PDHonline Course E275 (3 PDH)

AWG and Circular Mils

Instructor: David A. Snyder, PE

2020

PDH Online | PDH Center

5272 Meadow Estates Drive
Fairfax, VA 22030-6658
Phone: 703-988-0088
www.PDHonline.com

An Approved Continuing Education Provider

AWG and Circular Mils
David A. Snyder, PE

Introduction:

Conductors, also known as wires, cables, or busses, conduct electricity from one point to another. This course discusses the difference between solid and stranded conductors, and the size conventions (circular mils, KCMIL, and AWG) used to describe them. As the names would imply, solid conductors are composed of one solid piece of wire, whereas stranded conductors are composed of several smaller strands of solid wire. The terms circular mils, KCMIL, and AWG (American Wire Gage) are not quite as obvious and often require further explanation. We'll start our discussion with the concept of circular mils in the next section.

With regard to formulas and calculations in this document, we will be using the asterisk (*) for multiplication and the forward slash (/) for division. Numbers expressed in scientific notation will be presented in the format 1.2×10^{-6}. Since we will be discussing diameter (d), rather than radius (r), in this document, the familiar expression for the area of a circle will be shown as $A = \pi * d^2 / 4$, rather than $A = \pi * r^2$. The tables presented in this document are available as a separate file, if you have difficulty reading the tables in this document.

Circular Mils:

A <u>mil</u> is a length, distance, or diameter that is equal to $1 / 1,000^{th}$ of an inch (a milli-inch). A <u>circular mil</u> is a unit of cross-sectional area that is equal to the area of a circle that is one mil (0.001 inches) in diameter. A circular mil or c.m. is therefore equal to $\pi * (0.001)^2 / 4 = 7.85 \times 10^{-7}$ square inches. The advantage of using the units called circular mils is that the cross-sectional area of a solid conductor is the diameter of that conductor squared. For example, a solid conductor with a diameter of 0.0808 inches (80.8 mils) has a circular mil area of $(80.8)^2$ or 6,529 circular mils. To double-check this, look at Table 2 on the row for 12 AWG. The wire <u>diameters</u> shown on Table 2 are for the bare metallic (aluminum or copper) portion of a solid conductor and are given in mils. The wire <u>areas</u> shown on Table 2 are also for the bare part of the conductor and are given in circular mils, which is simply the solid diameter in mils squared. For another example, a solid 10 AWG conductor has a diameter of 101.9 mils (0.1019 inches) and a calculated area of $(101.9)^2 = 10,383.6$ circular mils. The nominal area from Table 8 of Chapter 9 of the NEC is shown in the green shaded column of Table 2 and is 10,380 circular mils in this case.

Notice in the first 11 rows of Table 2 that the wire sizes are designated in terms of their cross-sectional area. For example, 250 KCMIL is a conductor that has 250,000 circular mils (K means 1,000, in this case) of conductor area. The concept of circular mils also applies to shapes that are not circular, such as rectangular bus bar. Suppose that a bus bar was required to have, as a minimum, the equivalent cross-sectional area of 2,000,000 circular mils or 2,000 KCMIL. Table 1 shows some standard bus bar sizes from a fictitious company. How would we select the proper bus bar to meet the cross-sectional area requirement? Let's work it out in the following example:

EXAMPLE 1

Bus bars are available in different thicknesses, but let's assume that we are looking for bus bar that is ½"-thick. We could simply look at Table 1 and select the proper size of bus bar, but let's do a sanity check first by calculating the required cross-sectional area in square inches. To determine the dimensions of a bus bar to meet the required area of 2,000 KCMIL, let's first convert 2,000 KCMIL to square inches.

2,000,000 circular mils * (7.85 x 10^{-7} square inches/circular mil) = 1.57 square inches.

For a ½"-thick bus bar, the required width would be 1.57 in^2 / 0.5" = 3.14". From Table 1, the best choice in ½"-thick bus bar is 3.5" in width to meet the minimum cross-sectional area requirement. Looking at the circular-mils column in Table 1 confirms that our calculation is correct. This bus bar is shown in Figure 1.

This example is not intended as a guide for selecting bus bar, but to demonstrate the concept of circular mils. There are many factors to consider in selecting bus bar, including mechanical strength, voltage drop, resistance, capacitance, and inductance.   END OF EXAMPLE
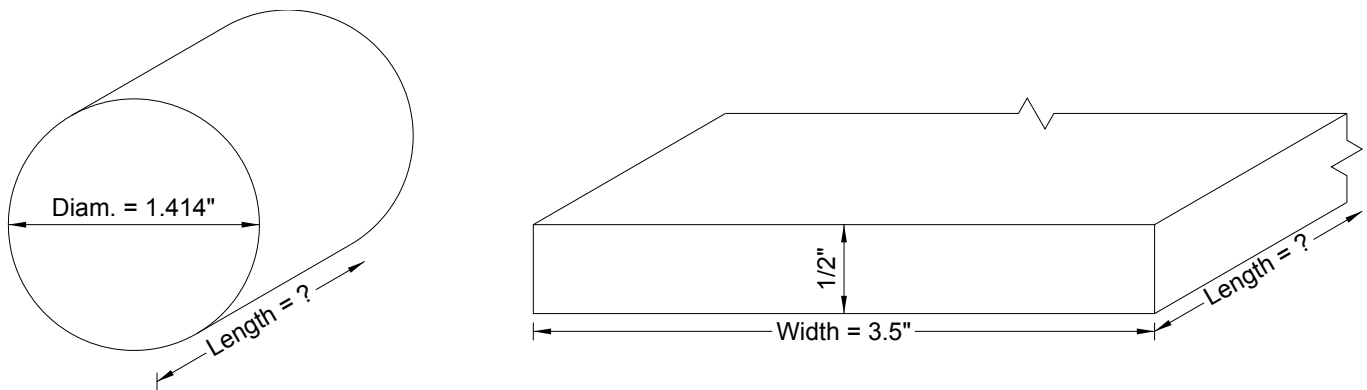
Solid 2,000 KCMIL Conductor and 1/2" x 3.5" Solid Bus Bar
Figure 1

A comment about the accuracy of the calculations in this document:
This document illustrates and explains the mathematical relationships between the various wire sizes and cross-sectional areas, but the dimensions given on Table 2, on other tables in this document, and in other industry publications are only accurate to 2, 3, or 4 decimal places. There will be some calculation results that will not match exactly the data in the tables in this document, but that is because of the low accuracy of the dimensional information. For example, the mathematical value for the diameter of 36 AWG, when calculated from a starting point of 1/0 AWG, is 4.99437 mils, but it is called 5.0 mils on Table 2. Going the other direction, the diameter of 1/0, when calculated from a starting point of 36 AWG, is 461.1 mils, but it is called 460.0 mils on Table 2. Don't let these approximations detract from the mathematical relationships presented in this document.

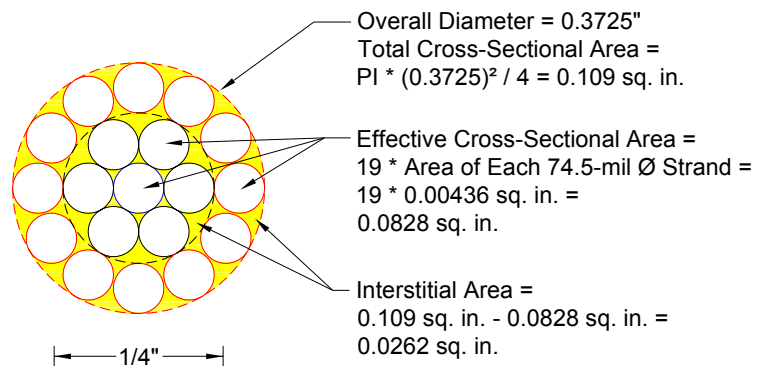| TABLE 1 - Bus Bar Choices				
Thickness (in.)	Width (in.)	Area (in²)	Calc'd Area (Circular Mils)	Nominal Area (KCMIL)
0.375	0.75	0.281	358,280	358
0.375	1	0.375	477,707	477
0.375	1.5	0.563	716,561	715
0.375	2	0.750	955,414	955
0.375	2.5	0.938	1,194,268	1,190
0.375	3	1.125	1,433,121	1,430
0.375	3.5	1.313	1,671,975	1,670
0.375	4	1.500	1,910,828	1,910
0.375	5	1.875	2,388,535	2,390
0.375	6	2.250	2,866,242	2,860
0.375	8	3.000	3,821,656	3,820
0.375	10	3.750	4,777,070	4,770
0.375	12	4.500	5,732,484	5,730
0.5	1	0.500	636,943	637
0.5	1.5	0.750	955,414	955
0.5	2	1.000	1,273,885	1,270
0.5	2.5	1.250	1,592,357	1,590
0.5	3	1.500	1,910,828	1,910
0.5	3.5	1.750	2,229,299	2,230
0.5	4	2.000	2,547,771	2,550
0.5	5	2.500	3,184,713	3,180
0.5	6	3.000	3,821,656	3,820
0.5	8	4.000	5,095,541	5,090
0.5	10	5.000	6,369,427	6,360
0.5	12	6.000	7,643,312	7,640
0.75	2	1.500	1,910,828	1,910
0.75	2.5	1.875	2,388,535	2,390
0.75	3	2.250	2,866,242	2,860
0.75	4	3.000	3,821,656	3,820
0.75	5	3.750	4,777,070	4,770
0.75	6	4.500	5,732,484	5,730
0.75	8	6.000	7,643,312	7,640
0.75	10	7.500	9,554,140	9,550
0.75	12	9.000	11,464,968	11,500

