By H. W. SCHENDEL

COILS, CORES AND MAGNETS

Part I—Magnetic Design Factors of Modern Radio Components

PROBABLY at some time or another most experimenters and amateurs as well as some servicemen have wished they could use the cores of some of those old electromagnets, filter chokes, or audio transformers in the junk box and rewind them to suit different conditions.

In rewinding power transformers to obtain new voltages it is possible to determine the essential final characteristics with a fairly small percentage of error even when all data on the core material are not available. Characteristics of other devices, especially those of reactors, filter chokes, audio chokes, and audio transformers, are more difficult to change. If due allowances are made for the many variables, it is possible to rewind the units for new operating conditions and obtain reasonably satisfactory results. This is true only when exact values of inductance are not critical.

In order to better understand the principles of magnetic devices let us get acquainted first with magnetic terms and symbols, magnetic effects and circuits, and the production of magnetic lines of force by electricity. Many beginners have much difficulty in remembering magnetic terms and the magnetic effects which the terms describe. These will be explained as clearly as possible as we go along.

Some confusion also arises from the fact that various systems use the same symbols but in each system the symbols have a different value. In this article all symbols and measurements will be in the English system with the inch as standard. Iron best exhibits the magnetic properties but a few other alloys and substances also do. There is no effective *insulator* for magnetism, but magnetism does travel more easily through some materials than others. Those materials may be used to *keep the magnetic effects confined to certain areas.* For such reasons we see heavy iron or alloy shields on transformers, chokes, and similar devices.

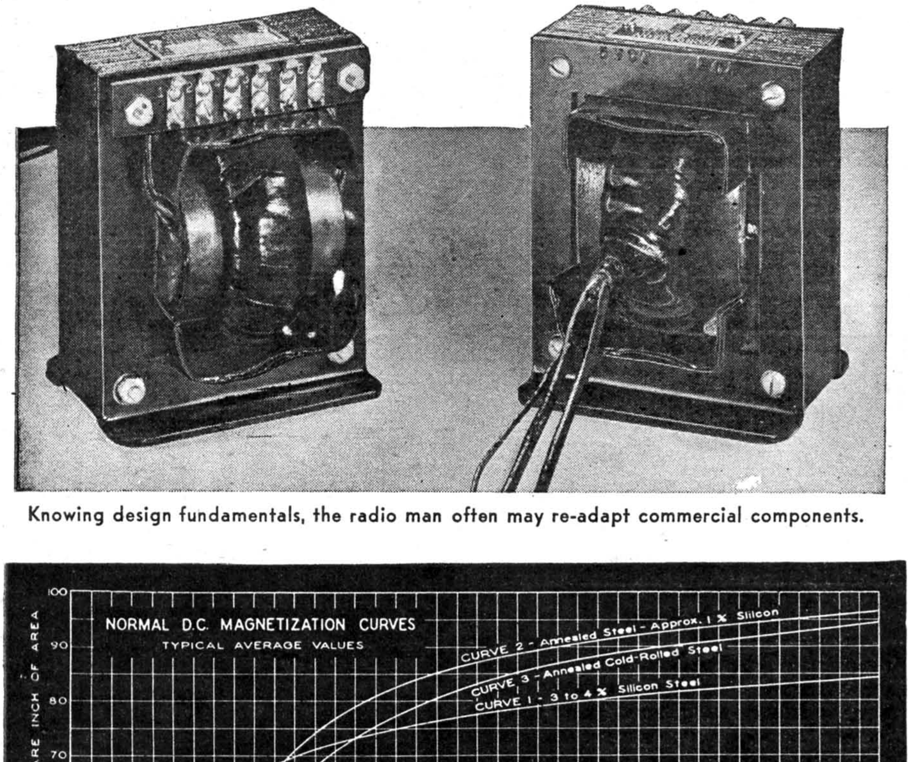
The attractive and repulsive effect of magnets is due to "magnetic lines of force" commonly called *magnetic flux* or just flux (Φ). A single line of force is called a *maxwell.*

Maxwells are measured by their effects. One method is to attach the ends of a single wire to a voltmeter. Then move the wire through a field of flux (as across the pole of a magnetic or electromagnet). If one volt is induced in the wire during a movement time of one second it would indicate the wire has just gone through, or cut, 100,000,000 (10^8) maxwells. More practical methods are usually used to obtain greater accuracy though the principles are the same.

