

Okay, so we have this letter and term "Q" that we use and toss around as if it was a real thing capable of being pinpointed and measured in much the same way as we can find Butte, Montana on a map. Most of us have never been to Butte, nor is it likely that we'll visit, but like Q, we have it on good faith that it's there. As VE3ERP puts it, "The Q of a coil is not a quantitative value like ohms or watts. It is a qualitative factor, more like the familiar 'on a scale of one to ten' method of evaluating girls in bikinis."

The Elusive Q of Single-Layer Air-Core Coils

BY GEORGE MURPHY*,¹ VE3ERP

Just as bikini-clad girls² of the same weight can have a variety of shapes from short and fat to long and skinny, so too can coils of the same inductance. The only difference in both cases is the L/d (Length-to-diameter) ratios of the members of each group. While a bikini beauty's L/d ratio may have little effect on her behavior, the behavior of a coil varies with frequency. Therefore, its L/d ratio is further factored into a Nebulous Abstract Frequency-Sensitive Relative Value known as "Q."

Definition of Coil Q

Coil Q is difficult to define. Inductors are the problem children of the component world. They are perhaps the most non-ideal of real-world components.³ Q has been defined as "a figure of merit or quality (no units), and in the case of inductors is the inductive reactance divided by the sum of all the resistances associated with energy losses in the inductor (in ohms)."⁴ But what if you do not know the sum of the resistances and energy losses?

True Coil Q can be determined for a specific frequency from the physical properties of the coil using the elegantly simple equation developed by M. V. Callender⁵ from Medhurst's formula for Q.⁶ Callender's equation is the one shown in the Q Equations, Table I.⁷ Coil Q can be calculated mathematically, either using the equations shown in Table I, or by a computer using software such as HAMCALC (version 38 or later).⁸

The Q equations in Table I compute theoretical mathematically true Q, which because of factors other than frequency and physical dimensions affecting Q, may not be attainable in the "real world." For these and other reasons to be discussed a little further on, the measured Q of a coil may be less than its theoretical true value.

Coil Q should never be thought of as an absolute stand-alone evaluation of quality. Coil Q is really just an abstract indication of relative performance of a coil of a specific L/d ratio at a specific frequency.

A relatively high Q indicates a physically large coil, a relatively high frequency, or both. On the other hand a relatively low Q indicates a physically small coil, a relatively low frequency, or both. By the same correlation, small coils at high frequencies and large coils at low frequencies commonly used in amateur radio applications typically have true Q values of up to about