The 2,000 KCMIL solid conductor in Figure 1 has slightly less cross-sectional area than the best-choice bus bar. Notice in Table 1 that, if we had required 3/8"-thick bus bar, we would have chosen the 3/8" x 5" bus bar. If we had required 3/4"-thick bus bar, we would have chosen the 3/4" x 2.5" bus bar. The length of the conductor and bus bar in Figure 1 is not important from the standpoint of calculating circular mil area, but was shown to illustrate the 3-dimensional shapes.

The bus bar in Figure 1 has a rectangular cross section with flat sides, but bus bar comes with several different choices for the shapes of the sides, including square corners (as in Figure 1), rounded corners, rounded edge, and full rounded edge (as in Figure 9).

AWG (American Wire Gage):

AWG or American Wire Gage [formerly known as Brown & Sharpe (B&S) wire gauge] defines the effective cross-sectional area of the conducting portion of a wire. It does not define the area or thickness of the insulation or jacket and therefore does not define the overall diameter of an insulated conductor.   The term 'effective cross-sectional area' is used because stranded conductors will take up a total cross-sectional area that is larger than its effective cross-sectional area because of the voids or interstices between the strands. Figure 2 shows a bare, stranded 1/0 AWG conductor without any insulation [the 1/4" length is shown to give a sense of scale, it is not a diameter]. The total cross-sectional area circumscribed by the outer layer of strands is 0.109 square inches (0.3725 inch diameter), but the effective cross-sectional area of the strands is the sum of the 19 cross-sectional areas of the strands, which is 0.0828 square inches. This means that there are 0.0262 square inches of non-conductive material taking up the voids in between the strands.

The conductors discussed in this document are bare, not insulated. The dimensions given are for bare solid or bare stranded conductors, which are the bare metallic wires inside of insulated conductors and cables.

Overall Diameter = 0.3725"
Total Cross-Sectional Area =
PI * (0.3725)² / 4 = 0.109 sq. in.

Effective Cross-Sectional Area =
19 * Area of Each 74.5-mil Ø Strand =
19 * 0.00436 sq. in. =
0.0828 sq. in.

Interstitial Area =
0.109 sq. in. - 0.0828 sq. in. =
0.0262 sq. in.

|← 1/4" →|

Effective Versus Total Cross-Sectional Areas for a Stranded 1/0 AWG Conductor
Figure 2

People use many different formats when describing wire sizes, such as #12, #12 AWG, or 12 AWG. This document will use the format 12 AWG to describe what is commonly known as a #12 conductor.

The information presented in Table 2 is generally based on Class B stranding and the NEC, but some supplementary information has been added and some values have been interpolated for the lesser-known wire sizes. Several of the wire sizes shown on Table 2 are not used very often but have been included for the sake of completeness.

Common AWG Sizes:
At the risk of receiving smoldering e-mails, here is a list of what many people and manufacturers consider to be standard, every-day, run-of-the-mill AWG sizes: 4/0, 3/0, 2/0, 1/0, 1, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, and 24 AWG. It is possible to find some of the other sizes not listed here, depending on the manufacturer and warehouse.

KCMIL versus MCM:
KCMIL is the same as MCM, which is 1,000 circular mil. KCMIL stands for 1,000 (K) circular (C) mil (MIL) and MCM stands for 1,000 (M, from Roman numerals) circular (C) mil (M). KCMIL is the term that is used more often nowadays, but MCM was more prevalent in the previous century.

AWG (American Wire Gage)	Solid Wire Diameter (Mils)	Calculated Area (C.M.)	Nominal Area NEC Table 8 (C.M.)	Strand Qty (May Vary)	Diam./ Strand (Mils)	Area/ Strand (C.M.)	Total Area of Strands (C.M.)
1,000 KCMIL	1,000.0	1,000,000.0	1,000,000	61	128.0	16,384.0	999,424.0
900 KCMIL	948.7	900,031.7	900,000	61	121.5	14,762.3	900,497.3
800 KCMIL	894.4	799,951.4	800,000	61	114.5	13,110.3	799,725.3
750 KCMIL	866.0	749,956.0	750,000	61	110.9	12,298.8	750,227.4
700 KCMIL	836.7	700,066.9	700,000	61	107.1	11,470.4	699,695.0
600 KCMIL	774.6	600,005.2	600,000	61	99.2	9,840.6	600,279.0
500 KCMIL	707.1	499,990.4	500,000	37	116.2	13,502.4	499,590.3
400 KCMIL	632.5	400,056.3	400,000	37	104.0	10,816.0	400,192.0
350 KCMIL	591.6	349,990.6	350,000	37	97.3	9,467.3	350,289.7
300 KCMIL	547.7	299,975.3	300,000	37	90.0	8,100.0	299,700.0
250 KCMIL	500.0	250,000.0	250,000	37	82.2	6,756.8	250,003.1
4/0 or 0000	460.0	211,600.0	211,600	19	105.5	11,130.3	211,474.8
3/0 or 000	409.6	167,772.2	167,800	19	94.0	8,836.0	167,884.0
2/0 or 00	364.8	133,079.0	133,100	19	83.7	7,005.7	133,108.1
1/0 or 0	324.9	105,560.0	105,600	19	74.5	5,550.3	105,454.8
1	289.3	83,694.5	83,690	19	66.4	4,409.0	83,770.2
2	257.6	66,357.8	66,360	7	97.4	9,486.8	66,407.3
3	229.4	52,624.4	52,620	7	86.7	7,516.9	52,618.2
4	204.3	41,738.5	41,740	7	77.2	5,959.8	41,718.9
5	181.9	33,087.6	N.A.	7	68.8	4,733.4	33,134.1
6	162.0	26,244.0	26,240	7	61.2	3,745.4	26,218.1
7	144.3	20,822.5	N.A.	7	54.5	2,970.3	20,791.8
8	128.5	16,512.3	16,510	7	48.6	2,362.0	16,533.7
9	114.4	13,087.4	N.A.	7	43.2	1,866.2	13,063.7
10	101.9	10,383.6	10,380	7	38.5	1,482.3	10,375.8
11	90.7	8,226.5	N.A.	7	34.3	1,175.4	8,227.9
12	80.8	6,528.6	6,530	7	30.5	930.3	6,511.8
13	72.0	5,184.0	N.A.	7	27.2	737.7	5,163.8
14	64.1	4,108.8	4,110	7	24.2	585.6	4,099.5
15	57.1	3,260.4	N.A.	7	21.6	464.4	3,250.8
16	50.8	2,580.6	2,580	7	19.2	368.6	2,580.5
17	45.3	2,052.1	N.A.	7	17.1	292.3	2,046.3
18	40.3	1,624.1	1,620	7	15.2	231.0	1,617.3
19	35.9	1,288.8	N.A.	7	13.5	183.2	1,282.5
20	32.0	1,024.0	N.A.	7	12.1	146.4	1,024.9
21	28.5	812.3	N.A.	7	10.8	116.1	812.7
22	25.3	640.1	N.A.	7	9.6	92.1	644.5
23	22.6	510.8	N.A.	7	8.5	73.0	511.1
24	20.1	404.0	N.A.	7	7.6	57.9	405.3
25	17.9	320.4	N.A.	7	6.8	45.9	321.4
26	15.9	252.8	N.A.	7	6.0	36.4	254.8
27	14.2	201.6	N.A.	7	5.4	28.9	202.1
28	12.6	158.8	N.A.	7	4.8	22.9	160.3
29	11.3	127.7	N.A.	7	4.3	18.2	127.1
30	10.0	100.0	N.A.	7	3.8	14.4	100.8
31	8.9	79.2	N.A.	7	3.4	11.4	79.9
32	8.0	64.0	N.A.	7	3.0	9.1	63.4
33	7.1	50.4	N.A.	N.A.	N.A.	N.A.	N.A.
34	6.3	39.7	N.A.	N.A.	N.A.	N.A.	N.A.
35	5.6	31.4	N.A.	N.A.	N.A.	N.A.	N.A.
36	5.0	25.0	N.A.	N.A.	N.A.	N.A.	N.A.
37	4.5	20.3	N.A.	N.A.	N.A.	N.A.	N.A.
38	4.0	16.0	N.A.	N.A.	N.A.	N.A.	N.A.
39	3.5	12.3	N.A.	N.A.	N.A.	N.A.	N.A.
40	3.1	9.6	N.A.	N.A.	N.A.	N.A.	N.A.

