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## Mastering Masts *The Wrong Stuff* Tom Cox, KT9OM

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### INTRODUCTION

**I** never gave more than a few moments' thought to the choice of an antenna mast, but I should have, as it turned out. *antenneX* readers may recall that I have a 120-foot tower in my back yard, which used to have two VHF SSB Yagis on top, as seen in these proud views.



Fig. 1. Glory Days! The KT9OM QTH tower top as it once was, (sigh).



Fig. 2. A photo I'm proud of, taken last summer, when the moon was "hamming it up" behind the Yagis.

"Used to" is an important choice of words, here, because those antennas are no longer there. During an ice storm in the first week of January 2005, the mast that held these antennas aloft failed. By "failed" I mean it bent nearly double, whacking the two Yagis against the side of the tower, beating the larger antenna into scrap aluminum and damaging the smaller antenna's reflector. From the proud views above, my installation was transformed into the following:



Fig. 3. What do you suppose all that ice weighs?  
My mood was as gray as the sky in the background, when I took this.

This was no trivial ice storm, at least for our area of the United States – East-central Indiana. Damage in my county (Delaware) is still in evidence in high summer, as this is written, and the cost of cleanup is in the high tens of millions of dollars. The ice alone didn't kill my antenna system, but, as the weather turned cold and windy after two days of freezing rain, the extra hundreds of pounds of weight, combined with the greatly increased wind load on the mast and antennas, the dirty deed was done.



Fig. 4. My bent mast was only a big problem for me – other people had more to worry about.

Nobody reasonably expects to control nature, but there was something I could have done that would have reduced the odds that the mast would have bent. I could have used the right material. What I used was 1- 7/8-inch ID, galvanized iron plumbing pipe. This type of pipe, as I have learned in this very expensive lesson, is great for plumbing, but bad for antenna masts. My goal here is to explain why that is, and to recommend other materials that will help you avoid my mistake.

### ***The Right Stuff***

This piece of pipe was very heavy, which helped me to convince myself that it was also very strong. As it turned out, the iron in iron pipe has a characteristic that I should not have wanted in a mast: high ductility. There are hundreds of places on the Web where one can find definitions of ductility, but, for its readability, I have chosen [http://www.engineersedge.com/material\\_science/ductility.htm](http://www.engineersedge.com/material_science/ductility.htm). I recommend that other non-engineers visit the site for the whole discussion, but here is the part that caught my attention:

**“Ductility** is more commonly defined as the ability of a material to deform easily upon the application of a tensile force, or as the ability of a material to withstand plastic deformation without rupture. Ductility may also be thought of in terms of bendability and crushability.”

Ductility turns out to be a desirable feature of iron pipe, because it enables pipe to survive the bending stresses of being transported, buried and then driven over with heavy machinery, and pushed around by changing soil moisture content and freeze/thaw cycles, all “without rupture.” While iron pipe is to be saluted

for this feature, we really don't want the mast at the top of a 120-foot tower, holding up close to a kilobuck (\$1,000 US) of antennas, to be terribly high in "bendability," now, do we? No, we do not. But mine was...



Fig. 5. How much force was required to bend this iron pipe? Mother Nature is a burly girl, isn't she? And a mean one, when she wants to be...

### ***Pipe Is Not Tubing!***

As I discovered in the process of this research, I was careless in using the terms "pipe" and "tubing" interchangeably. While I haven't come across the absolute last word on the distinctions between the two, I have been told that I should have been using tubing for the mast, and not pipe. The main difference seems to be in the fabrication. Plumbing pipe is formed by pouring molten metal into a mold, or spun in liquid form against the inside of a mold – it's a casting, in other words. This, and a high amount of carbon left in the iron, increases its ductility. Either casting method – relying on gravity or centrifugal force to distribute the molten iron in the mold – is adequate for pipe's intended uses, but is not precise. It results in variations in wall thickness, inside and outside diameters, and, therefore, in strength.

There is also a general agreement in the steel industry on a distinction based on the intended use of each. Pipe is for containing and transporting gases and liquids, and, as a result, pipe's resistance to bursting – to *internal* stresses – is an important rating.

Tubing, in contrast, is more likely to be applied to supporting weight, as in reinforcing structures. Or (and this is big business here in the near-field of the Indianapolis 500 Race) it might be used in for racecar roll cages and chassis, to protect racecars from collapse in the event of a crash. We also find it in the frames that hold engine, wheels, and driver together. Tubing, in other words, is designed and made to resist and contain *external* stresses. Weight versus strength is a much more important factor in tubing, as you may imagine, considering that every pound of a racecar carries a penalty in lost acceleration, fuel economy and handling.

