Optimum Q LFMF Antenna Loading Inductors

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Introduction

Most practical size amateur LFMF antennas will need a large loading inductor and in most cases inductor loss will be a major portion of the total antenna loss. To achieve reasonable radiation efficiency high Q inductors are needed. One way to obtain higher Q is to make the inductor physically larger increasing diameter, length, conductor size, etc, but there's problem: if you start with a small coil of a given inductance and geometry and scale up its dimensions, initially Q will increase nicely but simultaneously the self resonant frequency (SRF) will decrease. At some point SRF will limit the achievable Q. Unfortunately because of the large inductance values needed, to obtain high Q, the effect of SRF cannot be ignored. At the RF frequencies of concern there will still be both skin and proximity effects in addition to SRF.

We have reliable equations for calculating skin, proximity and SRF effects. However, some of the expressions are algebraically messy and interrelated in complicated ways. Finding optimum Q solutions, taking into account all the variables, can be a bear. Fortunately Brian Beezley, K6STI, has created an inductor design program[1] (COIL) which includes all the variables and equations combined with an optimizer. The math is all offstage which is a great boon. I have used Brian's program for the discussion which follows.

Narrowing the problem

To design an inductor the inductance value (L), the operating frequency (f) and wire size (#) are needed. The amateur bands are very narrow so optimization can be done at two frequencies: ≈137 kHz and ≈475 kHz. Only few wire sizes are generally used: #14, #12 and #10. In addition the range of inductor values is also limited:

At 475 kHz, L ≈300µH→1200µH.

At 137 kHz, L ≈3mH→12mH.

A modeling experiment

Using COIL I performed a modeling experiment, optimizing Q for the range of variables just given. The results were quite interesting. First, Q's of 500 to over 900 were readily obtained.

Second, the diameter (D) associated with each 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, ≈0.30-0.32, for every example over the entire range of variables! d/c can be converted to the more useful parameter p ("turns-per-inch") for each wire size as shown in table 1.

Table 1 - 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 2 shows the averaged diameters associated with optimized inductors.

Table 2 Averaged values for D and p (turns/in)

	#14	#14	#12	#12	#10	#10
SRF	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"

Using these values for wire size, diameter, p and SRF the Q's were recalculated and graphed as shown in figure 1. 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 2. The length of the winding (the minimum length of the coil form!) is simply:

