in the properties of rubber and copper when subjected to tension will cause the conductors to be wavy and fail prematurely.

To reduce tension on the cable:

1. Avoid backspooling, if possible.
2. If backspooling is unavoidable, locate the tie point as far back from the haulageway as possible.
3. Tram slowly when passing the tie point.
4. Set hydraulic tension on the cable reel so that approximately 12-15 feet of cable is picked up off the mine bottom when starting to tram.

Mechanical Damage

This is one of the most prevalent sources of trailing cable failures. Factors initiating mechanical damage include cutting, compression (crushing), punctures and abrasion. In extreme cases of mechanical damage, the failure is instant, and the cause can be assigned on the spot. Many times, however, the cable components are merely "injured" and become latent failures. At that point, it may be more difficult to pinpoint the exact cause and to take remedial action.

Current Overload

The temperatures of the conductors, insulation and jacket are, of course, elevated when cables are subjected to an electrical load. The resistance of the copper is increased, voltage drop in the cable is increased, and therefore, a reduced voltage is supplied to the machine. As a result, the machine calls for more current, which adds further to cable heating. A trailing cable's insulation and jacket materials exhibit maximum resistance to physical abuse at the rated conductor temperature of 90°C or less. The ability of these components to withstand damage decreases as the temperature increases. Conditions which normally cause few cable failures suddenly become a problem. At elevated temperatures, the jacket has lost much of its resistance to cutting, crushing, tearing and abrasion. The section of the cable that remains on the reel is most likely to be damaged by electrical overload. Layering on the reel hinders ventilation and heat dissipation. Continued exposure to elevated temperatures will age the jacket, making it hard and brittle and causing crazing or cracking upon subsequent reeling.

Improper Splicing and Termination Techniques

Over the years, much work has been done to improve both splicing materials and techniques.

The following items have been found to be primarily responsible for unsatisfactory splice service:

1. Ending up with a grounding or ground-check conductor which is shorter than the power conductors.
2. Semi-conducting residue on the insulation surface was not removed.
3. Gaps, voids or soft spots in insulating tape build-up.
4. Improper termination of shielding system, leaving inward-pointing projections.
5. Damage to factory insulation by improper removal of shielding systems.
6. Excessive slack in one or more individual conductors.
7. Splice has low tensile strength and is easily pulled in two.
8. Individual wires are damaged during application of connector.
9. Splice is too bulky — will not pass through cable guides or over sheaves.
10. Improper application of the outer covering, allowing water to enter the cable interior.

By choosing a cable with an adequate current rating, avoiding excessive tension and mechanical damage, and using proper splicing techniques, it is not unreasonable to reduce cable-related downtime by 50 percent or more. This will, of course, translate into increased production and profits.