Any time a racecar builder can reduce weight without reducing strength, he is beating his opponents before his car ever takes to the track.

Tubing is produced by a lot more “cold working,” which reducing the ductility and increasing the structural strength – making it more appropriate to become a racecar frame, or mast material, and less suitable to be buried and run over with heavy machinery.

“Cold working” is a broad term that refers to various forms of physical torture that metals are put through during manufacture to give them specific shapes and other engineering characteristics. One, particular form of torture is the “drawn over mandrel” (DOM) process. Tubing is first formed from flat steel by rolling the flat piece’s edges toward each other until they meet. The resulting seam is electrically welded. The tubing is then pulled through a hole in a die that reduces its outside diameter by a carefully controlled amount, with an inner die in place (the mandrel) that produces a very accurate inside diameter. This process, besides producing tubing with very uniform and accurate wall thickness, inner and outer diameter, and circular cross section, compresses the individual metal crystals and makes the steel stronger, harder, and more resistant to bending – just what we need in a mast.

For a good explanation of the DOM process, check out <http://www.steeltubeinstitute.org/domprocesses.htm>. And, the animation is very good, as well, in [http://www.steeltubeinstitute.org/process/Dom\\_Process.html](http://www.steeltubeinstitute.org/process/Dom_Process.html).

### ***Better Living through Metallurgy***

Another characteristic of tubing that is critical is the composition of the steel. As silicon is “doped” with impurities to give it the semi-conducting characteristics required for a certain application, steels are deliberately contaminated with small amounts of other substances to modify their metallurgical characteristics. Steel starts out as iron with a varying amount of carbon, depending on the amount needed, but that’s just the beginning for the “recipe” for a given type of steel.

Although the mixture never becomes a chemical compound – that is, the mixing doesn’t take place at the atomic level -- crystals of different metals are heated to a liquid state and mixed with iron and controlled amounts of carbon to yield the desired results. Ductility, tensile strength, hardness, corrosion resistance, and other characteristics are determined in this way. The resulting mixture is called an *alloy*.

### ***Not to Stretch a Point...***

One alloy I considered for mast material, but rejected due to its price tag, was “Chromoly,” “Chrome Moly,” or “chromo.” By doping the iron-carbon mix with very small amounts of Chromium and Molybdenum, the tensile strength of the resulting batch of steel improves dramatically. What’s tensile strength, and why would I want more of it?

To keep from treading on the engineers’ and materials scientists’ turf (and to reduce the chance of saying something stupid, since I am neither scientist nor engineer), I will limit this definition to the simplest terms. Tensile strength is basically the amount of stress applied to a material required to make it come apart. To measure the tensile strength of a metal, scientists place a piece of the metal in a machine that pulls it apart, while tracking the amount of force required to make it break.

Metals have an *elastic limit*, beyond which they will not return to their original shape when stretched. Although rubber bands have a large capacity for elasticity, they make poor masts, because of their well-known lack of rigidity. Steels also have a *plastic limit*, in which the tension begins to cause narrowing of the material, cracks may appear, and the material will not return to its original shape and cross-sectional area. The ultimate tensile strength is the amount of tension applied just before the material fractures.

You might reasonably wonder why I'm concerned with tensile strength. After all, there aren't too many kinds of weather that would cause wind to pull straight up on a mast until it breaks by stretching apart. In fact, I couldn't think of any that don't involve alien spacecraft, or unauthorized attempts by blimp pilots to anchor to my tower... at first.

Wait! One such set of circumstances has been pointed out to me, but I don't think I need to worry about it in my mid-continent, "flatland" QTH of east-central Indiana. An installation on the edge of a cliff, overlooking the ocean, is subject to updrafts when a strong wind blows onshore, climbs the cliff, and keeps rising through the antenna array. While such a location probably presents great opportunities for DX, it also offers the opportunity to test the tensile strength of the mast assembly in vertical extension. The updrafts we have around here are mostly of the slow and gentle kind that hawks and sailplane pilots like.

While we are lacking in ocean-front properties, perched on cliffs or anywhere else, we in Indiana certainly have our share of winds of the more common, horizontal persuasion. When a piece of mast is stressed by good old, *horizontal* wind, the *upwind* side is stretched, and the *downwind* side is compressed. The higher the tensile strength, the better the capacity of the upwind side to resist pulling apart. So, decreased ductility, which reduces flexion, combined with high tensile strength, which means the upwind side will resist stretching better, make for a stronger mast. Alien spacecraft and blimps need not apply.