TABLE 2 - Wire Gage, Mils, Circular Mils, and Strand Quantities

It might seem that AWG designations don't have any relationship to the actual physical dimensions of the conductors, but it is easier to understand if one considers each AWG number as a pass through another die (see Figure 3). In other words, to go from 10 AWG to 12 AWG would require that the solid 10 AWG wire pass through two dies. After it passes through the first die, it is reduced from 10 AWG to 11 AWG (which is not a standard wire size – see Common AWG Sizes sidebar). When the 11 AWG wire passes through the second die, it is reduced from 11 AWG to 12 AWG. The ratio of AWG sizes follows a geometric progression, which is often illustrated by comparing 4/0 AWG to 36 AWG. The diameter of 4/0 AWG is 0.46" and the diameter of 36 AWG is 0.005". Looking at Table 2, there are 39 steps (39 dies) from 4/0 AWG to 36 AWG, so the ratio between each size can be calculated by taking the 39th root of the ratio of the larger diameter to the smaller diameter, which is :

Ratio = $\sqrt[39]{(0.46 / 0.005)}$ = $\sqrt[39]{92}$ = 1.122932197, which we will call 1.123.

This ratio tells us is that the diameter of a certain wire size is 1.123 times the size of the next-smaller wire size. Taking the 39th root of a number can be cumbersome, so let's simplify the concept by comparing two adjacent wire sizes. For example, the diameter of a solid 9 AWG conductor is 114.4 mils and the diameter of a solid 10 AWG (the next size smaller) is 101.9 mils. The ratio is 114.4 / 101.9 = 1.1227, which we will call 1.123, which matches the ratio already determined. This means that we don't have to go from 4/0 AWG to 36 AWG to calculate this ratio, we can do it with wire sizes that are adjacent to each other, or separated by a certain number of sizes. Let's try an example going from 10 AWG to 12 AWG (using solid conductors):

EXAMPLE 2
We already know from the discussion directly above that the diameter of a solid 10 AWG conductor is 101.9 mils, so what would be the diameter of a solid 12 AWG conductor if the ratio from one size to the next-smaller size is 1.123?

Since there are two steps (rather than 39) between 10 AWG and 12 AWG, we can find the diameter of 12 AWG by using this formula (where X = the diameter):

Ratio = $\sqrt[2]{(101.9 / X)}$

1.123 = $\sqrt[2]{(101.9 / X)}$

$(1.123)^2$ = 101.9 / X

1.261 = 101.9 / X

X = 101.9 / 1.261 = 80.8 mils, which is the diameter of a solid 12 AWG conductor. Verify by looking at Table 2. Notice that we used the 2nd root or square root, rather than the 39th root, since there were two steps from one conductor size to the other. **END OF EXAMPLE**

Let's extend the above example by calculating the diameter of a solid 14 AWG conductor.

EXAMPLE 3

We already know from the discussion directly above that the diameter of a solid 10 AWG conductor is 101.9 mils and it is clear that there are 4 steps (passing through 4 dies) in going from 10 AWG to 14 AWG. Since there are four steps between 10 AWG and 14 AWG, we can find the diameter of 14 AWG by using this formula (where Y = the diameter):

Ratio = $\sqrt[4]{(101.9 / Y)}$

$1.123 = \sqrt[4]{(101.9 / Y)}$

$(1.123)^4 = 101.9 / Y$

$1.59 = 101.9 / Y$

Y = 101.9 / 1.59 = 64.1 mils, which is the diameter of a solid 14 AWG conductor. Verify by looking at Table 2. Notice that we used the 4th root, rather than the 39th root, since there were four steps from one conductor size to the other.

Re-verify this by going from 12 AWG to 14 AWG, which is two steps:

Ratio = $\sqrt[2]{(80.8 / Y)}$

$1.123 = \sqrt[2]{(80.8 / Y)}$
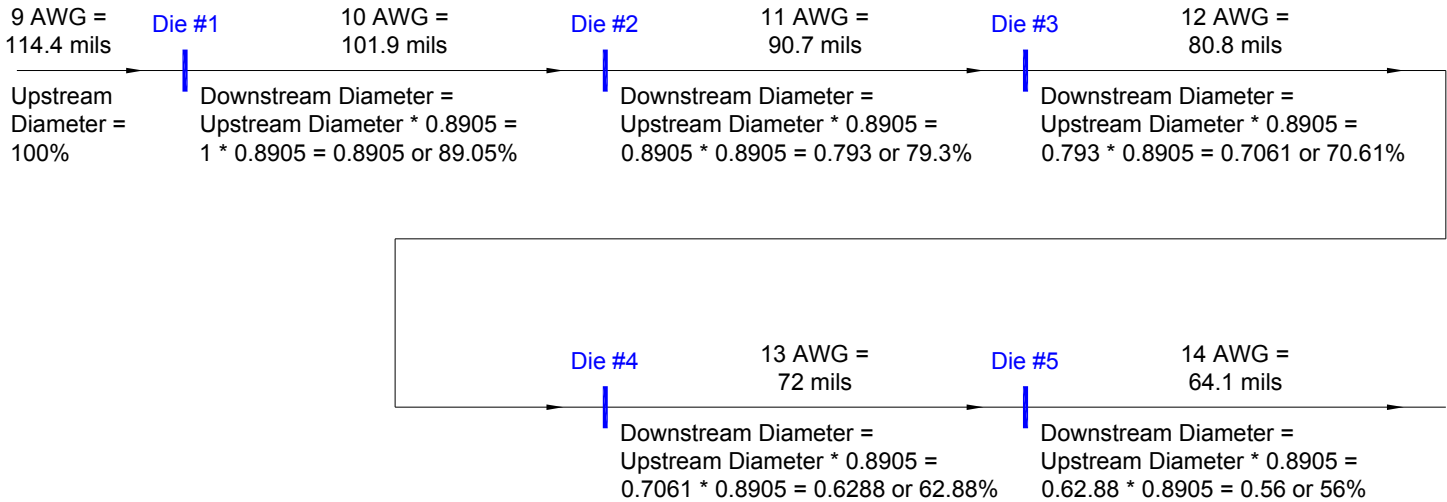
$(1.123)^2 = 80.8 / Y$

$1.261 = 80.8 / Y$

Y = 80.8 / 1.261 = 64.1 mils, which re-verifies the result earlier in this example.

END OF EXAMPLE

Let's simplify this concept further by turning it inside-out and upside-down. Instead of saying that a conductor is 1.123 times the diameter of the next-smaller conductor, let's take the reciprocal of that and say that a conductor is 1 / 1.123 = 0.8905 times the next-larger conductor. This is a bit easier to understand, since that is the way conductors are manufactured, by decreasing the diameter, not by increasing the diameter. Each time the conductor goes through a die, such as going from 9 AWG to 10 AWG, the diameter on the downstream side is 0.8905 times the diameter on the upstream side. This results in a decrease in diameter of 1 − 0.8905 = 0.1095, which is 10.95%. Since the area is equal to the diameter squared, passing through one die will change the area to $(0.8905)^2 = 0.793$ times the area on the upstream side, which is a decrease of 1 − 0.793 = 0.207 = 20.7%.

Figure 3 shows the wire diameters as the wire is drawn through five dies to go from 9 AWG to 14 AWG. Every time the wire passes through a die, the smaller diameter on the downstream side is 0.8905 times the larger diameter on the upstream side. Going through one die results in a

final diameter of 0.8905 compared to the starting diameter. Going through two dies results in a final diameter of $(0.8905)^2$ compared to the starting diameter. Going through three dies results in a final diameter of $(0.8905)^3$ compared to the starting diameter. In Figure 3, the resulting diameter after passing through five dies is $(0.8905)^5 = 0.56$ or 56% of the starting diameter of 114.4 mils for 9 AWG. This means that the final diameter after five dies is 114.4 mils * 0.56 = 64.1 mils for 14 AWG, which we already knew from Example 3. If there were a 6th die in Figure 3, the final diameter of the 15 AWG solid conductor after the 6th die would be $(0.8905)^6 = 0.499$ or 50% of the starting diameter, a ratio that will be discussed later in the section called "Rules of Thumb for Numbered AWG Sizes".