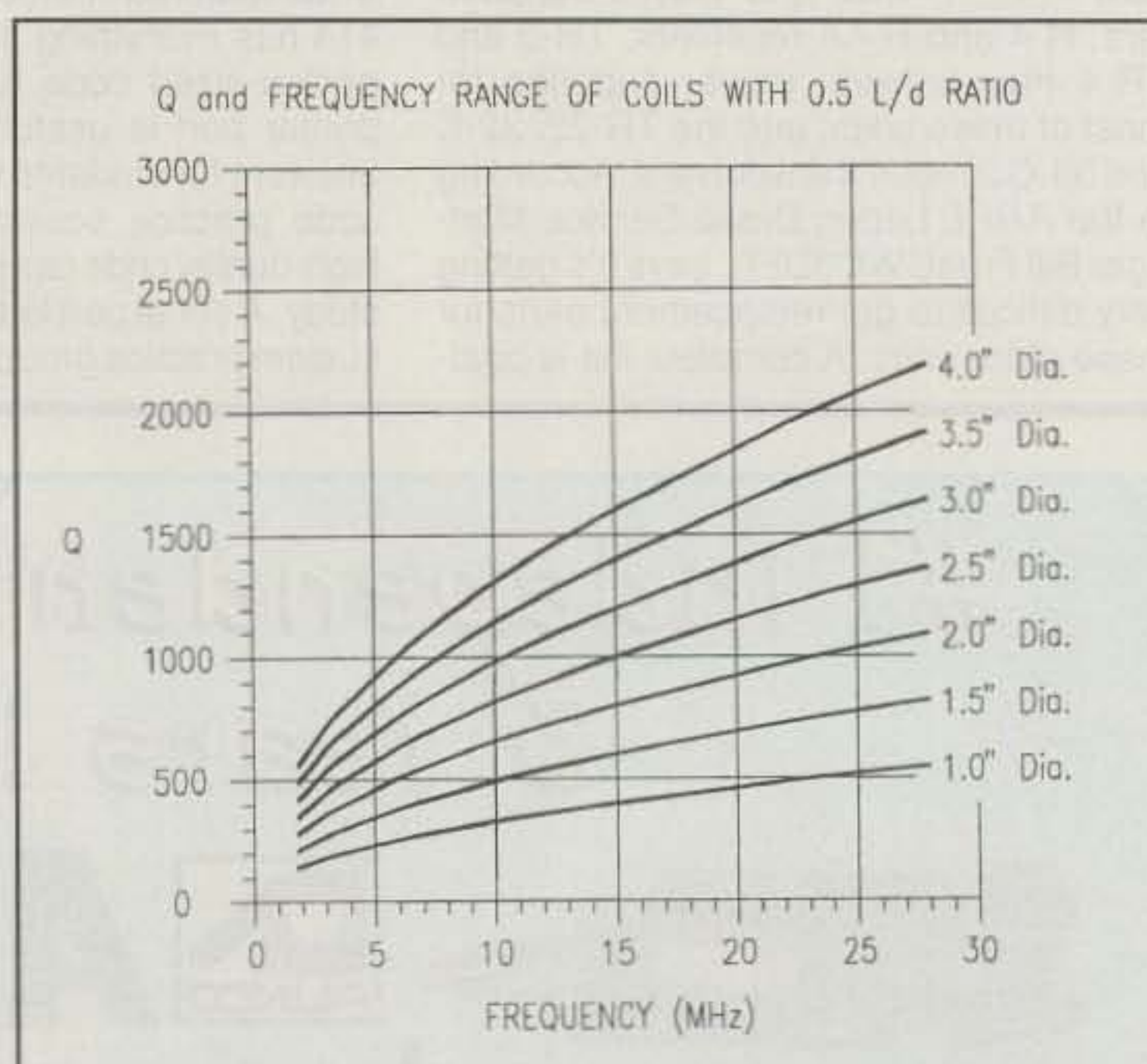


Fig. 1— Q and frequency range of coils with 0.5 L/d ratio.

800. Very few practical circuits require a Q above 900. Attempting to design a coil with a True Q much over 1,000 usually results in a coil with abnormal physical dimensions, wire sizes, and/or number of turns.

Measurement of Q

This is a gray area. Do not confuse coil Q with the Q of any circuit of which the coil is a component, including the internal circuitry of a Q meter. The two Q's are separate and can be quite different in value. According to Terman,⁹ Q meters assume the coil Q to be the same as the circuit Q (which it may not be), and the presence of the coil's distributed capacity causes the Q observed by the Q meter to be lower than the true Q of the coil.

