Conductors for HF Antennas

Putting up an antenna for the low bands? What kind of wire will you use? This analysis may change your plans.

By Rudy Severns, N6LF

Most of us give little thought to the wire from which we fabricate antennas. Most of the time that’s okay, but some antennas are quite sensitive to conductor loss. Then we need to think carefully about our choice of wire or other conductor. Recently, I have been building 160-meter wire arrays using hundreds of feet of wire in each. Some of the spans are over 600 feet, and they are attached to poles and trees that move in the wind. For this reason, I initially used #12 stranded Copperweld with PVC insulation. One of the antennas is a two-element, end-fire array—essentially a vertically polarized W8JK. It is a problem with any end-fire array that to obtain gain, the radiation resistance must be lowered by closely spacing the elements. In the case of a W8JK array, the impedance is in the range of 8 to 20Ω. As Krause pointed out in Reference 1, this makes the obtainable gain very sensitive to conductor resistance. The problem is particularly severe on 160 meters because the wire used is very long (over 700 feet in my array) and tubing is impractical.

The performance of the W8JK array was good, but I had a feeling that I could get much more from the antenna. This led me on a hunt to identify possible losses: to measure wire resistance, to analyze expected conductor losses, to finite-element model solid-copper and Copperweld (copper-clad steel) wire and to model the effects of wire losses on antenna performance. The results are interesting and give insight into appropriate conductor selection. It turns out my intuition was right, the conductor loss was high. The wire resistance was double the expected value, but the reason for that was a surprise.

Conductors

Many types of wire, conductive strips and tubes can be and are used for antennas. The reference against which other wires are judged is solid #12 AWG, soft-drawn, bare copper. Other common choices are:
- seven-strand, hard-drawn copper
- solid #12 AWG Copperweld
- 19-strand Copperweld (#12 AWG)
- aluminum electric-fence wire, in various sizes
- Alumoweld (aluminum-clad steel, see Reference 2)
- #8 AWG aluminum clothesline
- aluminum tubing
- thin copper or aluminum strips
- stainless steel tubing
- towers and galvanized steel guy wires

Occasionally galvanized steel fence wire, stainless steel or copper plated steel electric fence wire is suggested for antennas. These are very poor choices, as I will show shortly. Table 1 lists the resistivity and conductivity for some common conductors. The values for steel are only approximate because they vary greatly with the exact composition and processing history.

Sometimes silver plating is suggested for conductors. The conductivity of silver is only 6% better than copper, but when the surface oxidizes, silver oxide is a much better conductor than copper oxide. We will not be considering silver conductors for the rest of this article, however.

**Skin Effect**

The resistance of wire at a given frequency depends on three things: size, electrical properties of the material (including surface corrosion!) and the

<table>
<thead>
<tr>
<th>Table 1—Conductivity and Resistivity of Conductors</th>
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<tr>
<td>Material</td>
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<tr>
<td>Silver</td>
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<tr>
<td>Copper (annealed)</td>
</tr>
<tr>
<td>Aluminum (99.9%)</td>
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<tr>
<td>Iron</td>
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<tr>
<td>Low-carbon steel (AISI 1040)</td>
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<tr>
<td>Stainless steel (AISI 304)</td>
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*Fig 1—$R_{ac}/R_{dc}$ ratio for solid round wire. Wire diameter ($d$) is normalized to the skin depth, $\delta$, where $d$ is the actual wire diameter and $\delta$ is the skin depth in the same units.*

*Fig 2—Current density ($J$) in a solid copper #26 AWG wire (cross section A) at 1 (B) and 16 (C) MHz.*
resistance increase due to skin effect. Skin effect is the tendency for current to crowd to the outer perimeter of a conductor as frequency is increased. It is characterized by the depth at which the current density ($J$) has fallen to about 0.37 ($1/e$, where $e=2.718$). For good conductors, the skin depth ($\delta$) is expressed by:

$$\delta = \frac{1}{\sqrt{\mu \sigma f}} \text{ meter} \quad (Eq \ 1)$$

where:
- $\delta$ = skin depth (meters)
- $\mu$ = permeability = $\mu_r \mu_0$, $\mu_0 = 4\times10^{-7}$ H/m; $\mu_r$ = relative permeability
- $\sigma$ = conductivity in siemens/m (mho/m)
- $f$ = frequency (hertz)

For copper at room temperature:

$$\delta = \frac{2.602}{\sqrt{f/\text{MHz}}} \text{ mils} \quad (Eq \ 2)$$

For $f = 1.8$ MHz, $\delta = 1.94$ mils. For $f = 14.2$ MHz, $\delta = 0.69$ mils. The Appendix contains a graph of the relation between skin depth and frequency for copper at 20$^\circ$ and 100$^\circ$C.

