Chapter 6

Design and Fabrication of High-Q Tuning Inductors for LFMF Antennas

February 2020

6.0 Introduction

The electrically small antennas typical of 630m and 2200m amateur installations can be represented by the equivalent circuit in figure 6.1.

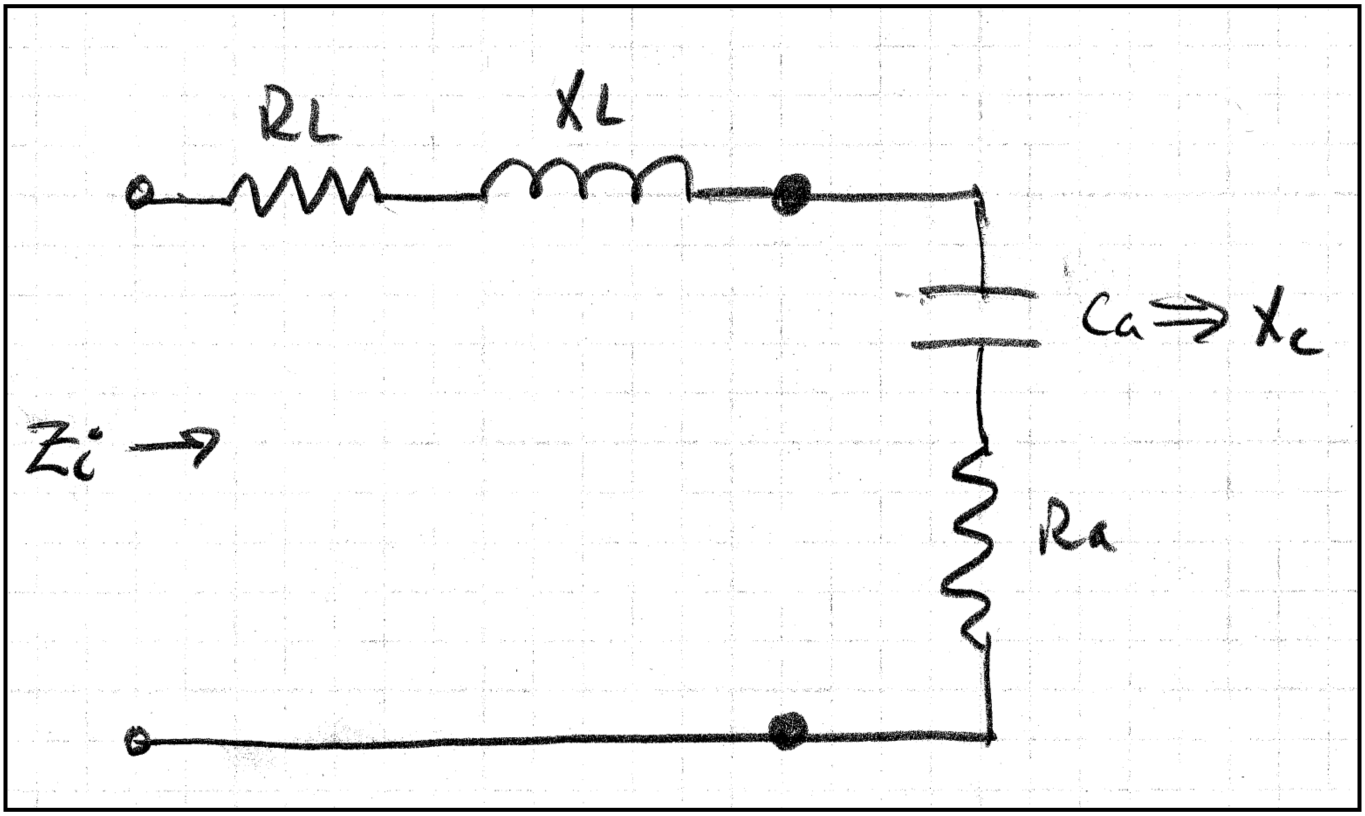

Figure 6.1 - LFMF antenna equivalent circuit.

The antenna is simply a capacitor in series with a resistor. The capacitive reactance (Xc) is very large and the series resistance (Ra) is small. Most of Ra comes from ground system and conductor losses. The radiation resistance (Rr) is typically only a very small part of Ra. To supply power to the antenna it's necessary to transform the highly reactive feedpoint impedance of the antenna to a resistive value compatible with the feedline, usually Ri=Zo=50Ω. The series inductor (XL) performs two functions: canceling the input reactance (+XL-Xc=0) and a means to transform Ra to the desired value for Ri which is often done with an adjustable tap on the inductor although there are other possibilities. Unfortunately any practical inductor will have losses (represented by RL) which can reduce efficiency very substantially.

The radiation efficiency ($\boldsymbol{\eta}$) can be expressed by:

$$\boldsymbol{\eta} = \frac{\mathbf{Rr}}{\mathbf{Ra+RL}} = \frac{\mathbf{Rr}}{\mathbf{Rr+RL+Rg+Rc+\cdots}} \qquad (6.1)$$

Where Rr is the radiation resistance, RL is the inductor loss resistance, Rg represents ground system loss, Rc represents conductor loss and miscellaneous other losses. Usually Rr will be very small, a fraction of an ohm, but RL and Rg are typically much larger. In most cases RL and Rg dominate the efficiency so every effort must be made to minimize these losses. For an inductor:

$$\mathbf{XL = 2\pi fL} \qquad (6.2)$$

$$\mathbf{Q} \equiv \frac{\mathbf{XL}}{\mathbf{RL}} \rightarrow \ \mathbf{RL} = \frac{\mathbf{XL}}{\mathbf{Q}} \qquad (6.3)$$

Where f is the operating frequency and L is the required inductance.

Increasing loading inductor Q is a primary tool for maximizing efficiency.

This chapter addresses the design and fabrication of high Q inductors using materials commonly available at local hardware stores. Historically many different coil constructions have been tried but the focus here is on <u>cylindrical single layer air wound coils using round wire</u> because these are common and practical. Examples of flat spiral or "pancake" inductors, toroidal inductors, non-circular coil forms and basket-weave windings are shown but not discussed in detail. Insofar as possible the math has been kept to a minimum. For most users this will be sufficient but for those who want them the math and many details have are available in a separate appendix.

The discussion covers a lot of ground at considerable length and it's fair to ask "is all this verbiage actually useful?" Many articles and even whole books on inductor design, along with free software design programs[1], already exist. From a practical point of view do we really need more? It turns out that the design of tuning inductors for 630m and 2200m is significantly more complicated than typical HF inductors. Fpr example, LF, MF and HF inductor designs must take into account both skin and proximity effects:

- The resistance of a wire is ≈Rdc at low frequencies but as the frequency is increased the resistance increases very substantially, this is called "skin effect".
- When a conductor is wound into a coil the current in one turn induces loss in adjacent turns, this is called "proximity effect".

These two effects impact the design when high Q is desired but there is another effect, "self-resonance", which is rarely important at HF but frequently limits Q at 630m and 2200m:

- Coil inductors behave very much like transmission lines with a multitude of harmonically related resonances. The lowest self frequency resonance (SRF) often significantly impacts both inductance and Q.

All three effects must be included in the design of LFMF inductors. Fortunately we are able to accurately calculate all these effects but some of the equations are complex and all of them are interrelated making pencil and paper calculations impractical. Spreadsheets can be used but that's practical for only the most dedicated algebraphiles. Fortunately Brian Beezley, K6STI, has created an inductor design program[1], COIL, which takes into account all the complexity while keeping it out of sight. Both COIL and spreadsheet calculations were used for this chapter.

6.1 How much inductance?

When designing a new inductor the very first question is "what value of inductance (L) is needed and at what frequency (f)?" To resonate the antenna enough XL is needed to cancel the capacitive reactance (Xa) at the feedpoint, i.e. XL=Xa (figure 6.1):

$$\mathbf{L} = \frac{\mathbf{XL}}{\mathbf{2\pi f}} \qquad (6.4)$$

When f is in MHz L will be in µH.

To estimate the needed inductance we can convert the values for Xa derived in chapter 3 to inductance in uH as shown in figures 6.2 and 6.3. In these figures an italic *L* identifies the total length in feet of the top-loading wire. It should be pointed out that although figures 6.2 and 6.3 assume a "T" with a single top-wire, the values for the loading inductor would be the same for any capacitive top-loading structure which provides the same amount of capacitive loading. The shape of the hat is not what's important, it's the added capacitance!

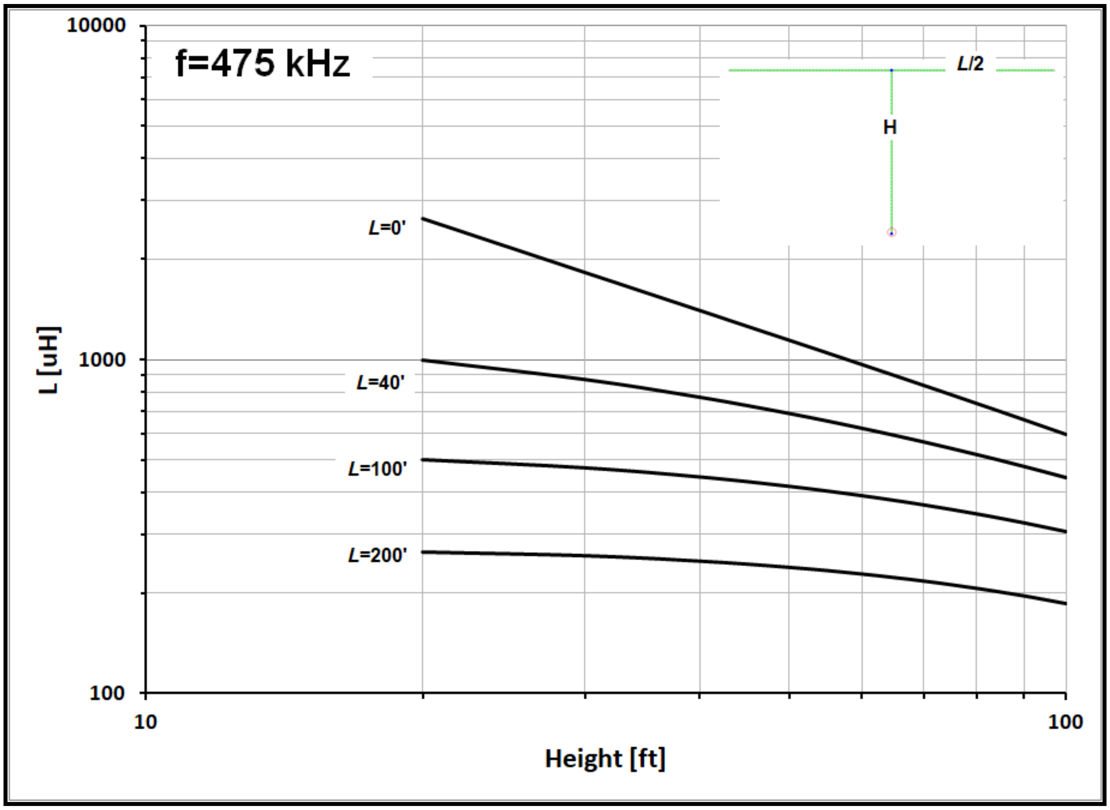

Figure 6.2 -Tuning inductor inductance for resonance at 475 kHz.

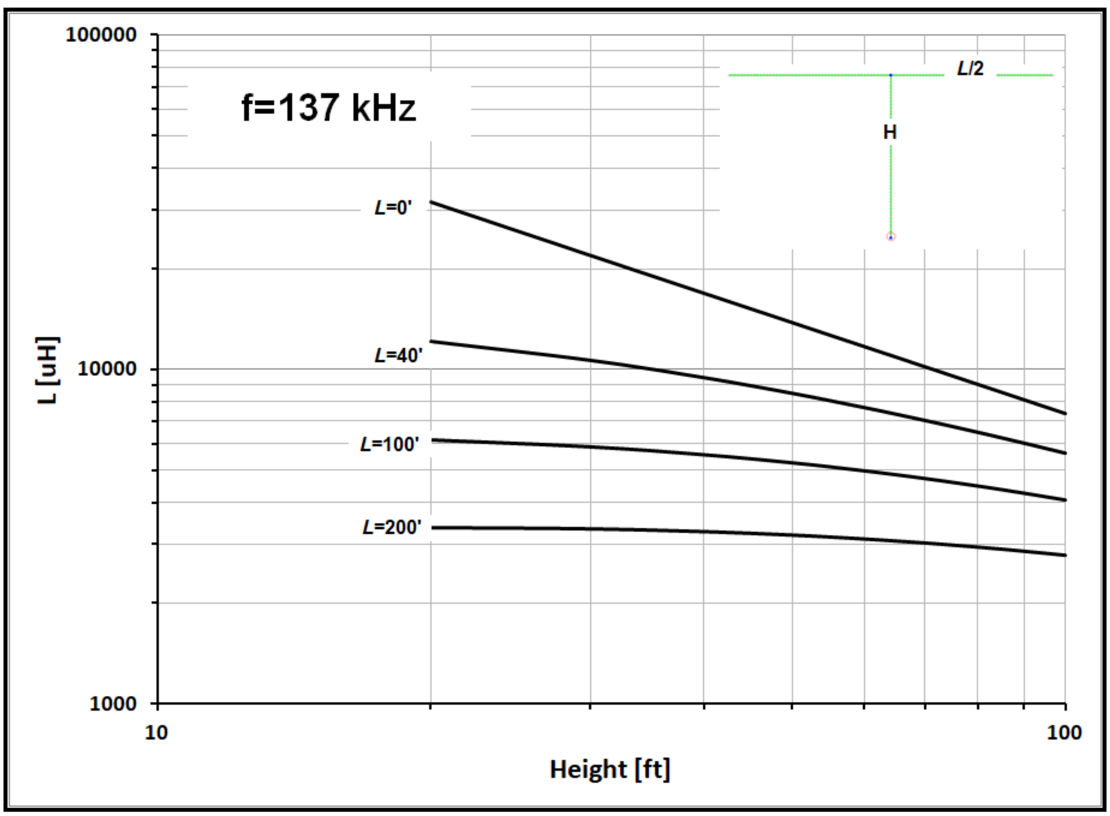

Figure 6.3 - Tuning inductor inductance for resonance at 137 kHz.

From figures 6.2 and 6.3 we see:

- At 475 kHz, for resonance, L ≈ 200µH →1000µH.
- At 137 kHz, for resonance, L ≈ 3mH→20mH.

6.2 Definitions

Some useful variables can be defined with the help of figure 6.4.

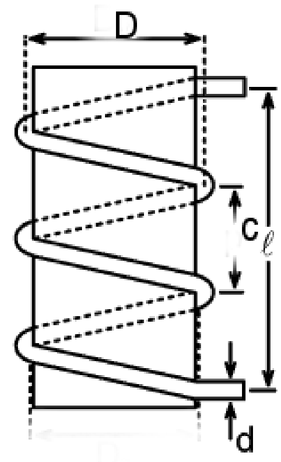

Figure 6.4 - inductor dimensions (From Knight)

c → winding pitch , center-to-center spacing between turns

d → diameter of the winding conductor

D → diameter of the winding. Wire center-to-wire center

l → coil length

L→ actual inductance at the operating frequency

lw→ length of the winding conductor

N → number of turns in the winding

Design graphs and equations can be made more general using geometric ratios as variables. For example:

- (d/c) → conductor diameter/turn center-to-center spacing ratio
- (l/D) → coil length/diameter ratio

In practice the normal ranges for these ratios are: 0.2<l/D<10 and 0.3<d/c<0.7. l/D=0.2 represents a very short winding with a large diameter. l/D=10 represents a long tubular coil with a small diameter. Figure 6.5 uses these ratios to illustrate how variable the inductance can be when the coil is wound in different ways. For this example lw=100' and d=0.081" (#12 wire). The dashed contours correspond to constant values of l/D. Note that for all values of d/c, maximum inductance occurs at l/D=0.45. In this example Lo varies from ≈50 to 460 uH, a range of 9:1 with the same piece of wire. How the coil is wound really matters!