The Effect of Coil Q In Circuit Design

When testing a circuit involving a coil, if the sharpness of a fil-

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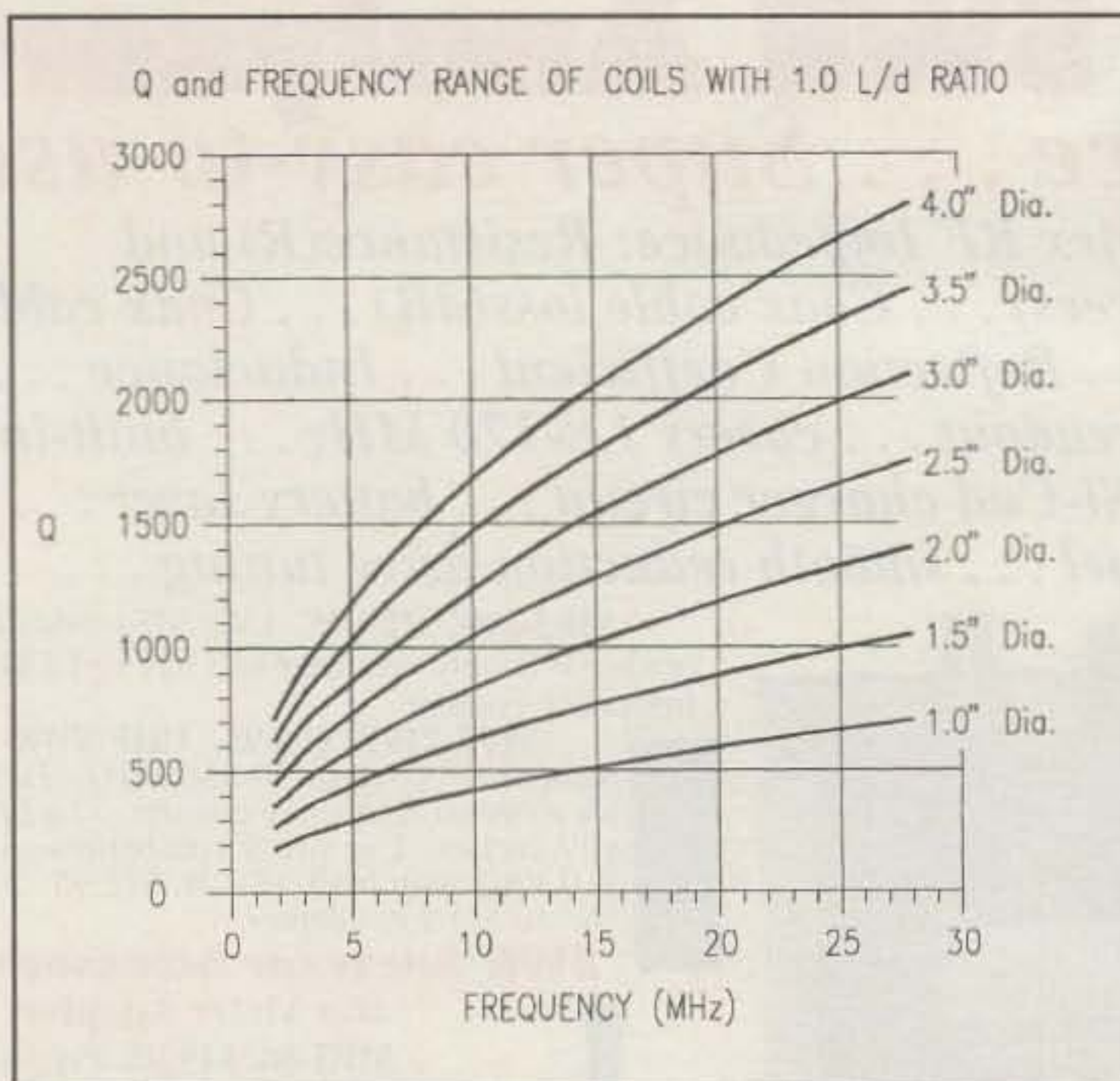


Fig. 2— Q and frequency range of coils with 1.0 L/d ratio.