$$\mathbf{l = N/p \;\; [inches]}$$

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

$$\mathbf{lw = \frac{N\pi D}{12} \;\; [ft]}$$

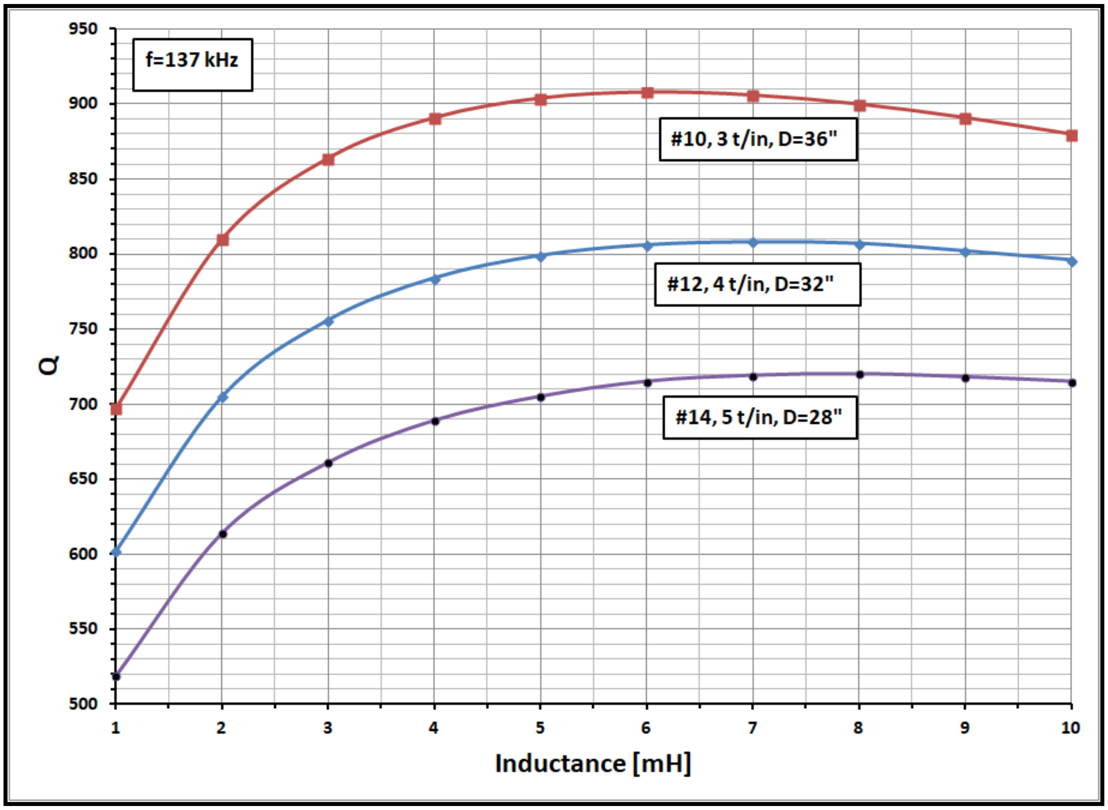

Figure 1A - Optimized Q at 137 kHz.

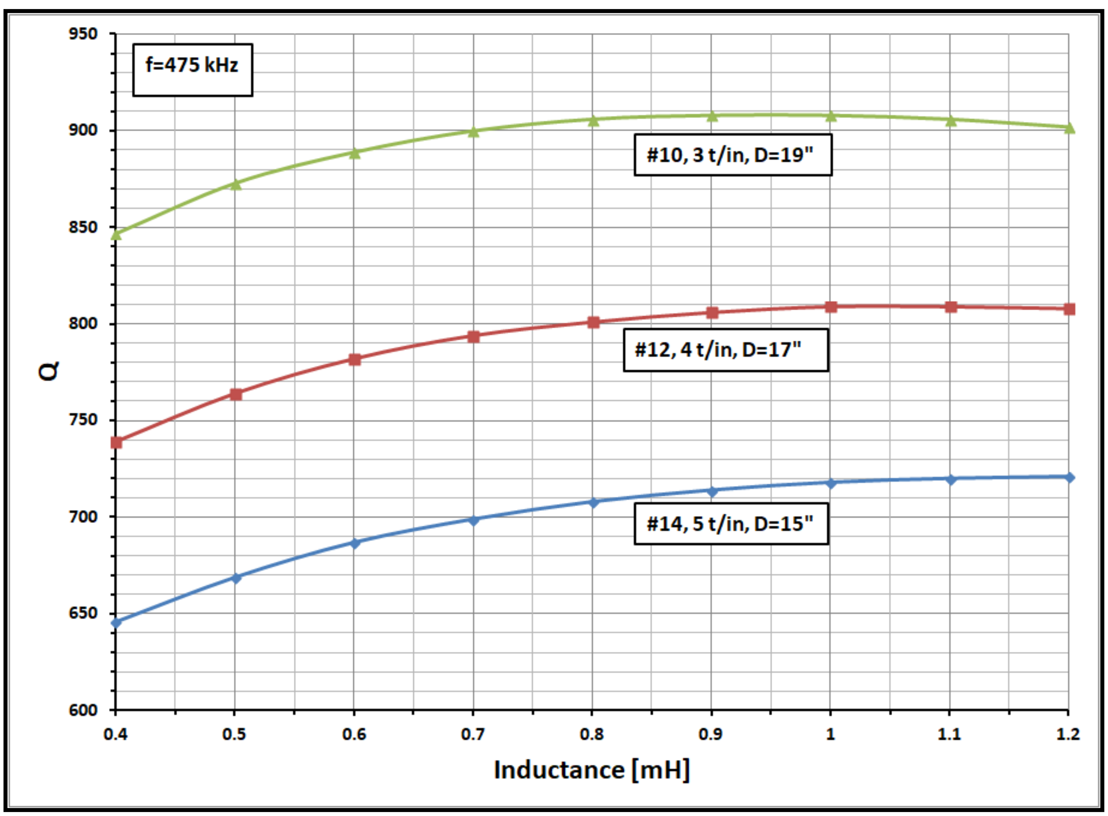

Figure 1B - Optimized Q at 475 kHz.