9 AWG = 114.4 mils	Die #1	10 AWG = 101.9 mils	Die #2	11 AWG = 90.7 mils	Die #3	12 AWG = 80.8 mils
Upstream Diameter = 100%		Downstream Diameter = Upstream Diameter * 0.8905 = 1 * 0.8905 = 0.8905 or 89.05%		Downstream Diameter = Upstream Diameter * 0.8905 = 0.8905 * 0.8905 = 0.793 or 79.3%		Downstream Diameter = Upstream Diameter * 0.8905 = 0.793 * 0.8905 = 0.7061 or 70.61%

	Die #4	13 AWG = 72 mils	Die #5	14 AWG = 64.1 mils
		Downstream Diameter = Upstream Diameter * 0.8905 = 0.7061 * 0.8905 = 0.6288 or 62.88%		Downstream Diameter = Upstream Diameter * 0.8905 = 0.62.88 * 0.8905 = 0.56 or 56%

9 AWG to 14 AWG Going Through 5 Dies
Figure 3

Let's take another look at going from a 4/0 AWG solid conductor to a 36 AWG solid conductor, which will take 39 dies, since there are 39 steps from 4/0 AWG to 36 AWG. Each die changes the diameter to 0.8905 of the upstream diameter, so passing through 39 dies will result in a final diameter of $(0.8905)^{39} = 0.0109$ or 1.09% of the starting diameter. To phrase it the opposite way, the starting diameter is $1 / 0.0109 = 92$ times the final diameter. We already know this is true from the beginning of this section, since 4/0 AWG has a diameter of 0.46" and 36 AWG has a diameter of 0.005" and the ratio is 0.46" / 0.005" = 92.

Let's try another scenario in which we will start with a 1/0 AWG (also known as 0 AWG) solid wire and draw it down to a 40 AWG solid wire by pulling it through the appropriate quantity and sizes of dies. How many dies would be required? Counting from 0 AWG to 40 AWG is 40 wire sizes, so it would require 40 dies. Starting with 0 AWG, after it passes through the 1st die, the wire size will be 1 AWG. After the 1 AWG passes through the 2nd die, the wire size will be 2 AWG. After the 2 AWG passes through the 3rd die, it will be 3 AWG, and so on until the 39 AWG wire passes through the 40th die, resulting in our finished product, a 40 AWG solid wire. Based on the previous discussions above, the final wire diameter after the 40th die, when compared to the starting diameter, will be $(0.8905)^{40} = 0.00967$. We can confirm this by dividing the diameter of the solid 40 AWG by the diameter of the solid 0 AWG, which is 3.1

mils / 324.9 mils = 0.00954. These two numbers don't seem to match, but that is because the conductor diameters are approximations of the mathematical results. In other words, 'close enough'. Confirm this by taking the reciprocals of the two numbers to find that they are 103.4 and 104.8, respectively (a difference of about 1.3%). Confirm this another way by multiplying the 0 AWG by 0.00967 to get the 40 AWG diameter of 324.9 * 0.00967 = 3.1 mils.

Figure 4 shows the relative sizes of conductors from 4/0 AWG to 40 AWG [the 1/2" and 1/16" lengths are shown to give a sense of scale, they are not diameters or radii]. Notice that the rings representing the wire sizes are not equally spaced but get tighter and tighter as they get smaller, or further and further apart as they get larger, as one would expect from a geometric progression.
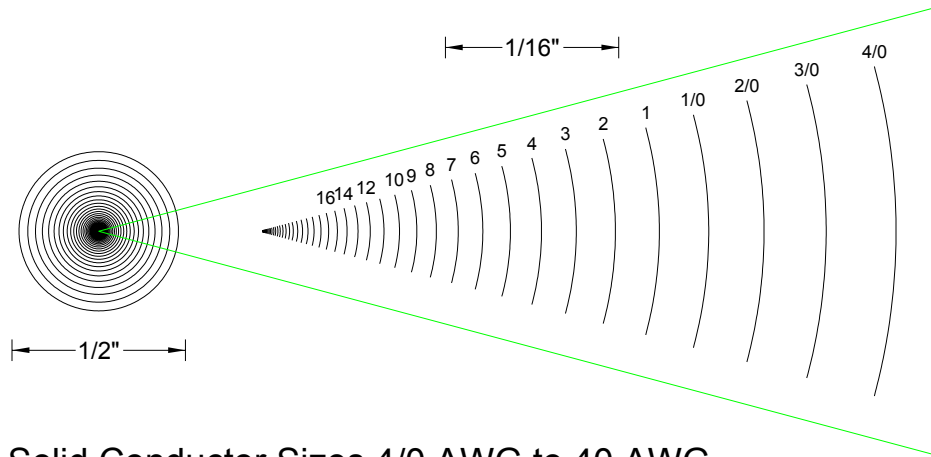
Solid Conductor Sizes 4/0 AWG to 40 AWG
Figure 4

Another way to look at the solid conductor sizes shown in Figure 4 is to look at the graph in Figure 5, which shows how the diameter decreases as the AWG designation increases.
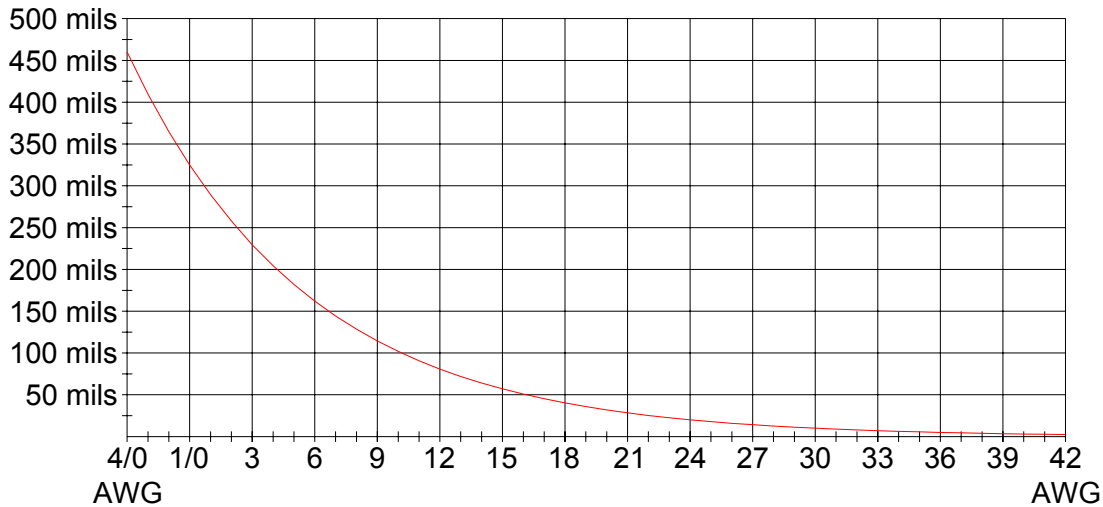
Geometric Progression of AWG Diameters
Figure 5

As you can see from Figure 5, the diameter keeps getting smaller and smaller, but more and more gradually, and it would never go to zero. Theoretically, a solid 100 AWG conductor would have a diameter [using 0 AWG as the starting point] of 324.9 mils * $(0.8905)^{100}$ = 3 x 10^{-3} mils or 0.003 mils or 0.000003" (thinner than a human hair).

The concept of numbered AWG size designations, such as 4/0 AWG and 12 AWG, does not apply to conductors larger than 4/0 AWG, such as 250 KCMIL, 300 KCMIL, and larger. The conductor sizes above 4/0 AWG are designated by their actual effective cross-sectional area in thousands of circular mils, or KCMIL. Since the concept of AWG designations does not apply to KCMIL conductor sizes, the ratios of 1.123 and 0.8905 do not apply to KCMIL conductor sizes.

The above discussion in this section has described the diameters of solid conductors, but it is unusual to encounter solid conductors that are larger than 8 AWG in everyday applications. Most conductors will be stranded, as discussed later.

Rules of Thumb for Numbered AWG Sizes:

For the numbered AWG sizes (4/0 AWG and smaller), certain rules of thumb for diameter and cross-sectional area apply, based on the geometric progression of the sizes. It is helpful to remember that, for a solid conductor, the cross-sectional area in circular mils is equal to the square of the diameter in mils. Refer to the Solid Wire Diameter column and Nominal Area NEC Table 8 column of Table 2 to confirm the relationships discussed here.

➢ Going **up** in size by **3** gage numbers, such as from 1/0 AWG to 4/0 AWG, increases the area by an approximate factor of 2 and the diameter by a factor of $\sqrt{2}$ = 1.414. This increase in diameter can be confirmed by solving $(1.123)^3$ = 1.416 [approximately 1.414].

