APPLICATION OF RADIO and TELEVISION PRINCIPLES

APPLIED PRACTICAL RADIO-TELEVISION

A Practical Book
on Radio
Covering

FREQUENCIES
INDUCTIVE REACTANCE
RESONANCE AND TUNING
COILS AND COIL WINDING
TUBES
RECTIFIERS, OSCILLATORS,
AMPLIFIERS, MODULATORS, ETC.
CIRCUITS
CAPACITANCE
COUPLINGS, ENERGY TRANSFER
TRANSFORMERS, ETC.

by

THE TECHNICAL STAFF

of

COYNE ELECTRICAL & RADIO-TELEVISION SCHOOL
CHICAGO 12, ILLINOIS

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APPLIED PRACTICAL RADIO-TELEVISION

FOREWORD

The purpose of this book on APPLIED PRACTICAL RADIO-TELEVISION is to present the principles of construction, operation and testing of radio and television equipment in a SIMPLE, EASY TO FOLLOW manner.

By using NEW and DIFFERENT methods of explanation the book clearly explains the *direct relation between the various parts of sets.* This information is especially helpful in service work where many times a burned out tube, resistor or transformer is actually caused by some other defective part in the circuit. Until the cause of the trouble is removed the parts would continue to burn out. For this reason, each part of the radio or television unit is explained, thus, making the material especially helpful to the *experienced radioman.*

Particularly valuable and interesting chapters cover Resonance and Tuning. Radio and television tubes and their characteristics (because of their importance) are given two complete chapters.

One very important way in which this book differs from many other radio and television books is that the publishers did not try to assume the "extent of technical knowledge" of the reader. Every subject is explained COMPLETELY — while at the same time keeping it *brief and to the point.*

You will find hundreds of photos, charts, diagrams, etc., in this book. These have been provided to make it easier to understand the explanations.

We have put into this book the knowledge of many years of radio and television teaching of the Coyne School Staff working closely with one of America's most experienced technical authors. In this way the information represents the knowledge of many experts and is not just one man's ideas — as is the case in most radio or television books. We feel this combination of the practical ideas of men who teach radio with a man who "can put it on paper" should make this book an ideal text for the student as well as a field reference book for the experienced radioman.

B W Cooke

B. W. COOKE, *President*
Educational Book Publishing Division
Coyne Electrical, Radio and Television School

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Chapter 1

TELEVISION AND RADIO

For thirty years the radios used by the general public reproduced nothing but sound. Then came television, and everyone could see as well as hear. The radio technician had to learn new things as suddenly as did the movie technician when silent pictures suddenly became sound pictures. It was almost as though automobile mechanics woke up some morning to find that all cars had wings, that they were combination automobiles and airplanes.

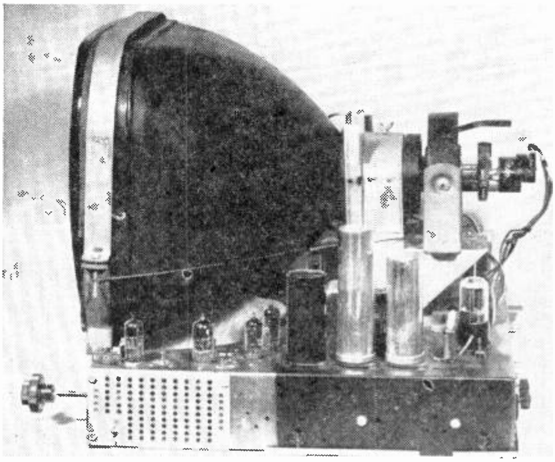

Fig. 11-1.—A television chassis removed from its cabinet to show the picture tube and many of the smaller parts.

Like all revolutionary changes, television smoldered along for years in a small way and then broke wide open. It caught most of us unprepared, for in a television receiver there are many circuits entirely unlike anything in radios which reproduce only sound.

The engineers who invented and perfected our present system of television began with radically new ideas. These were the methods of transmitting signals representing a series of lights and shadows, one after another in time, and of assembling them so fast and in such perfect order as to let us see a complete picture with smooth movement.

To make that system workable these engineers utilized nearly everything with which we are familiar in sound receivers. In the video or picture section they used amplitude modulation, like that in standard broadcast. For television sound they took frequency modulation, as used in f-m sound receivers. For both video and sound amplifiers they used the superheterodyne. In the matter of frequencies they took just about everything. The lowest frequency in a television receiver is below the lowest audio frequency. The highest is up into hundreds of millions of cycles, where only the hams experimented a few years ago. In between are all the frequencies found in standard broadcast, f-m broadcast, international and amateur short-wave transmission, and all the commercial services. Television is very nearly the whole field of radio wrapped up in one package.

Although these developments posed real problems for most of us, there was one class of radiomen who had no trouble at all. They were the ones who had commenced "playing with radio" twenty to thirty years ago. In those days you often built your own apparatus, and had to know the fundamentals to make it work. In television these men continually met new circuits which bore strong resemblance to what had been thought obsolete long since.

This state of affairs came about because, for the synchronizing and sweep circuits, the men who perfected television went back into what most of us thought was radio history. Separators, limiters, and clippers have grid leaks and capacitors like those used with tube detectors of the early 20's. Other tubes in the sync section work at plate current cutoff, to remind you of power detectors that followed the grid leak variety. In automatic controls for sweep frequency are many variations of circuits which helped make automatic tuning practical in the 30's. There are d-c amplifiers with which we experimented in an attempt to reproduce the bass notes. There are crystal detectors which are highly developed grandchildren of the 1915 variety.

Even though you aren't familiar with all these old circuits so recently rejuvenated they present no great difficulty, for all are simple enough once you get into them. The real difficulty comes with the "fundamentals." Take the matter of phase relations in a-c circuits, which used to seem rather theoretical and something we might very well skip. But changes of phase with frequency, and combinations of out-of-phase voltages and currents, are the basis of nearly all automatic controls which prevent the television picture from looking like a flock of chickens in a cyclone. Furthermore, human ears tolerate a lot of phase distortion in sound, but our eyes won't stand for it in pictures.

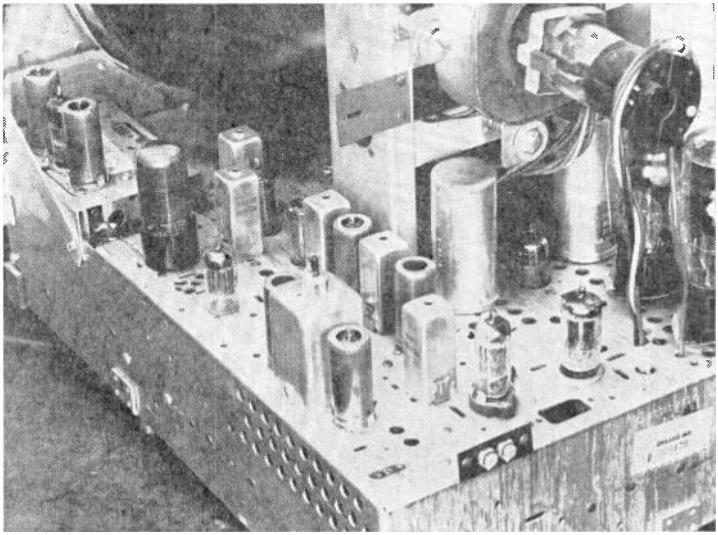

Fig. 11-2.—Parts which interest the service technician when working on a television receiver.

Time constants are something else which seemed only mildly interesting. But the correct selection of capacitive time constants keeps pictures recognizable, and of inductive time constants keeps magnetic sweep circuits out of oscillation. Something else which has emerged from test instruments and remote amplifiers to appear almost anywhere in the television set is the cathode follower. This taking of the output from the cathode rather than the plate isn't the only strange perversion of tube elements, for quite often you ground the grid and put the signal into the cathode.

Many other things seem to be wrong in television. For example, you will find high-Q tuned circuits with a resistor of only two or three thousand ohms across the coil. This wrecks the "Q," but it helps an amplifier pass a frequency band more than 120 times as wide as anything in intermediate transformers for sound, and do so uniformly. In about half the resonant circuits you will look in vain for tuning capacitors, for at frequencies of scores and hundreds of megacycles there is plenty of capacitance in wires and tubes.

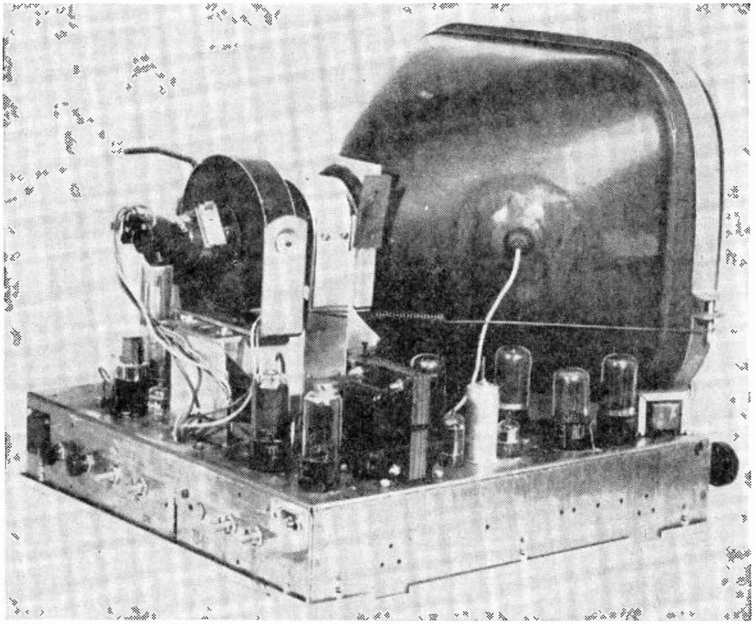

Fig. 11-3.—Service controls and adjusters for controlling picture quality are accessible at the rear of this chassis.

We might keep on through many pages pointing out the old and the new in television, the newest branch of radio. Television has been used to show what a radioman must know because here are nearly all the principles in a single instrument. But whether your immediate interest is in standard broadcast, f-m broadcast, international short-wave, public address, intercommunication. record players, or television, it all boils down to this: The only way to successfully and profitably handle all of them is to understand the fundamentals which apply in all these fields.

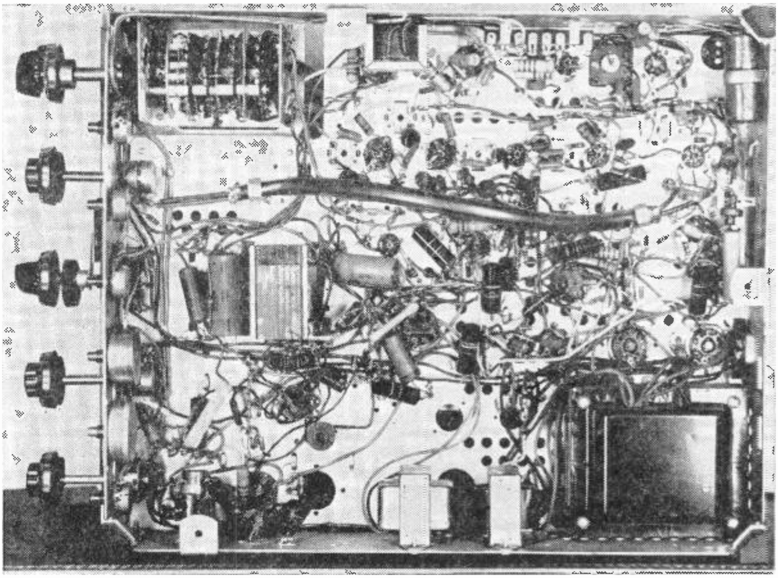

Fig. 11-4.—Underneath a television chassis are capacitors, inductors and resistors of many types and sizes.

When you look at radio apparatus you must not see just tubes, coils, capacitors, resistors, and wiring. In your mind you must see where those electrons start and where they go and what they do on the way. Only then will the hundreds of types and models of radio apparatus show themselves to be merely different combinations of things which really are elementary.

Almost certainly you will know a good deal about many of the things discussed in following pages. Just as certainly, there will be other things which are new. Later we shall be traveling fast through the really advanced applications, and there will be no time to come all the way back to the beginning to pick up a bit of information that explains the why of some method of testing or adjustment.

With this in mind let's review a few of the more important facts in radio and television as they are related to electrons and electron flow. It is only by thinking in terms of electrons at rest and in motion that everything comes within the same well-ordered pattern, to appear not only reasonable, but as the only thing which could happen under existing circumstances.

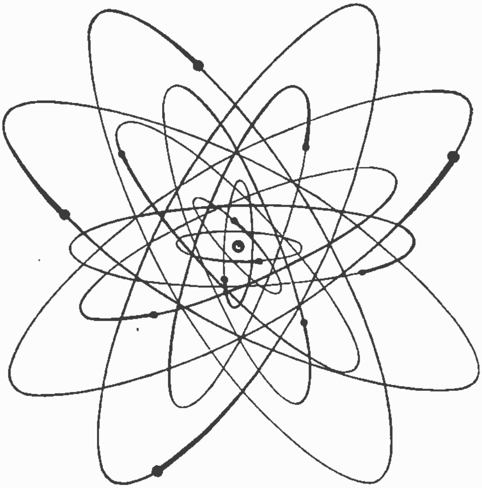

Fig. 11-5.—Electrons travel in orbits around the center of an atom.

Electrons.—As you know, electrons are particles which exist in all atoms. Atoms are the smallest particles of every elementary substance. And everything in existence consists of various combinations of 96 elements. For example, bronze is made from copper and tin, which are elements. The smallest particle of copper is an atom of copper, about 1/250000000 inch in diameter. If you break down the atom you no longer have copper, but have a collection of electrons, protons, neutrons, positrons, mesotrons, and other infinitesimal particles which could go back together in various combinations to form any other known element as well as copper.

An atom of any given element has normally a certain definite number of electrons. An atom of copper has 29. The electrons move around in the atom much as shown by Fig. 11-5. The outermost electrons are held rather loosely in the atom, and one or even two of them frequently become detached. The detached electrons are *free electrons.* This leaves the atom short of electrons, and almost immediately it pulls into itself one or two wandering electrons which have escaped from other atoms. The result is that vast quantities of free electrons always are moving about between the atoms of every substance.

The free electrons are electricity itself, the only electricity with which we are concerned in radio. It is important to realize that everything is full of electricity all the time, because it is full of free electrons. Nothing you can do will either produce or destroy electricity, it always is there. When great quantities of free electrons are caused to move in the same direction as they escape from and re-enter the atoms, these moving electrons form the electric *current.* We may move the electrons and thus produce or generate a current, but we have not generated electricity itself—only the motion. When electron movement is such that 6,280,000,000,000,000,000 of them pass a given point during one second of time this rate of flow is one *ampere.*

Electron Flow.—There are many ways in which free electrons may be caused to move together in one direction. This movement most often results from rotation of wires or of magnets in generators or dynamos, or from chemical action in cells and batteries. Electron movement is caused also in devices pictured by Fig. 11-6, from light acting in photocells, from heat in thermocouples, or from compression or flexing of crystals in some phonograph pickups and microphones. All these are *sources* of electromotive force, abbreviated *emf.* This force is measured in *volts.*

The emf in a source causes quantities of free electrons to move in the materials inside the source. These electrons move away from one terminal and toward the other to bring about a deficiency at the first terminal, which we call *positive,* and an equal excess of electrons at the other terminal, which we call *negative.*

Let's take for a source a single dry cell, as at the left in Fig. 11-7, wherein the emf is 1½ volts. This emf moves free electrons within the cell in such a direction as to leave a deficiency at the positive (+) terminal and to pile up an equal excess at the negative (—) terminal. But this small emf cannot drive any of the excess electrons out of the negative terminal into the surrounding space.

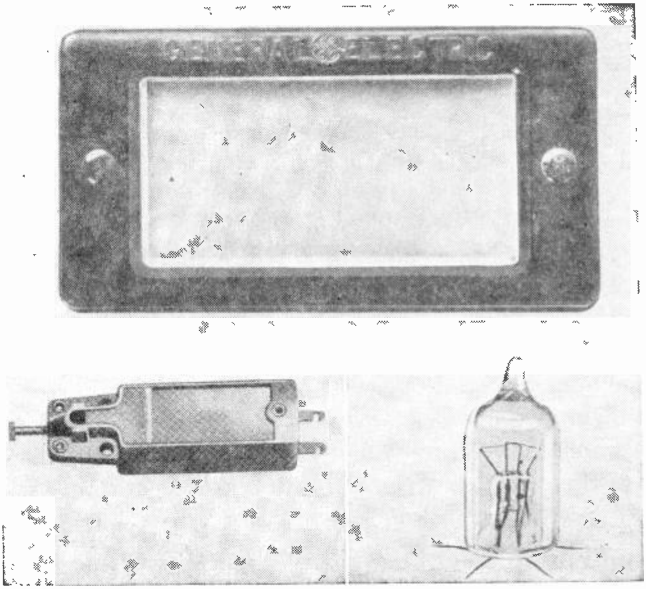

Fig. 11-6.—Some sources of emf; a photocell at the top, and below a crystal pickup and a vacuum thermocouple.

If we connect pieces of metal to the cell terminals, as in the center diagram, free electrons will be drawn out of the metal connected to the positive terminal and an excess will be forced into the metal connected to the negative terminal. Now we have electric *charges* in the pieces of metal. Wherever the concentration of free electrons is less than normal there is a *positive charge*. Wherever the concentration is greater than normal there is a *negative charge*. But again the emf does not furnish enough force to drive electrons off the negatively charged piece of metal, nor to pull electrons from the surrounding space into the positively charged metal.

Should we connect a wire between the cell terminals, as at the right, there will be continual flow of free electrons from the excess at the negative terminal through this wire to the deficiency at the positive terminal, then from positive back to negative within the cell. The electrons will keep moving around and around until chemical action uses up all the working ability of the cell.

Circuits.—The electrons which have been forced over to the negative terminal inside the source have gained *energy.* Energy is the ability to do work. You have lots of energy when you feel like doing a lot of work. The energy or working ability of the electrons at the negative terminal is directly proportional to the number of volts of emf developed in the source. A given quantity of free electrons at the negative terminal of a 90-volt B-battery has ten times the energy or working ability of an equal quantity at the negative terminal of a 9-volt battery.

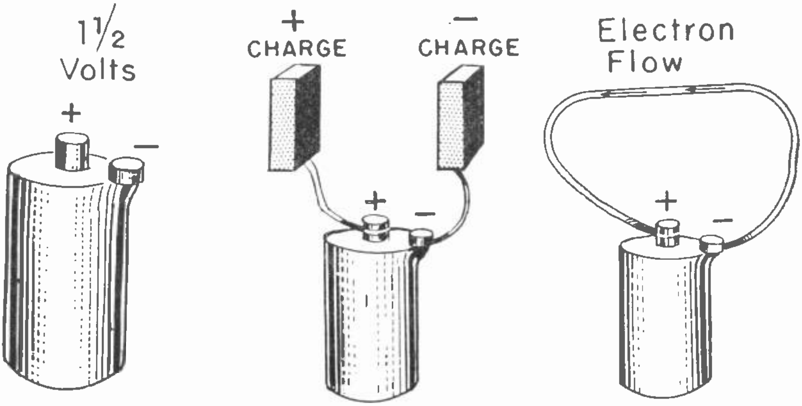

Fig. 11-7.—A source of emf will produce electric charges and cause electron flow.

When an electron gains energy it is seized with a desire to expend its working ability in going places. The electron doesn't like the company of others of its kind, so it tries to go from where there already are too many electrons to wherever there may be too few. That is, the free electrons try to move from where there is a negative charge (an excess of electrons) to wherever there may be a positive charge (a deficiency of electrons).

The path through which the electrons move to satisfy their desire is an *electric circuit.* At least it is the portion of a circuit which is outside the source. Strictly speaking, any complete circuit must include a source of emf or include some force which makes electrons move. In Fig. 11-8 the circuit in which electrons move includes fixed and adjustable resistors, a choke, an open coil, a current meter, and a rectifier power unit which is the source of emf for this circuit.

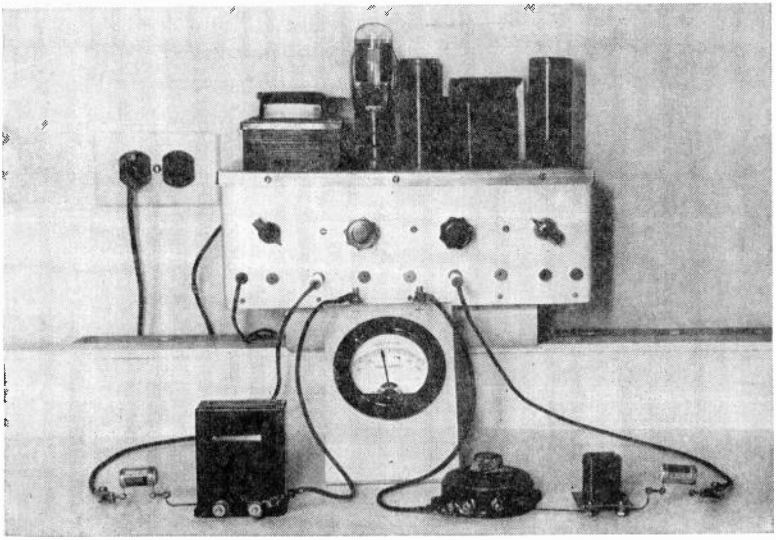

Fig. 11-8.—A circuit consisting of radio parts connected to a B-power unit which is the source of emf.

This source of emf acts to force an excess of free electrons to its negative terminal, from where they pass through all the remaining parts and connections to reach the positive terminal where there is a shortage of electrons. Sometimes we refer to only part of a complete electron path as a circuit. For instance, the resistance-capacitance coupling setup for demonstration in Fig. 11-9 might be called an amplifying circuit

If enough electrons can move from negative to positive to bring about a balance or equality of electron density at both places there no longer are electric charges. There is neither an excess to form a negative charge nor a shortage to form a positive charge. With no charges all the parts are *neutral.* If, however, the emf can maintain the charges and if there is path between them for electron flow, there will be continued flow from negative to positive.

Conductors and Insulators.—The energetic electrons will move in anything which is an electrical conductor. A conductor is any substance from whose atoms it is easy to detach electrons and in which there always are a great many free electrons. With so many free electrons ready to be moved it takes only a small emf in the source to move a lot of them and to produce a large current.

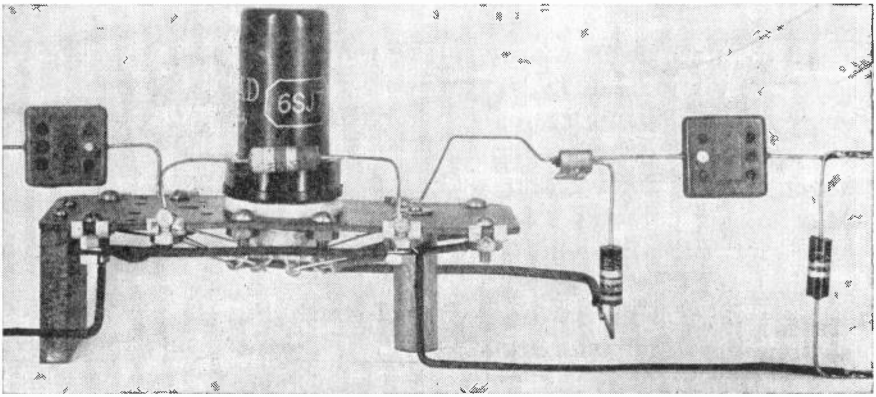

Fig. 11-9.—Principal parts of a resistance-capacitance coupling system, which may be referred to as a circuit.

An insulator is any material whose atoms hang onto their electrons tenaciously and in which there are very few free electrons. When you connect an insulator to a source of emf, current in the insulator is so small it is difficult to measure. If you apply more and more force it finally causes movement of a lot of electrons, but the attraction between atoms and their electrons in an insulator is so strong that the atoms themselves go along with the electrons. Then there is a breakdown of the insulation, an actual rupture or puncturing of the material. Electrons rush through the hole at such a rate that the heat burns or chars the insulation, or may set it afire.

Energy and Volts.—The electrons which start out full of energy have anything but a free path, even in a conductor. An electron moves about a quarter-billionth inch before it collides with an atom which, to the electron, is immovable. Maybe that electron gets pulled into the atom and stays there. If the atom already has a full complement, the electron bounces off and tries another route, only to hit against another atom. This jostling about takes energy out of the electron much as it would from you in trying to run through a forest where the trees were only two feet apart and every second tree had hooks to catch and hold you. Consequently, there is continual loss of energy from electrons flowing through any conductor.

All this talk about energy in electrons may sound like theory pure and simple, but it isn't. Wherever we have used the word energy we might substitute the word voltage or the word potential with practically no change in meaning. We are used to thinking about voltages and working with them. If we commence thinking of voltage or potential as a measure of energy or working ability of electrons it will simplify the explanations of many actions in radio.

Let's consider the battery source of emf in Fig.11-10, which we shall assume adds 90 units of energy to the electrons which are moved from positive to negative inside the battery. Then the electrons push themselves through the wire extending from the negative terminal to the resistor. To get through this wire takes 1 unit of energy, leaving 89 units remaining in the electrons. The path through the resistor is rather rugged, and the electrons use 14 units of energy—leaving them with 75 units. Then, to get through the tube with its evacuated space within the envelope, the electrons have to use 70 units of their remaining working ability. The last 3 units of energy are expended in getting through the connection leading back to the positive terminal of the source.

Direction of Flow.—If you changed the term "units of energy" to the word "volts" in the preceding explanation of the battery circuit it could describe what happens in a radio circuit. We would speak of a 90-volt battery, a drop of 14 volts in the resistor, of 70 volts in the tube, and so on. But where we think of maximum energy as being at the negative terminal of the source we have to think of maximum voltage as being at the positive terminal.

To talk in terms of volts the values have to be reversed, as in Fig. 11-11. The voltage drops in each separate section of the circuit still are numerically equal to the energy losses in the same section. But we start with the maximum voltage at the positive terminal of the source, then subtract as we go to the negative terminal.

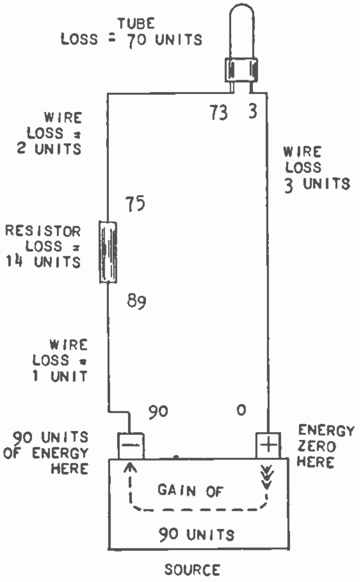

Fig. 11-10.—Energy is added to electrons in the source, and lost in the external circuit.

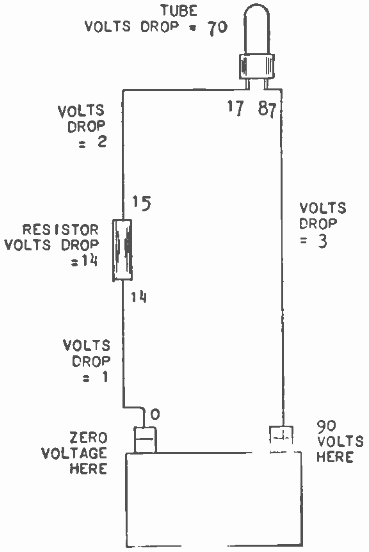

Fig. 11-11.—Voltage is increased in the source, and there is voltage drop in the external circuit.

This unfortunate confusion exists because the men who first experimented with electricity didn't know there are such things as electrons which really move. They assumed electricity to be something having no material existence, a so-called "imponderable fluid" which flowed from place to place. This much was all right, but those early scientists assumed the flow to be from positive to negative *outside* the source, from negative to positive *inside* the source, and they assumed the highest voltage or potential to be at the positive terminal with zero at the negative terminal.

By the time the direction of actual electron flow was determined, it was too late to change all the books and instructions in the whole electrical industry. In radio, a relatively new part of the general field of electricity, we do talk about electron flow as it really exists, but we think of positive as being at higher voltage than negative in the same circuit.

Resistance.—You know that various conductor materials have different degrees of opposition to electron flow. In copper there are exceedingly great quantities of free electrons, and the atoms don't hang onto their electrons so very tightly. So it is easy to produce a great rate of electron flow or a large current in copper. Copper has little *electrical resistance.* Atoms of iron hang onto their electrons more tightly. There are fewer free electrons to be acted upon by an emf, and the resistance of iron is relatively high.

How much energy or how much voltage is consumed in maintaining a current depends on the flow rate (amperes) and on the opposition or resistance (ohms) of the conductor. Consequently, energy loss or voltage drop in a conductor is equal to the product of amperes and ohms. Usually we show this by writing $E = IR$, volts equal the product of amperes and ohms. Every other form of Ohm's law for current, resistance, and voltage drop is explained by the action of energy-filled electrons pushing their way through the atoms of conductors.

Heating Power.—As electrons push through the tightly packed atoms of a conductor the continual rubbing generates friction. This friction produces heat and a rise of temperature in the conductor, just as rubbing your hands together makes them feel warm because of frictional heat. This is the reason why all conductors are heated to a greater or less degree when current flows in them.

The amount of heating is proportional to the density of the moving electrons, which is current in amperes, and to the opposition offered by atoms of the conductor, which is electrical resistance. To put it in ordinary radio language, the energy loss in heating, measured in watts of power, is equal to I^2R, the product of the square of the number of amperes and the ohms of resistance.

Electric Fields.—We have talked about emf as the force which moves free electrons from terminal to terminal inside a source. But emf is not the only force which moves electrons. Another electron-moving force, highly important in radio, is that which exists in the space between electric charges. Such a space is between the two sheets of metal connected to the terminals of a source in Fig. 11-12. Supposing an electron could escape from the negatively charged sheet and emerge into the space between the charges. Instantly this electron would move away from the negative charge and toward the positive charge.

An electron is repelled by a negative charge and at the same time is attracted by a positive charge. Although we have not said so before, electrons themselves are negative, they are negatively charged. A negative electron moves away from a negative charge because it is a natural law that negative charges *repel* each other. The negative electron moves toward the positive charge because it is a law that positive and negative charges *attract* each oher.

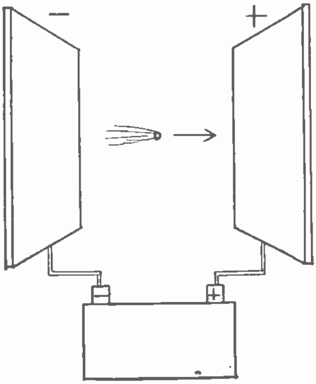

Fig. 11-12.—A free electron tends to move from a negative charge to a positive charge.

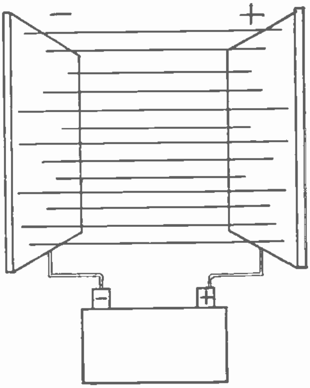

Fig. 11-13.—The electrostatic field between charges contains energy.

Now look at Fig. 11-13 where again we have the charged metallic sheets. There is an excess of electrons in the sheet negatively charged. All the negative electrons in this charge exert a repelling force on any negative electrons in the space between charges. The deficiency of electrons in the positive charge exerts an attracting force on any electrons in the space.

These forces which act in the space between charges have the ability to do work, the work of moving electrons through the space. Working ability is energy. Consequently, there is energy in the space between the charges. Any space in which there is energy or force due to electric charges is called an *electric field* or an electrostatic field. There is energy in all such fields.

Energy in electric or electrostatic fields is the basis of many of the most useful actions in radio and other branches of electricity.

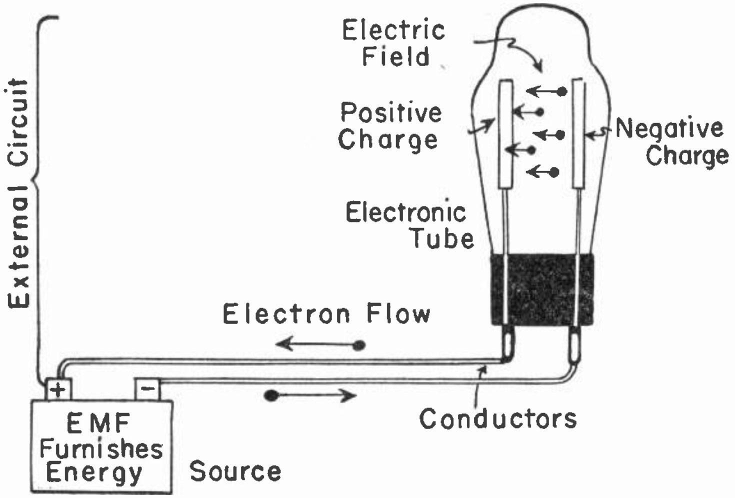

Fig. 11-14.—Free electrons pass from a negative to a positive charge inside a radio tube.

It is fundamental in the performance of all tuned or resonant circuits, in certain systems of high-speed welding, in the most common methods of improving the efficiency of some types of motors and other electrical devices, and in many other applications.

Tubes.—Television and radio tubes make use of positive and negative charges and of the electric field between them. Were it not for the fact that we can easily control the strengths and shapes of electric fields in tubes, and thereby control electron flow, we still would be in the days of crystal detectors and slide tuners.

In Fig. 11-14 is represented a tube containing only two elements. One element is negatively charged because it is connected to the negative terminal of a source. The other element is positively charged, being connected to the positive terminal of the same source. Between the charges is an electric field. If negative electrons can leave the negative charge these electrons will fly through the field space under the influence of repulsion and attraction.

To force free electrons out of the negatively charged element in the arrangement of Fig. 11-14 would require very strong forces of repulsion and attraction, highly concentrated charges, and high voltage to maintain them. It can be done and actually is done in "cold-cathode" tubes, but these are not common types.

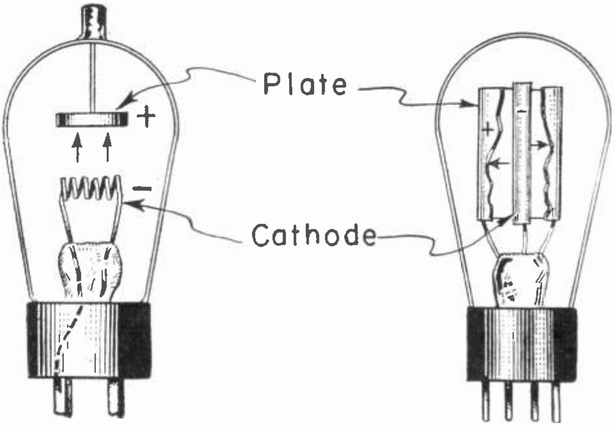

Fig. 11-15.—Heating the cathode gives electrons enough energy to emerge into the surrounding space.

The way to get electrons out of one element and into an electric field is to "boil" them out with heat. This is the reason why most tubes have means for heating one of the elements as in Fig. 11-15. The element from which electrons are made to emerge into the field space is called the *cathode.* At the left we have one style of *filament-cathode* which here is a coiled wire heated red hot or white hot by electron flow in its high resistance. This electron flow for heating may be furnished by any suitable source. The *heater-cathode* in the tube at the right is the small cylindrical element inside which is a coil or loop of high-resistance wire called the heater. The heater is connected to a source, becomes very hot, and makes the surrounding cathode red hot.

When a cathode is heated, the electrons in its atoms gain a great deal of energy from the heat and become violently agitated. Some electrons become so energetic as to actually jump right out of the hot cathode into the nearby space. Somewhere outside the cathode is an unheated element called the *plate* or sometimes the *anode*. If the plate or anode is maintained with a positive charge and the cathode with a negative charge, by connecting them to a source, an electric field will be maintained between these elements.

Electrons emitted from the cathode are repelled by the negative cathode, attracted by the positive plate, and fly through the field space to enter the plate. Electrons which thus leave the cathode are continually replaced by more coming from the negative terminal of the source, and electrons which reach the plate are drawn away to the positive terminal of the source.

Capacitors.—When there is a difference of voltage or potential on any two conductors separated by any kind of insulation, the conductor which is negative has more free electrons than the one which is positive. The conductors are charged, and there is an electric field extending through the insulation. If the charged conductors are disconnected from everything else, and if there is no electron leakage through the insulation, the charges will be retained. Such a combination of conductors and insulation constructed for the specific purpose of handling electric charges is called a *capacitor* or a condenser.

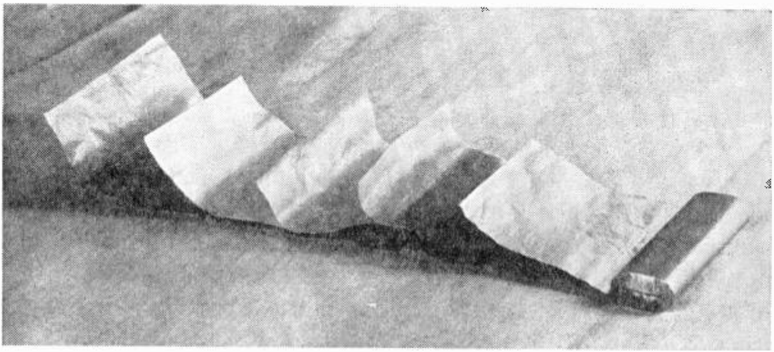

Fig. 11-16.—Plates and dielectric of a "paper" capacitor.

The conductors of a capacitor are its *plates*. The insulation between the plates is the *dielectric*. Fig. 11-16 shows a partially opened capacitor in which the plates are of thin aluminum foil and the dielectric is thin paper impregnated with wax.

The charge which a given capacitor will hold varies directly with the applied voltage difference. For any given voltage the charge depends on three characteristics of the capacitor. First is the kind of dielectric. If we consider the charge as 1.0 unit with air as the dielectric, it will be between 4.0 and 8.0 units with mica, from 3.5 to 4.5 units with fused quartz, and 90 to 150 units with titanium dioxide. These numbers are the *dielectric constants* of the materials.

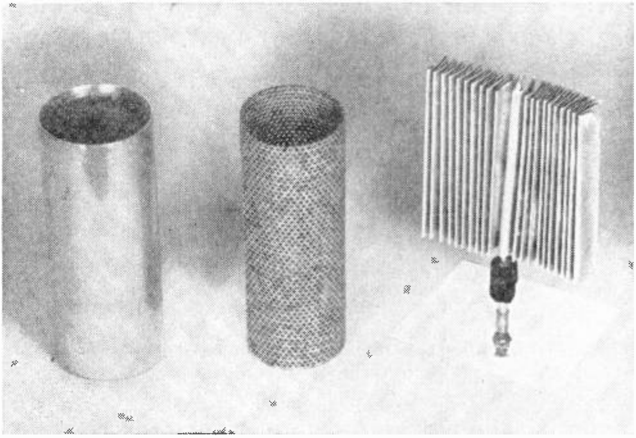

Fig. 11-17.—The parts of a wet electrolytic capacitor.

The second factor is plate separation. The thinner the dielectric and the less the separation between plates, the greater is the charge. Third, the greater the surface areas of the plates in contact with the dielectric the greater is the charge.

The ability of a capacitor to receive and retain a charge, or the quantity of charge received with a given potential difference, is proportional to *capacitance* or capacity. The fundamental unit of capacitance is the *farad*, which is a far greater capacitance than possessed by any capacitor. The usual units are the microfarad (one millionth of a farad) and the micro-microfarad (one millionth of a microfarad). Microfarad is abbreviated *uf*, *mf*, or *mfd* and micro microfarad as *uuf*, *mmf* or *mmfd*.

Types of Capacitors.—When a capacitor is so constructed that relative positions of plates and dielectric cannot be altered, and capacitance cannot be changed in service, it is a *fixed capacitor*, Fig. 11-16 illustrates such a type. Fixed capacitors have dielectrics of paper, mica, and certain materials of high dielectric constant coated on ceramic supports. Waxes and oils are used with paper and mica to increase the dielectric constant and improve the insulation for working at high voltages.

Electrolytic capacitors are fixed types providing large capacitance in small space. One plate is of oxidized aluminum, the other a liquid in which some hydroxide is dissolved to make it conductive. The dielectric is the oxide and an extremely thin film of gas formed upon it. The parts of such a capacitor are shown in Fig. 11-17. In "dry electrolytics" only enough liquid is used to saturate absorbent gauze or paper between the plate surfaces. The capacitor is enclosed within a moisture-proof carton or can.

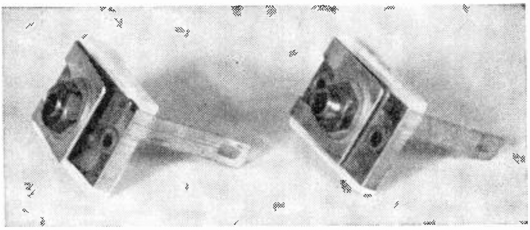

Fig. 11-18.—Adjustable trimmer capacitor having mica dielectric.

Most electrolytics are polarized, which means they must not be used with alternating voltages and currents, but only where polarities do not reverse. Terminals are marked for correct connection in direct-current circuits. Non-polarized electrolytics are available for use in alternating-current circuits.

Variable or adjustable capacitors are constructed so that their capacitance may be changed while in use by altering the separation between plates. The "trimmer" capacitor of Fig. 11-18 is adjusted for minimum capacitance at the left, and at the right,

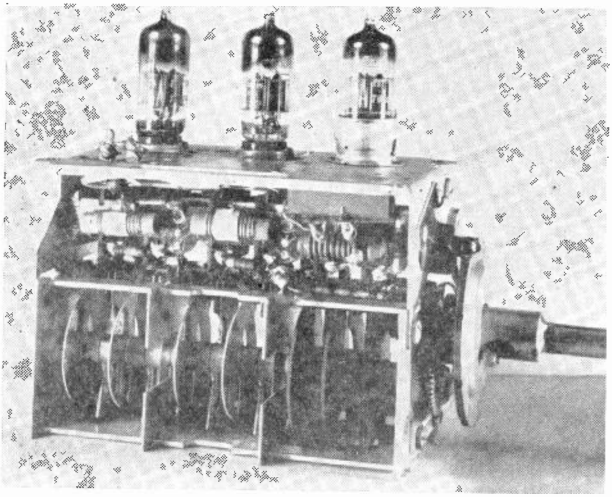

Fig. 11-19.—In the lower part of this television tuner are twelve variable capacitors.

with plates pressed together, for maximum capacitance. Other variable capacitors, as the tuning capacitor of Fig. 11-19, allow moving the rotor plates into or out of the air-dielectric spaces between stationary stator plates. Moving the plates together increases effective area, and increases the capacitance.

Capacitors in Parallel and Series.—When capacitors are connected in parallel, as shown in principle by Fig. 11-20, their capacitances add together. For example, capacitances of 2, 3, and 5 mfd in parallel provide a total capacitance of 10 mfd.

Total capacitance of capacitors in series may be found by three methods. *1*: If all are equal, divide one capacitance by the number

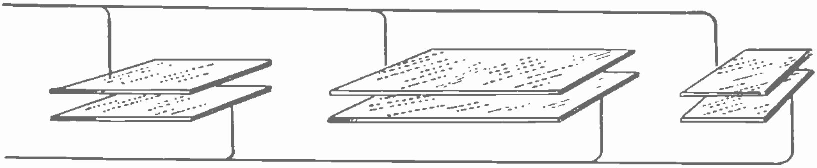

Fig. 11-20.—Capacitors in parallel add their capacitances.

in series. *2*: For any two capacitances, divide the product by the sum. *3*: For any number and size, the total is equal to the reciprocal of the sum of the reciprocals of the several values.

A potential difference applied to capacitors in series divides between them inversely as the capacitances. For example, Fig. 11-21 shows capacitances of 4, 12 and 6 mfd in series on 600 volts. The division is proportional to 1/4, 1/12, and 1/6, making the respective voltages 300, 100 and 200, as shown.

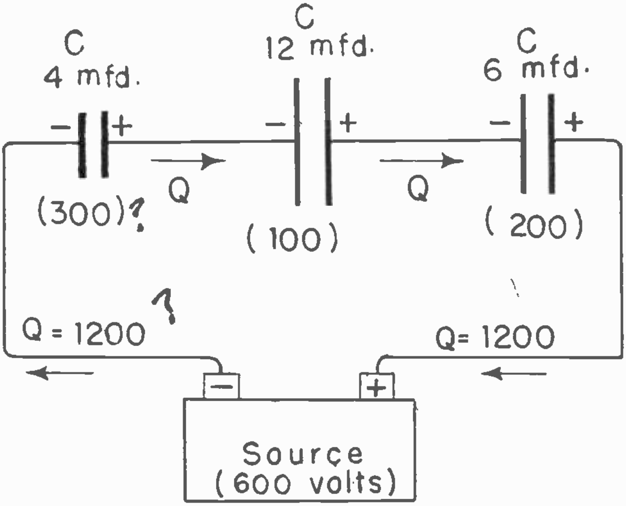

Fig. 11-21.—How an overall voltage divides between capacitances.

Divide the smaller Cap. into the larger Cap and the largest into its self- add the total and put each part of this total and mult by the voltage

Chapter 2

ELECTRONS AND MAGNETISM

The behavior of electric currents and magnetic fields, acting together, accounts for all our transformers, all impedance couplings, many filters, all wave traps, all loud speakers in common use, the majority of television sweep systems, and every motor and generator in existence. All these depend on one or more of three electromagnetic principles. First, a current produces a magnetic field around itself. Second, when a magnetic field moves or changes its strength it induces emf and current in a conductor which is in the field. Third, electrons passing through a magnetic field are pushed sideways out of the field.

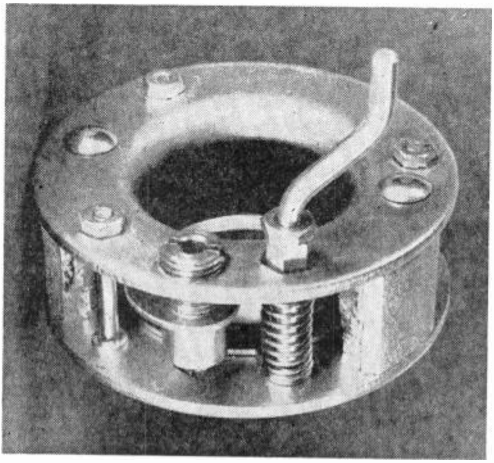

Fig. 12-1.—This permanent magnet centering and focusing device is used on television picture tubes.

Doubtless you have become acquainted with these three facts while studying electromagnetism, electromagnetic induction, and related subjects. Furthermore, you hear and see the results every time you work with radio and television. But the principles are so important that it will be worth while to go over them once more.

An easy way to gain real understanding of relations between currents and magnetic fields is to perform some simple experiments in which they work together. In every radio shop and in the equipment of every experimenter is plenty of apparatus to perform such experiments.

To begin with, we need a magnetic field. The easiest way to obtain such a field for experimenting is to use a permanent magnet, such as the common U-shaped or horseshoe type. The strongest field exists between the poles. With the magnet poles pointing upward we rest a sheet of stiff paper on them, then, from a height of about a foot, let iron filings fall onto the paper. The filings arrange themselves in the pattern of Fig. 12-2.

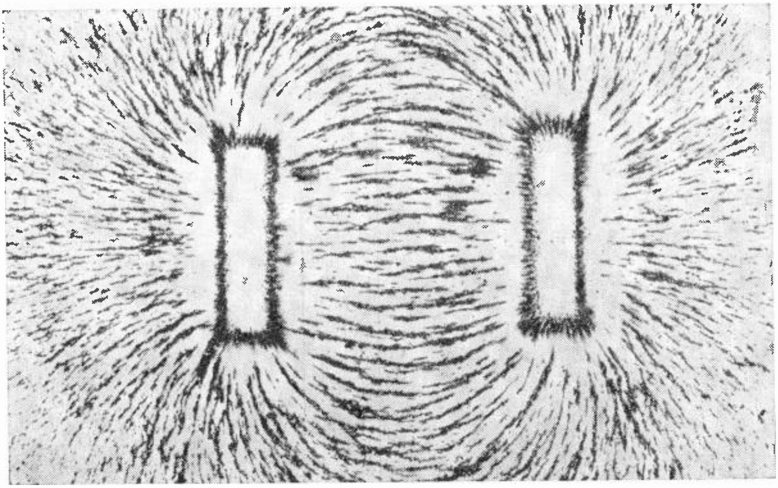

Fig. 12-2.—Paths of magnetic lines of force in the field of the permanent magnet.

This is a field pattern showing the magnetic *lines of force* which extend around and between the two poles of the magnet. All the space in which the force exists is called the *magnetic field.* As each iron filing drops into the field space the filing becomes a tiny magnet. Were it possible to have one of these magnets so small and light as to float in air, and were this magnet dropped anywhere in the field, it would move along one of the lines of force toward one of the poles. Between the poles the lines are straight, and there the floating magnet would travel a straight line. Elsewhere the lines curve, and in those parts of the field the floating magnet would follow a curved path.

The lines of magnetic force themselves cannot be seen or felt. In fact, these lines have no material existence, but are merely the directions in which the magnetic force acts—as shown by the filings. The lines of force commonly are called magnetic *flux*.

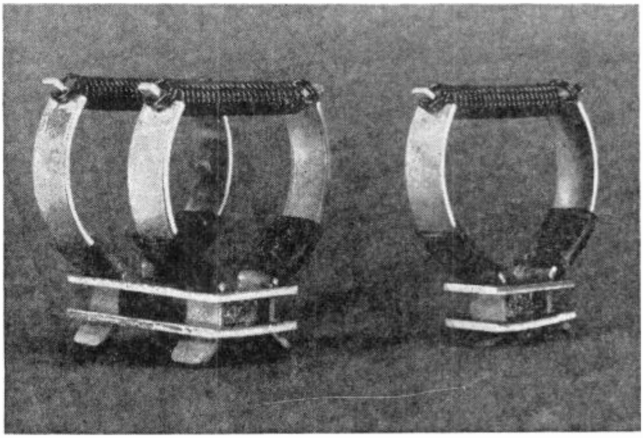

Fig. 12-3.—These permanent magnets with extended pole pieces are parts of ion traps used on television picture tubes.

These experiments may be continued with an *electromagnet*. An electromagnet consists of a coil or winding of wire through which flows an electric current. Inside the coil may be a *core* of soft iron. The poles are at the ends of the coil or at the ends of the core. The two ends of the coil may be connected to any source in order to have current or electron flow in the coil.

Again we shall place a sheet of stiff paper on the pole extensions of the electromagnet and sprinkle iron filings onto the paper. The filings form themselves into the pattern of Fig. 12-4. Except that the poles are a little farther apart, this pattern of the electromagnetic field is just like that of the permanent magnet field of

Fig. 12-2. The only difference between the field of an electromagnet and the field of a permanent magnet is in the kind of magnet producing the force. The kind of force and its direction, the magnetic lines or flux, and all else, are just the same in both fields. Anything which we can do with a permanent magnet field can be done also with an electromagnetic field, and vice versa.