As I said earlier, Chrome Moly tubing would be my first choice for the replacement mast, if I could stand to spend the extra money for it. I know, I said at the beginning of this article that "saving" money on mast was a very expensive decision for me the first time around, and I haven't changed my mind. However, it turns out that a less expensive alloy, "mild steel" tubing, made stronger by the drawn over mandrel method described earlier, can be almost as strong as Chrome Moly, if the wall thickness is great enough. If I had done this research before I bought the first mast, I would not have doomed my VHF yagis to damage and an ugly death. Ah, the clarity of hindsight.



Fig. 6. On a warm day in February, this was the view from the top of the tower, looking down, where Yagis are not supposed to be.

With a great deal of help from people who actually make a living by knowing what I have been studying for a month or two, I have made a very casual comparison of the relevant characteristics of DOM and Chrome Moly. I found that I could afford DOM tubing that will give me most of the protection I would get from Chrome Moly, at significantly less expense. Below is a table of results from calculations sent to me by Dave Cuthbert, WX7G, on the *antenneX* antenna-discussion list.

Table 1: Bending Moment for Various Tubing Sizes and Two Material Types

Alloy	Outside Dia. (IN)	Wall (IN)	Inside Dia. (IN)	Tensile Strength (PSI)	Bending Moment (PSI)	Weight (Lbs/ft)	Weight Lbs/20 ft.
4130	1.75	0.120	1.510	70000	14,356	2.089	41.78
4130	2.00	0.120	1.760	70000	21,997	2.409	48.18
4130	2.00	0.250	1.500	70000	37,563	4.673	93.46
4130	2.12	0.120	1.880	70000	26,471	n/a	n/a
4130	2.12	0.250	1.620	70000	45,719	n/a	n/a
4130	2.25	0.120	2.010	70000	31,962	2.730	54.60
4130	2.25	0.250	1.750	70000	55,809	n/a	n/a
4130	2.37	0.120	2.130	70000	37,662	n/a	n/a
4130	2.37	0.250	1.870	70000	66,356	n/a	n/a
1020DOM	2.00	0.120	1.760	70000	21,997	2.409	48.18
1020DOM	2.00	0.188	1.624	70000	31,061	3.638	72.76
1020DOM	2.00	0.250	1.500	70000	37,563	n/a	n/a

("n/a" = not available)

The Bending Moment values are from a spreadsheet I built in Microsoft Excel, using the formula from WX7G that takes into account the inside and outside diameters of the tubing, multiplied by the stated tensile strength, to arrive at a bending moment. Without going into painful detail as to what "Bending Moment" really means at this point, suffice it to say that, all else being equal, more is better.

$$\text{Bending Moment} = \frac{\pi(D^4 - d^4)}{64} \times \text{Tensile Strength}$$

Where  $D$  = Outside Diameter;  $d$  = Inside Diameter

The number in the **Alloy** column indicates either 4130 (Chrome Moly) or 1020 DOM, (Mild steel, Drawn Over Mandrel). Note that the bottom row, 1020DOM, with an outside diameter of 2.00 in., and a wall thickness of 0.250 in., has exactly the same TS (Tensile Strength) as Chrome Moly, and the same Bending Moment (force applied to cause bending failure), as well as the same weight. Here's where I made my decision: it costs about 30% less than Chrome Moly tubing of the same size, as offered by the supplier I have chosen. If you're buying mast from a supplier that is far enough away that you have to have the mast shipped, that difference will probably make up for the shipping cost. Shipping cost is significant, since the shortest pieces offered are generally 10 to 11 feet, or 20 to 22 feet. These dimensions eliminate UPS and FedEx as potential shippers, and pretty much limit you to motor freight (truck) companies, which charge higher rates than the above, and are pretty picky about delivery terms. Many will not deliver to residential addresses, or charge extra for doing that.

Now, the figures I have gathered for making the calculations in the spreadsheet vary from one source to another, and some tensile strength ratings I found for these materials were significantly higher. It's reasonable to expect that these characteristics will vary among manufacturers, and some offer such information on the web with a disclaimer that values are nominal, and should not be used for precise engineering calculations. I

decided to use lower tensile strength values, to keep my errors on the conservative or pessimistic side of reality. Better to “err on the side of caution,” as they say.

