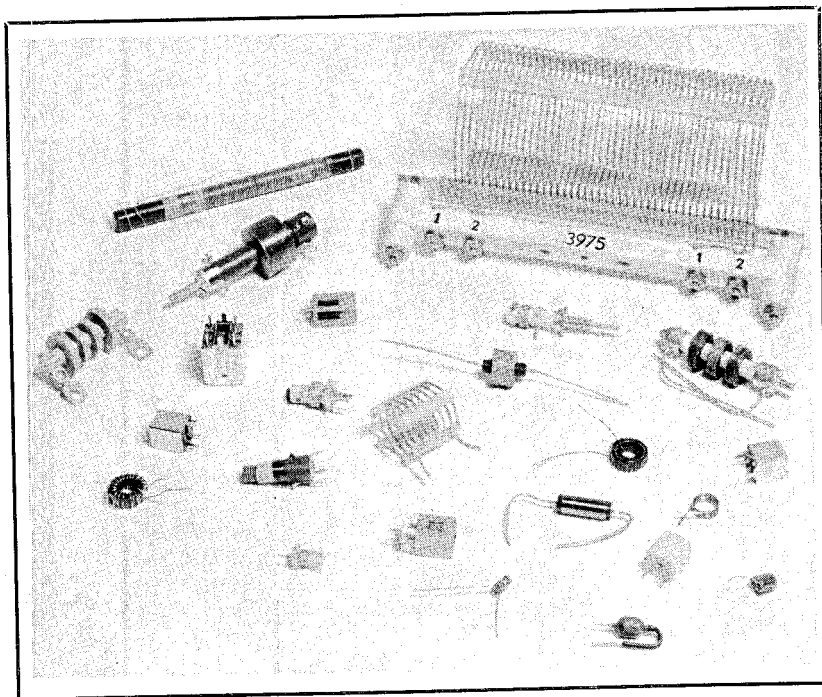




Understanding Coils and Measuring Their Inductance



Winding your own rf coils or selecting good ones from the surplus market is easy when you understand the basics of inductors. Let's discuss selection and simple methods for measuring inductance in the ham workshop.

By Doug DeMaw,* W1FB

How many times have you bought a surplus or unidentified coil for use in a homemade circuit, only to discover it wouldn't function properly in your project? Or, how about all the head-scratching you've done while perusing bargain inductors at ham radio flea markets? It's not uncommon to see a dozen or more nice-looking slug-tuned inductors or small rf chokes for as little as \$1. But, what are the coil characteristics? Is the Q high enough for our proposed circuits? What is the fixed-value inductance, or what might be the tuning range of the slug-adjusted inductor?

Unfortunately, that valuable information can be gotten only by means of measuring equipment. If no measurements are possible in your workshop, you could be buying the oft-mentioned "pig in a poke" when acquiring assorted coils.

I would never discourage anyone from buying bargain components. The cost of

any commercial coil of recent production (new, that is) is enough these days to make one consider a less-expensive hobby — such as carving artifacts from wood! The economical alternative to purchasing new, expensive coils is to wind our own, or to acquire them at flea markets or from surplus outlets. The various coils or rf chokes can be graded out at home and labeled with their approximate characteristics for use later on.

We can apply simple techniques in our workshops to learn easily what the coil inductance is, and what the relative Q of the inductor might be. We'll discuss those approaches later. But first, let's talk about coils and chokes in general.

The Fundamental Nature of Coils

The word "coil" is self-explanatory. That is, it is a length of conductor — generally wire — that has been formed into a multiturn coil. Some coils are solenoidal (single-layer winding), while others have two or more layers of wire. These are often referred to as "pi-wound" or "bank-wound" inductors. The layers of wire are

laid rather precisely on top of each other by means of machinery. We hams might simulate this winding style by using what is called "scramble winding." The coil Q (figure of merit) may not be quite as high when we scramble-wind, at least with respect to a machine-wound multilayer coil, but it will usually be adequate for our needs.

A thorough treatment of the subject of inductors and inductance can be found in *The Radio Amateur's Handbook* (ARRL), Chapter 2. We will not delve into the theory of inductance here, but shall look at some practical aspects of the subject.