An important point is that one maxwell is one unit magnetic line of force or flux and that *moving the field of flux* or changing its density (the number of lines of force per unit area) around a wire *has the same effect as moving the wire.*

To produce a strong field of magnetic flux, one having many lines of force or maxwells, with a single wire would require too much current and would not be practical for most applications. Therefore the wire is formed into a loop concentrating the flux within it. Then if we connect many loops in series, forming the turns of a coil, the magnetic flux of one turn will add to that of the next. This is the basic principle of the electromagnet.

The current flowing through a coil is the force which sets up the magnetic flux. This is *magnetomotive force* (m.m.f.) and may be compared to electromotive force in electricity. It is



Knowing design fundamentals, the radio man often may re-adapt commercial components.

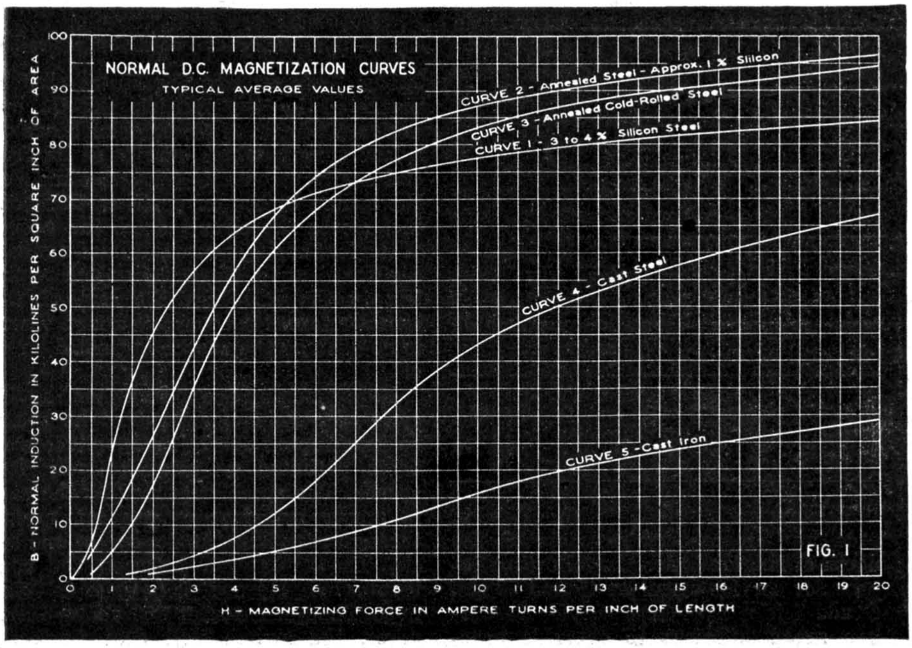


FIG. 1

Fig. 1—The curves of the magnetic properties of steel are a prime design requisite.

measured by the number of *ampere turns* (NI). This number is obtained by multiplying the number of turns (N) in the coil by the amperes (I) flowing through the turns. For example, one ampere flowing through one hundred turns will produce one hundred ampere turns. Many other combinations will give the same product or whatever product is required.

Just as electrical resistance hinders the flow of electricity, magnetic resistance, or *reluctance* (R), hinders the flow of flux in a magnetic circuit. Therefore a formula similar to that for Ohm's Law is applicable to magnetic circuits. It is:

$$NI = R\Phi \text{ or, } \frac{NI}{\Phi} = R \text{ or } \Phi = \frac{NI}{R}$$

where symbols have the meanings explained above.

Permeance (P) is a term describing the ease with which flux may travel through a substance. It is the reciprocal (opposite effect) of reluctance ($P = 1/R$). In a magnetic circuit having different reluctances in series, the ampere turns—like voltage drops across series resistors—must be figured individually for each reluctance and then all added together for the total m.m.f.

Closely related to permeance is *permeability* (μ). Permeability is a value used to express the flux multiplying power of a material. If a certain m.m.f. produces one maxwell in an air core but will produce 5000 maxwells in an equal size core of some other material, the permeability of this other material is 5000. To simplify comparisons air is considered to have a permeability of one ($\mu = 1$) and all other materials are commonly rated to this base.

Magnetic induction (B), or flux density, is the number of lines of force, or maxwells, induced in each square inch of cross-sectional area (A) of the magnetic circuit. Thus $B = \frac{\Phi}{A}$ where Φ is the total flux of the entire area under consideration. Note closely that *B* refers to *a specific value of area.* This distinction must be remembered. Similar ones will appear in other terms to follow.