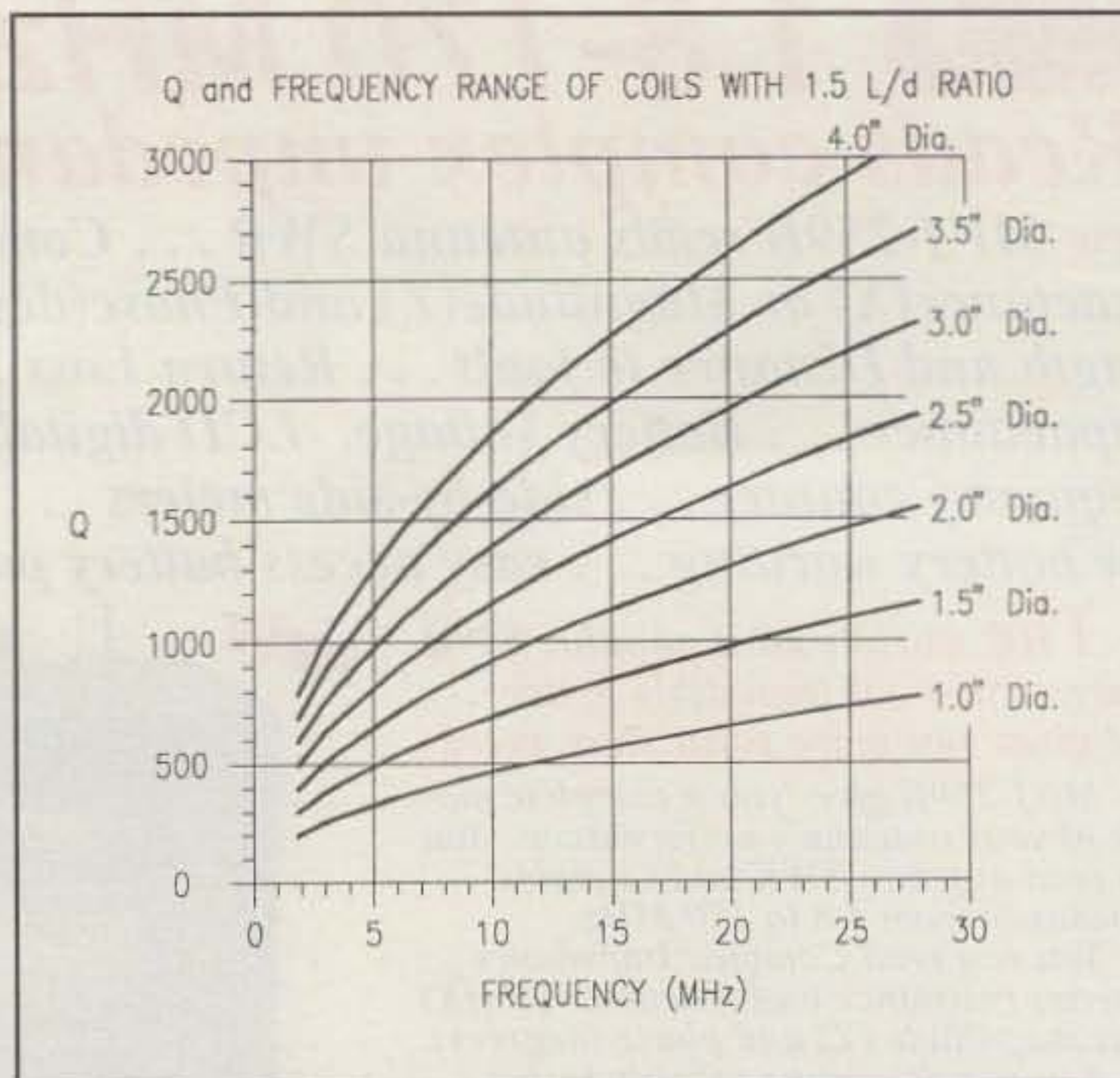


Fig. 3— Q and frequency range of coils with 1.5 L/d ratio.

ter or the bandwidth of a tuned circuit is not quite as expected, it is probably because the coil L/d ratio (and thus the Q) is inappropriate for the application.

A high Q (low L/d ratio) coil is recommended for applications requiring high efficiency, narrow bandwidth, and minimum wide-band noise. Some circuits require a coil of maximum Q, some a specific Q at a specific frequency, and others a relatively low Q. Many circuits do not mention coil Q at all. Unfortunately, current popular handbooks offer little advice on selecting L/d ratios (and hence Q) for various applications.

As a general observation, L/d ratios from about 0.5 to 2.0 are commonly used in many practical amateur radio circuits.

The Rules of Coil Q

1. The conductor diameter must be within the range of 0.45 and 0.70^{10,11,12,13} times the center-to-center distance between adjacent turns (not all commercial stock coils meet this condition).