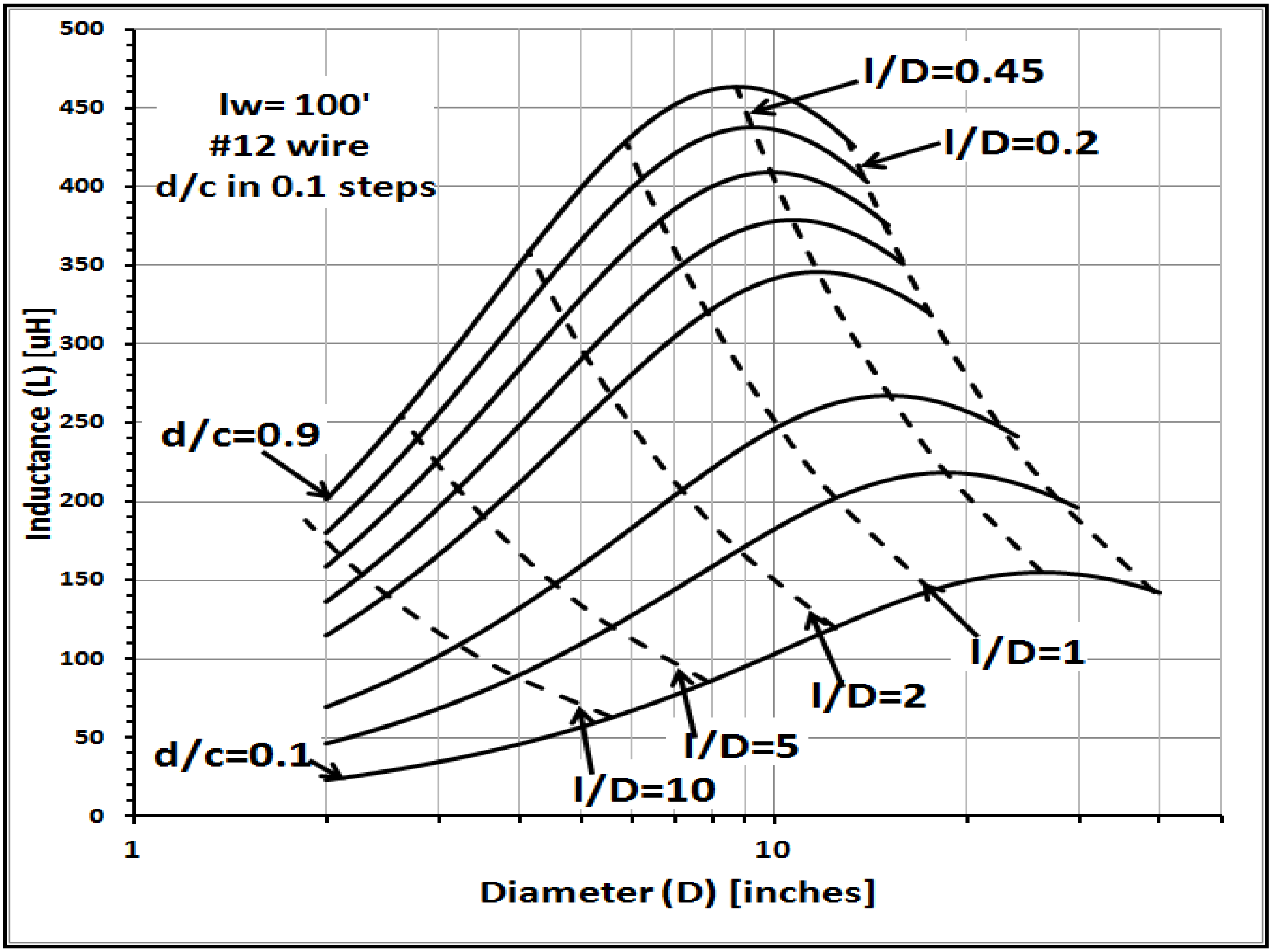

Figure 6.5 - Inductance versus diameter with d/c and l/D as parameters.

6.3 Practical inductors

A new design starts with the value for the inductance (L) and the operating frequency (f). It's a good idea to make L 5-10% larger to allow for adjustment using taps on the coil but you don't want to go overboard as the unused portion of the coil still affects fr potentially lowering Q. Keep in mind that the actual inductance will vary with frequency so the value chosen needs to be the correct value at the operating frequency.

Because coil loss (RL) and value of L depend on frequency it is necessary to know f right at the beginning. For amateurs, the values for f are very limited (2200m→135.7-137.8 kHz, 630m→472-479 kHz) so in the following discussion f=137 kHz is used for 2200m coils and f=475 kHz for 630m coils.

To fabricate an inductor some details are needed:

- diameter (D),
- winding length (l),
- number of turns (N),
- wire size or diameter (# or d)
- turn spacing (d/c)
- length of the wire in the winding (lw).

Some of these will be chosen initially and the rest derived either from graphs or COIL.

Insulated THHN wire is frequently used for windings. Because it's wide use in home wiring this wire is relatively inexpensive and readily available locally. Other types of wire can certainly be used. Three sizes are commonly used: #14 (0.064"/1.63mm), #12 (0.081"/2.05mm) and #10 (0.102"/2.59mm). For winding design some wire dimensions are needed. These are listed in table 1.

Table 1 - Typical wire dimensions

wire #	nominal diameter	diameter over insulation	assumed diameter	maximum turns/inch	d/c maximum
10	0.102"	0.165"	0.17"	5.9	0.60
12	0.081"	0.117"	0.12"	8.3	0.69
14	0.064"	0.098"	0.10"	10.2	0.64

The "nominal" diameters come straight out of a standard wire table. Using a micrometer one often finds wire diameters are a tad under the specification, perhaps a mil or more, which usually doesn't matter too much. The diameters over the insulation are measured values from a several samples but there can be considerable variation so don't be surprised if you can't get as many turns on a form as exptected or the winding is not as long as predicted. The "assumed" diameter allows for some additional insulation thickness and is the value used for the graphs and calculations that follow. The maximum turns/inch and d/c maximum are based on the assumed diameters.

With insulation the maximum turns/inch will be less that with bare wire. However, with bare wire some spacing will be needed between the turns and it's usually not practical to have spacings much smaller than typical insulation thickness.

6.3.1 Turn spacing warning!

Do not use tightly wound windings with no air space between turns!

Here's the reason for that warning.

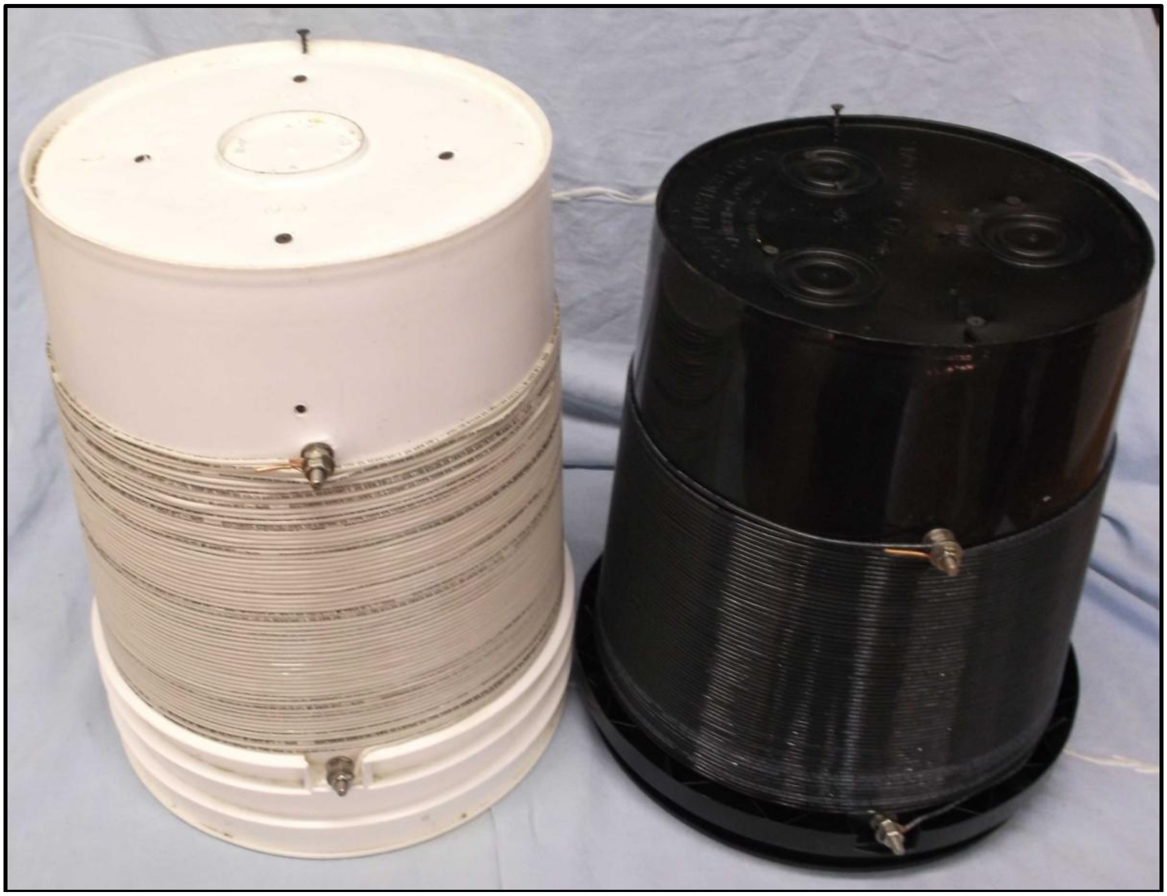

Figure 6.6 - Plastic bucket inductor examples.

Either insulated or bare wire can be used for the winding. Q measurements comparing the same coil with insulated wire versus bare wire[11,12] shows very little difference except for very tight (closely packed) windings being used. This effect was demonstrated by experiment. To illustrate tight versus loose windings two inductors ($L_o \approx 1mH$) were fabricated with insulated wire on plastic buckets. The black bucket had a very tight winding and the white bucket a somewhat looser winding. Two versions were wound on the white bucket and the Q measured. In the first example the inductor was wound with new #12 THHN wire directly off the original spool so it was smooth allowing a very tight winding like that shown on the right in figure 6.6. After completing some measurements the winding on the white bucket was unwound and as a result of handling the wire became a bit lumpy. This wire was then rewound on the same bucket but this time the winding was significantly longer, ≈+1", with small air gaps between the turns as shown on the left in figure 6.6.

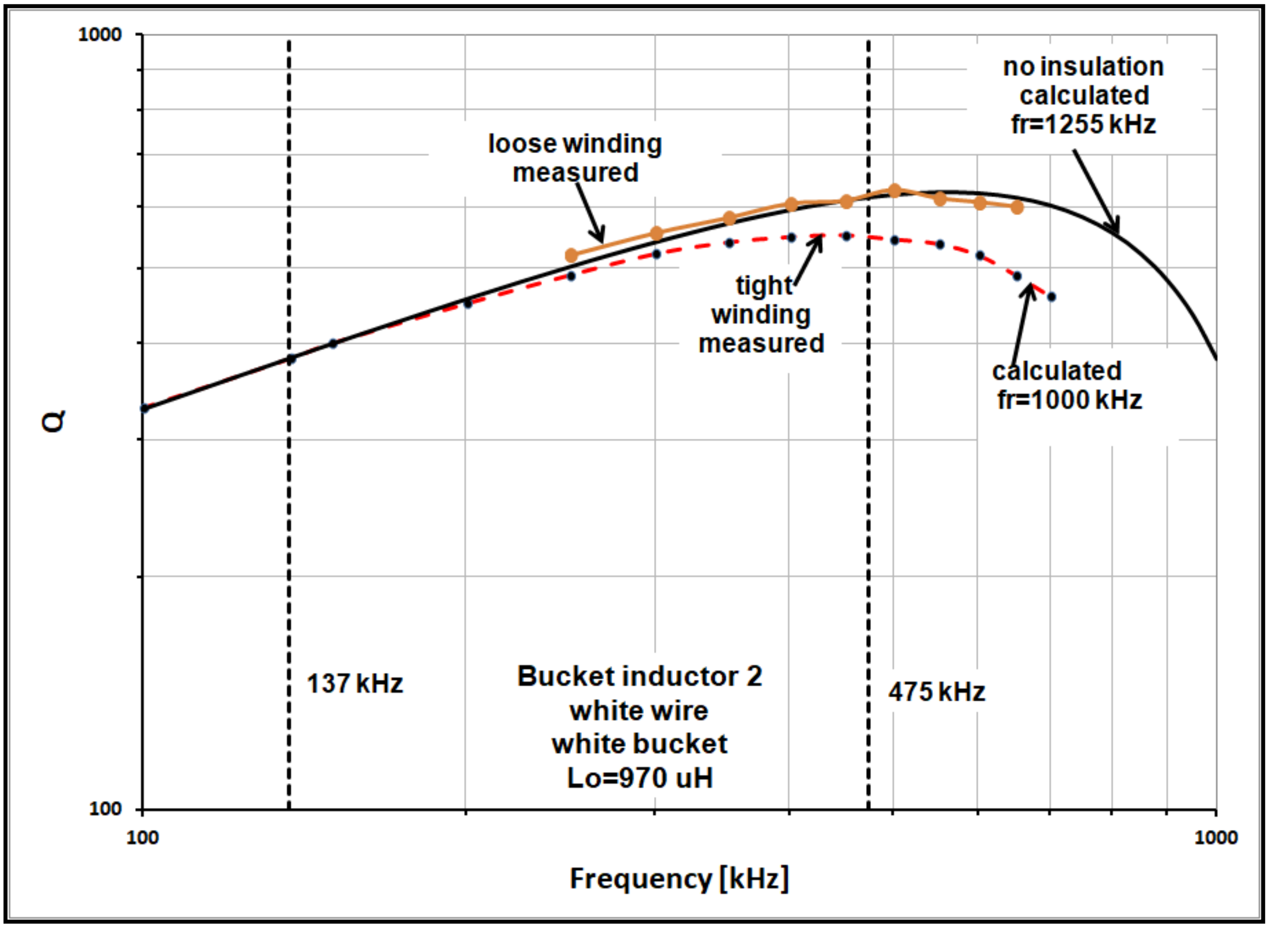

Figure 6.7 - Comparison between tight and loose windings.

Figure 6.7 compares the Q measurements with tight and loose windings compared against calculated values. There is a substantial difference! In a tight winding the insulation on each turn is pressed closely to the turns on either side which increases winding capacitance and reduces self-resonant frequency which in turn reduces Q as f approaches fr. It should be noted that the reduction in Q with an insulated wire winding is due to a lower self-resonant frequency (fr) not dielectric loss in the insulation.

Here is some more experimental work. Figure 6.8 is a trial bucket inductor for a variometer. Q measurements and COIL predictions are graphed in figure 6.9. Note

SFR differs by almost a factor of 3! Note the internal variometer coil was not present for this test.

Figure 6.8 - Bucket inductor.

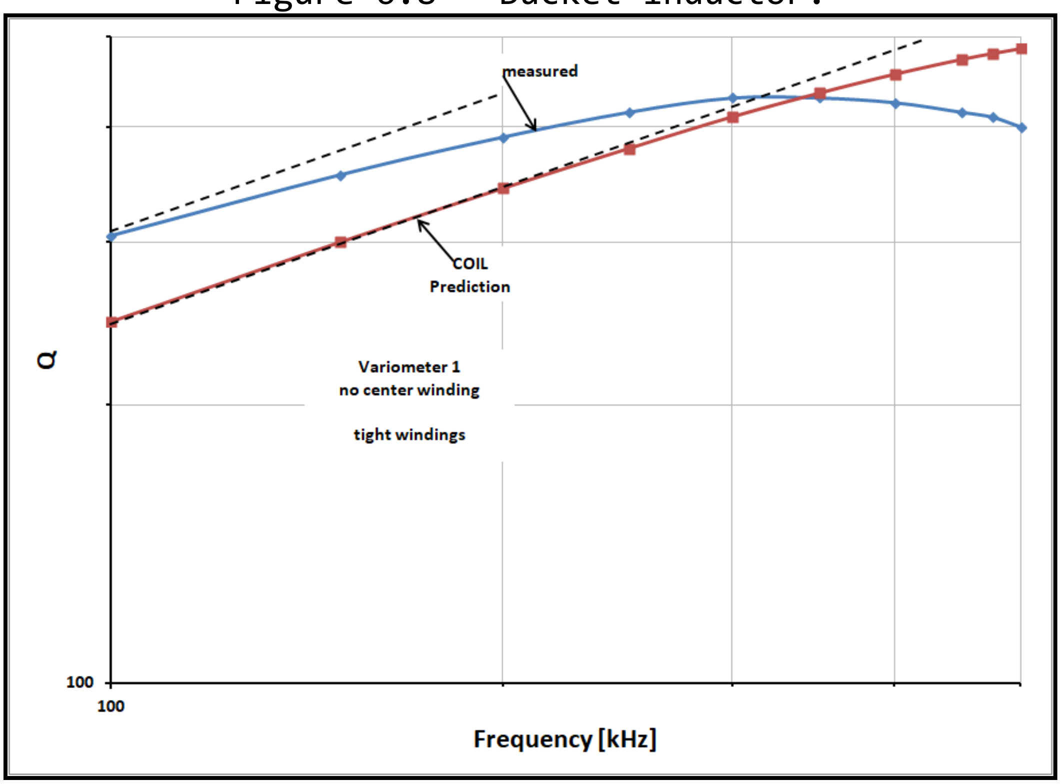

Figure 6.9 - Bucket inductor Q measurements versus prediction.

Now, same kind of bucket, same wire, about the same inductance but using a spaced winding shown in figures 6.10 and 6.11.

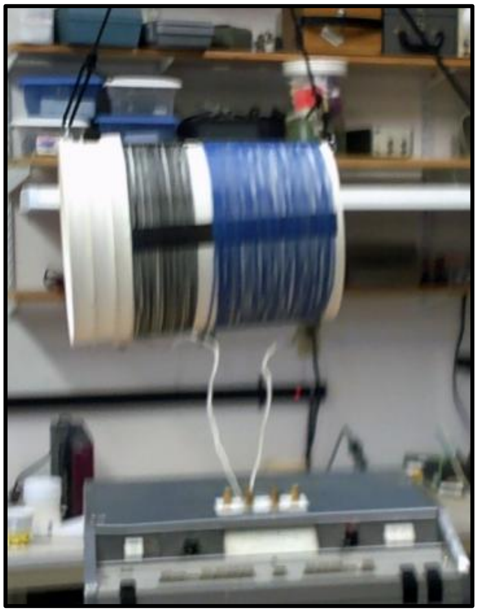

Figure 6.10 - Spaced winding

With the following comparison graph.