Previously we learned that ampere turns is a measure of magnetomotive force for an entire magnetic circuit. If we divide the ampere turns (NI) by the length (l) in inches of magnetic circuit we obtain a value of *magnetizing force* (*H*) for each inch length of the magnetic circuit. Therefore,

$$H = \frac{NI}{l}$$

THE MAGNETIC CIRCUIT

We now have definite magnetic terms covering units of volume, area, and length.

It has been proven by experiment that one ampere flowing through one turn of wire (one NI) enclosing exactly one square inch of area will force 3.19 maxwells through an air path one inch in length. With that as a base we have a magnetizing force, $H = 1$, a magnetic induction or flux density, $B = 3.19$. With $\mu = 1$ we can form a basic formula, $\mu = \frac{B}{3.19H}$, suitable for any material. Rearrangement of previous formulas will show the reluctance, *R*, of air to be .313 per cu. in.

The permeability, $\mu = 1$, for air has a constant value for all strengths of magnetic induction. As the ampere turns per inch is varied the lines of force per square inch, or magnetic induction, will vary in direct proportion. In iron the permeability is a variable and may go from one to over 10,000 depending on both the type of iron and the normal induction (the name for magnetic induction in a ferromagnetic material.) As the normal induction is increased from zero until the iron is saturated with flux the permeability will vary from a low value through a maximum to a final low approaching the μ of air.

Occasionally no information is available on the original coils. In those cases and in new designs it is desirable to have electrical and magnetic data on the steel or other material to be used. This information is obtained either by measuring the qualities of the material or from average curves furnished by most manufacturers of electrical steel. Most useful are *normal d.c. magnetization* curves, typical ones being shown in Fig. 1.

Curves vary not only with each different steel and alloy but also with the way the material is handled. Punching, shearing, machining, heat-treating, core shape, and other factors contribute to variations. Therefore it would be practically impossible to show curves for all steels under all conditions. Fig. 1 is intended to show only *average* magnetization curves.

In rewinding magnetic devices the induction will have an important effect on satisfactory results. The ampere turn product NI, once it has been carefully determined in the original design, is the main consideration in rewinding relays, speaker fields and similar devices for different d.c. voltages or currents.

The amperes and the turns may be varied through wide limits as long as the product of the two is kept the same. If we have .010 ampere flowing through 1000 turns our NI product equals 10 ampere turns. Our magnetic effect would be exactly the same if we had one ampere flowing through 10 turns.

DESIGNING RELAY COILS

When the turns in the old winding are known or can be counted and the amperes for correct operation are known the rewinding problem is simplified. Otherwise it is necessary to know the original voltage or voltage drop, count the turns, obtain the size and length of wire to estimate the total resistance, then apply Ohm's Law to obtain the current, and finally determine the ampere turns. A reversal of the procedure with proper juggling of the values will enable you to rewind the coil for some specific current or voltage.

To find the wire length, add length of an inside turn to the length of an outside turn; divide by two; then multiply the answer by the number of turns in the coil.

A wire table may be consulted to estimate resistance, space required and other data for coil rewinding. In most cases relay, solenoid, speaker, and similar coils may be jumble wound with enamel wire unless extremely high voltage is used. Fine wires should have flexible leads attached. An article in the September 1942 RADIO-CRAFT gave many pointers on handling windings.