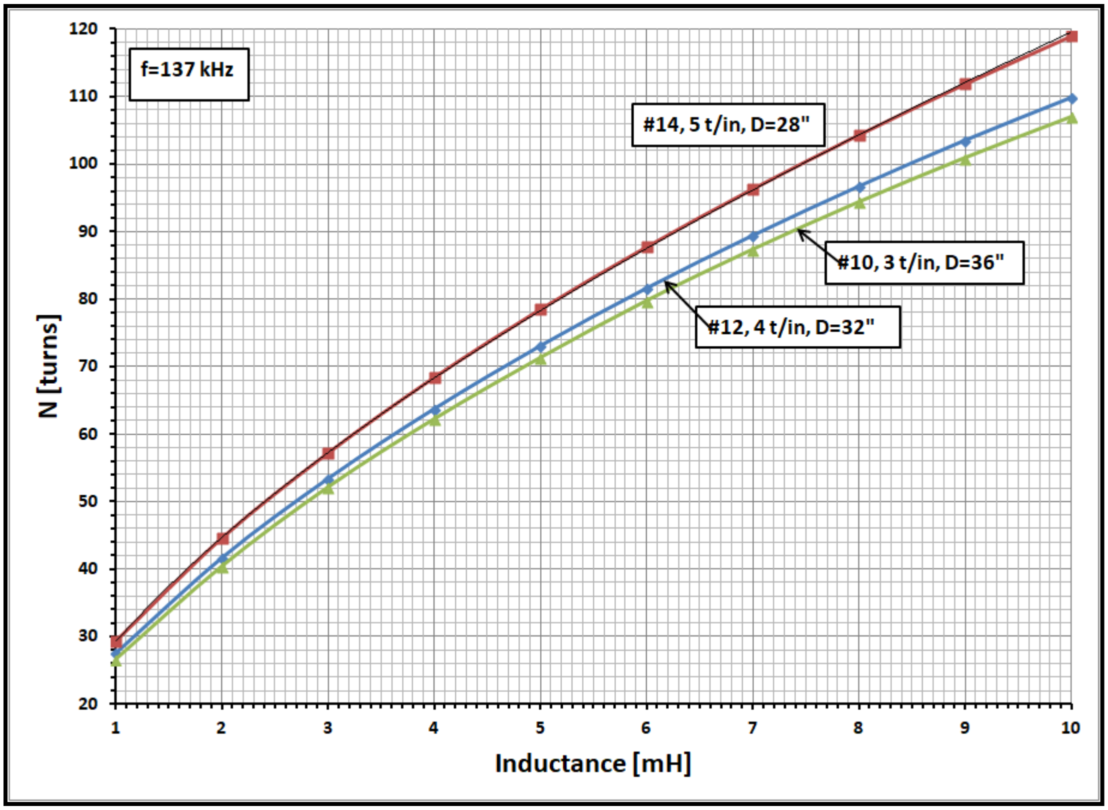

Figure 2A - N versus L for optimized inductors at 137 kHz.