➢ Going **down** in size by **3** gage numbers, such as from 1/0 AWG to 3 AWG, decreases the area by an approximate factor of 1/2 and the diameter by a factor of $\sqrt{1/2}$ = 0.707. This decrease in diameter can be confirmed by solving $(0.8905)^3$ = 0.706 [again, it's approximate].

➢ Going **up** in size by **6** gage numbers, such as from 10 AWG to 4 AWG, increases the area by an approximate factor of 4 and the diameter by a factor of $\sqrt{4}$ = 2. This increase in diameter can be confirmed by solving $(1.123)^6$ = 2

➢ Going **down** in size by **6** gage numbers, such as from 10 AWG to 16 AWG, decreases the area by an approximate factor of 1/4 and the diameter by a factor of $\sqrt{1/4}$ = 0.5. This decrease in diameter can be confirmed by solving $(0.8905)^6$ = 0.499.

➢ Going **up** in size by **10** gage numbers, such as from 10 AWG to 1/0 AWG, increases the area by an approximate factor of 10 and the diameter by a factor of $\sqrt{10}$ = 3.16. This increase in diameter can be confirmed by solving $(1.123)^{10}$ = 3.19 (approximate).

> ➤ Going **down** in size by **10** gage numbers, such as from 10 AWG to 20 AWG, decreases the area by an approximate factor of 1/10 and the diameter by a factor of $\sqrt{1/10} = 0.316$. This decrease in diameter can be confirmed by solving $(0.8905)^{10} = 0.314$ (approximate).

Let's confirm the above rules of thumb in the following three examples.

EXAMPLE 4
Going up 3 gages and down 3 gages:

Up 3 Gages	Area (C.M.)	Solid Diam. (mils)
4/0 AWG	211,600	460.0
1/0 AWG	105,560	324.9
Ratio	2.005	1.416

Down 3 Gages	Area (C.M.)	Solid Diam. (mils)
3 AWG	52,624	229.4
1/0 AWG	105,560	324.9
Ratio	0.499	0.706

END OF EXAMPLE

EXAMPLE 5
Going up 6 gages and down 6 gages:

Up 6 Gages	Area (C.M.)	Solid Diam. (mils)
4 AWG	41,738	204.3
10 AWG	10,384	101.9
Ratio	4.020	2.005

Down 6 Gages	Area (C.M.)	Solid Diam. (mils)
16 AWG	2,581	50.8
10 AWG	10,384	101.9
Ratio	0.249	0.499

END OF EXAMPLE

EXAMPLE 6
Going up 10 gages and down 10 gages:

Up 10 Gages	Area (C.M.)	Solid Diam. (mils)
1/0 AWG	105,560	324.9
10 AWG	10,384	101.9
Ratio	10.166	3.188

| Down 10 Gages	Area (C.M.)	Solid Diam. (mils)
20 AWG	1,024	32.0
10 AWG	10,384	101.9
Ratio	0.099	0.314

END OF EXAMPLE

Stranded Conductors:

There are many applications that use solid conductors, such as Romex® for residential wiring and some telephone wiring within buildings, but the majority of commercial and industrial wiring installations use stranded conductors. When compared to solid conductors, stranded conductors are easier to pull through conduits and are easier to bend into place in cabinets and panelboards.

A stranded conductor is composed of several smaller solid conductors, usually of 7, 19, 37, 61, or 91 strands (see Figure 6). The most common type of stranding is Class B stranding, as defined by ASTM B8 and formerly ANSI C7.8. There are other classes of stranding defined in ASTM B8, such as AA, A, C, and D, which won't be discussed in this course. Figure 6 shows that the quantity of strands follows a hexagonal progression, such that there are six more strands in successive layer of strands. For example, the first layer on the single-strand core has 6 strands, the second layer has 12 strands, the third layer has 18 strands, etc. This is also illustrated in Table 3.

> *Other Types of Stranding:*
> *There are other types of concentric-lay stranding, such as compressed and compact, which will not be elaborated on in this document.*

You can lay seven identical coins on a flat surface to confirm the seven-strand arrangement shown in Figure 6. You can also confirm the rest of the hexagonal arrangements by adding the number of layers and strands (all identical coins) indicated.

7-Strand	19-Strand	37-Strand	61-Strand	91-Strand
1 Layer	2 Layers	3 Layers	4 Layers	5 Layers
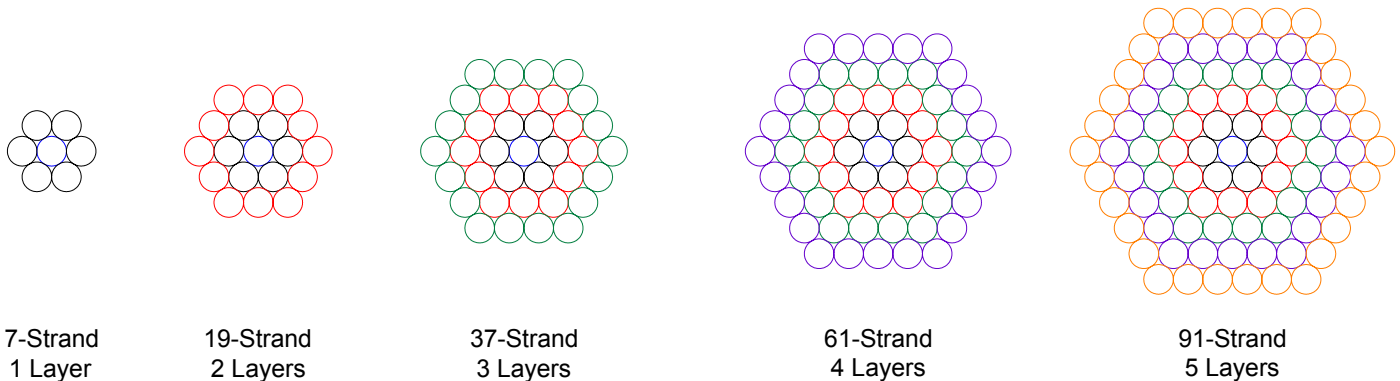
Hexagonal Relationship of Class B Concentric-Lay Strand Quantities
Figure 6

TABLE 3 - Number of Strands per Layer									
n = # of Layers on Core	Core Only	1st Layer of Strands	2nd Layer of Strands	3rd Layer of Strands	4th Layer of Strands	5th Layer of Strands	6th Layer of Strands	7th Layer of Strands	8th Layer of Strands	Total # of Strands*
0	1									1
1	1	6								7
2	1	6	12							19
3	1	6	12	18						37
4	1	6	12	18	24					61
5	1	6	12	18	24	30				91
6	1	6	12	18	24	30	36			127
7	1	6	12	18	24	30	36	42		169
8	1	6	12	18	24	30	36	42	48	217

*The formula for the total number of strands based on the number of layers is $[3n * (n+1)] + 1 = \underline{3n^2 + 3n + 1}$ where n = # of layers.

If each layer of strands were permitted to nestle in between the strands of the previous layer of strands, as illustrated in Figure 6, then the shape would indeed be a hexagon. However, Type B stranding requires each layer of strands to be twisted in the opposite direction of the previous

layer of strands. This pushes the strands out of the hexagonal shape and forces them into the circular arrangement shown in Figure 7.

Hexagon   Circular Arrangement
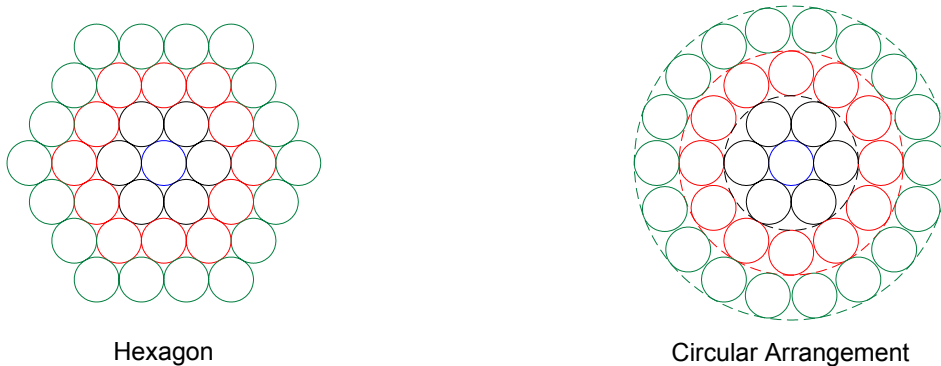
Circular Arrangement Resulting from Opposite Twists of Each Layer
Figure 7

As can be seen in Figure 7, the hexagon is the tightest arrangement, but the conductors of layers 2, 3, and beyond are forced out of the hexagonal shape by the oppositely-twisted conductors in the previous layer and will form a circular shape. The three dashed-line circles in Figure 7 represent the outer boundary of the twisted strands, which also defines the inner boundary of the next layer of strands.