Besides the cost difference, another factor in choosing mild steel DOM over Chrome Moly was weldability. While mild steel can be welded with a conventional arc welder (and I have a neighbor who is a good welder), Chrome Moly can only be welded with a gas torch or a gas-shielded arc welder, neither of which is common equipment in most home workshops. I was considering welding because I didn’t want to buy and have shipped a 22-foot piece of tubing to my house, since the cost would be high, and the tube would be long and heavy.

I wanted to have two pieces delivered to a nearby commercial address, and carry the pieces home from there in my pickup truck. A twenty-foot piece would have been a challenge to get home, possibly resulting in negative interaction with local law enforcement, which is best avoided. Two, ten-to-eleven-foot pieces could be welded together in my back yard, or rigged with a coupling device that would allow me to put them together on top of the tower, and take them apart later for maintenance or changes to the antennas.

I was also cautioned by one of the helpful people on the *antenneX* lists that Chrome Moly needed extra care to prevent rust. Actually, either steel would rust, so I would be faced with periodic painting of the masts (inside and out), or with knowing that my mast had begun to rust before I got done climbing down from installing it. One supplier of mast tubing, Array Solutions ([www.arrayolutions.com](http://www.arrayolutions.com)) sells galvanized tubing for not much more than some suppliers charge for tubing without any rust protection. Since I don’t relish climbing my tower at short intervals to remove and paint my mast, galvanizing is an attractive feature, and I went for it.

Another Array Solutions feature is that each piece of tubing (or, in my case, both halves of the piece they cut in half before shipping to me) comes with its own engineering and metallurgical pedigree. A manufacturer’s certificate shows the “chemical composition, mechanical properties and metallurgical properties” of the tubing you buy, pretty much assuring you that what you bought is what you thought you bought, in terms of performance. I plan to scan my certificate and frame a copy, storing the original in the fire safe with the mortgage papers, wills and other important documents. The framed copy will go up on the wall, and I will gaze at it next ice storm, and remind myself I made a good investment, for once. I might even frame the following picture (antenna lover discretion advised – there is some serious aluminum gore, here) to help me remember the results of scrimping on mast material, as well.



Fig. 7. The earthly remains of my 6-Meter Yagi, resting in pieces.

### ***Conclusion, With Apologies to Ben Franklin...***

This brings *antenneX* readers current on my process for selecting a new mast. Obviously (at least to me, at least in retrospect), there is a lot more to choosing the right mast than going down to the plumbing supply store or the big-box outlet and dragging home the biggest piece of iron pipe that will fit in the rotor. Pipe is not tubing! “Cheaper”, as I can testify, is not always better, even among some of the most frugal (or stingy, depending on your point of view) people on the planet: amateur radio operators. Despite Ben Franklin’s memorable saying, a penny saved now may mean lots of dollars spent later.



← Fig. 8. Replacement tubing cost: \$400, plus about \$40 shipping. Ouch!

Likewise, more expensive is not *always* better. Chrome Moly tubing definitely has its place in high-stress mast applications, but research, smart friends on the *antenneX* lists, and honest vendors may tell you that mild steel DOM will do the job, with a safety margin, and with a little cash left in your wallet for – who knows? -- maybe some antennas.

In a future installment, we’ll take a closer look at the damaged mast, removed in pieces from the tower, and examine the replacement pieces in detail.

Knowing how much lateral stress your choice of mast material will shrug off is a good first step, but it’s not the whole story. Chances are, you will be putting some antennas on that mast, and Mother Nature may decide to throw in some ice and snow. You need to know how much stress your mast will have to live with -- not just on an average day, but on the worst day you are likely to have. We’ll cover that, next time, too. –30–

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### **BRIEF BIOGRAPHY OF THE AUTHOR**

Tom Cox, [KT9OM](#), is assistant director of the information technology department of a 10,000-student, 7,000-computer public school corporation. His most recent project is replacing the corporation’s leased digital telephone lines with high-speed wireless connections. On his own time, Tom plays with antennas, reads fiction and non-fiction, and gardens or removes snow and splits firewood, depending on the season, and rides about 250 miles a summer on a bicycle.



He was born to generous and patient parents, Jim and Jeannette Cox (both deceased), in 1949, and has been a Ham since 1982. He shares his Muncie, Indiana home with his lovely and indulgent wife, Sherry, and three dogs. He shares his

neighborhood with his brother, KA9PBO, with whom he plays radio and attends hamfests. Tom is an active member of the GARDS.

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