For example, a given length of conductor will have a particular inductance value when stretched out. All conductors have some value of inductance (Fig. 1). That same length of wire will exhibit increased inductance when it is formed into a coil. The greater the number of turns, the higher the inductance. We can observe also that the greater the spacing between the coil turns, the lower the inductance. Maximum inductance for a given coil winding will occur when the coil turns are immediately

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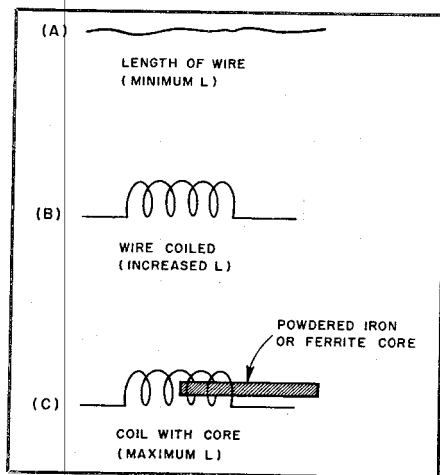


Fig. 1 — Even a straight piece of wire has an inductance value (A). The same wire formed into a coil (B) will have considerably more inductance. When a powdered-iron or ferrite core is inserted into the same coil (C), the inductance increases markedly.

adjacent to one another, or when the windings are stacked atop one another.

The inductance of a coil can be increased further by inserting a magnetic core inside it. Such core materials (suitable for rf work) are ferrite and powdered iron. Some coils contain brass cores or slugs rather than ferrite or iron ones. Brass has the opposite effect on coils: it decreases the coil inductance over that which exists when no core is used. Slug-tuned coils that contain brass cores are used mainly at vhf. The iron or ferrite cores are employed in circuits from vhf down to the low frequencies (broadcast band and lower). We must be aware, however, that the right core material must be used for a particular operating range. This and the general subject of ferrite and iron-core materials are discussed in plain language in the reference cited at note 1.¹

The Wrong Core Material

I have witnessed a lot of frustration among inexperienced amateurs when they bought slug-tuned coils, blank forms and toroids at flea markets or from surplus dealers. Such vendors rarely provide the electrical characteristics of the coils or the core material. We may have the "gut feeling" that a particular coil looks great for that neat circuit we're putting together, but after installing it (even though the inductance value may be correct), that part of the circuit performs poorly, or not at all! How can this be? Ah, ha! The core material is wrong for the operating frequency!

Let's suppose our circuit is an oscillator and the operating frequency is 7 MHz. Our bargain coil has a core meant for use at, say, 500 kHz. At 7 MHz, the core has spoiled the Q of the inductor. Because of this low Q, our oscillator won't function, or if it does it will operate in a very slug-

gish manner (hard to start and keep oscillating). The irony is, if I may resort to still another pun, that the coil might have a marvelous Q — perhaps 400 — at 500 kHz, whereas it could drop to as low as 10 at 7 MHz. This phenomenon can occur with ferrite or powdered-iron cores.

The lower the intended operating frequency of the proper core, the greater its permeability. Permeability (μ) is the trait that determines the effect of the core material on the inductance. That is, the higher the permeability of the core, the greater the inductance for a specified number of coil turns. This can provide an excellent clue to the relative characteristics of an unknown core. Specifically, if a coil has only a few turns but has a large value of inductance, the core material is probably designed for use at medium or low frequencies. Conversely, if the inductor has many turns but the inductance seems low for a coil that contains a core, the slug is probably ideal for high-frequency use. In fact, it may be suitable into the vhf region. Many cores and toroids have a color coding that identifies their optimum frequency ranges. The J. W. Miller Co. coil catalog lists the color codes versus frequency (given also in the reference cited in note 1).²

The improper core material can be identified readily when it is used in an rf-amplifier stage. If the stage gain seems too low and if the tuning is very broad, it's likely that the Q of the tuned circuit has been degraded seriously by the core in the coil. A sharp-tuning circuit is indicative of high Q (usually desirable).