For round wire, the variation of $R_{ac}/R_{dc}$ ($F_r$, or resistance factor) with normalized wire diameter $X = d/\delta\sqrt{2}$ is shown in Fig 1. The variable $d$ is the wire diameter, in the same units as $\delta$. The equation from which the graph is derived is given in the Appendix. For #12 AWG copper wire at 1.8 MHz, $X = 29.5$ and $F_r = 10.8$. For the same wire at 14.2 MHz, $X = 83$ and $F_r = 30$. This thirty-fold resistance increase at 20 meters is due to skin effect! It cannot be ignored on any amateur band.

I am fortunate to have access to finite-element modeling (FEM) CAD software that can directly calculate and graph current distribution and power loss in conductors such as solid copper wire or Copperweld, which is made of two different materials. The graphs in Figs 2 through 5 were generated using FEM software (see Reference 2).

Figs 2B and 2C give plots of the current density ($J$ in A/m$^2$) along the line shown in Fig 2A, for solid #26 AWG copper wire ($\delta = 15.9$ mils) at 1 and 16 MHz. The crowding of current to the outside perimeter of the wire and how crowding worsens as frequency increases is clearly shown. This is why the apparent resistance of the wire increases so much. At some points within the wire, the instantaneous current is actually flowing backwards (minus signs) due to the self-induced eddy currents that are the underlying phenomena responsible for skin effect. These currents must be balanced by more forward current (+) to keep the average current unchanged. That is, the same number of carriers must come out one end of the wire that you put in the other end. The net result is increased power dissipation for a given RMS current.

In Copperweld wire, the copper cladding on the outside of the wire is typically about 10% of the wire radius. For #26 AWG wire, the cladding thickness would be about 0.8 mils (0.0008 inches). Fig 3 graphs $J$ for #26 AWG Copperweld. It is clear that the current is flowing only in the copper cladding; there is almost no current in the steel core. This is predictable from the skin-depth equation; $\delta$ is inversely proportional to the square root of the permeability. For steel, $\mu_r$ is highly variable, affected by the composition of the steel, the processing and even normalized wire diameter $X_{dc} = d/\delta$ is shown in Fig 1. The variable $d$ is the wire diameter, in the same units as $\delta$. The equation from which the graph is derived is given in the Appendix. For #12 AWG copper wire at 1.8 MHz, $X = 29.5$ and $F_r = 10.8$. For the same wire at 14.2 MHz, $X = 83$ and $F_r = 30$. This thirty-fold resistance increase at 20 meters is due to skin effect! It cannot be ignored on any amateur band.

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the current level. Losses can actually increase as the current increases because $\mu_r$ increases with flux density (B), reducing the skin depth and increasing $R_{ac}$. Thus, $\mu_r$ can be from 1000 to 10,000 or more, which means that the skin depth at 1 MHz and above is very small. Copperweld behaves very much like a tubular conductor. This can allow the conductor loss to actually be less or greater than a solid conductor of the same outside diameter, depending on the wall thickness and frequency.

A graph of $R_{ac}$ for 1-meter lengths of #26 AWG solid copper and Copperweld (0.8-mil cladding) wires is given in Fig 4. Below about 14 MHz, the solid copper wire has less resistance. In fact at 2 MHz (160 meters), the Copperweld has more than twice the resistance of solid copper wire. This is simply because current in the Copperweld is crowded into a thin layer. The tube is too thin! Above 14 MHz, however, the tube has less resistance and the Copperweld is superior. Notice also that at low frequencies, the resistance of the Copperweld is nearly constant.

This can be explained from Fig 3, which shows that at low frequencies the current density is basically uniform and changing frequency doesn’t change J much. As you reach the middle range of frequencies, current distribution in the tube is better than that in the solid wire and the loss is less. At some high frequency, current distribution in the tube will equal that in the solid wire (the core no longer matters) and its resistance will be the same. In Fig 4, the resistances begin to converge above 50 MHz. The resistances shown in Fig 5 for #12 AWG wires clearly illustrate the convergence at high frequencies.