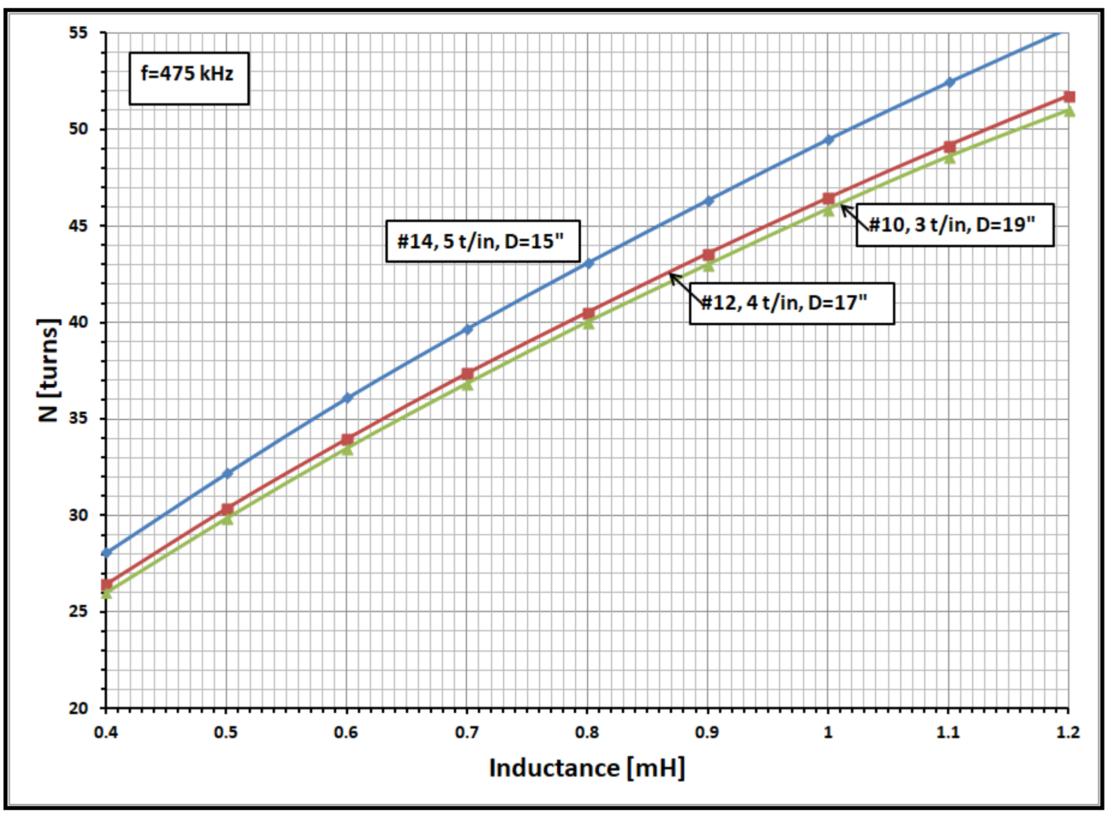

Figure 2B - N versus L for optimized inductors at 475 kHz.

Table 2 suggests coil diameters of 1.5' to 3', these are not small coils! A calculation shows lw values of 100' to over 1000'! Are they practical to build? The answer is absolutely yes, both practical and inexpensive if PVC pipe cage coil forms like those shown in figure 3 are used.

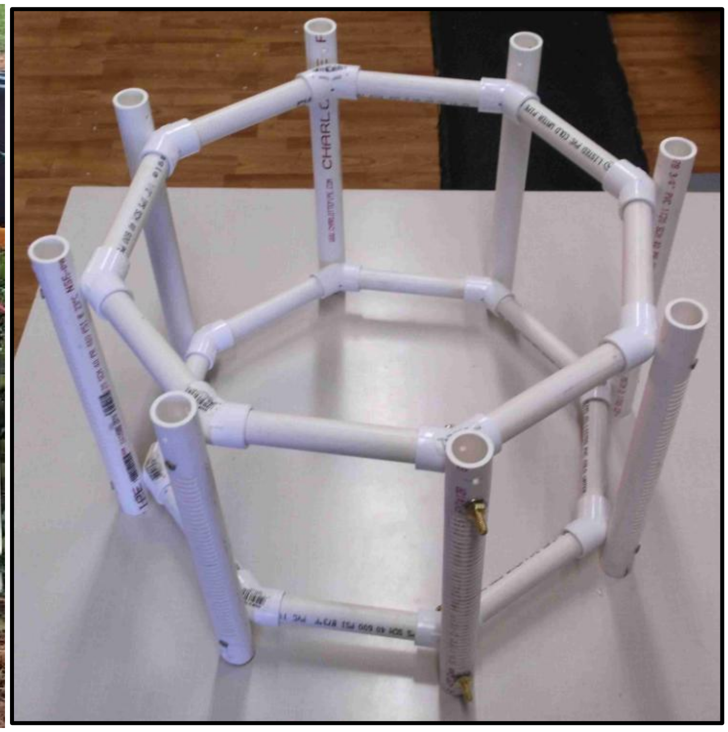

Figure 3A - N1DAY PVC coil form.   Figure 3B - N6LF PVC coil form

References

[1] Brian Beezley, K6STI, Coil.exe, http://ham-radio.com/k6sti/coil.zip
[2] Frederick Terman, Radio Engineers Handbook, McGraw-Hill, 1943

Appendix

Some readers may want the underlying data from which the optimum Q tables were derived. that information has been placed in this appendix. Figure 4 shows the coil diameter associated with each of the test coils. The associated values for D are listed in table 1A.