The only purpose of using an iron core for the electromagnet is to make the field stronger and more concentrated, or to bring a strong part of the field into a position where it may be used to best advantage. Magnetic force acts far more easily through iron or steel than through air or any other substance. With a given current in the coil of an electromagnet, the strength or density of flux through a certain length of iron or steel is hundreds of times greater than through an equal length of air or any other substance.

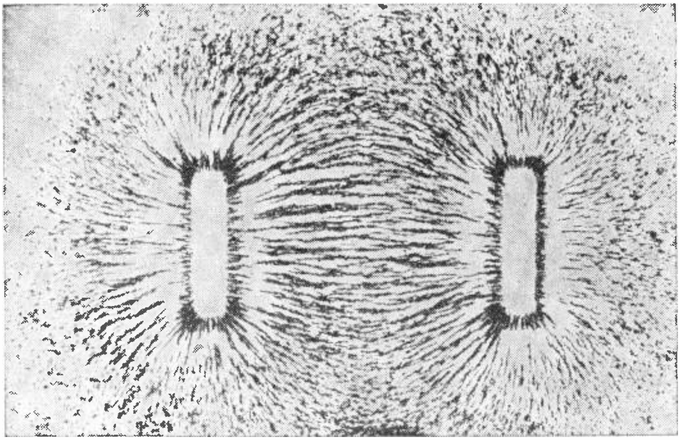

Fig. 12-4.—The field of the electromagnet is like that of the permanent magnet.

The magnetic field does not depend on having an iron core. This is proven by Fig. 12-5. Here we have the same coil used on the electromagnet, but no iron core. A sheet of paper has been placed through and around the coil, and filings sprinkled onto the paper. Here you can see how the lines of force come out at each end of the coil and extend around to the other end. Although we cannot see their effects, the field lines pass through the center opening of the coil from one end to the other.

It is not easily demonstrated with simple equipment, but the magnetic field or flux does not depend on having even the coil. It is the current or electron flow which produces the field. The insulated turns of coil conductor simply provide a path through which electrons may be guided. If we might have the electron flow without the coil conductor, the magnetic field would be just the same. There is a magnetic field around every stream of moving electrons, whether or not the electrons are flowing in a conductor.

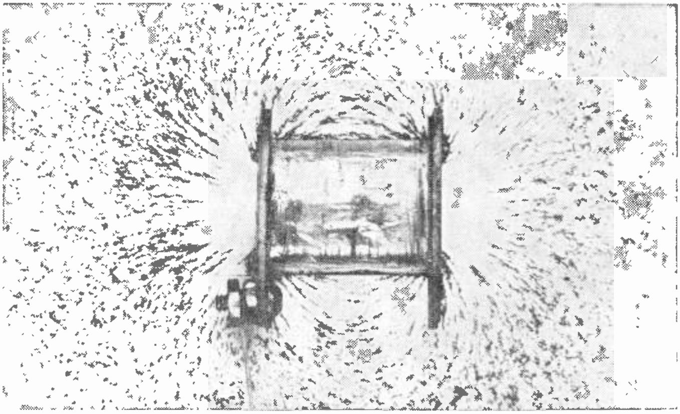

Fig. 12-5.—The magnetic field after removing the iron core from the coil.

Were there no current in the coil, but only the free electrons without definite movement in either direction through the conductor, there would be no magnetic field. With no current the sprinkled iron filings would fall into a shapeless mass with no distinct pattern of any kind. But were those filings evenly distributed over the paper, the current turned on, and the paper lightly tapped, the filings would form themselves into a pattern showing the existence of a magnetic field.

Electromagnetic Induction.—In Fig. 12-3 we made use of an electric current to produce a magnetic field. Now we shall reverse the process and watch a magnetic field induce an electric current. It is to be especially noted that in neither of these cases will anything happen unless there is movement. The magnetic field is produced only when there is movement of free electrons in the form of current. If the free electrons do not move as an electric current there is no magnetic field. Now for the second case, the induction of emf and current.

In Fig. 12-6 we have the permanent magnet between whose poles there is known to exist a magnetic field and magnetic lines of force. We have also the same coil used to produce magnetic fields, now with only the terminal end in place. The coil terminals are connected to a zero-center milliammeter whose range is one milliampere each way from zero. Any reasonably sensitive current meter would do as well, although it is easier to see the performance with a zero-center type. The coil is outside the magnetic field, and there is no current. Keep in mind that we are using a permanent magnet field only because the permanent magnet is simple and easy to handle; a field from an electromagnet would act in the same way.

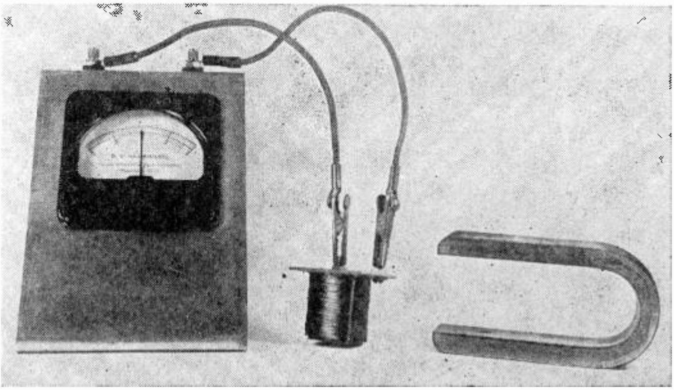

Fig. 12-6.—The experimental setup for electromagnetic induction.

If the coil is moved into the magnetic field, as in Fig. 12-7, the meter pointer will swing one way or the other. Here the swing is to the right. This indicates that an emf has been induced in the coil conductor, and that this emf has caused electron flow or current shown by the meter.

The meter will indicate emf and current only while the coil is moving. As soon as the coil comes to rest, no matter what its position, the emf and the current cease and the meter returns to zero. There is induction of emf only while the turns of conductor in the coil are cutting through the lines of force of the magnetic field.

Were you to hold the coil stationary and slip the poles of the magnet over the coil there would be just the same kind of induction of emf and current. There is induction whenever there is relative movement between a conductor and a magnetic field. The conductor may move, the field may move, or both of them may move — and there will be an emf induced in the conductor. If the conductor is part of a closed circuit, as with the coil and meter in our experiment, the emf will cause electron flow or current.

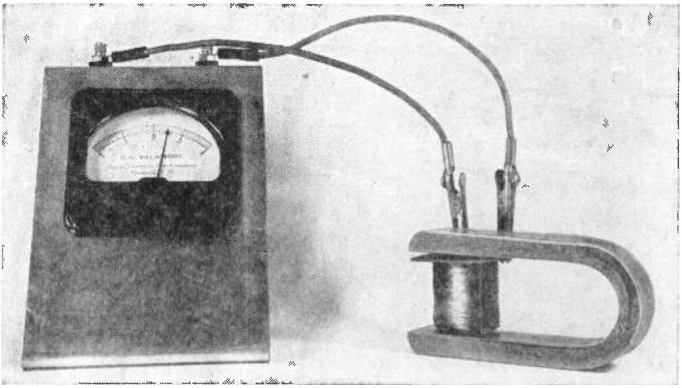

Fig. 12-7.—Moving the coil into the magnetic field induces current in one direction.

The faster the movement of either the coil or the magnet the farther the pointer of the meter will swing, the slower the motion the less will be the swing. The emf, in volts, depends directly on the number of turns of conductor and the number of lines of force cut through during one second. When the number of cuttings (the product of magnetic lines and twice the turns) is 100 million per second the emf is one volt. If you try this experiment with a coil of many turns and a strong magnet there will be appreciable meter deflection even with a slow rate of motion.

When you move the coil back out of the magnetic field, or move the field (and magnet) off the coil in the reverse direction, as in Fig. 12-8, there will be deflection of the meter pointer in the opposite direction. The direction or polarity of the emf and current depends on the polarity (north and south) of the magnetic field and on the direction the conductor moves through the field. You can reverse the emf by turning the magnet (and its field) upside down.

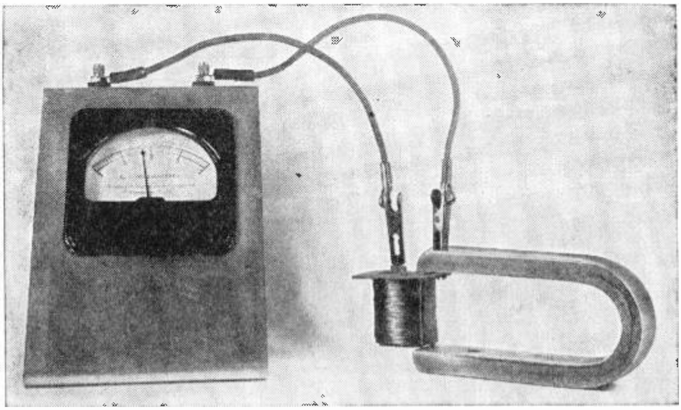

Fig. 12-8.—When the coil is moved out of the field there is induction in the opposite direction.

Fig. 12-9 shows relations between directions of field flux, motion, and emf or electron flow. The direction of field lines is assumed to be from the north to the south magnetic pole in all cases. At the left is shown the rule when the conductor is moved through a stationary field. Hold the thumb, forefinger, and middle finger of your *left* hand so that each is at right angles to the other two. When your forefinger points in the direction of field lines, north to south, and your thumb points in the direction the conductor moves through the field, then your middle finger points in the direction of induced electron flow. Electron flow is, of course, from negative to positive.

At the right is illustrated the rule applying when the conductor is stationary and the magnetic field moves. Here the *right* hand is used. Now, when the forefinger points in the direction of field lines and the thumb in the direction the field and magnet are moved, the middle finger will point in the direction of induced emf and electron flow.

Electromagnetic induction is the basic principle of all generators in which there is relative movement of conductors and magnetic fields. It is the basis also of loop antennas, wherein emf is induced by the magnetic portion of the radiated field moving through the loop conductor.

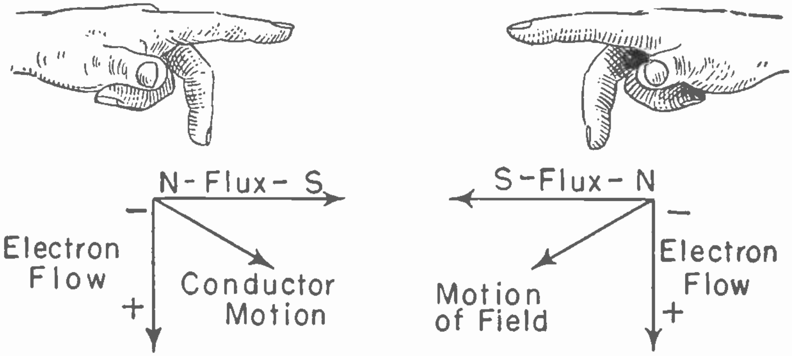

Fig. 12-9.—Relative directions of field lines, motion, and induced electron flow.

Deflection of Electrons.—Electric motors, radio loud speakers, and the movement of the electron beam in television picture tubes all depend on the same electromagnetic principle. This principle is illustrated with the simple apparatus of Fig. 12-10. In a series circuit we have a large dry cell, a switch, and a loop of wire whose lower end is in the field of our permanent magnet. The long loop may be made of number 20 hookup wire or any reasonably flexible insulated or bare wire. The large dry cell is needed because, upon closing the switch, the current must be greater than could be furnished without almost complete and permanent discharge of a small cell.

Note that the portion of the looped wire extending through the magnetic field is at right angles to the field lines. The field lines

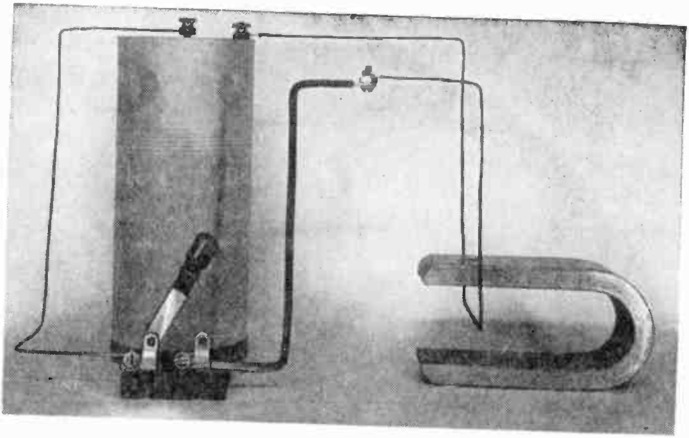

Fig. 12-10.—Picture tubes and oscilloscopes utilize the principle illustrated by this simple equipment.

extend up and down in the space between magnet poles, while the length of conductor in the field extends from front to back. Closing the switch will permit electrons to flow, in the wire, at right angles to the field lines.

When the switch is closed, as in Fig. 12-11, the wire is forced part way out of the field. Really it is the moving free electrons

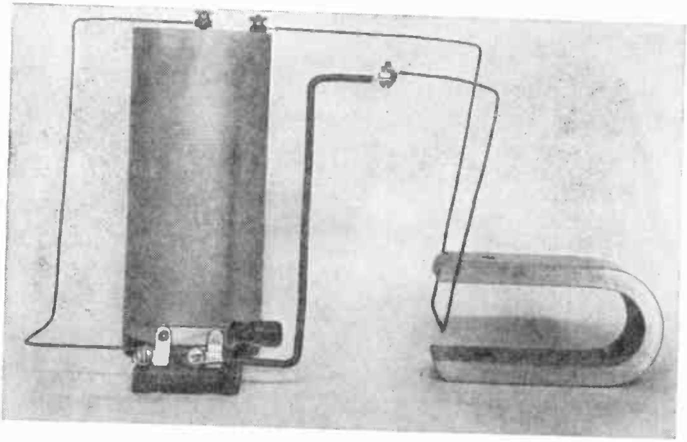

Fig. 12-11.—The electron flow, and the conductor too, are deflected out of the magnetic field.

which are forced out of the field. Because these electrons cannot escape from the wire, they carry the wire along with them. The moving electrons and the wire will remain deflected by the field as long as there is current. How great is the deflection depends on the rate of electron flow in amperes and on the strength of the magnetic field. The greater the current and the stronger the field the farther the wire is deflected.

The direction in which the wire and electron flow are deflected depends on the relations between direction of electron flow and direction of field lines. If you turn the magnet upside down, thus reversing the field direction, the wire will be deflected in the opposite direction upon closing the switch. If you leave the magnet and field in their original positions and reverse the connections to the dry cell you will reverse the direction of electron flow through the field. This again will reverse the direction in which the wire and electrons are deflected out of the field.

The current-carrying wire of our experiment might represent one of the wires on the armature or rotor of an electric motor. These wires move out of fields produced by the field structure or stator structure of the motor when current flows in the conductors, and thus cause rotation of the armature or rotor. This wire might represent also the moving coil of any loud speaker of this style. The moving coil is suspended in the field of either a permanent-magnet (PM) speaker or an electromagnetic speaker. When current in the moving coil or voice coil varies at sound frequencies the coil and attached cone vibrate back and forth at these frequencies.

The electrons flowing in the wire of our experiment represent the electrons flowing in the beam of a television picture tube, from cathode to screen. As the electron beam passes through the varying magnetic field of the deflection magnets the beam is moved up, down, and sideways to travel over all parts of the "raster."

The relative directions of electron flow, field lines (north to south poles) and resulting motion or deflection of the conductor or electron beam are shown by using your *right* hand with thumb, forefinger, and middle finger extended at right angles to one another. With the forefinger pointing in the direction of the field lines and the middle finger pointing in the direction of electron flow, the thumb will point in the direction which the conductor or electron beam is deflected out of the field. The direction of deflection always is at right angles to both the field lines and the electron flow.

Self-induction.—Our next experiments will be with the apparatus of Fig. 12-12. Connected in series with one another are a small dry battery, an iron-cored choke coil, and a switch. Across the switch or in parallel with the switch is a high-resistance voltmeter. The circuit is shown more clearly by Fig. 12-13. When the switch is closed the coil carries a current proportional to battery voltage divided by coil resistance. At the same time the closed switch is short circuiting the meter so that the meter reads zero, as in the photograph.

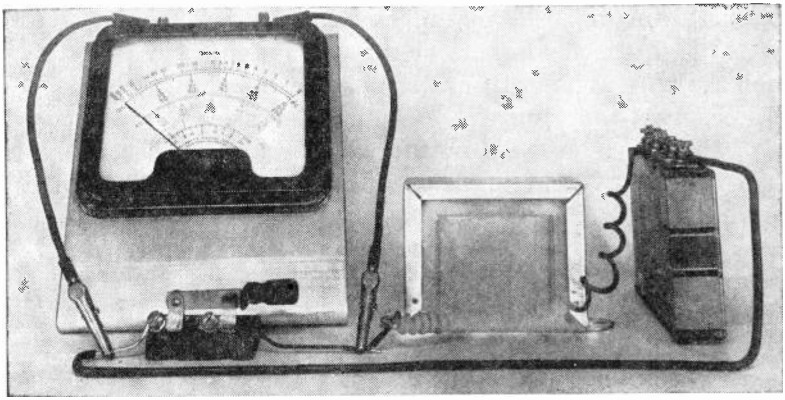

Fig. 12-12.—Experimental setup for observing some effects of self-induction.

When you open the switch, as in Fig. 12-14, the high resistance of the meter is placed in series with the battery and coil. Because of the high resistance the coil current drops nearly to zero, and the meter reads the voltage of the battery.

To perform the experiment, close the switch, watch the meter pointer, and then open the switch with the quickest possible motion. Note the point on the meter scale to which the pointer rises. The maximum reading will be higher than the battery voltage. This higher reading is due partly to the swing of the meter move-

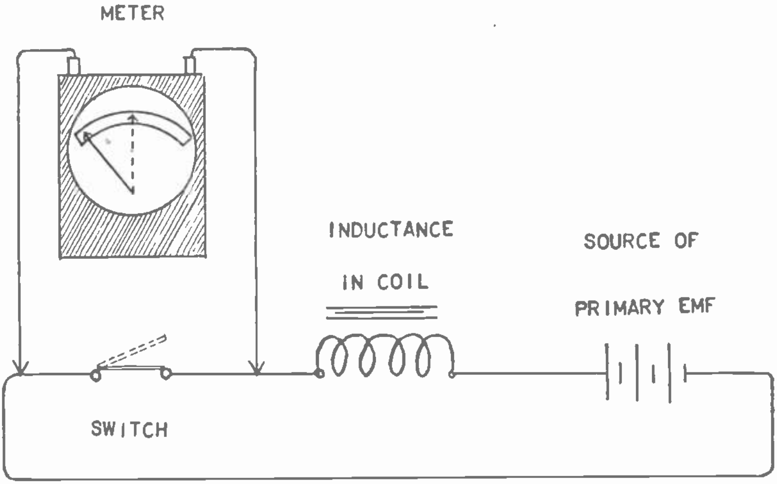

Fig. 12-13.—Circuit of the apparatus illustrating self-induction.

ment, since no ordinary meter is fully damped, and due partly to "inductive kick" of emf induced in the coil.

To check the amount of voltage overshoot due to counter-emf, disconnect one side of the coil and connect the meter directly to

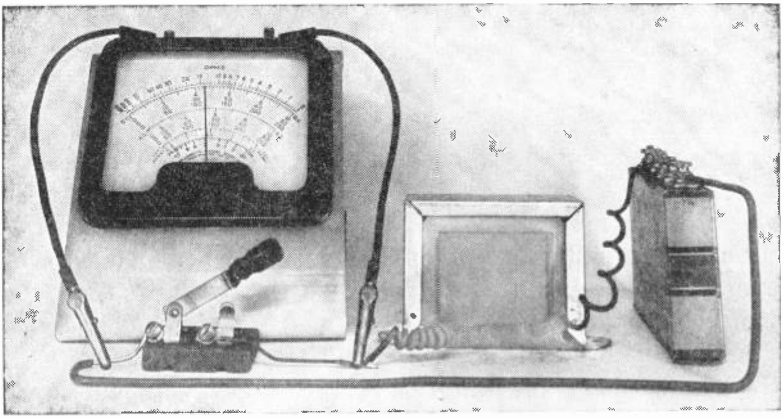

Fig. 12-14.—Opening the switch drops coil current nearly to zero and allows the meter to read applied voltage.

the battery, as in Fig. 12-15. Again close and open the switch while watching the highest point on the scale reached by the meter pointer. This maximum reading will be less than with the coil in circuit.

When current in the coil is suddenly decreased, by opening the switch, the coil momentarily furnishes an emf which is greater than the battery voltage. Because the voltage then indicated by the meter is greater than the battery voltage we know that the coil emf is acting in the same direction as the battery emf.

The reasons for this performance are as follows: First, we know that current in a coil produces a magnetic field around the coil. Therefore, while the switch is closed there is a magnetic field around the coil being used in our experiment. We know also that a moving magnetic field induces emf in a conductor through which the field moves. The field which is around the coil with the switch closed will move when the switch is opened. The field moves because it disappears, its lines shrink back into the coil and in doing so the lines cut through the coil conductor. This cutting of the lines of force through the conductor induces emf in the coil.

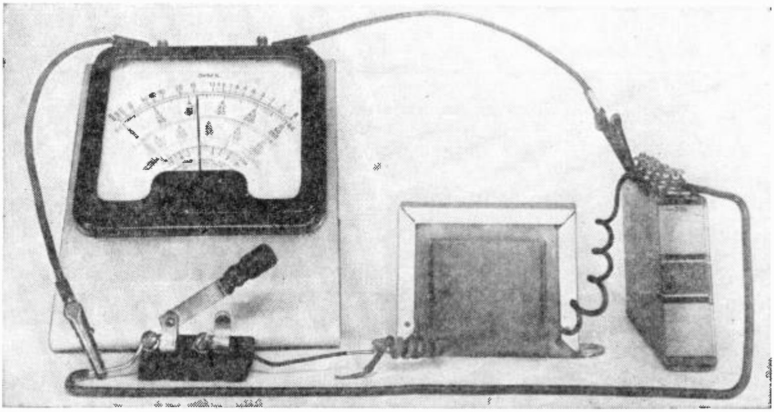

Fig. 12-15.—With the coil out of circuit there will be no "inductive kick."

This induced emf is greater than the battery voltage because of the speed with which the field lines move back through the coil conductor when the field suddenly collapses. We know that any induced emf is proportional to the rate of cutting of magnetic field lines and the conductors. When the field suddenly shrinks back through the coil conductors there are a great many cuttings per second, and a proportionately high induced emf in the coil.

The shrinkage of the magnetic field which induced the emf results primarily from a change of current in the coil. The current changes from maximum to nearly zero when the switch is opened. The *action* by which any change of current in a conductor induces an emf in that same conductor is called *self-induction.*

The *ability* of a conductor to permit self-induction is called *self-inductance.* Usually we say that the property of a circuit or coil by which a change of current induces an emf in the same circuit or coil is the property of self-inductance.

Self-inductance is measured in a unit called the *henry.* To have self-inductance as great as one henry a coil ordinarily must be provided with an iron core, which increases the magnetic flux and the rate of cutting between field lines and conductors. Coils with no cores, called air-core coils, or with cores of any substances other than iron, usually have self-inductances measured in *millihenrys* (thousandths of a henry) or in *microhenrys* (millionths of a henry).

A circuit or coil possesses one henry of self-inductance when a change of current at the rate of one ampere per second induces an emf of one volt. A change at the rate of one ampere per second would mean, for example, a decrease from three to two amperes during one second of time, or an increase from two to three amperes during one second.

All conductors, even straight wires, possess self-inductance. This is because a change of current in any conductor causes either an expansion or contraction of the magnetic field around that conductor. Then the field lines move outward or inward through the conductor material and induce emf in the material.

The emf of self-induction always acts in such direction or polarity as to oppose the *change* of current which is the cause of induction. We have just seen that decrease of current induces an emf acting in the same direction as the battery emf which was causing the original current. This emf of self-induction tries to keep the current flowing, it opposes the decrease of current. Here we have the explanation of sparking or arcing at switch contacts which open an inductive circuit — the self-induced emf is strong enough to force current to continue through the gap formed as the switch contacts first separate.

Inductive Time Constant.—The rule about the direction or polarity of induced emf applies also when current increases. While current is increasing, the self-induced emf acts in such direction as to oppose the increase. This comes about because the magnetic field is expanding while current increases. The field lines are moving outward through the coil or other conductor, whereas when current is decreasing there is inward movement of the field lines. This reversed motion of the field lines naturally reverses the direction or polarity of the induced emf.

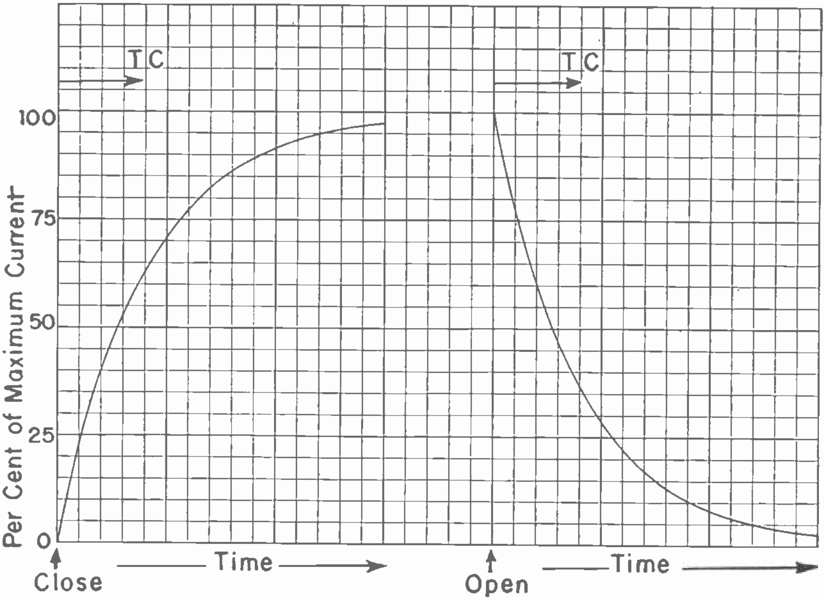

Fig. 12-16.—The manner in which current increases and decreases in a circuit containing inductance.

With the coil out of circuit, as in Fig. 12-15, closing of the switch permits current to instantaneously reach the maximum value determined by battery voltage and circuit resistance. In resistance alone there is no emf induced by changes of current and there is nothing to oppose the change. Resistance does limit the current to some certain maximum value, but it does not hinder reaching that value instantaneously.

But with the coil in circuit, Fig. 12-14, the current does not immediately reach its full or final value upon closing of the switch. The opposing emf of self-induction acts against battery voltage, and the actual increase of current is as at the left in Fig. 12-16. At the instant the switch is closed there is rapid increase of current, but the rate of increase then slows down.

The time during which current increases from zero to 63.2 per cent of its maximum final value is the *inductive time constant* of the coil or circuit. This is the period of time from the start of current until the vertical time line *TC* on the graph.

The time constant, in seconds, of a circuit containing self-inductance and resistance is found from dividing the number of henrys self-inductance by the number of ohms resistance.

Time constant, seconds = henrys/ohms

The resistance which affects the inductive time constant is the total resistance of the entire circuit. It includes the resistance of the coil, the connections, and the source.

At the right in Fig. 12-16 is shown how current decreases after the instant at which battery voltage or other primary emf is removed from a circuit containing self-inductance and resistance. Current does not fall instantaneously to zero, but decreases gradually as the self-induced emf acts to oppose the decrease. Here the time constant is the period during which the current decreases by 63.2 per cent of its initial maximum value, it is the time lasting to the vertical line marked *TC*. For any given circuit the time constant is the same number of seconds or fraction of a second for both increase and decrease of current.

Mutual Induction.—In Fig. 12-17 we have one winding of a small iron-core transformer connected in series with a dry cell and a switch, and have the other winding connected to the zero-center current meter. The switch is open, there is no current in the winding connected to the dry cell, and the meter reads zero.

In Fig. 12-18 the switch has been closed. Immediately following the instant of closing there will be an increase of current from zero to maximum value in the transformer winding connected to the dry cell. We shall call this winding the primary of the transformer. This change of current from zero to maximum causes an expanding magnetic field around the primary winding. The other winding, called the secondary, is around the primary winding and on the same iron core. The lines of the expanding magnetic field cut through the turns of the secondary winding and induce an emf in the secondary. This emf induced in the secondary causes current to flow in that winding and in the meter to which it is connected.

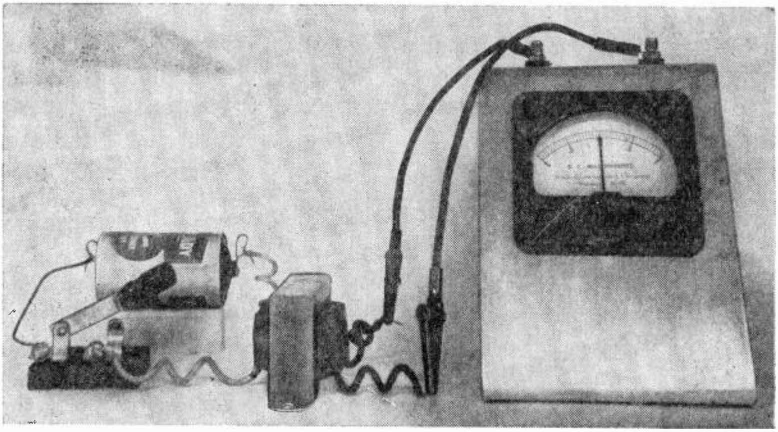

Fig. 12-17.—With no CHANGE of current in a transformer primary there is no emf induced in the secondary winding.

The meter pointer may swing in either direction, as shown by broken lines on the dial. The direction of swing depends on which way the dry cell is connected into the primary circuit, and on which end of the primary winding is connected to the cell. In any event, the meter pointer will immediately return to zero. Emf and current are induced in the secondary winding only while there is *change* of current in the primary winding, only while there is movement of the magnetic field through the secondary. Steady current and the resulting stationary field cause no induction.

Earlier we looked at some results of self-induction. Now we are looking at *mutual induction.* Mutual induction is the action which induces emf in one circuit (or coil) when there is change of current in another nearby circuit (or coil). The conductors between which there is mutual induction need not be coils, nor need they be very close together as in a transformer. There will be mutual induction and induced emf in one conductor whenever magnetic lines of force from some other conductor cut through the first one. As you can imagine, this may lead to plenty of trouble where circuits thus "couple" when we don't want them to do so.

When you open the switch in the primary circuit the meter pointer will swing in a direction the opposite of that in which it moves as the switch is closed. When the switch is opened there is decrease of primary current and the magnetic lines shrink back through the secondary winding. When the switch is closed there is increase of primary current and the magnetic lines move outward. This reversal of field motion reverses the direction of emf and current induced in the secondary winding and indicated by the meter.

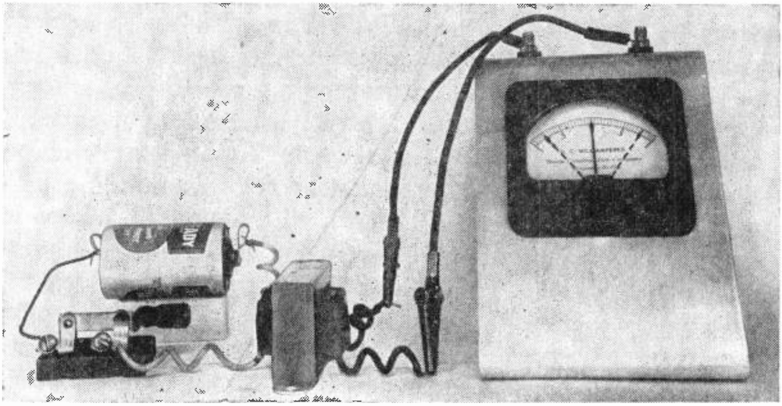

Fig. 12-18.—Closing the switch causes change of primary current, and there is mutual induction.

When we have two circuits close enough together to allow a changing magnetic field around one circuit to induce emf in the other circuit we have mutual induction. But at the same time there is self-induction in the first circuit. The emf's of self-induction in the primary winding of the transformer oppose every change of current in that winding just as though the secondary winding were not present. We always have self-induction in every circuit wherein there is changing current. We have mutual induction when there is another circuit near enough to be affected by the changing magnetic field.

The property of circuits by which either may induce an emf in the other is called *mutual inductance.* Mutual inductance, like self-inductance, is measured in henrys, millihenrys, or microhenrys. Mutual inductance in henrys is equal to the number of volts emf induced in one circuit by a current changing at the rate of one ampere per second in the other circuit.

Energy in Magnetic Fields.—While current flows in a circuit containing inductance the moving electrons are losing energy. Part of the energy is used for overcoming resistance, and produces heating of the conductors. The remaining loss of energy is due to overcoming the induced emf's which oppose every change of current. This part of the energy goes into the building up of magnetic fields around the conductor or coil. Although this energy is lost so far as the electrons are concerned, it reappears in a new form — in the magnetic field. There is energy in a magnetic field just as there is energy in an electrostatic field.

When current decreases and the magnetic field shrinks, energy from the field goes back into the electrons. This returned energy becomes the emf which acts in such direction as to keep the current flowing. It is the emf which prevents current in an inductive circuit from instantly decreasing to zero when externally applied voltage is removed, and which causes the more gradual decrease shown at the right in Fig. 12-16.

Measured in watt-seconds, the energy which exists in a magnetic field around a steady current is equal to half the product of inductance and the square of the current, thus:

$$\begin{array}{c}\textit{Energy,}\\ \textit{watt-seconds}\end{array} = \frac{\textit{inductance, henrys} \times (\textit{current, amps})^2}{2}$$

Alternating Currents.—You know, of course, that an alternating current is one in which free electrons flow first one direction and then the opposite direction, and that an alternating emf or voltage is one which acts first in one polarity and then in the opposite polarity. It will be well to check over a few of the more important facts associated with such currents and emf's.

An alternating emf would be induced, as in Fig. 12-19, in a conductor rotating at constant speed through a uniform magnetic field. The emf would alternate or reverse in direction because, during the half-circle from *A* to *E*, the conductor cuts across the field from right to left, then cuts across from left to right during the other half-circle from *E* back to *A*.

The alternating emf thus induced or generated would be of the ideal form called a *sine wave* emf. There would be zero emf while the conductor travels parallel with the field lines at *A* and *E*, without cutting across the lines. The emf would increase to maximum value at *C* and *G* where there is the greatest rate of cutting. While the conductor travels around the full circle the emf goes from zero to maximum in one polarity and back to zero, then to maximum in the opposite polarity and again back to zero.

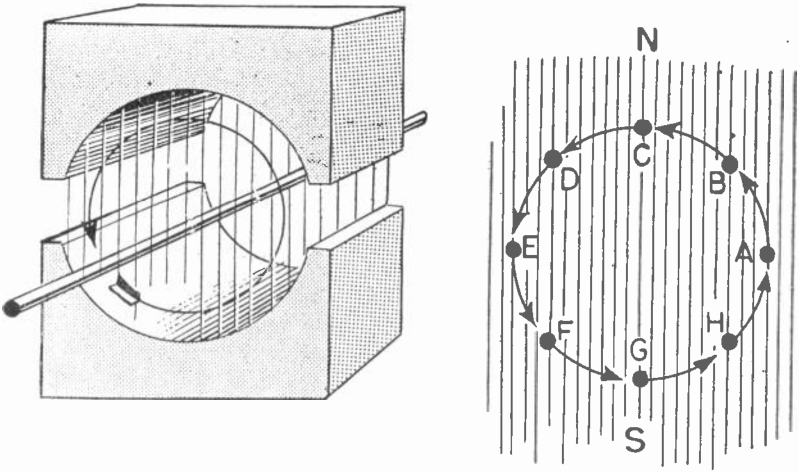

Fig. 12-19.—How a sine-wave emf is induced or "generated" in a conductor.

This double alternation of emf is called one *cycle*. Were the conductor part of a closed circuit there would be corresponding double alternations of current or electron flow caused by the emf. The changes of either emf or current during one cycle usually are represented by a rising and falling curve as in Fig. 12-20. Here the peak value or maximum value in each polarity is assigned the arbitrary value of 1.000. These peak values are reached only momentarily twice during each cycle, while during other parts of the cycle the values vary all the way down to zero.

Were this alternating current used for heating it is obvious that the heating effect could not equal that of a steady current which remains at the maximum value. Rather the heating effect would equal that of a steady current having a value of only 0.707 of the peak. Consequently we say that the *effective value* of a sine-wave alternating emf or current is equal to 0.707 of its peak value, as marked on the graph. The effective value sometimes is called the root-mean-square value, abbreviated r-m-s value.

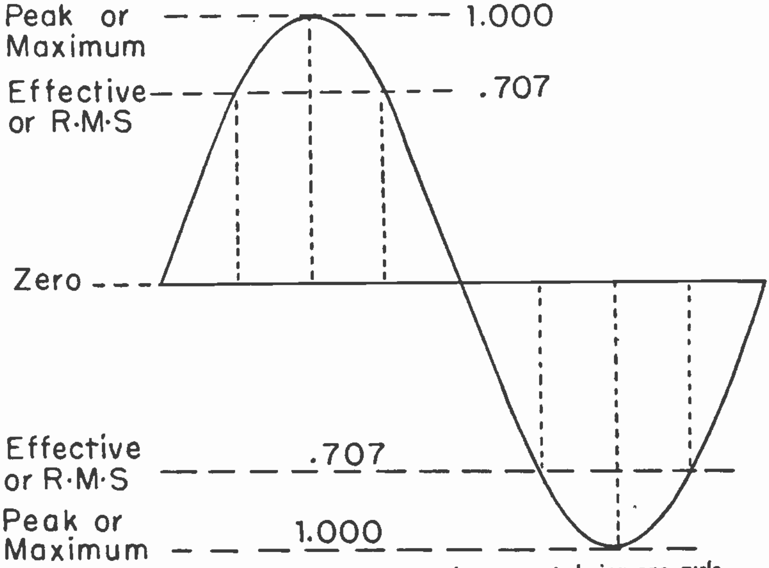

Fig. 12-20.—The change of alternating emf or current during one cycle.

Unless definitely stated otherwise it always is effective or r-m-s value that is referred to when talking about alternating emf's and currents. All ordinary meters for alternating voltages and currents indicate effective values, not peak values. To determine the peak value corresponding to a measured effective value of sine wave voltage or current, multiply the effective value by 1.414.

Reactances.—Earlier we performed experiments showing that every change of current is opposed by emf's of self-induction, that these emf's oppose both increase and decrease of current. An alternating current is continually increasing and decreasing, so it is continually opposed by the emf's or self-induction which tend to reduce the alternations and thus to reduce the value of the alternating current.

Here we have a kind of opposition to alternating current which is in addition to the resistance opposing all current. This opposition which exists only for alternating or changing current, and which is due to emf's of induction, is called *inductive reactance.* Reactance is measured in ohms, just as is the opposition of resistance. A given number of ohms of inductive reactance has exactly the same effect in limiting alternating current as has an equal number of ohms of resistance.

The number of cycles of alternating emf or current which occur during one second is called the frequency of the emf or current in cycles per second, usually spoken of simply as "cycles" with the "per second" omitted. High frequencies are specified in kilocycles (thousands of cycles) or in megacycles (millions of cycles) per second.

Inductive reactance increases directly with frequency, because the greater the frequency the more rapid are the changes of current, the greater become the number of magnetic line cuttings per second, the greater are the opposing emf's. Inductive reactance increases also directly with self-inductance, because the greater the inductance the stronger are the opposing emf's. Here is a formula for inductive reactance in ohms.

$$\begin{matrix}\textit{Inductive} \\ \textit{reactance, ohms}\end{matrix} = \begin{matrix}\textit{frequency,} \\ \textit{cycles}\end{matrix} \times \begin{matrix}\textit{inductance,} \\ \textit{henrys}\end{matrix} \times 6.2832$$

In Fig. 12-21 we have, in a series circuit, the secondary winding of a transformer, a small coil with an iron core, and a meter which measures alternating current. The primary of the transformer is connected to a 60-cycle a-c (alternating-current) power line. The continually changing alternating current in the primary induces a continually changing alternating emf in the secondary, and this secondary emf causes current to flow in the secondary, the coil, and the meter — as indicated by the meter reading. The frequency in the secondary is the same as in the primary of the transformer.

Each numbered division on the scale of the a-c current meter indicates about 12 milliamperes. The pointer stands at about 2½ on the scale, indicating an effective current of about 30 milliamperes. This is the current permitted by the combined inductive reactance and resistance of the circuit containing the meter.

In Fig. 12-22 enough iron has been added to the core of the coil to provide a complete path all the way around the outside of the coil and through its center opening. This more complete core allows an increase of magnetic field strength which, in turn, increases the emf's which oppose the alternating current and thus increases the self-inductance of the coil. The result of more self-inductance is greater inductive reactance. The increased reactance drops the current to about 1½ units or to about 18 milliamperes. The resistance of the circuit is the same as before, because none of the current-carrying conductors have been changed. The only change has been in self-inductance and in inductive reactance.

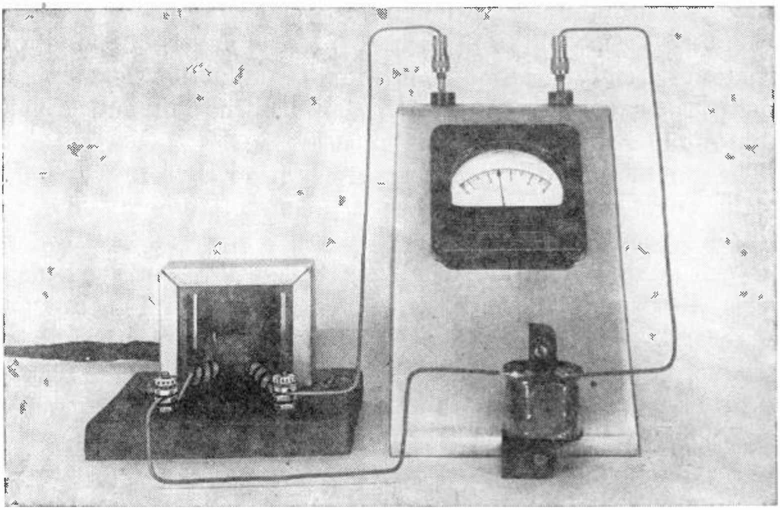

Fig. 12-21.—Inductive reactance in the coil, combined with resistance in the entire circuit, limits the alternating current.

Capacitive Reactance.—Alternating current will flow in a circuit containing a capacitor. The reason is shown in an elementary way by Fig. 12-23. Here the emf of the source is represented as reversing its polarity between the two diagrams, just as would a source furnishing alternating emf.

In the diagram at the left the left-hand terminal of the source is negative. Electrons will flow away from this terminal, as indicated by arrows, and enter the left-hand plate of the capacitor. At the same time, other electrons will leave the right-hand plate and pass to the positive terminal of the source.

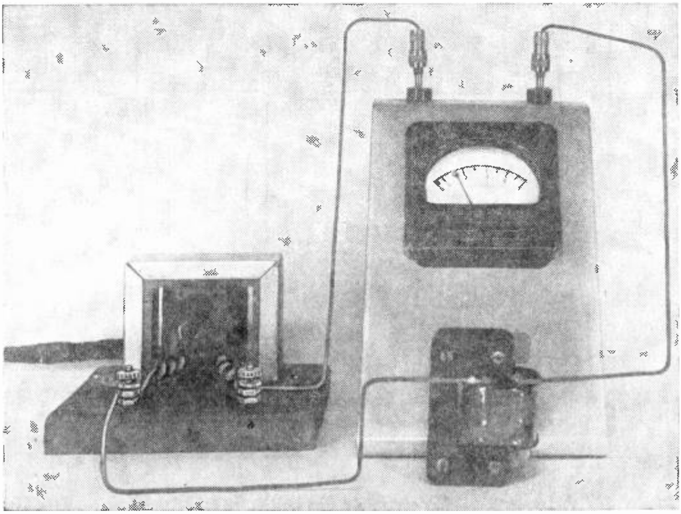

Fig. 12-22.—Adding iron to the core of the coil increases inductive reactance and decreases the current.

In the diagram at the right, where the source polarity is reversed, electrons previously added to the left-hand plate of the capacitor now flow away from this plate and to the positive terminal of the source. At the same time there is flow of electrons from the negative terminal of the source into the right-hand plate of the capacitor.

Every time the emf of the source reverses, there is a surge of electrons out of one capacitor plate, through the source, and into the opposite capacitor plate. The electron flow or current alternates, flowing first one way and then the other. We have an alternating current, although no electrons can pass all the way through the insulating dielectric of the capacitor. The alternating current or alternating electron flow simply charges and discharges the capacitor plates.

It is quite evident that the larger the capacitor plates, the thinner the dielectric, and, in general, the greater the capacitance, the greater will be the electron flow and alternating current in the circuit. Greater electron flow means less opposition to flow.

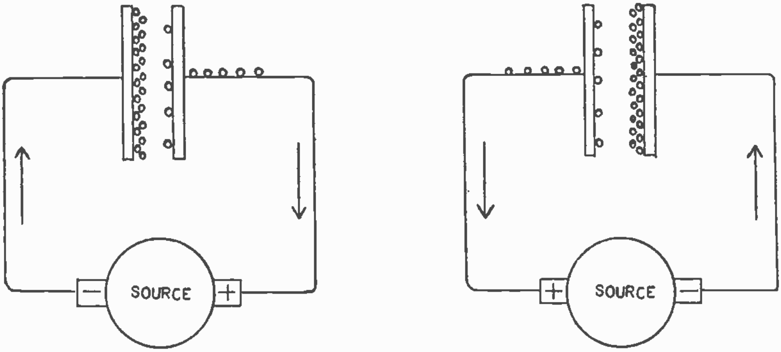

Fig. 12-23.—Alternating current flows into and out of a capacitor, but not through the dielectric.

Opposition to flow of alternating current in a capacitor is called *capacitive reactance*. Then we may say that an increase of capacitance reduces capacitive reactance, because it allows more current to flow.

Capacitive reactance is reduced also by an increase of frequency. When frequency increases there are, of course, a greater number of charges and discharges of the capacitor during each second of time. Every charge and discharge means a flow of a certain quantity of free electrons past each point in the circuit. And we know that the greater the quantity of electrons passing any one point during one second the greater is the current in amperes. Thus a greater frequency allows a greater current to flow in the circuit containing the capacitor, and more current means that there must be less capacitive reactance.

Capacitive reactance, like all other kinds of opposition to current, is measured in ohms. A given number of ohms of capacitive reactance acts to limit alternating current just as does an equal number of ohms of resistance. If we measure frequency in cycles (per second) and measure capacitance in farads, the formula for capacitive reactance is this:

$$\text{Capacitive reactance, ohms} = \frac{1}{\text{frequency, cycles} \times \text{capacitance, farads} \times 6.2832}$$

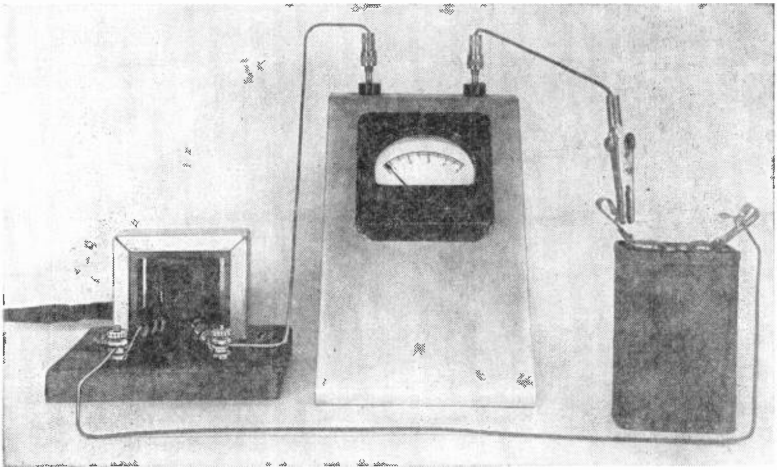

Fig. 12-24.—Reactance at 60 cycles is great enough to allow only a little current through even a large capacitance.

In Fig. 12-24 we have in a series circuit the secondary winding of our small transformer, the a-c current meter, and a capacitor whose capacitance is 2 microfarads. At the low frequency of 60 cycles supplied from the building power line the reactance of 2 microfarads is about 1,325 ohms. This very considerable reactance limits the alternating current to a small value, as indicated by the meter.

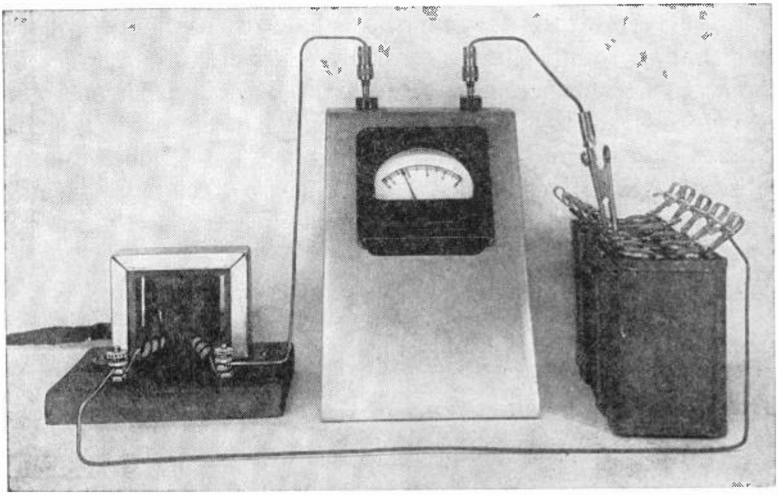

Fig. 12-25.—Adding capacitance reduces capacitive reactance, and allows alternating current to increase.

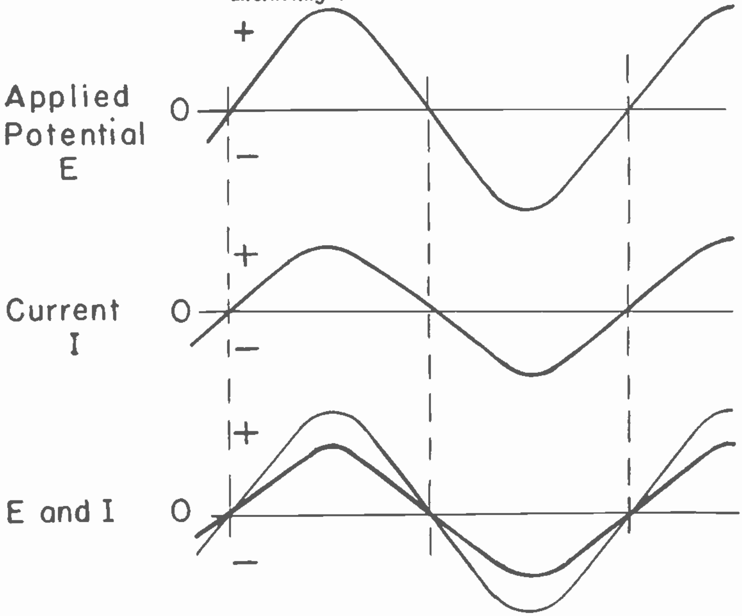

Fig. 12-26.—Alternating current in a resistance is in phase with the potential or voltage.