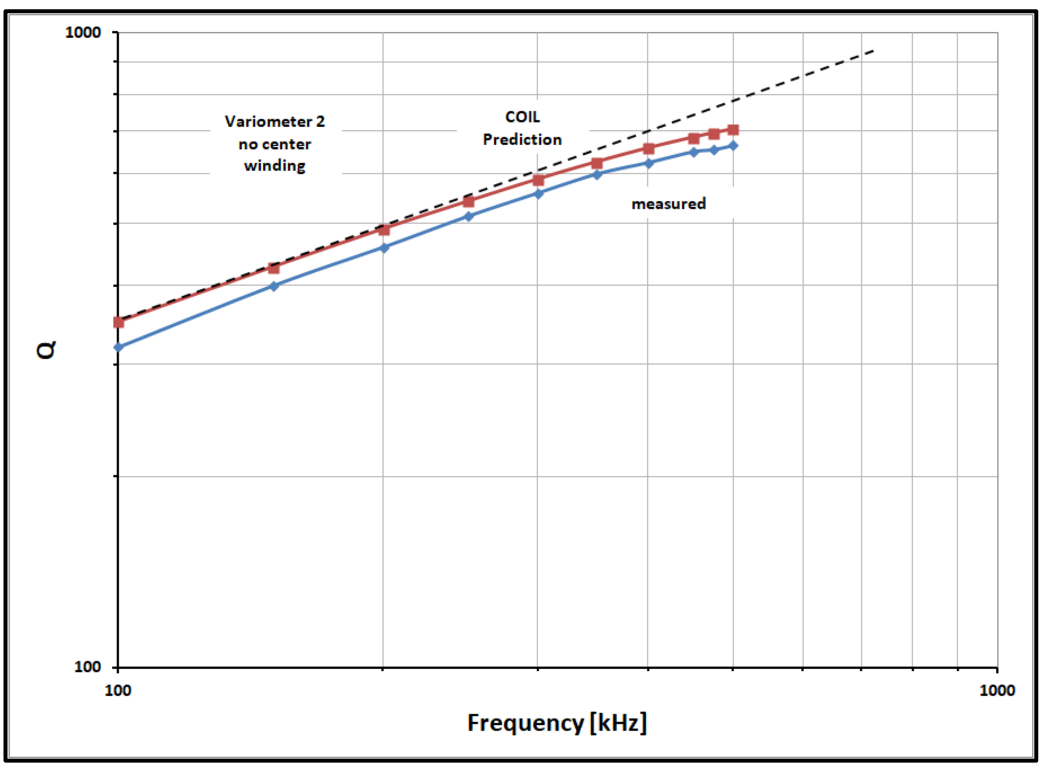

Figure 6.11 - spaced winding inductor example.

Enough said, space the turns at least a small amount.

6.3.2 Bucket inductors

Plastic buckets are inexpensive and universally available in many different sizes (1, 2, 5, 7, etc gallon) as shown in figures 6.12. Five gallon buckets are probably the most used size for coil forms. Better quality buckets are made from High Density Polyethylene (HDPE). At LFMF PVC and HDPE have very little dielectric loss. Not all buckets are HDPE, while the HDPE is common there are many lower quality buckets on the market. Look on the bottom of a prospective bucket, there should be a small triangle with 2 in it and HDPE underneath. The wall thickness of the bucket in mils should also be there

Figure 6.12 - Typical buckets.

A plastic bucket can be used as a coil form but some thought must be given to the winding process. Because the bucket is smooth plastic with some taper and wire insulation is also smooth plastic the wire tends to slide around as the coil is moved. There is a simple trick which helps keep the turns in place with the desired turn-to-turn spacing: attach several (6-8) vertical strips of double sided mounting or carpet tape vertically before winding. These are the dark strips in figure 6.10. This does a good job of holding the wire in place. If the wire in the winding is not tight, but rather carefully spaced to reduce proximity loss using a simple 2"X4" frame (like that shown in figure 6.14) as a "winding machine" will make the job a lot easier. Figure 6.13 shows 1/2" iron pipe fittings attached to the top and bottom of the bucket. Small square plywood blocks were used on the inner sides of the bucket bottom and lid to stiffen them and anchor the screws. The stanchion bases are attached with screws through the bucket into the blocks.

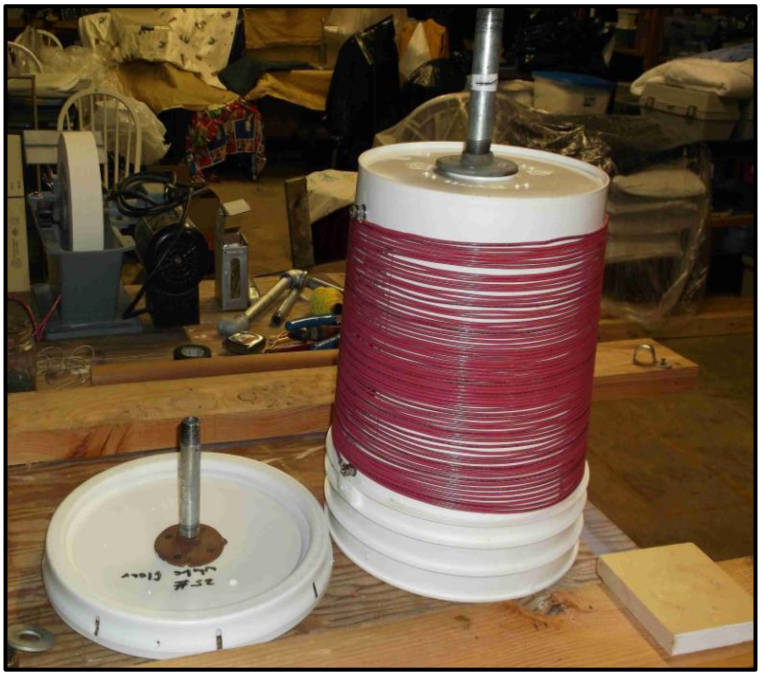

Figure 6.13 - Bucket modification for winding.

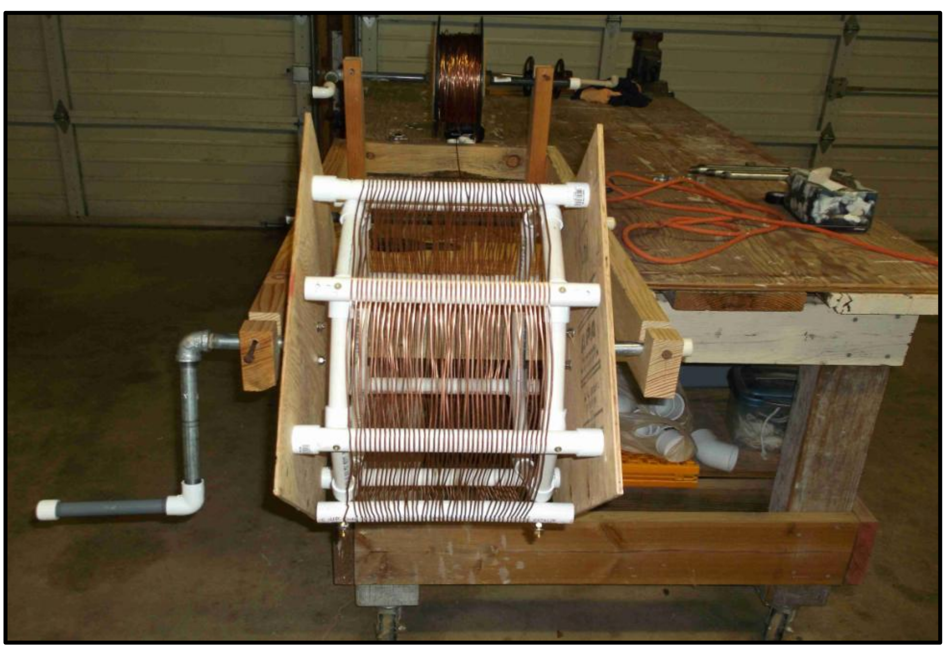

Figure 6.14 - Winding machine example.

Buckets come in a wide variety of sizes but once a choice is made both the diameter and the maximum winding length are predetermined which limits the possible inductance values. A 5 gallon bucket example can be used to illustrate these limits.

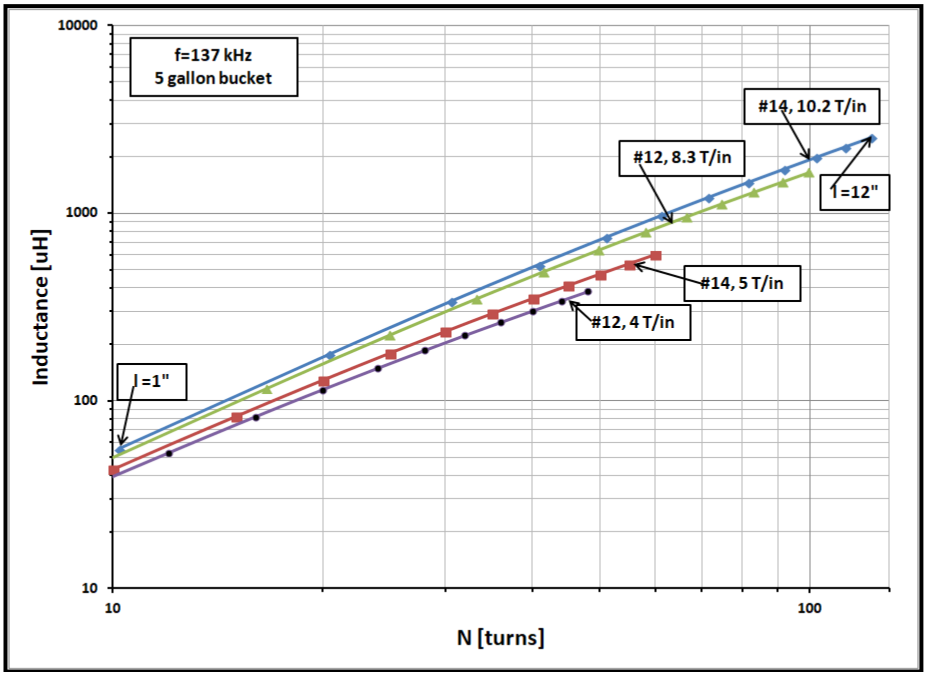

Figure 6.15A - 5 gallon bucket example L versus N at 137 kHz.

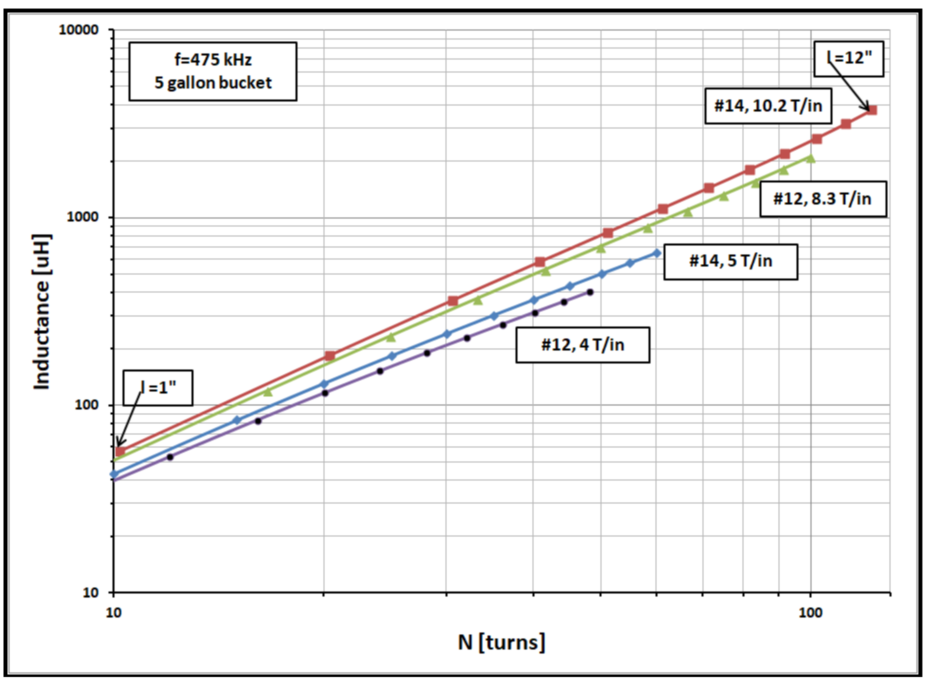

Figure 6.15B - 5 gallon bucket example L versus N at 475 kHz.

Figure 6.15 shows the relationship between N and L at 137 kHz and 475 kHz for two wire sizes (#12 & #14). For each wire size there are two turn spacings (Turns/inch). For #14 wire 10.2 T/in represents about the tightest possible winding. 5 T/in represents wider spacing which is used to reduce proximity loss increasing Q. For #12 wire 8.3 and 4 T/in are used. The graphs illustrate that larger wire and greater spacing means fewer turns because the maximum winding length is constrained to <12". But as shown in figure 6.16, larger wire and greater turn spacing yield higher Q.

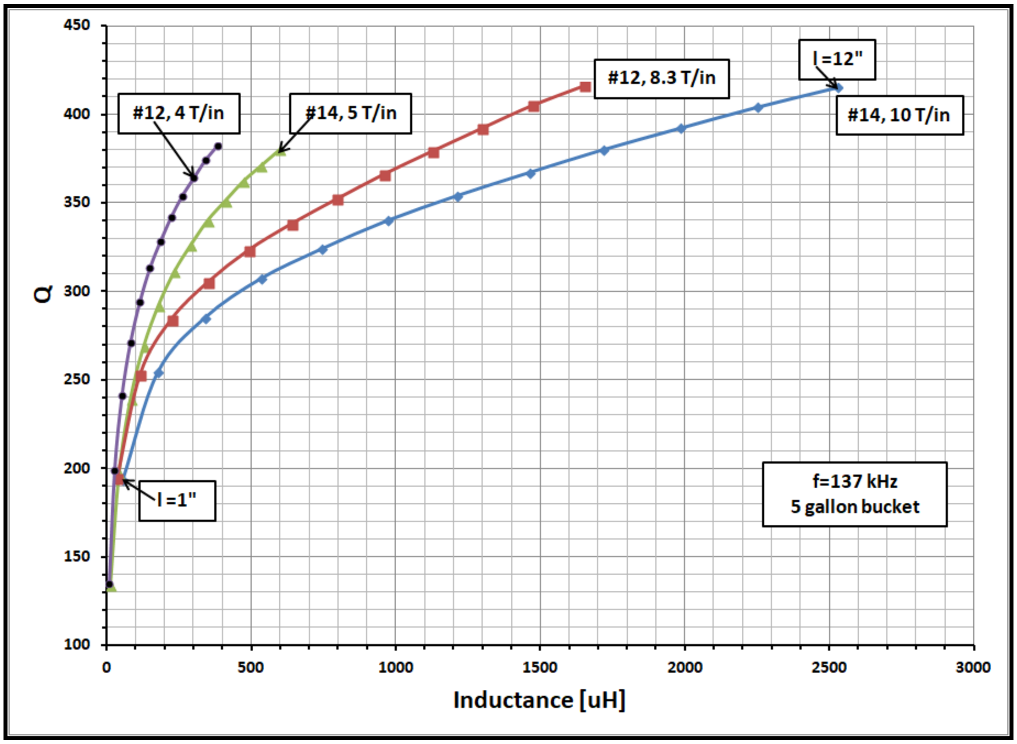

Figure 6.16A - Inductor Q at 137 kHz.

Using #14 wire tightly wound an inductance of 2.5 mH at 137 kHz and almost 4 mH at 475 kHz can be obtained but the Q for that inductor will be modest: ≈420 at 137 kHz and ≈520 at 475 kHz. As the graphs show, either increasing the wire size and/or the turn spacing increases Q but reduces the maximum inductance. For example at 475 kHz, increasing the wire size from #14 to #12 increases Q (@L=2mH) from ≈550 to ≈610 but the maximum L is now <2.1 mH. For L=400 uH, if we go from closely spaced # 14 to wide spaced #12 Q goes from 500 to 780 which is a considerable improvement, but L is now constrained to <400 uH. The user has to keep these trade-offs in mind when choosing inductor parameters.

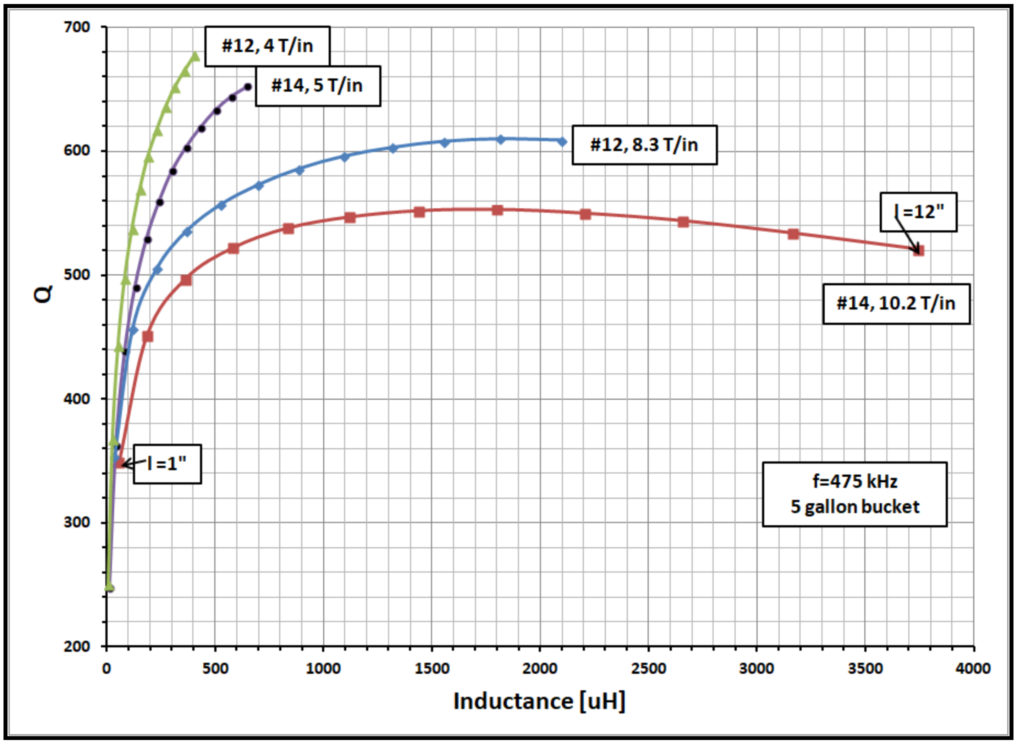

Figure 6.16B - Inductor Q at 475 kHz.