Note one important point: as the dashed lines on the graphs indicate, the diameters for optimized Q inductors at a given SRF and wire size <u>do not vary greatly as the inductance is changed!</u> This observation prompts another question: how much does the Q degrade from optimum if a constant average value for D, as suggested by the figures, is used for all values of inductance within the ranges shown?

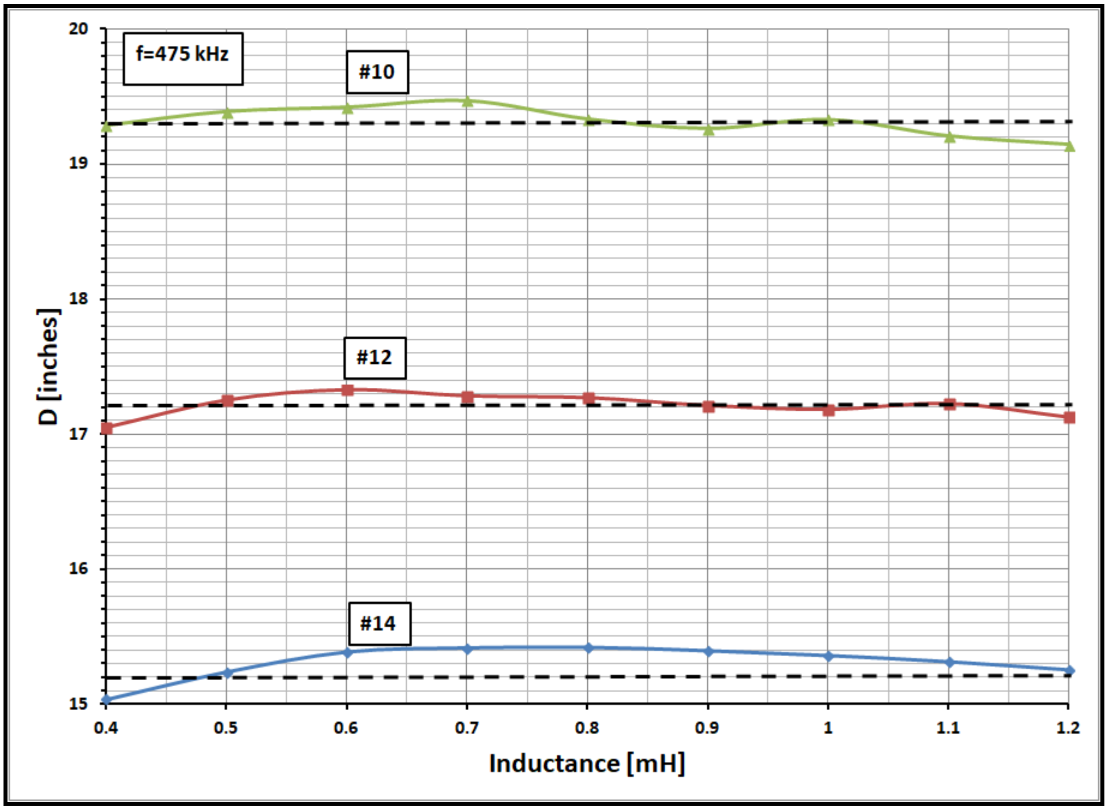

Figure 4A - 475 kHz coil diameters [inches]