In Fig. 12-25 we have connected in parallel with the first capacitor four more having capacitances of 2 microfarads each. The total capacitance of five 2-mfd capacitors in parallel is 10 mfds. Earlier it was stated that an increase of capacitance reduces capacitive reactance. Here we have the proof, for the greater capacitance allows a much greater current to be indicated by the meter, and more current always means less reactance when other factors remain unchanged.

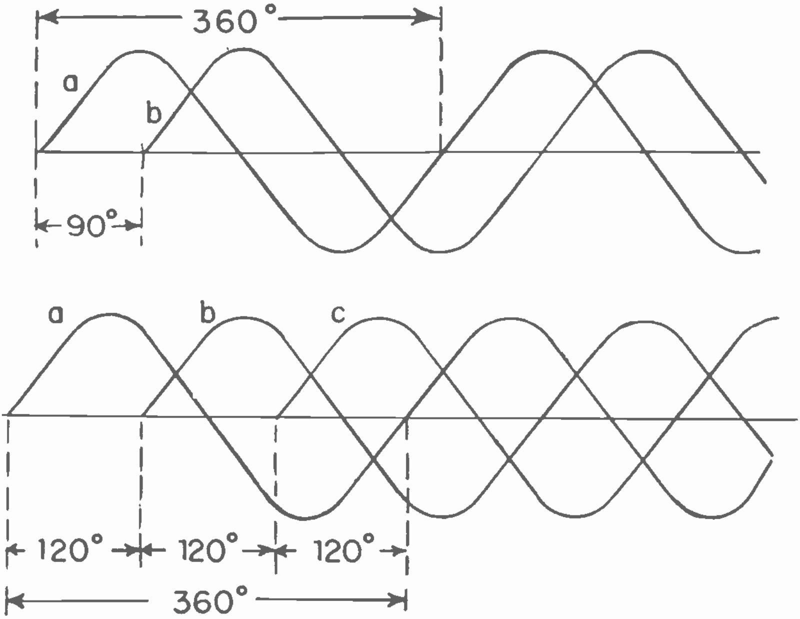

Fig. 12-27.—Currents or voltages which are out of phase do not go through similar values at the same instant of time.

Phase Relations.—The upper curve of Fig. 12-26 represents an alternating potential, emf, or voltage, in a circuit containing only resistance, no inductance or capacitance. The middle curve represents the resulting alternating current. Voltage and current in a resistance always pass through their zero values at the same instants of time, they reach peak positive values at the same instants, and peak negative values at the same instants. Voltage and current are exactly in step or in time with each other. When this is the case we say that the voltage and current are *in phase.*

Phase has much the same meaning as time when the time refers to instants at which alternating voltages, currents, or both, go through certain values. The lower curve shows voltage and current together.

If two alternating voltages, two alternating currents, or a voltage and a current are not in phase then they are said to be *out of phase.* This condition is represented in Fig. 12-27. The time differences or phase differences may be little or great. In Fig. 12-28 one of the quantities goes through its peak positive value while the other goes through its peak negative value. When this happens, the two quantities (voltages, currents, or both) are said to be in *opposite phase.*

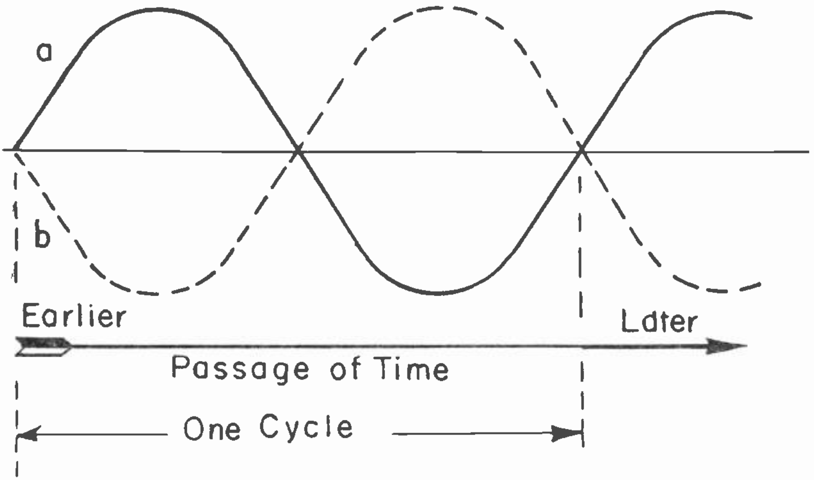

Fig. 12-28.—Here are represented alternating currents or voltages which are in opposite phase.

Phase differences usually are measured in electrical degrees. We consider one complete cycle as consisting of 360 electrical degrees, just as the circle traveled by the conductor in Fig. 12-19 consists of 360 angular degrees.

Fig. 12-29 shows important phase relations in a circuit assumed to contain only inductance and inductive reactance, with no resistance. Curves are drawn for applied potential, which is the same as primary emf or applied voltage, also for the induced emf of self-induction, and for the alternating current. The induced emf is in opposite phase to the applied potential, there is a phase difference of 180 electrical degrees or a half-cycle.

The emf of self-induction so retards the alternating current that, as shown, the positive peaks of current occur 90 degrees after the positive peaks of applied potential, and negative peaks of current occur 90 degrees after negative peaks of voltage. In a circuit containing only inductance and inductive reactance the alternating current *lags* the alternating voltage by 90 degrees or by a quarter-cycle.

Fig. 12-30 shows important phase relations in a circuit containing only capacitance and capacitive reactance, with neither inductance nor resistance. The broken-line curve marked *Capacitor Voltage* represents the voltage difference between opposite plates of the capacitor as the plates alternately charge and discharge. This capacitor voltage always opposes the applied potential or applied voltage, just as the emf of self-induction opposes changes of current in an inductive circuit. Consequently, the capacitor voltage is in opposite phase to the applied potential or voltage.

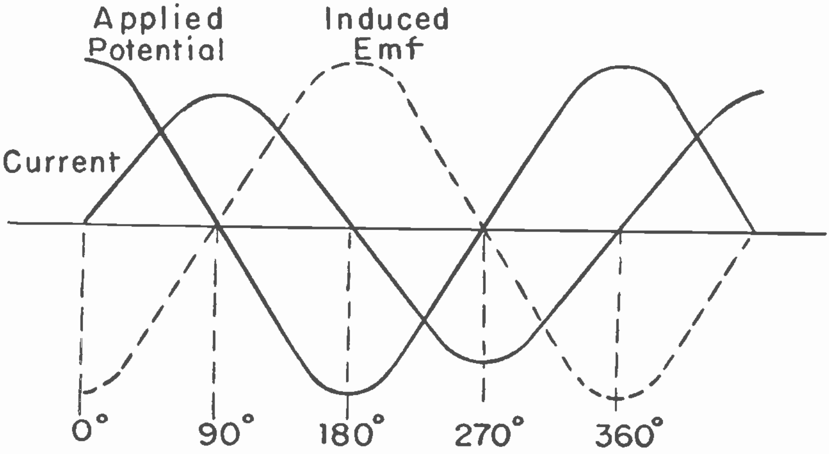

Fig. 12-29.—In a circuit containing only inductance the alternating current lags the voltage by 90 degrees.

The capacitor voltage acts on electron flow or current in such manner that the alternating current flowing into and out of the capacitor plates reaches its peak values before the corresponding peaks of applied potential or voltage. As shown by the curves, the alternating current in a circuit containing only capacitance *leads* the applied voltage by 90 electrical degrees or by a quarter-cycle.

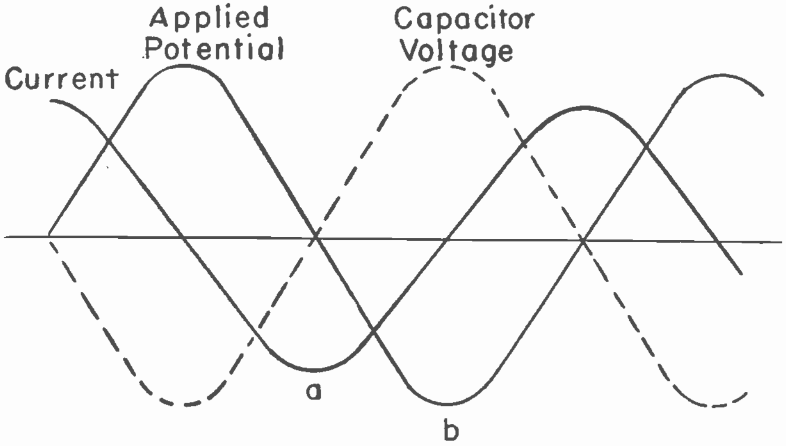

Fig. 12-30.—In a circuit containing only capacitance the alternating current leads the applied potential or voltage by 90 degrees.

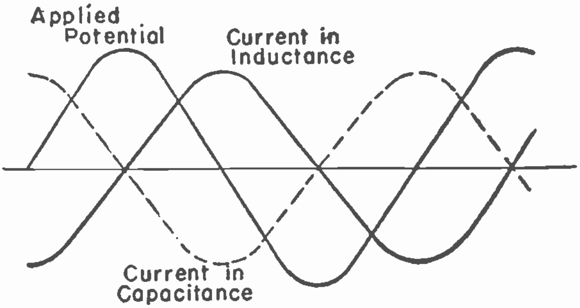

Fig. 12-31.—Lagging inductive current and leading capacitive current are in opposite phase with reference to each other.

In Fig. 12-31 we have curves for applied potential or voltage, for lagging current in an inductance, and for leading current in a capacitance. The two currents are in opposite phase with reference to each other. one reaches its peak positive value while the other reaches its peak negative value. This means that, were the two currents of equal values in the same circuit, there would be no current at all. They would cancel or balance each other. In any actual circuit there still would be current, for every circuit contains resistance. The real significance of the opposite currents is that they indicate oppositely acting reactances. If the inductive reactance in ohms is exactly equal to the capacitive reactance in ohms, one reactance makes the current lag just as much as the other makes it lead. Then there is neither lag nor lead. The reactances balance and cancel, and the only opposition to current is that due to resistance. Then we have the condition called *resonance*, which is something to be examined during the following chapter.

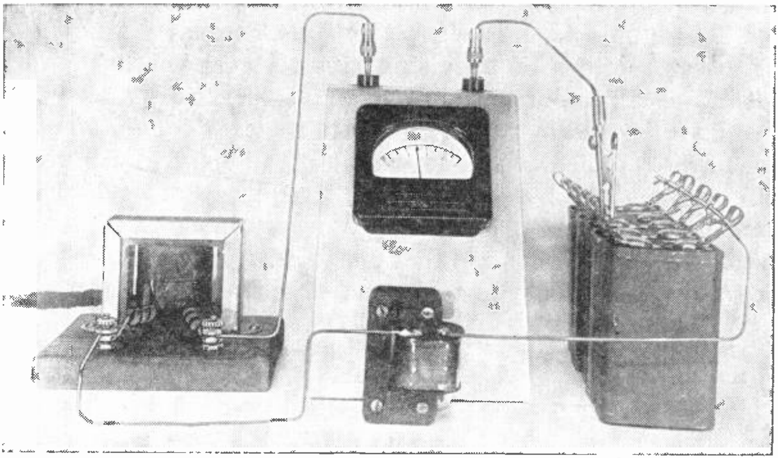

Fig. 12-32.—Inductive and capacitive reactances are equal, they cancel, and only resistance remains to oppose the alternating current.

Before going on we may look at one example of resonance. In Fig. 12-32 we have the transformer and meter used for earlier experiments. But now we have the coil with its completed core as used for Fig. 12-22 and also the five capacitors used for Fig. 12-25, with the coil and capacitors in series. Look back at the currents indicated by the meter with only the coil in circuit and with only the capacitors in circuit. In both cases the reactances limit the currents to about 20 milliamperes. Yet when we have the two reactances in series with each other, Fig. 12-32, the current increases to about 30 milliamperes. This is because the inductive reactance of the coil is practically equal to the capacitive reactance of the capacitors. The opposite kinds of reactance very nearly cancel each other, and the current is limited only by the remaining resistance of the circuit.

Technicians who work only with the smaller types of sound radios seldom encounter service problems which arise from faulty phase relations. But in high fidelity sound receivers and in public address systems the faithful reproduction of sound is dependent in great measure on maintaining the correct phase of voltages and currents throughout the amplifiers. In f-m radio receivers and in the sound sections of television receivers, which operate from f-m signals, the production of audible sound from the transmitted and amplified signals depends almost entirely on changes of phase.

In other sections of television receivers the matter of phase relations is all-important. For example, practically all modern TV receivers contain rather intricate systems for automatically preventing rapid sidewise movement of the pictures. These automatic controls for horizontal sweep frequency depend for their operation on combining two voltages in certain very definite phase relations. You must not feel that phase relations are merely something theoretical. They are of great practical importance.

Chapter 3

RESONANCE AND TUNING

By choosing certain values of inductance, capacitance, and resistance, and by varying these values in suitable ways, we may select from all the signals simultaneously reaching the antennas of our receivers only the one signal that we wish to reproduce. Then other circuits containing inductance, capacitance, and resistance in particular combinations strengthen the selected signal while reducing the strength of other unwanted signals.

These circuits which select and amplify desired signals in standard broadcast radios operate at frequencies of 450,000 to 1,600,000 cycles, or at 450 to 1,600 kilocycles per second. For reception of f-m sound broadcasts the frequencies extend to 108,000,000 cycles or 108 megacycles per second. Television signals in the very-high channels 2 through 13 are at frequencies up to 216 megacycles, and in the ultra-high frequency bands they go to nearly 1,000 megacycles per second. Principles explained in following pages apply equally at all these frequencies, and in all the applications of radio, television, and electronics in general.

Current and Potentials That Oppose It.—At the top of Fig. 13-1 is represented an inductance *L* in series with a source of alternating potential. Such a source is shown by a symbol consisting of a circle enclosing a wavy line. The wavy line represents an alternating cycle. It has previously been shown that in a circuit containing only inductance, with no resistance, the counter-emf has the time relation to electron flow (current) that is shown by *C-emf* and *I* curves at the top of Fig. 13-1.

At the center of Fig. 13-1 is shown a circuit containing only capacitance *C* in series with a source of alternating potential. As previously shown, the relation of capacitor voltage and electron flow is as represented by the curves *V* and *I*.

Now supposing that we have both inductance and capacitance in series with each other and with a source of alternating potential, as at the bottom of Fig. 13-1. Because the inductance *L* and the capacitance *C* are in series there must be the same current

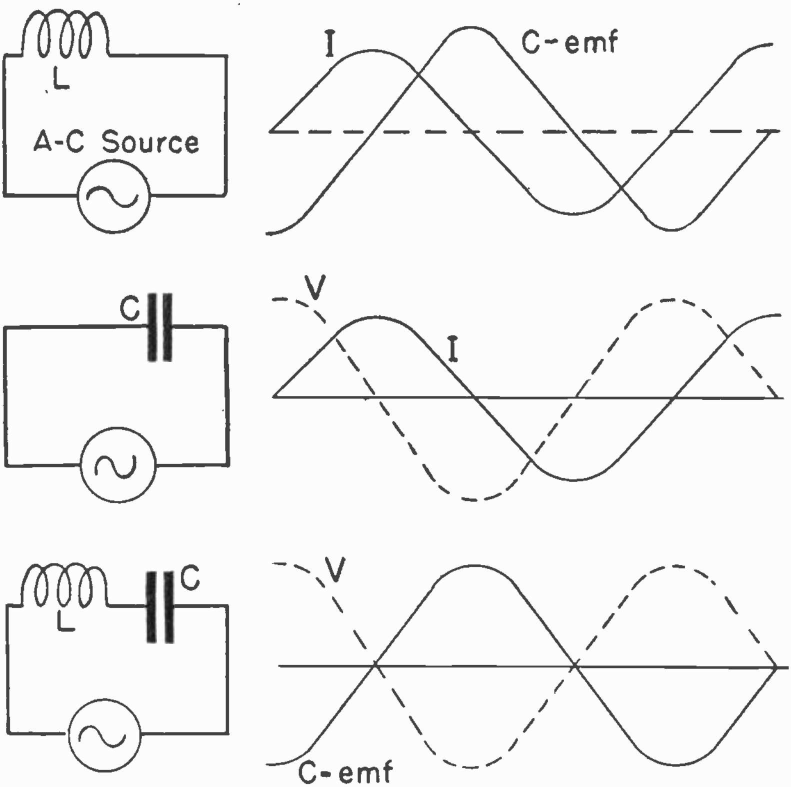

Fig. 13-1.—Potentials which accompany a current in inductance and capacitance.

in both of them, just as in any other series circuit. Then this single current will cause an induced counter-emf in the inductance and will cause a capacitor voltage in the capacitor as shown by the curves *C-emf* and *V*. These two potentials, both of which oppose changes of electron flow, act in opposite directions at the same time, and both pass through their zero values at the same time.

In Fig. 13-2 there is a series circuit containing a coil of large inductance, which gives it a large inductive reactance, and containing a capacitor of large capacitance, which gives it a small capacitive reactance. The counter-emf in the inductance of the coil and the voltage on the capacitor are proportional to the capacitive reactances of these two elements, since it is these potentials that oppose changes of flow that are responsible for the existence of the reactances. Then, as shown by the curves of the middle graph of Fig. 13-2, the counter-emf, *C-emf*, will be large in proportion to the capacitor voltage *V*, as at *a* and *b* on the graph.

Because *C-emf* and *V* act in opposite directions at the same time, the effective potential or the net potential that opposes changes of electron flow will have a value equal only to the difference between *C-emf* and *V*. This net opposing potential has a value as shown by the lower graph, where it is marked *reactive potential*. Note that this net reactive potential acts in the same direction as the C-emf in the inductance. Therefore, with the

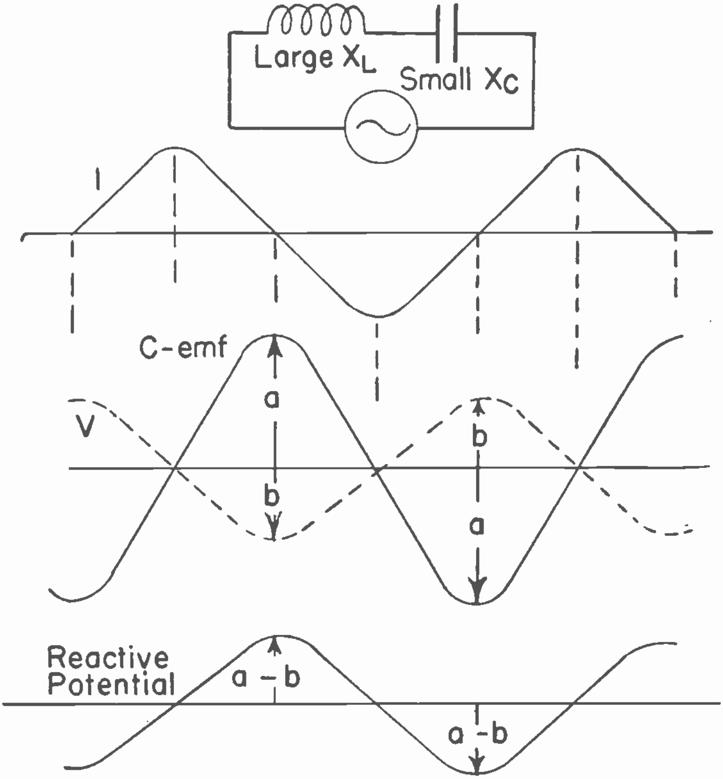

Fig. 13-2.—The potentials vary with change of reactance.

inductive reactance greater than the capacitive reactance in a circuit, the reactive potential and the net reactance will act like the potential and reactance of an inductance. The circuit will behave as though it contained only inductive reactance.

In Fig. 13-3 is represented a series circuit containing a coil of small inductance, which means small inductive reactance, and containing a capacitor of small capacitance, which means large capacitive reactance. Now the potentials opposing changes of

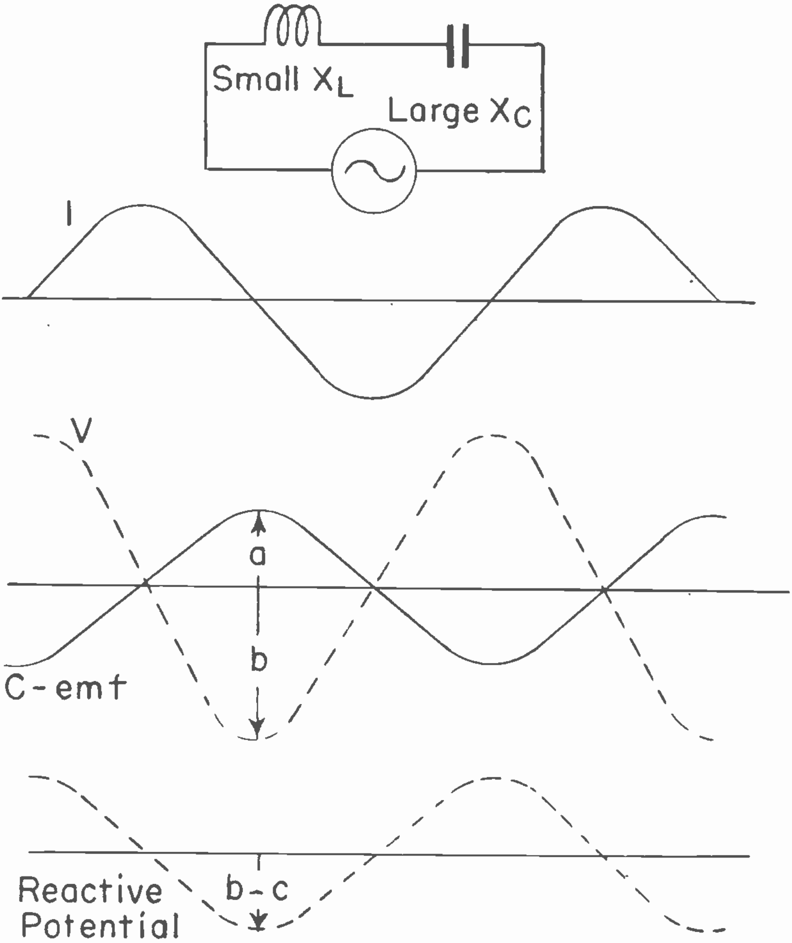

Fig. 13-3.—The greater potential exists across the capacitance.

flow will be as shown by the center graph; the capacitor voltage *V* will be greater than the counter-emf *C-emf.* The net reactive potential again will be equal to the difference between the two opposing potentials, or will be the value of capacitor voltage *a* minus the value of inductor emf *b*. The net reactive potential now acts in the same direction as the capacitor voltage *V*, so the circuit which has more capacitive reactance than inductive reactance behaves like one containing only capacitive reactance.

Resonance. — Assume now that the inductive reactance and capacitive reactance which are in series are exactly equal to each other. Then, as shown by Fig. 13-4, the counter-emf induced in the inductance will be exactly equal at every instant to the voltage on the capacitor, which is due to the charge of the capacitor. But these two forces always are acting in opposite directions at the same time. The result is that the opposition to changes of electron flow (current) which is due to inductance always is exactly counterbalanced by the opposition to changes of current which is due to capacitance. These two forces nullify each other, the difference between their opposite values always is zero, and there remains no reactive potential to oppose changes or to oppose the flow of alternating current.

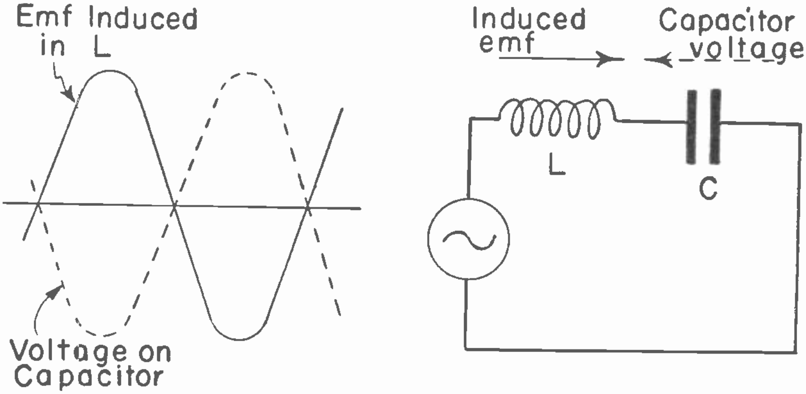

Fig. 13-4.—The opposing potentials balance each other when the reactances are equal.

This is the condition called *resonance.* Resonance exists when the inductive reactance and capacitive reactance in the same circuit are exactly equal. The reactances neutralize each other, and there is no remaining reactance to flow of alternating current. The circuits so far considered have contained only inductance and capacitance, with no resistance. But in every actual circuit there must be some resistance. At resonance, with all reactive effects cancelled, the only opposition to electron flow is that due to resistance. The amount of resistance which may be in a resonant circuit has no effect one way or the other on the frequency at which resonance occurs; that depends only on the relative values of inductance and capacitance.

Series Resonance.—When resonance occurs in a circuit wherein the inductance and capacitance are in series with each other and with the source, as in circuits so far examined, we speak of *series resonance.* Such circuits may be called series resonant circuits. Resonance occurs also in circuits wherein the inductance and capacitance are in parallel with each other. Then the condition is called parallel resonance. For the time being we shall continue to examine the actions of series resonant circuits, and farther along shall take up the actions of parallel resonant circuits.

Frequency and Resonance.—The inductive reactance of a coil or of an inductive circuit increases with increase of frequency. The capacitive reactance of a capacitor or of any capacitance decreases with increase of frequency. Therefore, as the frequency of the applied potential is gradually increased in a circuit containing inductance and capacitance, the inductive reactance will rise and the capacitive reactance will fall until, at some particular frequency, their values become equal and we have the condition of resonance.

These values, found in standard broadcast radio receivers, are such as permit simple analysis. We must not forget, however, that precisely the same principles apply in just the same way when working with the smaller inductances and capacitances, and higher frequencies, of f-m and television reception.

Fig. 13-5 shows the increase of inductive reactance and the decrease of capacitive reactance of the assumed values of inductance and capacitance when frequency is changed from 500

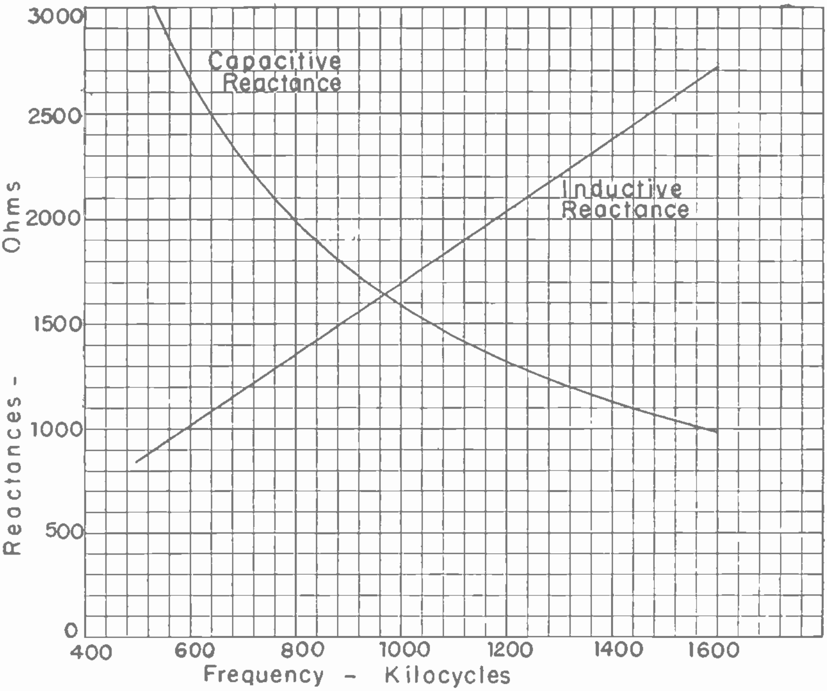

Fig. 13-5.—How the two reactances vary with change of frequency.

to 1600 kilocycles. The increase of inductive reactance is directly proportional to frequency throughout the range, but the decrease of capacitive reactance is not at a uniform rate. The values of the reactances are computed from the two formulas,

$$X_L = 0.006283 \times \text{kilocycles} \times \text{microhenrys}$$

$$X_C = \frac{159155000}{\text{kilocycles} \times \text{micro-microfarads}}$$

At a frequency of 968.5 kilocycles the two reactances are equal, and each has a value of 1643.2 ohms. Consequently, this combination of inductance and capacitance is resonant at a frequency of 968.5 kilocycles.

At each frequency the net reactance is equal either to the inductive reactance minus the capacitive reactance, or to the capacitive reactance minus the inductive reactance, depending on which is greater. Fig. 13-6 shows the net reactances as they vary with frequency; these curves representing the differences between the two reactances of Fig. 13-5. As the frequency is changed from 500 kilocycles to the point of resonance, the net reactance decreases. This net reactance is the excess of capacitive over inductive reactance, and so, at frequencies lower than that for resonance, the circuit would behave like one having capacitive reactance. As the frequency is changed from resonance upward to 1600 kilocycles, the net reactance increases. Now the net reactance is the excess of inductive over capacitive reactance, which makes the circuit behave like one having inductive reactance at frequencies higher than resonance.

Effect of Series Resistance. — The graph of Fig. 13-6 shows that the reactance of our circuit becomes zero at the resonant frequency, and, so far as reactance alone is concerned, there would be nothing to oppose an infinitely large flow of current even with the smallest applied potential. But in all actual circuits there is resistance, and when the reactance becomes zero

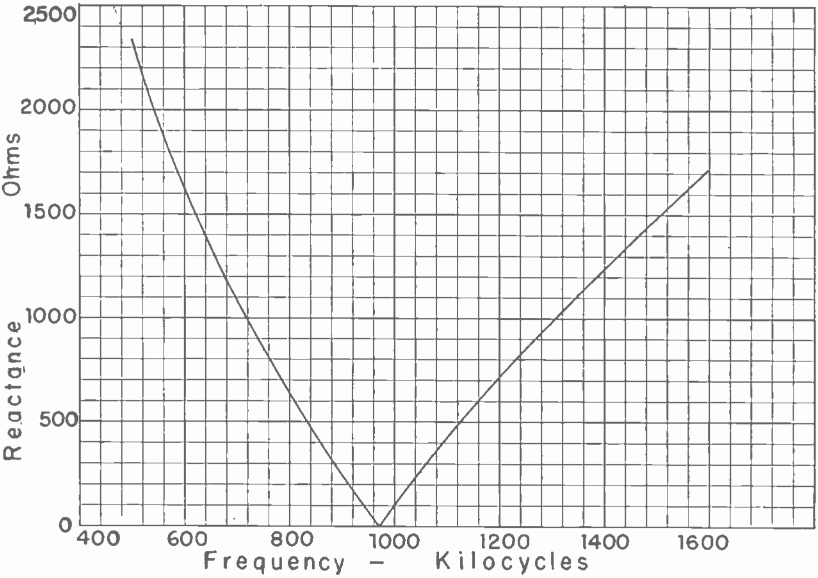

Fig. 13-6.—The net reactance becomes zero at a certain frequency.

there still is the effect of resistance to oppose the flow of electrons (current). The effect of resistance at frequencies near resonance is of great importance. There the total opposition to electron flow is that of impedance, which is the combined effect of reactance and resistance taken together. As previously shown, impedance is equal to the square root of the sum of the squares of reactance and resistance, all in ohms.

To show the effect of resistance we may consider the impedances which appear in our circuit when resistances of 5, 10 and 20 ohms are added to it in series with the inductance, the capacitance, and the source. These impedances are shown by Fig. 13-7 for frequencies from 955 to 985 kilocycles. The least impedance always occurs at the frequency of resonance which, in this case, is 968.5 kilocycles. The addition of resistance to the circuit increases the opposition to electron flow at resonance more than at any other frequency. In each of the cases shown, the minimum impedance occurs at the frequency of resonance, and at reso-

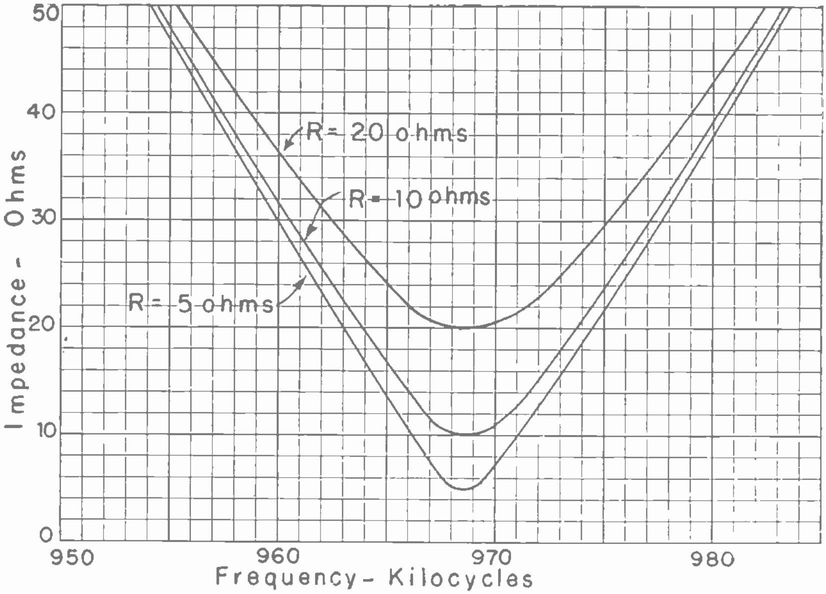

Fig. 13-7.—The impedance at resonance varies with resistance of the circuit.

nance, the value of this minimum impedance is the same as the value of the resistance in the circuit. That is, at resonance the effects of reactance are completely nullified, and only the effect of resistance remains.

The matter which is of most direct importance is that of electron flow in the series resonant circuit when some certain alternating potential is applied to it from the source. The current, in amperes, is equal to the number of volts of applied potential divided by the number of ohms of impedance. Fig. 13-8 shows electron flow in milliamperes, at frequencies between 950 and 985 kilocycles when an alternating potential of 1 volt is applied to the circuits containing 5 ohms, 10 ohms, and 20 ohms of resistance.

In the 5-ohm circuit of Fig. 13-8 the maximum current is 200 milliamperes, in the 10-ohm circuit it is 100 milliamperes, and in the 20-ohm circuit it is 50 milliamperes. The gain in current with decreased resistance in the circuit is important, but of still more importance is the difference between currents at resonance

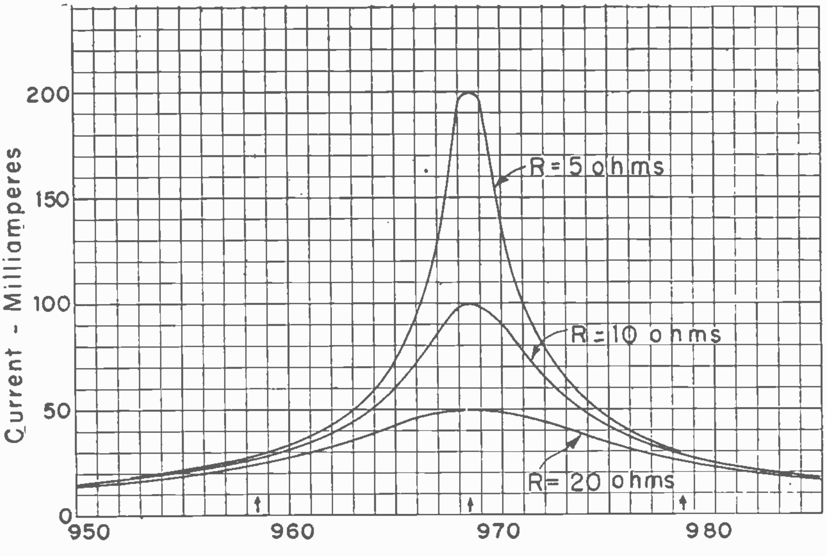

Fig. 13-8.—The current at resonance increases when there is less resistance.

and those a few kilocycles away from resonance with the several values of resistance in the series resonant circuit.

Supposing, for example, that this circuit has applied to it simultaneously equal potentials which are at the resonant frequency (968.5 kilocycles), at a frequency which is 10 kilocycles less than that for resonance, and at a frequency 10 kilocycles higher than that for resonance. Here are the amperes of flow which will result.

	At Resonance	10 kc Below Resonance	10 kc Above Resonance
5-ohm Circuit	200	29	30
10-ohm Circuit	100	27	28
20-ohm Circuit	50	25	25

With only 5 ohms resistance the off-resonance flows are only about 15 per cent of that at resonance. With 10 ohms resistance

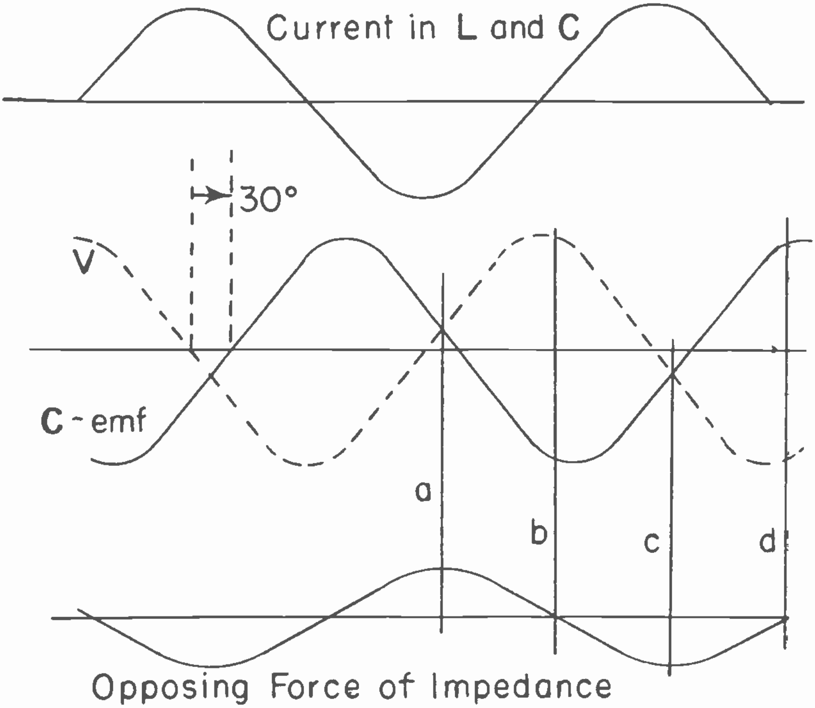

Fig. 13-9.—Resistance causes a phase difference at resonance.

the off-resonance flows are 27 to 28 per cent of the resonant flow. and with 20 ohms of resistance the off-resonance flows are 50 per cent of that at resonance. If the equal applied potentials at the three frequencies were those produced by three signals on this radio circuit, and were the resonant frequency the one to be strengthened, it is plain that the less the resistance in the series resonant circuit the greater will be the strength of the desired signal in comparison with the strengths of those which are to be weakened or rejected.

In Fig. 13-4 was shown the manner in which the emf induced in the inductance and the voltage on the capacitor are of equal magnitude and opposite phase at resonance, a condition which balances these forces that oppose changes of electron flow and leaves only the effect of resistance in the circuit. When the circuit contains resistance in addition to inductance and capacitance we have the opposing force of impedance shown by Fig. 13-7 and the flow shown by Fig. 13-8.

The reason that there is opposition to electron flow at resonance, even when the inductive and capacitive reactances are exactly equal, is shown by Fig. 13-9. Here it is assumed that there is enough resistance associated with the inductance to displace the emf induced in the inductance, which is the counter-emf marked *C-emf*, by 30° with reference to the voltage on the capacitor, *V*. Where, in Fig. 13-4, these two opposing forces were in opposite phase with no resistance present, they now have been displaced 30° with reference to each other because resistance has been introduced.

In Fig. 13-9 *C-emf* and *V* do not offset each other at every instant during a cycle. Instead we have the following conditions: At *a* and, at other similar instants in the cycle, such as *c*, both *C-emf* and *V* are acting in the same direction, which means an opposing force of impedance, shown on the bottom graph, that is equal to the sum of these two forces. At *b*, and again at *d*, *C-emf* and *V* are of equal magnitude but in opposite directions, so that they nullify each other and, at this instant, leave a zero force of impedance. But during every cycle there is some opposing force in spite of the fact that the inductive and capacitive reactances that result respectively from *C-emf* and *V* are equal. The greater the resistance associated with the inductance the greater will be the displacement between *C-emf* and *V*, and the greater will become the opposing force of impedance. Were the resistance associated with the capacitance instead of with the inductance, the curve representing capacitor voltage, *V*, would be displaced in the opposite direction, and, with the curve of *C-emf* remaining in its original position, the effect in building up impedance would be equivalent to that shown.

Voltages In Series Resonant Circuit.—The potential drop across a resistance is shown by Ohm's law to be $E = I \times R$. Across an impedance the potential drop is $E = I \times Z$. Across any opposition to electron flow (current) the potential drop is equal to the product of the flow and the opposition. It follows that, across a reactance, the potential drop in volts is equal to the product of the flow in amperes and the reactance in ohms, or, $E = I \times X$.

In the series resonant circuit that has been considered, the inductive reactance and the capacitive reactance at resonance are both equal to 1643.2 ohms. If resistance is associated with either the inductance or the capacitance, their impedances will be somewhat greater than their reactances. But, even though we consider only the reactance values, the potential drops across the inductance (coil) and the capacitance (capacitor) in a series resonant circuit may be very great. In the circuit whose performance has been followed, the electron flow at resonance is 200 milliamperes, or 0.2 ampere, when the resistance is 5 ohms. But the reactances still are 1643.2 ohms, and so the potential drops across the two elements must be equal to 0.2 (ampere) times 1643.2 ohms, or to more than 328.6 volts. This happens when the applied potential, from the source, is only 1 volt.

These very great reactive voltages in the inductance and capacitance are in opposite directions, and so they cancel each other so far as the external circuit is concerned. But the insulation of the coil and the insulation and the dielectric of the capacitor must be able to withstand a potential difference several hundred times as great as the potential difference from the source. The dielectrics of capacitors frequently are punctured by the high reactive voltages, especially in transmitting apparatus where there are large electron flows in the resonant circuits.

Parallel Resonance. — In preceding pages has been explained the behavior of series resonant circuits such as shown at *1* and *2* in Fig. 13-10. At *1* is shown the ideal series resonant circuit with only inductance and capacitance, which are in series with each other and with the source. There will also be resistance in all actual series resonant circuits, as shown at *2*.

In diagram *3* of Fig. 13-10 is shown the ideal *parallel resonant* circuit. Here the inductance *L* and the capacitance C are in parallel with each other, or are in parallel across the source potential *E*. In the parallel resonant circuit there may be resistance in the inductive branch, as at *4*, or there may be resistance in the capacitive branch, as at *5*, or there may be resistance in both branches, as at *6*. In actual parallel resonant radio circuits there

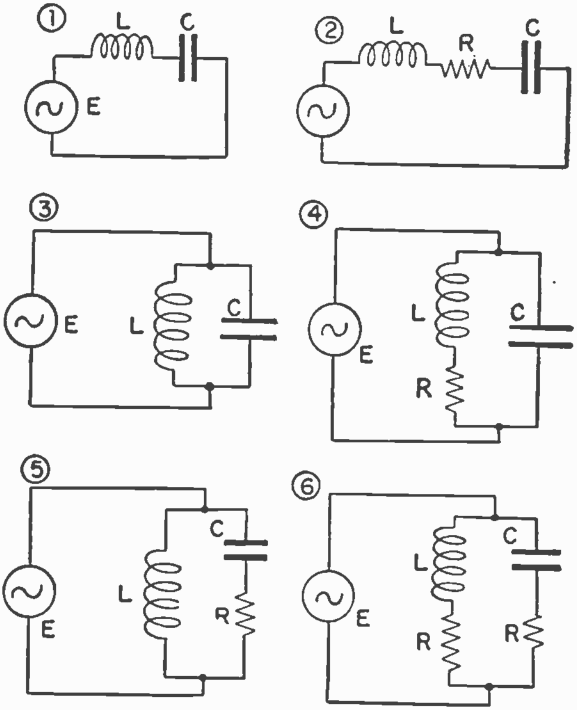

Fig. 13-10.—Various types of resonant circuits.

usually is enough resistance to have important effects in the inductive branch, but almost negligible resistance in the capacitive branch.

At the top of Fig. 13-11 is represented a series resonant circuit with the inductance between *A* and *B*, and with the capacitance between *B* and *C*. Potential from an a-c source is applied at *A* and *C*. The *C-emf* of inductive reactance acts in the opposite direction to the *V* of capacitive reactance. At resonance these two forces are equal; they nullify each other, and there is no reactive opposition to electron flow (current) from the source through this series resonant circuit. The flow is the same in both parts of the series resonant circuit, because the parts are in a series circuit.

In the lower diagram of Fig. 13-11 the circuit has been "folded" at *B* so that *A* and *C* are brought together. Now the inductance and capacitance are in parallel with each other, and we have a parallel resonant circuit with its terminals at *B* and *A-C*. Just as the *C-emf* is in a direction from *A* to *B* in the series resonant circuit during a half-cycle, so it is in the same direction, from *A* to *B*, during a given half-cycle in the parallel resonant circuit.

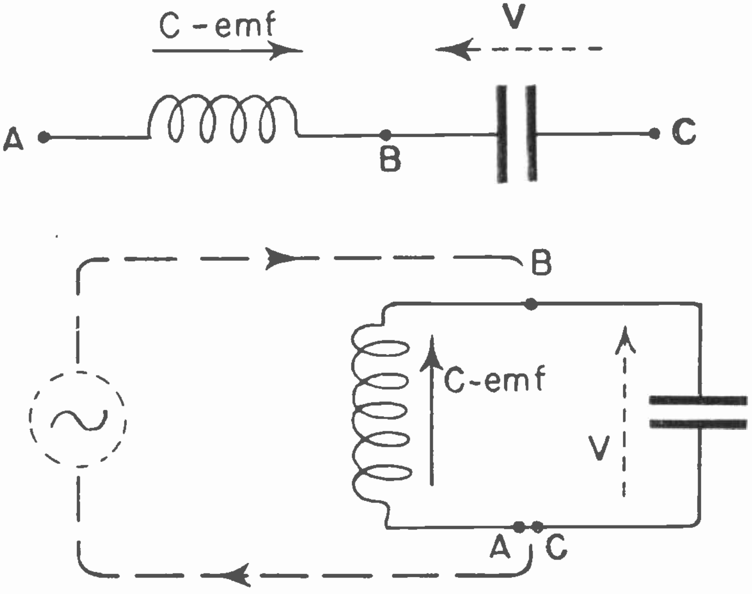

Fig. 13-11.—The potentials in a parallel resonant circuit

And, just as the simultaneous voltage *V* is in a direction from *C* to *B* in the series resonant circuit, so it is from *C* to *B* in the parallel resonant circuit. But, where the two forces that oppose changes of electron flow act against each other in the series circuit, and leave zero opposition to the flow from the source; in the parallel circuit these two forces act together in opposing the potential of the source, and, at resonance, provide maximum opposition to the flow from the source. That is, during the half-cycle in the parallel resonant circuit of Fig. 13-11, both *C-emf* and *V* act in the same direction (upward) to oppose at *B* the potential of the source that is acting toward *B*. During the opposite half-cycle *C-emf* and *V* will reverse their direction, but so will the potential from the source, and again the forces in the parallel circuit will oppose the force from the source.

In a series resonant circuit the flow is the same in both parts. Potential differences across the inductance and capacitance are proportional to the two reactances; because reactive potentials are $E = I \times X$ in the same manner that resistive potentials are $E = I \times R$. As the values of reactance change with changes of frequency, the reactive potential differences must vary also with changes of frequency.

In a parallel resonant circuit the same potential differences must exist across both branches. For example, in the parallel resonant circuit of Fig. 13-11 the potential difference from *A* to *B* can be no different from the potential difference between *C* and *B*, because *A* and *C* are joined together, while *B* is the same point in both cases.

But in any parallel resonant circuit the electron flow in the two branches may differ. This comes about because the reactances of the two branches change as the frequency is changed, and, at any instant, the flow in either branch is equal to the potential divided by the reactance. That is, reactive currents are $I = E/X$ just as resistive currents are $I = E/R$. With the potential E unchanged, it is plain that changes of reactance *X* must bring about changes of flow *I*.

To summarize what happens: In a parallel resonant circuit there are equal potential differences across the two branches, but there may be different values of electron flow in the two branches. In a series resonant circuit there are equal flows (the same current) in both parts, but there may be differences in potential drops across the two parts.

Currents In Parallel Resonant Circuits. — The time or phase relations between electron flow (current) and the induced counter-emf in an inductance are shown at the top of Fig. 13-12, where the current curve is marked *I-L* for flow in the inductance, and the counter-emf curve is marked *C-emf*. The phase relations between voltage and electron flow for a capacitor are as at the center of Fig. 13-12, where the current curve is marked *I-C* for current in the capacitance, and the curve for capacitor voltage is marked *V*. These are the same relations that were explained in detail in the section on alternating currents.

In the two upper graphs of Fig. 13-12 the current *I-L* and the current *I-C* would be the same current, because they are exactly in phase with each other. The forces *C-emf* and *V* are in opposite phase. Then, in the two upper graphs we have a single current and two opposing forces or voltages, which is the condition existing in a series resonant circuit.

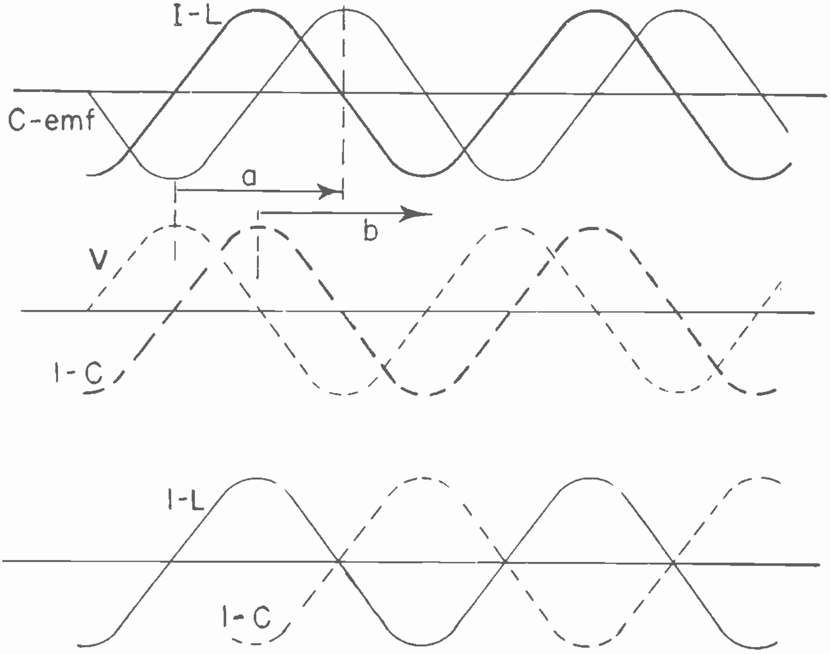

Fig. 13-12.—The currents in a parallel resonant circuit.