For 40 meters and up, stranded Copperweld is a good choice: It has low resistance, good strength and is reasonable to work with. For 80 and 160 meters however, the resistance is quite a bit higher and may be a problem for some antennas. Solid copper or Copperweld would be a better choice. In the case of iron fence wire, stainless steel wire or copper-plated steel electric-fence wire, the skin depth will be very small and the ac resistance very large. The copper plating on electric-fence wire is simply too thin to be of any help at HF.

We must also consider that the current distribution on all but the shortest antennas is not constant but nearly sinusoidal or a portion of a sinusoid. Because the losses are proportional to $I^2R_{ac}$ the loss will be different in different parts of the antenna. This can be accounted for by placing an equivalent resistance ($R_{eq}$) at the current loop, such that $R_{eq}$ dissipates the same total power as the wire. The efficiency ($\eta$) of an antenna, taking into account only the radiation resistance ($r_\lambda$) and the equivalent wire resistance, will be $\eta = r_\lambda/(r_\lambda + R_{eq})$. For $\lambda/2$ or $\lambda/4$ conductors with sinusoidal current distributions, $R_{eq} = R_{ac}/2$, where $R_{ac}$ is the ac resistance for the entire wire length. A derivation of this result is given in the Appendix. For constant current distribution along the conductor, $R_{eq} = R_{ac}$.

![Fig 5—Resistance comparison of 1-meter lengths of #12 AWG solid copper, #12 AWG Copperweld with 4-mil cladding and an equivalent wire for 19-strand #26 AWG Copperweld with 0.8-mil cladding from 1 to 30 MHz. Derived from FEM modeling.](image)

<table>
<thead>
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<th>Table 2—Wire loss comparison for #12 wires.</th>
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<tr>
<td>Perfect</td>
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<td>Copperweld</td>
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<table>
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<th>Table 3—Wire loss comparison for #18 wires</th>
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<td>14.2 MHz Dipole</td>
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<tr>
<td>Perfect</td>
</tr>
<tr>
<td>Copper</td>
</tr>
<tr>
<td>Aluminum</td>
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Effects of Wire Loss on Gain

Okay, so as frequency increases, the resistance of the wire increases and different conductors have more or less loss. So what! Does it really matter?

One way to get a handle on this question is to model some typical antennas and determine the effect of different wire sizes and materials on gain. You can also calculate $R_{eq}$ and then calculate the efficiency of the antenna. This is done in the Appendix. Tables 2 and 3 show the results of modeling three different antennas using perfect, copper (Cu), aluminum (Al) and iron (Fe) conductors of two different sizes. I assumed a resistivity of $10^{-7} \Omega \cdot m$ and a relative permeability of 1000 for the iron wire. Steel wire could actually be worse (lower conductivity and higher permeability). The dipoles and the WSJK array are modeled in free space. The WSJK array has two λ/8 dipoles, spaced λ/8 apart and fed 180° out of phase. The ground-plane antenna has four radials, 10 feet above perfect ground.

The tables show several things of interest. First, for the same wire size, as frequency decreases the wire loss increases. This is because even though the wire resistance per-unit-length is decreasing ($1/f$) the wire length is increasing $(1/f)$. The net wire resistance increases as frequency decreases if the antenna length is scaled. This increase in wire loss can become important in low-band antennas. Second, except for the iron wire, the effect of wire loss and wire size is very small in dipole antennas. You can use copper or aluminum wire in fairly small sizes without compromising performance much. It is also clear that using iron fence wire is bad news.

The ground-plane antenna is more sensitive to wire characteristics than are the dipoles because of its lower impedance, but again the changes are small as long as copper or aluminum wire is used. The use of more radials will reduce wire loss.

The WSJK array, however, is very sensitive to wire size and material. With perfect conductors, the gain over a dipole is 3.8 dB. Using #18 AWG aluminum wire gives away most of that gain (~2.65 dB). Even with #12 AWG copper wire, there is still a loss of over 1 dB. In the WSJK, changing to a #6 AWG wire or two parallel, spaced #12 AWG wires reduces the wire loss to ~0.53 dB.

Any low-impedance antennas, such as Yagis, end-fire arrays or short loaded verticals will be sensitive to wire size and conductivity. On 80 and 160 meters, many verticals are short and heavily loaded!