2. Maximum Q occurs at a coil L/d ratio of between (depend-

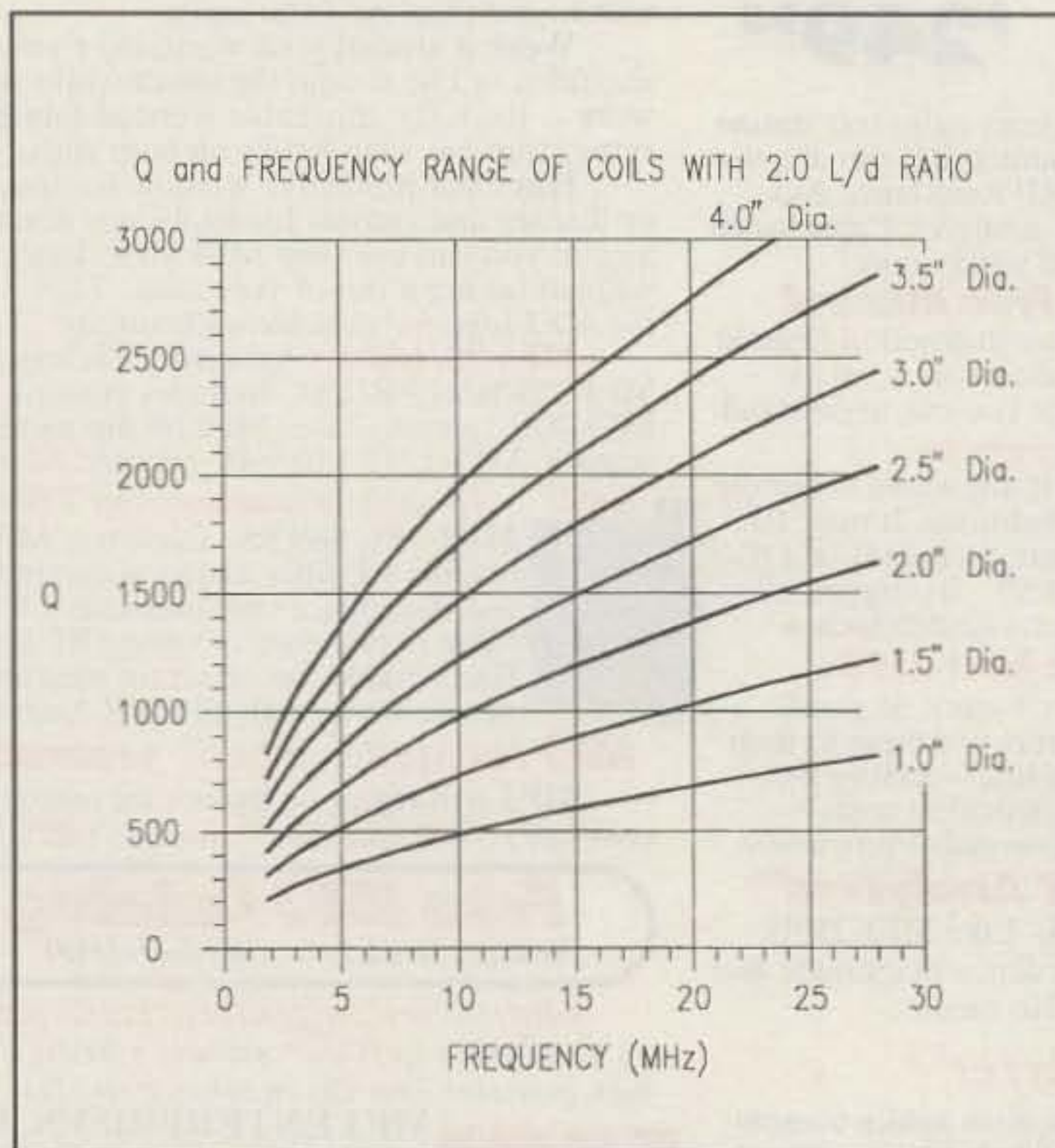


Fig. 4— Q and frequency range of coils with 2.0 L/d ratio.