Table 2 shows the typical quantity of strands for each size of wire, but how does one determine the size of each individual strand? The strands are all the same size and we know how many strands are needed, so it is a simple matter to determine the minimum size of the strands for each conductor size. Using 1/0 AWG as an example, we know from Table 2 that there will be 19 strands and that they need to add up to 105,600 circular mils (c.m.) to meet the nominal NEC requirement. This means that each of the 19 strands should have a minimum cross-sectional area of 105,600 c.m. / 19 = 5,558 c.m. A cross-sectional area of 5,558 c.m. means the solid strand would have to have a diameter of $\sqrt{5,558}$ = 74.55 mils. This could be accomplished with 19 strands of 12 AWG, which has 6,530 c.m. per strand, for a total cross-sectional area of 19 * 6,530 c.m. = 124,070 c.m. This is 18,470 c.m. more than we need, which is like giving away a free 8 AWG wire with every 1/0 AWG wire, but we are locked in to having 19 strands for the reasons illustrated in Figure 6.

When looking at the dimensional data in manufacturer's literature for stranded conductors, one notices that the strands aren't exactly the same diameter as typical AWG sizes. For example, we determined that 19 strands of 12 AWG would be suitable for a stranded 1/0 AWG conductor, but Table 2 says that the strands are actually 5,550 c.m. each (a diameter of 74.5 mils), which is in between 12 AWG and 13 AWG. By using these in-between strand sizes, manufacturers won't have the extra 18,470 c.m. we calculated when making a stranded 1/0 AWG conductor from 19 strands of solid 12 AWG. Using the in-between strands of 5,550 c.m. each, the total cross-sectional area of the 1/0 AWG stranded conductor is 19 * 5,550 c.m. = 105,455 c.m. This cross-

sectional area falls a little bit short of the nominal NEC value of 105,600 c.m., but that is okay, since it is a nominal value.

There is another way to calculate strand sizes. In the previous paragraph, we said that if the number of strands is 19, we divide the required area by 19 to determine the required cross-sectional area for each strand. Alternatively, since the area is based on the square of the diameter, we could have divided the diameter of the solid conductor by the square root of 19 to determine the required diameter of each strand. For example, a solid 1/0 AWG conductor has a diameter of 324.9 mils. If we divide that diameter by the square root of the number of strands, we get 324.9 / $\sqrt{19}$ = 74.5 mils. Similarly, for a 10 AWG stranded conductor, the number of strands is 7 and the diameter of a solid 10 AWG conductor is 101.9 mils. To determine the required diameter of each of the 7 strands for 10 AWG, divide 101.9 mils by $\sqrt{7}$ to get 38.5 mils per strand.

EXAMPLE 7

What would be the quantity and size of the strands required for a 500 KCMIL stranded conductor as described in Table 2?

Looking at the 500 KCMIL row on Table 2 tells us that there will be 37 strands and we know that the equivalent cross-sectional area is 500 KCMIL or 500,000 circular mils. Dividing 500,000 by 37 gives us a minimum requirement of 13,514 c.m. per strand, which is equal to a diameter of $\sqrt{13,514}$ = 116.2 mils per strand. Double-check these two values agree approximately with those shown on Table 2.

Let's triple-check our work by using the other method described above. The diameter of a solid 500 KCMIL conductor would be $\sqrt{500,000}$ = 707.1 mils. To find the minimum diameter of each strand, we divide the solid diameter by the square root of the number of strands, which is 707.1 / $\sqrt{37}$ = 116.2 mils per strand. The area of each strand in circular mils would be the diameter squared, which is $(116.2)^2$ = 13,502 c.m..

END OF EXAMPLE

Notice in Table 4, which is a different representation of a portion of Table 2, that the strands used to make up the numbered AWG sizes (not KCMIL) also follow the geometric progression discussed above, namely 1.123 and its inverse, 0.8905. The 19-strand diameters are not related to the 7-strand diameters. Let's look at some of the 19-strand diameters.

TABLE 4 - Each Strand Is 0.8905 * Next-Larger Strand		
Stranded Wire Gage	19-Strand Diameters	7-Strand Diameters
4/0	105.5	
3/0	94.0	
2/0	83.7	
1/0	74.5	
1	66.4	
2		97.4
3		86.7
4		77.2
5		68.8
6		61.2
7		54.5
8		48.6
9		43.2
10		38.5
11		34.3
12		30.5
13		27.2
14		24.2
15		21.6
16		19.2
17		17.1
18		15.2
19		13.5
20		12.1
21		10.8
22		9.6
23		8.5
24		7.6
25		6.8
26		6.0
27		5.4
28		4.8
29		4.3
30		3.8
31		3.4
32		3.0
33		N.A.
34		N.A.
35		N.A.
36		N.A.
37		N.A.
38		N.A.
39		N.A.
40		N.A.

EXAMPLE 8

Going from 3/0 AWG to 2/0 AWG (1 step), the ratio of the <u>strand</u> diameters is (from Table 4 or Table 2):

Ratio = 94 / 83.7 = 1.123

Going from 3/0 AWG to 1/0 AWG (2 steps):

Ratio = $^2\sqrt{(94 / 74.5)}$

Ratio = $^2\sqrt{1.262}$

Ratio = 1.123

Going from 3/0 AWG to 1 AWG (3 steps):

Ratio = $^3\sqrt{(94 / 66.4)}$

Ratio = $^3\sqrt{1.416}$

Ratio = 1.123   END OF EXAMPLE

Now, let's consider some of the 7-strand diameters:

EXAMPLE 9

Going from 17 AWG to 18 AWG (1 step):

Ratio = 17.1 / 15.2 = 1.125 (pretty close to 1.123)

Going from 16 AWG to 18 AWG (2 steps):

Ratio = $^2\sqrt{(19.2 / 15.2)}$

Ratio = $^2\sqrt{1.263}$

Ratio = 1.124 (close enough to 1.123)

Going from 10 AWG to 18 AWG (8 steps):

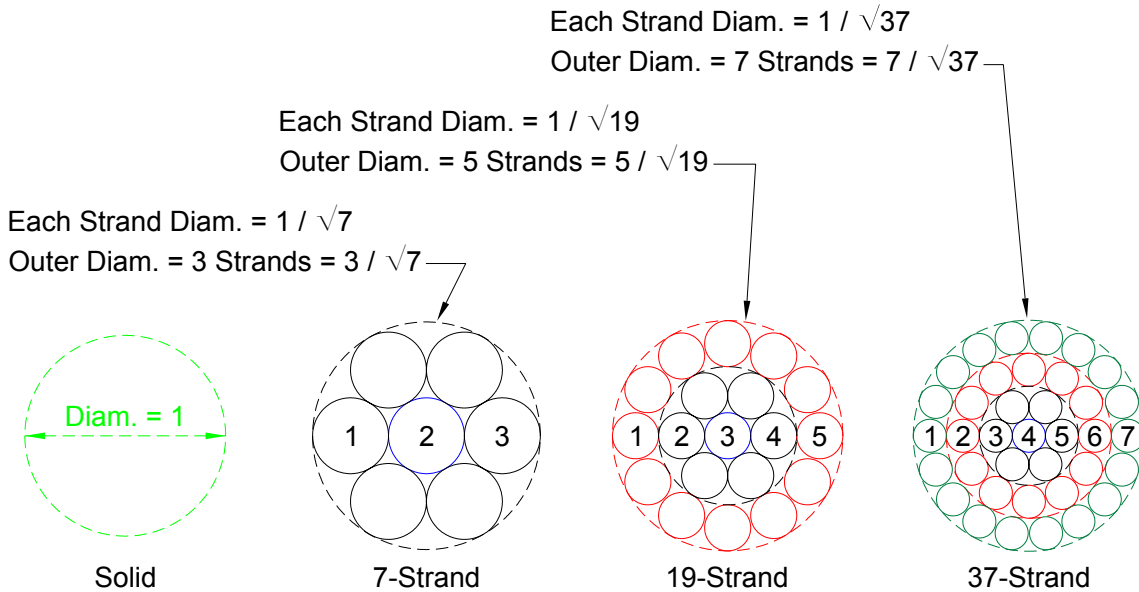Ratio = $^8\sqrt{(38.5 / 15.2)}$

Ratio = $^8\sqrt{2.533}$

Ratio = 1.123   END OF EXAMPLE

One might find tables in industry publications that compare the overall diameter of a bare stranded conductor to the diameter of a bare solid conductor of the same effective cross-sectional area. Such a table is shown in Table 5.