9.3 Table 25: Unit Conversion Table

UNIT CONVERSION FACTORS

UNIT	X CONSTANT	= UNIT	UNIT	X CONSTANT	= UNIT
BTU	778.0	foot-pound (ft-lb)	gallons	3.785332	liters (l)
BTU	1054.8	joules	gallons	0.13368	cubic foot (ft^3)
BTU	0.293	watt-hours (w-hr)	gallons	231.0	cubic inch (in^3)
centimeters (cm)	0.032808	feet (ft)	gallons	3785.332	cubic centimeter (cm^3)
centimeters (cm)	0.3937	inches (in)	grams (g)	15.432	grains
centimeters (cm)	0.00001	kilometers (km)	gram/centimeter^3 (g/cm^3)	0.0361275	pounds/in^3 (lb/in^3)
centimeters (cm)	0.010	meters (m)	horsepower (hp)	33000.0	ft-lb/min
centimeters (cm)	10.0	millimeters (mm)	horsepower (hp)	550.0	ft-lb/sec
circular mils	0.00064516	circular millimeters	horsepower (hp)	745.7	watts (w)
circular mils	0.0000007854	inches^2 (in^2)	inch (in)	0.027178	yards (yd)
circular mils	0.00050671	square millimeters (mm^2)	inch (in)	0.083333	feet (ft)
circular mils	0.7854	mils^2	inch (in)	0.00002540	kilometer (km)
cubic centimeter (cm^3)	0.000035314	cubic foot (ft^3)	inch (in)	0.025400	meter (m)
cubic centimeter (cm^3)	0.061023	cubic inch (in^3)	inch (in)	2.54000514	centimeter (cm)
cubic centimeter (cm^3)	0.000001	cubic meter (m^3)	inch (in)	25.4000514	millimeter (mm)
cubic centimeter (cm^3)	0.0026417	gallons	inch (in)	1000.0	mils
cubic foot (ft^3)	1728.0	cubic inch (in^3)	joules	0.000948	BTU
cubic foot (ft^3)	28317.016	cubic centimeter (cm^3)	joules	10^7	ergs
cubic inch (in^3)	0.00057870	cubic feet (ft^3)	liters (l)	61.0250	cubic inch (in^3)
cubic inch (in^3)	0.000016387	cubic meter (m^3)	meters (m)	1.093611	yards (yd)
cubic inch (in^3)	16.387162	cubic centimeter (cm^3)	meters (m)	3.2808333	feet (ft)
cubic meter (m^3)	1000000.0	centimeter (cm)	meters (m)	39.37	inch (in)
cubic meter (m^3)	35.314456	cubic foot (ft^3)	meters (m)	100.0	centimeter (cm)
cubic meter (m^3)	264.17	gallons	miles	1760.0	yards (yd)
feet (ft)	0.00018939	miles	miles	5280.0	feet (ft)
feet (ft)	0.33333	yards (yd)	miles	1.6093	kilometer (km)
feet (ft)	12	inches (in)	millimeters (mm)	0.0032808	feet (ft)
feet (ft)	0.00030480	kilometers (km)	millimeters (mm)	0.03937	inch (in)
feet (ft)	0.30480	meters (m)	millimeters (mm)	0.001	meters (m)
feet (ft)	30.480	centimeters (cm)	millimeters (mm)	0.01	centimeters (cm)
feet (ft)	304.80	millimeters (mm)	millimeters (mm)	39.3701	mils
feet/pound (ft/lb)	0.00067197	meters/grams (m/g)	millimeters (mm)	1000.0	microns (u)
foot-pound (ft-lb)	0.001285	BTU	watts (w)	44.25	ft-lb/minute
foot-pound (ft-lb)	1.356	joules	watts (w)	0.737562	ft-lb/sec
foot-pound (ft-lb)	0.1383	kilogram/meter (kg/m)	watts (w)	0.001341	horsepower (hp)

9.4 Table 26: Temperature Conversion Chart

To use this chart, find your known temperature (˚F or ˚C) in the shaded column. If the known temperature is in ˚C and you wish to know its value in ˚F, move to the adjacent right-hand column. If the known temperature is in ˚F and you wish to know its value in ˚C, move to the adjacent left-hand column.