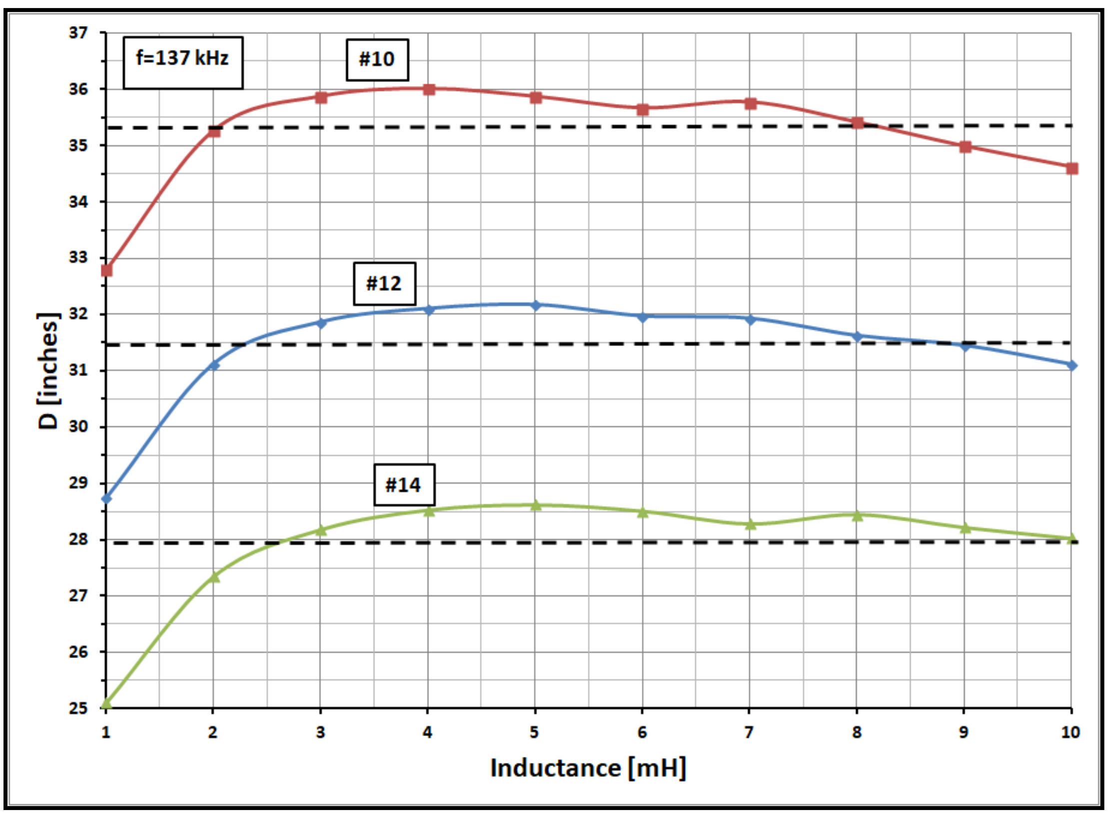

Figure 4B - 137 kHz coil diameters [inches].

Table 1A Optimum Diameter D

475 kHz	#14	#12	#10	137 kHz	#14	#12	#10
L [mH]	D [in]	D [in]	D [in]	L [mH]	D [in]	D [in]	D [in]
0.4	15.036	17.048	19.287	1	25.109	28.755	32.796
0.5	15.237	17.251	19.391	2	27.352	31.127	35.271
0.6	15.383	17.328	19.423	3	28.184	31.865	35.878
0.7	15.413	17.282	19.472	4	28.533	32.103	36.015
0.8	15.417	17.269	19.335	5	28.626	32.172	35.876
0.9	15.392	17.211	19.263	6	28.514	31.971	35.671
1	15.357	17.182	19.33	7	28.289	31.929	35.777
1.1	15.312	17.225	19.207	8	28.455	31.626	35.419
1.2	15.253	17.124	19.143	9	28.225	31.451	34.994
				10	28.031	31.119	34.628

Before we can answer that question we need to ask one more question: what is the turns spacing radio (wire diameter/turn-to-turn spacing, d/c) associated with each value of L? Table 2A shows the values for d/c associated with maximum Q as a function of L at 475 kHz.

Table 2A - Examples of d/c at Q maximums at 475 kHz

L [mH]	#14 d/c	#12 d/c	#10 d/c
0.4	0.30	0.30	0.29
0.5	0.30	0.30	0.30
0.6	0.30	0.30	0.30
0.7	0.30	0.30	0.30
0.8	0.30	0.31	0.31
0.9	0.31	0.31	0.31
1	0.31	0.31	0.31
1.1	0.31	0.31	0.32
1.2	0.31	0.32	0.32

For the entire range of inductance d/c is very close to 0.31, regardless of wire size. Even more interesting the same table for 137 kHz coils shows the same result, i.e. d/c≈0.30-0.32 over the entire range of inductance! It appears that we may be able to use the average values for D and d/c from tables 1 and 2 as indicated in table 3A.