But in the parallel circuit of Fig. 13-11 we have the forces *C-emf* and *V* acting in the same direction at the same time, and they are of equal values. To represent this condition in Fig. 13-12 we may shift *V* on the middle graph in the direction of arrow *a* until *V* coincides with the curve for *C-emf* of the upper graph. Then we have *V* and *C-emf* acting in the same direction at the same times, and they are of equal values. We do not have a single potential corresponding to *V* and to *C-emf* because one of them exists in the inductive branch and the other in the capacitive branch of the parallel circuit.

When moving the curve for *V* through the time represented by the length of arrow *a* we must move the accompanying current curve *I-C* in the same direction by the same interval of time, which is along arrow *b*. Now, in the lower graph of Fig. 13-12, we have current curve *I-L* in its original position, but have current curve *I-C* shifted as described. Thus we have one current, *I-L*, in the inductance of the parallel circuit, and another current, *I-C*, in the capacitance of the parallel circuit, and these two currents are in opposite directions, although their voltages are acting in the same direction. The simultaneous voltages, *C-emf* and *V*, and the currents *I-L* and *I-C*, have the directions shown by Fig. 13-13. The voltages are in the same direction, both upward, while the currents are in opposite directions. This is the condition during a half-cycle. During the opposite half-cycle all the directions would reverse.

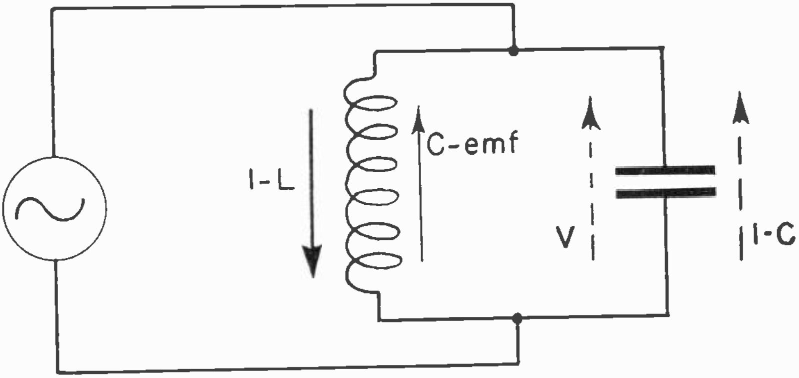

Fig. 13-13.—Currents and potentials in the inductance and the capacitance.

At the frequency of resonance the reactances of the two branches of the parallel circuit are equal, just as with series resonance. The potentials across the two branches also are equal, which means that *C-emf* and *V* are equal. With the same potentials across the same reactances the currents must be equal in the two branches, so *I-L* is equal to *I-C*. Considering the relative directions of electron flows, this means that electrons from the negative plate of the capacitor are flowing over into one end of the coil, while electrons from the other end of the coil are flowing over into the positive plate of the capacitor. Electron flow, or current, is circulating between the capacitor and the coil, going around in one direction during one half-cycle, then reversing and going around in the opposite direction during the opposite half-cycle.

As electrons circulate first one way and then the other between the capacitance and the inductance of the resonant circuit there is an accompanying transfer of energy from the electric field in the dielectric of the capacitor to the magnetic field around the coil, and then back again. What happens during one cycle is shown by Fig. 13-14, in diagrams numbered from *1* to *12*.

1. The capacitor is assumed to be highly charged. Its upper plate, with an excess of electrons, is negative. Its lower plate is positive. Electron flow is in the direction of the arrows, from the upper plate of the capacitor through the coil and to the lower plate of the capacitor. This flow causes the charge of the capacitor to commence decreasing, but at the same time it causes a magnetic field to commence building up around the coil. It is assumed that the coil is wound and connected in such directions that electron flow in this direction makes the upper end of the coil a north pole, and the lower end a south pole.

2. The capacitor continues to discharge, electron flow continues in the same direction as it increases in rate, and the magnetic field around the coil becomes stronger. Magnetic and electric polarities remain unchanged.

3. The capacitor has become completely discharged, with its plates becoming neutral, or being neither positive nor negative. At this instant there is maximum electron flow through the coil, the magnetic field is of maximum strength, and all of the energy

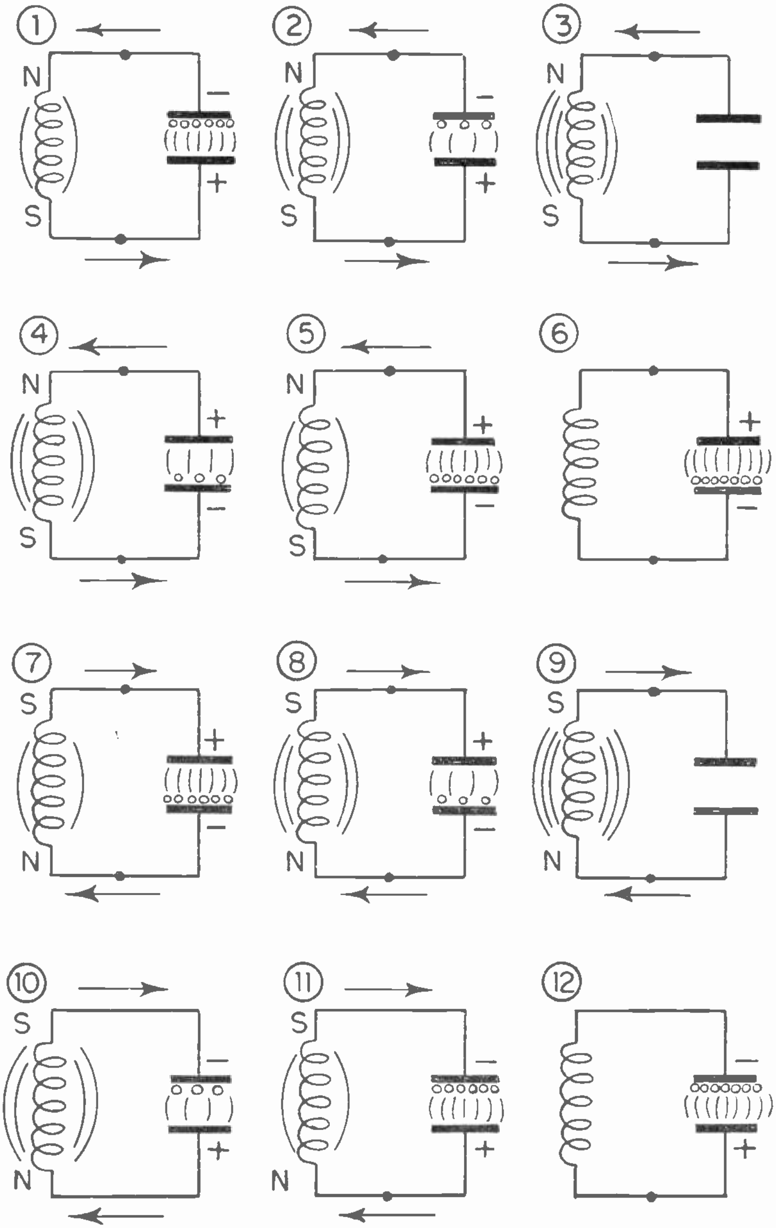

Fig. 13-14.—The changes during one cycle in an oscillatory circuit.

which originally was in the electric field of the capacitor now is in the magnetic field of the coil.

4. The strong magnetic field of the coil commences to collapse. The effect of the induced emf is to oppose change of electron flow, and the flow is continued in the same direction as before. This flow commences to charge the capacitor, but now the lower plate becomes negative and the upper one positive. Since the direction of electron flow in the coil has not changed, the magnetic polarity of the coil is not changed.

5. The magnetic field of the coil has nearly disappeared, but the charge of the capacitor is increasing.

6. The magnetic field of the coil has disappeared completely just as the charge of the capacitor becomes maximum. At this instant there is no electron flow. All of the energy which was in the magnetic field of the coil in diagram *3* now has been transferred to the dielectric field of the capacitor.

7. The strong charge, and high accompanying potential difference, of the capacitor has started electron flow in the reverse direction. This reversed direction of flow through the coil reverses the polarity of the coil, and its upper end becomes a south pole, with the lower end a north pole.

8. The charge on the capacitor is decreasing, but the magnetic field of the coil is increasing, as energy is being transferred from the capacitance to the inductance branch.

9. The capacitor charge has disappeared, the electric field in the dielectric has disappeared, and the magnetic field around the coil has become of maximum strength. All of the energy formerly in the capacitor dielectric field now has gone over to the magnetic field of the coil. The condition is like that of diagram *3*, except that the magnetic polarity of the coil is reversed.

10. Again the magnetic field of the coil is decreasing as the electric field of the capacitor dielectric increases while energy is passing from the magnetic to the electric field. Conditions are similar to those of diagram *4*, except that the direction of electron flow and all of the polarities are reversed.

11. Most of the energy now has passed from the magnetic field into the electric field. Conditions are like those of diagram *5*, but with direction of electron flow and the polarities of coil and capacitor reversed.

12. The magnetic field has disappeared, the electric field is of maximum strength, all of the energy is in the electric field, and for an instant, there is no electron flow. The condition is like that of diagram *6*, but with reversed polarity of the capacitor plates. From here we start over again with diagram *1*, and so the performance continues.

During the action shown by Fig. 13-14 the energy swings back and forth or oscillates between the electric and magnetic fields; between the capacitor and coil. A circuit in which this happens may be called an *oscillatory circuit.* During each electron flow or current flow some energy is used up in overcoming resistance of the circuit elements. If energy is being supplied to the oscillatory circuit from some outside source that energy need be only enough to make up for the resistance losses. So far as capacitance is concerned it returns to the circuit or to the coil every bit of energy that it receives. And, so far as the inductance is concerned, it also returns to the circuit, as its magnetic field collapses, every bit of energy that went into forming that field. The only losses of energy are those due to resistance, assuming, of course, that the frequency is that for resonance. If the supply of energy from the external source is cut off, the oscillations will die away as the energy is used in overcoming resistance in the circuit.

Since the only energy losses in a parallel resonant circuit operating at resonant frequency are those in the resistance, the electron flow from the external source can be only enough to bring in the equivalent of the lost energy. If the circuit has but little resistance there will be required only a correspondingly small flow from the source. Therefore, the flow of "line current," or electron flow from the external source, through a parallel resonant circuit at resonance is only that corresponding to the circuit resistance. The less the resistance the smaller will be the line current, for the smaller are the losses of energy, and the more the resistance the greater will be the line current, to compensate for the greater losses.

Impedance of Parallel Resonant Circuit. — In the parallel resonant circuit of Fig. 13-13 the frequency was assumed to be that of resonance for the values of inductance and capacitance employed. Then, with equal potential differences and equal reactances in the two branches, the two electron flows (currents) were of equal value and they would flow only back and forth within the resonant circuit. But at frequencies other than that for resonance the reactances of the inductance and capacitance are not equal, and then the equal potential differences cause unequal flows in the two branches. The greater flow will be in the branch having the smaller reactance, and the smaller flow will be in the branch of greater reactance.

In Fig. 13-5 were shown curves for capacitive reactance and for inductive reactance at various frequencies with the inductance of 270 microhenrys and the capacitance of 100 micro-microfarads. Assuming that this inductance and reactance are used in a parallel resonant circuit, and that the potential is 100 volts across both branches, the currents which will flow in the two branches at various frequencies near resonance (968.5 kilocycles) are shown by Fig. 13-15. As the frequency increases, current in the inductance shows a steady drop while current in the capacitance shows a steady rise. At the resonant frequency,

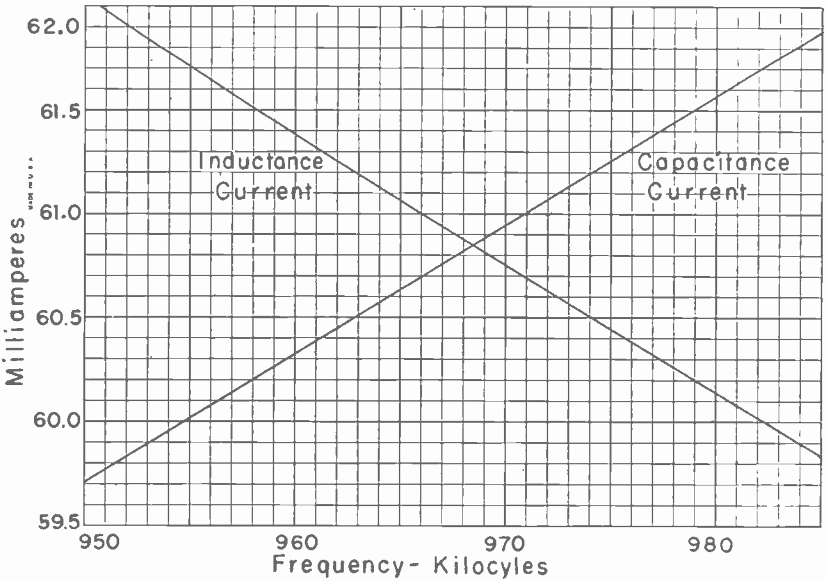

Fig. 13-15.—Current values at and near the frequency of resonance.

which here is 968.5 kilocycles, the two currents are of equal value. At all other frequencies the two currents are unequal.

When the two currents are unequal the flow is as shown by Fig. 13-16. At frequencies below that for resonance the current in the inductance is greater than that in the capacitance, as shown in Fig. 13-15. Then the current from the `inductance flows, as in the left-hand diagram of Fig. 13-16, partly over into the capacitor and partly through the source as shown by arrows. At frequencies above resonance there is a greater flow in the capacitor, again as shown by Fig. 13-15. Then, as at the right in Fig. 11-16, part of the electrons from the capacitor flow around through the inductance, while the excess goes through the source as shown by the arrows.

As may be seen in Fig. 13-16, at frequencies below resonance the electrons that flow through both the source and a parallel resonant circuit flow through the source in a direction corresponding to that of flow in the inductance. At frequencies above resonance the flow through the source is in a direction that corresponds to the direction through the capacitance of the parallel resonant circuit. Therefore, at frequencies below resonance the parallel resonant circuit acts toward the source as though this circuit were an inductive reactance, and at frequencies above resonance it acts like a capacitive reactance. This behavior is

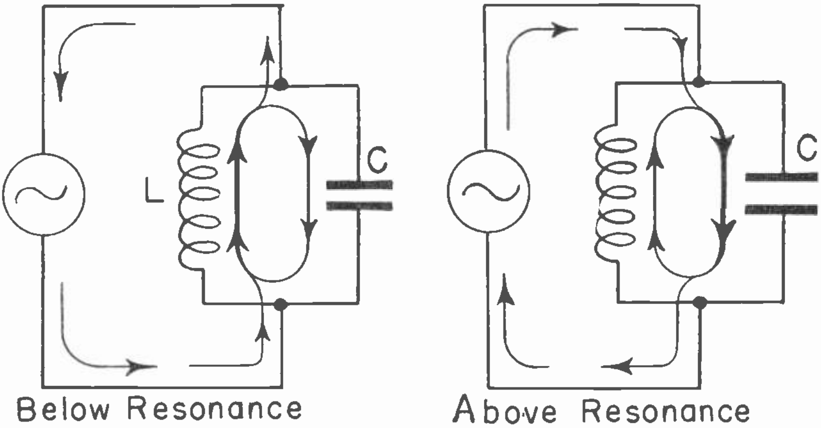

Fig. 13-16.—An excess of current may flow in either the inductance or the capacitance.

the opposite of a series resonant circuit, which acts below resonance like a capacitive reactance, and above resonance like an inductive reactance. The difference becomes apparent when comparing Fig. 13-15 with Fig. 13-5.

The electron flow through the source in Fig. 13-16 is the difference between the flows in the inductance and in the capacitance, and is the difference between the flows shown by Fig. 13-15. The difference between the flows, in milliamperes, is shown by Fig. 13-17. At frequencies below resonance this difference current, which is like that in an inductive reactance, decreases steadily as the resonant frequency is approached and becomes zero at the resonant frequency. At frequencies above resonance the electron flow, which now is like that in a capacitive reactance, shows a steady increase.

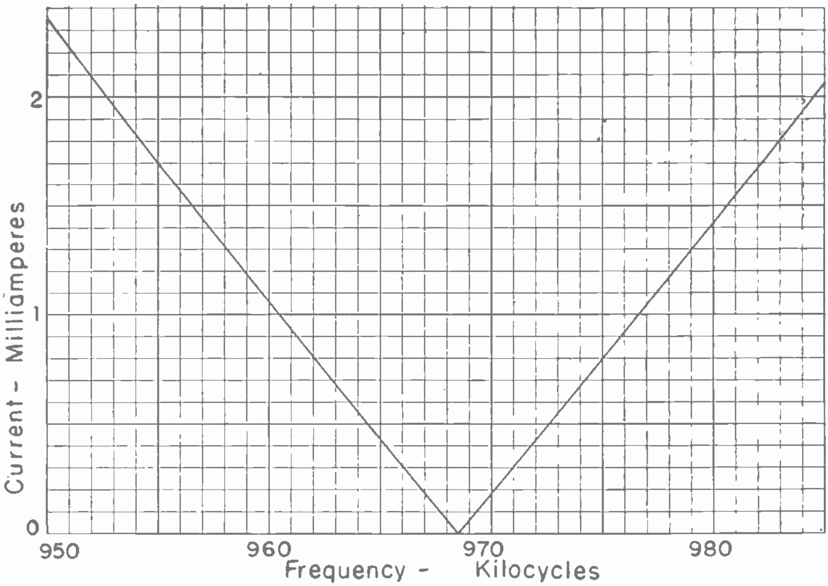

Fig. 13-17.—At the resonant frequency the difference between the currents is zero.

The electrons flowing in the portion of the circuit that contains the source must have a value shown by $I = E/Z$, where Z is the impedance of the whole circuit connected across the source.

It is equally true that the impedance of this connected circuit must have a value shown by $Z = E/I$. We have assumed the value of the potential E to be 100 volts, and from Fig. 13-17 we may read the values of the current I. By using these values in the formula, the impedance of the parallel resonant circuit connected across the source turns out to be as shown by Fig. 13-18.

At frequencies well removed from resonance the impedance is small, in the neighborhood of 40 to 50 ohms. But as the frequencies approach resonance the impedance commences to rise rapidly. Within a few kilocycles of resonance the parallel impedance increases at a very great rate. Right at the resonant frequency, for this circuit which is assumed to contain no resistance, the impedance would become infinitely great, because we know that at resonance no current would flow from the source through the parallel circuit, although there would be large circulating currents or oscillating currents in this circuit between its inductance and capacitance. The circulating currents, at resonance, are limited only by the resistance that must be in every actual circuit.

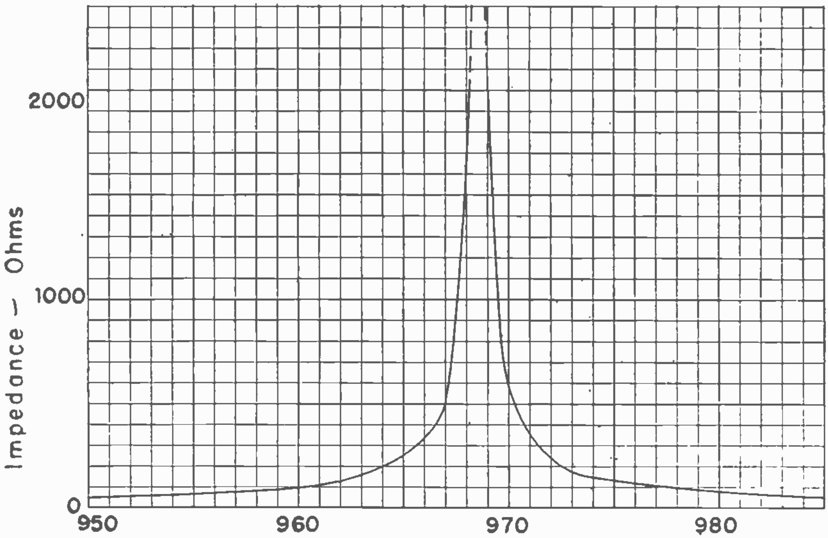

Fig. 13-18.—A parallel resonant circuit has high impedance at the resonant frequency.

Note that the curve showing impedance of a parallel resonant circuit in Fig. 13-18 is of the same general form as the curves of Fig. 13-8 which show current values in a series resonant circuit. The similarity extends further, for resistance added to the parallel resonant circuit, as at *4*, *5* or *6* in Fig. 13-10, will flatten the tops of impedance curves for a parallel resonant circuit just as resistance flattens and lowers the current curves for the series resonant circuit.

Tuning. — At the left in Fig. 13-19 is a circuit having capacitance *C* and inductance *L* in series. Assume that very small alternating potentials and currents act between points *1* and *2*. These weak potentials and currents might be produced in the antenna system of any television, f-m, or radio broadcast receiver by radio waves coming through space. The received radio waves are at many different frequencies as radiated from transmitters operating at the various frequencies.

If the values of capacitance and inductance in the series circuit are such as bring about resonance at one of the incoming frequencies the circuit will have minimum impedance at this frequency, and relatively high impedances at other frequencies. Then the weak alternating potential of this selected frequency will cause maximum current of the same frequency in the series

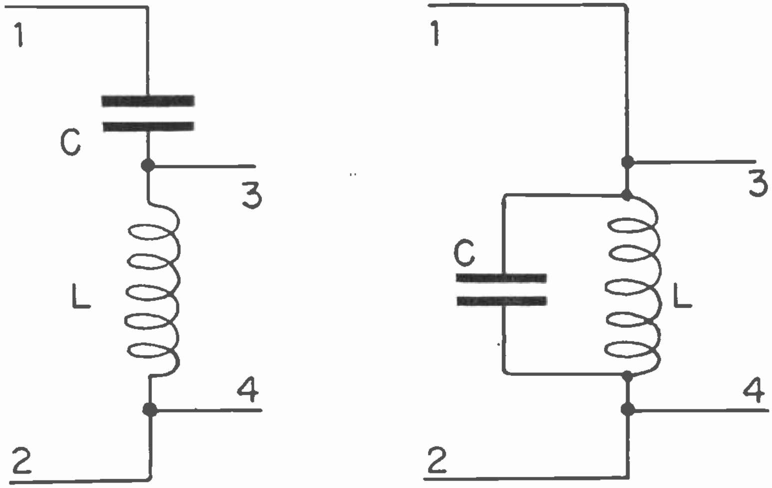

Fig. 13-19.—Tuned circuits of the series resonant type and the parallel resonant type.

circuit. Even though this current still be a small one, its flow in the high reactance of the inductance will induce across the inductance counter-emf's far greater than the value of the potential applied between *1* and *2*. This is a characteristic of series resonant circuits, as explained in preceding pages. Then the relatively large alternating potential which occurs at the selected frequency in the inductive reactance of *L* may be applied through terminals *3* and *4* to some other circuit, which might be the grid-cathode circuit of an amplifying tube. The importance of resonance in this case is that it permits obtaining fairly strong potentials at a frequency selected from many other frequencies, while delivering but weak potentials at the other frequencies for which the impedance of the resonant circuit is small.

At the right-hand side of Fig. 13-19 is a circuit containing inductance *L* and capacitance *C* in parallel with each other. It may be assumed that weak alternating potentials and currents of many frequencies act between terminals *1* and *2*. If the values of inductance and capacitance are such as to cause resonance at one of these applied frequencies the impedance of the parallel circuit will be maximum at this frequency and will be relatively small at all the others. Now, even though only a very small current at the resonant frequency flows through the parallel circuit, the circulating currents in the inductance and capacitance may be relatively very large. These large currents in the inductance and reactance are accompanied by correspondingly large potential differences across the elements, and, at every instant, the reactive potentials in the two elements are acting together, either upward or downward in the diagram. Thus it becomes possible to apply to another circuit, through terminals *3* and *4*, the effect of the strong alternating potentials. The action of the small current passing through the high impedance of the parallel circuit is similar to that of a small current passing through a high resistance; in both cases the small current is accompanied by a large difference of potential.

Previously it has been shown that when the frequency applied to an inductance and capacitance, which are in series or in parallel, is varied through a sufficient range there will be one frequency at which the combination is resonant. But in radio reception the incoming frequencies are fixed, and in order to make the receiving circuit resonant to a certain desired frequency either the capacitance or the inductance must be varied until, in combination with the other element, there is resonance at the desired frequency. This variation of capacitance or inductance for the purpose of bringing about resonance at a certain frequency is called *tuning,* and the circuit is said to be *tuned* to the certain frequency.

A circuit may be tuned by varying either the capacitance or the inductance. In standard broadcast and in most f-m radios it is common practice to vary the capacitance and use fixed inductance. In television receivers we more often find variable inductance and fixed capacitance. A variable capacitor used for tuning is called a tuning capacitor, and a variable inductor is called a tuning inductor.

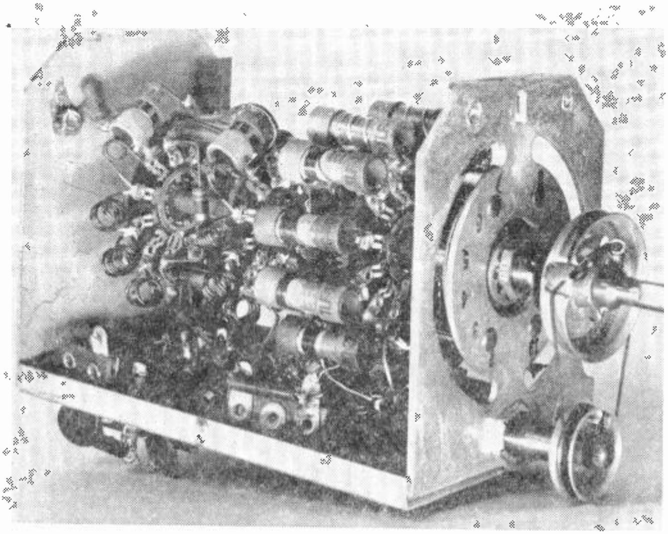

Fig. 13-20.—A television tuner containing adjustable inductors.

A tuning capacitor consists of one set of plates supported in a fixed position, called the stator, and of a second set of plates which may be moved with reference to the stator. The movable plates are called the rotor. A tuning inductor most often consists of a coil wound on an insulating form. Inside the form is a core made of finely divided iron cemented into cylindrical shape. This core may be moved farther into or out of the coil, to vary the inductance.

Fig. 13-20 shows such inductors.

Fig. 13-21 shows how the capacitance must be varied for tuning throughout the frequency range from 300 to 1,000 kilocycles when using a fixed inductance of 500 microhenrys. The change of capacitance is not proportional to the resulting change in the resonant frequency. For instance, when tuning from 300 to 400 kilocycles the capacitance must be changed by about 250 micro-microfarads, but tuning from 400 to 500 kilocycles requires a change of only about 100 micro-microfarads. At higher and higher frequencies the required change of capacitance becomes less and less until, from 900 to 1,000 kilocycles the change need be only about 12 micro-microfarads. In order that equal changes of frequency may be covered by approximately equal movements of tuning capacitor plates and tuning dials, the capacitor plates have to be shaped as to provide large changes of capacitance when they are nearly in mesh (for high capacitance and low

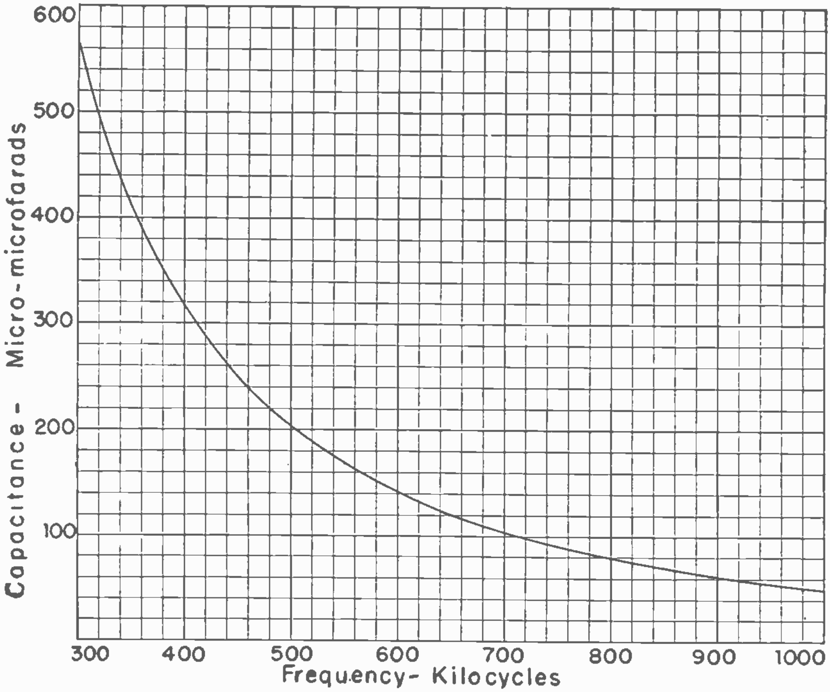

Fig. 13-21.—How the capacitance is varied when tuning to various frequencies.

frequencies), and to provide small changes of capacitance at the other end of their tuning range.

If a similar check is made of the changes of inductance required to tune with a given fixed capacitance in covering a certain range of frequencies the curve for inductance would be of the same general shape as that of Fig. 13-21. Just as it takes a large variation of capacitance, so it takes a large change of inductance to tune through a given difference of frequencies in the low frequency range, and a small change to tune through the same difference of frequencies in the high frequency range.

Distributed Capacitance. — There is capacitance between any two conductors which are separated by insulation. Consequently, there is capacitance between every turn of wire on an inductance coil and every other turn. The closer the turns are to one another the greater is the capacitance. There is capacitance also between the conductors or wires that connect parts of the circuit together. All of these small capacitances considered together are called the distributed capacitance of the coil or of the circuit.

The distributed capacitance is in the coil and wiring, and it is not subject to adjustment as is the capacitance of a tuning capacitor, but it has its effect in tuning of the circuit. In considering the capacitance for resonance, the distributed capacitance adds to the capacitance of the variable capacitor. If the distributed capacitance is, for example, 15 micro-microfarads, and if the capacitance range of the tuning capacitor is from a minimum of 20 to a maximum of 360 mmfd, then the actual minimum capacitance of the circuit is 20 mmfds in the capacitor and 15 in the coil and wiring, or is a total of 35 mmfds. And the maximum capacitance is 360 mmfds in the capacitor plus 15 mmfds in the coil and wiring, or is a total of 375 mmfds. Most important, the range through which the total capacitance may be tuned is from 35 to 375 mmfds, not from 20 to 360 mmfds as in the capacitor alone.

Coils and wiring have enough distributed capacitance so that its value combined with the inductance of the coil form a circuit which is resonant to some high frequency. For example, if a coil having 270 microhenrys inductance had also 10 mmfds of distributed capacitance it would be resonant at a frequency of about 3 megacycles even with no capacitor connected in the circuit.

In those tuned circuits of television receivers which employ adjustable inductances the fixed tuning capacitance usually consists of only the distributed capacitance in the coil, the internal capacitance of a tube, and the "stray" capacitances which always exist between wires and other parts of the tuned circuits. These capacitances cannot readily be varied for tuning, this being one of the reasons for using adjustable inductors.

Distributed, stray, and tube capacitances seldom total less than 15 mmf, and often amount to about 30 mmf. To tune with such capacitances at the midband f-m broadcast frequency of 98 megacycles requires inductance of only about 0.18 to 0.09 microhenry. In the tuned circuits of television receivers the required adjustable inductance is on the order of 0.02 to 1.8 microhenrys.

When employing variable tuning capacitors in similar circuits the fixed inductances are in the ranges just mentioned, while the tuning capacitors are designed to furnish anything from a fraction of one mmf up to a maximum of possibly 5 to 20 mmf. In any case the fixed capacitances of the circuit and tube are important, for the greater the non-adjustable fixed capacitance the less becomes the frequency tuning range of the variable capacitor.

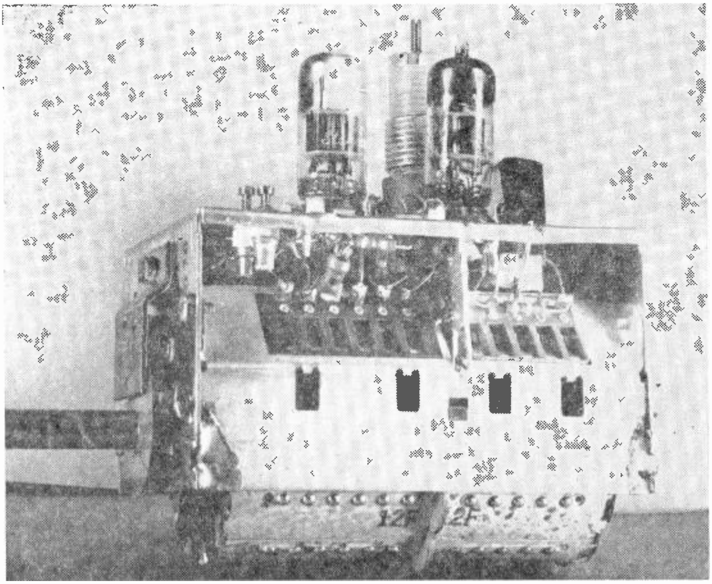

Fig. 13-22.—A television tuner which switches different adjustable inductances into circuit for reception of various channels.

Chapter 4

COILS FOR HIGH FREQUENCIES

At the moderately high frequencies employed for standard radio broadcast the inductive reactances of coils are so low that rather large values of inductance are needed for most circuits. By large values we mean inductances in the range of 50 to 200 microhenrys. Such values are provided by coils of many turns and of fairly large diameter and length. In any coil there is much inductance within small space, consequently a coil often is called a "lumped inductance."

Capacitive reactances are so low at these frequencies that we need capacitors whose maximum capacitance is from 150 to 500 mmf. A capacitor, in which much capacitance is concentrated in

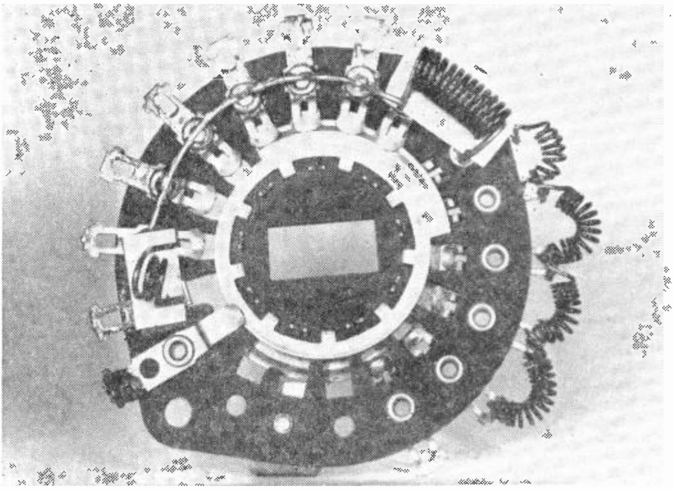

Fig. 14-1.—The inductors on this switch plate tune a television receiver for reception in various channels

small space, may be called a "lumped capacitance." Tuned circuits in standard broadcast radio receivers always include lumped inductance and capacitance. The distributed, stray, and internal capacitances of coils, wiring, and tubes are so relatively small as not to greatly affect the total circuit capacitance. Likewise, the inductances of wire connections and other conductive parts are so much smaller than in the coils as to have little influence on total circuit inductance.

When we work with television and f-m broadcast frequencies ranging from 20 to more than 200 megacycles the inductive reactances become so great and the capacitive reactances so small, for any given inductance and capacitance, that we no longer may think of a tuned circuit as consisting only of its lumped inductance and capacitance. Inductances in parts of a circuit outside the coil often are as great or greater than in the coil. Capacitances in coils, tubes, and connecting wires are comparable to those of tuning capacitors.

At a frequency of 40 megacycles, for example, the effective inductance of six inches of straight wire may be about 0.13 microhenry. If this wire and its connected parts are close enough to

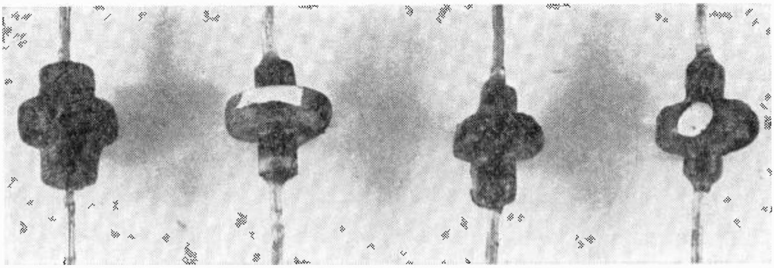

Fig. 14-2.—Peaking coils whose inductance, in combination with circuit capacitances, is resonant at a frequency around four megacycles.

other conductors to provide capacitance of six mmf we have a circuit which is self-resonant or which tunes to a frequency of 180 megacycles without any coil or capacitor. This frequency is at the high end of channel 7 and at the low end of channel 8 in the television band.

If you change the length of a wire, or move a wire closer to or farther from other conductors in the high-frequency circuits of television or f-m receivers you are likely to completely upset the tuning. Six of the contact points on the upper left quarter of the switch plate in Fig. 14-1 carry a single slightly curved wire. The difference in length of this wire from one contact to the next changes the tuning from one television channel to the adjacent channel. The length is varied by about one-quarter inch from channel to channel.

High-frequency circuits always are resonant at frequencies which depend on values of circuit inductance and capacitance, just as are low-frequency circuits. But in high-frequency practice we must consider all parts of the circuit as contributing to the totals of inductance and capacitance. There is inductance in all wire connections, in all tubes, even in capacitors, because all these include conductors. There is capacitance between all parts which include conductive materials, which means all the wiring connec-

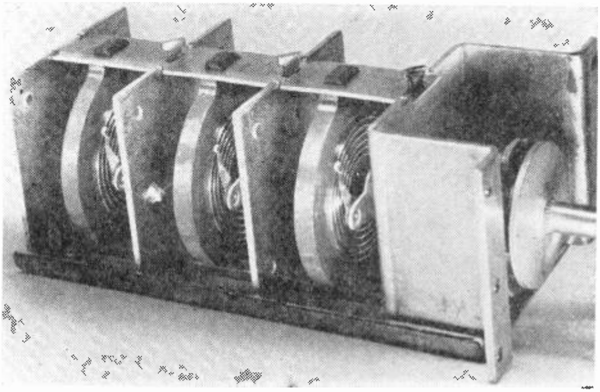

Fig. 14-3.—The spiral inductors or coils in this unit are used for several different television tuners.

tions, the elements within the tubes, and the windings of the coils. The lumped inductances and capacitances in coils and capacitors are only enough so that, when added to the circuit values, the total will be resonant at the required operating frequency.

A coil possesses inductive reactance because alternating magnetic lines of force which spread and contract around every turn pass through or cut all other turns, and there are a great many cuttings. It is the number of cuttings per second of magnetic lines of force that largely determines the inductive reactance. A straight wire possesses inductive reactance because the lines of force which expand and contract move out and back through the wire itself. Total cuttings are few, but they provide reactance.

If the number of coil turns is relatively few, and if adjacent turns are spread apart, there is less inductance than with more turns and close spacing. In any case the inductance depends on the number of turns through which the alternating currents may flow. Fig. 14-3 pictures a three-section tuning inductor in which each coil is a flat spiral rather than being of cylindrical form. The small sliders are rotated around the turns to include more or less of the windings in the active circuit, and thus effective inductance is varied.

Many high-frequency coils are of the air-core type, meaning

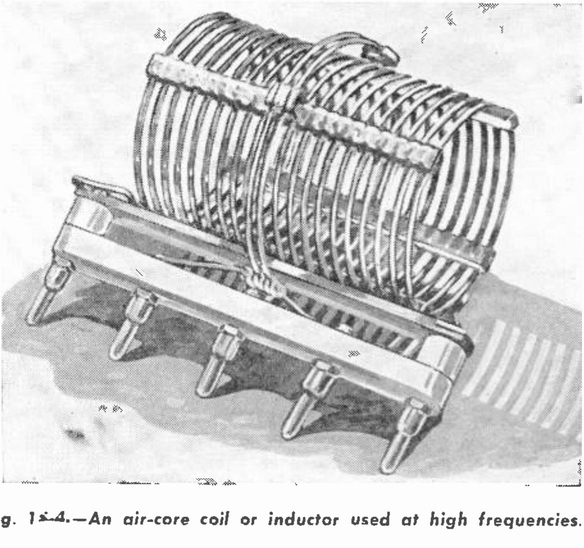

Fig. 14-4.—An air-core coil or inductor used at high frequencies.

that no iron is placed within the coil to increase the permeability and inductance for a given number of turns. An air-core may be wound with wire large enough and stiff enough to be self-supporting, or to require only small strips of insulation to preserve spacing, as in Fig. 14-4. Coils may be wound also on tubular forms of insulating material, as in Fig. 14-5. These still are air-core coils, because permeability of the supporting material is unity, or 1.0, which is the same as the permeability of air. Then there is no increase of inductance due to material inside the coil, and it behaves just like one having only air inside the turns.

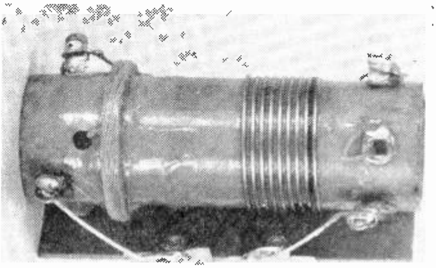

Fig. 14-5.—Tuning coils supported in insulating tubing.

Iron Cores for High Frequencies. — At audio frequencies and power frequencies the magnetic cores of laminated iron or steel which are used in transformers and choke coils provide permeabilities and inductances hundreds of times greater than would be had from the same coils used without the iron. Although such cores would provide similar advantages at radio frequencies they cannot be used because of the great losses of energy and consequent heating that would result from production of strong eddy currents in the iron.

To provide some of the advantage without the disadvantage, cores for high-frequency coils are made with particles of iron formed chemically in diameters of about 0.0004 inch. These particles are individually coated with insulation having a thickness only about one-tenth the diameter of the iron particles and they are held together by a phenolic binder of the thermo-setting plastic type. The result is a tough, hard mass containing a high percentage of iron, yet having the iron so finely divided that eddy currents have almost no chance to form and circulate.

Fig. 14-6 illustrates at the left a high-frequency television tuning coil mounted on an insulating form within which is a movable core of powdered iron. The core, to which is attached the adjusting screw, is shown at the center. At the right is the coil and form with the core removed.

The permeability of these high-frequency core materials is about 10 to 12 in most varieties. This means a flux density of 10 to 12 times that which would exist in the same volume and form of air with the same magnetizing force.

There is maximum inductance with the core centered along the coil axis, and minimum inductance with the core withdrawn as far as allowed by the adjusting means. The variation of inductance between these limits is enough to tune the coil over a range of frequencies. An additional fixed or adjustable capacitor may be connected in parallel to form a parallel resonant circuit, or in series to form a series resonant circuit tuned by movement of the core, by adjustment of the capacitor, or by both. These units which are designed for "permeability tuning" do not bring about any great increase in the Q of the coil because so much of the magnetic circuit still is of air, and the inductance is not increased much, if any, more than the effective resistance so far as their ratio is concerned.

Q-factor of Inductance Coils.—Whether a coil is used for tuning, for transfer of energy, or for filtering, the coil is used

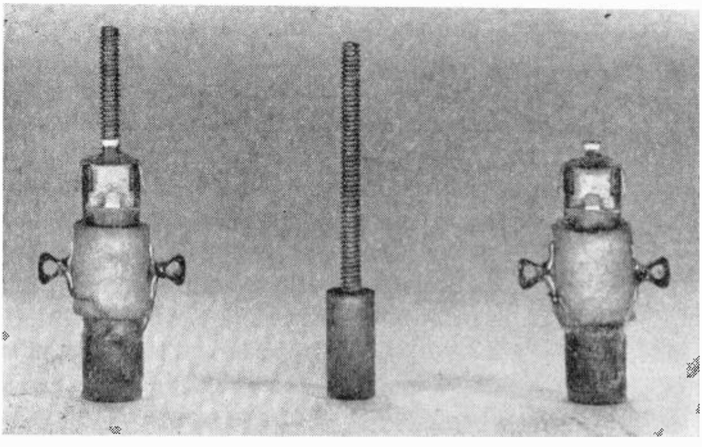

Fig. 14-6.—A tuning inductor having an adjustable powdered iron core.

because it provides inductive reactance where such reactance is needed. The less of the energy in the circuit that is wasted by being taken from the coil to produce heat the better the coil will be for its purpose. We may say that the less the energy loss for a given inductive reactance the better is the quality of the coil. The ratio of inductive reactance to energy loss is called the *Q-factor* of the coil, or simply the Q of the coil.

Instead of speaking of energy loss we usually speak of high-frequency resistance, which is the resistance in ohms that would cause the same dissipation of energy that actually occurs because of all the losses associated with the coil. Usually you will find the characteristic called Q specified as being the ratio of inductive reactance to resistance of the coil, or we may write,

$$Q = X/R$$

Of course, when showing the meaning of Q in this manner we must keep in mind that R does not mean the ordinary ohmic or direct-current resistance of the wire in the coil, but means a resistance which represents all the energy losses. Such a resistance often is called effective resistance. This effective resistance is that due to skin effect in the wire, to losses in insulating dielectrics which are associated with the self-capacitance of the coil,

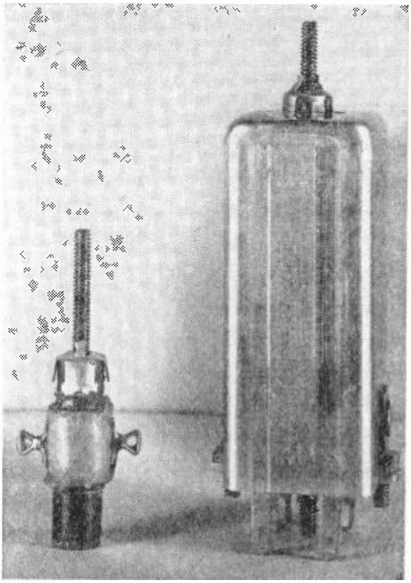

Fig. 14-7.—This tuned transformer, used in television receivers, has windings of small diameter, made with small wire.

Distributed Capacitance.—There is capacitance between adjacent turns of a coil winding, also between each turn and every other turn. If a coil, with its inductance and its distributed capacitance or self-capacitance, is connected to a source of alternating potential there will be some frequency at which the inductance and capacitance will be resonant and the coil becomes a parallel resonant circuit in which the reactances balance and in which there will be large currents at this frequency. Unless the coil alone is intended to act as a tuned resonant circuit at some frequency or in some band of frequencies, the inductance and capacitance always are made of such relative values that there will be no resonance effects.

Self-capacitance in a coil is objectionable at all working frequencies because the potential differences between turns set up electrostatic fields in the spaces between turns. These fields are alternating, and in any dielectric which is between the turns or near the turns the electrons in the atoms are attracted first one way and then the opposite way. These movements of the electrons cause dissipation of energy in the form of heat in the dielectric material, and all energy so used represents a loss so far as useful action of the coil is concerned. The energy loss means an increase of high-frequency resistance because of the self-capacitance.

Since the energy loss is due to the electrostatic fields, and since these fields exist only when there are potential differences between turns, it is apparent that it is the combination of self-capacitance and potential differences that get us into trouble; it is not the self-capacitance alone. If we reduce the capacitance and at the same time bring about a proportionate increase of potential difference there is nothing gained. We wish to reduce both factors.

The self-capacitance of a coil is reduced by several different constructions. It is reduced by spacing the turns farther apart, because the capacitance of any capacitor decreases as the separation between its plates is increased. Self-capacitance is reduced by using smaller wire, because this lessens the surface area of the "plates" which are the conductor, and less plate area means less capacitance.

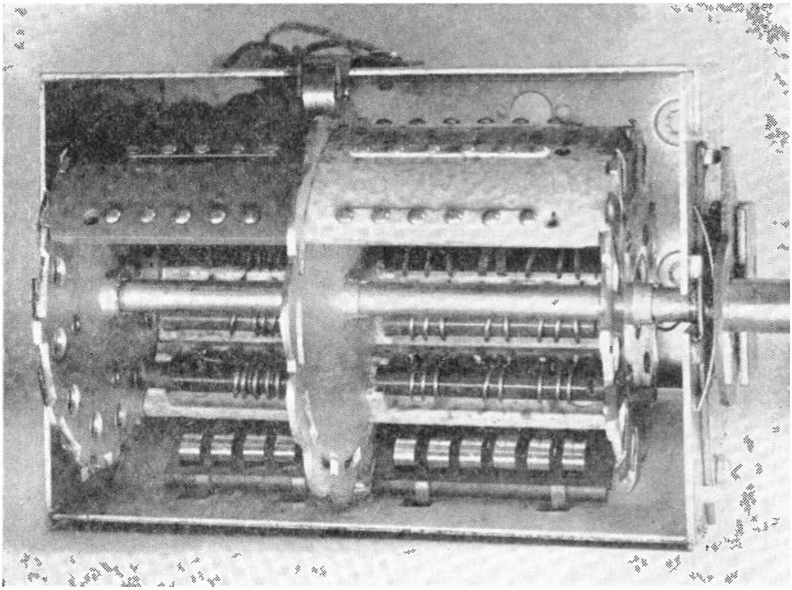

Fig. 14-8.—The coils which are inside this television tuner are space wound to reduce distributed capacitance, and are on tubing having low energy losses.

The self-capacitance is reduced by having in the space between turns of a coil a dielectric of low dielectric constant. No solid insulating materials have dielectric constants so low as that of air, so air is the ideal insulation. But the winding must be supported by solid insulation. The lower the dielectric constant of the insulation that has to be used the less will be the self-capacitance.

The effect of the self-capacitance that exists in a coil of any design is lessened by reducing the potential differences between turns, or between adjacent turns, and thus weakening the electrostatic fields. Potential differences are relatively small in a single-layer coil because the points of maximum potential difference are at opposite ends of the winding. In multi-layer coils the potential differences are reduced by banked windings and by pie windings whether used singly or with several sections connected together in series.

Whether a coil of given inductance is long and of small diameter, or is short and of large diameter has relatively little to do with the effects of self-capacitance. The coil of small diameter will have more turns, but, with the same overall potential difference there will be less potential difference per turn than in the coil of large diameter with its fewer turns.

to similar losses of energy into other nearby dielectric materials, to losses of energy represented by emf's and currents induced in nearby conductors by the magnetic field of the coil, and to every other use of energy in a manner not desired.

Fig. 14-9 shows how high-frequency resistance or effective resistance increases with frequency in a single-layer coil of an experimental type. Between the frequencies of 500 and 1,500 kilocycles the resistance goes from about 4.5 to 15.7 ohms. Above 1,200 kilocycles the resistance commences to increase at an ever greater rate, showing that this particular coil would not be satisfactory at frequencies much higher than those in the standard broadcast band.