°C	KNOWN TEMP	°F	°C	KNOWN TEMP	°F	°C	KNOWN TEMP	°F	°C	KNOWN TEMP	°F	°C	KNOWN TEMP	°F
-45.0	**-49.0**	-56.2	-17.2	**1.0**	33.8	10.6	**51.0**	123.8	38.3	**101.0**	213.8	66.1	**151.0**	303.8
-44.4	**-48.0**	-54.4	-16.7	**2.0**	35.6	11.1	**52.0**	125.6	38.9	**102.0**	215.6	66.7	**152.0**	305.6
-43.9	**-47.0**	-52.6	-16.1	**3.0**	37.4	11.7	**53.0**	127.4	39.4	**103.0**	217.4	67.2	**153.0**	307.4
-43.3	**-46.0**	-50.8	-15.6	**4.0**	39.2	12.2	**54.0**	129.2	40.0	**104.0**	219.2	67.8	**154.0**	309.2
-42.8	**-45.0**	-49.0	-15.0	**5.0**	41.0	12.8	**55.0**	131.0	40.6	**105.0**	221.0	68.3	**155.0**	311.0
-42.2	**-44.0**	-47.2	-14.4	**6.0**	42.8	13.3	**56.0**	132.8	41.1	**106.0**	222.8	68.9	**156.0**	312.8
-41.7	**-43.0**	-45.4	-13.9	**7.0**	44.6	13.9	**57.0**	134.6	41.7	**107.0**	224.6	69.4	**157.0**	314.6
-41.1	**-42.0**	-43.6	-13.3	**8.0**	46.4	14.4	**58.0**	136.4	42.2	**108.0**	226.4	70.0	**158.0**	316.4
-40.6	**-41.0**	-41.8	-12.8	**9.0**	48.2	15.0	**59.0**	138.2	42.8	**109.0**	228.2	70.6	**159.0**	318.2
-40.0	**-40.0**	-40.0	-12.2	**10.0**	50.0	15.6	**60.0**	140.0	43.3	**110.0**	230.0	71.1	**160.0**	320.0
-39.4	**-39.0**	-38.2	-11.7	**11.0**	51.8	16.1	**61.0**	141.8	43.9	**111.0**	231.8	71.7	**161.0**	321.8
-38.9	**-38.0**	-36.4	-11.1	**12.0**	53.6	16.7	**62.0**	143.6	44.4	**112.0**	233.6	72.2	**162.0**	323.6
-38.3	**-37.0**	-34.6	-10.6	**13.0**	55.4	17.2	**63.0**	145.4	45.0	**113.0**	235.4	72.8	**163.0**	325.4
-37.8	**-36.0**	-32.8	-10.0	**14.0**	57.2	17.8	**64.0**	147.2	45.6	**114.0**	237.2	73.3	**164.0**	327.2
-37.2	**-35.0**	-31.0	-9.4	**15.0**	59.0	18.3	**65.0**	149.0	46.1	**115.0**	239.0	73.9	**165.0**	329.0
-36.7	**-34.0**	-29.2	-8.9	**16.0**	60.8	18.9	**66.0**	150.8	46.7	**116.0**	240.8	74.4	**166.0**	330.8
-36.1	**-33.0**	-27.4	-8.3	**17.0**	62.6	19.4	**67.0**	152.6	47.2	**117.0**	242.6	75.0	**167.0**	332.6
-35.6	**-32.0**	-25.6	-7.8	**18.0**	64.4	20.0	**68.0**	154.4	47.8	**118.0**	244.4	75.6	**168.0**	334.4
-35.0	**-31.0**	-23.8	-7.2	**19.0**	66.2	20.6	**69.0**	156.2	48.3	**119.0**	246.2	76.1	**169.0**	336.2
-34.4	**-30.0**	-22.0	-6.7	**20.0**	68.0	21.1	**70.0**	158.0	48.9	**120.0**	248.0	76.7	**170.0**	338.0
-33.9	**-29.0**	-20.2	-6.1	**21.0**	69.8	21.7	**71.0**	159.8	49.4	**121.0**	249.8	77.2	**171.0**	339.8
-33.3	**-28.0**	-18.4	-5.6	**22.0**	71.6	22.2	**72.0**	161.6	50.0	**122.0**	251.6	77.8	**172.0**	341.6
-32.8	**-27.0**	-16.6	-5.0	**23.0**	73.4	22.8	**73.0**	163.4	50.6	**123.0**	253.4	78.3	**173.0**	343.4
-32.2	**-26.0**	-14.8	-4.4	**24.0**	75.2	23.3	**74.0**	165.2	51.1	**124.0**	255.2	78.9	**174.0**	345.2
-31.7	**-25.0**	-13.0	-3.9	**25.0**	77.0	23.9	**75.0**	167.0	51.7	**125.0**	257.0	79.4	**175.0**	347.0
-31.1	**-24.0**	-11.2	-3.3	**26.0**	78.8	24.4	**76.0**	168.8	52.2	**126.0**	258.8	80.0	**176.0**	348.8