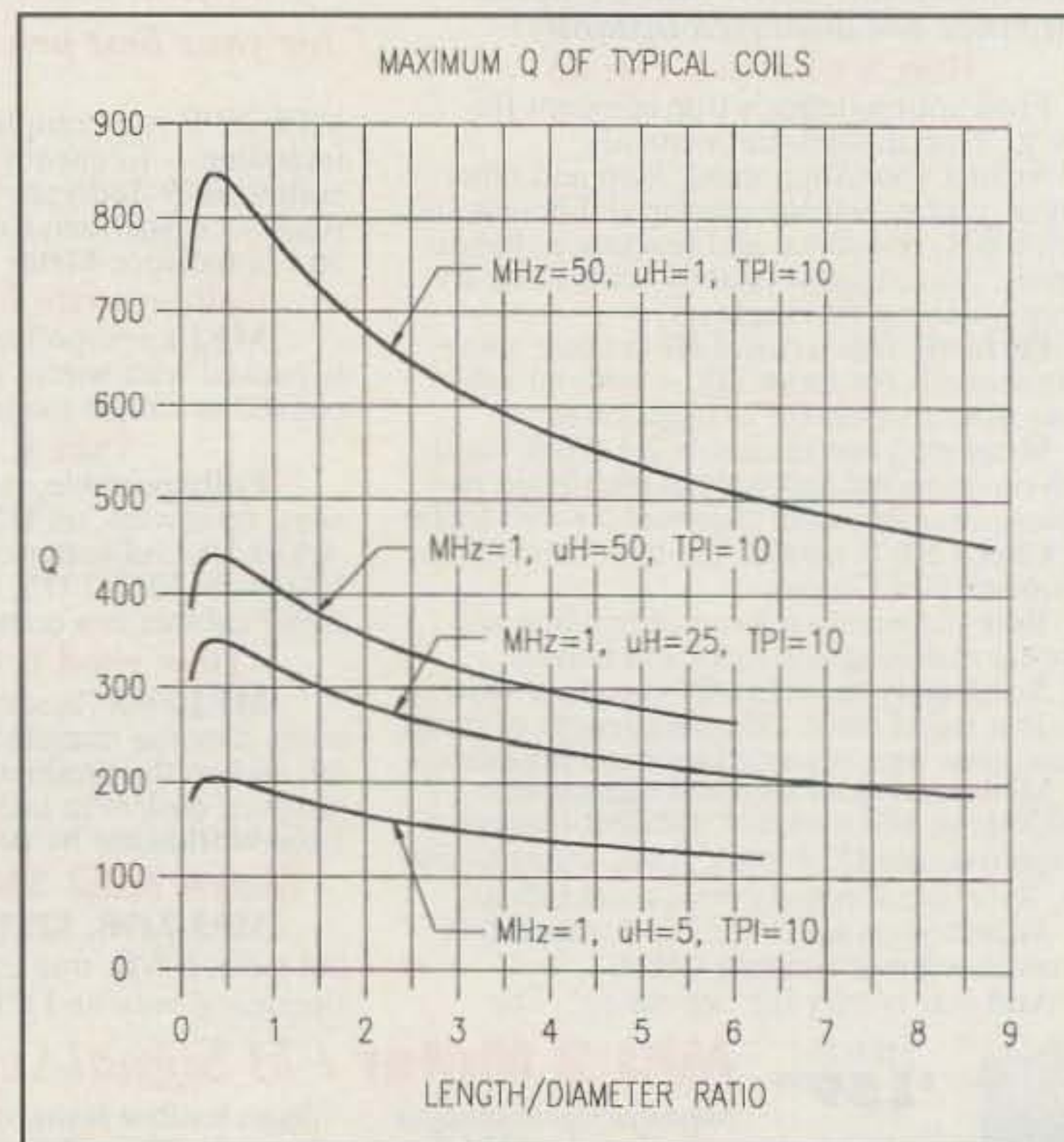


Fig. 5— Maximum Q of typical coils.

COIL DESIGN EQUATIONS For Single-Layer Air-Core Coils

These equations do not allow for length of leads or losses due to dielectric properties of insulation or coil form material.

The equations do not hold for coils with a length-to-diameter ratio of less than 0.35:1, coils with less than about 4 turns, or coils with conductor diameter-to-turn spacing ratios of less than 0.45:1 or greater than 0.70:1.

INDUCTANCE EQUATIONS

$$L_{\mu} = \frac{d^2 n^2}{18d + 40L_{GTH}} \quad n = \frac{\sqrt{L_{\mu} (18d + 40L_{GTH})}}{d} \quad L_{GTH} = \frac{d^2 n^2 - 18d}{40}$$

Q EQUATIONS

(*Radiotron Designer's Handbook*, 4th Edition, chapter 11.5)

$$n = \frac{\sqrt{f_{Hz}}}{\frac{6.9}{R_{cm}} + \frac{5.4}{L_{cm}}} \quad L_{GTH} = 0.3937 \frac{5.4}{\frac{\sqrt{f_{Hz}}}{Q} - \frac{6.9}{R_{cm}}}$$

$$S_w = \frac{L_{GTH}}{n} \quad W_{MAX} = 0.70 S_w \quad W_{MIN} = 0.45 S_w$$

where:

- L_{μ} = inductance in μ H
- n = number of turns
- d = coil pitch circle diameter in inches
- L_{GTH} = coil length in inches
- Q = coil Q
- f_{Hz} = frequency in Hertz
- R_{cm} = coil pitch circle radius in centimeters
- L_{cm} = coil length in centimeters
- S_w = turn spacing (center-to-center) in inches
- W_{MAX} = maximum wire diameter in inches
- W_{MIN} = minimum wire diameter in inches

ing on other coil design parameters) 0.35 and 0.45, decreasing rapidly below that ratio and more slowly above (see fig.5).¹⁴

3. To allow margin for error in designing a practical coil, an initial design L/d ratio of not less than 0.5 is recommended.¹⁵

4. Q increases with coil diameter (see figs. 1-4).

5. Q increases with coil length, rapidly when the L/d ratio is small, and very slowly when the L/d ratio is 1:1 or more (see fig. 6).

6. Q increases with frequency (fig. 6).

How to Find the True Q And Inductance of a Coil

Measure the diameter and length of the

coil, and count the number of turns. Use the Inductance Equations in Table I for L_{μ} to find inductance, and the Q Equation for Q to find the coil true Q at the frequency of your choice. Or you can input the known factors into HAMCALC's "Coil Equation Calculator" and it will find both, as well as further define the coil.

How to Design a Coil With a Specific Q

There are three ways to do this:

1. The interminable and tedious way—by hand using only the equations in Table I (takes forever).

2. The slow and approximate way—use the accompanying graphs and

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LENGTH vs. FREQUENCY, with CONSTANT Q

TYPICAL COIL - 3.0 in. DIA., 10 TURNS PER INCH, WIRE DIA. .05 - 0.07 in.