Table 5 - Ratio Between Bare Solid & Stranded Conductors Outside Diam.			
# of Strands	# of Layers	Ratio of Stranded / Solid O.D.	How They Did It
7	1	1.134	3 / √7
19	2	1.147	5 / √19
37	3	1.151	7 / √37
61	4	1.152	9 / √61
91	5	1.153	11 / √91
127	6	1.154	13 / √127
169	7	1.154	15 / √169
217	8	1.154	17 / √217

There is nothing magical or mysterious about the ratios shown in Table 5, they are based on simple geometry and the relationship we've already discussed between solid and stranded conductor diameters. Figure 8 shows a theoretical solid conductor with a diameter of 1 to make our results easier to understand. Let's start with the 7-strand bare conductor. We know from Example 7 that the diameter of each of the 7 strands will be the diameter of the solid conductor (1, in this case) divided by √7. We can see from Figure 8 that the overall or outside diameter of the 7-strand conductor is equal to the diameter of three strands, which are numbered in Figure 8. To phrase this differently, it is three strands across. The outside diameter of the 7-strand conductor is therefore 3 * (1 / √7) = 3 / √7, as shown in Table 5 and Figure 8.

Each Strand Diam. = 1 / √37
Outer Diam. = 7 Strands = 7 / √37

Each Strand Diam. = 1 / √19
Outer Diam. = 5 Strands = 5 / √19

Each Strand Diam. = 1 / √7
Outer Diam. = 3 Strands = 3 / √7

Diam. = 1

Solid   7-Strand   19-Strand   37-Strand

Ratios of Bare Solid Conductor to Bare Stranded Conductors
Figure 8

In a similar fashion, for the 19-strand bare conductor, the outside diameter is five strands across and the diameter of each strand is 1 / √19. Therefore, the outside diameter is equal to 5 / √19. For the 37-strand bare conductor, the outside diameter is 7 strands across and the diameter of each strand is 1 / √37, so the outside diameter is equal to 7 / √37.

As one more layer is added to the stranding, the outside diameter is increased by two more strands, such that the series (starting at one layer and stopping at eight layers) is 3, 5, 7, 9, 11, 13, 15, and 17, but this series will keep going from layers nine to beyond. The first eight layers are shown in Table 5 and the first three layers are illustrated in Figure 8.

Skin Effect or Depth of Penetration:

We know how to determine the cross-sectional area of a certain conductor, but how much of that cross-sectional area is utilized by the electrical signal? Let's consider a solid conductor or bus bar. A direct current (DC) electrical flow is spread out or distributed evenly over the cross-sectional area of a conductor. By contrast, an alternating current (AC) electrical flow is more dense at the surface of the conductor and less dense in the center of the conductor. This is known as the skin effect or the depth of penetration. The formula for depth of penetration into a conductor (in meters) is:

$$\delta = 1 / \sqrt{(\pi * f * \mu * \sigma)}$$

Where: f = frequency in Hz
              $\mu = 4 * \pi * 10^{-7}$ H/meter
              $\sigma = 5.8 \times 10^{7}$ mhos/meter for copper.

The depth of penetration into the conductor depends on the frequency (f) of the signal. At the standard AC electrical frequency of 60Hz, the depth of penetration into a copper conductor is:

$\delta = 1 / \sqrt{[\pi * f * \mu * \sigma]}$

$\delta = 1 / \sqrt{[\pi * 60 * (4 * \pi * 10^{-7}) * (5.8 \times 10^{7})]}$

$\delta = 1 / \sqrt{[1.374]}$

$\delta = 1 / 1.172$

$\delta = 8.532 \times 10^{-3}$ meters $= 8.532$ mm

Converting from metric, the depth of penetration in inches is:

$\delta = 8.532$ mm $/ 25.4$ mm/inch $= 0.336$ or 1/3"

The higher the frequency, the less the depth of penetration of the signal into the conductor. As we calculated above, at a frequency of 60 Hz, the depth of penetration into a copper conductor is approximately 1/3". This is one reason that bus bars for 60 Hz AC power are usually less than 1" thick.

The depth of penetration is not a sharp division between flow and no-flow, but is a gradual lessening of current flow. The current density or amount of flow (at 60 Hz) that is present at a certain distance (d) into the conductor when compared to the surface of the conductor is an exponential function that is described by:

Percentage of flow $= e^{-d/\delta}$

For example, if the distance (d) into the conductor is 1/3" and the depth of penetration (δ) is 1/3", then the percentage of flow at that distance into the conductor is:

Percentage of flow $= e^{-(1/3 \ / \ 1/3)}$

Percentage of flow $= e^{-1}$

Percentage of flow $= 0.368 = 37\%$

This means that $100 - 37 = 63\%$ of the current flow is present in the first 1/3" of the conductor's skin. At a distance (d) of 2/3" into the conductor, the percentage of flow is:

Percentage of flow $= e^{-(2/3 \ / \ 1/3)}$

Percentage of flow $= e^{-2}$

Percentage of flow = 0.136 = 14%

This means that 100 – 14 = 86% of the current flow is present in the first 2/3" of the conductor's skin. At a distance (d) of 1" into the conductor, the percentage of flow is:

Percentage of flow = $e^{-(1/1/3)}$

Percentage of flow = e^{-3}

Percentage of flow = 0.0498 = 5%

This means that 100 – 5 = 95% of the current flow is present in the first 1" of the conductor's skin at 60 Hz.

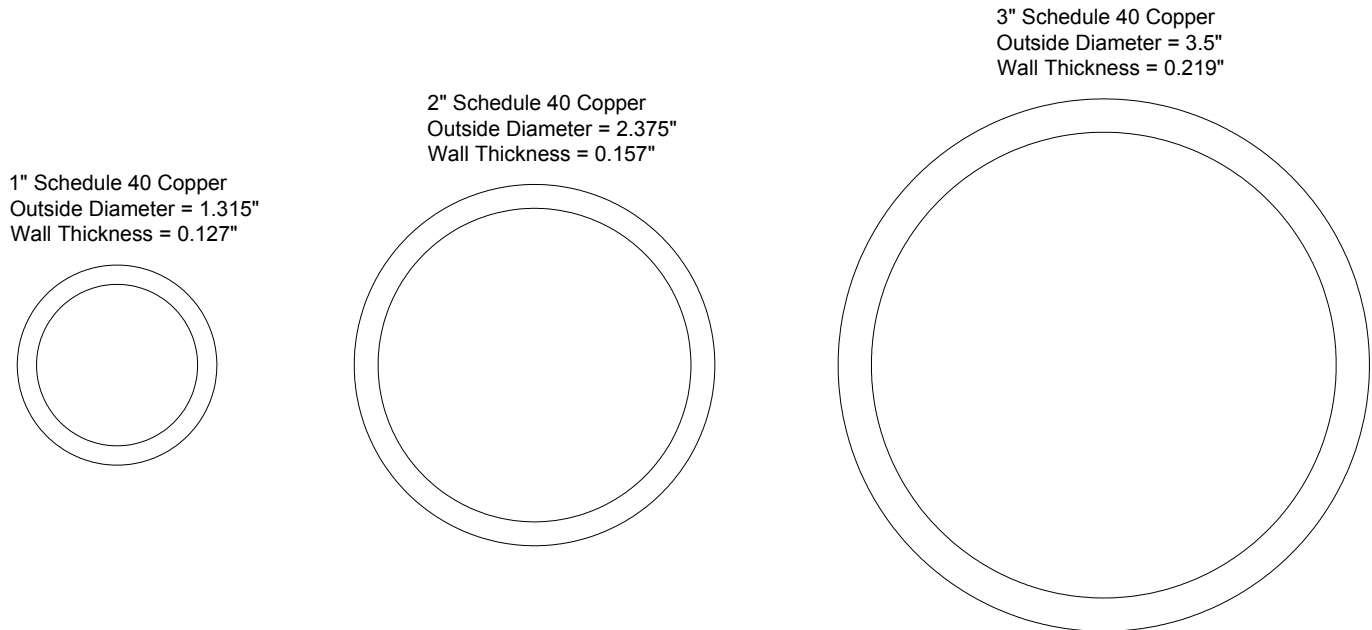Table 6 shows the depths of penetration for a variety of frequencies.

Table 6 - Depth of Penetration at Various Frequencies			
Freq. (Hz):	Depth of Penetration (δ):		
1	0.06609 meters	66.0855 mm	2.6018 inches
50	0.00935 meters	9.3459 mm	0.3679 inches
60	0.00853 meters	8.5316 mm	0.3359 inches
100	0.00661 meters	6.6085 mm	0.2602 inches
1,000	0.00209 meters	2.0898 mm	0.0823 inches
10,000	0.00066 meters	0.6609 mm	0.0260 inches
100,000	0.00021 meters	0.2090 mm	0.0082 inches
1,000,000	0.00007 meters	0.0661 mm	0.0026 inches

Figure 9 shows some examples of solid copper conductors that are thicker than they need to be at 60 Hz, since the interiors of the solid conductors are under-utilized material that do not carry much current.