6.3.3 Maximum Q inductors

If a really high-Q inductor is wanted then the dimensional constraints imposed by the limited bucket dimensions have to be eliminated and an arbitrary size coil form fabricated. Using PVC pipe and fittings makes it very easy to fabricate a large form with arbitrary dimensions. Figure 6.17 shows two examples of PVC cage coil forms. In figure 6.17A the octagonal rings are 1/2" pipe joined with 45° elbows. Because the winding compresses the form it is usually not necessary to glue the rings which makes fabrication much easier! The eight vertical supports used 3/4" pipe with slots cut at intervals (=c) to hold the wire. The turns in figure 6.17B were constrained with double sided tape as suggested for bucket inductors.

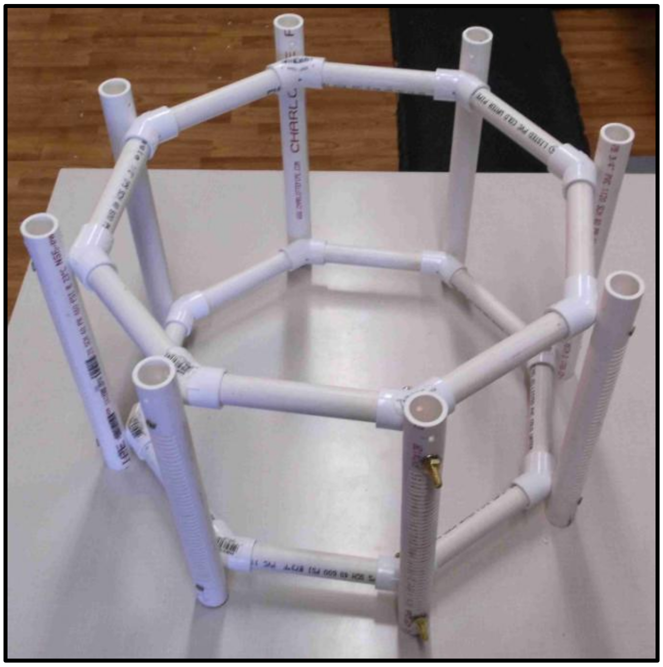

Figure 6.17A - PVC cage coil form.

Figure 6.17B - N1DAY PVC cage coil form.

Figure 6.18 - Cutting the wire slots.

Figure 6.18 shows a practical way to cut slots. Attaching the supports to a board makes it much easier to align all the slots and mounting holes. The use of slots to fix wire positions is very robust but wire ties could also be used.

A clever example of a very light weight inductor (≈18"X18") is shown in figure 6.19. Pat, W5THT, fabricated the coil form by wrapping F/G mat around a cardboard tube, then impregnating the mat with epoxy and when it had cured, soaking the assembly in water to soften the cardboard for removal, leaving a thin shell on which he wound 1/2" wide copper tape. A protective covering of paint was then applied. The light weight of the inductor allowed him to hoist it to the top of his vertical where it joined the capacitive hat. For 630m and 2200m a foil thickness of 0.005"→0.010" would be close to optimum. One could also purchase a sheet of thin plastic and roll it to make the coil form.

Figure 6.19 - Pat W5THT, foil wound lightweight inductor.

Optimizing Q

Using COIL a modeling experiment optimizing Q was done with very interesting results. First, Q's of 500 to over 900 were readily obtained. Second, the diameter (D) associated with each optimized test value was found to change only a small amount over the full range of inductance values for a given wire size and frequency. Third, the spacing ratio (i.e. wire diameter/turn-to-turn spacing, d/c) was found to have a very small range, d/c≈0.30-0.32, for every example over the entire range of inductance and wire size! d/c can be converted to the more useful parameter p ("turns-per-inch") for each wire size as shown in table 2.

Table 2 - Turns/inch for d/c=0.31

wire size	p [T/in]	rounded p [T/in]
14	4.84	5
12	3.83	4
10	3.07	3

Table 3 shows the averaged diameters associated with optimized inductors.

Table 3 Averaged values for D and p (turns/in) for optimum Q

	#14	#14	#12	#12	#10	#10
frequency	**T/in**	**D**	**T/in**	**D**	**T/in**	**D**
137 kHz	**5**	**28"**	**4**	**32"**	**3**	**36"**
475 kHz	**5**	**15"**	**4**	**17"**	**3**	**19"**

Table 3 suggests coil diameters of 1.5' to 3', these are not small coils! Using these values for wire size, diameter, T/in and frequency, the Q's were recalculated and graphed as shown in figure 6.20. When compared to the original "optimized" Q values, the Q values derived using the averaged dimensions were within a few percent. The difference was not worth worrying about! What this means is that right up front, for a given frequency and wire size you know the coil diameter and the turns spacing. The only missing information is the number of turns (N), the required coil form length (l) and the total length of wire needed for the winding (lw). N can be determined from COIL or figure 6.21.

The length of the winding (the minimum length of the coil form!) is simply:

$$\mathbf{l = N/p \ \ [inches]} \quad (6.5)$$

And the total length of the wire in the winding is:

$$\mathbf{lw = \frac{N\pi D}{12} \ \ [ft]} \quad (6.6)$$

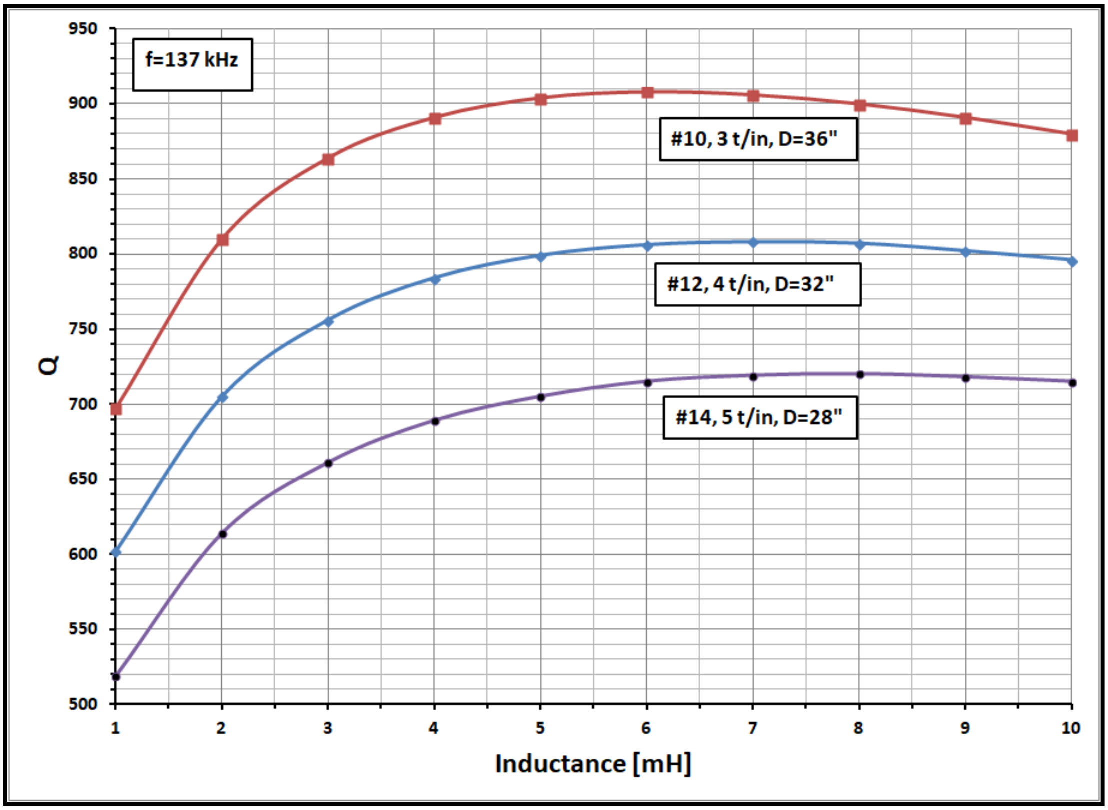

Figure 6.20A - Optimized Q at 137 kHz.

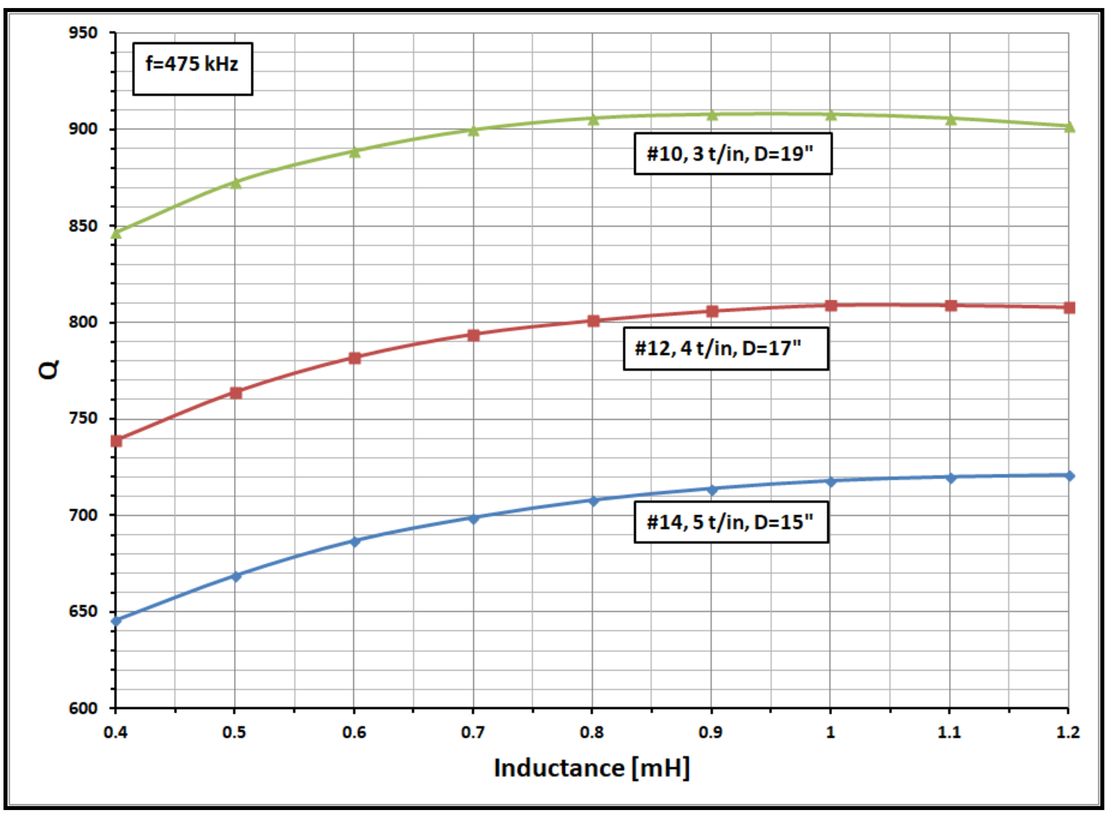

Figure 6.20B - Optimized Q at 475 kHz.

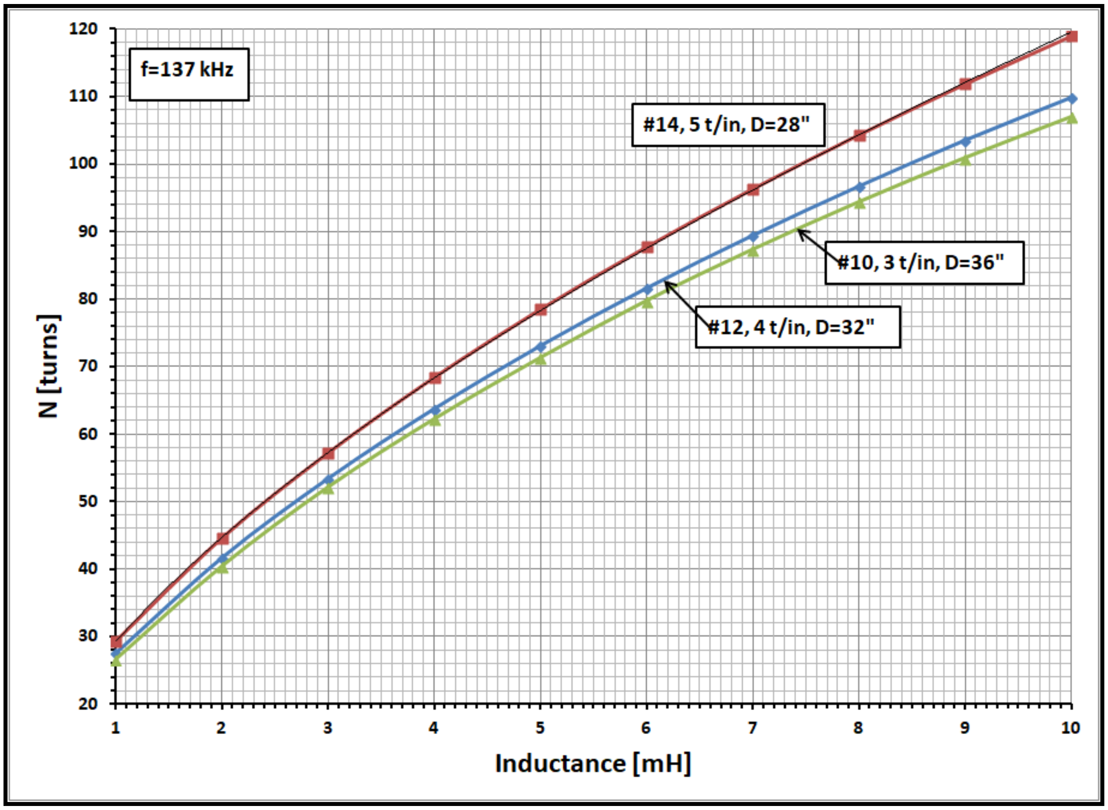

Figure 6.21A - N versus L for optimized inductors at 137 kHz.

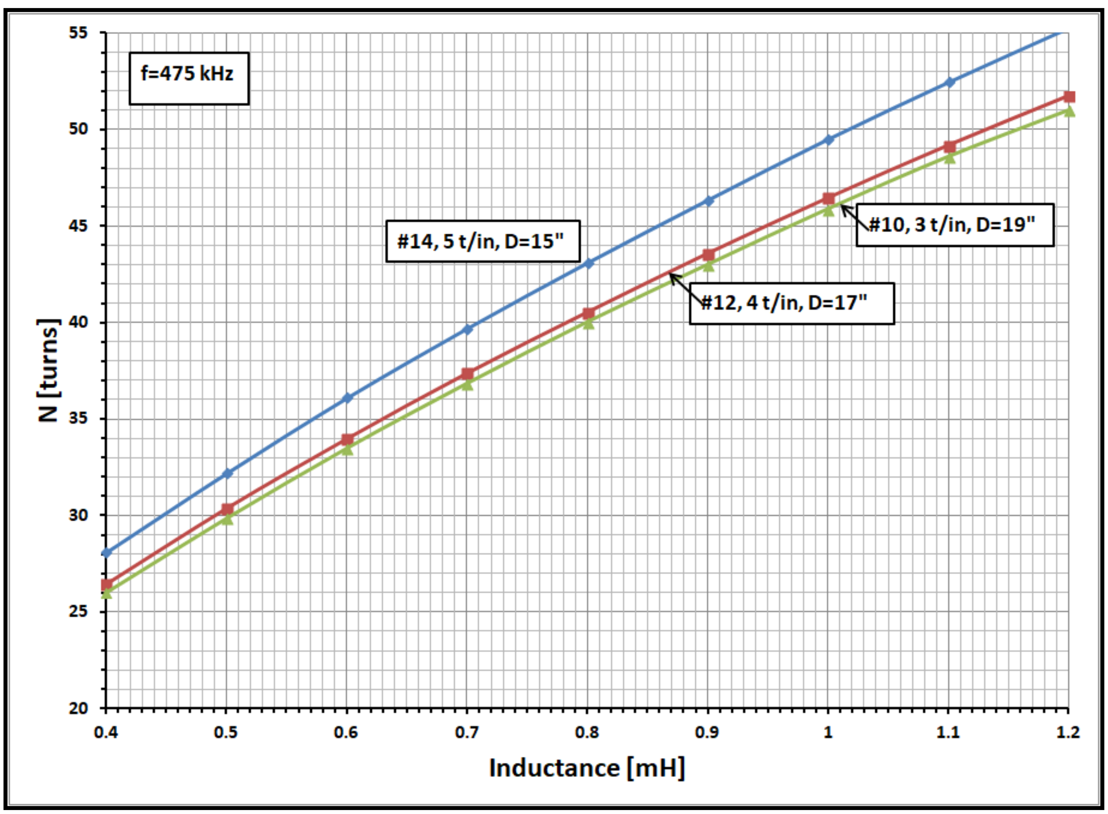

Figure 6.21B - N versus L for optimized inductors at 475 kHz.