Flat-Strip Conductors

Up to this point, we have been considering round conductors. An alternative would be to use thin, flat conductors of either copper or aluminum. Fig 6A is a graph of $R_{ac}/R_{dc}$ for thin, flat-strip conductors (see the Appendix for generating equation). For #12 AWG round copper wire at 1.8 MHz, $F_r = 11$. If we take the same wire and roll it out into a strip approximately 0.010×0.625 inches, the thickness of the strip in skin depths will be about 5. Looking at Fig 6 we see that for $X = 5$, $F_r = 2.4$, which is a factor of 4.6 lower than for the equivalent round wire. By dividing $F_r$ by the corresponding values of $X$, we can create Fig 6B, which is a graph of resistance normalized to 1 Ω for a thickness of 1 skin depth. Notice that for $X < 1.5$, the $R_{ac} = R_{dc}$, but as foil thickness increases the resistance goes through a minimum at $X = \pi$ and then back up about 9% to level out at a constant $R_{ac}$ regardless of the thickness. For $X < 1.5$, the current distribution in the conductor is almost uniform, so $R_{ac} = R_{dc}$. Above this point, the distribution in increasingly on the outer surfaces of the strip.

At high frequencies, all the current is on the outer perimeter of the strip so the thickness of the inside doesn’t matter. Only the length of the perimeter counts. This is the same as for a round wire. The important difference between round and strip conductors is that for a round wire, you have to increase the diameter to reduce $R_{ac}$. This means you have a lot of unused copper (inside the wire) to buy. Strip or foil conductors can be kept thin and simply made wider to reduce $R_{ac}$. You put the extra copper to good use and in the end buy less.

Of course, there is the issue of increased wind area with a foil conductor. Foil also tends to “sail” and/or flutter in the wind, distorting the antenna shape and stressing the array. That is a downside! Putting a spiral twist in a foil conductor helps to keep it from flying around in the wind. I have found that 0.010×0.5- to 1-inch strip works pretty well and doesn’t fly around or flutter too much. Unfortunately, copper and alu-

![Fig 6—Resistance factor ($F = R_{ac}/R_{dc}$) for flat-strip conductors as a function of thickness in skin depths.](image-url)
minum foils of appropriate sizes are not so readily available as round wire.

**Composite Antenna Assemblies**

In some cases, straight copper wire simply does not have the strength required, but the alternatives may have too much resistance. It is possible to compromise by using different conductors at different places in the antenna. Keep in mind that the losses are FR in nature. This means that the bulk of the losses occur in the high-current regions of the antenna. Fig 7 shows a 160-meter, two-element end-fire array mentioned earlier. The horizontal portions have high current levels; they are made from 0.010 × 0.625-inch copper strip. The horizontal portions have much less current. The antenna is supported from the top between two poles 300 feet apart, so the upper wires have considerable stress. These are stranded Copperweld. The lower horizontal wires have very little stress; they are copper. The result is an antenna with minimum loss but strength where it is needed.

The 50-pF capacitors tune out the inductive reactance at the feedpoint. These must be high-voltage, high-current capacitors, which usually come in only a few standard sizes. The position of the capacitors and the lengths of the upper horizontal wires can be adjusted to give 450 Ω resistive at the feedpoint. That allows the use of 450-Ω ladder line as the feedline to ground level, where a 9:1 balun transforms to 50 Ω as the feedline to ground level, where a 9:1 balun transforms to 50 Ω for the run back to the shack. Stub matching could be used instead.

**Measurement of Wire Resistance**

Theory and modeling are nice, but I wanted to make some actual measurements of wire resistance to confirm the modeling and calculations. Unless you have access to an impedance analyzer such as an HP4192 (50,000 please!), this is not an easy measurement to make directly. After several false starts, I found it best to wind the wire into a large coil of well spaced turns and measure the Q on a Boonton 260A Q-meter. This gave reasonable results that are shown in Tables 4 and 5. The values for resistance are probably not very precise, but the relative differences between different wires are clearly shown.

| Table 4—#12 AWG bare solid copper wire test results using new wire |
|-----------------|----------------|----------------|----------------|
| Frequency       | Resonating Capacitance | Measured Q | $X_L$ | $R_S$ |
| 1.8 MHz         | 359 pF            | 410          | 246.3 Ω | 0.601 Ω |
| 3.9 MHz         | 69 pF             | 360          | 591 Ω  | 1.64 Ω  |

| Table 5—19-strand #26 AWG Copperweld test results using new wire |
|-----------------|----------------|----------------|----------------|
| Frequency       | Resonating Capacitance | Measured Q | $X_L$ | $R_S$ |
| 1.587 MHz       | 460 pF           | 250          | 218 Ω  | 0.87 Ω  |
| 1.8 MHz         | 358 pF           | 270          | 247 Ω  | 0.92 Ω  |
| 3.9 MHz         | 68 pF            | 323          | 600 Ω  | 1.85 Ω  |