1" Diameter Solid Conductor   1" x 2" Solid Busbar
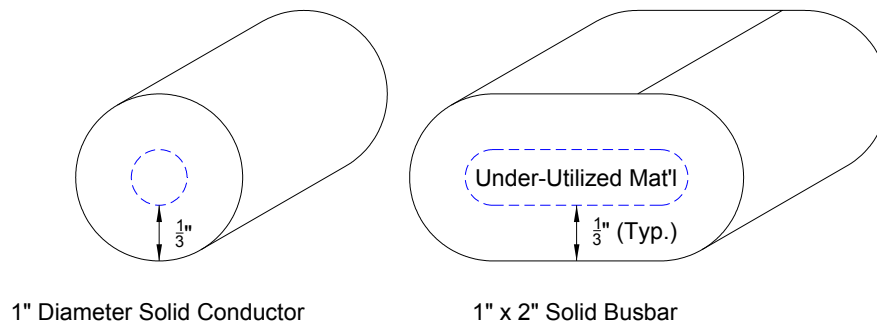
Skin Effect and Depth of Penetration at 60 Hz
Figure 9

The skin effect also explains one of the reasons that hollow aluminum or copper tubes or pipes are often used as electrical buswork, since the current flow of AC signals occurs mostly toward the outside of the conductor, the extent of which depending on the frequency of the signal. Consider Figure 10, which shows some examples of Schedule 40 copper bus pipes.

3" Schedule 40 Copper
Outside Diameter = 3.5"
Wall Thickness = 0.219"

2" Schedule 40 Copper
Outside Diameter = 2.375"
Wall Thickness = 0.157"

1" Schedule 40 Copper
Outside Diameter = 1.315"
Wall Thickness = 0.127"

Copper Bus Pipe, Schedule 40
Figure 10

Let's calculate the effective cross-sectional area of the 2" bus pipe shown in Figure 10.

EXAMPLE 10

We will calculate the effective cross-sectional area by finding the area of the outside diameter and subtracting the area of the inside diameter. This will leave us with the cross-sectional area of the pipe walls, which is the conductor.

The area of the outside diameter is:

$A_1 = \pi * d^2 / 4$

$A_1 = \pi * (2.375)^2 / 4$

$A_1 = \pi * 5.64 / 4$

$A_1 = 4.43$ square inches

The inside diameter is equal to the outside diameter minus the wall thickness twice:

Inside Diameter = 2.375 – (2 * 0.157)

Inside Diameter = 2.375 – 0.314

Inside Diameter = 2.061 inches

So, the area of the inside of the pipe will be:

$A_2 = \pi * d^2 / 4$

$A_2 = \pi * (2.061)^2 / 4$

$A_2 = \pi * 4.25 / 4$

$A_2 = 3.34$ square inches

Subtracting the area of the inside circle from the area of the outside circle:

Effective cross-sectional area = $A_1 – A_2$

Effective cross-sectional area = 4.43 – 3.34

Effective cross-sectional area = 1.09 square inches

To put this in terms of circular mils:

Effective cross-sectional area = 1.09 in^2 / (7.85 x 10^{-7} in^2/c.m.)

= 1,388,535 c.m. or 1,390 KCMIL   END OF EXAMPLE

Table 7 shows a few sizes of Schedule 40 copper bus pipe and the effective cross-sectional area for each.

Table 7 - Sch. 40 Copper Bus Pipe		
1" Sch. 40 Copper		
Outer Diameter	1.315	inches
Wall Thickness	0.127	inches
Conductive Area:	0.474	sq. in.
Conductive Area:	603,810.1	cir. mils
2" Sch. 40 Copper		
Outer Diameter	2.375	inches
Wall Thickness	0.157	inches
Conductive Area:	1.094	sq. in.
Conductive Area:	1,393,610.5	cir. mils
2.5" Sch. 40 Copper		
Outer Diameter	2.875	inches
Wall Thickness	0.188	inches
Conductive Area:	1.587	sq. in.
Conductive Area:	2,021,648.9	cir. mils
3" Sch. 40 Copper		
Outer Diameter	3.500	inches
Wall Thickness	0.219	inches
Conductive Area:	2.257	sq. in.
Conductive Area:	2,875,613.8	cir. mils

Table 7 shows us that, if we need a Schedule 40 copper bus pipe with an effective cross-sectional area of 2,000 KCMIL (similar to the bus bar in Example 1), we would need a 2.5" pipe. Figure 11 shows three different ways we have discussed to meet the minimum requirement for 2,000 KCMIL.

Diam. = 1.414"

1/2"

Width = 3.5"

2.5" Schedule 40 Copper
Outside Diameter = 2.875"
Wall Thickness = 0.188"
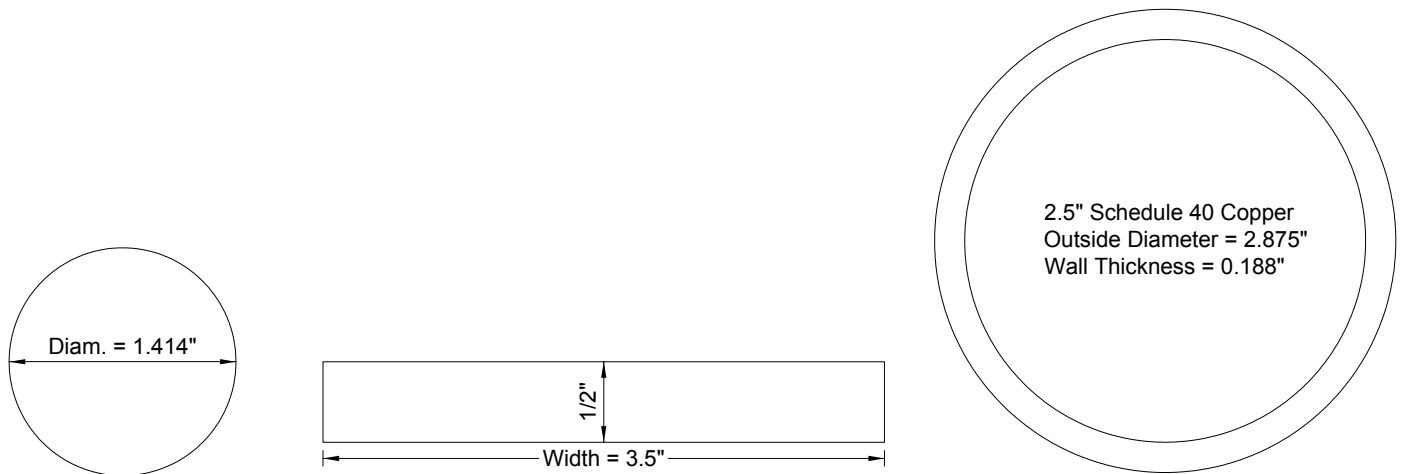
Solid 2,000 KCMIL Conductor, 1/2" x 3.5" Solid Bus Bar, and 2.5" Sch. 40 Copper Bus Pipe
Figure 11

This discussion of skin effect and depth of penetration has been with regard to solid conductors. Stranded conductors are less prone to skin effect, since they have more surface area.

In Closing:

Although the concept of AWG wire size designations may seem somewhat arbitrary, it is actually based on the manufacturing technique used to draw the wires down to smaller and smaller diameters. The unit of cross-sectional area known as circular mils might also be confusing, but it is really intended to be a simple conversion from the diameter to the area (and vice-versa) of a solid cylindrical conductor. The skin effect was presented to explain why large solid conductors are rarely seen.

Abbreviations:

AC – Alternating Current.
AWG – American Wire Gage
C.M. – Circular Mils – a measurement of cross-sectional area that is equal to the area of a circle
     that is 0.001" (one mil) in diameter.
DC – Direct Current.
f – frequency in Hz or cycles per seconds
KCMIL – Thousand (K) circular (C) mil (MIL) – formerly known as MCM.
MCM – Thousand (M) circular (C) mil (M) – now more-commonly known as KCMIL.
NEC – National Electrical Code (NFPA 70).[2005 edition was used for this course]
μ – Permeability in Henries per meter = $4 * \pi * 10^{-7}$ H/meter
σ – Conductivity in mhos per meter = 5.8×10^7 mhos/meter for copper

The author wishes to thank Joe Taylor, PE, for his time and invaluable input on this project.

— ···· ·— —· —·— —·—— ——— ··—