Other factors that affect the Q of a coil are the wire size, the form factor, the insulating material used in the coil form and the proximity of the completed coil to nearby conductive objects. The larger the cross-sectional area of the wire, the greater the coil Q. This is because the current will flow more easily through the larger conductor (reduced I^2R losses). The form factor is the ratio of the coil diameter to the winding length (Fig. 2). For example, if our coil was 3 inches long and 1½ inches in diameter, the form factor would be 2.³ I have found during laboratory measurements that a form factor of 1 to 1.5 yields the best unloaded Q for a particular coil, although the Q does not deteriorate seriously with form factors as great as 3. These values of Q are for an "unloaded" condition, or more commonly specified as the Q_u value of a coil. Once the inductor is installed in a circuit, this value of Q becomes rather insignificant, since the other circuit elements change the Q to some lower value through loading effects. The value of greatest interest to us is the "loaded Q," or Q_L . The Q_u value is of importance when designing a circuit, however. For instance, we may design a VFO tuned circuit for a Q_L of 15. The Q_u of the coil should be somewhat higher to ensure that the design Q is realized. I like to select a Q_u that is three

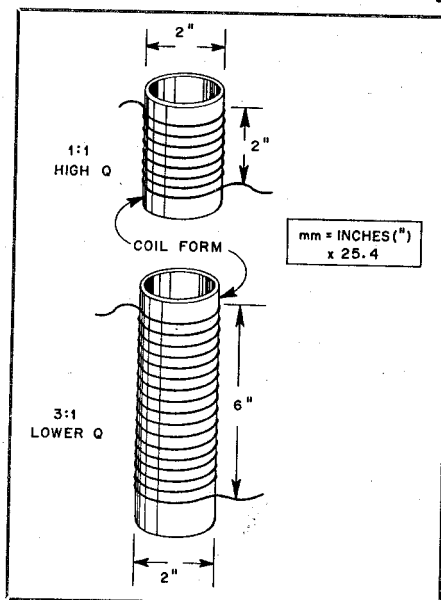


Fig. 2 — Illustration of form factor for coils. The highest Q should result with a factor of 1 (A). As the coil is lengthened (B), the Q will decrease somewhat.

times or greater than the required Q_L .

The coil form can affect the Q of the inductor, also. The better the dielectric material (insulating properties), the higher the Q. An air-wound coil will have the best Q, of course, but coils of this type are seldom practical below vhf because they are too floppy and unstable. So, our choice is to use a coil form. Ceramic or steatite forms are very good in terms of Q. Phenolic forms are fine for hf and lower, and there are a variety of modern materials (plastics) that are satisfactory, also. PVC tubing is not recommended in circuits that handle rf power at high impedances. In the presence of high levels of rf voltage, the PVC tubing may heat, break down and melt; likewise with nylon.

Earlier, we mentioned the proximity of nearby conductive objects and their effect on the coil Q. A good rule of thumb is to keep your coil (toroids excepted) at least one coil diameter away from nearby conductors, such as chassis, shield plates, variable capacitors, and the like. Iron will have a significant effect on the coil Q and inductance. Iron will increase the inductance, whereas aluminum and brass will decrease the inductance. Since a toroidal coil is self-shielding in nature, it will not be affected particularly by nearby metal objects and other coils.

Types of Coil Wire

You may have wondered why some coils, especially the smaller ones, have stranded wire that has insulation (silk, cotton or enamel) on each strand. Other coils simply used plain enameled wire, which was a lot easier to solder! Well, the multistrand wire is capable of providing a much higher Q than the single strand winding of enameled

¹Notes appear on page 26.

wire. The former is known as *Litz wire*. By combining many individual insulated strands of wire to form a single conductor effectively, the I^2R losses are reduced dramatically and the Q increases accordingly. This is because the rf currents flow on the surface of a conductor, for the most part. They do penetrate the conductor to some degree, and the penetration becomes more pronounced as the operating frequency is lowered. The higher the operating frequency, the more troublesome the I^2R losses. This phenomenon is called "skin effect." The use of Litz wire greatly increases the effective conducting surface of the winding (many skins, so to speak, in parallel) and enhances the Q .

When you are shopping for surplus coils, it is a good idea to watch for Litz wire inductors. This wire can be taken from the coil form and used when winding new coils. Litz wire is especially useful in the hf range, where high Q becomes more difficult to realize with small wire. Litz wire (new) is very expensive. We can fabricate our own Litz wire by weaving several strands of no. 30 enamel wire together with a hand drill and a vise. Larger gauges of enameled wire can be treated in a like manner for heavier "Litz" conductors. Each strand of wire must be stripped properly at the ends of the coil winding so that they may be soldered in parallel. Otherwise, the good effects of the Litz winding will be lost.

Measuring Unknown Inductance Values

Perhaps one of the most common methods of learning the inductance value of an unknown coil is to use a dip meter. Although this is a rather unsophisticated procedure, compared to the use of high-cost lab equipment for precise measurements, it is suitable for us hams. When using a dip meter, we must also have a calibrated receiver with which to monitor the dip-meter signal (unless your dipper has a very accurate dial scale). The remaining ingredient is a collection of high-quality, known-value capacitors. Silver-mica capacitors are my preference for doing this type of testing.