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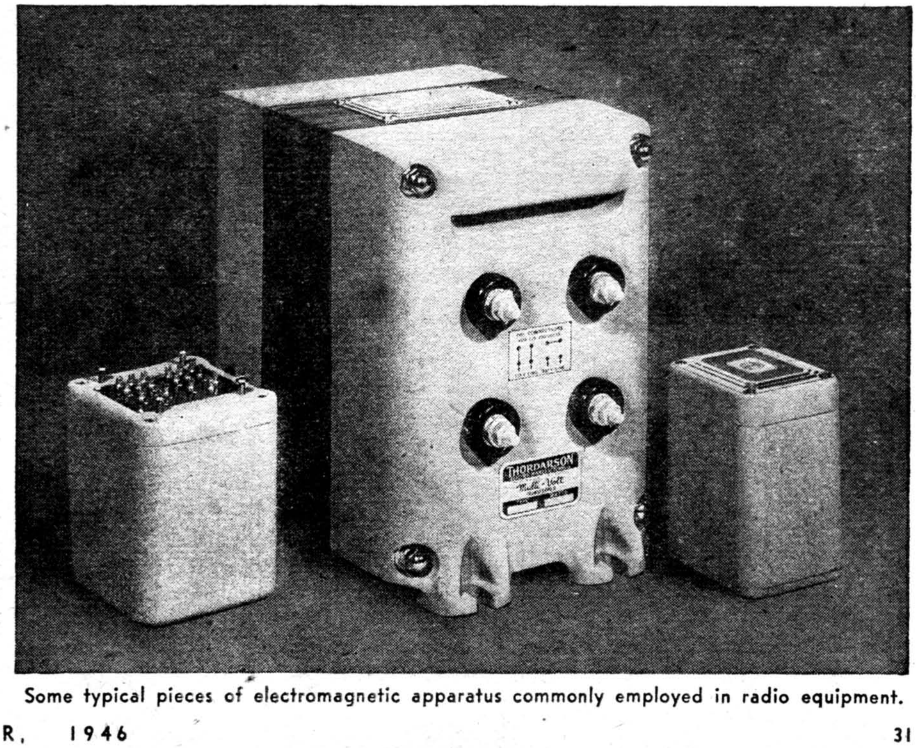

Some typical pieces of electromagnetic apparatus commonly employed in radio equipment.

Let us suppose we are to find the ampere turns for a coil to excite the magnetic circuit of a relay or electromagnet constructed along the lines shown in Fig. 2. The coil is to be operated from a d.c. circuit. The steel usually used for this type of application has magnetic properties similar to that of Curve 2, Fig. 1.

Assume the core is laminated, .75-inch wide, and is stacked to a height of .89 inch. Because scale, varnish, and other variations cause minute spaces between laminations the stacked height should be multiplied by a *stacking factor*, usually about 0.9, to obtain the effective value of solid metal. Thus, 0.9 x .89 = .80 inch effective stack, and .80 x .75 inch = 6 square inches, the effective cross-sectional area of metal in the core. The average or effective length l_s of the core is nine inches while the effective length of series air gap l_a is assumed to be .005 inch. This is the sum of l_{a1} plus l_{a2} (Fig. 2). The effective cross-sectional area of the air gap will be equal to the gross area of the core or, .75x.89″ = .67 square inch.

The ampere turns will have to be computed separately for the steel and for the air gap. The results are added because the reluctances are in series.

Lines of force in magnetic circuits always travel through the complete circuit just as electricity does. This means we have the same number of lines of force or flux across our air gap as through the steel.

Magnetic induction for any specified area determines the total flux to be used throughout the magnetic circuit. Usually a normal induction of 45,000 to 100,000 lines per square inch is common for steel, depending on the type of steel, overall efficiency, and the necessary magnetic pull, if any. Magnetic efficiency is best at the highest permeability ($\frac{B}{3.19H}$). The steel of Curve 2, Fig. 1 has highest permeability at a normal induction B between 50,000 and 55,000 lines per square inch. For Fig. 2 we will use a B of 55,000 for the steel. As the core area is only 0.6 square inch, the total flux will be 0.6 times 55,000 or 33,000 maxwells.

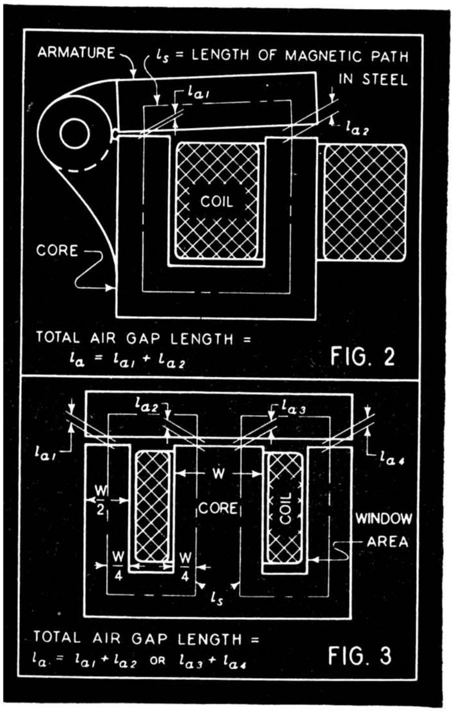

Fig. 2 (above)—The air gap shown here, and in Fig. 3 (below), are functions of the induction.