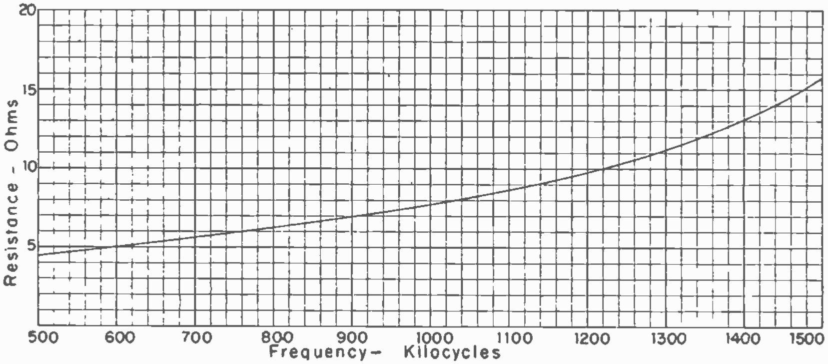

Fig. 14-9.—High-frequency resistance of a single-layer coil at various frequencies.

The inductance of the experimental coil is about 159.1 microhenrys. Its inductive reactance in ohms, at the various frequencies, is shown by the upper curve (a straight line) in Fig. 14-10. The reactance increases with rising frequency, as does also the effective resistance, but the rates of increase are not everywhere the same. At any one frequency the ratio of the reactance to the resistance, or the ohms of reactance divided by the ohms of resistance, is the *Q* of the coil at that frequency.

The *Q* of a coil operating at any frequency is increased by all of the design factors which reduce the high-frequency losses and the effective resistance. Since reactance is directly proportional to inductance, the Q is increased by any designs which increase the inductance with a given length of wire, provided that the high-frequency resistance is not at the same time increased in even greater ratio.

Sometimes you will see references to the *power factor* of a coil. The power factor is the ratio of high-frequency resistance to impedance, both in ohms. The power factor is equal to the number of ohms of resistance divided by the number of ohms of impedance at the frequency being considered. Because we desire small values of effective resistance combined with large values of impedance, an efficient coil will have a small power factor.

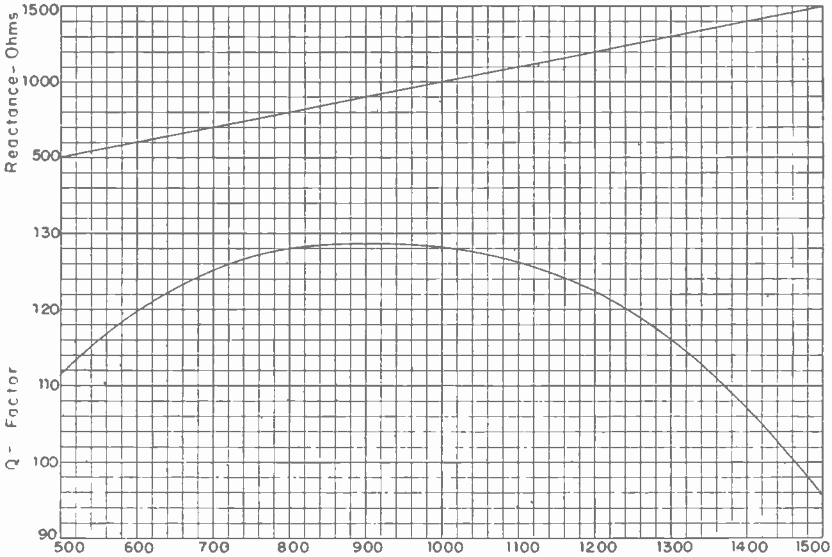

Fig. 14-10.—Reactance (top) and Q-factor (bottom) of the single layer coil.

Coil Forms.—Single-layer coils may be wound on thin-walled tubing made of any insulating material which is a good dielectric, is mechanically strong, and is not subject to warping, shrinking, or other deformation during normal use. Tubing diameters range from 1/4 inch to 1 inch in most cases. Wall thicknesses are from 1/32 inch to 1/8 inch. Low-loss plastics, polystyrene, and high-grade ceramic materials are in general use for coil forms.

Windings on smooth surfaced forms may be held in place by coating them with suitable coil cement, covering either the whole surface of the winding or else strips and spots where holding is required. Cements are available which add very little to the energy losses at very high frequencies. These cements make the winding moisture-proof. When a cement becomes too thick for brushing it may be thinned with a solvent suited to that particular kind of cement. A solvent suitable for one kind of cement may not work with other kinds. A correctly applied cement of good quality forms a smooth surface which does not collect dust readily and which maintains high surface resistance.

Multi-layer coils may be made self-supporting, even when the turns are spaced in layers, by impregnating them with high-grade coil cement. The coil should be dried before cementing by baking in an oven for about one hour at a temperature only a little above 200° F. Immediately upon taking the coil from the oven it is dipped into the cement, or cement is flowed over and through the winding. Impregnating may be done with moisture-repellent paraffin wax which has been thinned by heating it.

Multi-layer Coils.—It is desirable that the difference of potential between adjacent turns be as small as possible, for this will lessen the effect of the distributed capacitance which exists between turns. In a single-layer winding the potential difference

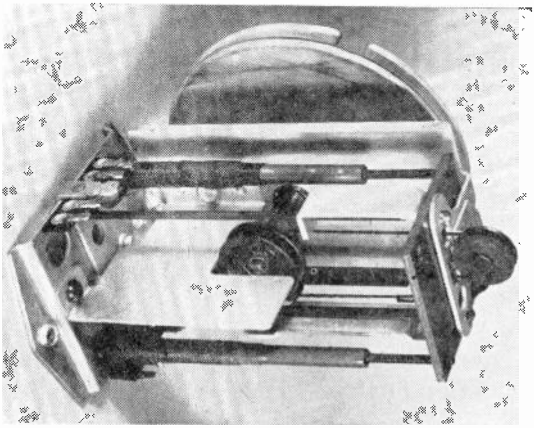

Fig. 14-11.—A standard broadcast radio tuner in which coil cores are raised or lowered by the tuning dial to vary the inductance and resonant frequency.

between adjacent turns will be the overall potential divided by one less than the number of turns. For instance, with fifteen turns there are fourteen spaces between the turns. With an overall potential difference of fourteen volts there would be a difference of one volt per turn.

Supposing that we put the fifteen turns into two layers, as at the left in Fig. 14-12, by winding eight turns and then coming back with the remaining seven turns in the order shown by the numbers. Now, between turns *1* and *15* we have the whole potential difference for the coil, and between most of the other turns there are potential differences several times as great as with an equivalent single-layer winding. To reduce the potential differences we should make the two-layer winding as started for the first six turns in the center diagram. We wind on turns *1* and *2*, then bring number *3* up over the finish of number *2* and into the groove between *1* and *2*. Then turns *4*, *5* and *6* are put on in the positions shown, and the winding is carried along thus to its end. Here we have a two-layer *banked winding* or bank winding. The greatest potential difference will be between turns *2* and *5*, and between others having the same relative positions. This is a great improvement over the arrangement shown at the left.

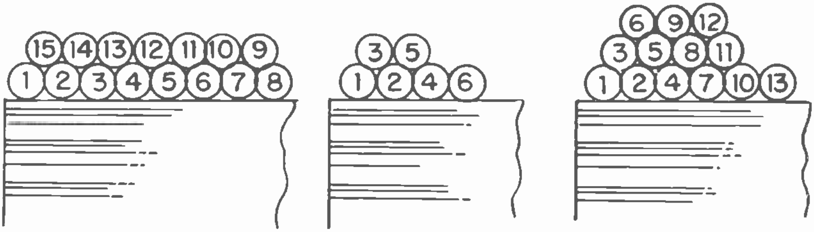

Fig. 14-12.—A multi-layer winding (left) and two kinds of banked windings (right).

A three-layer banked winding is started as shown by the right-hand diagram in Fig. 14-12, and is continued in the same manner until completed. Even more layers may be put on by banking the successive layers in accordance with this principle.

At the left in Fig. 14-13 is shown the principle of another method for lessening the potential differences between adjacent turns of a multi-layer winding. The winding is built up with

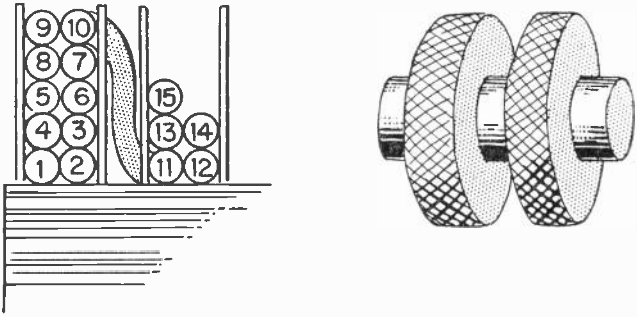

Fig. 14-13.—Successive turns in a pie winding, and how two pies may be mounted.

sections having very short lengths along the coil axis, but of considerable depth. Each such section, as the section containing turns *1* to *10*, is called a pie, and the whole arrangement is called a *pie winding*. The pies may be wound in deep grooves on a form, or they may be supported by spacers as in the diagram. When each pie is a small self-supporting multi-layer coil, several of them may be assembled on an insulating rod or dowel as at the right. Many radio coils used at standard broadcast frequencies are of this pie type.

Fig. 14-14 shows the general appearance and the method of construction of a type of multi-layer coil having adjacent turns spaced to a greater or less degree and having the turns cross one another at an angle. This is called a *duolateral winding*. When the spacing between adjacent turns in the same layer is as great or greater than the diameter of the wire, this type may be called a ***honeycomb coil*** because the openings down through the winding somewhat resemble a honeycomb.

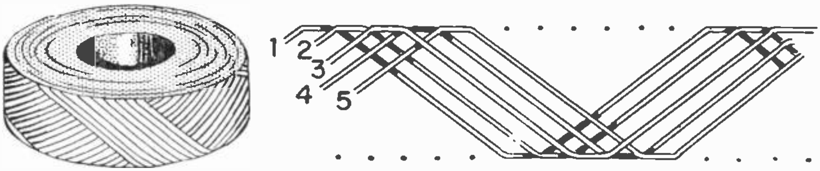

Fig. 14-14.—A duolateral winding and the manner of placing successive turns.

The diagram at the right in Fig. 14-14 shows, considerably enlarged, the manner in which successive turns may be applied to form a duolateral or a honeycomb winding. The few turns which are shown would be applied one after another in the order of their numbering. Coils of this type are impregnated with cements or binders to make them self-supporting. If duolateral windings are made of little length in comparison with their diameter they may be assembled to form the several pies of a pie winding.

Wire for Coil Windings.—Any size or gage of copper wire having sufficient mechanical strength for winding onto a form will be amply able to carry any high-frequency currents likely to exist in television or radio receivers. The wire usually is insulated with a thin layer of enamel or with impregnated fabric. High-frequency coils are wound with solid wire, not stranded. Self-supporting coils with spaced turns sometimes are made with silver plated copper wire or occasionally with solid silver wire. Bare copper wire is not used, because the surface becomes covered with a coating of high-resistance oxide.

A type of wire which is named Litzendraht, but generally is called *Litz* wire, often is used for winding coils which are to operate in the frequency range from about 400 kilocycles to about 3 megacycles or 3,000 kilocycles. This wire is braided from small strands, each having a complete insulating covering of thin enamel. A common size for the individual strands is number 38 gage, with 5, 7, 9, 15 and up to 32 strands in the complete wire. The strands are braided or woven in such manner that each one is on the outer surface for about the same total length as is each other strand. High-frequency losses or high-frequency resistance will be reduced by using Litz wire in the frequency range mentioned. There is little advantage in using it at either lower or higher frequencies.

Unless the separate strands are individually and completely insulated, as they are in Litz wire, stranded wire should not be used for coil windings. The oxide which forms on the bare strands offers high resistance to currents which pass from one strand to others in the wire, and performance will be poor.

R-f Chokes.—Radio-frequency chokes are inductors whose purpose is to oppose the flow of high-frequency currents into or out of various circuits. Often it is necessary to prevent high-frequencies produced in one circuit from escaping to other circuits, and again it may be necessary to keep external high-frequency currents out of a circuit. In either case the inductive reactance of the r-f choke offers great opposition to the alternating currents while allowing almost free flow of direct currents. A resistor, on the other hand, offers equal opposition to both alternating and direct currents.

Several types of r-f chokes are illustrated by Fig. 14-15. Most of these units are of the air core style, with multi-layer duolateral or honeycomb windings on forms of plastic or of ceramic materials. R-f chokes sometimes are made with powdered iron cores. For large inductances and reactances the windings often are arranged in several pies. The inductance needed to provide any given reactance depends, of course, on the frequencies to be opposed. Inductances may be almost anything from a few microhenrys at the highest television frequencies to two or three millihenrys (thousands of microhenrys) for the lower radio broadcast frequencies.

An r-f choke should have very small distributed capacitance. Otherwise the inductance and distributed capacitance are likely to cause self-resonance at some of the frequencies to be opposed, or the addition of distributed capacitance to other circuit capacitances may result in resonance. When two or more r-f chokes are used in different parts of the same circuit the chokes should be placed physically as far apart as possible. Two or more chokes should not be mounted with their axes or center lines lying on or near the same straight line. These precautions are necessary to prevent high-frequency magnetic fields from one choke inducing alternating currents of the same frequency in other chokes and

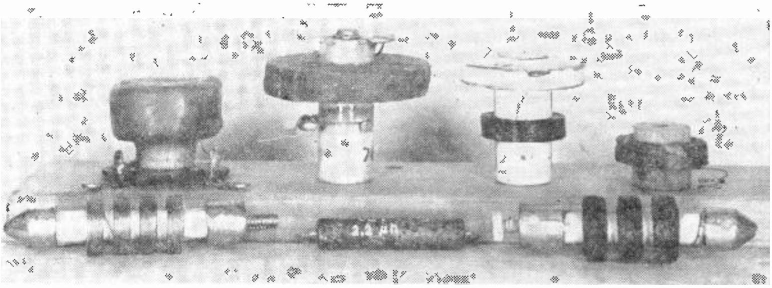

Fig. 14-15.—R-f chokes used wherever high-frequency alternating currents are to be opposed.

their connected circuits. A type of r-f choke occasionally used in high-frequency circuits is illustrated by Fig. 14-16.

Shielding.—Tuning coils, and sometimes r-f chokes, often are enclosed by shields or "cans" made of aluminum or copper. The purpose is to prevent magnetic and electrostatic fields produced by the coil from escaping into other circuits, and to protect the coil from such fields which may be produced by other nearby coils and circuit parts which carry high-frequency alternating currents.

When lines of force of a magnetic field pass into the shielding metal the lines set up eddy currents. These are small currents which circulate in the metal, around the field lines. The eddy currents produce other magnetic fields whose polarity is such as to oppose that of the inducing field lines. Thus the force of the undesired field is largely neutralized in the shield metal, and does not pass through in either direction.

When lines of force in an electrostatic field reach the shielding metal they either draw free electrons toward the surface or repel electrons from the surface. If the field lines are of positive polarity they attract electrons to the surface of the shield. The excess of negative electrons forms a negative charge which largely neutralizes the positive lines of force or positive field. If the field lines are negative they repel free electrons from the surface of the shield metal. The resulting deficiency of electrons forms a positive charge at the surface, and this charge largely neutralizes the negative field lines. Electrons at the inner surface of the shield dis-

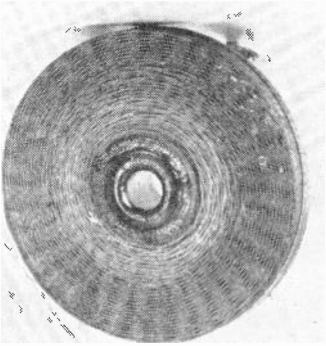

Fig. 14-16.—A honeycomb coil suitable for use as an r-f choke.

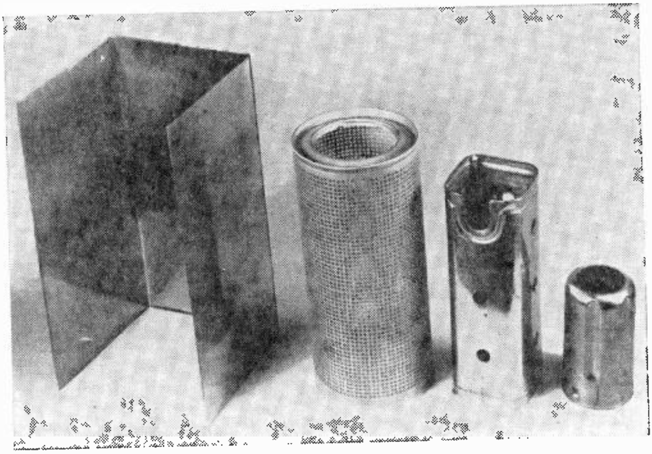

Fig. 14-17.—Shielding enclosures and cans.

tribute themselves uniformly, with the result that there is no effect from the external field. For an electrostatic shield to have maximum protective effect the shield metal must be conductively connected or "grounded" to the main body of chassis metal.

There is effective shielding between two sets of coils or other parts when one set is mounted on top of the chassis and the other set underneath, with chassis metal acting in as the shield. Any partition of metal which is grounded to the chassis acts similarly as a shield for lines of force moving or extending at approximate right angles with the metal surface.

The presence of a shield, or of any metal close to a coil, lessens the effective inductance of a coil. The more closely the shield fits around the coil the greater is the drop of inductance, which, in extreme cases may be as much as 20 to 40 percent of the inductance without a shield. Fig. 14-18 is a picture of a television tuning coil and of the shield which encloses it. Note that width and depth of the shield are more than double the coil diameter, while height of the shield is many times that of the coil, which consists of the dark colored winding at the bottom of the form. A shield so large in comparison with a coil causes negligible loss of effective inductance.

Since a shield reduces the effective inductance it causes a coil to tune or to be resonant at a higher frequency with the shield in place than with it removed. If tuning is adjusted with a shield removed, the resonant frequency will change when the shield is

Because there is a drop in effective inductance, combined with some additional energy loss in the shield metal, shielding reduces the Q-factor of a coil to an extent depending on how closely the shield fits the coil. A shield brings an additional body of grounded metal near the coil, and consequently increases the capacitance between the coil and chassis metal. This is generally equivalent to an increase of distributed capacitance in the coil or circuit.

Parts other than coils may be provided with shields. Many tubes operating at high frequencies are thus protected. Circuit wires sometimes are enclosed with flexible metal braid which, when grounded, acts as a shield. The braid is applied over the insulation of the wire. Entire sections of a receiver may be enclosed within a shield. This often is done with television and f-m tuners, which operate at very high frequencies.

Coil Winding Computations.—Occasionally it is desirable to wind a coil of some given inductance, length, and diameter to suit a purpose for which no ready-made unit is available. The required number of turns may be computed from charts and formulas. When we know the number of turns to be wound in the given length, the wire must be chosen of such diameter or gage size as

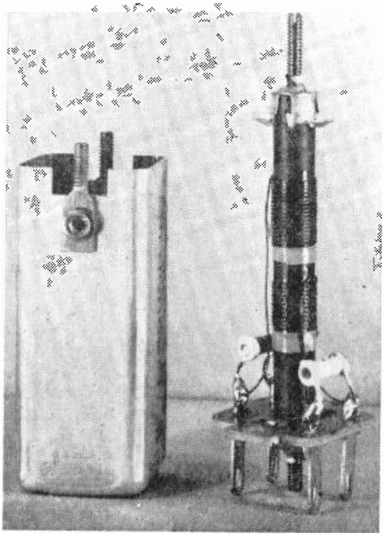

Fig. 14-18.—A television tuning inductor and the shield which protects it.

will meet these requirements.

The greater the required inductance and the greater the number of turns, the more likely it is that the coil, as computed, will perform satisfactorily. For inductances less than 10 to 20 microhenrys, also for diameters of less than a half-inch, the results of computations may not work out any too well. It is advisable to wind 20 to 25 per cent more turns than the computed number, then try the coil in the circuit where it is to be used, and remove turns one at a time or in fractions of a turn until the desired performance is realized.

Charts which have been found useful for coil computations are shown by Figs. 14-20 and 14-21. These charts apply only in the case of single-layer coils.

The first step is to divide the winding length by the diameter, then go to the left-hand vertical scale of Fig. 14-20, follow across to the curve and down to the bottom scale, and there read the *winding form factor*. Second, divide the inductance in microhenrys by the winding diameter in inches, find this result in the left-hand vertical scale of Fig. 14-21, follow across to the curve, down to the bottom scale, and there read the *diameter factor*. Multiplying the two factors together gives the number of turns to be wound on the coil.

As an example, assume a length of 2 inches, a diameter of 1 inch, and inductance of 181 microhenrys. Dividing length (2) by diameter (1), gives 2 as the result. Fig. 14-20 shows the corresponding form factor to be about 9.9. Next we divide the inductance (181) by the diameter (1), which gives 181. Fig. 14-21 shows the corresponding diameter factor as about 13.4. Then the

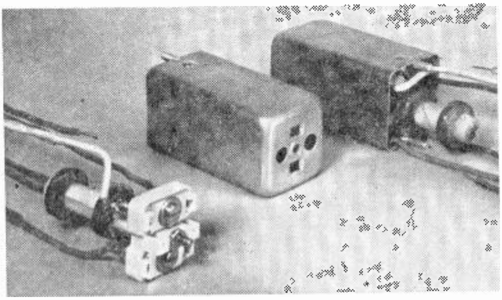

Fig. 14-19.—A tuned transformer used in radio receivers, and the shield which encloses it.

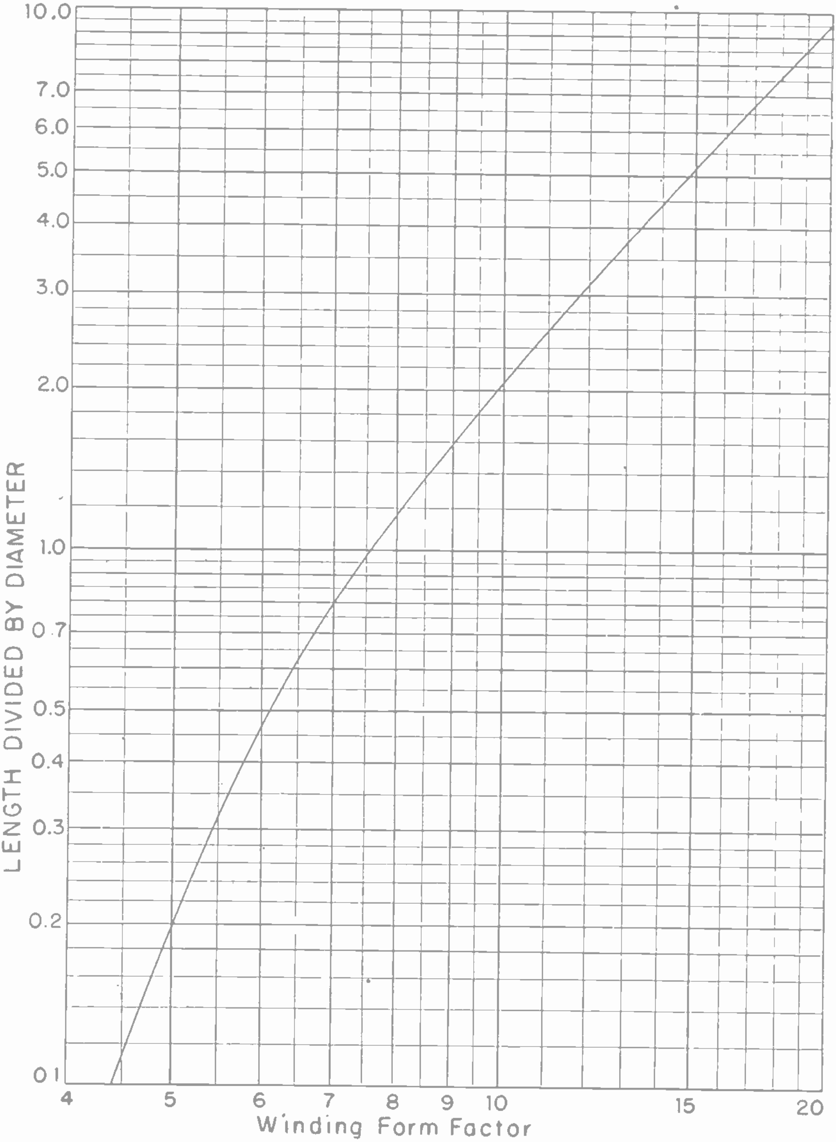

Fig. 14-20.—Chart for determining the form factor of single-layer coils.

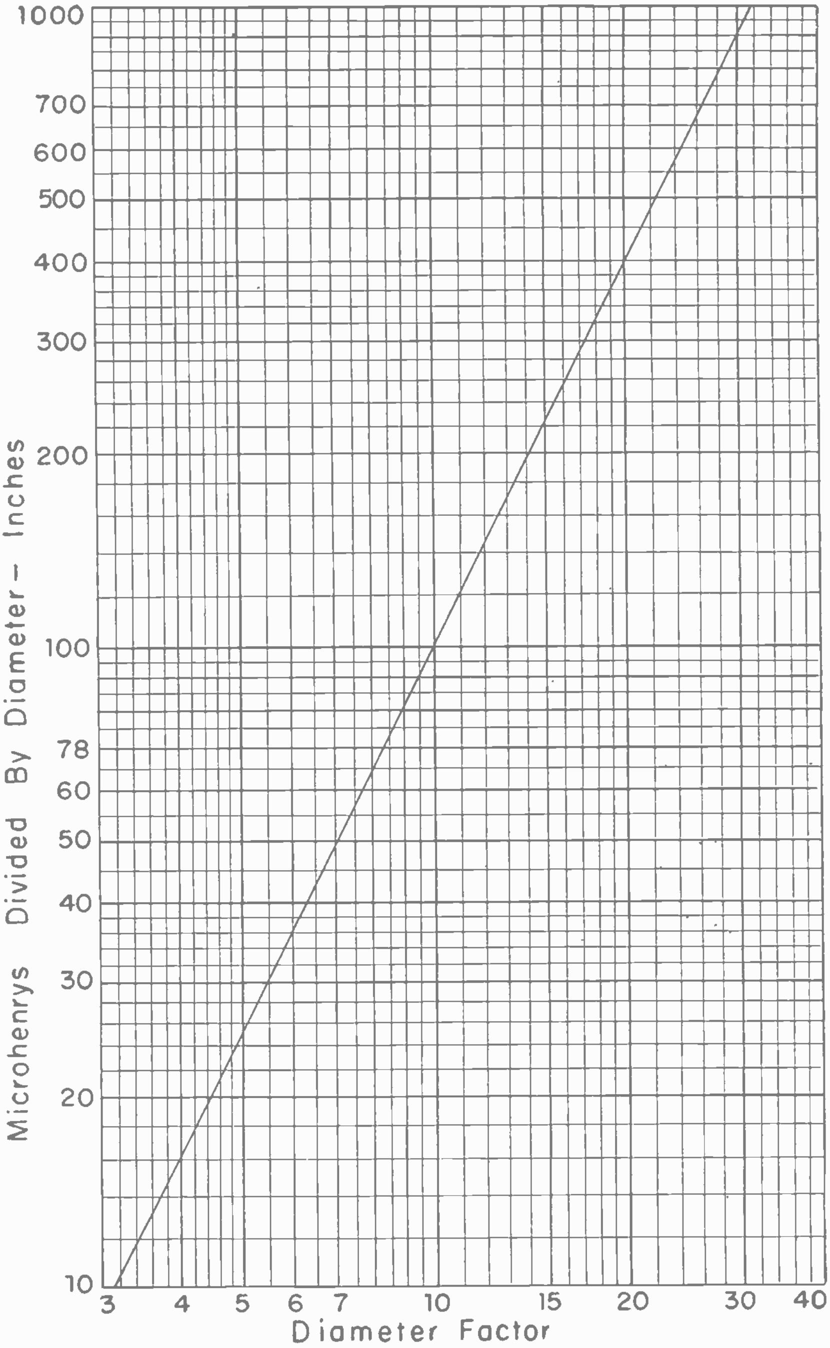

Fig. 14-21.—Chart for determining the diameter factor of single-layer coils.

factors are multiplied, thus,

$$9.9 \times 13.4 = 132.7 \text{ turns}$$

Multi-layer Coils.—The number of turns required in a multilayer coil may be computed from this formula.

$$\text{Turns} = \sqrt{\frac{10 \times \text{winding length} \times \text{microhenrys}}{(\text{mean radius})^2 \times E}}$$

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Dimensions used in this formula are shown by Fig. 14-6. The mean radius is the distance from the coil axis to the center of the height of the winding. The square root of this radius may be found from Fig. 14-5 21, as previously explained. The factor *E* in the formula is the shape factor as found from the table.

To determine a shape factor from the table we first compute two ratios, one for length to height, the other for height to diameter. The value of the length-height ratio then is found in the left-hand column, and that of the height-diameter ratio is found along the tops of the columns. At the intersection of the line and column is listed the shape factor.

For an example in using the table and formula assume a required inductance of 300 microhenrys in a coil 1.25 inches long, 0.25 inch in winding height, and with mean diameter of 1 inch or mean radius of 0.5 inch.

To determine the shape factor we first divide length (1.25) by height (0.25), which gives 5. Then the factor will be found from a line of the table having the number 5.0 at its left. Second, we divide height (0.25) by diameter (1), which gives 0.25. There is no column in the table for this ratio of 0.25, so we use a value midway between those listed in the columns for 0.2 and 0.3. These two values are 0.575 and 0.607. Their average, half way between, is 0.591. This is the shape factor to be used as *E* in the formula.

Placing all the values in the formula, we have,

$$\text{Turns} = \sqrt{\frac{10 \times 1.25 \times 300}{0.5^2 \times 0.591}}$$

$$= \sqrt{\frac{3750}{0.148}} = \sqrt{25330} = 159 \text{ turns}$$

SHAPE FACTORS FOR MULTI-LAYER COILS

Length / Height	Height / Diameter					
	0.025	0.05	0.1	0.2	0.3	0.4
0.1	0.0071	0.0121	0.0197	0.0307	0.0386	0.0445
.2	.0140	.0235	.0383	.0592	.0737	.0845
.3	.0206	.0346	.0559	.0857	.1061	.1209
.4	.0270	.0451	.0727	.1106	.136	.154
.5	.0332	.0553	.0887	.1339	.164	.184
.6	.0392	.0651	.1040	.1559	.189	.212
.7	.0450	.0747	.119	.177	.213	.238
.8	.0508	.0839	.133	.196	.236	.262
.9	.0563	.0928	.146	.215	.257	.283
1.0	.0618	.1015	.159	.233	.276	.304
1.11	.0677	.1109	.173	.251	.297	.325
1.25	.0749	.1222	.190	.273	.321	.349
1.43	.0838	.136	.210	.299	.348	.376
1.67	.0953	.154	.236	.331	.381	.408
2.0	.1107	.177	.268	.370	.421	.447
2.5	.1322	.210	.312	.420	.470	.491
3.3	.1650	.257	.374	.486	.530	.545
5.0	.2219	.336	.467	.575	.607	.611
10.0	.3498	.495	.628	.701	.705	.691

	Height / Diameter					
	0.5	0.6	0.7	0.8	0.9	1.0
0.1	0.0491	0.0529	0.0561	0.0590	0.0617	0.0645
.2	.0928	.0924	.1049	.1097	.1142	.1189
.3	.1320	.1406	.1476	.1536	.1594	.1654
.4	.167	.177	.185	.192	.199	.206
.5	.199	.210	.219	.226	.233	.240
.6	.228	.239	.248	.256	.263	.271
.7	.254	.266	.275	.282	.289	.297
.8	.279	.290	.299	.306	.313	.321
.9	.301	.312	.320	.327	.334	.342
1.0	.321	.332	.340	.346	.352	.360
1.11	.342	.352	.359	.365	.371	.379
1.25	.365	.375	.381	.386	.392	.399
1.43	.392	.400	.405	.410	.415	.422
1.67	.422	.429	.433	.436	.440	.447
2.0	.458	.462	.464	.466	.469	.475
2.5	.499	.500	.500	.499	.501	.505
3.3	.548	.544	.540	.537	.536	.540
5.0	.603	.595	.586	.579	.576	.579
10.0	.672	.653	.638	.627	.621	.620

When you assume certain dimensions for a multi-layer coil the wire will have to be of such size, and so spaced, as to fill out the assumed dimensions. How the wire is wound or arranged makes little difference so long as it is fairly uniform. It is length, height, diameter, and number of turns which determine the inductance.

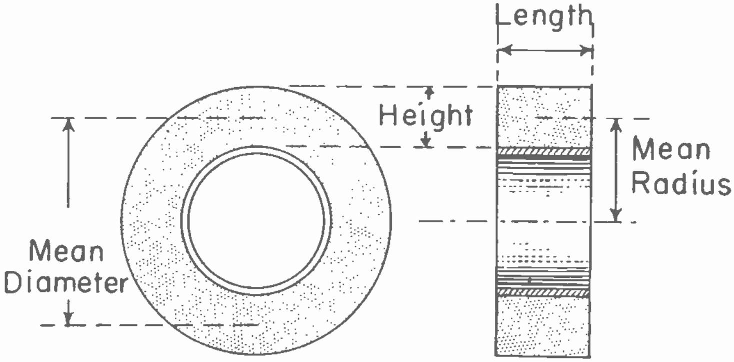


Fig. 14-22.—How and where to measure the dimensions of a multi-layer coil.

Fig. 14-21 is really a chart of numbers and their square roots. You may select any number on the left-hand vertical scale, follow across to the curve, thence down to the bottom scale, and there read the square root of the selected number. To handle numbers larger than those on the figure, add two ciphers to the number on the vertical scale for each single cipher added to roots on the bottom scale. For example, to find the square root of 5,000 add two ciphers to 50 on the left-hand scale. The square root of 50 is about 7.1. Adding one cipher to 7.1 is the same as moving the decimal point one place to the right, which gives 71 as the square root of 5,000. For smaller numbers than listed, move the decimal point two places to the left in any number on the vertical scale, and one place to the left in the bottom scale of roots.

When you assume a certain winding length for a single-layer coil the finished winding must be of this length or else the inductance will be wrong. If the wire is so big as to make a greater length, use wire of smaller diameter or else assume a greater length and start over again. If the winding is too short, spread or space the turns to reach the assumed length.

To determine the number of turns required for a multi-layer coil we may use this formula.

Chapter 5

TUBES FOR TELEVISION AND RADIO

Of all the devices which have been developed within the present century the electronic tube is the one which has been applied in more different ways and in a greater number of fields of endeavor than any other. Like so many things which have turned out to be of great usefulness, the discovery of the basic action in the electronic tube was quite accidental. While Thomas A. Edison was experimenting with his electric lamps in 1883 he observed a glow which appeared in the space between the ends of the filament inside the evacuated bulb, and made note that this effect probably meant a flow of electricity through the space. The faintly luminous appearance resulted from collisions of electrons with gases remaining in the poorly evacuated bulb. The emission of electrons from one end of the hot filament, and their flow through the space to the other end, meant only a leakage of electricity which should pass through the filament itself so far as the production of an efficient incandescent lamp was concerned.

Not until about twenty years later was any practical use made of Edison's discovery. Then Sir Ambrose Fleming put a small metallic plate inside the lamp bulb, near the filament, and used the filament and plate as the two elements of a radio detector. The performance of this detector was far superior to that of the crystals and coherers which at that time were being used for detection. In 1906 Dr. Lee de Forest placed between the filament and plate an open-work grid or mesh. This third element permitted regulation of the rate of electron flow through the tube in accordance with potentials applied to the grid. It was the introduction of the control grid that made possible the remarkable advancement of radio transmission and reception that followed immediately.

Fleming called his two-element tube a *valve*, because it permitted electricity or electrons to flow in only one direction between filament and plate. Today we call such a tube a diode. De Forest called his three-element tube an *Audion*. Now we speak of such tubes as triodes. The diode and the triode are the basic

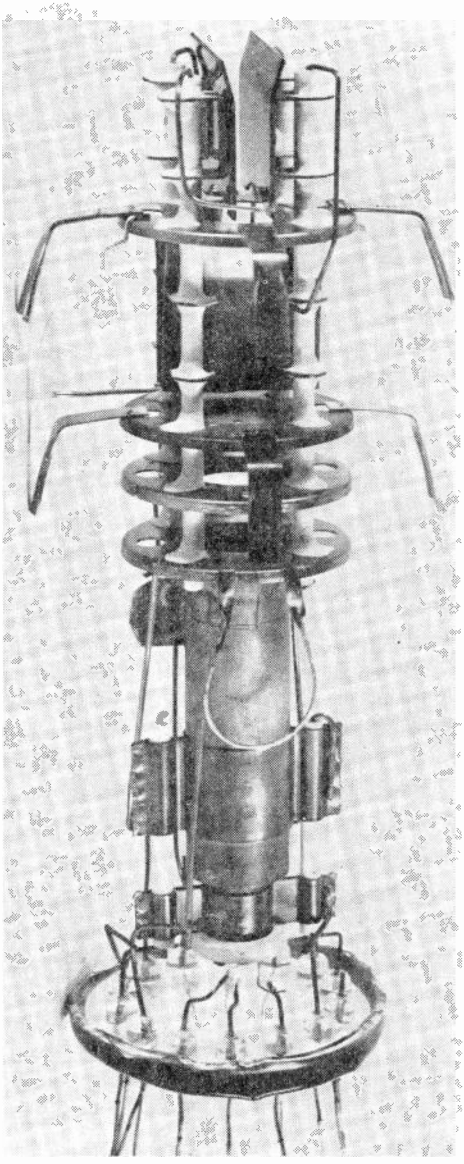


Fig. 15-1.—The elements of a cathode-ray tube used for oscilloscopes.

types of radio tubes. Other grids have been added, and various modifications and combinations have been evolved, until today we have more than three hundred varieties of electronic tubes used in television and radio receivers.

The Parts of a Tube.—The simplest type of tube consists of a tightly sealed bulb, made of metal or of glass, and of two conductors which pass through the walls of the bulb to its interior where the conductors are separated from each other by a space of a fraction of an inch. Electron flow enters the tube through one of the conductors, passes through the space to the other conductor, and leaves the tube by way of that other conductor.

The bulb is more correctly called the *envelope* of the tube. From the interior of the envelope air and other gases have been pumped until the remaining pressure is only about one one-hundred-millionth of normal atmospheric air pressure. The extremely small pressure inside the envelope is called a high vacuum. The tube is evacuated for several reasons. First; all except a few of the gases of which air is composed would eventually corrode some of the internal parts of the tube if allowed to remain in the envelope. Second; were many gas molecules to remain inside the envelope they would prevent free travel of the electrons through the tube space and would interfere with control of the rate of electron flow through the tube. Third; the molecules of some of the gases in air are quite heavy in relation to their size, and when colliding with the surface of the conductor through which electron flow enters the tube these heavy molecules would seriously damage the emitting surface.

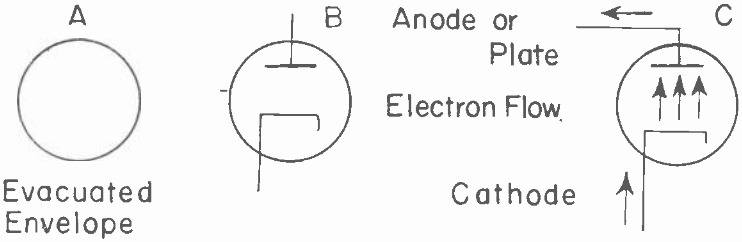


Fig. 15-2.—The symbol for a diode, and the electron flow in this type of tube.

The conductor through which electron flow enters the tube is called the *cathode*. The conductor through which the electron flow leaves the tube is called the *anode.* The anode of tubes used in radio usually is called the *plate.* When radio tubes are shown by symbols the evacuated envelope is indicated by a circle as at *A* in Fig. 15-2. The cathode and the anode or plate are shown as at *B.* As shown at *C,* electron flow enters the tube through the cathode, passes through the space between cathode and anode, and leaves the tube through the plate.

At the left-hand side of Fig. 15-3 are shown large and small radio tubes of types having metal envelopes. At the right are shown one of the smallest and one of the largest of the types having glass envelopes. Glass envelopes have advantages for operation at high voltages; metal envelopes have advantages for operation at high rates of power. Glass is an excellent insulator, and with a glass envelope the conductor connections may be brought out at points well separated and thus well insulated from one another. But high-power glass tubes must be of large size because glass does not so easily conduct and radiate internal heat as does metal. Furthermore, metal will withstand higher temperatures than glass without softening. Any metal-envelope tube of given power rating may be smaller than a glass tube of the same rating. This is one of the principal reasons why many radio tubes have metal envelopes.

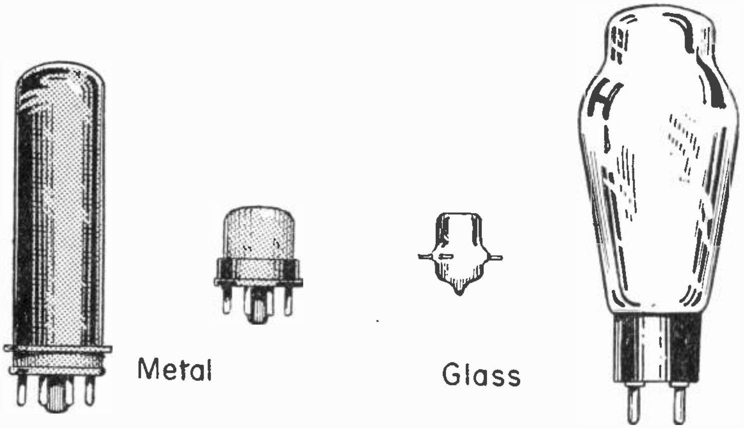


Fig. 15-3.—The relative sizes of large and small radio tubes having envelopes of metal and of glass.

Inside of the envelope are the cathode and the plate. When electron flow passing through the space between cathode and plate is controlled and regulated by a grid, the grid is located between the cathode and plate. In addition to the control grid there are, in many tubes, various other grids whose action improves the performance of the tube and overcomes certain difficulties which may arise when using only a single control grid. A little further along we shall become acquainted with the functions of the several kinds of grids. The cathode, the plate, and all the grids, are called the *elements* of the tube.

Before proceeding with our discussion of the manner in which tubes act it will be instructive to examine the way in which a typical tube is built. For this examination we shall select a type of tube called a *pentode.* The name pentode means that the tube has five elements; a cathode, a plate, and three different grids. After breaking away the envelope, the remaining parts of our tube appear as in Fig. 15-4. At the top is a metallic cap which was supported by the envelope and through which electrical con-

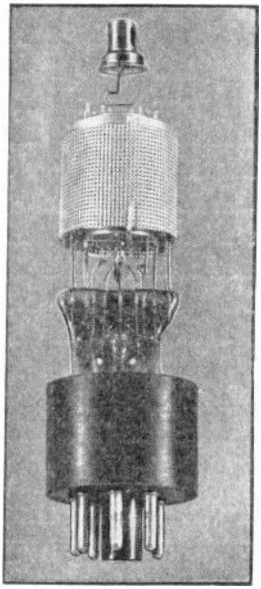


Fig. 15-4.—The pentode tube with its glass envelope removed

nection is made to the control grid. The large perforated cylinder is the outer section of the screen grid which prevents undesirable capacitive couplings between the plate and the control grid. All of the elements are supported on stout wires which extend upward from a glass part called the press or the seal. This glass part is fastened into the insulating base of the tube. Down through the glass extend wire leads which are soldered into the pins on the bottom of the base. With the tube inserted in its socket, connections from the elements are completed through the pins to the circuits which come to the tube socket.

In Fig. 15-5 we have removed the outer section of the screen grid and have exposed the plate. The plate is an open-ended cylinder of thin metal. The surface is blackened to allow more effective radiation of heat than would occur from a bright surface. From one of the two wires that support the plate a connection is made to one of the base pins. In this illustration the control grid cap has been taken off the upwardly extending wire which provides connection between the cap and the control grid.

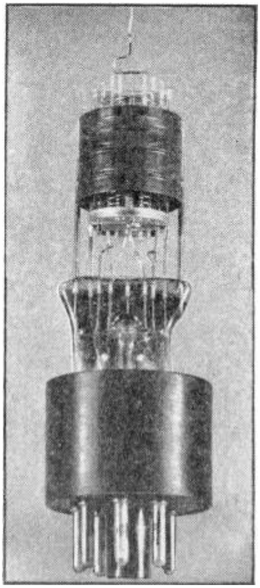


Fig. 15-5.—The plate is the blackened metallic cylinder which encloses other elements.

In Fig. 15-6 the plate has been removed and now we see the several grids which are between the cathode and the plate. All of these grids are made of spirals of wire which measures a little less than 0.005 inch in diameter. The outermost of the grids seen in the picture is the suppressor grid. The purpose of the suppressor is to prevent passage of electrons to the screen grid when these electrons should go instead to the plate. The suppressor grid is connected to one of the base pins.

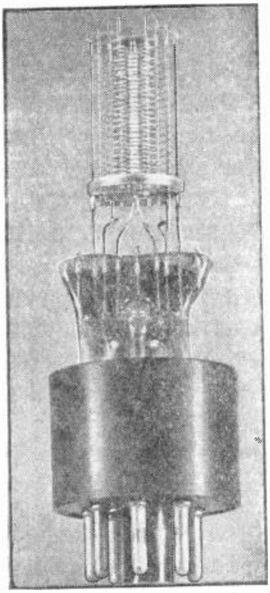


Fig. 15-6.—With the plate removed we see the several grids.

In Fig. 15-7 the suppressor grid has been removed. To show the remaining grids more clearly we may look at the enlarged picture of Fig. 15-8. The outer one of the two grids shown here is the inner section of the screen grid, whose outer section is the perforated cylinder seen in Fig. 15-4. The two sections are electrically joined together so that the screen grid almost completely surrounds the plate and the suppressor grid.

In Fig. 15-9 the screen grid has been removed and now we have remaining only the control grid and the cathode. The control

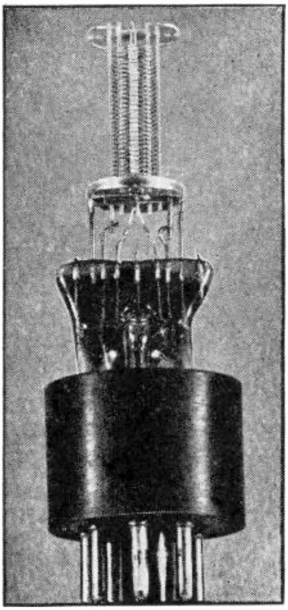


Fig. 15-7.—Removing the suppressor grid exposes the inner section of the screen grid.

grid, like the other grids between the turns of which electrons flow, is a spiral of small wire. The cathode is the white cylinder which is surrounded by the control grid. In this picture may be clearly seen the mica spacer, through holes in which pass the vertical wires that support the various elements of the tube. There is a similar mica spacer carried in the flat metal disc which is below the control grid and cathode and which is itself supported by two of the vertical wires coming from the glass press.

In Fig. 15-10 is shown the cathode by itself. The cathode structure consists of a cylinder of very thin metal. The outside diameter of the cathode cylinder used in our tube is about 0.035 inch. On the outer surface of this metallic cylinder is deposited a thin layer of material from which great quantities of electrons are emitted when the temperature is raised to a dull red heat. Thus the cathode is adapted to its function of furnishing the electrons which pass between the turns of the various grids and enter the plate. The white cathode may be seen through the wires of the grids in several of the preceding pictures.

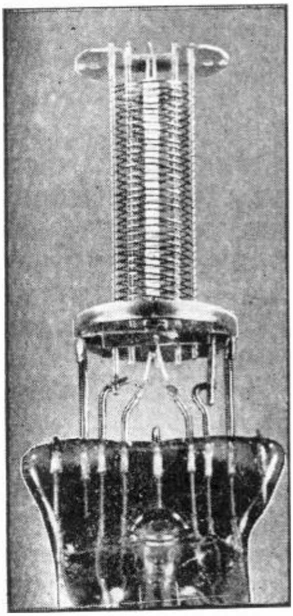


Fig. 15-8.—Here we see the screen grid which surrounds the control grid.

Inside the cathode cylinder is the heater wire shown by Fig. 15-11. In the picture the heater wire has been spread apart to show its connections to the leads running through the glass press, but in actual use the strands of the heater are pressed closely together for insertion into the cathode cylinder. The strands of the heater are only about 0.009 inch in diameter. When either alternating or direct current flows in the heater the wire becomes red hot and raises the temperature of the cathode to a point at which electron emission occurs.

At the left-hand side of Fig. 15-12 are shown the coated cathode cylinder with a heater wire inside the cylinder. At the right are the symbols with which these two parts are represented in wiring and circuit diagrams. The circle represents the envelope of the tube.

To represent a diode tube, having only a cathode and a plate, we add to the symbols for cathode and heater the symbol for a plate, and have the diode symbol shown at the left in Fig. 15-13. Next toward the right we have added between the cathode and

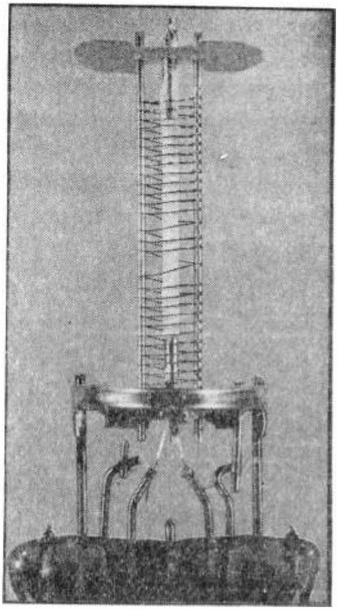


Fig. 15-9.—The control grid surrounds the cylindrical cathode.

the plate a symbol for a grid, and we have the symbol for a *triode* with its three elements. The broken line used to represent a grid clearly indicates that the grid is of open-work construction and that electrons may flow through the spaces. In the next diagram we have added a second grid, making four active elements in the tube. A tube with four elements is called a *tetrode.* Adding still another grid, as in the right-hand diagram, makes a total of five active elements and we have the symbol for a *pentode.* The word pentode means a tube with five elements. The actual construction of one kind of pentode was shown by Figs. 15-4 to 15-11. The symbol at the right in Fig. 15-13 represents that pentode or any other pentode. The grid nearest the cathode in the symbol is the control grid. The next one is the screen grid, and the one nearest the plate is the suppressor grid.

Construction and Action of a Diode.—In Fig. 15-14 is shown the construction of one style of diode tube, which is the type of tube having only a cathode and a plate. The particular tube illustrated really consists of two diodes inside of one envelope. The

Fig. 15-10.—The coated cathode is exposed by removing the control grid.

envelope has been removed in the picture. From one of the diode sections the plate has been removed and laid down by itself at the right of the tube base. Removal of the plate, which is an open-ended metallic structure of rectangular shape, leaves exposed the cathode which you may see still carried by the wires coming through the glass press.