Fig. 2 illustrates the test procedure when using a dip meter. A known-value capacitor is placed in parallel with the unknown value of inductance. The dipper is swept through its tuning range until a dip (resonance) is observed on the meter. Next, the dip meter is moved farther and farther from the coil until the dip is just discernible. Now we remove our hands from the dipper and tune the monitor receiver to find the dipper signal. This will give us the approximate resonant frequency of the coil and capacitor. The inductance value can then be determined quickly by using the ARRL L/C/F Calculator, Type A. If you prefer to find the inductance value mathematically, you can use the following equation:

$$L(\mu H) = \frac{X_L}{2\pi f(\text{MHz})} \quad (\text{Eq. 1})$$

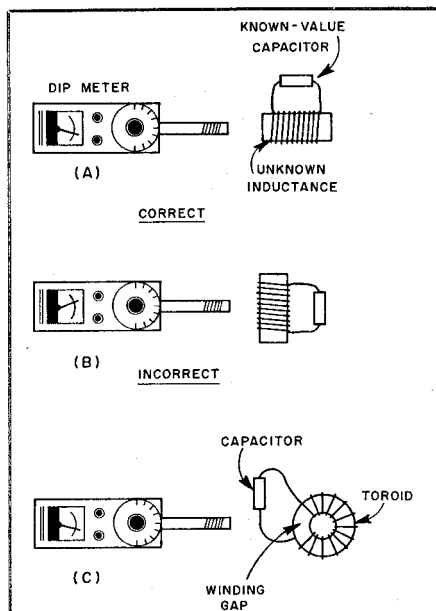


Fig. 3 — Correct coupling between the dip meter and the test coil is shown at A, where the axis of the dipper coil matches that of the test coil. Incorrect placement of the test coil is shown at B. The toroid at C can be dipped if the dipper probe coil is inserted into the capacitor leads at the winding gap.

where X_L is equal to X_C (resonance) and is expressed in ohms.

The reactance (X) of the capacitor connected across the coil can be found from

$$X_C = \frac{1}{2\pi f(\text{MHz}) \times C(\mu F)} \quad (\text{Eq. 2})$$

Let's take an example and work it out to help you understand the progression of the equations. Suppose we placed a 100-pF silver-mica capacitor across our unknown inductance. The dip meter and the receiver told us that the resonant frequency of the LC combination was 3.9 MHz. First, we will find the reactance of the 100-pF capacitor.

$$X_C = \frac{1}{6.28 \times 3.9 \times 0.0001} \quad (\text{Eq. 3})$$

$$(2\pi) \quad (\text{MHz}) \quad (\mu F)$$

$$\text{hence } X_C = 408\Omega$$

Note that pF has been changed to μF for this equation.

Now that we know the X_C we can proceed with Eq. 1 to learn the inductance of our coil. Remember that the coil reactance (X_L) is equal to the X_C (408 ohms) because X_C and X_L are equal at resonance.

$$L(\mu H) = \frac{408}{6.28 \times 3.9} \quad (\text{Eq. 4})$$

$$\text{hence } (L\mu H) = 16.65$$

If the coil were the type that has a movable slug, we could learn the tuning range by obtaining a dip reading with the core at each end of its travel. The Q would

be highest with the core material inside the coil winding.

When using a dip meter, we can get a feel for the relative Q of a coil by noticing how far from the coil we must put the dip-meter probe to obtain a meter reading (dip). The farther we move from the coil under test (still observing a dip), the higher the Q . If we must couple the dipper probe very tightly to the test coil, the Q is quite low. Fig. 3 shows the correct way to couple to an unknown coil. The axis of the dipper-probe coil must match that of the coil being tested. No dip will occur if we approach the test coil from its side.

We will experience a similar difficulty when attempting to measure a toroidal inductor with a dip meter. This is because of the inherent self-shielding nature of the toroid, as mentioned earlier. However, by probing the gap on the toroidal coil (Fig. 3C) it should be possible to find a dip. This is because the discontinuity of the self-shielding at the winding gap permits some coupling to the dipper. The capacitor leads become part of the overall inductance and provide a coupling point.