The coil is 17 turns (except for the #8 AWG aluminum wire which used 16 turns) spaced 1.5 wire diameters (with 1/8-inch Dacron rope) on a 4.2-inch ID PVC-pipe form. 4.5 inches long. The coil requires 19.5 feet of Copperweld is substantially lower than that of the solid copper wire coil.

- The variation in Q over frequency is different for each coil.
- The coil Qs begin to converge as the frequency is increased. Remember that $Q = \frac{X_L}{R_S}$, where $X_L = 2\pi f L$ is the impedance, and $R_S$ is the total series loss resistance.

In an antenna, we are interested in the resistance due to skin effect ($R_{ac}$), so we must separate the components of coil loss to get an estimate of the skin-effect loss. $R_S$ has several components:

- skin effect in the conductor
- turn-to-turn and geometric proximity effects
- losses in the coil form
- loss in wire insulation
- radiation from the coil
- losses due to eddy currents in nearby conductors

Skin effect can be calculated quite accurately using the equation of Fig 1.
for a solid, round conductor. For 19.5 feet of #12 AWG copper wire at room temperature and 1.8 MHz:

\[ R_{dc} = 0.031 \, \Omega \], from wire table (I measured the coil as 0.030 \, \Omega on a bridge).

\[ R_{ac}/R_{dc} = F_r = 10.79, \text{ from Fig } 1, \]
\[ R_{ac} = R_{dc} \times F_r = 0.334 \, \Omega \]

At 1.8 MHz, the total \( R_s \) in Table 4 is 0.601 \, \Omega, which indicates an additional loss resistance of 0.267 \, \Omega beyond the skin effect.

Given the close similarity between the two coils, we can estimate the stranded Copperweld coil resistance component due to skin effect to be:

\[ R_{skin} = R_s - 0.267 = 0.915 - 0.267 = 0.648 \, \Omega \]

This is 1.9 times the resistance of solid copper wire! This agrees rather well with the comparison in Fig 5 between 0.8-mil clad Copperweld and solid copper wires. In a dipole, I don’t think this would matter but in a W8JK array, it’s bad news.

Looking again at Fig 5, we would expect the skin-effect loss for the two types of wire to converge as we go higher in frequency, reflected in more similar Qs. This is what we see in Tables 4 and 5. We would also expect the Q of the Copperweld coil to decrease with frequency because \( X_L \) is decreasing, but \( R_s \) is not. For the solid wire coil, both \( X_L \) and \( R_s \) are decreasing, so Q is more stable.

Emboldened by these results, I wound coils using several other wires I had on hand or was able to scrounge from friends. The test results are given in Table 6. I threw in the iron fence wire just for kicks!

The differences in the 14 different wires tested are quite easy to see:

- The #12 AWG wire is better than #14 AWG
- New insulation has very little effect (but weathered insulation may not be so benign!)
- Oxidation of bare wire definitely reduces the Q. Both samples were only mildly oxidized. Longer exposure would have further reduced the Q.
- Stranded wire is inferior to solid.
- Very fine stranding (168-strand sample) reduces the Q significantly
- For the same size wire, solid Copperweld is just as good as solid copper
- At least at low frequencies, stranded Copperweld is inferior to solid Copperweld and other copper wires, solid or stranded
- Iron fence wire is bad news!

I also wanted to verify the advantage of Copperweld wire implied by Fig 4. Using #14 AWG solid copper and solid Copperweld, I wound free-standing three-turn coils and then two coils on a ceramic coil form. The results are shown in Table 7.

In both cases, the Copperweld produced a coil with somewhat higher Q, as predicted by Figs 4 and 5. Remember that only part of \( R_s \) results from skin effect, so the difference between the two wires is diluted by other losses. The tests were run a number of times to be sure the differences were real and repeatable.