The cathode shown in Fig. 15-14 does not consist of a coated cylinder with a heater wire inside, but consists only of a flat ribbon or wire which is coated with the materials which permit ready emission of electrons from its surface. When alternating or direct current flows through this wire it is heated to the dull red temperature at which electron emission occurs directly from the coated surface on the hot wire. A cathode of this type is called a *filament-cathode,* or sometimes is called simply a *filament.* A cathode having a separate internal heater, as shown by Figs. 15-10 and 15-11, is called a *heater-cathode.*

At the left in Fig. 15-14 the plate of that diode section is in its normal operating position around the filament-cathode, the

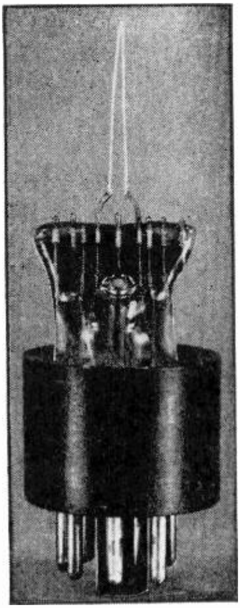


Fig. 15-11.—This is the heater wire which is inside of the cathode cylinder.

bottom ends of which may be seen extending upward into the space inside the plate.

In Fig. 15-15 a single diode with a filament-cathode is shown connected in series between a source of alternating potential

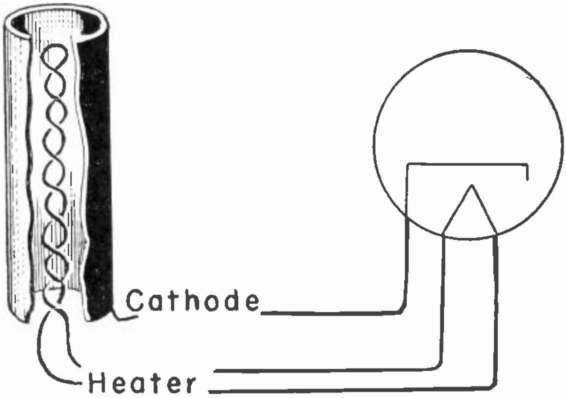


Fig. 15-12.—At the right are the symbols for the cathode and its heater.

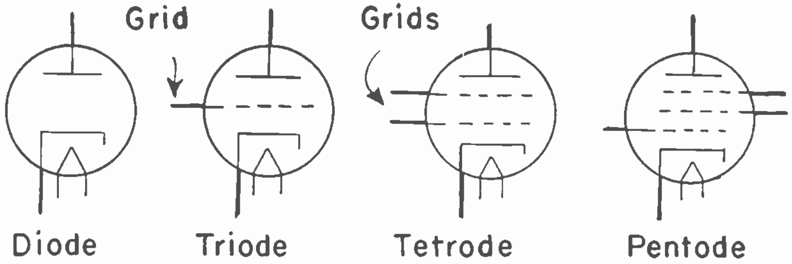


Fig. 15-13.—The symbols for four types of tubes.

and a load. The filament-cathode is heated from a separate source. The electron flow for heating the filament is indicated by broken-line arrows. The electron flow in the source, the tube space, and the load is indicated by full-line arrows. During one-half of each cycle of alternating potential from the source the upper terminal

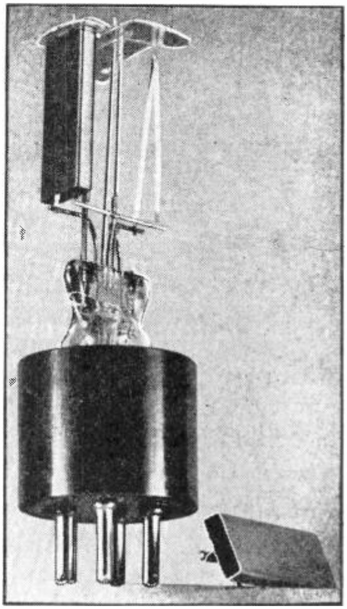


Fig. 15-14.—The glass envelope has been removed to show the parts of a tube containing two complete diodes.

of the source will be positive and the lower terminal negative, as marked. During the opposite half-cycle the polarities of the source terminals will be reversed. The upper terminal of the source is connected through the load to the plate of the tube and the lower terminal is connected directly to one end of the filament-cathode of the tube. During the half-cycle in which the tube plate is made positive, and its cathode negative, the negative electrons emitted from the cathode will be drawn through the space between cathode and plate, and will enter the plate. During the opposite half-cycle the plate of the tube will be made negative and its cathode positive. With the plate negative with reference to the cathode no electrons will flow through the tube. This is

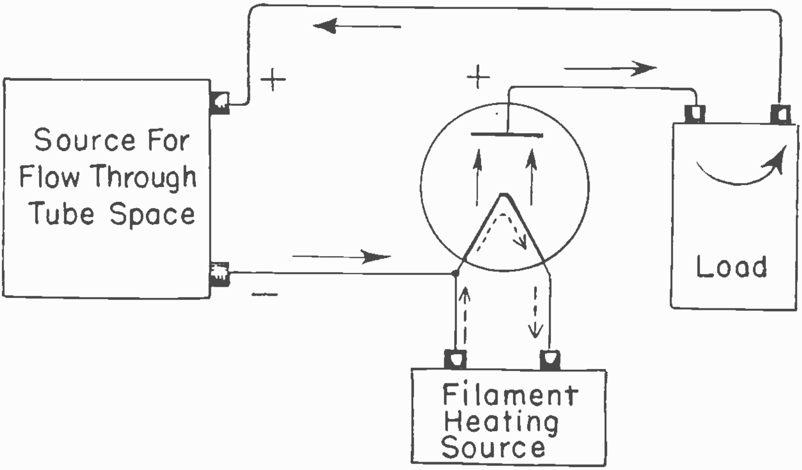


Fig. 15-15.—Connections for a diode tube having a filament-cathode.

true because electrons are being emitted only from the hot cathode and not from the relatively cold plate, and because negative electrons will flow only to a positively charged body and not to one that is negatively charged.

It is important to keep in mind that electron flow in a tube always is from cathode to plate, never from plate to cathode under any normal conditions of operation, also that this electron flow from cathode to plate occurs only while the plate is positive with reference to the cathode. Whether a tube has no grids at all, or has any number of grids, the electron flow always is from the cathode to a positive plate. The electron flow or current that heats the cathode takes no part in the flow from cathode to plate. This heating current passes only through a filament-cathode or through a separate heater from end to end of the heating unit. None of it leaves the filament-cathode or the separate heater to flow to the plate.

Fig. 15-16 shows a diode with a heater-cathode connected between a source of alternating potential and a load to serve the same purpose as the filament-cathode tube of Fig. 15-15. Any diode used in this general manner acts as a *rectifier*. A rectifier is a device which permits only one-way flow or which permits flow of only a direct current when the source furnishes alternating potential. The alternating potential of the source in Fig. 15-16 is indicated by the full-line arrow for one polarity and by the broken-line arrow for the opposite polarity. Electron flow through the diode tube occurs only during the half-cycle in which the plate is made positive with reference to the cathode. Since the tube is in series between source and load, there will be pulses of one-way flow, indicated by full-line arrows, only during the half-cycles in which the tube plate becomes positive. Thus, with the help of a diode used as a rectifier, we may have a pulsating or intermittent direct current through a load when the source furnishes alternating potential.

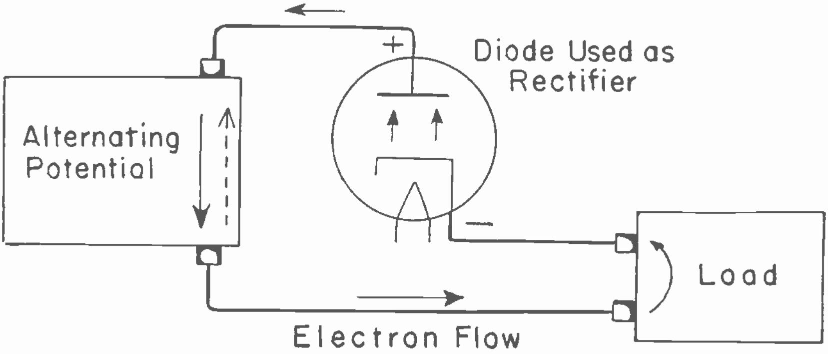


Fig. 15-16.—A heater-cathode type of diode used as a rectifier.

Electron Emission.—It is apparent from Figs. 15-15 and 15-16 that electrons passing through the tubes from cathode to plate continue on through the source, the load, and back to the cathode. Electrons enter the cathode at the same average rate at which they leave through the plate. Were this not the case, the cathode almost instantly would run out of free electrons and there could be no continued flow through the circuit containing the tube. In order that there may be electron flow through the tube it is necessary that great numbers of free electrons leave the emitting surface of the cathode. For such numbers of free electrons to get out of the cathode and into the tube space the electrons must be given enough additional energy for them to break away from the surface of the cathode material. Liberation of electrons from the cathode surface is called *electron emission.*

There are several ways in which electron emission may be assisted. In high-vacuum tubes the commonest method of giving the electrons extra energy is to heat the cathode material. Emission due to heating is called *thermionic emission*, and tubes employing this method of emission may be called *thermionic tubes.* Most radio tubes employ this method of emission. In phototubes the extra energy comes from the energy of light and of other radiations which reach the cathode material. This method is called *photoemission.*

In most tubes operated at cathode-to-plate potential differences up to a few hundred volts the electron emitting material on the cathode is made of salts of barium and strontium applied on a support of nickel or of some alloy metal capable of withstanding high temperatures. These *coated cathodes* provide ample electron emission when operated at dull red heat, around 1,300° to 1,400°F. Another type of heated cathode is made of thoriated tungsten ribbon or wire. Thoriated tungsten is an alloy of tungsten with a little thorium. These cathodes, used chiefly in tubes handling medium amounts of power, are operated at a bright red or yellow heat. In high-power high-voltage transmitting tubes and in some other heavy-duty tubes the cathodes are made of pure tungsten. Tungsten cathodes are operated at white heat, as hot as the filament in an incandescent lamp.

While cathodes are made of materials which are good electron emitters, or are coated with such materials, the plates are made of materials which are poor emitters of electrons unless their temperature is very high. Plate materials include molybdenum, nickel, nickel-chromium-iron alloys, tantalum, tungsten, and graphite.

Electric Fields.—Before proceeding with our examination of the methods employed for control of electron flow in radio tubes it will be well to review some of the elementary principles relating to electric fields and to the behavior of electrons in such fields. There is an electric field between cathode and plate in every tube while the plate is positive with respect to the cathode. The function of the various grids is to modify this field in one way or another, and it is these modifications of the electric field that bring about the remarkable results found in radio circuits.

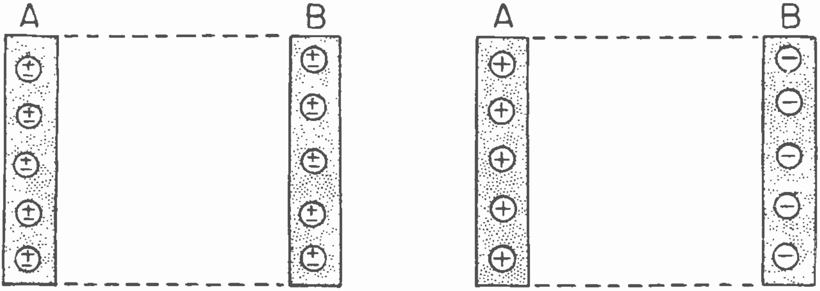


Fig. 15-17.—The charges at the right are produced by transfer of electrons.

At the left in Fig. 15-17 are represented two bodies which are neutral, or in each of which are equal positive and negative charges. Between the bodies is a space in which may be a vacuum. At the right there have been transferred from *A* to *B* enough electrons to produce a negative charge on *B* and a positive charge on *A*.

If, as at the left in Fig. 15-18, a positively charged atom is in the space between *A* and *B*, this positively charged particle will be repelled from *A* and will be attracted toward *B*. It will tend to move toward the negative charge on *B*. If, as at the right, there is a negatively charged particle, a free electron, in the space between *A* and *B*, this negative particle will be attracted by *A* and repelled by *B*. It will tend to move toward the positive charge at *A*.

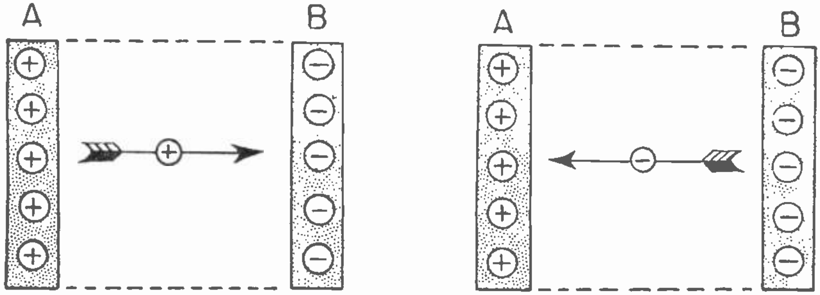


Fig. 15-18.—Charges are attracted toward other charges which are of opposite polarity.

In the space between the positive charge on *A* and the negative charge on *B* there are forces which tend to move all charges that are within the space. Any space in which there are such forces is said to contain an *electric field.*

When representing electric fields in diagrams they are shown, as in Fig. 15-19, by lines along which charges such as negative electrons and positive atoms would tend to move when in the field. This graphic method of indicating electric fields is of help in understanding what goes on. The direction of these lines is shown as the direction in which a positive charge would move through the field. The lines which represent the field are called *lines of electric force.* Of course, such lines have no real existence, but are shown simply for convenience.

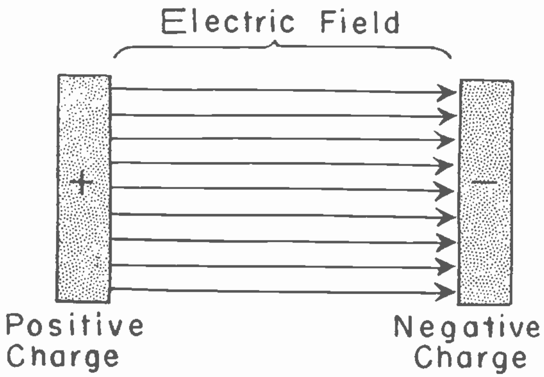


Fig. 15-19.—An electric field exists in the space between charges.

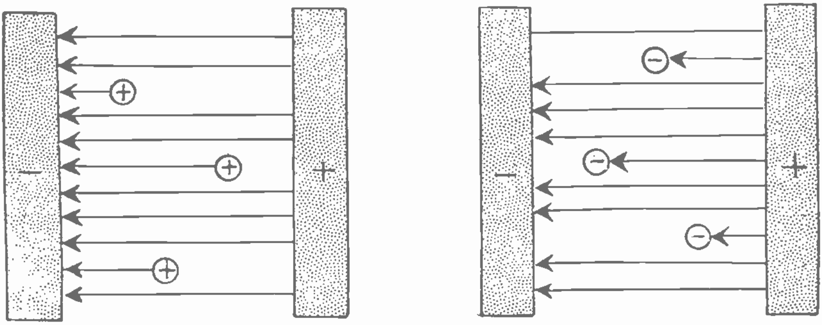


Fig. 15-20.—Lines of electric force start from one charge and end on another charge of opposite polarity.

Lines of electric force in a field are assumed always to start from a positive charge and to end on a negative charge. When there are negative electrons in the field, as at the right in Fig. are positive charges in the field space, as at the left, lines of charge will end on these intervening negative charges. If there are positive charges in the field space, as at the right, lines of force starting from these positive charges will end on the principal negative charge, which is one of the charges that is sustaining the electric field.

Potentials in the Electric Field.—When electrons in Fig. 15-17 were moved from *A* to *B* in establishing the charges, work had to be done on the electrons to get them across the space from *A* to *B*. That work added energy to the electrons. Consequently, the excess negative electrons at *B* have more energy than they had when at *A*. These electrons gained potential energy, which is the kind of energy due to change of position.

While the electrons were moving from *A* to *B* they gained energy at a continual and uniform rate; assuming that the space contained nothing but a vacuum. At any instant during the transfer the potential energy in the electrons was proportional to the fraction of the distance that they had traveled toward *B*. The potential energy possessed by electrons in an electric field depends on their position in the field, or on their distance from the charges which are sustaining the field. In Fig. 15-21 it is shown how an electron traveling through an electric field from positive to negative gains greater and greater fractions of its final increase of potential energy as the electron moves through the field.

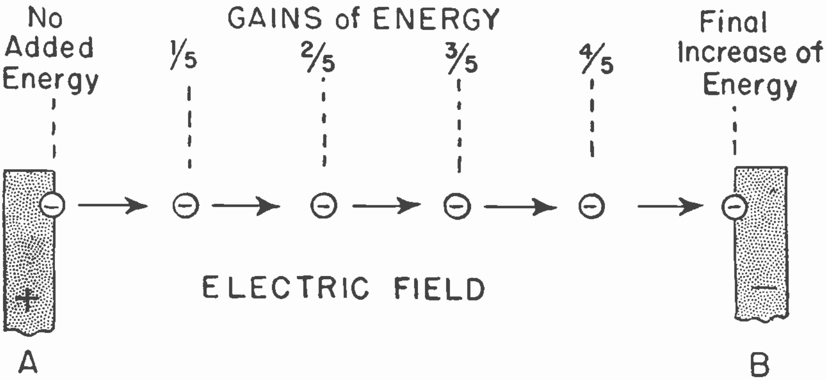


Fig. 15-21.—When electrons move through an electric field they gain energy if movement is from positive to negative.

Every position in an electric field or every point in such a field has associated with it a value of potential energy which would have been added to a charge moved to that position. These various positions or points in a field are said to be of certain *potential.* Electric potential is simply a value which describes the property of a position or point in an electric field.

If the dimensions of the space and the material in the space between *A* and *B* of Fig. 15-21 are such that the movement of one coulomb of electricity from *A* to *B* requires the expenditure of 0.737 foot-pound (one joule) of work, the difference of potential between *A* and *B* is *one volt.*

Should electrons now be released from *B* they will use their excess energy in doing the work necessary to get back through the field and reach *A*. As the electrons travel in this direction through the field they lose more and more energy. The energy which remains in an electron as it reaches any position in the field corresponds to the potential in volts of the field at that position.

Relations between field strengths and potentials are summarized thus: The total field strength between a positive charge and a negative charge is measured in volts, and is equal to the total potential difference between the charges. There is a potential difference of one volt between any two positions in a field when 0.737 foot-pound of work must be done to transfer one coulomb of electricity from one position to the other in the direction of positive to negative. There is likewise a potential difference of one volt between any two points when one coulomb of electricity will do 0.737 foot-pound of work when moving from one point to the other in the direction of negative to positive.

The relations between work and energy in an electron moving through an electric field due to electric charges are like those in a weight moving up and down in the field of force due to gravity.

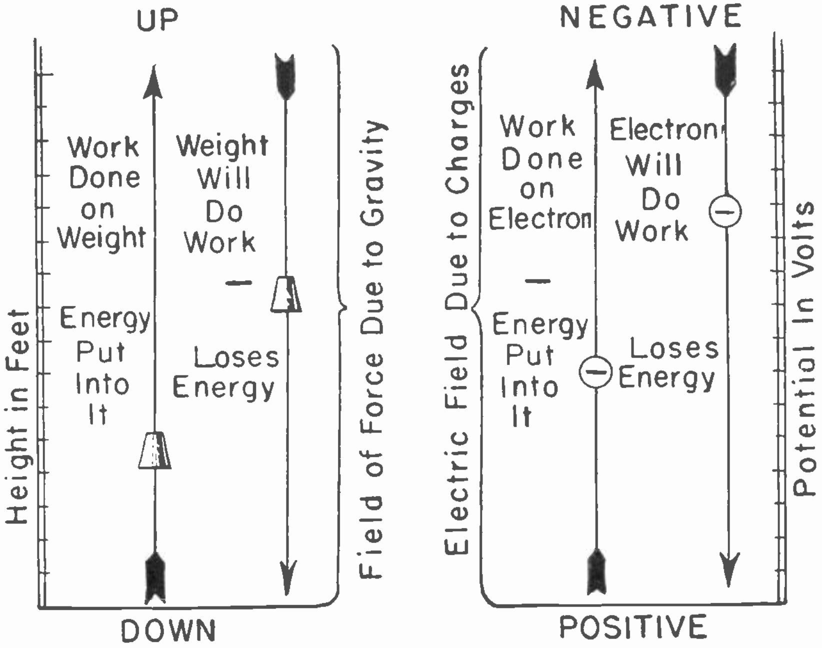


Fig. 15-22.—Energy and work in a mechanical system, at the left; and in an electric system, at the right.

This is shown by Fig. 15-22. The work done on the weight, the work it will do, and the energy it possesses in the gravitational field are proportional to the height in feet of the point in the field at which the weight may be. The work done on an electron, the work it will do, and the energy it possesses in an electric field are proportional to the potential in volts of the point in the field at which the electron may be.

Electron Flow in Conductors.—While discussing the behavior of electrons in electric fields we may look also at the effects of electric fields on free electrons which are in a conductor rather than in an open space between charges. In Fig. 15-23 there has been placed in the electric field between positive and negative charges a conductor in which there are free electrons. The free negative electrons are attracted toward the positive charge, and they accumulate in the end of the conductor which is toward the positive charge. Lines of electric force from the positive charge end on these negative electrons. Other free electrons are repelled by the negative charge, and in the end of the conductor toward this charge there remain atoms or molecules which have lost some of their negative electrons and which thus have become positive. Lines of electric force from these positive atoms or molecules extend to the negative charge.

What actually happens is shown by the lower diagram of Fig. 15-23. There is a shifting of electrons throughout the entire length of the conductor which is between the charges. As an electron is drawn away from the atom at the extreme left this

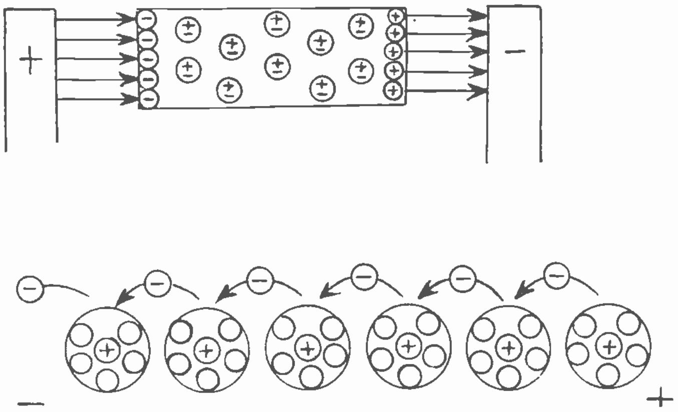


Fig. 15-23.—An electron flow means that there is movement of free electrons.

atom momentarily becomes positive. Note that it is shown as lacking one negative electron. Then this positive atom attracts an electron from the atom next toward the right. This action repeats from atom to atom until, in the atom at the extreme right, there remains a deficiency of one electron; this electron having been repelled by the negative charge at the same time that it was attracted by the positive atom on its left.

Note that the electric field does not extend through the conductor from end to end. The field exists between the positive charge and the excess of negative electrons drawn by this charge to one end of the conductor. The field exists also between the excess of positive charges remaining at the other end of the conductor and the principal negative charge.

At the left-hand side of Fig. 15-24 the conductor between the charged bodies has been placed in direct contact with these bodies. The surplus of electrons which would have accumulated in the end toward the positive charge now passes over into the positively charged body, while the deficiency of electrons in the end toward the negative charge is replaced by electrons entering the conductor from the negatively charged body. This action continues until enough electrons have entered the positively charged body to neutralize its charge, and until enough electrons have left the negatively charged body to leave it neutral. The accompanying flow of electrons through the conductor between the

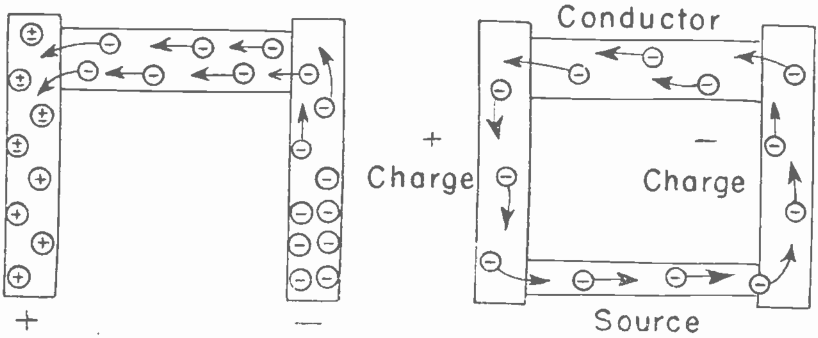


Fig. 15-24.—Electric charges and an electron flow are maintained by a source of electromotive force.

charges would continue for only an instant; only while the charges are being neutralized.

To maintain a flow of electrons through the conductor, the positive and negative charges must be maintained rather than being allowed to neutralize. The charges are maintained by connecting the charged bodies, or by directly connecting the conductor, to a source of electromotive force. Such a source is represented at the right in Fig. 15-24. The source continually removes electrons from the end of the conductor which is to be maintained positive, and continually supplies electrons to the end which is to be maintained negative.

As we have seen, electron flow through the conductor is maintained by the electric fields and by the forces of attraction and repulsion. But in the source the electrons must be made to flow against these natural forces, they must flow from positive to negative. Electrons may be made to flow from positive to negative only by doing work on them and adding energy to them. The energy which is lost by the electrons as they themselves do the work necessary to get through the conductor from negative to positive must be put back into the electrons as work is done on them during their movement from positive to negative in the source.

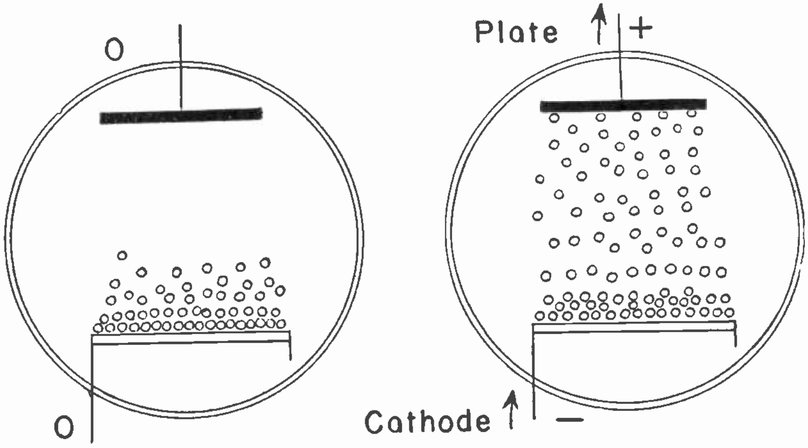


Fig. 15-25.—Emitted electrons form the space charge, and from this charge electrons pass to a positive plate.

There are many ways of doing work on the electrons and adding energy to them in the source. With all of these ways we employ energy which originally is in some form other than electrical. We may use the energy of mechanical motion, or the energy which exists as heat, or as light, or the energy which exists in chemical combinations. A generator translates energy of mechanical motion into electromotive force, which is the force that imparts energy to electrons. A thermocouple translates heat energy into electromotive force. Certain types of photocells translate light energy into electric energy. A battery translates chemical energy into electric energy. Any of these sources may be used in an electric circuit wherein electron flow is to be maintained.

The Space Charge.—Now we may return to our radio tube and examine what happens when electrons are emitted from the cathode surface and when there are electric charges maintained on the elements inside of the tube envelope. At the left-hand side of Fig. 15-25 is represented a heated cathode. The cathode and the plate are at the same potential; there is no potential difference between them. Great quantities of negative electrons are emitted from the surface of the cathode. This loss of negative electrons, which are negative charges, leaves the cathode somewhat less negative or relatively more positive than when there is no emission. Consequently, many of the negative electrons are pulled back into the cathode while others are being driven out of the cathode by the energy added to them because of heating.

The electrons which are in the space between cathode and anode at any instant form what is called the *space charge.* The space charge is a negative charge because electrons are negative charges. This negative charge existing in the space near the cathode repels other electrons which are leaving the cathode or which are attempting to leave it. This effect of the negative space charge limits the rate at which electrons are emitted from the cathode.

At the right in Fig. 15-25 the plate has been made positive with reference to the cathode. Now negative electrons from the space charge are attracted to the positive plate and enter the plate. Taking these electrons out of the space charge reduces this charge, or makes it less negative. This reduction of the negative space charge reduces the repelling action on electrons coming out of the cathode and permits an increase of emission rate.

The rate of emission is increased by higher cathode temperature. Consequently, the higher the cathode temperature the greater will become the space charge and the more negative it will be. At the same time the rate at which electrons are taken away from the space charge and carried into the plate increases with increase of potential difference between plate and cathode, assuming, of course, that the plate is positive with reference to the cathode and to the space charge. Thus the space charge is reduced by increasing the plate-cathode potential difference. It follows that the space charge in a diode tube varies with the temperature of the cathode and with the plate-cathode potential difference.

The plate-cathode potential difference is called *plate potential* or *plate voltage*. The usual symbol for this potential or voltage is *Ep*. If the plate potential is made great enough the electrons will be drawn away from the cathode as fast as they are emitted, and there will be no negative space charge around the cathode surface. Also, if the cathode temperature is unduly reduced, with no change of plate potential, the rate of electron emission will be so lessened that all of the emitted electrons will go to the plate the instant that they emerge from the cathode, and again there will be no negative space charge remaining around the cathode.

With no negative space charge around the cathode to oppose the emission there is a strong tendency for excessive emission to occur from any spots on the cathode surface where this surface happens to have greater emissive ability than the surrounding areas. The excessive rate of emission overheats these spots. The emissive coating or the cathode metal itself is overheated and the cathode is permanently damaged. Then, to provide the original rate of emission the remaining undamaged portions of the cathode surface have to provide more emission than that for which they are designed, and soon these areas break down from overload. Within a short time the cathode becomes unable to provide enough emission for normal operation of the tube, and the tube becomes useless. It is for this reason that no tube should normally be operated at a plate potential in excess of the rated maximum potential, nor should the cathode be underheated by

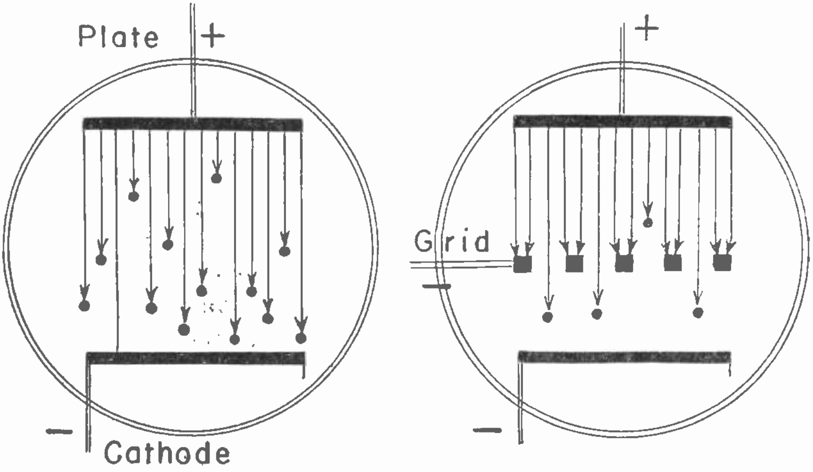


Fig. 15-26.—How the electric field acts on free electrons, and how the field is modified by a negative control grid.

supplying it with a heating current less than the minimum rated value which will maintain a suitable temperature.

When all of the emitted electrons are drawn away from the cathode as fast as they emerge from it, the rate of electron flow or the current through the tube is called the *saturation current* or the total emission current. Tubes are operated in this manner only during certain tests or for special and unusual requirements. When a tube is so operated that a negative space charge is maintained the operation is said to be *space charge limited.*

Action of a Control Grid.—At the left-hand side of Fig. 15-26 is represented a diode with lines of electric force extending from the positively charged plate to negative electrons which are in the space between plate and cathode. Each line is considered to represent one unit of positive charge. Each line ends on one electron, which is one unit of negative charge. This is the operating condition when there is one space charge electron for every unit of positive charge on the plate. If there are too few electrons in the space charge, as would happen with insufficient cathode heating, some of the field lines of force from the plate will extend all the way to the negatively charged surface of the cathode rather than ending on negative electrons. The lines of force which reach a free electron in the space charge cause the electron to travel along these lines to the plate.

At the right-hand side of Fig. 15-26 there has been inserted between plate and cathode an open-mesh grid on which is maintained a negative charge. Now a great many of the lines of force from the positive plate end on the negative charge of the grid instead of on negative electrons. Only those lines which do not end on the grid, but which pass through its open spaces, can reach electrons being emitted from the cathode and can cause these electrons to be drawn through the grid to the plate. Placing the negative grid between plate and cathode has greatly reduced the effectiveness of the plate in attracting electrons, and, in effect, has the same result as a reduction of plate potential in lessening the rate of electron flow through the tube.

Note that no negative electrons are entering the negative grid, because no lines of force start from the grid while it is negative. Since no electrons flow to and into the grid there is no electron flow or no current in the grid or in any circuit connected to it. It is only the charge on the grid, which is a matter of relative potentials, that is controlling electron flow. Since the grid and the grid circuit are here carrying no electron flow there can be no power used in the grid circuit. So we have a means of controlling an electron flow or a current flow without having to use any power for the job. There is no other means of control that approaches such efficiency as this.

It is quite plain that the grid may be given a potential sufficiently negative with reference to the cathode, or a charge sufficiently negative, so that all lines of force from the plate end on the grid, none get through to the space between grid and cathode, and no electrons flow through the grid to the plate. This is the condition called *plate current cutoff*, and the necessary negative potential of the grid is called the *cutoff potential.*

In Fig. 15-27 the grid has been made positive with reference to the cathode, although not nearly so positive as is the plate. Lines of force now extend from the positive grid toward the cathode and reach negative electrons in the space charge. The grid is so much closer to the cathode than is the plate that a given charge on the grid is far more effective in pulling electrons than

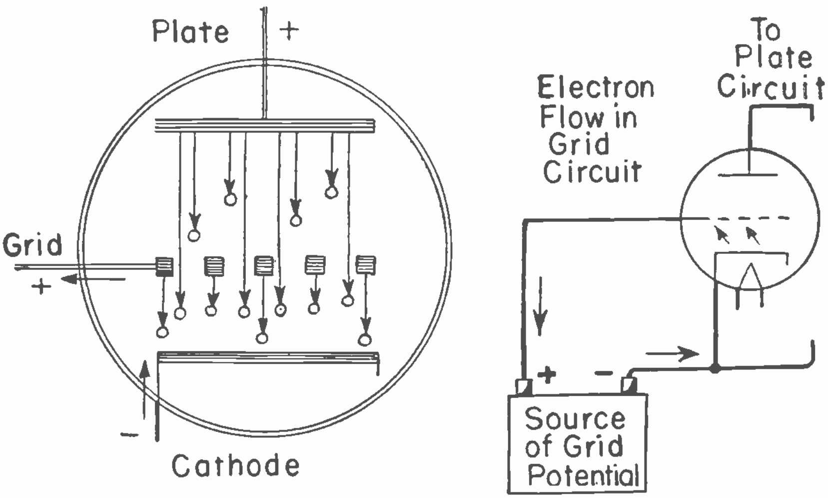


Fig. 15-27.—When the grid is made positive it attracts electrons just as does the positive plate.

would be an equal charge on the plate. The result is that many electrons are drawn into the grid itself. They form an electron flow in the grid circuit, or form a *grid current.* In the circuit between grid and cathode is the source of grid potential, also conductors in which there is more or less resistance. Electron flow in this resistance means power, because $P = I^2R$, and this power must be furnished from some outside source. Therefore, a positive grid means that power must be furnished to the grid circuit.

Most of the electrons attracted to the positive grid do not enter the grid. By the time they reach the grid the electrons are traveling so fast that they go on through the grid spaces, then are attracted to the plate, which is much more positive than the grid. A positive grid not only draws electron flow into itself, but it greatly increases the electron flow to the plate.

By varying the potential of the grid with reference to the cathode, by making the grid more or less negative or else more or less positive than the cathode, it is possible to control the rate of electron flow from cathode to plate, and this means control of electron flow in any circuit into which the plate and cathode of the tube are connected.

Television Tubes.—All of the principles which have been explained in this chapter apply equally whether a tube is used in a television receiver, an f-m broadcast receiver, or a standard broadcast radio receiver. Miniature tubes are more common in the high-frequency circuits of television and f-m sets than in standard broadcast receivers, because more miniature types than larger types have been designed especially for efficient operation at high frequencies. Miniature tubes also are space savers, and for this reason are finding increasing application in the smaller sizes of sound radios.

Diodes, triodes, and pentodes are used in all types of receivers, but undoubtedly the most common of these is the pentode. This is chiefly because more circuits or more "stages" are used for strengthening or amplifying signals than for any other one purpose, and the pentode is a highly effective amplifier. We find more diodes and triodes in television receivers than in sound radios, because diodes and triodes lend themselves well to the many special means of controlling movement of the electron beam in television picture tubes.

Chapter 6

TUBES AS AMPLIFIERS

In the preceding chapter we became acquainted with the construction of certain kinds of electronic tubes, also with the manner in which electrons flow through these tubes and with one method for controlling the rate of flow. Now we are ready to investigate the purposes for which tubes are used in television and radio, and how the purposes are served.

The six principal functions of receiving tubes are shown graphically by Fig. 16-1. Here are represented tubes acting as a rectifier, an oscillator, an amplifier, a modulator, a mixer, and a demodulator which may be called also a detector. It would be entirely possible to use the same tube for all of the functions represented in the six diagrams provided the circuits in which the tubes were used were suitable for the purpose to be served and provided that the potentials and currents were adapted to the circuits used. How a tube behaves depends more on the connected circuit than on the design of the tube. However, certain constructions and modifications adapt tubes especially well to certain functions.

At the left of each diagram is given the name applied to a tube when used for the purpose shown. Next toward the right is a small graph showing the input waveform of alternating or direct potential applied to the tube. At the right is shown the resulting output waveform.

Rectifier: As we learned in the preceding chapter a rectifier is a tube used because of its ability to permit only one-way electron flow (current) when inserted in a circuit containing a source of alternating potential. A rectifier produces a direct current from a source of alternating potential. Since most power and lighting lines furnish alternating potentials, and since radio receivers and transmitters require direct potentials and currents, we find one or more rectifiers in nearly all of our radio apparatus which is operated from such supply lines.

Oscillator: When a tube is used as an oscillator it produces in its output circuit alternating potentials and electron flows when

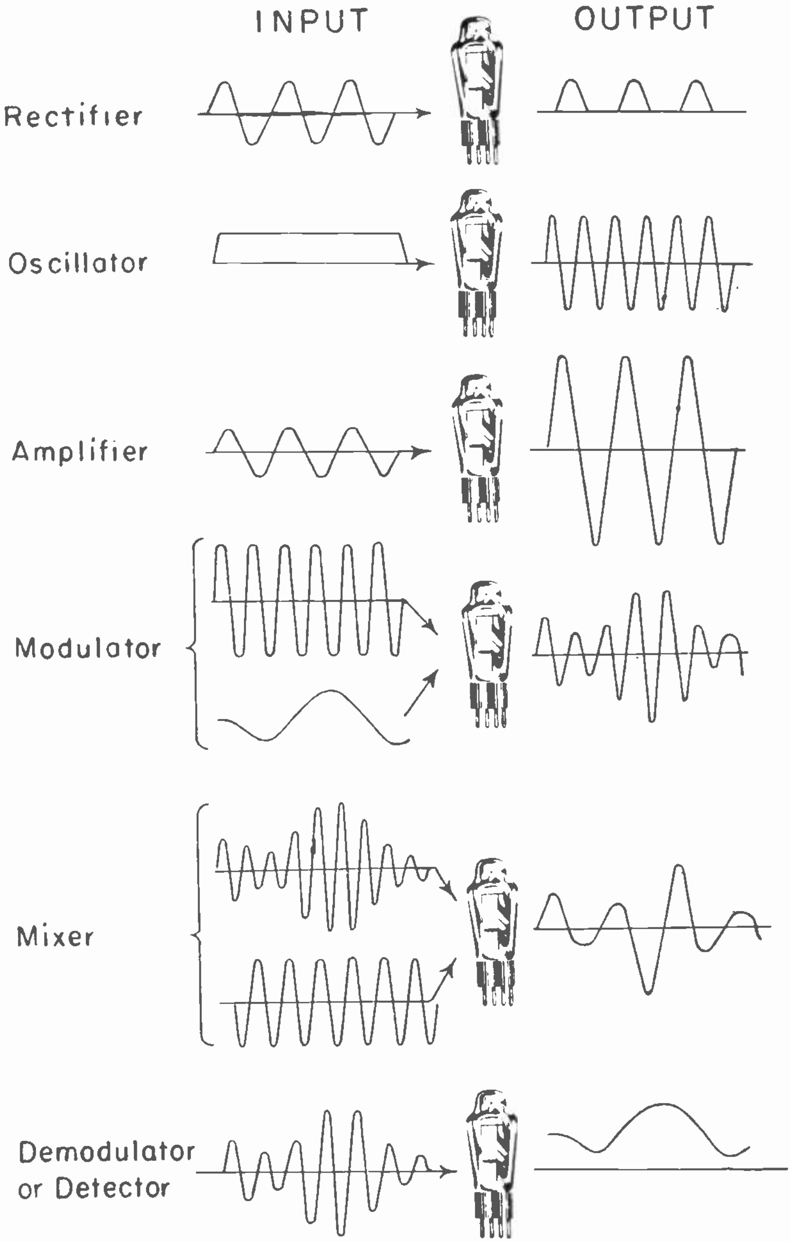


Fig. 16-1.—The six principal functions of radio tubes.

direct potentials and electron flows are supplied to the tube. Oscillator circuits may be designed or adjusted to produce practically any alternating frequency desired; from a few cycles per second up to hundreds of millions of cycles per second. No other device will produce frequencies so high as an oscillator tube in a suitable circuit.

Amplifier: When a tube is used as an amplifier relatively small changes of potential are applied between its control grid and cathode. Between the cathode and plate of the tube, and also in whatever load is connected in series with the plate of the tube, there are produced changes of potential which are much greater than the changes applied to the control grid. The frequencies in the output and in the connected load are the same as the frequencies applied to the control grid, but the amplitudes in the output are increased or amplified over those applied to the control grid. A tube designed for and operated with small currents in its plate and load circuit, but with considerable gains in potential changes, is called a *voltage amplifier.* If the tube handles relatively large currents together with fairly large changes of potential in its plate circuit a considerable amount of power may be controlled and the tube is called a *power amplifier.*

Modulator: A tube used as a modulator is employed in the circuits of a radio transmitter. The input to the modulator consists of two varying potentials. One of these potentials varies at a radio-frequency rate and the other varies at audio frequencies or at other relatively low frequencies which represent a signal to be transmitted. The two input potentials are combined in the output with the result that the radio-frequency output potentials vary in either amplitude or in frequency in accordance with the low frequency which represents the signal. The output is said to be modulated at the signal frequency.

Mixer: A tube used as a mixer is employed in the superheterodyne type of radio receiver, which is the type in most general use. The input for the mixer consists of two potentials. One of the input potentials is that which comes from the antenna; it is a modulated radio-frequency potential in which the modulation represents the audio signal. The other input potential for the mixer is a high-frequency potential supplied from an oscillator which is part of the receiver. The output of the mixer contains a frequency which is much lower than either of the input frequencies, but which retains the signal modulation either in the form of variations of amplitude or else as variations of frequency. The output frequency which carries the modulation is called the intermediate frequency.

Converter: The converter is a type of tube not represented by any one set of graphs in Fig. 16-1. It is a combination tube in which some of the elements act as a mixer and in which some of them act as an oscillator. The converter takes the place of a separate mixer and separate oscillator in a superheterodyne receiver, combining the functions of both in a single tube.

Demodulator or **Detector:** The input for a demodulator or detector tube consists of the modulated intermediate frequency shown as the output of the mixer tube, or else consists of the modulated radio frequency shown as the output of the modulator tube in the diagrams. The demodulator or detector separates the modulation, which is the signal frequency or low frequency, from the much higher intermediate or radio frequency. Thus the demodulator or detector recovers the signal which is being applied as a portion of the input for the modulator tube at the transmitter.

The tubes whose functions have been described are used more generally than any others in radio, but they are not the only types to be found. For example, the type called an electron-ray tube, shows by means of a shadow on a visible disc whether or not the radio receiver is correctly tuned. Then there is another type of tube, called a voltage regulator, which maintains a nearly constant potential difference between two points in a circuit when there are rather large variations of current in the circuit. There are also current regulators which maintain a fairly constant current when there are variations of potential difference.

Television Circuits.—In addition to the six functions just discussed, which are carried out in all kinds of receivers, there are a number of other actions which occur only in television. Although picture lights and shadows, and the accompanying sound in television are reproduced by amplifiers, oscillators, and demodulators operated in much the same manner as for sound radio, many special circuits are needed for controlling horizontal and vertical movement of the electron beam and to control overall illumination of the television screen. Here we find tubes called limiters, clip-

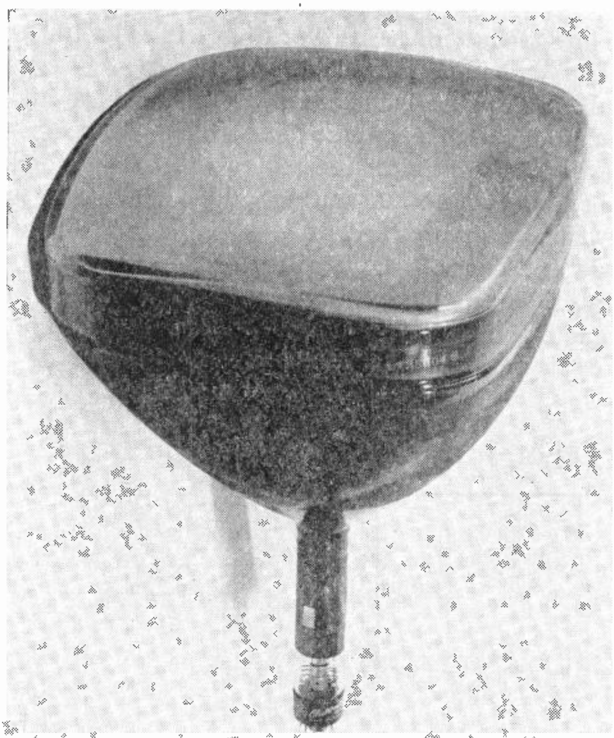


Fig. 16-2.—A television picture tube, in which are employed the principles of a triode for controlling intensity of the beam.

pers, inverters, phase detectors, restorers, dampers, multivibrators, and by other special names. All are only special applications of amplifiers, oscillators, and rectifiers. The differences are not in the kinds of tubes employed, but rather in the circuits. These special circuits will be discussed in volumes dealing especially with television.

Amplification.—At the left-hand side of Fig. 16-3 are shown connections to the plate and cathode of a tube which is to be used as an amplifier. In series between plate and cathode are a load and a source. The load may be any unit in which work is to be done by electron flow through it. The simplest load, and the one which we shall assume in our explanations, is a resistance. The source which furnishes the potential difference between plate and cathode may be any source of electromotive force. In the diagram the source is represented by the symbol for a battery. In diagrams which are intended to illustrate working principles in the simplest manner it is common practice to represent all the sources of potential differences as batteries even though in actual practice some other kind of source might be used. The source of Fig. 16-3 has its negative terminal connected to the tube cathode and its positive terminal connected through the load to the tube plate. Thus the plate is maintained at a potential more positive than the cathode and electron flow will pass as shown by the arrow through the tube, the load, and the source.

To complete the elementary circuits for the amplifier tube we shall connect a resistor *R* between the control grid and the cathode, as in the right-hand diagram of Fig. 16-3. If the upper and lower ends of this resistor are connected also to some external source of potential difference that external potential difference will cause an electron flow to pass through the resistor. If the polarity of the external source is such as to cause electron flow from top to bottom of the resistor, as indicated, the top of the resistor will be more negative than the bottom. Then, because the top of the resistor is connected to the control grid, and the bottom of the resistor to the cathode, the control grid of the tube will be made more negative than the cathode. Making the grid negative with reference to the cathode will reduce the rate of electron flow from cathode to plate in the tube in comparison

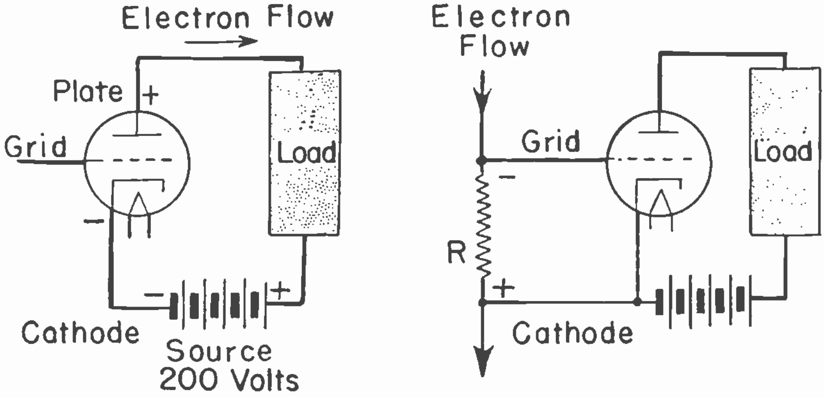


Fig. 16-3.—Connections for a triode tube used as an amplifier.

with the rate of flow with the grid at the same potential as the cathode. Were we to reverse the polarity of the external source connected to resistor *R* the upper end of this resistor would be more positive than its lower end, and the control grid of the tube would be made more positive than its cathode. Then the rate of electron flow from cathode to plate would be increased in comparison with the rate when the grid and cathode are at the same potential.

If there is no electron flow in resistor *R* there will be no difference of potential between top and bottom of this unit. The top and bottom of the resistor will be at the same potential, and the grid and cathode of the tube will be at the same potential. Grid potential or grid voltage always is specified with reference to the cathode in the same tube. When these two elements are at the same potential there is zero potential difference. Then we say that the control grid is at zero potential or at zero voltage, or we say that there is a *zero grid.* If the control grid is more negative than the cathode we have a *negative grid,* and if the control grid is more positive than the cathode we have a *positive grid.*

The circuit shown at the left in Fig. 16-3 is the *plate circuit* of our amplifier tube. The plate circuit includes the space between cathode and plate inside the tube, also the load connected to the plate, the source of potential difference that causes electron flow in the plate circuit, and the connections between the plate, the load, the source, and the cathode. In the diagram at the right we have added the *control grid circuit.* The control grid circuit includes the space between cathode and control grid inside the tube, the external connection (such as resistor *R*) between control grid and cathode, and usually whatever external potential sources affect the potential of the control grid. When a tube is represented as having a heater-cathode it is not necessary to show the circuit which supplies current to the heater, because the heater does not carry any of the electron flow for the plate circuit and grid circuit.