A Homemade Inductance Meter

Wouldn't it be convenient to have a homemade instrument that could be used to measure small values of inductance? Such a device can be made from ordinary components, and it need not be complex. The two most important parts of the unit would be the tuning capacitor and the indicating meter. The variable capacitor ($C1$ of Fig. 4) needs to be calibrated in picofarads through its tuning range. This can be done with the aid of a dip meter, a calibrated receiver and a known-value inductance. Coarse calibration can be achieved by checking the resonant frequency of the test circuit (coil and variable capacitor) at 5° settings of $C1$. A dial scale can be plotted as we proceed with the resonance checks. A vernier drive with a 0-100 dial scale is ideal for use during this exercise. Once the capacitance per 5° increment is known, the value of an unknown inductor can be calculated by means of the equations given earlier, or we may use the ARRL L/C/F slide-rule calculator. Greater sophistication can be had by developing a chart that compares the tuning-dial readings with inductance values.

A suitable circuit is given in Fig. 4. $Q1$ is a crystal oscillator that operates at 5 MHz. $Y1$ can be for some other frequency in this general range; it is not a magic number. $Q2$ is lightly coupled to the output of $Q1$, and it operates as a broadband amplifier with feedback. Output from $Q2$ is sampled lightly by means of a 5-pF capacitor, then fed to a voltage-doubler diode detector, $D1$ and $D2$. The resultant dc voltage is supplied to a microampere meter, $M1$. As $C1$ is tuned through resonance with the test inductor (plugged in at $J1$ and $J2$), a peak meter reading will

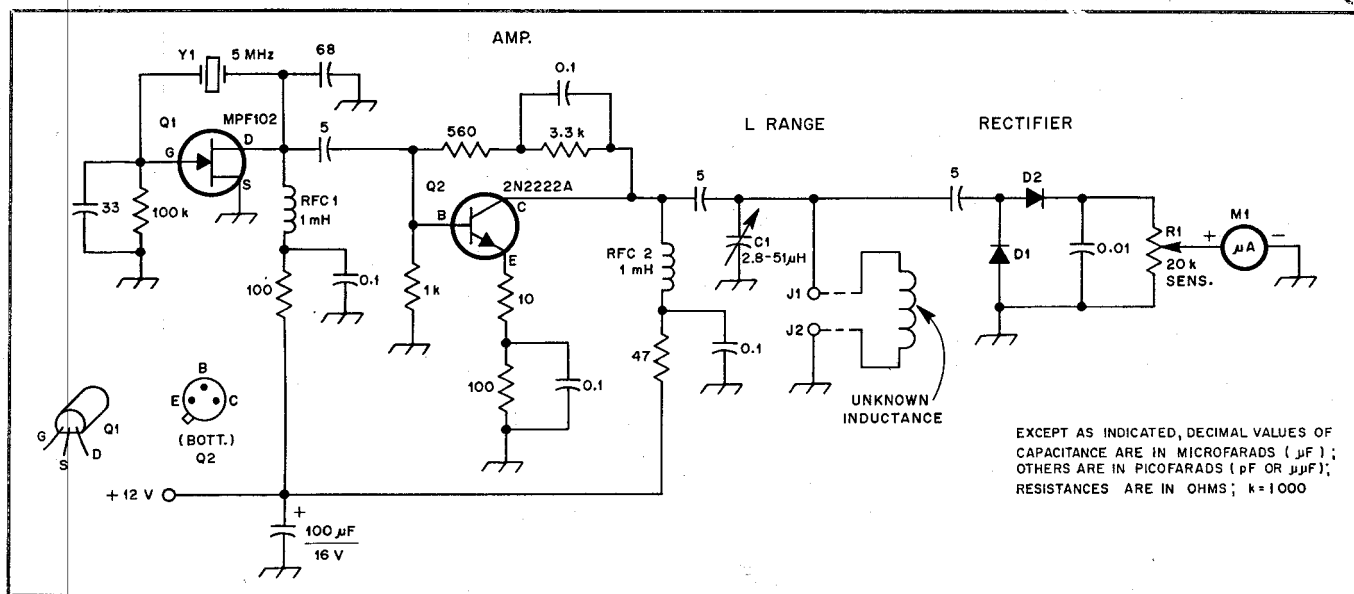


Fig. 4 — Schematic diagram of a test instrument for measuring inductance and relative Q. Fixed-value capacitors are disc-ceramic. The capacitor with polarity marked is tantalum or electrolytic. Fixed-value resistors are 1/4- or 1/2-W carbon composition. J1 and J2 can be plastic binding posts. RFC1 and RFC2 are miniature rf chokes (2.5 mH also suitable). R1 is a linear-taper carbon control.

be noted. The inductance or capacitance can then be read from the C1 tuning dial, depending on whether you calibrate your dial for picofarads or microhenrys.