### Aluminum Wire Connections

Aluminum wire has the advantages of very low cost and a better strength-to-weight ratio (=3×) than copper. The reduced conductivity (\( \sigma \)) of aluminum can be accommodated by using a larger wire size. For an equal resistance, it will still weigh less than copper. Keep in mind we are talking about equal \( R_{dc} \) not \( R_{ac} \). The difference arises because of skin effect, which is proportional to \( 1/\sqrt{\sigma} \). The skin depth will be greater in aluminum than in copper (at the same frequency) because of the lower conductivity. The lower weight and higher strength is helpful in long spans and may put off the need to use Copperweld conductors.

However, aluminum has one major disadvantage. Making a low resistance connection that will remain low during extended exposure to the elements is not a trivial exercise. It is very possible for a poor connection to introduce significant loss, especially if it is at a high-current point. There are also corrosion problems with connecting copper conductors to aluminum conductors.

### Alumoweld Wire

In addition to Copperweld, aluminum-clad steel wire is available under the name Alumoweld. It is available in a variety of sizes, although the smallest size available is #12 AWG. It is also available as stranded wire and stranded guy wire equivalent to the galvanized wire used for guys. While it is very stiff—handling very much the same as Copperweld or steel wire—it has some advantages. In most atmospheres, it is much more resistant to corrosion than galvanized steel. It is electrolytically compatible with the aluminum tubing frequently used in antennas, so it can be used for support wires in aluminum antenna structures to avoid dissimilar-metal corrosion.

### Towers and Supports

It is quite clear that iron fence wire is a very poor choice for antennas, but what about steel towers and the use of galvanized or stainless steel guy wires as antenna elements? In towers, the surface area is much larger than that

### Table 6—Comparison of Q for coils made with various wires at 1.8 MHz

<table>
<thead>
<tr>
<th>Wire description</th>
<th>Q</th>
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<tbody>
<tr>
<td>New #12 bare soft-drawn solid copper</td>
<td>410</td>
</tr>
<tr>
<td>New insulated solid #12</td>
<td>410</td>
</tr>
<tr>
<td>New insulated stranded #12 THWN</td>
<td>350</td>
</tr>
<tr>
<td>New insulated 19 strand #26 Copperweld</td>
<td>270</td>
</tr>
<tr>
<td>New #14 bare soft-drawn solid copper</td>
<td>353</td>
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<tr>
<td>New #14 bare solid Copperweld</td>
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<tr>
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<tr>
<td>Oxidized #14 bare stranded Copperweld</td>
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<tr>
<td>New #14 bare 7/22 stranded hard-drawn copper</td>
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<td>#14 aluminum electric fence wire</td>
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<td>#8 aluminum clothesline</td>
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<td>#13 iron fence wire</td>
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### Table 7—Coil Qs measured at 25 MHz

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<tr>
<th>Coil form</th>
<th>Wire</th>
<th>Measured Q</th>
<th>( X_L )</th>
<th>( R_s )</th>
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<td>Ceramic</td>
<td>Copperweld</td>
<td>282</td>
<td>193 , \Omega</td>
<td>0.68 , \Omega</td>
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</table>
Appendix

A. Skin depth in copper

Fig A is a graph of skin depth in copper as a function of frequency for two temperatures.

![Graph of skin depth in copper at 20°C and 100°C](image)

Fig A—Skin depth in copper at 20°C and 100°C; dimensions are in mils and millimeters.

B. $R_{eq}$ Derivation

The current distribution in an antenna is usually a sinusoid or a portion thereof as indicated in Fig B. With the center as the origin:

$$I = I_{o(RMS)} \cos \left( \frac{\pi x}{L_2} \right)$$  \hspace{1cm} (Eq A)

Note that $I_o$, the current at $x = 0$, is RMS! The wire loss is:

$$\Delta P = \Delta R I^2 dx$$  \hspace{1cm} (Eq B)

Where $\Delta R$ is the resistance per unit length. The total power loss is then:

$$P = \int_a^b \Delta R I^2 dx = \Delta R \int_a^b I_o(RMS)^2 \cos^2 \left( \frac{\pi x}{2L} \right) dx$$

$$P = \left[ \Delta R I_o \right] \left[ \int_a^b \sin \left( \frac{\pi x}{2L} \right) \cos \left( \frac{\pi x}{2L} \right) + \frac{x}{2} \right]_a^b$$

$$R_{eq} = \frac{P}{I_o^2} = \Delta R \left[ \int_a^b \sin \left( \frac{\pi x}{2L} \right) \cos \left( \frac{\pi x}{2L} \right) + \frac{x}{2} \right]_a^b$$  \hspace{1cm} (Eq C)