Measurement of Tube Performance.—To measure the effect of varying grid potentials on the rate of electron flow (current) in the plate circuit of our triode we may use the test connections of Fig. 16-4. Connected between the control grid and cathode is a battery or any suitable source of potential differences between whose terminals is a voltage divider. Moving the slider makes the control grid more or less negative with reference to the cathode. A voltmeter connected between grid and cathode indicates the grid potential. In the plate circuit is another source which furnishes plate potential and current which are adjusted to various values by moving the slider on the voltage divider connected across this source. In series with the plate of the tube is a current-measuring meter which indicates the plate current (electron flow) in milliamperes.

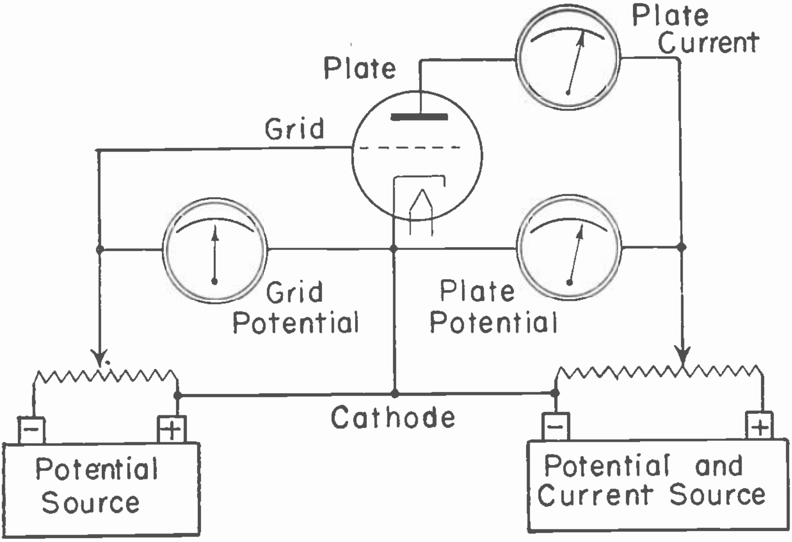


Fig. 16-4.—A testing apparatus for measuring tube performance.

Across the portion of the voltage divider which is between the plate and cathode is connected a voltmeter which indicates plate potential. This voltmeter really measures the combined potential drop across the plate-cathode path in the tube and the drop across the current meter, but the resistance of the current meter is assumed to be negligible in comparison with that of the plate-cathode path in the tube, and the slight extra potential drop in the meter does not materially affect the indications of plate potential.

Moving the slider on the voltage divider in the grid circuit all

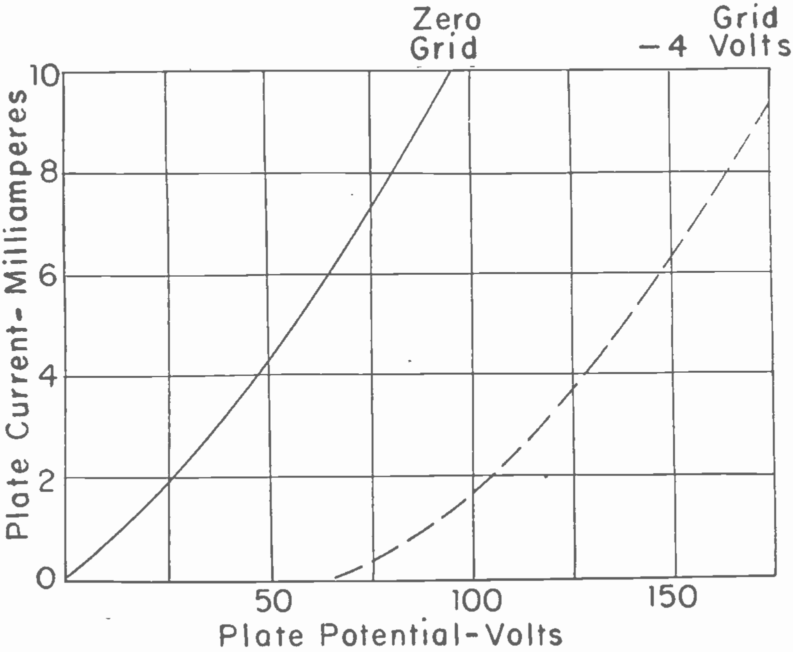


Fig. 16-5.—How the plate current is varied by changes of plate potential.

the way to the right connects the grid directly to the cathode to maintain zero grid potential. If the plate potential then is adjusted to several values the resulting plate currents in milliamperes might be as follows with a typical voltage amplifying triode.

Grid Potential	Plate Potential, volts	Plate Current, milliamps
zero	0	0.0
zero	25	1.9
zero	50	4.3
zero	75	7.3
zero	95	10.0

If we plot these values and other intermediate values on a graph we will have the full-line curve of Fig. 16-5. This curve shows the relations between plate current and plate potential for a given grid potential. It is called a *plate characteristic* curve for the tube whose performance is thus shown.

If we now make the control grid four volts negative and run another series of measurements of plate current with various plate potentials, the resulting values when shown as a plate characteristic curve will appear as the broken-line curve of Fig. 16-5. All plate characteristics for triode amplifiers have the general form of the two curves shown. As an example, we might make measurements of plate potentials and currents on a large number of the type of triode tube designated as type 6J5, with grid potentials of zero and then every two volts negative until reaching 16 volts negative. The averages of the measurements would be shown by the curves of Fig. 16-6. This graph shows a *family of plate characteristics* for the average 6J5 tube. Individual tubes might have performances considerably at variance with the curves, but the average would be as shown. As will appear in our further studies, practically everything that we may desire to learn about the behavior of a given type of tube may be determined from a family of its plate characteristics.

Effects of Plate and Grid Potentials.—The plate characteristic curves show that plate current (electron flow) increases when the plate potential is increased while the grid potential remains constant. For instance, if we take readings from the characteristic curve which applies to a grid potential of —2 volts we find the following relations between plate current and plate potential.

Plate Potential volts	Plate Current milliamperes
0	0.0
30	0.0
60	1.5
90	4.3
120	7.6
150	11.7

Note that there is no plate current at all until the plate becomes 30 volts positive with reference to the cathode. This is because the combined effects of the negative space charge and of the 2 volts negative potential on the control grid more than counteract the positive plate potential until the plate potential reaches 30 volts. With a plate potential of 30 volts the opposing forces are equal, and at all higher plate potentials the combined effects of the space charge and the negative grid are overcome and there is a flow of electrons from cathode to plate.

The curves show that, were the grid potential made 4 volts negative, there would be no plate current until the plate potential was raised to almost 70 volts. With the grid 6 volts negative there would be no plate current until the plate potential was made 100 volts or more. For every other grid potential there is a certain plate potential below which there will be no plate current, and above which there will be a plate current which increases with higher plate potentials.

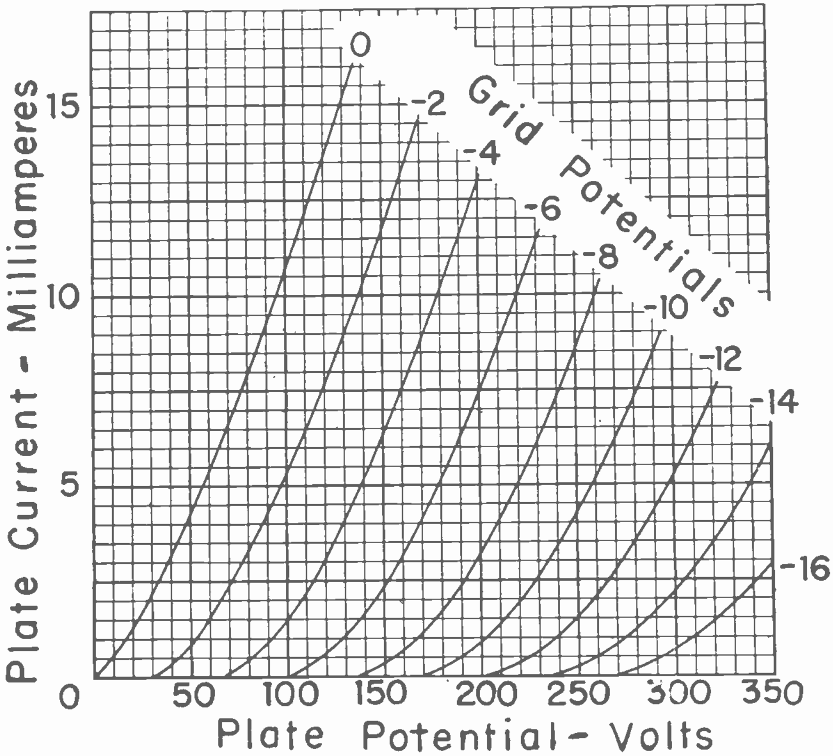


Fig. 16-6.—Average plate characteristics for a 6J5 triode tube.

We may state the same general facts in another way. We may say that for every positive plate potential there is a certain negative grid potential which will reduce the plate current to zero. For example, we would say that for a plate potential of 100 volts the plate current will be reduced to zero when the control grid is made 6 volts negative. This reduction of plate current to zero is called *plate current cutoff*. The grid potential and the plate potential at which cutoff occurs are called the *cutoff potentials.*

The next thing to note from the characteristic curves is that the plate current does not increase at a uniform rate with increasing plate potential with the grid held at any negative potential. All of the curves bend rather sharply at their lower ends, and become straighter as they rise. This is because there is a considerable excess of negative space charge just above cutoff, but this space charge soon is reduced to a fairly constant value as the plate potential is increased.

The curves of Fig. 16-6, which we call plate characteristics, were originally drawn by maintaining a constant negative grid potential while varying the plate potential and reading the resulting plate currents. Consequently, each curve shows the effect of plate potential on plate current when the grid potential does not change. It would be possible to go back to the test setup of Fig. 16-4 and make a different set of readings by maintaining certain constant plate potentials while varying the grid potential. Were we to hold the plate potential at 150 volts, as an example, while varying the grid potential from zero to a value which causes plate current cutoff, the average of readings on a number of 6J5 triode tubes would be as follows.

Plate Potential, volts	Grid Potential, volts	Plate Current, milliamps
150	0	17.7
150	— 2	11.8
150	— 4	6.7
150	— 6	2.4
150	— 8.8	0.0

By maintaining several different plate potentials while gradually varying the grid potential with each, we could obtain meter readings of resulting plate currents which would allow plotting the curves shown by Fig. 16-7. This graph shows the effect of varying grid potential on the resulting plate current when plate potentials are held constant at 50 volts, 100 volts, and every following increase of 50 volts up to 300 volts of plate potential. Curves of this kind may be called *grid-plate characteristics*, or sometimes they are called *mutual characteristics*. They are not so generally useful as the plate characteristics shown in the preceding graph. Tube manufacturers usually publish graphs showing families of plate characteristics for tubes in most common use, but grid-plate characteristics are less frequently available.

The grid-plate characteristic curves are quite similar in form

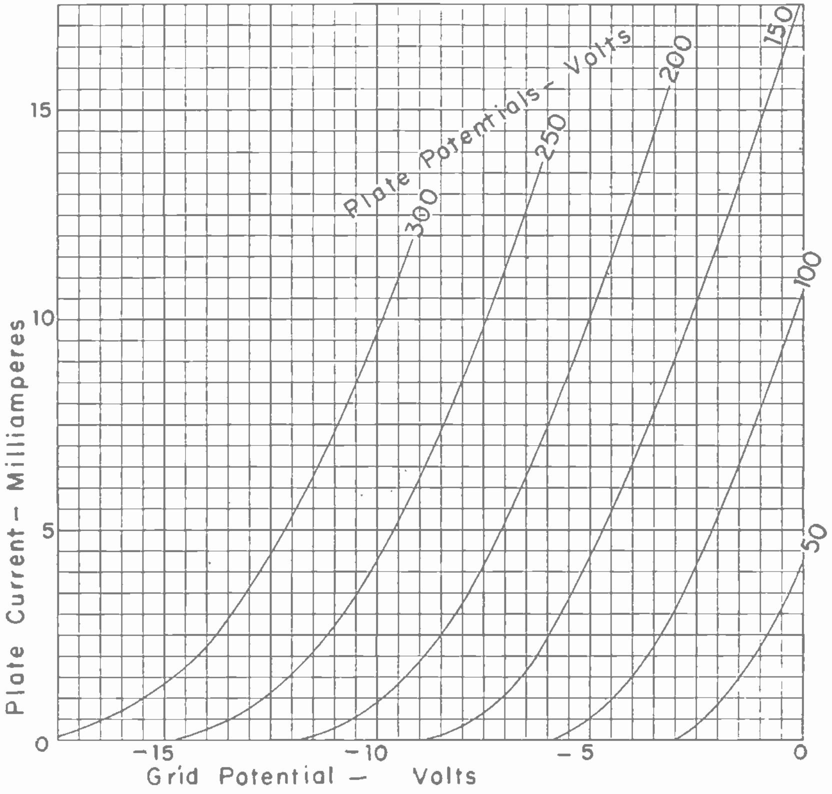


Fig. 16-7.—Average grid-plate characteristics or mutual characteristics of 6J5 tubes.

to the curves of plate characteristics. From the grid-plate characteristics we may read grid potentials for plate current cutoff at various plate potentials. We note again the increasing curvature at the bottoms of the curves where the space charge is still great enough to have an effect that is large in comparison with the effect of grid potential.

All of the curves show two facts of prime importance. First; plate current is increased by higher plate potentials and by less negative grid potentials. Second; plate current is decreased by lower plate potentials and by more negative grid potentials.

Electron Flow in the Grid Circuit.—Probably you have noticed that in all of the graphs representing tube performance we show the effect of negative grid potentials but not the effect of positive grid potentials. The reason for not showing the effect of positive grid potentials is that radio amplifier tubes very seldom are operated with such potentials, but nearly always are operated with the grid more or less negative with reference to the cathode.

The reason for not operating an amplifier with its control grid positive is that the waveform of a signal potential applied to the grid then would not reappear as the same waveform amplified in the plate circuit, but would be distorted. To find why this happens we may commence with an examination of Fig. 16-8. In diagram *A* is shown a control grid circuit containing a resistor between the grid and the cathode. It is assumed that electron flow from an external source passes through the resistor in the direction of the arrows. Then the upper end of the resistor is positive with reference to its lower end, and the grid is made positive with reference to the cathode. When the grid is positive with reference to the cathode it acts like a positive plate. That is, the positive grid attracts negative electrons from the space charge and from the cathode just as does the plate. These electrons enter the positive grid just as they enter a positive plate. Because the grid is so much closer to the cathode than is the plate, even a small positive potential on the grid will attract great quantities of electrons in comparison with the quantity that would be attracted to the plate were the plate at the same small positive potential.

If we consider only the effect of the positive grid, without reference to the electron flow passing through the grid resistor

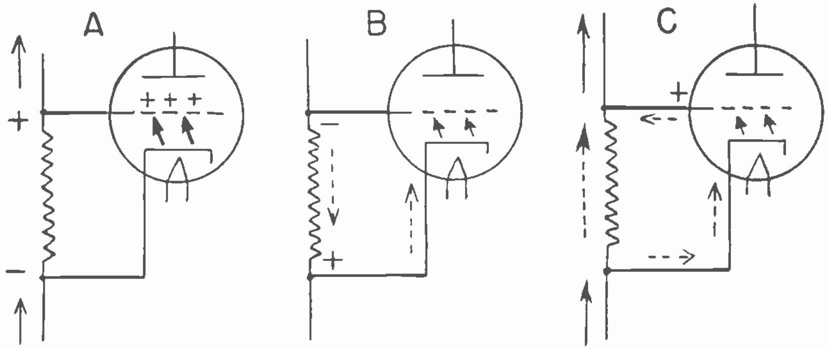


Fig. 16-8.—There is flow of grid current when the control grid is positive.

from the external source, we would have the conditions of diagram *B*. Electrons flowing from the cathode to the grid would flow from the grid downward through the grid resistor and back to the cathode. This direction of electron flow in the resistor would mean that its upper end would be negative and its lower end positive. This would make the grid negative with reference to the cathode. Actually the potential differences produced across the grid resistor by the external electron flow and by the effect of the positive grid oppose each other. The positive grid potential due to the external electron flow is lessened, or is made less positive, by the action of the positive grid.

Electron flows in the two circuits, the grid circuit and the external circuit, are shown by diagram *C*. Part of the external electron flow goes upward through the grid resistor and the remainder goes to the cathode, to the grid, and then rejoins the main flow at the top of the grid resistor. This diversion of part of the electron flow away from the resistor and through the tube lessens the flow through the resistor and decreases the potential drop across the resistor. Thus the grid is made less positive than as though there were no electron flow through the cathode-to-grid path. But still the grid remains more or less positive. It never can make itself negative, for that would mean no electron flow from cathode to grid, and with no electron flow here there would be nothing to oppose the external positive potential difference.

Now refer back to Fig. 16-7 and assume that the plate of our tube is maintained at a potential of 100 volts, with performance as shown by the curve second from the right. The upper part of this curve is nearly a straight line. This means that variations of grid potential on the upper part of the curve will cause variations of plate current that are almost exactly proportional to the changes of grid potential. This is the relation between grid potential and plate current that we need in order to have uniform reproduction or amplification of potential changes applied to the control grid circuit.

In Fig. 16-9 there has been redrawn the 100-volt curve from Fig. 16-7, and the curve has been extended for positive grid potentials. The bottom horizontal scale shows potentials applied from an external source. With the grid negative the values of plate current shown by the curve are exactly the same as those in Fig. 16-7. Were there no electron flow from cathode to grid in the tube the curve would extend into the positive grid region as shown by the broken line. Actually the grid potential will be made enough less positive to produce the values of plate current shown by the full-line extension to the right of zero grid potential.

If the control grid originally were at zero potential and then were changed to 2 volts negative, the plate current would change from 10.7 to 5.3 milliamperes, which is a change of 5.4 milliamperes. But were the grid potential varied from zero to 2 volts positive the plate current would change from 10.7 to 15.0 milliamperes (on the full-line curve), which is a change of only 4.3 milliamperes. Thus equal changes of grid potential above and below zero would fail to cause equal changes of plate current.

While we are on the subject of the effects of positive grid potential it will be interesting to observe the relations between electron flow from cathode to plate, electron flow from cathode to grid, and the resulting total electron flow from the cathode at various positive potentials on the grid. Such relations are shown by Fig. 16-10 for an average 6J5 triode tube whose plate potential is maintained constant at 100 volts. The upper curve shows total cathode current, which is in the sum of the plate current and grid current. The other two curves show currents in the plate circuit and to the control grid at grid potentials between zero and 20 volts positive. The plate current curve of this graph does not correspond to the curve of Fig. 16-9 because

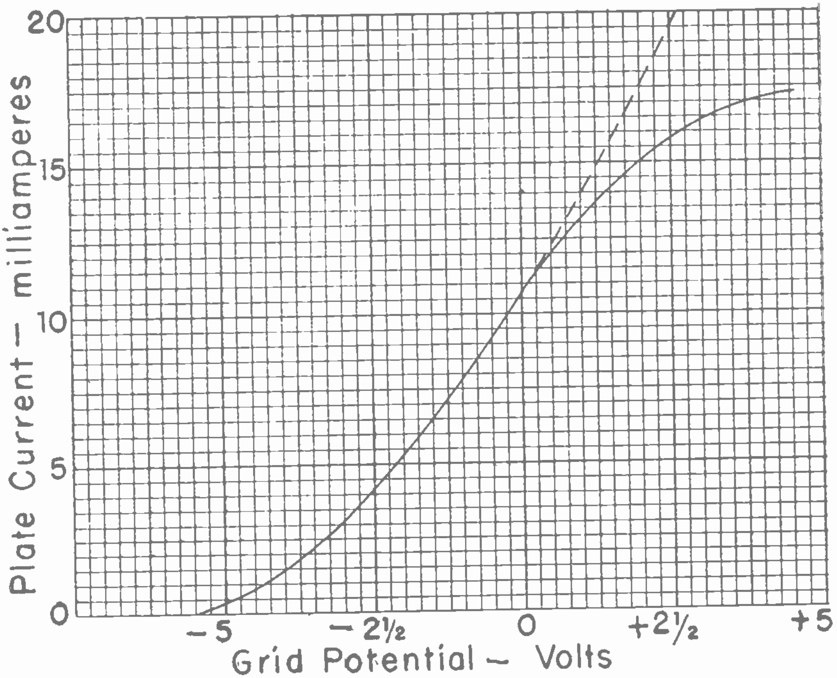


Fig. 16-9.—A positive grid tends to lessen the increase of plate current that would occur with no grid current.

there we were observing the effect of grid potential as modified by the flow of current to the grid and the resulting subtraction of current from a grid resistor, while here we are observing the effects of grid potentials held at certain values regardless of any effects of the grid current in connected circuits.

The total cathode current with a positive grid is greater than the plate current, because it is equal to the plate current plus the grid current. With a negative grid the cathode current is the same as the plate current in a triode, because then there is either no grid current or else a negligible grid current of only a very few microamperes at most.

A Load in the Plate Circuit. — All of our measurements and all of our graphs showing the performance of a triode with variations of grid and plate potentials have been made with no load in the plate circuit. That is, the measurements and graphs apply

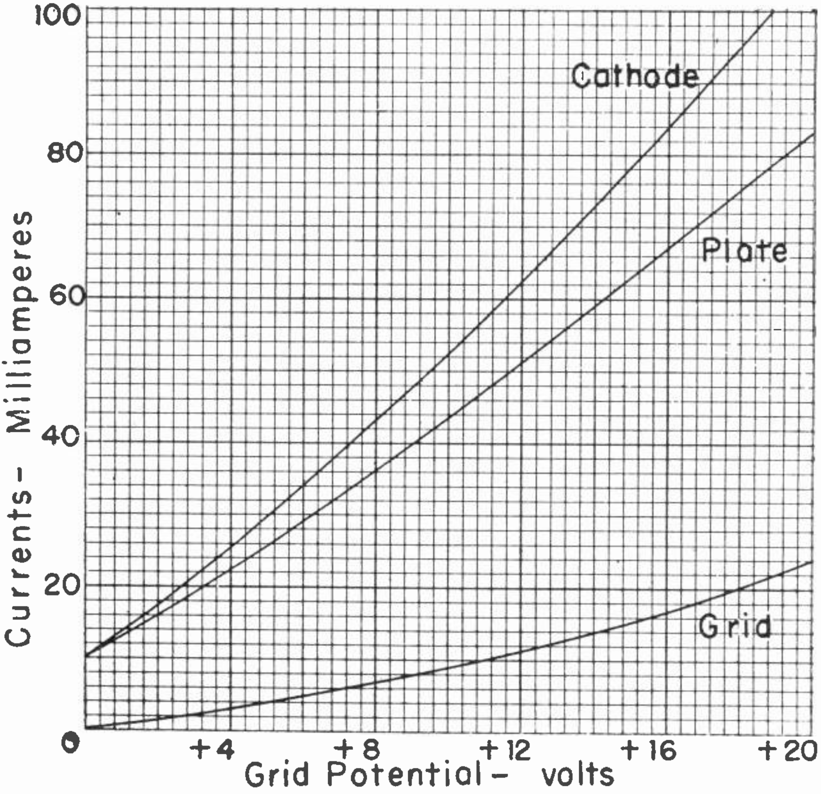


Fig. 16-10.—Currents in the grid, plate, and cathode when the grid is positive.

when there is between the plate and the cathode only a source of plate potential and current, and when this source is assumed to have no resistance. Of course, tubes are not operated in this manner in practical applications, because in order for useful work to be done there must be some kind of load in the plate circuit. Now we shall examine the effects of such a load on tube behavior. A resistance load will be assumed, because whether the load is a pure resistance or is an impedance the results are much the same.

Our first experimental circuit may be shown as in Fig. 16-11. The control grid is maintained at a potential of 6 volts negative. The resistance of the plate circuit load is 10,000 ohms. We shall assume that the tube is a 6J5 so that its performance may be read from the family of plate characteristics in Fig. 16-6.

The plate-cathode path in the tube, the load resistance, and the source, all form a series circuit. Whatever electron flow passes through the tube must pass also through the load and the source. The direction of electron flow in the tube is from cathode to plate, and so the direction of the same flow through the load and source must be as shown by the arrows. Because electron flow always proceeds from negative to positive, the end of the load resistance toward the plate must be more negative than the end which is toward the source. Keep this relation of load polarity in mind; it will be important many times in the future.

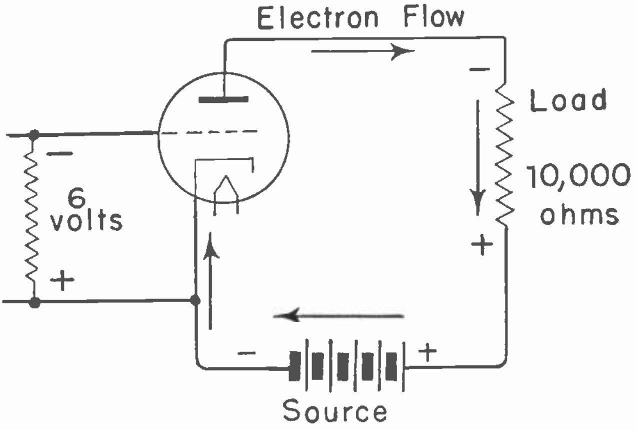


Fig. 16-11.—A resistance load is placed in the plate circuit.

When there is an electron flow (current) in a resistance there must be a difference of potential across the resistance. Consequently, there is a difference of potential or a potential drop across the load of Fig. 16-11. There is also a drop of potential between plate and cathode of the tube itself; this drop being the plate potential or the difference of potential between plate and cathode. The two potential drops are in series with each other. Then the potential difference furnished by the source must be equal to the sum of the potential drops in the load and in the tube. So long as there is any flow of plate electrons, with an accompanying drop of potential in the load, the potential difference furnished by the source must be greater than the plate potential at the tube. Or, we may say that the plate potential always will be less than the source potential when there is electron flow in the plate circuit.

Let's say that the plate potential on the tube in our experimental circuit is 200 volts, which will bring about the conditions shown at the left in Fig. 16-12. From the plate characteristics (Fig. 16-6) we find that a plate potential of 200 volts with the grid 6 volts negative results in a plate current of 7.5 milliamperes or 0.0075 ampere. With this current in the load of 10,000 ohms the potential drop across the load must be 75 volts, because Ohm's law says that $E = IR$ with I in amperes and R in ohms. Then the source must furnish the sum of 200 volts plate potential and 75 volts drop in the load for a total of 275 volts. The source potential required for any other combination of plate current and load resistance might be similarly computed.

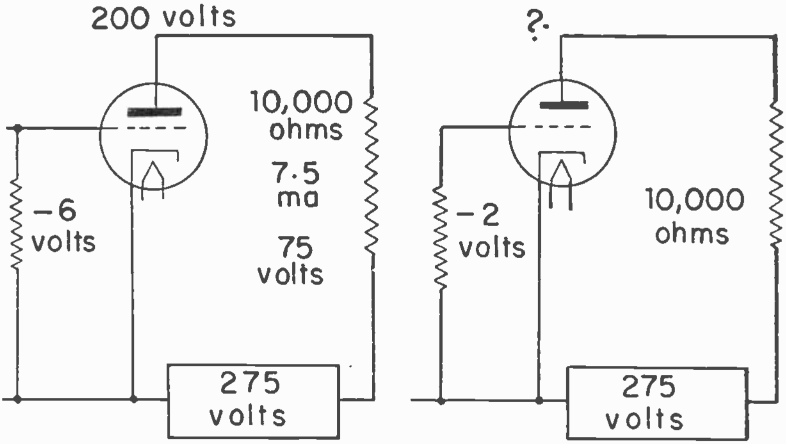


Fig. 16-12.—The source potential difference equals the sum of the load potential and the plate potential.

Supposing that we install a source delivering 275 volts of potential difference in order to cause a plate current of 7.5 milliamperes in the 10,000-ohm load with the grid 6 volts negative. Then, as at the right in Fig. 16-12, assume that the grid is made 2 volts negative, or is made of any potential other than the original 6 volts negative. What will be the resulting plate current, the plate potential, and the potential drop in the load? This is a thoroughly practical problem, because when using a tube for amplification we will have continually varying grid potentials but will have an unchanging load and an unchanging potential from the source. Of course, the new value of plate current will fall somewhere on the — 2 volt curve of our plate characteristics, but where will it fall? The problem is complicated by the fact that every change of plate current causes a change of potential drop in the load and a corresponding but opposite change of plate potential at the tube. More plate current means more load current, a greater potential drop in the load, and less potential difference remaining for the tube. Less plate current means less drop in the load and more plate potential at the tube.

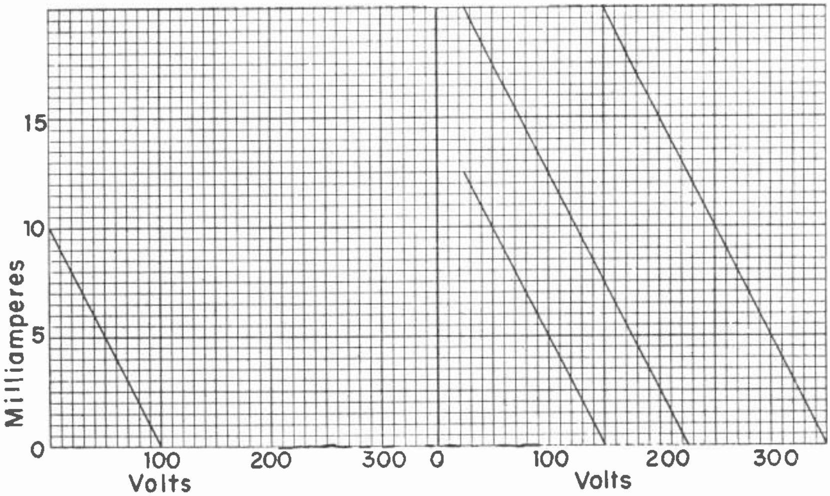


Fig 16-13.—Load lines for a load resistance of 10,000 ohms.

Load Lines. — Our present problem, and many other equally practical problems in radio are easily solved by using a load line in connection with the family of plate characteristics for whatever tube may be employed. A *load line* is a straight line which, when placed on a family of plate characteristics, shows for the selected load resistance all of the combinations of grid potentials, plate potentials, and plate currents that may exist with that particular load.

A load line considered by itself, before being applied to the characteristic curves, is a sloping line such as those shown in Fig. 16-13. The degree of slope shows the number of volts potential change required to cause some given change of current in the resistance for which the line is drawn. The line at the left in Fig. 16-13 shows a change of 100 volts for a change of 10 milliamperes. It is a load line for a load resistance of 10,000

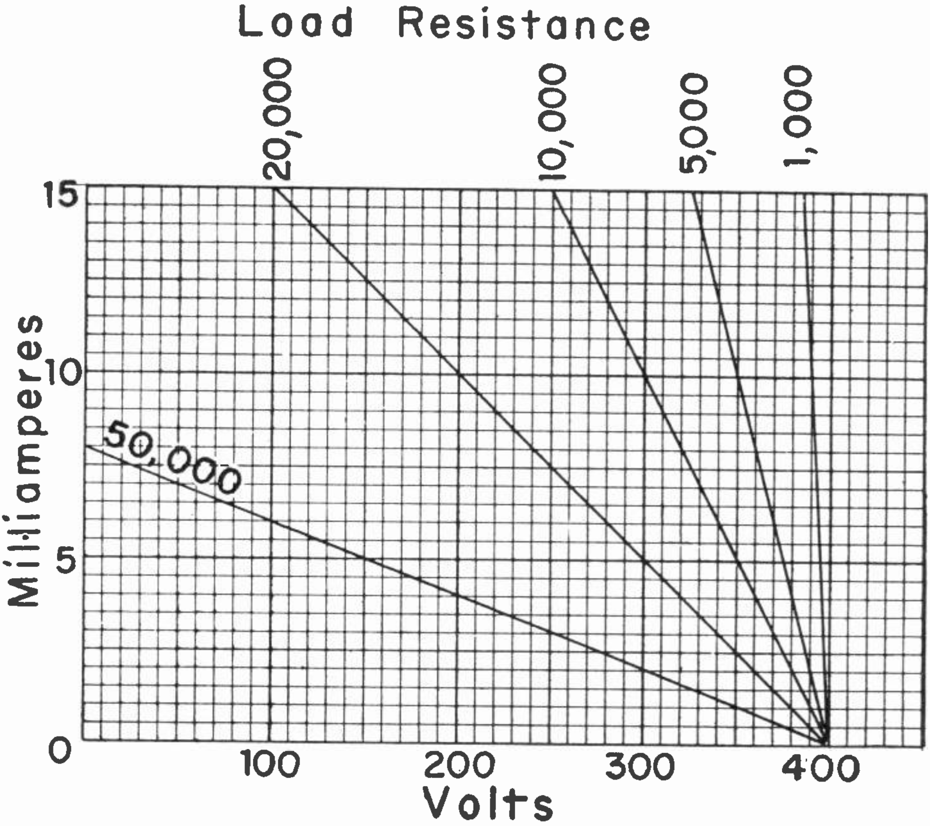


Fig. 16-14.—The slope of a load line depends on the load resistance.

ohms because, by using Ohm's law $(R = E/I)$, you will find that this is the resistance corresponding to 100 volts and 10 milliamperes or 0.010 ampere.

All of the other lines in Fig. 16-13 are load lines for 10,000 ohms resistance, because in every case there is the same ratio of volts to milliamperes. That is, for every change of 10 milliamperes there is a change of 100 volts, and for every change of 1 milliampere there is a change of 10 volts on any of the lines.

To draw a load line for any resistance we need only determine the ratio of volts to milliamperes for that resistance. Load lines for several different resistances are shown by Fig. 16-14. The slope of the line depends on the resistance for which it is drawn. The less the resistance the more nearly vertical is the load line, and the greater the resistance the more nearly horizontal is the line. The number of volts for any change in milliamperes is easily determined with the following modification of an Ohm's law formula.

$$\text{Volts} = \text{milliamperes} \times \frac{\text{ohms}}{1000}$$

For the milliamperes in this formula we must select some number that is shown on the graph of plate characteristics to which the load line is to be applied. All of our characteristic graphs have included the value of 10 milliamperes, so this is a good number to use. Then, as shown by the formula, we multiply 10 (milliamperes) by the number of ohms in the load resistance divided by 1,000, and this gives us the number of volts per 10 milliamperes. For the load resistances of Fig. 16-14 the computations are,

$$1{,}000 \text{ ohms.} \quad 10 \times \frac{1000}{1000} = 10 \text{ volts}$$

$$5{,}000 \text{ ohms.} \quad 10 \times \frac{5000}{1000} = 50 \text{ volts}$$

$$10{,}000 \text{ ohms.} \quad 10 \times \frac{10000}{1000} = 100 \text{ volts}$$

$$20{,}000 \text{ ohms.} \quad 10 \times \frac{20000}{1000} = 200 \text{ volts}$$

$$50{,}000 \text{ ohms.} \quad 10 \times \frac{50000}{1000} = 500 \text{ volts}$$

The lines are drawn so that they rise through 10 milliamperes on the graph while going to the left through the number of volts computed for each resistance. In the case of 50,000 ohms resistance we arrive at a number of volts greater than shown on the volts scale of the graph. When this happens we make another computation with a smaller number of milliamperes. If we take 5 milliamperes in the formula we find that there is to be a change of 250 volts per 5 milliamperes, and draw the 50,000-ohm line accordingly. Note that the change in volts always is measured backward along the volts scale on the graph, or is measured from the bottom of the load line toward the left on the potential scale.

Now that we know how to determine the slope of the load line for any load resistance it remains to place the line correctly on the graph of plate characteristics. There are two easy ways of locating the load line on the plate characteristics. With one method we make the line pass through any combination of plate current and plate potential or grid potential at which we know the tube will operate, or at which we wish to have it operate. As an example, at the left in Fig. 16-12 we found that with a 10,000-ohm load resistance there would be a flow of 7.5 milliamperes with a plate potential of 200 volts and a grid potential of 6 volts negative. In Fig. 16-15 a 10,000-ohm load line has been drawn through these values on the graph of plate characteristics. Note that the slope of this line has been made equal to 100 volts per 10 milliamperes. The line has been made long enough to cut across all of the curves for grid potential.

Another method of locating the load line is in accordance with the potential difference furnished by the source in the plate circuit. In the problem illustrated by Fig. 16-12 we found that the potential difference of the source should be 275 volts. Then the load line should be placed so that its lower end is at 275 volts on the plate potential scale and on the line for zero plate current of the graph. Were the line to be located in accordance with this method we would, of course, have the same line as shown by Fig. 16-15. The lower end of this line is at 275 volts on the zero current line of the graph.

The tube whose characteristics are shown by the graph will operate along the load line when the load resistance is 10,000

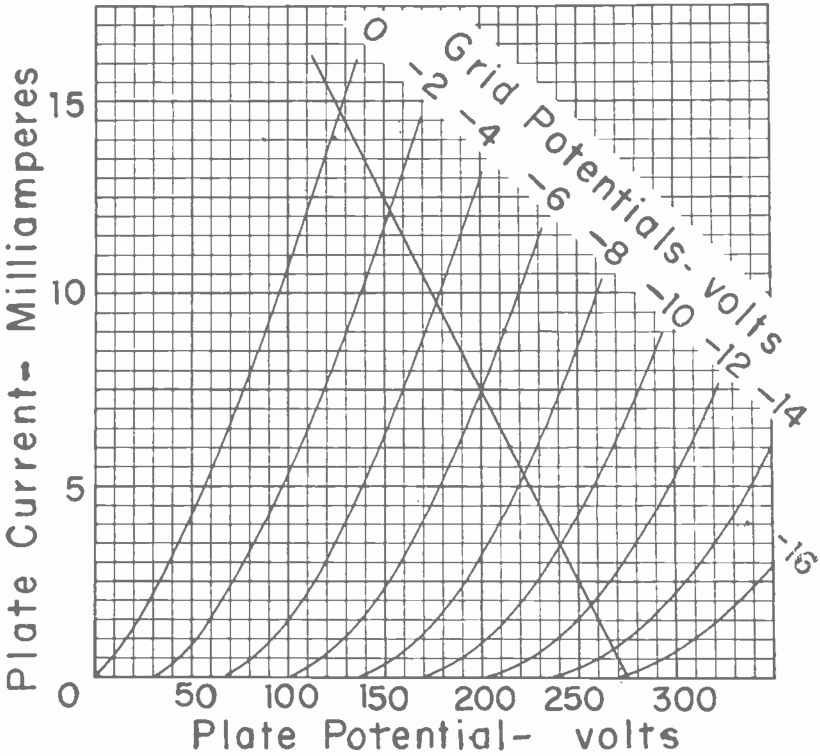


Fig. 16-15.—A 10,000-ohm load line on a family of plate characteristics.

ohms and when the plate supply potential is 275 volts. If the plate supply potential were made less than 275 volts the load line would be moved to the left, but would retain the same slope, and if the supply potential were increased the line would be moved to the right. The line would be moved so that its lower end came to the new value of plate supply potential on the zero current line of the graph.

There is no need to actually draw load lines on your graphs of plate characteristics. Any ruler or other straight edge laid on the graph at the correct slope and in the correct position for any assumed conditions will allow taking all necessary readings. Placing a lot of different load lines on a graph makes it hard to read.

With the load line we easily solve the problem illustrated at the right in Fig. 16-12. There we had a 10,000-ohm load, a 275-volt plate supply potential, and a 2-volt negative grid potential. On Fig. 16-15 the load line intersects the 2-volt negative curve of grid potential at a plate current of 12.2 milliamperes and a plate potential of 153 volts. If the supply potential is 275 volts and the plate potential is 153 volts, the potential drop in the load resistance must be the difference, or must be 122 volts. The current, the plate potential, and the load potential drop for any other value of grid potential may be read from the load line.

Amplification. — Now we are ready to employ the tube as an amplifier, using the connections shown by Fig. 16-16 and values of plate load resistance and plate supply potential which will cause operation along the load line of Fig. 16-15. Between the grid and cathode of the tube is connected a resistor of 500,000 ohms or a half-megohm value. From some external source there is applied between *A* and *B* a potential that changes from 6 volts to 4 volts in a polarity that maintains the grid of the tube negative with reference to its cathode at all times. This change of potential is applied between the grid and the cathode. The extent of the change is 2 volts.

From the load line of Fig. 16-15 we read the plate currents corresponding to the negative grid potentials of 6 volts and 4 volts. The currents are, respectively, 7.5 and 9.8 milliamperes. These currents flow in the 10,000-ohm load resistance as well as in the tube. By using Ohm's law we find that the potential drops across the load resistance will be 75 and 98 volts for the two values of current. The change of potential across the load resistance is the difference between 75 and 98 volts, or is 23 volts. Thus a 2-volt change of grid potential has brought about a 23-volt change of potential in the plate load. The change of grid potential has been amplified 11.5 times in the plate load, and for the tube operating at the specified conditions we have a *voltage amplification* of 11.5.

When speaking of the amplification of a tube we ordinarily refer to the voltage amplification. The voltage amplification is the ratio of potential change in the plate load to potential change between control grid and cathode, or is the plate load change divided by the control grid change.

The change of potential produced in the plate circuit load resistance of Fig. 16-16 may be applied to a following circuit by connecting that circuit to points *C* and *D* of the diagram.

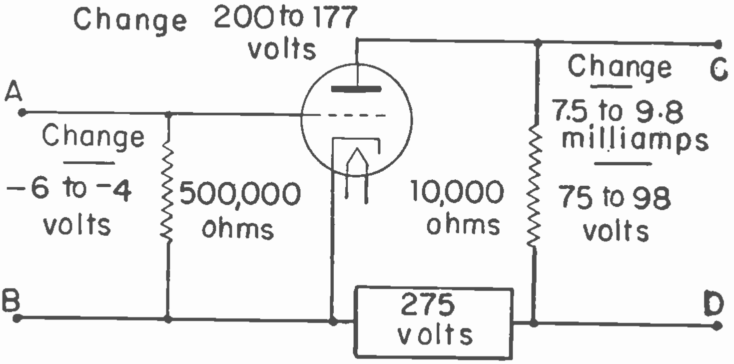


Fig. 16-16.—A circuit for using the triode tube as a voltage amplifier.

The parts shown in the diagram make up one *stage* of amplification. The input to this stage is through *A* and *B*, while the output is from *C* and *D*. By using suitable connections, which we shall investigate later on, it is possible to connect the output of one stage of amplification to the input of another following stage to obtain high values of overall amplification. More than two stages sometimes are thus connected together. An amplifier consisting of two or more stages with the output of one forming the input for a following stage may be called a *cascade* amplifier.

The total amplification or the overall amplification of two or more stages in cascade is equal to the separate amplifications multiplied together. Were we to use two stages, each with voltage amplification of 11.5, the overall amplification would be equal to 11.5 times 11.5, or would be 132.25. Adding a third similar stage would again multiply the amplification by 11.5 to make a total of about 1521. This would be the theoretical overall amplification. Due to unavoidable losses in the connections between stages the actual amplification would be somewhat less.

Although we speak of the action of the tube as voltage amplification, the action really is a controlling of the voltage or potential differences furnished by the source which is in the plate circuit. The changes of potential in the control grid circuit never reach the plate circuit, either amplified or unamplified, but they merely control the changes of potential in the plate circuit.

In the same sense that there is amplification of voltage, which really is control of voltage, there is amplification or control of current and of power. Considering the current amplification of our amplifying stage, we may compute with the help of Ohm's law the change of current in the grid resistor and in the plate load resistor. These changes, shown at the left in Fig. 16-17, are respectively 0.004 milliampere and 23,000 milliamperes. The ratio is 5,750. The changes of current in the grid resistor control changes of current in the plate resistor which are ~~5,750~~ 575. times as great.

Considering the power in the two resistors, we may compute with the help of power formulas the powers corresponding to

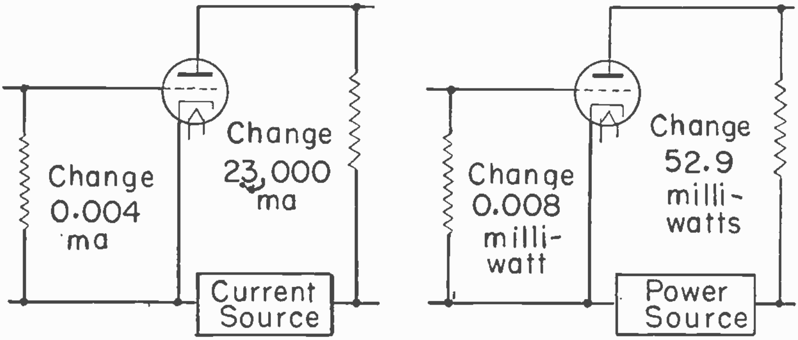


Fig. 16-17.—Current amplification (left) and power amplification (right) with the triode.

the changes of potential or to the changes of current in these resistances. The power values are shown at the right in Fig. 16-17, where in the grid circuit resistor we have 0.008 milliwatt and in the plate circuit resistor have 52.9 milliwatts. The ratio of powers is about 6,620, which means that the power used in the grid resistor controls 6,62~~0~~ times as much power in the plate resistor. In spite of this very efficient control of power, the 6J5 is not classed as a power amplifier but is rather a voltage amplifier. This tube is not a power amplifier because the plate circuit power of only a little more than 50 milliwatts is such a small amount of power as to be quite useless in operating loud speakers or other devices which are to have any considerable output of sound or other effects.

Effect of Load on Amplification. — Now let's see what kind of amplification we get from our 6J5 tube by using a load resistance of 25,000 ohms and by adjusting the potential difference from the plate power supply to give a plate current of 9 milliamperes when the grid is 6 volts negative. The load line for this condition is shown by Fig. 16-18.

To draw this load line in its correct position we determine two points through which it is to pass. One of the points will be the intersection of the curve for 6 volts negative grid and the current line for 9 milliamperes, for these are specified values. To arrive at the position of the second point we may use the earlier formula, with 25,000 ohms load resistance and a current change of 5 milliamperes. Multiplying 5 (milliamperes) by 25,000 divided by 1,000 (equivalent to multiplying by 25) shows a change of 125 volts per 5 milliamperes, this giving the slope of the line. For the current change of 5 milliamperes we may deduct this current from the original 9 milliamperes and place the second point on the line for 4 milliamperes. The point first determined comes at a plate potential of 212 volts on the graph. Since the change of potential is to be 125 volts, we add this change to 212 volts and find that the second point is to be at 337 volts. Now, as on the graph of Fig. 16-18, we mark a spot at 337 volts on the 4 milliampere line. The load line is drawn through the two points or spots which have been determined and is extended as a straight line as far as may be required in both directions.

The 25,000-ohm load line does not reach the zero current line on the graph, and so we cannot get a direct reading of the plate supply potential required. However, we know that the current under the assumed operating condition is to be 9 milliamperes or 0.009 ampere, and we know the load resistance to be 25,000 ohms. This combination of current and resistance in the load means a potential drop in the load of 225 volts, which we determine by using Ohm's law, $E = IR$. The plate potential across the tube has been found to be 212 volts. Adding this plate potential to the potential drop in the load gives a total potential drop of 437 volts, which must be the potential difference required from the plate supply.

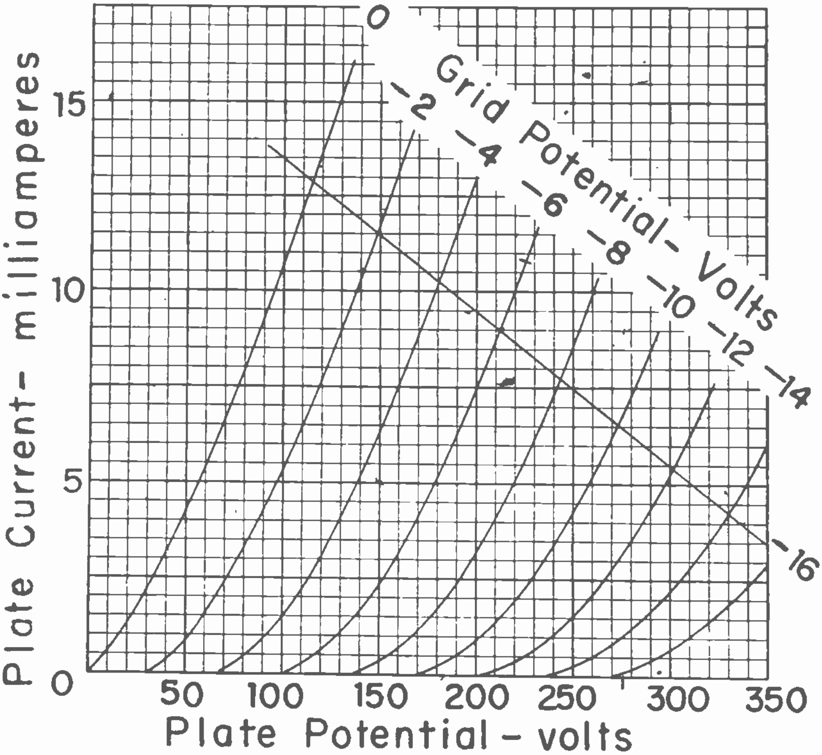


Fig. 16-18.—The load line for a load of 25,000 ohms resistance.

Now we have the operation shown by Fig. 16-19, for which the plate current and potential values are taken from the graph of Fig. 16-18. The 2-volt change of grid potential causes the plate current to change from 9.00 to 10.25 milliamperes. These currents in the load of 25,000 ohms mean potential drops across the load of 225 and 256.25 volts. The change of voltage across the load is the difference, or is 31.25 volts. Now, dividing the potential change in the load by the potential change applied to the grid (31.25 ÷ 2) shows that the voltage amplification is 15.63 as compared with the amplification of 11.5 when using the load of 10,000 ohms.

It is a general rule that the greater the load resistance the greater is the voltage amplification. However, an increase of load resistance requires a greater potential difference from the plate supply if the plate current and load current is not to drop to low values; this because it is necessary to supply the additional potential drop occurring in the greater load resistance with the same current.

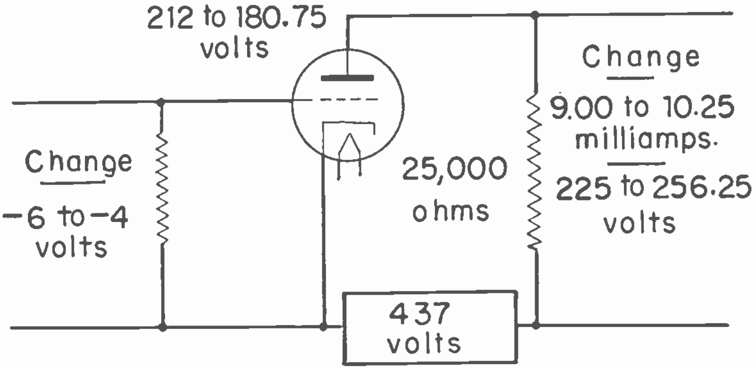


Fig. 16-19.—Operating conditions with a 25,000-ohm load.

To illustrate the effect of plate supply potential, assume that we keep the plate circuit load of 25,000 ohms but go back to the earlier supply potential of 275 volts. You can lay off the load line on the graph of Fig. 16-18 by using a slope of 125 volts for 5 milliamperes (as previously determined for a 25,000-ohm load) and by placing the lower end of the line at 275 volts on the line for zero current. The second point on the line then will be at a plate potential which is 125 volts lower than the supply potential of 275 volts, or at 150 volts, and at a current of 5 milliamperes. The values are easily read by laying a straight edge on these two points of the graph.