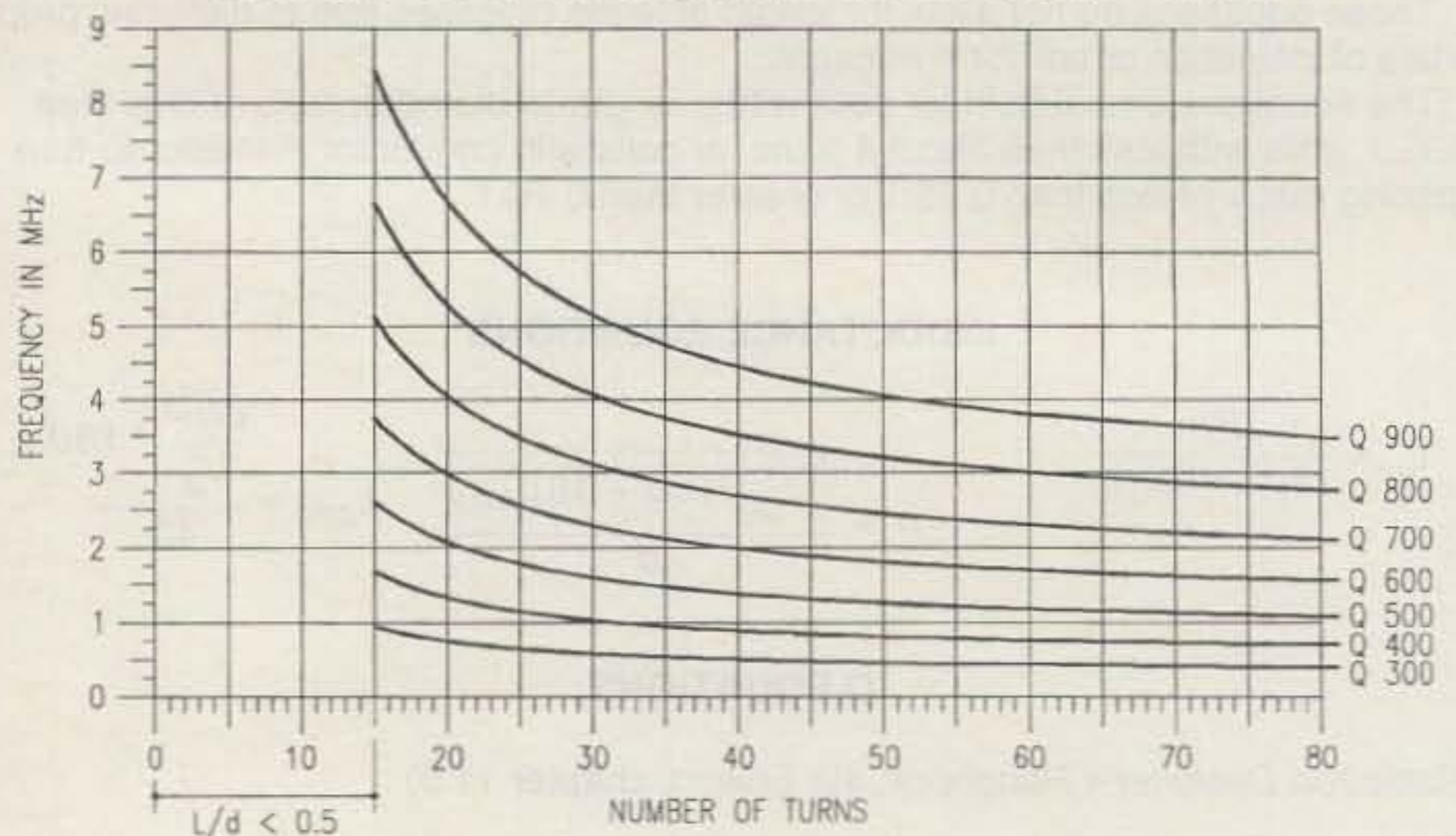


Fig. 6—Length vs. frequency, with a constant Q.

make a few calculations (takes several minutes).

3. The fast and easy way—use HAM-CALC's "Coil Q Calculator" computer program (takes a few seconds).

Method 1

From known values of Q, inductance, and frequency, by iterative solution of simultaneous equations find the coil length where L_{GTH} (Inductance Equation) is equal to L_{GTH} (Q Equation). From the known L/d ratio and the Inductance Equations calculate the coil diameter and number of turns, and from the Q Equations determine the allowable range of wire sizes for the coil.

To demonstrate methods 2 and 3, assume a coil with an inductance of 9 μ H, an L/d ratio of 0.5:1, and a true Q of 500 at 10 MHz.