6.3.4 Litz wire windings

To minimize skin and proximity effects might appear all we have to do is use very small wire. The New England Wire Technologies catalog suggests #40 for 137 kHz and #44 for 475 kHz. The problem with single wires this small is high Rdc. The solution is to use many small wires in parallel but simply paralleling wires in a bundle doesn't buy anything because the current still flows on the outside of the bundle. In fact ordinary stranded wire has slightly greater loss than solid wire at RF frequencies. But if we use individually insulated wires and twist the bundle during assembly in such a way that every wire is periodically transposed from the outside to the inside and then back, the current distribution can be much more uniform across the wire bundle and RL significantly lower. This type of construction is known as "litz wire". The formal name is "litzendraht", which comes from German, litzen→strands and draht→wire, "stranded wire". The strands in this wire are individually insulated and twisted to provide the required transposition. Figure 6.22 (taken from the New England catalog) shows how the strands are assembled. Initially seven strands are twisted together. To make the wire bundle larger (Rdc smaller) multiple bundles are twisted together. This process can be extended to have an Rdc equivalent to a given solid wire as shown in table 4.

Table 4 - Litz wire examples.

frequency	equiv. AWG	Cir. mil area	no. strands	strand AWG	nom. O.D.	Rdc Ω/1000'
137 kHz	12	6,727	700	40	0.118	1.76
475 kHz	12	6,600	1650	44	0.117	1.91

The advantage of litz is that it can substantially increase Q at LF and MF when used in place of solid wire. It is also very soft and pleasant to work with. But there are downsides! The cost is much higher than equivalent solid wire and there is the problem of reliably soldering 1600+ individually insulated wires to make connections at the wire ends. Soldering can be done but requires a careful choice of wire insulation and technique. Those interested in using litz should go to the wire manufactures catalogs and applications notes.

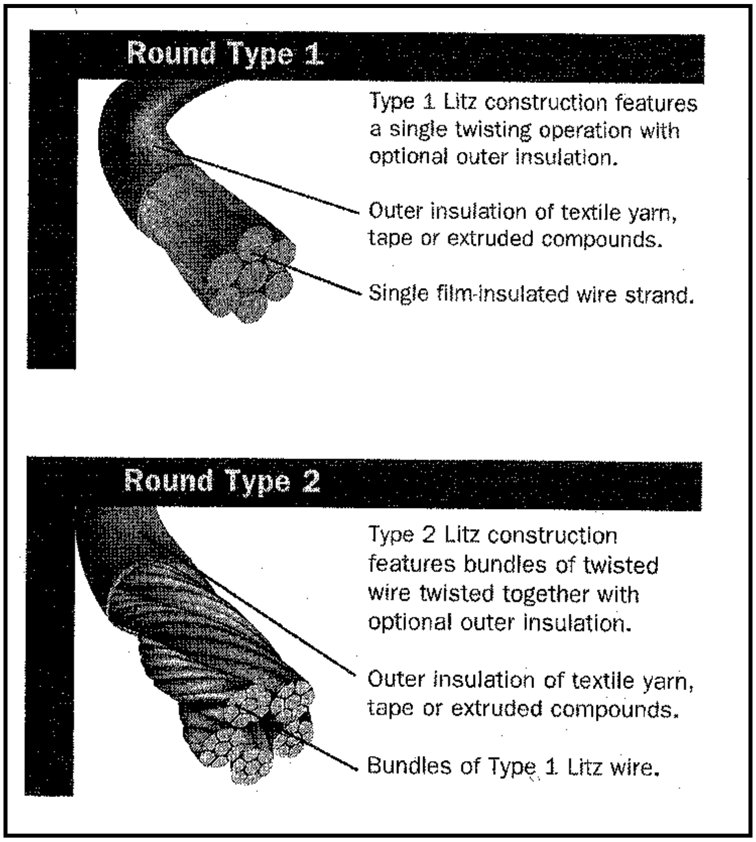

Figure 6.22 - Examples of litz construction.

Litz wire can be useful but we cannot use just any litz. Michael Perry[7] has published a formal analysis of litz wire construction which contains a cautionary tale as shown in figure 6.23!

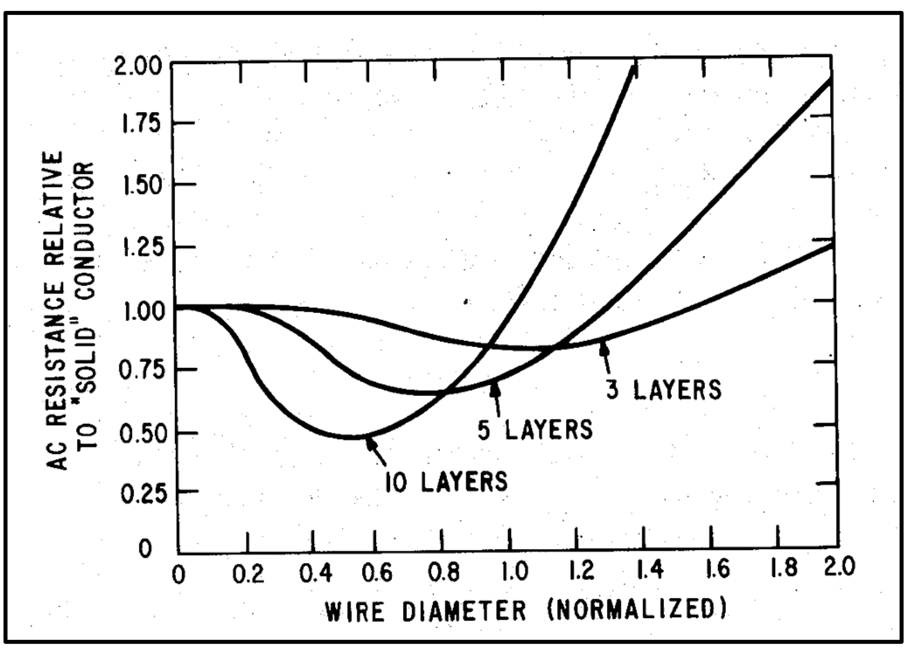

Figure 6.23 - Rac comparison between solid and litz wire. From Perry[7].

The wire diameter is in skin depths. Rac between a solid conductor and a litz conductor are compared. Litz can have a small number of wires and only a few layers or many wires forming many layers. In general the more layers and the smaller the individual strands the greater the improvement. However, there is a trap here! The reduction in Rac occurs only over a small range of wire sizes at a given frequency or, for a given wire size, over only a narrow range of frequencies. The key point shown in this graph is:

> ***If the individual wire size is too large or equivalently if the frequency is higher than the minimum Rac point, <u>Rac can be much higher using litz than in an equivalent solid wire!</u>***

The following quotation from Perry should be taken to heart if you are considering litz wire:

> ***"The foregoing analysis indicates some surprising design results which may directly contradict widely held beliefs regarding ac resistance in wires and cables. For example, suppose a solid conductor is excited at a certain frequency which results in a radius which is many times the skin-depth. Then, assume a designer switches to a cable of the same total diameter but with several layers of stranded wire to reduce losses such that d/δ>2. By inspection of Fig. 6.23, this process can result in far greater losses than if the "solid" conductor were employed. Stated another way, an uninformed design of Litz wire can result in a performance characteristic which is much worse than if nothing at all were done to reduce losses!***
>
> ***A second and important fact is that the cross-sectional area of a cable comprising stranded wires is substantially reduced from the conducting area of a "solid" cable of the same radius. This is due to the fact that each strand is usually round and insulated with a varnish or other nonconductor. The round insulated wires in the cable yield a "packing factor" which reduces the conducting area by a significant fraction, usually at least 40 percent. The transposition process further reduces the cross-sectional area available for carrying current. The final result is a substantial reduction the net savings available in ac resistance by utilizing Litz wire. Due to these limitations, the Litz wire principle for reducing ac losses must be thoroughly understood in the context of a specific application before it should be employed."***

6.4 Variable inductors

Often the exact value of L needed to resonate the antenna may not be known in advance! If the antenna has already been built and an accurate measurement of the input impedance is available, L will known but the necessary instrument may not be available or the antenna may not yet have been built! With careful modeling we can get a good estimate of the value for L within ≈5-10% depending on how close the model is to the actual antenna. Even if we measure the input impedance with a VNA that measurement is only at one particular time! The short heavily loaded verticals used at LFMF have high Q's, i.e. very narrow bandwidths and are very prone to detuning, particularly as the seasons change from dry to wet. The shunt capacitance of the antenna will change with soil conductivity which changes with moisture content. Frost or water droplets on the wire will also detune the antenna. To accommodate this change in shunt capacitance some adjustment of L is almost always needed. How much adjustment is needed? Referring to figure 6.1, the antenna and loading coil form a simple series resonant circuit where the resonant frequency (fo) can be expressed by:

$$\mathbf{fo} = \frac{\mathbf{1}}{\mathbf{2\pi\sqrt{L \cdot Ca}}} = \frac{\mathbf{1}}{\sqrt{\mathbf{XL \cdot Xa}}} \quad [\mu H] \ (6.7)$$

At the least you will want to be able to tune across a band. On 630m the band is 7 kHz wide or ≈1.5%. On 2200m the band is 2.1 kHz wide, also ≈1.5%. fr varies as the square root of XL so a range of ≈3% minimum is needed. Again, as a practical matter, you should be able to vary the value of L over a range of at least 5% to 10%, with a resolution or steps smaller than 1%.

6.4.1 Tapped inductors

One of the simplest ways to vary L is with taps as illustrated in figure 6.24. The idea is to have a few widely spaced taps for coarse adjustment and then a group of closely spaced taps for finer resolution. The initial coarse adjustment is made by tapping down from the top of the coil and the fine adjustment by tapping up from the bottom (referring to the picture). However, installing a lot of taps can be a nuisance. An alternative is to put only a few taps on the main loading inductor and add a small roller inductor, like that shown in figure 6.25, in series for fine adjustment. This is a particularly convenient arrangement when doing final adjustments or making adjustments to compensate for seasonal changes. While roller inductors are often seen at ham flea markets usually the inductance is <100 uH which is usually too small for all the variation needed. The best option is usually a roller inductor for trimming in series with a larger tapped high-Q inductor providing the bulk of L.

Figure 6.24 - Large commercial inductor.

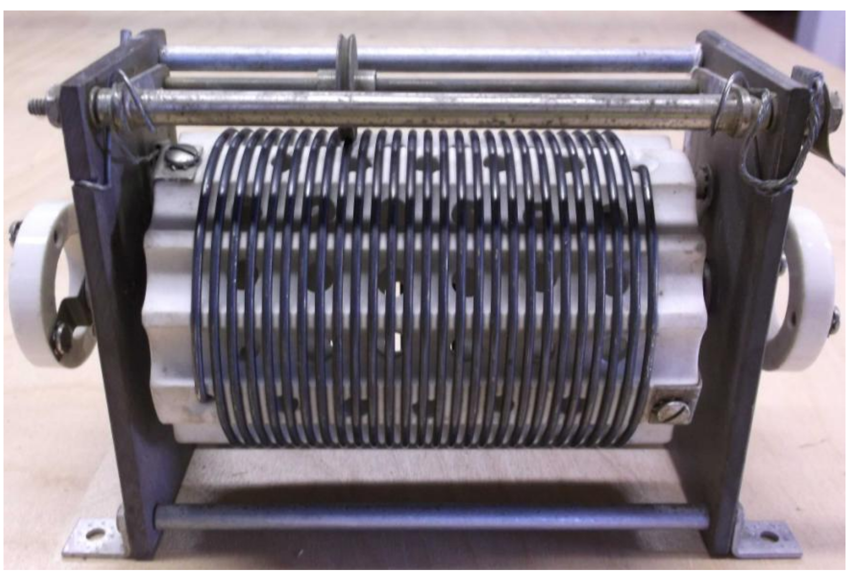

Figure 6.25 - Roller inductor example.

Tap placement

Locating taps requires some thought. When l and D are constant, L is proportional to N^2. However, when you are adding/removing turns or moving between taps the rate of change of L will vary between because you're changing both N and l. For small N the rate of change of L is close to $\propto N^2$ but as more turns are added the rate of change decreases approaching $\propto N$. Keep this in mind when selecting tap locations.

One additional point when using taps, SRF does not change greatly when moving to a lower tap. An analog for that situation is tapping down on a transmission line as shown in figure 6.26. SRF is still determined by the total length of the transmission line. In practice moving to a tap will shift the location of the parasitic capacitance (Cp) and this will shift SRF but usually not a lot.

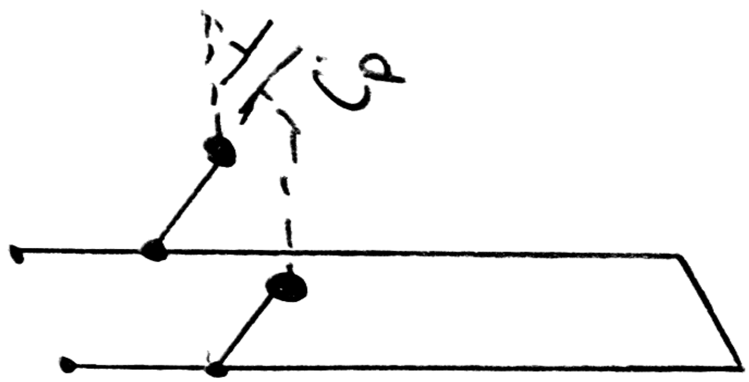

Figure 6.26 - Tapped transmission line model.

6.4.2 The variometer

Another option is to use a "variometer", which mechanically varies the coupling between two windings in series. Early radio books show an astonishing range of mechanical arrangements well worth reviewing for useful ideas. One of the most common arrangements is shown in figure 6.27 where a small secondary coil is inserted inside a primary coil, connected in series with the primary and rotated to change the coupling. The outer or primary coil has length = l_1, radius = r_1 and N_1 turns. The inner or secondary coil has length = l_2, radius = r_2 and N_2 turns. The angle between the coil axis is θ°.

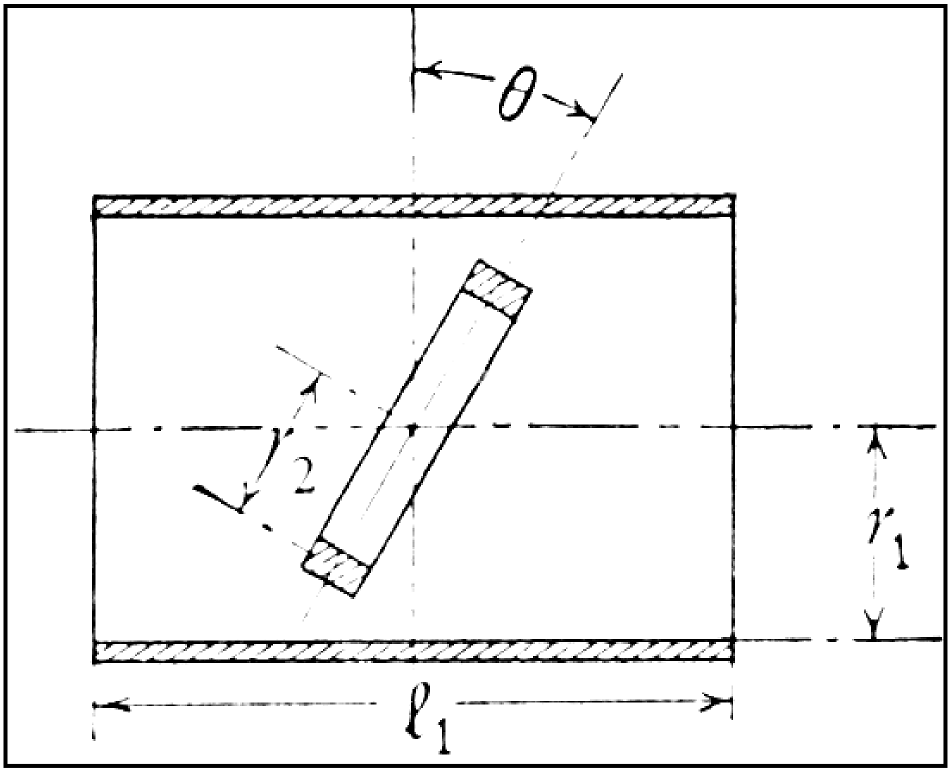

Figure 6.27 - Variometer principle.

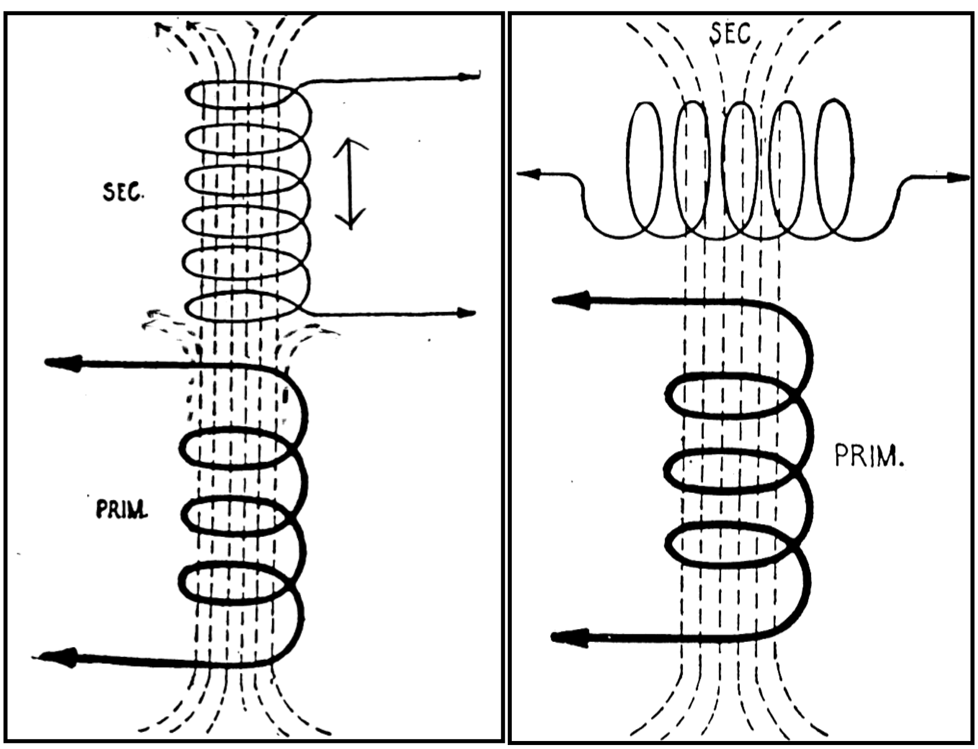

Figure 6.28 - Approximate coil flux.