The circuit shown will measure inductances from approximately 2.8 to 51 μ H when C1 is a 365-pF broadcast-radio variable capacitor. Minimum capacitance for these units is approximately 20 pF, according to measurements I have made on a number of them. But, other values of tuning capacitance can be used if desired. The lower the maximum capacitance of C1, the more restricted the inductance range of the instrument.

The range of the circuit in Fig. 4 can be extended upward and downward by switching the crystal at Y1 to a higher or lower range. This could be done manually or by means of a wafer switch. For example, if we change Y1 to 10 MHz, the circuit of Fig. 4 will have an inductance-measuring range of 1.4 to 25 μ H. Changing Y1 to 2 MHz, the range would be 7 to 127 μ H.

The relative Q of the coil under test can be observed by the meter deflection versus the setting of the sensitivity control, R1. The higher the meter reading as R1 is turned down, the greater the unloaded Q.

For best sensitivity of the test instrument, I would suggest using germanium diodes at D1 and D2. But, good results can be obtained when silicon switching diodes, such as 1N914s, are used. M1 can be a 50- or 100- μ A meter. The 50- μ A movement will provide the better sensitivity. You may want to try one of the low-cost edgewise fm tuning meters that are available on the

surplus market. Most of them are in the low microampere range. Meters and tuning capacitors are available from Surplus Electronics Corp.⁴

A Way to Measure the Q

A colleague of mine, W7ZOI, who is an ARRL Technical Advisor, described a simple method for the measurement of tuned-circuit Q. It is a technique he uses in his home workshop. The circuit under test, which consists of a parallel combination of L and C, with L being the unknown inductor in our case, is swept with a signal generator or low-power amateur transmitter. The tuned circuit is sampled lightly with a scope or VTVM (vacuum-tube voltmeter or FET VOM) and rf probe. The 3-dB points on the tuned-circuit response curve are noted in terms of signal frequency. From this information we can calculate the unloaded Q of the circuit. This is explained in detail on page 29 of the *ARRL Electronics Data Book*. A circuit diagram and pertinent equations for Q calculations are included.

Some Final Thoughts

Simple measurements of the kind discussed in this article are not beyond the beginner. The methods and circuits for simple measurement of inductance should not be difficult for you, either. We can learn far more by *doing* than by simply reading or thinking about these projects. A basic knowledge of coils and their properties will help you to save a lot of money when buying parts for new circuits.⁵ You will know how to select surplus or flea-market

inductors if you remember the simple guidelines of this article. Winding your own coils should be easier, too!

Notes

- ¹D. DeMaw, *Ferromagnetic Core Design & Application Handbook* (Englewood Cliffs, NJ: Prentice-Hall, Inc.).
- ²19070 Reyes Ave., Compton, CA 90221.
- ³mm = in. \times 25.4.
- ⁴7294 N.W. 54th St., Miami, FL 33166. Catalog available.
- ⁵Circuit boards and parts kit are available from Circuit Board Specialists, P.O. Box 969, Pueblo, CO 81002.

Mini Directory

As a convenience to our readers, here is a list of items of particular interest and when they most recently appeared in *QST*.

Advisory Committee	
Members	Oct. 1982, p. 46
Amateur Radio Station	
Call Sign Assignment System	June 1983, p. 61
ARRL QSO Party Rules	Sept. 1983, p. 75
FCC Wrap-Up	Sept. 1983, p. 65
License Renewal	
Information	Jan. 1983, p. 53
Major ARRL Operating	
Event and Conventions — 1983	Jan. 1983, p. 54
Pending Dockets	
Affecting Amateur Radio	June 1983, p. 64
QST Abbreviations List	Dec. 1982, p. 65
Reciprocal-Operating	
Countries	Nov. 1982, p. 64
September VHF QSO	
Party Rules	Aug. 1983, p. 85
Third-Party-Traffic	
Countries	April 1983, p. 81
U.S. Amateur Frequency	
and Mode Allocations	Jan. 1983, p. 53