For $a = 0$ and $b = L$:

$$P = \frac{I_o^2 \left( \Delta R \right)}{2}$$

$$R_{eq} = \frac{\Delta R}{2}$$  \hspace{1cm} (Eq D)

Where $\Delta R$ is the total $R_{ac}$ for the length of wire. $R_{eq}$ can be used directly to calculate the gain decrease due to conductor loss. The loss is simply the log of the efficiency:

$$loss = 10 \log \left( \frac{r_r}{r_r + R_{eq}} \right)$$  \hspace{1cm} (Eq E)

Table 8—Loss due to conductor resistance for dipoles using #12 AWG solid copper wire

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>$\delta$ (mils)</th>
<th>$X$ (feet)</th>
<th>$F_r$</th>
<th>$L$</th>
<th>$R_{eq}$ (Ω)</th>
<th>Loss (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.84</td>
<td>1.92</td>
<td>29.8</td>
<td>10.8</td>
<td>267</td>
<td>2.29</td>
<td>-0.13</td>
</tr>
<tr>
<td>3.75</td>
<td>1.35</td>
<td>42.5</td>
<td>15.3</td>
<td>131</td>
<td>1.59</td>
<td>-0.09</td>
</tr>
<tr>
<td>7.15</td>
<td>0.98</td>
<td>58.7</td>
<td>21.0</td>
<td>68.8</td>
<td>1.15</td>
<td>-0.07</td>
</tr>
<tr>
<td>14.2</td>
<td>0.69</td>
<td>82.7</td>
<td>29.5</td>
<td>34.6</td>
<td>0.81</td>
<td>-0.05</td>
</tr>
</tbody>
</table>
of a wire. Although the skin depth will be very small, the large surface area should help greatly. I would be more concerned with the joints between tower sections, particularly in high-current regions. This problem has been addressed by attaching copper wire jumpers across tower joints. The problem will be much worse in crankup towers, where the sections have sliding joints between them.

Why is there Skin Effect?

When a time-varying current flows in a conductor, a time-varying magnetic field will be created around the conductor. A simple example is shown in Fig C. A current flowing in the wire creates a magnetic field around the wire as indicated. The direction of the magnetic field in relation to the current obeys the “right-hand rule”—that is, if the thumb of your right hand extends in the direction of positive current flow as shown, the magnetic field will curl around the wire in the same direction as your fingers.

Just as a current creates a magnetic field, a time-varying field, from some external or internal source, will induce a time-varying current in a conductor. This is called an “eddy” current and higher frequencies yield greater-amplitude eddy currents in a given conductor. The direction of the eddy current is such that its magnetic field opposes the inducing field.

We can see how these currents and fields create skin effect by examining Fig D. This is a section of a round wire carrying a current from one end to the other. This current is labeled “A.” It is simply the net current flowing through the wire. This current creates a magnetic field both inside and outside the wire as indicated by the dashed lines “B.” This field, in turn, creates an eddy current (“C”) as shown.

Notice that near the center of the wire, the eddy current opposes the desired current, but on the outer part of the wire, the eddy current aids the desired current. If we look at a cross-section of the wire, we see that the current density near the center is reduced, but near the outside, the current density is increased. As frequency increases, less current flows on the inside of the wire and more flows near the outside surface. Of course, the net current stays the same, but it is crowded into a smaller and smaller portion of the wire’s cross-sectional area.

The result is that the apparent resistance of the wire increases because we are using only a small portion the available copper area to carry current. This means that the loss for a given current will be higher. In copper at HF, the current is crowded into a layer of 2 mils, or less, in thickness. The rest of wire only provides mechanical support for the thin outer layer that conducts.

There is another way to look at skin effect. If you have a large sheet of conductor and you irradiate it with an electromagnetic wave perpendicular to the surface, the wave will penetrate the surface for some small distance. The amplitude of the wave decreases exponentially and the depth at which the amplitude has decreased to $1/e \approx 37\%$ ($e \approx 2.718$, the base of natural logarithms) is referred to as the penetration or skin depth ($\delta$). Increasing frequency decreases $\delta$.—N6LF.

I would be more concerned about loss in a steel tower if it were being used as part of an array with low impedances, especially if the tower is electrically short and heavily loaded. In that case, I would consider installing a collar at the top of the antenna and attaching several parallel copper wires in a cage around the tower from top to bottom. This way the copper is the conductor not the tower. This allows the tower to be grounded directly but still have the feed point open. If the collar were made significantly larger than the tower, then it would not only reduce loss but also increase bandwidth and reduce the loading necessary because of the larger effective diameter of the antenna.