Figure 6.28 is a sketch of the magnetic field associated with two coils. On the left the axis of both coils is collinear. On the right the axis' are at 90º. When the axis is parallel most, but not all, of the magnetic flux is the primary coil also passes through the secondary coil.

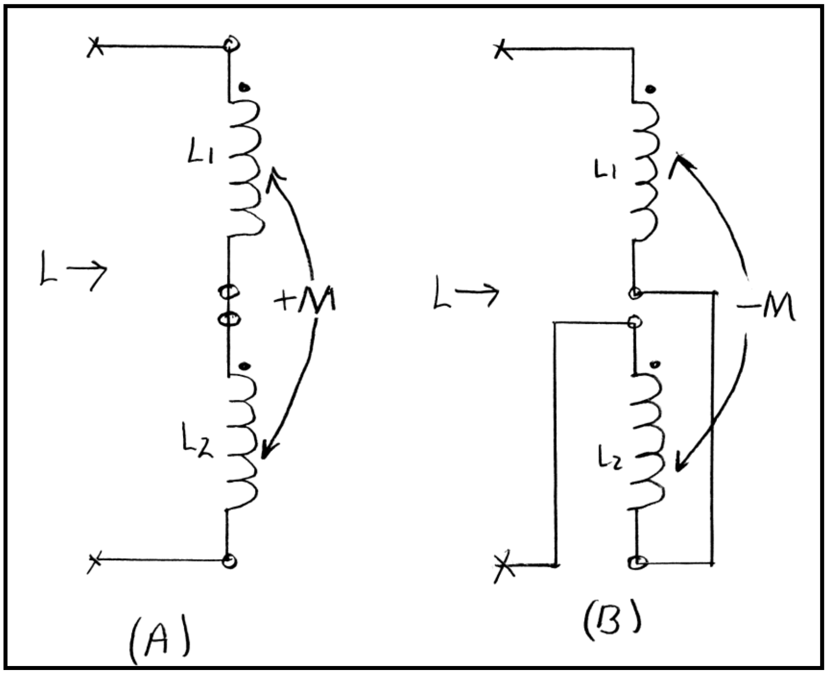

Figure 6.29 -

How do we get a variable inductance by varying the coupling? Figure 6.29 shows two coils (L1, L2) connected in series. In (A) L1 and L2 are connected series aiding and in (B) series apposing. The value for L can be expressed as:

$$\mathbf{L = L1 + L2 \pm 2M} \quad (6.8)$$

Where M is the "mutual" inductance:

Note that M can be either + or -. +M corresponds to series aiding connection and -M to series apposing which can be adjusted by rotating the secondary coil. M will vary approximately as the cos(θ).

We can calculate M from:

$$\mathbf{M = \frac{0.4 N_1 N_2 \pi^2 r_2^2}{l_1 + r_1}} \quad \mathbf{uH} \quad (6.9)$$

Where r and l are in meters.

6.4.2.1 Bucket variometers

We can gain good understanding of variometers by designing and testing an example shown in this section. A frequent form of variometer among amateurs is built on a plastic bucket. An example is shown in figure 6.30

Figure 6.30 - bucket variometer example.

Note, the turns in figure 6.30 have some air space between the turns as per the earlier warning. Figure 6.31 shows three possibilities for the inner inductor, L2. the largest form is the top of a 2 gallon bucket, r_2≈4.6"/0.117m. The smallest form is a section of 4" PVC pipe, r_2≈2.09"/0.053m The middle form is the top of a 1 gallon bucket, r_2≈3.5"/0.089m. For this discussion we'll compare two of them: PVC pipe and the 2 gallon bucket top.

The first question is: how much variation in inductance (±ΔL) is wanted? L1 for this example is ≈639 uH. A typical range of variation would be ±10% or ±60 uH in this example. For this inductor N1=56 turns, l_1=11"/0.279m, r1=5.4"/0.137m.

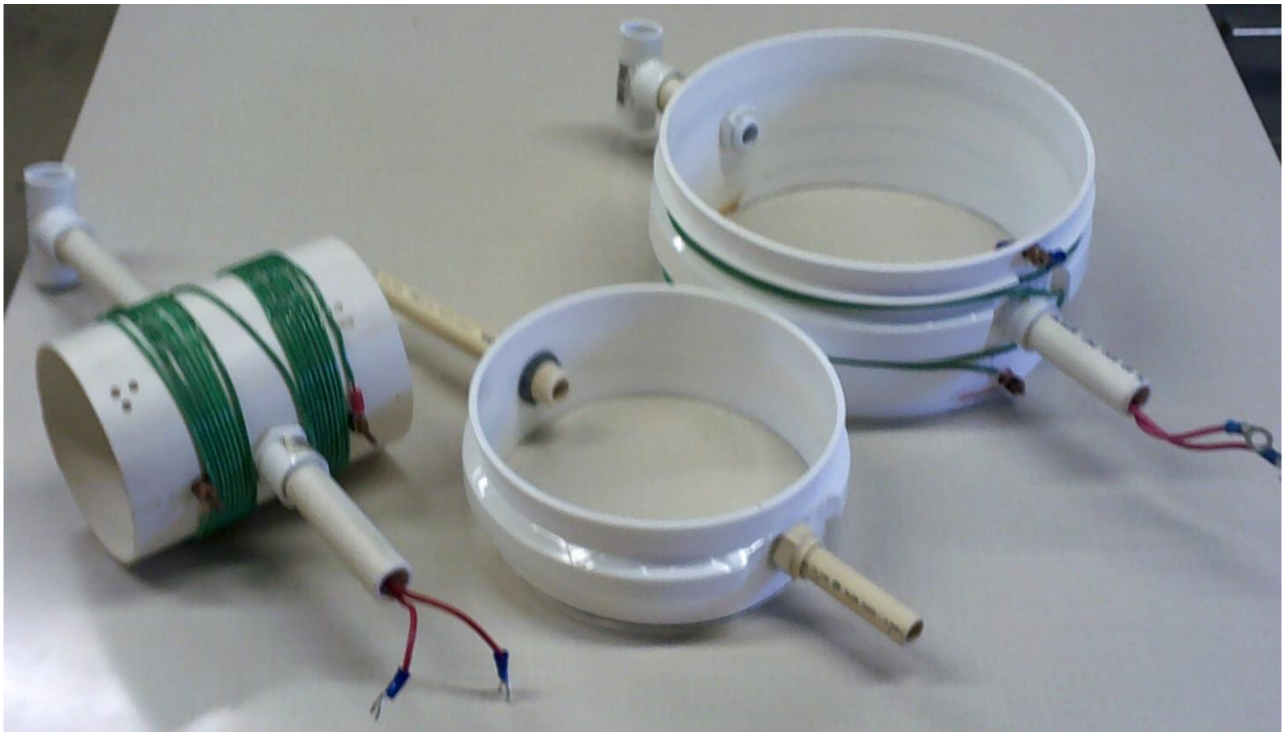

Figure 6.31 - Alternative L2 coil forms.

From equation 6.8, ∆L=2M

$$\Delta \mathbf{L} = \mathbf{2M} = \frac{\mathbf{0.8N_1N_2\pi^2r_2^2}}{\mathbf{l_1+r_1}} \quad \mathbf{uH} \quad (6.10)$$

We know the following variables:

ΔL=60 uH, N1=56, l_1=0.279m, r_1=0.137m

For the 2 gallon ring, r_2=0.117m and for the PVC pipe, r_2=0.053m.

What we don't know is N_2! Rearranging equation 6.10 solving for N_2:

$$\mathbf{N_2} = \frac{\mathbf{\Delta L(l_1+r_1)}}{\mathbf{0.8N_1\pi^2r_2^2}} \qquad (6.11)$$

We can now calculate N_2 for the two examples:

- 2 gallon bucket top, N_2=4.1 turns, use 4 turns.
- PVC pipe, N_2=19.5 turns, use 19 turns.

Winding the calculated number of turns on each form and inserting them into the bucket and measuring, $\Delta L=61$ uH for the large ring and $\Delta L=62$ uH for the PVC pipe. Equation 6.11 is approximate but certainly close enough for practical purposes.

In this example L≈639 uH with 56 turns. Tapping down one turn L≈614 uh which is a shift of ≈25 uH. Choosing $\Delta L=60$ uH is comparable to moving the tap roughly two turns. You could use less ΔL which should improve Q as shown in the next section but then you would need to insert a sufficient number of taps.

6.4.2.2 Variometer Q

There is one very important consideration: how is the Q of L1 affected by inserting L2 inside it? In figure 6.27 we see that L2 is inside L1 immersed in the internal field of L1. This means that L2 will have it's normal self loss but also additional loss from the field of L1. In addition, the external field of L2 will interact with the winding for L1, more loss. There is also another reason for decreased Q.

$$\mathbf{Q} = \frac{\mathbf{XL}}{\mathbf{RL}} \quad (6.12)$$

When L1 and L2 are connected series aiding XL will be a maximum but when they are series apposing XL will be lower. RL however, will probably not be lower so Q must decrease as L decreases. Here are some Q measurements at 475 kHz for the variometer shown in figure 6.30:

No center coil, Q=700

For the 9" diameter 4T center coil, Q=500 for Lmax and Q=420 for Lmin.

For the 4" diameter 19t center coil, Q=550 for Lmax and Q=530 for Lmin.

The message here is that adding a variable center coil to an inductor to create a variable inductor will significantly reduce Q. I suggest the following guidelines:

Use as few turns as possible on L2, i.e. design for the minimum needed inductance variation. Use L2 for fine adjustments. Use taps on the coil for course adjustments.

From limited experiments it appears that very large and small L2 diameters give lower Q. I suggest having the diameter of L2 equal to roughly half that of L1.

6.4.2.3 Classic examples

Figure 6.27 is just one of many arrangements as shown in figures 6.32 through 6.34. Some of these examples show flat strip windings but round wire will also work.

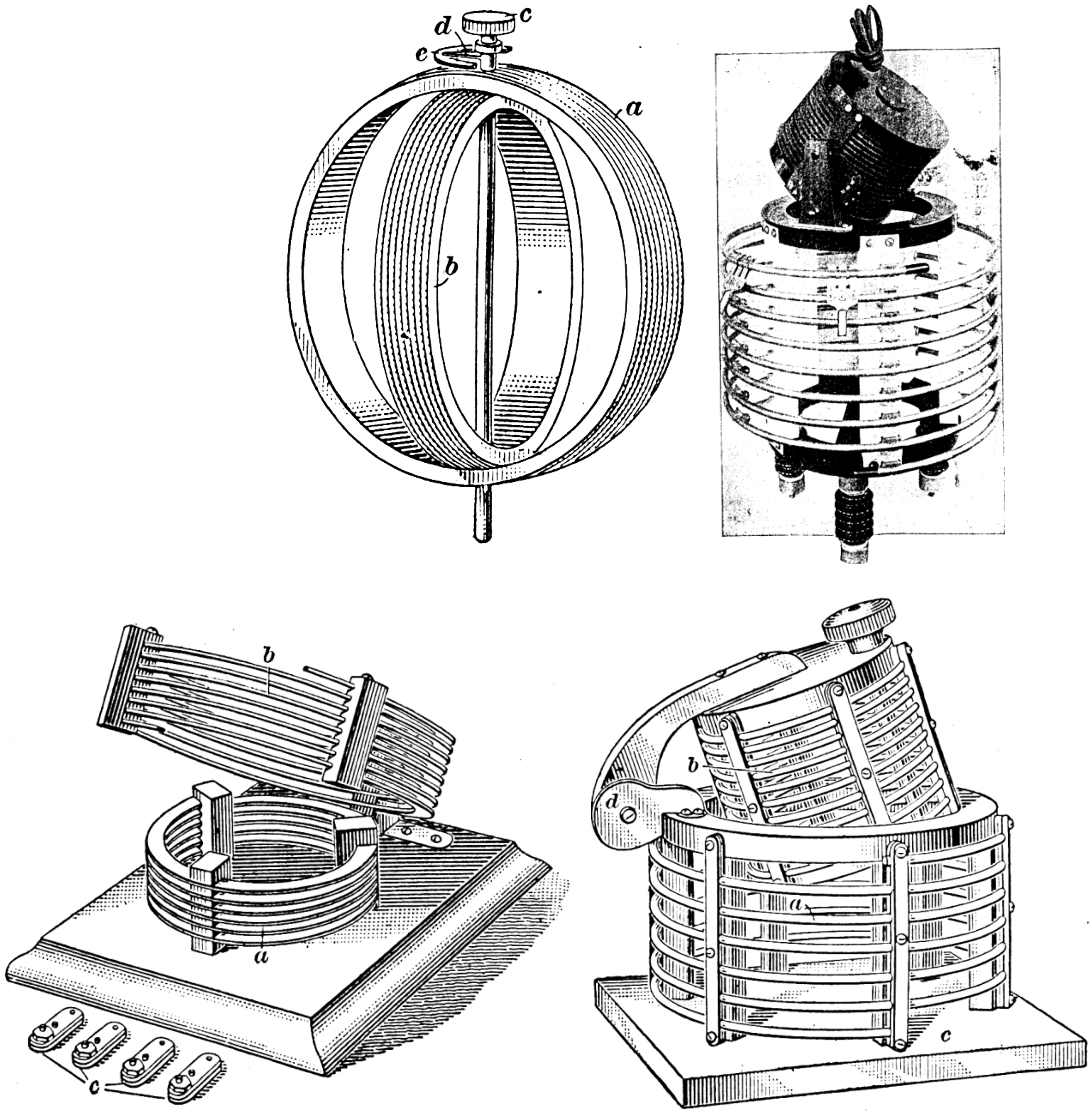

Figure 6.32 - Variometer examples

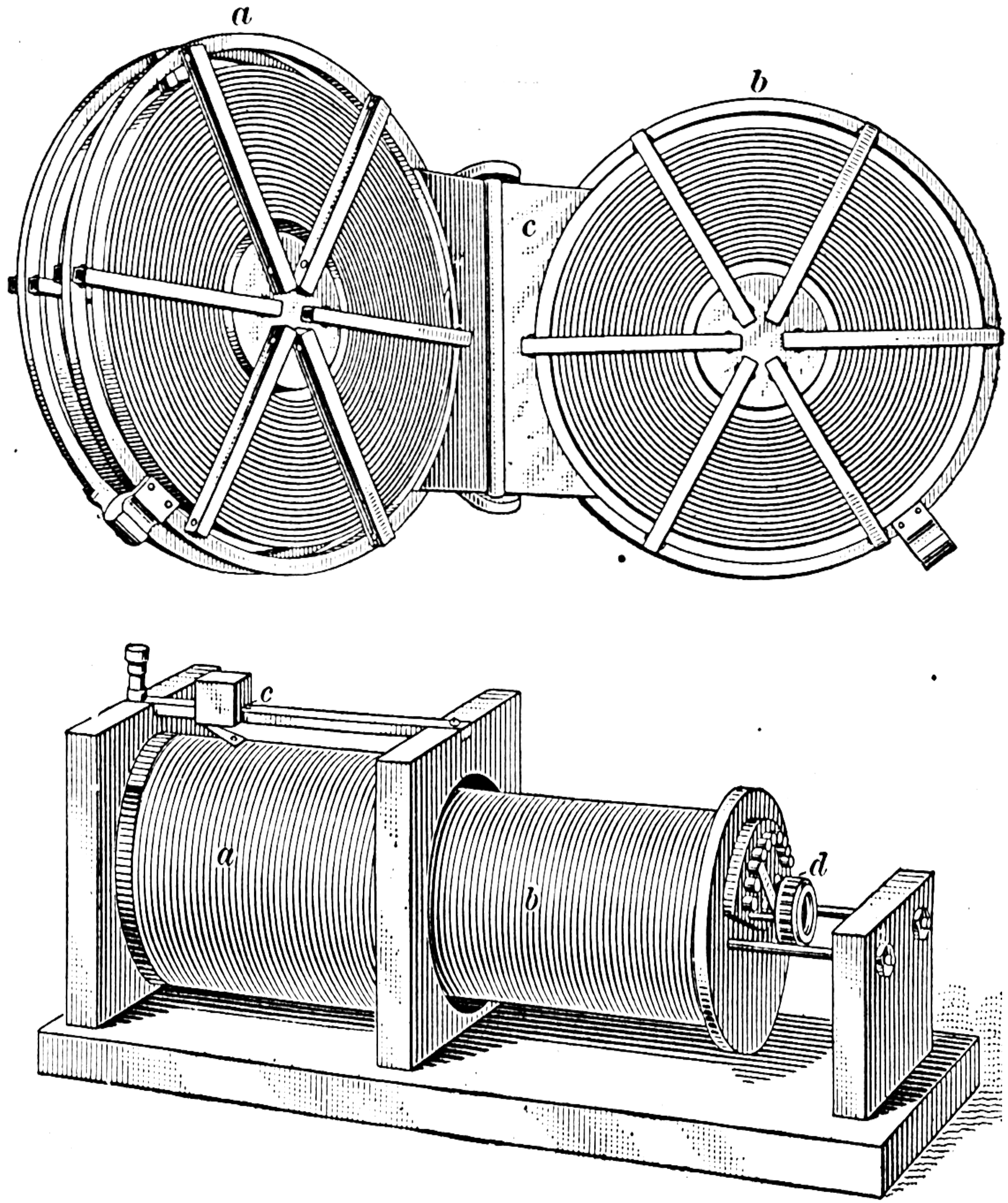

Figure 6.33- More variometer examples.