The same number of maxwells will have to be forced across the air gap where the magnetic induction *B* will be 33,000/.67 or 49,250 lines per square inch.

Again referring to Curve 2, Fig. 1, we find at a *B* point of 55,000 that *H* will be 3.9, the ampere turns necessary to force the flux through each inch length of the steel. As the steel core has an average length of 9 inches we will need a total of 9 x 3.9 = 35.1 ampere turns for the steel.

In the air gap, Fig. 2, the magnetic induction is 49,250 as explained previously. Applying the formula, $\mu = \frac{B}{3.19H}$ (μ = 1, for air) we find the magnetizing force *H* to be 15,440, the ampere turns per inch. As the air gap has a length of only .005 inch we will need a total of .005 x 15, 440 = 77.2 ampere turns for it.

You will notice that a small change in the effective length of air gap will produce a great change in ampere turns needed. For an air gap length of .2 inches we would need .2 x 15, 440 = 3,088 ampere turns to force 33,000 maxwells across the gap. The ampere turns for the steel would be small compared to this.

Summing up the ampere turns for the steel, 35.1, and air gap, 77.2, shows we would need a coil having about 112 ampere turns, the total MMF. It is well to allow some extra ampere turns for flux leakage.

The following formula, a combination of previous formulas, which may be applied to any material and cross-section, may simplify calculation of ampere turns. Thus $NI = \frac{H\Phi l}{BA}$ where NI equals ampere turns for a specified material of uniform cross-sectional area and length, *H* is magnetizing force per inch length, Φ is the total flux in the magnetic circuit, *l* is length of uniform cross-section in inches, A is area of cross-section in square inches, and *B* is the induction per square inch. For air the formula would become $NI = \frac{\Phi l_a}{3.19A}$ where l_a would be length of air gap in inches.

In new or rebuilt designs consideration must be given to the maximum watts (W_{max}) which a coil can safely dissipate. These may be determined from the formula (W_{max}) = m.d. x l_c x 5.6, where m.d. is the mean or average diameter of the coil and l_c is its length.

The watts (W) actually used by any d.c. coil can be found from W = EI where E is the voltage across the coil and I is the current flowing through it. For safe design W_{max} will be larger than W. Preferred size of coil is one whose length is about 1½ times its outside diameter. This may be varied.

Thus far d.c. coils have been discussed but many relays and electromagnets must operate on a.c. The pull of the a.c. type also depends on the maximum flux in the air gap and is determined the same as for d.c. types. If a.c. and d.c. ampere turns are the same, results would be about the same except that on a.c. types the pull stroke is more uniform. This is due to the varying inductance and varying current consumption throughout a pull stroke.

When used on a.c. it is imperative that the core be laminated. Usually No. 26 to No. 29 gauge steel is used. This is done to lower the eddy current losses and reduce the core heating to a minimum. Hysteresis losses (energy expended to reverse the magnetism) depend on and vary with the a.c. frequency.

The number of turns in an a.c. coil is determined by the voltage, frequency, and maximum flux, so $N = \frac{10^8E}{4.44f\Phi_{max}} = \frac{10^8E}{4.44fAB_{max}}$ or $E = \frac{4.44fN\Phi_{max}}{10^8}$ where N = turns in a.c. coil, E = a.c. volts across coil, Φ_{max} = maximum flux, f = frequency in cycles per second, *B* = induction, and A = cross-sectional area of core in square inches.

Wire size is not very important because resistance is not considered in a.c. applications. It is well, though, to use a wire size as large as can be conveniently wound in the space allotted. If the pull is known the wire size may be, c.m. = $10\sqrt{F}$, where c.m. = circular mils area of wire, and F = pull in pounds.

Any appreciable load applied to the armature of a single-phase a.c. electromagnet will result in a chattering sound. To overcome this a device called a *pole shader* is used. This device produces a flux of its own somewhat out of phase with the main flux, the result being similar to two-phase action.

A pole shader is a short-circuited loop or turn, usually of brass or copper, sized to give the resistance needed, imbedded in the pole or armature face, and covering about ½ to 2/3 of its cross-sectional area. The pole faces must make good mechanical contact in the pole shader area. Exact pole shader design is too involved to explain here in detail.

Part II of this article—to be published in an early issue—will tell how to calculate and design filter chokes and audio reactors and describe apparatus for measuring characteristics of magnetic circuits.