Table 3A Averaged values for D and d/c

	wire size→	#14	#12	#10
frequency	d/c	D [in]	D [in]	D [in]
137 kHz	0.31	28.5	32.0	35.5
475 kHz	0.31	15.25	17.25	19.4

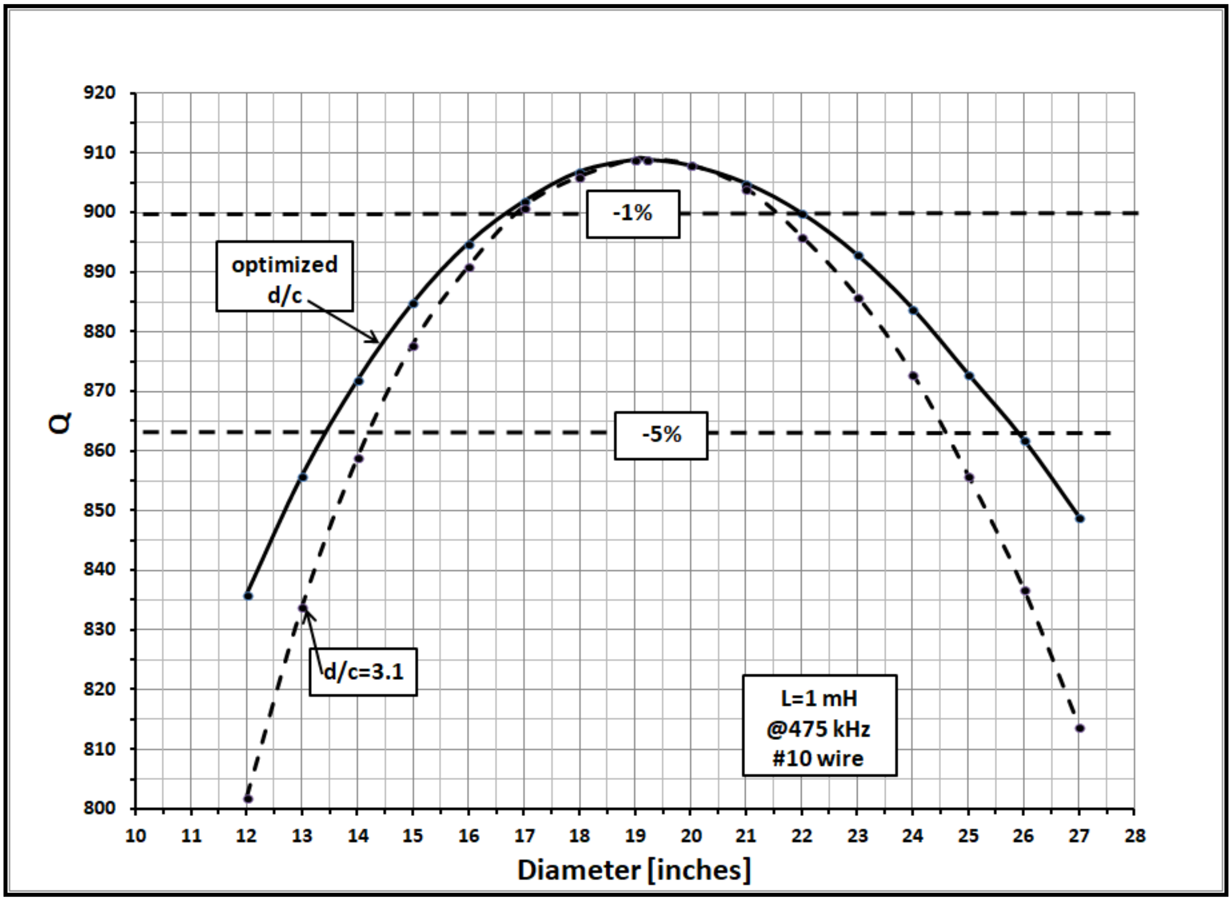

Figure 5 - Effect of diameter on Q. L=1 mH @475 kHz, #10 wire.

As indicated in figure 5, Q is not very sensitive to D. Using the average values results in Q values that differ from the optimized values by only a few percent! This agrees with Terman's comment that l/D "is not at all critical".