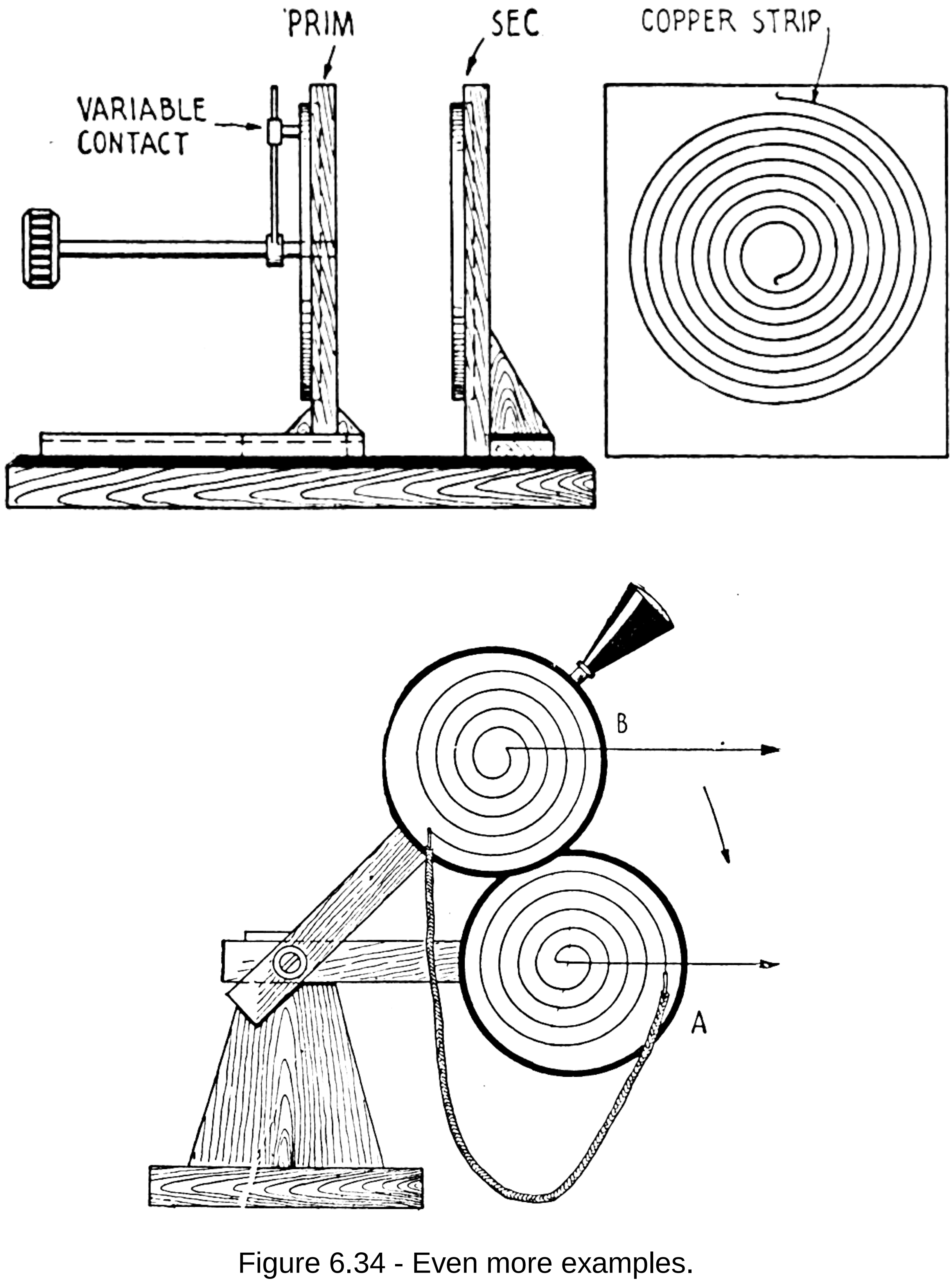

Figure 6.34 - Even more examples.

6.4.2.4 Home brew examples

Figure 6.35 - Ralph, W5JGV variometer example.

As shown in figure 6.35, Ralph, W5JGV, has built lovely variometers using PVC pipe and copper wire. The inductance of these variometers is not large but adequate for fine adjustment in combination with a tapped main inductor. The other option is to incorporate the variable inductance into the main inductor as shown in figure 6.36.

LFMF hams have shown great creativity in the design of practical variometers as the following examples show.

Figure 6.36 - Laurence, KL7L. Bucket variometer example.

Figure 6.37 was fabricated by John, KB5NJD. The base inductor is wound on the outside of a plastic bucket. Inside the bucket is a smaller rotatable inductor. The two inductors are connected in series. By rotating the inner inductor the total inductance goes from the sum of both to the difference. Given the need for adjustment at inconvenient times (pitch dark and snowing) many variometers have some form of remote tuning. KB5NJD used an inexpensive TV antenna rotor for remote tuning!

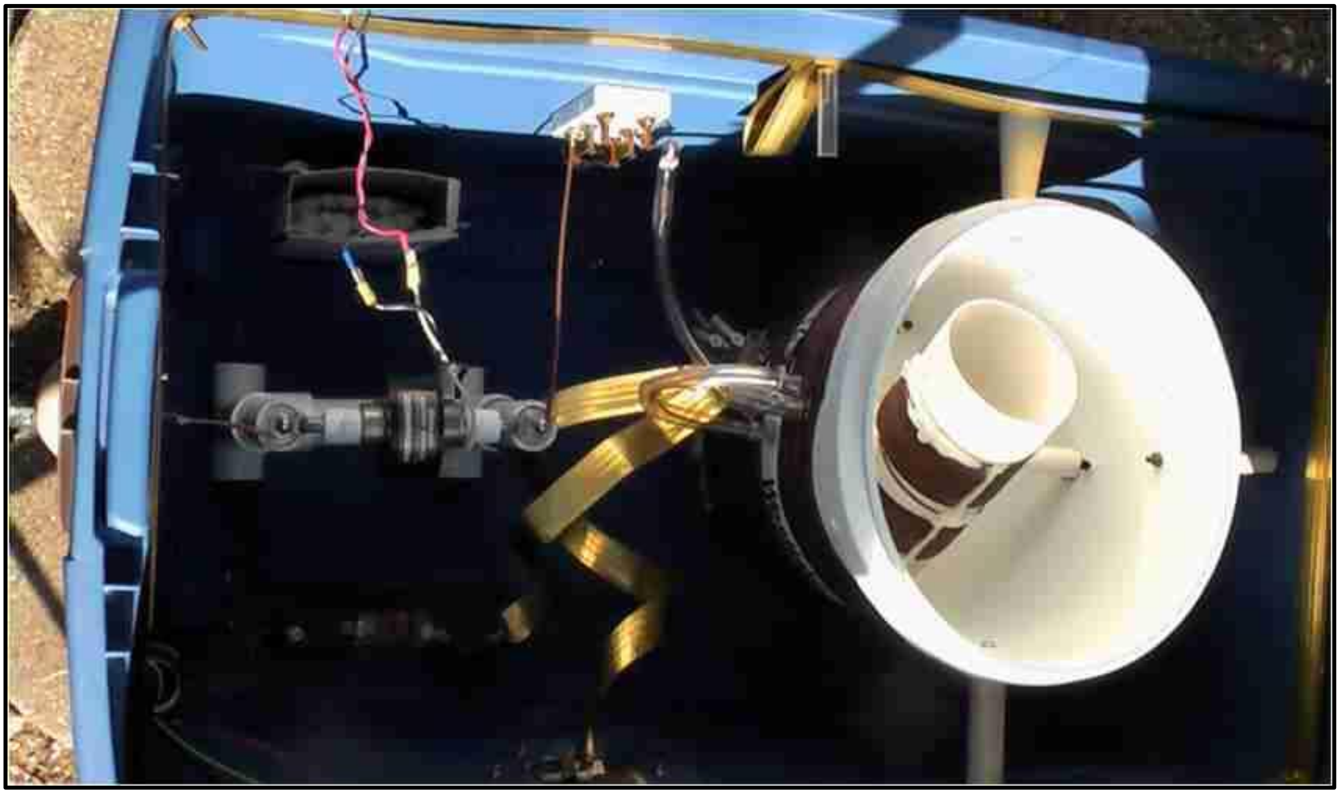

Figure 6.37A- KB5NJD variometer.

Figure 6.37.B - John, KB5NJD variometer adjustment with a TV rotor.

Figure 6.38A - Jay, W1VD, WD2XNS variometer.

Figure 6.38B - Jay, W1VD, WD2XNS variometer.

Figure 6.38C - Jay, W1VD, WD2XNS variometer enclosure.

Figure 6.39 - Steve, KK7UV, variometer.

Figure 6.40A -Neil, W0YSE, variometer.

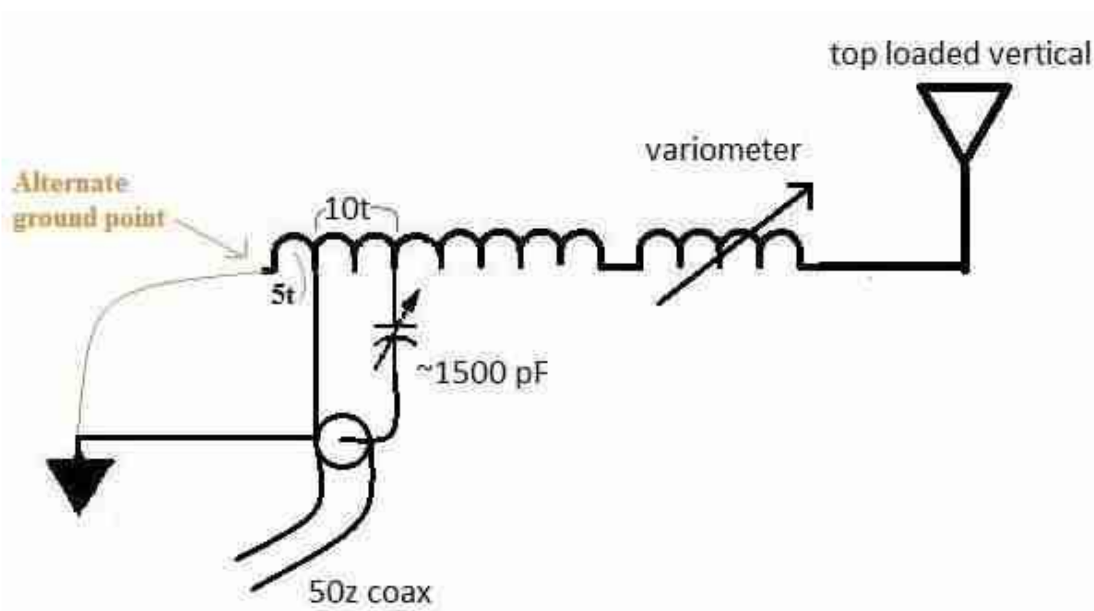

Figure 6.40B - W0YSE tuning unit circuit diagram.

Figure 6.40C - W0YSE variometer location.

Neil, W0YSE, has located his variometer just outside a window of the shack. Adjustment is manual: open window, twist variometer knob, close window.

6.5 Winding voltages, currents and power dissipation

The current at the base of the antenna (Io) is also the current in the inductor. The voltage across the inductor is the same as the voltage at the base of the antenna (Vo).

Io is determined by the radiated power Pr and the radiation resistance Rr:

$$\mathbf{Io} = \sqrt{\frac{\mathbf{Pr}}{\mathbf{Rr}}} \quad (6.13)$$

As explained in chapter 1, the maximum radiated power (Pr) is limited to 1.67W on 630m and 0.33W on 2200m. Combining the band specific values for Pr with Rr values we can use equation (6.13) to create the graphs for Io shown in figures 6.41 and 6.42. Note that L is the overall length of the top-wire in feet in all of the graphs in this section.

Vo is the voltage at the feedpoint:

$$\mathbf{Vo = XiIo} \quad (6.14)$$

We can use typical Xi values from chapter 3 to generate values for Vo as shown in figures 6.43 and 6.44. Despite the low radiated powers (Pr) the voltages at the base will often be >1kV and can be much higher, particularly when H is small. This must be kept in mind when selecting a base insulator. A high Vo also means there will be significant voltage turn-to-turn in the loading inductor and across matching network components.

PL is the power dissipated in the loading inductor, $PL=Io^2RL$. As shown in figures 6.45 and 6.46 this power can easily be >100W (assuming that level of transmitter power is available). The loading inductor must dissipate PL without damage! In general the larger the physical size of the inductor the better heat can be dissipated. QL=300 is assumed for both 137 kHz and 475 kHz. This is a bit pessimistic given the earlier discussion since increasing QL reduces PL proportionately:

$$\frac{\mathbf{PL_2}}{\mathbf{PL_1}} = \frac{\mathbf{QL_1}}{\mathbf{QL_2}} \quad (6.15)$$

In short verticals with limited top-loading Io, Vo and PL can be very high. The key to reducing these values is to use sufficient top-loading.

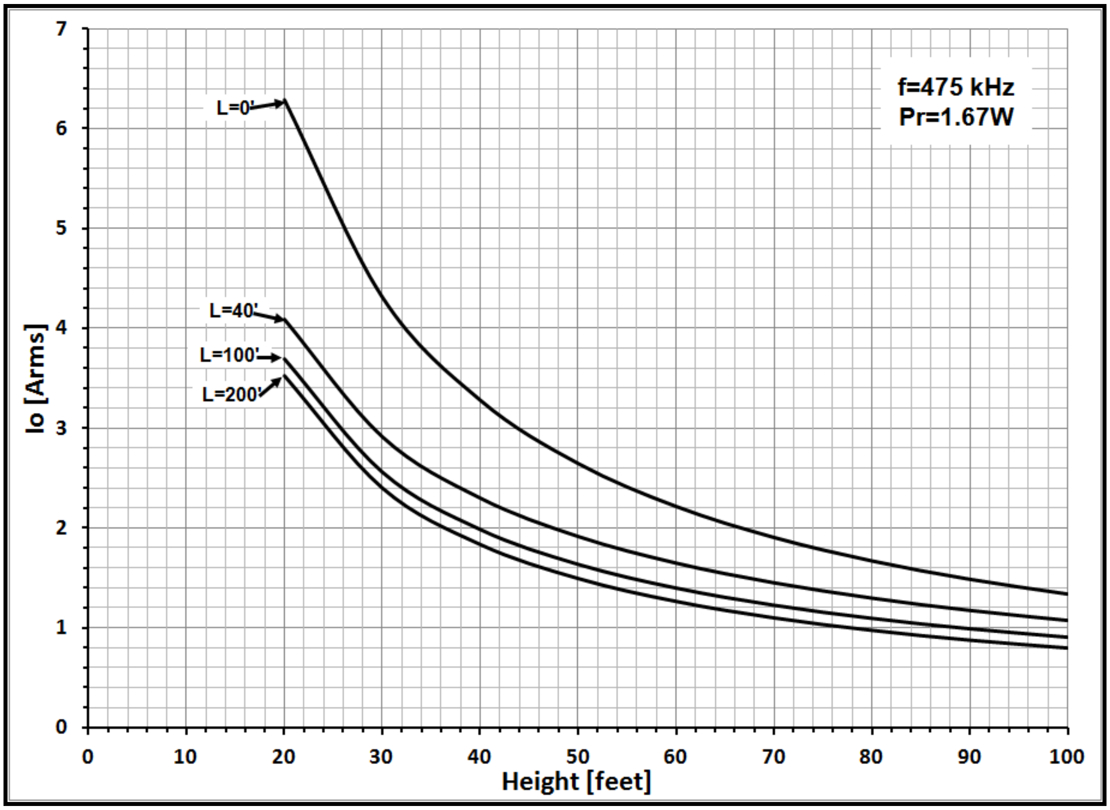

Figure 6.41 - Io for Pr=1.67W at 475 kHz.

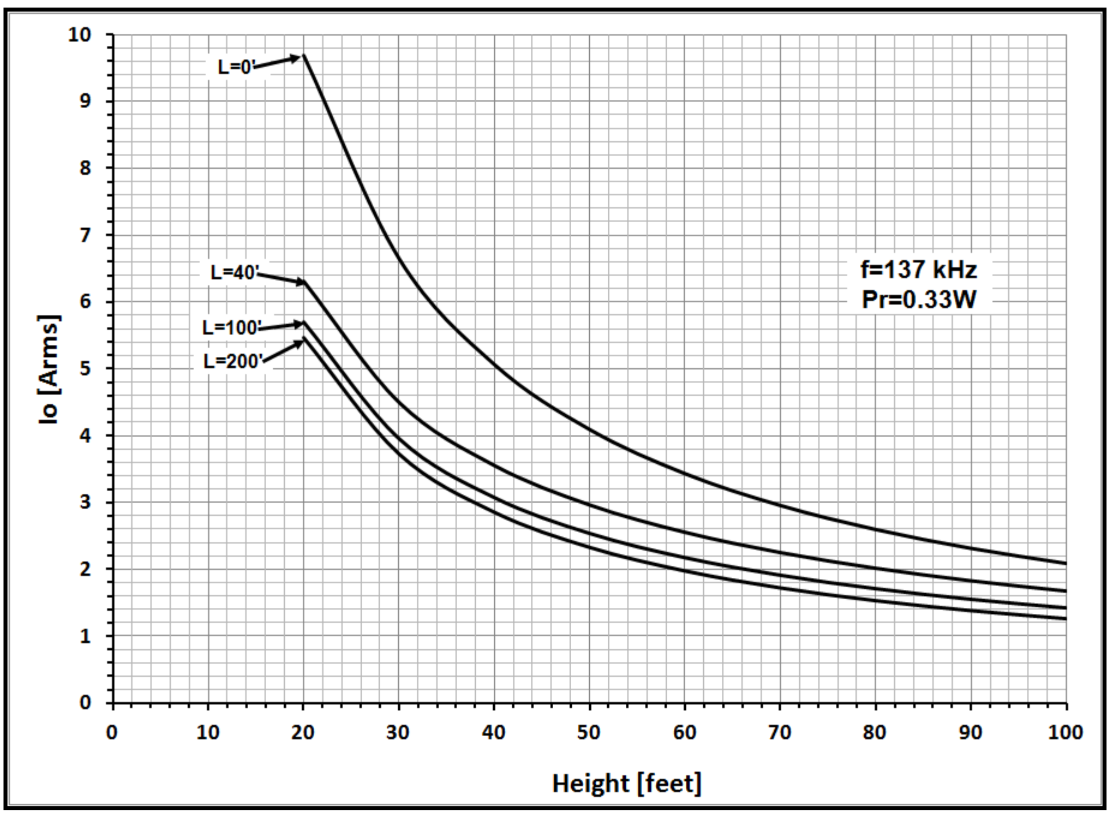

Figure 6.42 - Io for Pr=0.33W at 137 kHz.