-30.6	**-23.0**	-9.4	-2.8	**27.0**	80.6	25.0	**77.0**	170.6	52.8	**127.0**	260.6	80.6	**177.0**	350.6
-30.0	**-22.0**	-7.6	-2.2	**28.0**	82.4	25.6	**78.0**	172.4	53.3	**128.0**	262.4	81.1	**178.0**	352.4
-29.4	**-21.0**	-5.8	-1.7	**29.0**	84.2	26.1	**79.0**	174.2	53.9	**129.0**	264.2	81.7	**179.0**	354.2
-28.9	**-20.0**	-4.0	-1.1	**30.0**	86.0	26.7	**80.0**	176.0	54.4	**130.0**	266.0	82.2	**180.0**	356.0
-28.3	**-19.0**	-2.2	-0.6	**31.0**	87.8	27.2	**81.0**	177.8	55.0	**131.0**	256.8	82.8	**181.0**	357.8
-27.8	**-18.0**	-0.4	0.0	**32.0**	89.6	27.8	**82.0**	179.6	55.6	**132.0**	269.6	83.3	**182.0**	359.6
-27.2	**-17.0**	1.4	0.6	**33.0**	91.4	28.3	**83.0**	181.4	56.1	**133.0**	271.4	83.9	**183.0**	361.4
-26.7	**-16.0**	3.2	1.1	**34.0**	93.2	28.9	**84.0**	183.2	56.7	**134.0**	273.2	84.4	**184.0**	363.2
-26.1	**-15.0**	5.0	1.7	**35.0**	95.0	29.4	**85.0**	185.0	57.2	**135.0**	275.0	85.0	**185.0**	365.0
-25.6	**-14.0**	6.8	2.2	**36.0**	96.8	30.0	**86.0**	186.8	57.8	**136.0**	276.8	85.6	**186.0**	366.8
-25.0	**-13.0**	8.6	2.8	**37.0**	98.6	30.6	**87.0**	188.6	58.3	**137.0**	278.6	86.1	**187.0**	368.6
-24.4	**-12.0**	10.4	3.3	**38.0**	100.4	31.1	**88.0**	190.4	58.9	**138.0**	280.4	86.7	**188.0**	370.4
-23.9	**-11.0**	12.2	3.9	**39.0**	102.2	31.7	**89.0**	192.2	59.4	**139.0**	282.2	87.2	**189.0**	372.2
-23.3	**-10.0**	14.0	4.4	**40.0**	104.0	32.2	**90.0**	194.0	60.0	**140.0**	284.0	87.8	**190.0**	374.0
-22.8	**-9.0**	15.8	5.0	**41.0**	105.8	32.8	**91.0**	195.8	60.6	**141.0**	285.8	88.3	**191.0**	375.8
-22.2	**-8.0**	17.6	5.6	**42.0**	107.6	33.3	**92.0**	197.6	61.1	**142.0**	287.6	88.9	**192.0**	377.6
-21.7	**-7.0**	19.4	6.1	**43.0**	109.4	33.9	**93.0**	199.4	61.7	**143.0**	289.4	89.4	**193.0**	379.4
-21.1	**-6.0**	21.2	6.7	**44.0**	111.2	34.4	**94.0**	201.2	62.2	**144.0**	291.2	90.0	**194.0**	381.2
-20.6	**-5.0**	23.0	7.2	**45.0**	113.0	35.0	**95.0**	203.0	62.8	**145.0**	293.0	90.6	**195.0**	383.0
-20.0	**-4.0**	24.8	7.8	**46.0**	114.8	35.6	**96.0**	204.8	63.3	**146.0**	294.8	91.1	**196.0**	384.8
-19.4	**-3.0**	26.6	8.3	**47.0**	116.6	36.1	**97.0**	206.6	63.9	**147.0**	296.6	91.7	**197.0**	386.6
-18.9	**-2.0**	28.4	8.9	**48.0**	118.4	36.7	**98.0**	208.4	64.4	**148.0**	289.4	92.2	**198.0**	388.4
-18.3	**-1.0**	30.2	9.4	**49.0**	120.2	37.2	**99.0**	210.2	65.0	**149.0**	300.2	92.8	**199.0**	390.2
-17.8	**0.0**	32.0	10.0	**50.0**	122.0	37.8	**100.0**	212.0	65.6	**150.0**	302.0	93.3	**200.0**	392.0

Temperature Conversion Formulas

°C =	$\frac{5}{9}$ (°F - 32)
°F =	($\frac{9}{5}$ x °C) + 32

NOTES

General Cable

4 Tesseneer Drive,
Highland Heights,
Kentucky 41076-9753

Printed in USA

Phone:	1.888.593.3355
Fax:	1.800.335.1270
International Tel.:	+1.859.572.8000
International Fax:	+1.859.572.8058

www.generalcable.com
Form No. INS-0084-0908
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