Sometimes the guy wires on a tower or the rigging on a sailboat are used as antennas. Depending on the antenna, these can be very lossy and should be

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**Fig C**—The “right-hand rule” relates the direction of current flow to the magnetic field it produces.

**Fig D**—Eddy currents in wire produce the skin effect. The through current (A) produces a magnetic field (B) that induces eddy currents (C). The eddy currents offset through current near the wire center and add to through current near the wire surface.
used with some caution. Note from Table 1 that the standard marine stain-
less steel (304) has a resistivity greater
than 50 times that of copper. A number
of years ago, I used an insulated back-
stay on my sailboat as a half-sloper, fed
at the top and driven against the alu-
minum mast. To minimize the loss in
the stainless steel backstay, I used a
strip of copper (encased it in plastic
tape to control corrosion) bent over the
backstay in the form of a U for the dis-
tance between the two insulators. This
proved very satisfactory during several
years of cruising in temperate and
tropical waters.

Stainless Steel and
Mobile Antennas
Most mobile antennas are
electrically short and heavily loaded,
especially at and below 7 MHz. The
result is very low radiation resistances.
Because of its very high resistivity,
stainless steel may not be a very good
choice for these antennas despite the
obvious mechanical and corrosion-
resistance advantages. For example,
consider an 8-foot center-loaded whip
with a 0.5-inch diameter base section
and a 0.125-inch diameter top section.
The loss due to conductor resistance
using stainless steel is 0.6 dB at
7.150 MHz, 1.3 dB at 3.8 MHz and
3.1 dB at 1.84 MHz. The use of stainless
steel wire would result in losses very
similar to steel fence wire.

Conclusions
For antennas with current-loop
impedances above 35 Ω or so, any
copper, Copperweld or aluminum wire
in a variety of sizes will work just fine;
however, for lower-impedance anten-
as, copper or Copperweld wire size #12
AWG or larger should be used. Copper
or aluminum tubing is very effective for
low-impedance antennas. For 80- and
160-meter antennas, the resistance of
stranded Copperweld may be
unacceptably high.

New insulation does not seem to
affect loss, at least at 1.8 MHz, but
surface oxidation does. Thin insulation
should have only a very small effect on
tuning but will suppress oxidation.
This is a consideration for low-imped-
ance antennas only.

By careful choice of conductor or
combinations of conductors, consid-
ering both electrical and mechanical
properties, it should be possible to keep
the conductor loss low in almost any
kind of antenna, with the possible
exception of very small antennas.

Loose Ends
Despite the extensive discussion in
this article, several subjects need more
attention. I think the losses in steel
towers need to be analyzed more
closely. I also have not addressed losses
from currents induced in guy and
support wires. Usually these currents
are small if the wire is short compared
to λ/2, but steel wire can be quite lossy
even with small currents. This subject
needs some scrutiny. In searching
through the literature, I found very
little in the way of measurements or
even discussion of antenna conductors.
Books in the reference list contain some
very useful tables, but if you know of
any important articles I have missed
please tell me.

Acknowledgment
I would like to express my thanks for
the review and helpful comments
provided by George Cutsgeorge,
W2VJN. Mark Perrin, N7MQ, and Joe
Brown, N7EZG, were very helpful in
digging out great examples of “cruddy”
wire for me to test. Tom Schiller, N6BT,
told me about Alumoweld wire and
related a number of hilarious anecdotes
concerning antenna conductors.

Notes
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IRE, February 1940, pp-76-84, see Fig 5.
2. “Maxwell” by Ansoft Corporation, Four
Station Square Ste 200, Pittsburgh, PA
15219-1119; tel 412-261-3200, fax 412-
471-9427; e-mail info@ansoft.com;
3. United States Alumoweld Company, Inc,
115 USAC Dr, Duncan, SC 29334; tel 800-
342-8722, 864-848-1901, fax 864-848-
1909; e-mail sales@alumoweld.com;
4. F. Terman, Radio Engineers Handbook
5. D. Fink and W. Beaty, Standard Hand-
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Chapter 4.
7. M. Abramowitz and I. Stegun, Handbook of
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3rd Ed. (ARRL, 1999), pp 8-5 through 8-7.