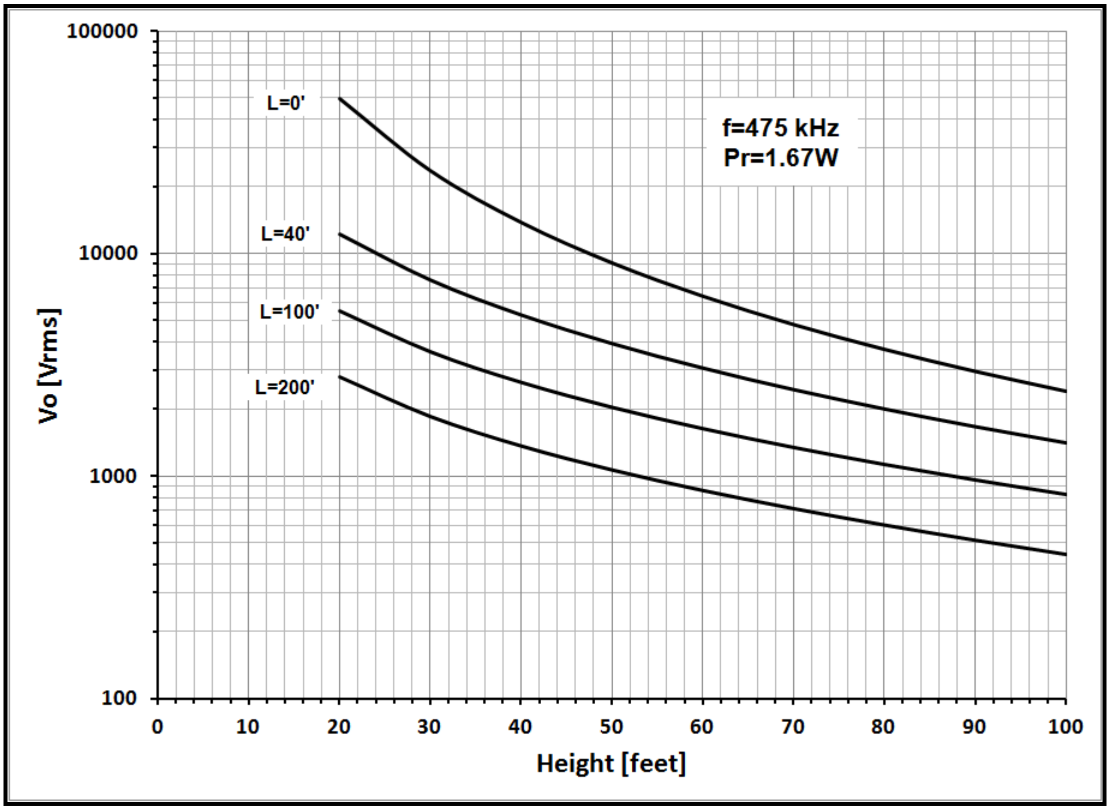

Figure 6.43 - Vo for Pr=1.67W at 475 kHz.

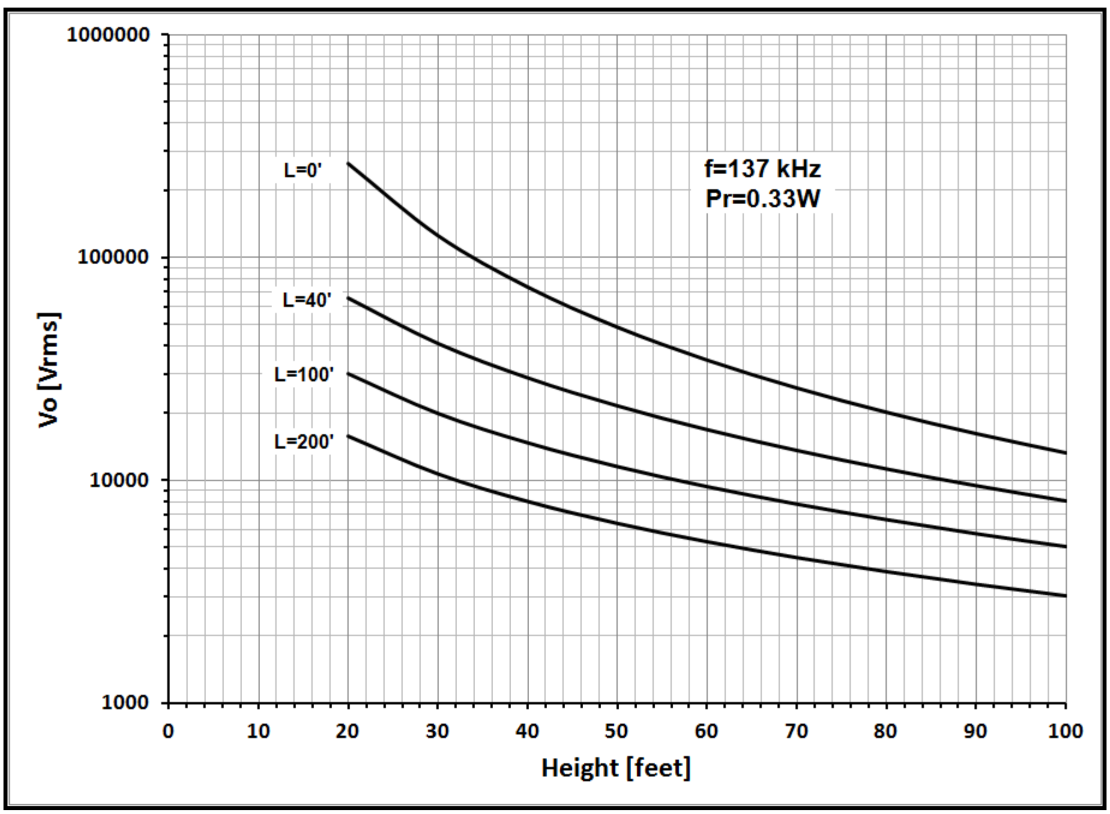

Figure 6.44 - Vo for Pr=0.33W at 137 kHz.

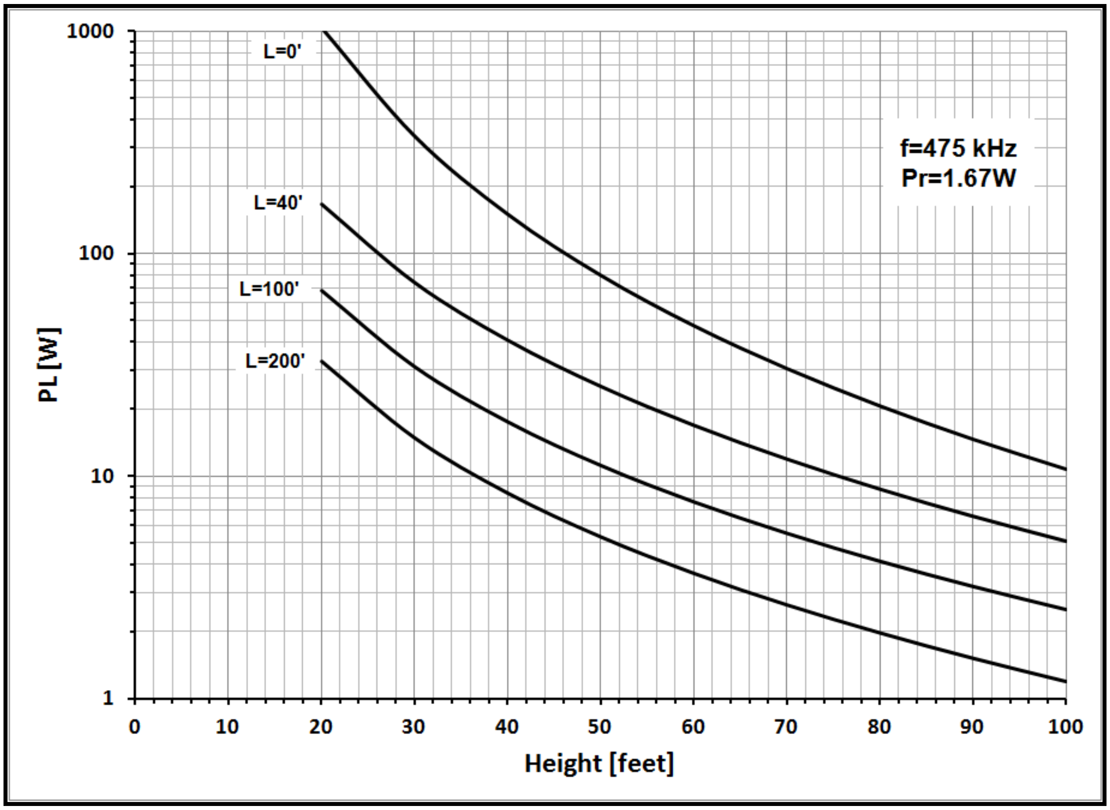

Figure 6.45 - PL for Pr=1.67W at 475 kHz.

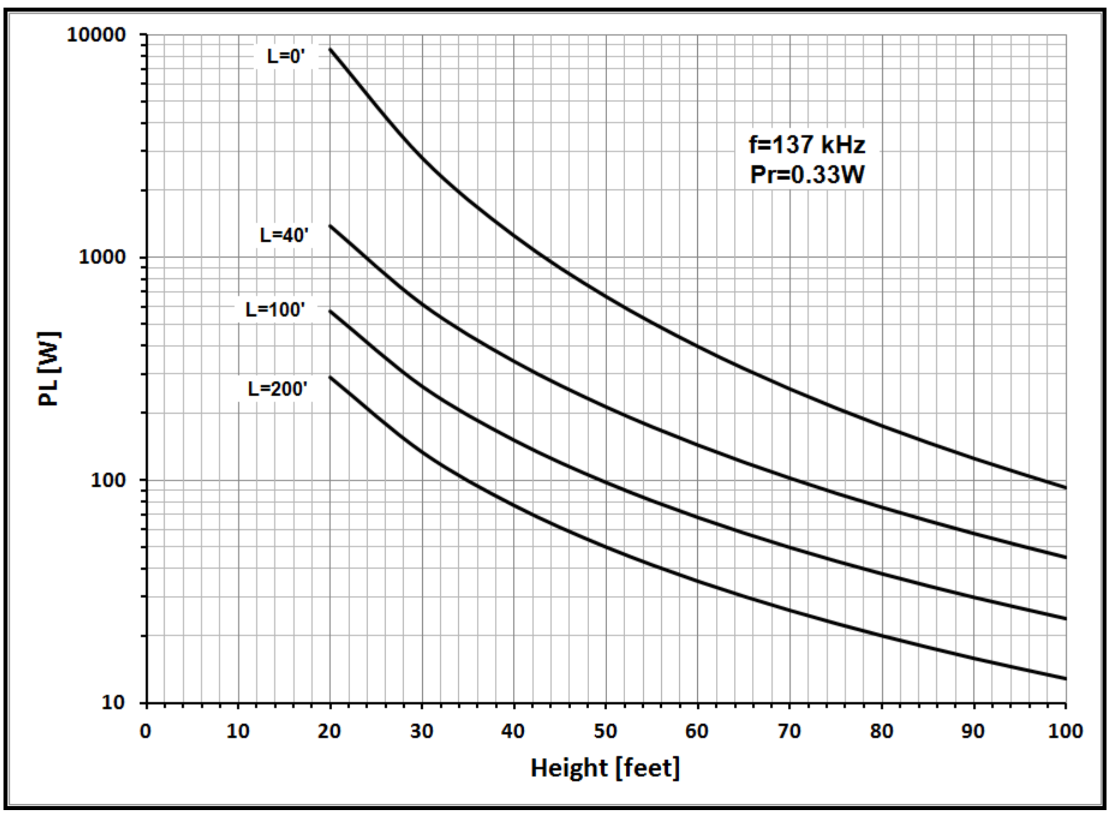

Figure 6.46 - PL for Pr=0.33W at 137 kHz.

6.6 Enclosures

Most amateurs will use some form of large plastic box for the tuning inductor enclosure. These are inexpensive, readily available in a very wide range of sizes and have little or no effect on QL. One shortcoming of typical plastic containers is their susceptibility to degradation from the UV in sunlight. A coat of white house paint is usually enough to allow them to last several years. Metal enclosures can also be used although large enclosures will usually be custom fabricated and are expensive. In general a metal enclosure needs to be substantially larger than the inductor. In particular the spacing from the ends of the coil to the enclosure wall should be at least equal to the coil diameter. A conducting enclosure will tend to reduce both L and QL if it isn't large enough.

The primary purpose of the enclosure is to protect the coil from the weather, in particular keep it dry. As the following experimental work shows, moisture can severely degrade inductor Q. Some form of enclosure usually covers the coils but they can still be quite damp and perhaps even have some icing. K6STI sent me a link (http://www.n3ox.net/tech/coilQ/) to a note reporting some experiments on wet inductors. The news was not good, moisture does not benefit Q! After some discussion I ran a few simple experiments on two large coils using an HP4342A Q-meter to judge the effects of water on Q. All the Q measurements were made at 475 kHz. In each test the Q-meter Cr was adjusted to re-resonate by adjusting for peak Q on the meter. Most of the experiments were repeated to check consistency.

6.6.1 Experiment 1

I had on hand the bucket inductor shown in figure 6.47. L≈650uH. I began with the coil dry: Q=460. Using a spray bottle, I sprayed water over the outside of the winding to simulate rain: Q=200! The coil was not happy being wet!

Figure 6.47 - Bucket inductor.

6.6.2 Experiment 2

The next test used the bare #12 wire coil on a PVC cage shown in figure 6.48. L≈1 mH @475 kHz.

Figure 6.48 - PVC cage inductor.

Note: in the photo there is a plastic bag of ice lying in the bottom of the coil. The ice was placed there later in the experiment. The initial test was a dry coil, Q≈700 which was then sprayed: Q≈400. Wiping the coil with a towel, the Q increased to 500 and slowly rose as the coil dried returning to ≈700 after some hours. This coil was very sensitive to even a small film of moisture.

The water used for the initial test was from my well which has a very small amount of salt in it. As a check I bought a gallon of distilled water, rinsed the spray bottle carefully, and when the coil was again dry, re-sprayed it with distilled water: Q≈530. Then I switched back to well water and re-sprayed: again Q≈400. One might argue that rain water is closer to distilled water than my well water but any inductor outside will have deposits from the air and rain water also brings down local pollution so I don't think the improvement using distilled water is cause for joy. Up to this point the shift in Q-meter Cr was very small, a pF or so, essentially all the variation in Q was due to additional loss not a shift in SRF.

6.6.3 Experiment 3

Brian had suggested that ice might have higher losses than water so I ran a test. As shown in figure 6.48 I placed a bag of ice inside the coil: Q≈250, not good! To see if ice had more loss than water I allowed the ice to thaw completely and then put the now water-bag back in the coil: Q<200. That looks like the ice is less lossy than water but I think that's deceiving. The ice was pretty lumpy and the contact with the winding intermittent but when thawed the bag of water lay much closer to the winding. In practice I think the ice and water have the same effect. Outside in icing conditions the ice might very well build up a much thicker layer on the winding than a thin film of water so the effect might be much greater.

6.6.4 Experiment 4

I wanted to see if water on the outside of an enclosure would have any effect so I placed a plastic bag over the cage inductor as shown in figure 6.49. Note, the bag is quite close to the coil. I sprayed the outside of the bag with the coil connected to the Q-meter: no observable effect. Now if the bag had heavy icing then maybe it might make some difference but I was not able to run that experiment.

6.6.5 Experiment 5

During all the earlier experiments the shift in Cr was quite small, a pF or so, even when Q was severely reduced. Just for the heck of it I placed the one gallon jug of distilled inside the coil: Q dropped from 700 to 360 and Cr was reduced by 5 pF. This was the only time I saw a significant shift in Cr, which would be a dielectric effect.

Figure 6.49 - Coil with plastic cover.

6.6.6 Conclusions

This series of experiments was hardly rigorous, but I think they convincingly give the message: keep your coils dry and out of the weather and condensation. To fight condensation the enclosure needs to be, drained and ventilated but be careful, don't make the vent holes large enough for the bees and wasps to get in. A hornet nest in the coil does not improve Q!

The rule of thumb suggesting the walls of any enclosure, soil or other objects be at least one coil diameter away from the coil seems like reasonable advice.

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