Method 2

Select from figs. 1 to 4 the graph closest to the known L/d ratio (in this case fig. 1). Draw lines from the known Q (500) and frequency (10 MHz). At the point where the lines intersect read (or extrapolate) the coil diameter (1.5"). From the known L/d ratio (0.5) and diameter (1.5) calculate the length ($L_{GTH} = 0.5 \times 1.5 = 0.75$). From the Inductance Equations calculate n (15 turns) and L_{μ} (9 μ H), and from the Q Equations determine the range of allowable wire sizes.

Method 3

Input Inductance, Frequency, Desired

Q, and L/d ratio. Eureka!¹⁶ As fast as you can type in four numbers, you get a detailed specification for a coil 1.531" dia., 0.765" long, with 14.9 turns using a conductor diameter within the range .045" to .071". Using HAMCALC's "Coil Designer" program you can further refine this to a practical coil with 15 turns of AWG 28 wire wound on a 1 1/2 inch form, with a Q of 499.

Conclusion

Coil design is far too complex a subject for some of its aspects (such as Q) to be resolved by simple equations containing only some of the factors involved. However, Callender's approximation of Medhurst's formula¹⁷ for Q (as shown in Table I) comes close enough for many amateur radio applications, and as a starting point for further development, experimentation, and research.

For less-than-laboratory-research purposes the best advice I can offer is forget about coil Q when designing a circuit. Concentrate on the L/d (Length-to-diameter ratio) and let Q fall where it may. All you really have to decide is what L/d is best for your application (Low L/d = High Q, High L/d = Low Q, Maximum Q occurs when L/d = 0.5). If in doubt about the most suitable L/d to select, do what I do:

Imagine coils as a lineup of bikini-clad girls sorted in order from short and fat on one end to long and thin on the other. Then do what comes naturally—pick one near the middle and hope for the best.

Footnotes

1. . . . with a lot of help from Yardley Beers,

W0JF; L. B. Cebik, W4RNL; and Bob Tellefsen, N6WG.

2. If you are a YL or XYL, wherever reference is made herein to girls in bikinis, replace with muscular beach boys.

3. The 1997 ARRL Handbook for Radio Amateurs, page 10.8.

4. The 1997 ARRL Handbook for Radio Amateurs, page 6.21.

5. Callender, M. V. (letter) "Q of solenoid coils" Wireless Engineer 24.285 (June 1947) 185.

6. Medhurst, R. G. "H.F. resistance and self-capacitance of single-layer solenoids" (1) Wireless Engineer 24.281 (Feb. 1947) 35; (2) Wireless Engineer 24.282 (March 1947) 80.

7. Radiotron Designer's Handbook, fourth edition, Wireless Press, chapter 11.5 "Short-wave coils."

8. HAMCALC, over 200 programs of interest to radio amateurs and professionals, is shipped on a 3 1/2" 1.44 Mb floppy disc that will run in either MS-DOS or Windows computers that contain a GWBASIC.EXE file. For a free HAMCALC disc send US\$5.00 (US\$6.00 if you want a GWBASIC.EXE disc [80Mb] included) to cover my costs of materials and airmail shipping anywhere in the world, to the author at the address shown at the beginning of this article.

9. Terman, Radio Engineers' Handbook, 1943, page 916.

10. Approximately 0.45 claimed by Meyerson, A. H. "V-H-F coil construction" (1) Communications 24.4 (April 1944) 29; (2) "Coil Q factors at v-h-f" Communications 24.5 (May 1944) 36.

11. Approximately 0.5 claimed by Barden, W.S. and D. Grimes "Coil design for short-wave receivers" Electronic Engineering 7.6 (June 1934) 174.

12. Approximately 0.6 claimed by Harris, W. A. and R. H. Siemens "Superheterodyne oscillator design considerations" R.C.A. Radiotron Division Publication No. ST41 (Nov. 1935).

13. Approximately 0.7 claimed by Pollock, D. "The design of inductances for

frequencies between 4 and 25 megacycles" (1) R.C.A. Review 2.2 (Oct. 1937) 184; (2) Electronic Engineering 56.9 (Sept. 1937) 1169.

14. All graphs accompanying this article were plotted from tabular data generated by HAMCALC's "Coil Q Calculator" program.

15. Terman, Radio Engineers' Handbook, 1943, page 74.

16. As near as I can figure, "Eureka!" is an ancient Greek translation of the French "Voila!" which is a medieval translation of the contemporary American "Bingo!"

17. Radiotron Designer's Handbook, fourth edition, 11.5(G), page 464. ■

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