The plate current values are shown alongside the plate resistor in Fig. 16-20. With the same change of grid potential that has been used before, the plate current and load current will change from 4.2 to 5.3 milliamperes. The corresponding potential drops in the 25,000-ohm load will be 105 and 132.5 volts, making a change of 27.5 volts in the load. Dividing this change of 27.5 volts in the load by the change of 2 volts at the grid shows that the voltage amplification now is 13.75.

By using the much greater load resistance with the original plate supply potential, 25,000 ohms with 275 volts, we have raised the amplification from 11.5 to 13.75. This shows that we get increased amplification with more load resistance even when using the same plate supply potential. But to have a decided rise of amplification with a greater load resistance we must use a plate supply potential enough higher to maintain about the original values of plate current and load current.

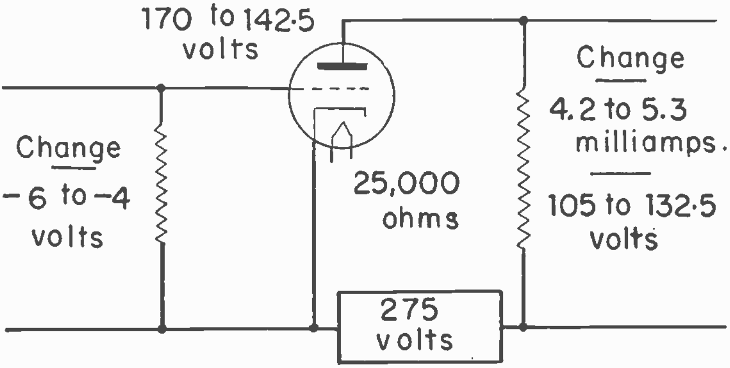


Fig. 16-20.—Operation with a 275-volt plate supply and a 25,000-ohm load.

The power used in the plate circuit, including the load and the tube, is taken from the plate supply source. This power is proportional to the product of supply potential and average plate or load current. Part of the total power is used in the load and the remainder is used in getting current through the tube. The load power is proportional to the product of the averages of load potential and current, while the tube power is proportional to the averages of tube plate potential and current. The useful power is that in the load. The power dissipated in the tube serves only to heat the tube, which is undesirable. In the accompanying list are given the power divisions for the three operating conditions which have been examined.

Fig. No.	Load ohms	Supply volts	Supply watts	Tube watts	Load watts	Per cent in load
16-16	10,000	275	2.38	1.63	0.75	31.5
16-20	25,000	275	1.31	0.74	0.57	43.5
16-19	25,000	437	4.21	1.89	2.32	55.0

The list brings out several points which are of interest. For one thing, increasing the load resistance while using the same supply potential decreases the power taken from the supply while increasing the percentage of this power that is used in the load rather than in the tube. Increasing the supply potential while using the same load resistance causes a considerable increase in total power taken from the supply, but raises the percentage of this power that is used in the load. Note that between the conditions of Figs. 16-16 and 16-19 we have made but a small increase in the power dissipated in the tube, but have brought about a great increase in the percentage used in the load and, of course, have brought about a great increase of amplification.

So long as we do not overtax the plate power supply it is generally desirable to work with high values of plate load resistance and with high values of plate or load current; this latter calling for high potential differences from the supply. In no case may we allow so much power dissipation in the tube as to overheat it, for that would mean a quick breakdown. The maximum permissible power dissipation for the plate in the 6J5 tube is 2.5 watts. The greatest dissipation shown in our list is 1.89 watts, which is well under the limit for safe operation.

Amplification Factor.—If you look in the published ratings or characteristics of the 6J5 tube you will find that its amplification factor is listed as 20, and quite likely you will wonder why, when the amplification factor is 20, we have been able to obtain actual voltage amplifications of only 11.5 to 15.63. The reason is that the amplification factor of a tube is the theoretical maximum voltage amplification which might be obtained under certain ideal operating conditions, but is not obtainable in practice.

Amplification factor is defined as the ratio of the change in plate voltage to the change in control grid voltage with the plate current remaining unchanged, and, if there are other grids in the tube, with the voltages of all those other grids remaining constant. To have a change of grid potential cause a change of plate voltage without an accompanying change of plate current the load would have to be an infinitely high resistance. Then there would be no current in the plate circuit and nothing useful could be done by the tube. The amplification factor is a measure of the relative effects on plate current of changes in grid potential and changes in plate potential. For instance, with a factor of 20, changes of grid voltage are 20 times as effective as changes of plate voltage, or, it would be necessary to have a change of plate voltage 20 times as great as a change of grid voltage to cause the same change in plate current.

The amplification factor of a tube may be determined with fair

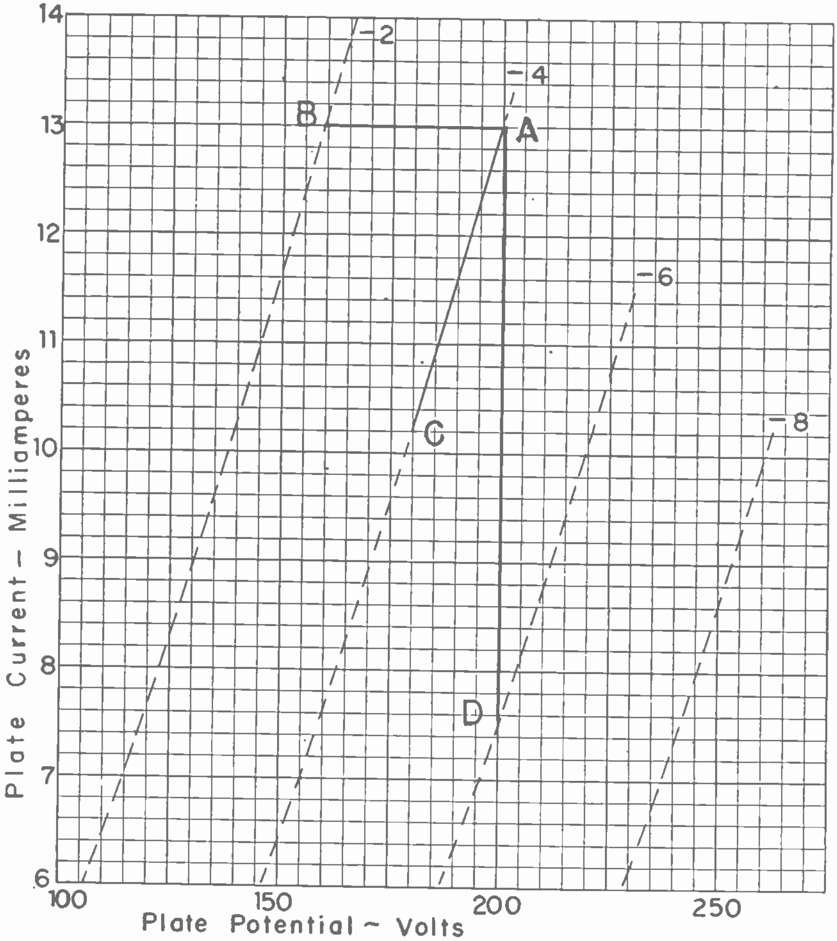


Fig. 16-21.—Measurements on plate characteristics for amplification factor, plate resistance, and transconductance.

accuracy from a family of plate characteristics. The method is shown by Fig. 16-21, where are shown also certain other measurements which we shall use in determining other characteristics. This graph is an enlarged portion of the graph of plate characteristics for the 6J5 tube. It includes the portion between 100 and 275 volts of plate potential, and between 6 and 14 milliamperes of plate current, and shows parts of the curves for negative grid potentials of 2, 4, 6 and 8 volts.

Because amplification factor is the ratio of a change in plate potential to a change of grid potential with the plate current constant we must make our measurement along some one line for plate current. Using the line for 13 milliamperes, we make a measurement from *A* to *B*. This line extends from —4 volts to —2 volts of grid potential, which is a change of 2 volts. The line extends also from 200 volts to about 160 volts of plate potential, which is a change of 40 volts. The ratio of 40 to 2 is 40/2 or is 20, and so we read the amplification factor as 20.

Plate Resistance.—The plate resistance of a tube is the number of ohms of opposition offered to a changing current or an alternating current by the plate-cathode path in the tube. Plate resistance in ohms is equal to the ratio of the change in volts of plate potential to the accompanying change in plate current measured in amperes when the grid potential remains constant.

Plate resistance may be determined, again with fair accuracy, from measurements on a family of plate characteristics. Because the grid potential is to remain constant we must take our measurements along some one curve of constant grid potential. In Fig. 16-21 we use the curve for —4 volts and take readings at points *A* and *C*. Between these two points there is a change of 20 volts in plate potential, from 180 to 200 volts. There is a change of plate current from 13.0 milliamperes at *A* to 10.2 milliamperes at *C*. This is a change of 2.8 milliamperes or 0.0028 ampere. The ratio of 20.0 (volts) to 0.0028 (ampere) is 20.0/0.0028, which gives the plate resistance as about 7,140 ohms.

Transconductance.—Conductance, as mentioned in an earlier chapter, is a measure of the ease with which current flows in a circuit or in part of a circuit; it is the reciprocal of resistance. The symbol for conductance is *G* just as the symbol for resistance is *R*. The formula for resistance in ohms, in terms of volts and amperes, is $R = E/I$. To change to the formula for conductance we invert the volts and amperes, and write $G = I/E$. When I and E are volts and amperes the inductance G is in mhos.

The word transconductance refers to the change in plate current that is caused by a change in grid voltage, or, in general, to the change of current in any element of a tube when this change is caused by a change of potential on some other element. Referring to the effect of the control grid on the plate current the correct name is *control-grid—plate transconductance.* This particular transconductance formerly was known as *mutual conductance* and still may be called by this name. When we speak of transconductance, without specifying any particular elements, we usually refer to control-grid—plate transconductance.

Transconductance in mhos is equal to the number of amperes change in plate current divided by the number of volts change in grid potential. That is, transconductance in mhos is a measure of *amperes per volt.* To avoid the fractions which would result from the small changes that occur in plate current, transconductance usually is specified in *micromhos.* Then it is equal to the number of microamperes of change in plate current per volt of change in grid potential. If we make our measurements in milliamperes of change in plate current per volt of change in grid potential, the result must be multiplied by 1,000 to change it to micromhos.

Transconductance (grid-plate) may be determined quite accurately from measurements on plate characteristics. We take the ratio of a change in plate current to a change in grid potential with the plate potential remaining constant, which means that the measurement must be taken along some one line for plate potential. Such a measurement is shown from A to D in Fig. 16-21, where the plate potential is 200 volts at both points. The change of plate current is from 13 to 7.5 milliamperes, making a difference of 5.5 milliamperes. There is a 2-volt change of grid potential; from 4 to 6 volts negative. Dividing the current change (5.5) by the voltage change (2) gives 2.75, and multiplying by 1,000 gives the grid-plate transconductance of the 6J5 tube as 2750.

Variation in Characteristics.—Measurements for amplification factor, plate resistance, and transconductance might be made anywhere on the family of plate characteristics. So long as the plate current exceeds about 5 milliamperes the value of amplification factor would remain around 20 for the 6J5 tube. The factors for other tubes would also remain practically constant with plate currents above some minimum value.

Values of plate resistance would drop with the measurements made at greater and greater currents. The manner in which plate resistance varies with plate current is shown by Fig. 16-22 for the 6J5 tube. Other triodes behave in a generally similar way. When the tube is operated with potentials which cause very small currents the plate resistance is very high. With greater currents, including those through the usual range used in practice, the plate resistance does not change a great deal.

Fig. 16-23 shows how transconductance of the 6J5 tube varies with operating conditions which cause various values of plate current. With zero plate current the transconductance is, of course, zero. There is a rapid increase of transconductance as plate current commences to flow, and then the rate of increase falls off with further rise of current. Since transconductance indicates the effect of changes of grid potential in causing changes of plate current, it is plain that a tube must be operated with fairly large plate currents if we are to have high amplification.

The values shown by Figs. 16-22 and 16-23 are very close to those computed from measurements on the plate characteristics, but they are not always exactly the same. This is because the measurements taken on the characteristic curves are supposed to be made with exceedingly small changes of current and potential, while our measurements on Fig. 16-21 were made with large changes of both currents and potentials.

Multiplying the plate resistance in ohms by the transconductance in mhos will give the accompanying amplification factor. If the transconductance is taken in micromhos the product must be divided by 1,000,000 to find the amplification factor. For example, on Fig. 16-22 we read the plate resistance at a current of 10 milliamperes as about 7,300 ohms, and on Fig. 16-23 we read the transconductance at the same current as about 2,710 micromhos. Multiplying 7,300 by 2,710 gives 19,783,000, and dividing by 1,000,000 shows the amplification factor at this value of plate current to be 19.78, or approximately 20.

Symbols for Tube Characteristics. — The various potentials,

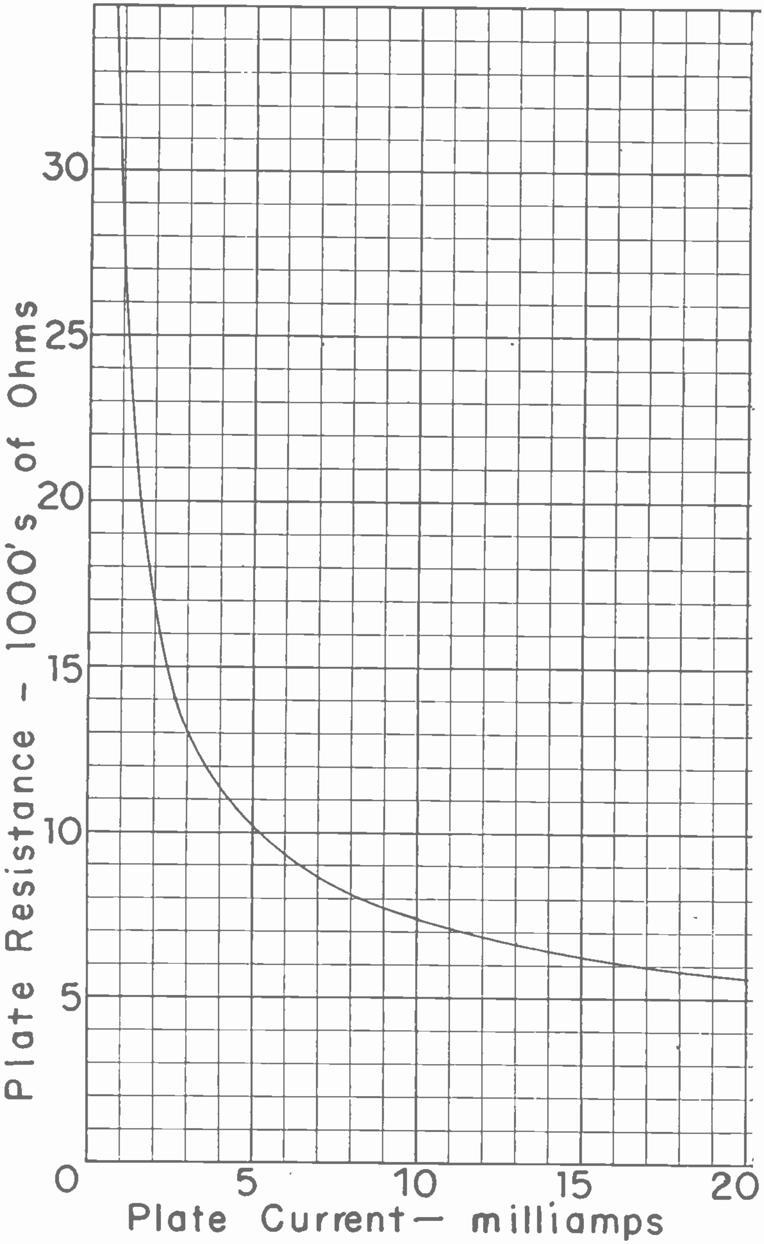


Fig. 16-22.—How plate resistance varies.

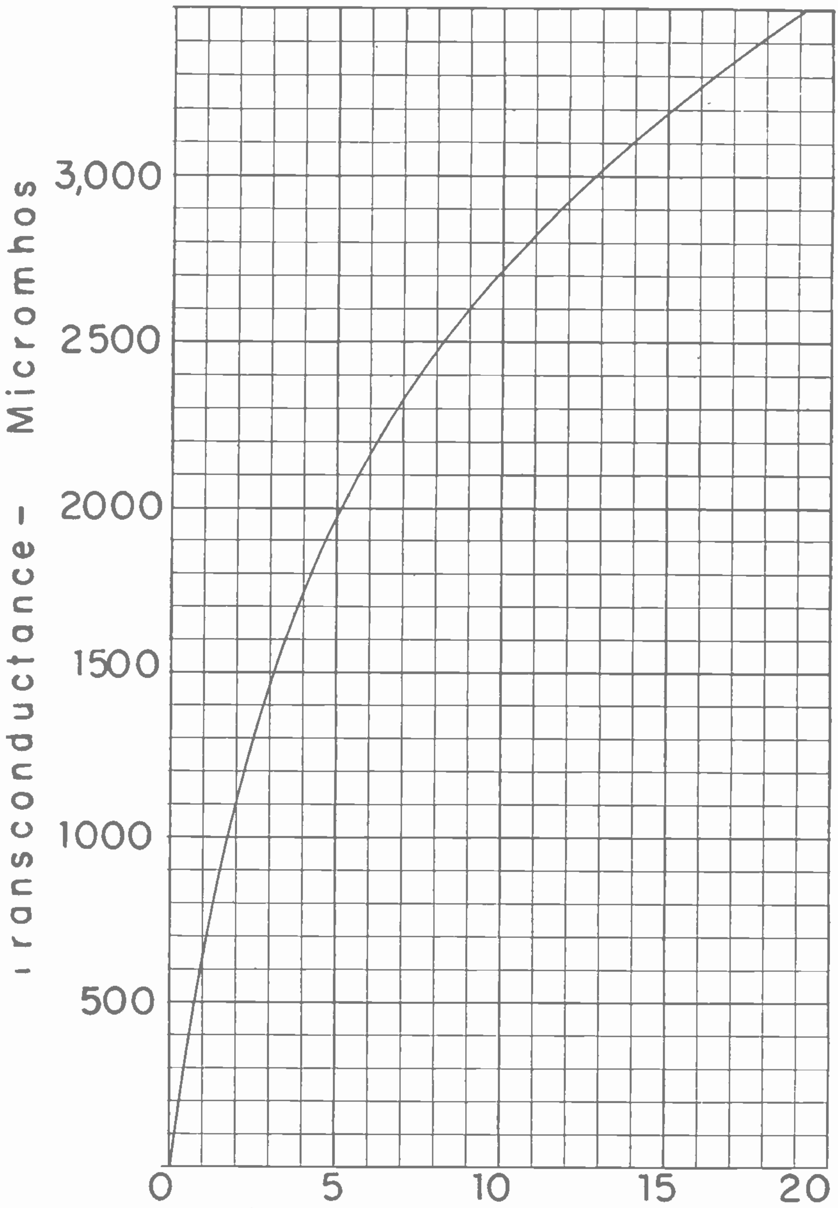


Fig. 16-23.—How transconductance varies.

currents, and other characteristics of triodes may be indicated by certain symbols, which are,

Ep	Plate potential, plate to cathode, in volts.
Ip	Plate current (electron flow), usually in milliamperes.
Eg	Control grid potential, grid to cathode, in volts.
Ig	Control grid current (electron flow), usually in microamperes.
Rp	Plate resistance, in ohms.
u	or *mu.* (The Greek letter mu) Amplification factor.
Gm	Transconductance, control-grid to plate, usually in micromhos.

In this chapter we have analyzed quite thoroughly the performance of the 6J5 voltage amplifier triode. This one tube has been chosen so that we might have actual values with which to make our computations, because its performance is typical of all other voltage amplifying triodes and, in a general way, is typical of all triodes. The methods which have been applied in solving practical problems may be applied to similar problems involving any other triode tube, and most of them apply as well with tubes having more than three elements.

The 6J5 tube is of special interest because it is equivalent in performance to each section of the type 6SN7, which is a double triode or twin triode employed in the control circuits of many makes and models of television receivers. The 6SN7 contains two complete triodes within a single envelope. There are two plates, two grids, and two cathodes, each with its separate base pin. Only the single heater is common to both sections of the 6SN7. Either section of this twin triode may be employed for any purpose served by one 6J5 tube, either in the same circuit or in two separated circuits. One 6SN7 tube is the equivalent of two 6J5's, but saves space, costs less, and takes less heater current and power than two separate tubes.

Chapter 7

GRID CIRCUITS AND GRID BIAS

Most of the potentials which are amplified by radio tubes are alternating. An alternating potential commences at zero value, increases more or less gradually until it reaches some maximum number of volts in one polarity and decreases from that maximum to zero. Then the potential increases in the opposite direction until it reaches the same maximum number of volts as before, and again decreases to zero. So the changes of potential continue.

In all except a few special applications it is the *changes* of potential that are amplified. The potentials which are caused by or which cause radio frequencies, intermediate frequencies, and audio frequencies are alternating or varying. They are continually changing, and it is the changes that are to be amplified. Were a steady potential applied to a control grid it would permit some certain rate of electron flow from cathode to plate, but this plate current would remain steady

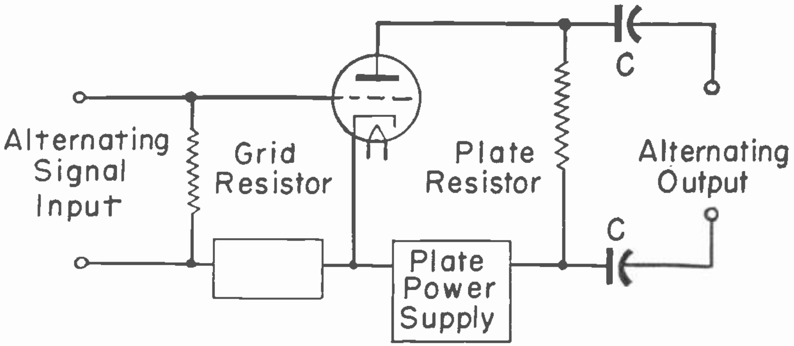


Fig. 17-1.—A stage of amplification using a triode tube.

Connections for a typical amplifying stage using a triode tube are shown by Fig. 17-1. An alternating signal input is applied across the grid resistor and between the grid and cathode of the tube. In the plate circuit is a plate resistor which is the plate load resistor. The changes of potential produced across the plate resistor pass through capacitors *C* and *C* to the output. The capacitors are used to prevent the high direct potentials in the plate resistor from reaching the output connections. As you know, capacitors do not permit the flow of direct currents which would result from the direct potentials, but readily permit alternating currents to flow in a circuit containing the capacitors.

In order to have definite potentials and currents with which to illustrate what happens we shall assume that the amplifier tube is a type whose plate characteristics are shown by Fig. 17-2. On this graph we have the usual curves for zero grid potential and for various negative grid potentials, and have in addition a curve

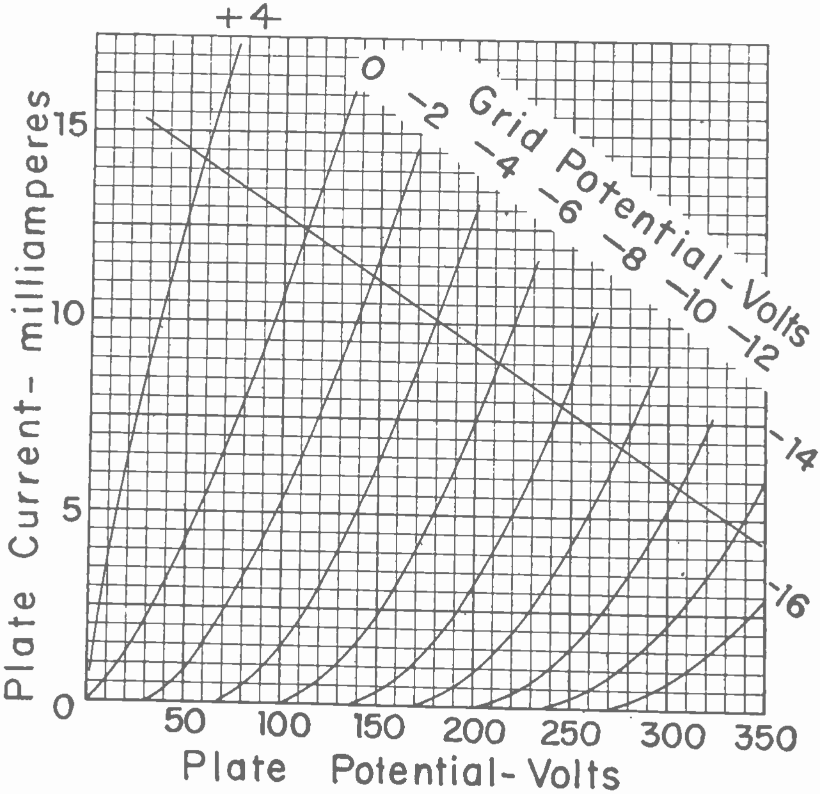


Fig. 17-2.—The plate characteristics, including a curve for a 4-volt positive grid potential.

showing values of plate current when the grid is 4 volts positive. On the characteristics has been drawn a load line for a resistance of 30,000 ohms, which is the load we shall assume for the plate circuit.

Our experiments in amplification will be performed with an alternating input potential having peak or maximum values of 4 volts in each polarity. The alternating potential will first cause an electron flow in one direction through the grid resistor, and then in the opposite direction. The grid will be made 4 volts negative with reference to the cathode, and then 4 volts positive with reference to the cathode. At the instants in which the alternating input potential passes through its zero values the grid of the tube will be at zero potential with reference to the cathode.

On the load line of Fig. 17-2 we may read the values of plate current corresponding to the grid potentials.

Grid: + 4 volts = 14.25 milliamperes Ip.
Grid: 0 volts = 12.40 milliamperes Ip.
Grid: — 4 volts = 10.10 milliamperes Ip.

These grid potentials and plate currents are shown by Fig. 17-3. During the half-cycle of input potential in which the grid potential is changed from zero to 4 volts positive the plate current changes from 12.40 to 14.25 milliamperes, which is a change of 1.85 milliamperes. During the opposite half-cycle of input, when the grid potential changes from zero to 4 volts negative, the plate

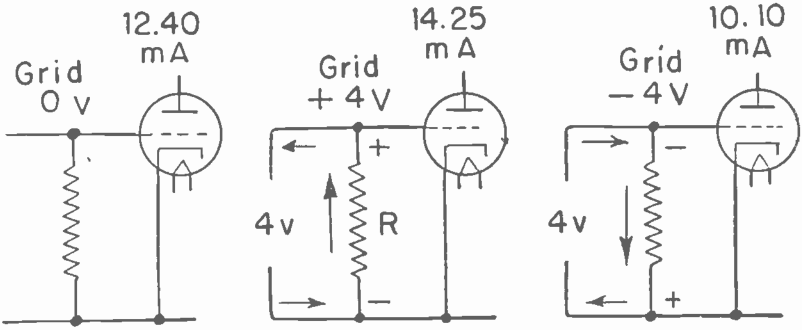


Fig. 17-3.—Grid potentials and plate currents with the 4-volt alternating signal potential.

current changes from 12.40 to 10.10 milliamperes, which is a change of 2.30 milliamperes.

The unequal changes of plate current accompanying the equal changes of grid potential would produce in the 30,000-ohm load resistance unequal changes of potential difference. The load potential changes would be 55.5 volts as the grid goes positive, and 69.0 volts as the grid goes negative. The result would be as in Fig. 17-4, where the output amplitudes are not equal in both directions, and where the output signal is distorted with reference to the input signal.

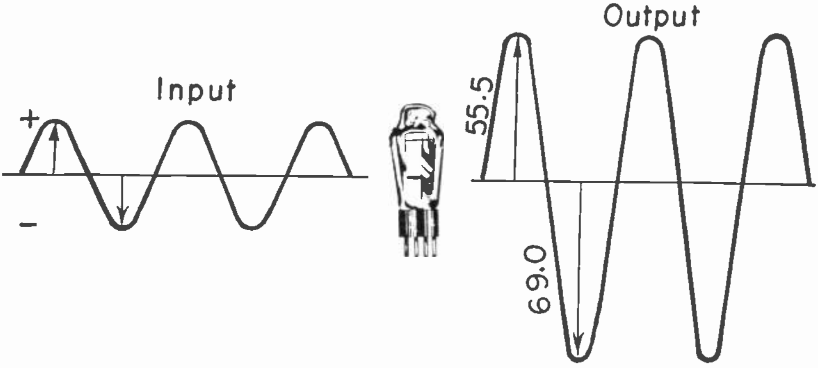


Fig. 17-4.—The output amplitudes are not equal in both directions.

Now let's take the same rates of change of input potential, but make them of such values as to maintain the tube grid always negative. This might be done with an input signal having an average value of —4 volts, and changing from zero to 8 volts negative. Then our center point would be —4 volts instead of the former zero, the maximum in one polarity would be zero, and in the other polarity would be 8 volts negative. Again taking the values from the load line of Fig. 17-2 we would have,

Grid: —4 volts = 10.10 milliamperes Ip.
Grid: —8 volts = 7.90 milliamperes Ip.

Grid: 0 volts = 12.40 milliamperes Ip.

Now the plate current changes, from the center value of 10.10 milliamperes, to a value of 12.40 milliamperes with the grid at zero potential (a change of 2.30 milliamperes), and to a value of 7.90 milliamperes with the grid 8 volts negative (a change of 2.20 milliamperes). The corresponding changes of potential difference in the 30,000-ohm load resistance would be 69 and 66 volts. That is, the amplitude of the load potential change would be 69 volts with the grid made less negative, and would be 66 volts with the grid made more negative than its center value. The difference between the amplitudes amounts to less than 4½ per cent, and so we have an amplitude distortion of less than 4½ per cent whereas with the operation shown by Fig. 17-4 the amplitude distortion is nearly 20 per cent.

Were we now to operate the grid with a center value of —6 volts, with changes to —2 volts and —10 volts, again having changes of 4 volts in each direction, the plate currents would be about 11.25, 9.00, and 6.80 milliamperes. The changes of current would be 2.25 milliamperes in one direction and 2.20 milliamperes in the other direction. The changes of potential in the load would be about 67.5 volts and 66.0 volts, and there would be but little amplitude distortion.

Grid Bias. — The preceding analyses of operating conditions show that, in order to have amplification which is fairly free from amplitude distortion, we must not allow the control grid to become positive at any time.

If we continue to use the 4-volt alternating input potential the

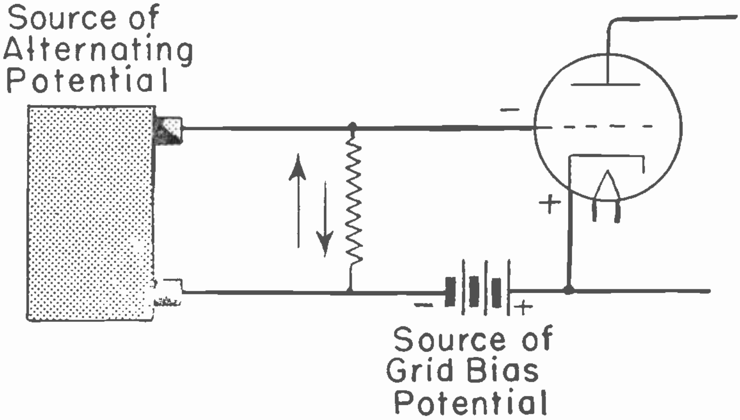


Fig. 17-5.—A grid bias potential furnished by a battery.

grid potentials may be kept between zero and 8 volts negative if we apply to the grid a potential that makes it 4 volts negative with no signal applied. One way of doing this is shown by Fig. 17-5. Here there is connected between the lower end of the grid resistor and the cathode of the tube a battery which furnishes a potential difference of 4 volts. The battery is connected with its negative terminal toward the grid resistor and toward the grid of the tube, and with its positive terminal toward the cathode. When no input signal is being applied to the grid resistor the effect of the battery will be to make the grid 4 volts negative with reference to the cathode.

With a 4-volt alternating signal applied across the grid resistor the alternating potentials will act first in one direction and then in the opposite direction, as shown by arrows in Fig. 17-5. When the input reaches its peak of 4 volts positive it will exactly counteract the 4 volts of negative potential from the battery, and the net grid potential with reference to the cathode will be zero. When the input signal reaches its negative maximum of 4 volts its effect will be added to that of the battery, and the potential of the grid will become 8 volts negative with reference to the cathode.

The potential which is applied to the control grid in order to fix its operating center point, and its average potential at all times, is called a *grid bias*. When the grid bias is furnished by a battery, the battery is called a *C-battery*. Biasing batteries or C-batteries seldom are used in practice. The biasing potential usually is furnished in other ways, which we shall investigate.

With a 4-volt negative grid bias and a 4-volt alternating input potential the operation of the tube may be shown as in Fig. 17-6. The values of plate current are those previously read and noted from the plate characteristics. At the left the input potential is zero, or else there is no input signal. The control grid is 4 volts negative, which is the same value of potential as the potential difference of the biasing battery. The grid is at the same potential as the grid end of the battery because there is no electron flow in the grid resistor, and with no electron flow in this resistance there is no difference of potential between its ends. Then the grid, connected to the upper end of the resistor, must be at the same potential as the terminal of the battery which is connected to the lower end of the resistor. There is no electron flow in the resistor because there is no grid current while the grid is maintained negative.

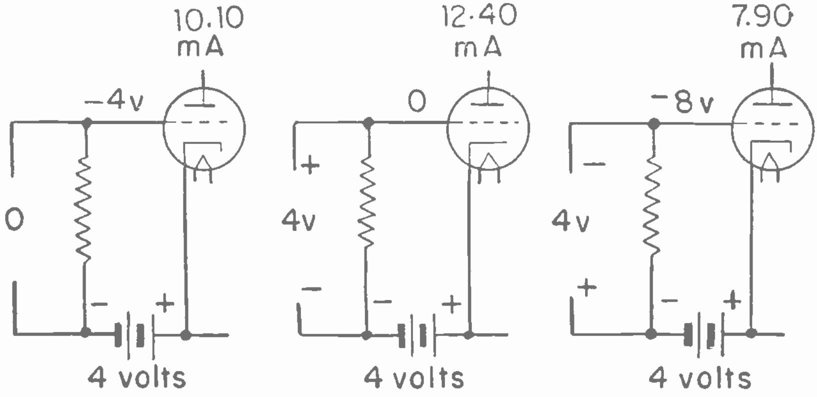


Fig. 17-6.—Operation of the tube with a 4-volt negative bias.

In the center diagram of Fig. 17-6 the input signal is of such polarity as would make the grid positive except for the effect of the biasing battery. But the signal potential and the biasing potential are equal and of opposite polarity, so they balance each other to leave the grid at zero potential. In the right-hand diagram the signal is of such polarity as would make the grid 4 volts negative were the biasing battery not present. But now

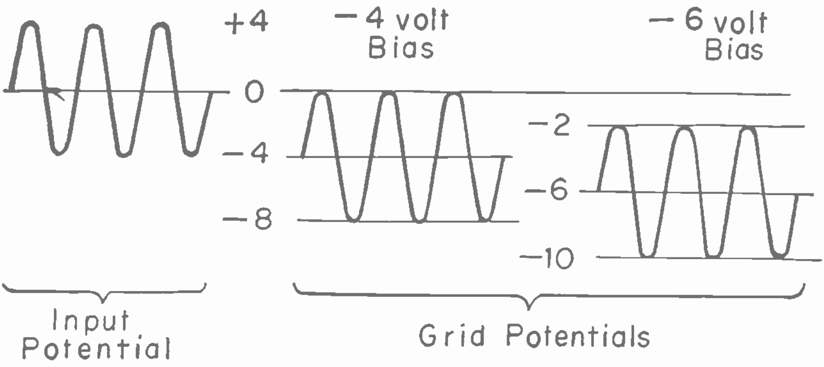


Fig. 17-7.—The grid bias acts to change the average potential of the grid.

the signal and biasing potentials act in the same direction; they add together and make the grid 8 volts negative.

The effect of negative grid bias may be shown as in Fig. 17-7. At the left is represented a 4-volt alternating potential which is the input signal. The average value is zero, and the peaks are at + 4 volts and — 4 volts. The effect of a 4-volt negative bias is shown at the center. The signal goes through the same changes, but now they center around the bias potential which is 4 volts negative, and the peaks are at zero and at — 8 volts. At the right is shown the effect of a 6-volt negative bias. Again the signal goes through the same changes so far as amplitude is concerned, but the center is at a negative potential of 6 volts with peaks at —2 volts and at —10 volts.

From Fig. 17-7 it is quite plain that the negative bias potential must be at least equal to the peak value of the alternating input potential if the grid never is to become positive. With a negative bias just equal to the signal peak, the grid will become of zero potential when the signal reaches its peak positive value. Usually we employ a bias potential somewhat more negative than the maximum positive signal peak, thus avoiding the possibility of amplitude distortion due to the grid becoming momentarily positive.

Sources of Biasing Potential.—There are four principal sources of biasing potential for control grids: (1) We may use a C-battery as in Figs. 17-5 and 17-6, (2) The biasing potential may be taken from the same power supply system that furnishes plate potentials and currents as well as potentials for whatever grids are used in the tubes, (3) we may use the method called cathode-bias with which the biasing potential is the voltage drop in a resistor connected in series with the tube cathode, or, (4) we may employ the method called grid rectification in which the bias potential results from flow of grid current in the grid resistor connected between the control grid and the cathode of the tube.

There are two principal objections to the use of a battery for biasing. One objection is the weight of the battery, which weight is greater than that of the additional parts needed with other methods. The other objection is that the battery eventually becomes discharged or "run down" and then its biasing potential decreases to allow greater plate currents than are desired. Common types of dry cells used in biasing batteries have potential differences of 1½ volts each. Therefore, the voltages furnished by these batteries must be in multiples of 1½ volts; such as 3 volts, 4½ volts, 6 volts, and so on. To obtain intermediate potential differences it is necessary to use a voltage divider on the biasing battery, and the divider allows a current drain which discharges the battery in much less time than without such a drain.

Because a biasing battery furnishes no current, but only a difference of potential, it will have a service life that is as long as though the battery were kept in storage. The chief advantage of battery bias is that the potential difference remains more nearly constant than with any of the other methods. With all other methods there are greater or smaller variations of biasing potential which occur with variations in operation of the apparatus, but the C-battery is unaffected by such things.

Bias From D-c Power Supply.—The principle of obtaining a grid biasing potential from the same source that furnishes plate potential and current is shown by Fig. 17-8. Across the terminals of the source of direct current and potential are connected resistors *A-B* and *B-C* in series with each other. The load resistor *Ro* is connected between the plate of the tube and the positive terminal of the power supply. The grid resistor *Rg* is connected between the control grid and the negative terminal of the power

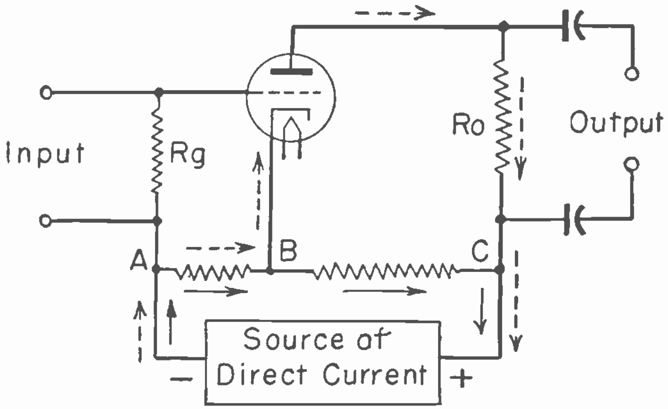


Fig. 17-8 —Bias obtained from the source of plate potential and current.

supply. The cathode of the tube is connected to a point between resistors *A-B* and *B-C*.

Electron flow from the power supply through resistors *A-B* and *B-C* is indicated by full-line arrows. The potential drop due to electron flow in resistor *A-B* is the grid biasing potential for the tube. Point *A* is more negative than point *B*, as shown by the direction of electron flow between these points, and so the grid of the tube is maintained more negative than the cathode.

The supply potential for the plate circuit is the potential drop between *B* and *C*. As shown by the direction of electron flow between these points, *C* is more positive than *B*, and so the plate of the tube, through the load resistor, is maintained more positive than the cathode which is connected to *B*.

Electron flow in the plate circuit is indicated by broken-line arrows. This flow goes from the plate through load resistor *Ro*, through the source, then through resistor *A-B* and back to the cathode. Since plate current flows in resistor *A-B*, and since it is the potential drop across this resistor that is the grid bias, every variation of plate current will cause a corresponding variation in the bias. The greater the current indicated by the full-line arrows in comparison with the variations of plate current, the less will be the effect of these variations in causing momentary changes of bias potential. For example, were the current from the source to be 20 milliamperes and the plate current variations to be only 2 milliamperes, the changes of potential drop due to plate current would not be very great. However, were the current from the supply source to be something like 4 milliamperes, with plate current variations of 2 milliamperes, the plate changes would cause relatively large variations of grid bias.

A disadvantage of the biasing system of Fig. 17-8 is that the current indicated by full-line arrows must be in addition to the plate current, and the power supply must be capable of furnishing considerably more current than would be required for the plate circuit alone. The chief advantage of this method is in the maintaining of quite constant values of grid bias provided the current in *A-B* and *B-C* is made great enough to make variations of plate current small in comparison.

Cathode-bias. — Fig. 17-9 shows the principle of the biasing method which is called cathode-bias or which sometimes is called self-bias. Directly in series with the cathode of the tube is a bias resistor. Consequently, all of the electron flow entering the cathode and being emitted from the cathode must pass through this resistor. The path of electron flow in the plate circuit is indicated by arrows. This flow leaves the plate, goes through the load and the source, then returns to the cathode through the bias resistor. The direction of electron flow through this resistor shows that its lower end is negative with reference to its upper end or cathode end. The lower end of the bias resistor is connected through grid resistor *R* to the control grid of the tube. With no electron flow in *R*, and no difference of potential across this unit, the grid will be at the same potential as the lower end of the bias resistor and thus will be at a potential more negative than that of the cathode.

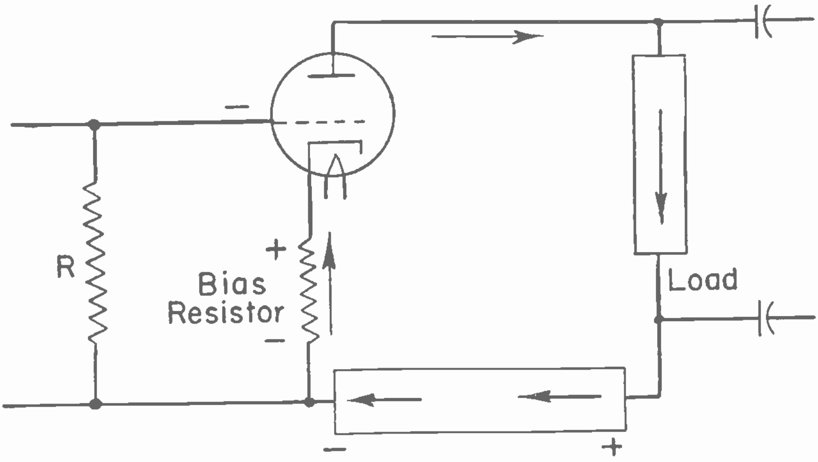


Fig. 17-9.—How the bias resistor is placed in a cathode-bias system.

With a triode the cathode current is the same as the plate current when there is no current in the control grid circuit. With tubes having grids other than the control grid the cathode current is equal to the sum of the plate current and any currents which may flow in those other grids.

As is apparent from examination of the circuit diagram, every change of plate current means a change of current in the bias resistor; all of these current changes mean corresponding changes of potential difference across this resistor, and changes of grid bias.

For an example in the action of cathode-bias we shall assume that we wish to have the tube performance shown by the load line of Fig. 17-2, with an average plate current of 9 milliamperes (0.009 ampere) and an average grid potential or bias potential of 6 volts negative. Ohm's law, R = E/I, shows that to have a current of 0.009 ampere with a potential difference of 6 volts the resistance must be 667 ohms. This will be the value of our bias resistor, as shown at *A* in Fig. 17-10. The resistance for any other bias potential and cathode current might be similarly computed; by dividing the number of volts of bias by the number of amperes of cathode current.

If we had a steady bias of 6 volts negative, and applied a 4-volt alternating signal potential, the grid potential would vary between — 2 volts and — 10 volts, as was shown by Fig. 17-7. At a grid potential of — 2 volts the plate current would become 11.25 milliamperes or 0.01125 ampere. This current in the bias resistor of 667 ohms would mean a potential drop (*E* = *IR*) of 7.5 volts. But this then would be the negative bias potential, and subtracting the 4-volt signal peak we would have a grid potential

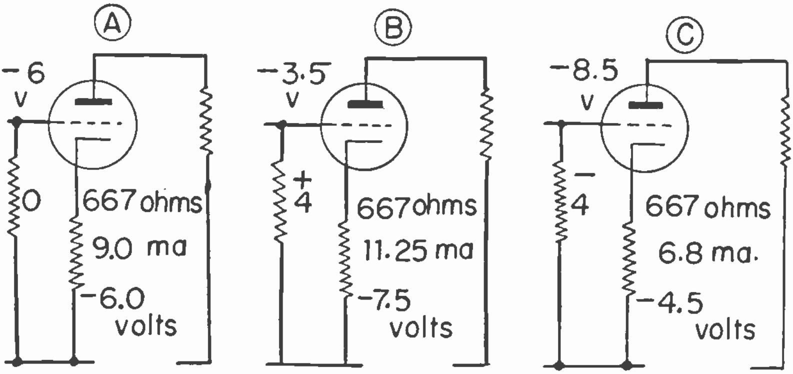


Fig. 17-10.—These potentials and currents would exist if the cathode-bias did not alter the values of plate current.

of 3.5 volts negative instead of the assumed 2 volts negative. With this greater negative bias the plate current and cathode current would not increase to the assumed 11.25 milliamperes, but would be something less. The computed values are shown at *B* in Fig. 17-10.

There would be an opposite effect when the signal potential went to its opposite peak of 4 volts negative. If the plate current actually went down to the value corresponding to a grid potential of — 10 volts the current would be 6.8 milliamperes or 0.0068 ampere. This current in the 667-ohm bias resistor would mean a potential difference of about 4.5 volts, which would be our bias potential. Adding to this bias the negative signal peak of 4 volts would make the grid potential 8.5 volts negative instead

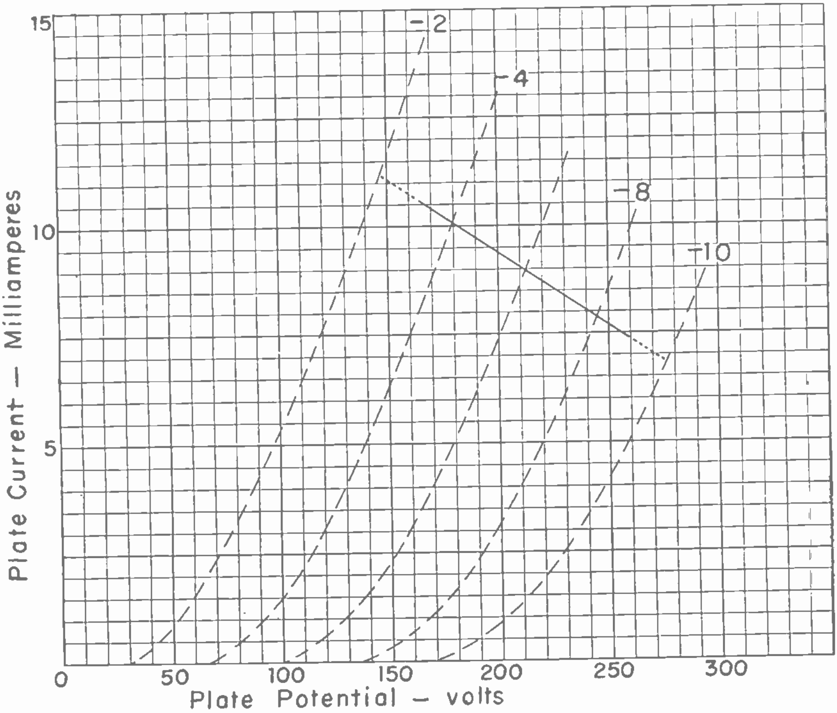


Fig. 17-11.—The portions of the load line on which the tube operates with cathode-bias and with fixed bias

of the assumed 10 volts negative. Then the plate current and cathode current would not drop to 6.8 milliamperes, but to some value greater than this current. The computed values are shown at *C* in Fig. 17-10.

Actually the effect of the cathode-bias with our assumed operating conditions would be to limit the change of grid potential to between about 3.1 volts and 8.9 volts negative. With a fixed bias of — 6 volts the grid potential would change between 2.0 and 10.0 volts negative with the applied alternating signal having 4-volt peaks.

The result of cathode-bias is shown by Fig. 17-11. Here we have, in broken lines, the plate characteristic curves for grid potentials between 2 and 10 volts negative. We have also a portion of our 30,000-ohm load line, along which the tube must work regardless of the biasing method so long as we have this load and the corresponding plate power supply potential.

The solid portion of the load line is the portion along which the tube operates when the grid potential varies between about 3.1 and 8.9 volts negative, as is the case when using the 667-ohm biasing resistor in series with the cathode. The dotted extensions of the load line, which continue to — 2 volts and to — 10 volts of grid potential, show the portion of the line along which the tube would operate with a fixed bias of 6 volts negative and with an applied alternating signal of 4 volts peak in each polarity.

Now let's see how the tube operates with cathode-bias. With zero applied signal potential the plate current is 9.0 milliamperes, the potential drop in the bias resistor is 6.0 volts and the grid bias is 6.0 volts negative. These are the values shown at A in Fig. 17-10.

When the applied signal reaches its positive peak of 4 volts the grid potential, as shown on the load line, becomes about 3.1 volts negative and the plate current becomes a little more than 10.6 milliamperes. This plate current flows in the bias resistor of 667 ohms, and there is a potential drop of about 7.1 volts in this resistor. Thus the effect of the resistor potential is to make the grid 7.1 volts negative, and the effect of the signal potential is to make the grid 4.0 volts positive. The net grid potential is the difference, or is 3.1 volts negative.

When the applied signal reaches its negative peak of 4 volts we take readings from the lower end of the solid portion of the load line. There we have a grid potential of about 8.9 volts negative and a plate current of about 7.4 miliamperes. This current in the 667-ohm bias resistor causes a potential drop of about 4.9 volts in the resistor, and tends to make the grid 4.9 volts negative. Adding the effects of the resistor potential and the signal potential, both of which now are negative, makes the grid 8.9 volts negative. Thus we find that the tube really does operate on the solid portion of the load line. The operating currents and potentials are shown by Fig. 17-12. At *A* there is zero input signal. At *B* the signal is 4 volts positive. At *C* the signal is 4 volts negative.

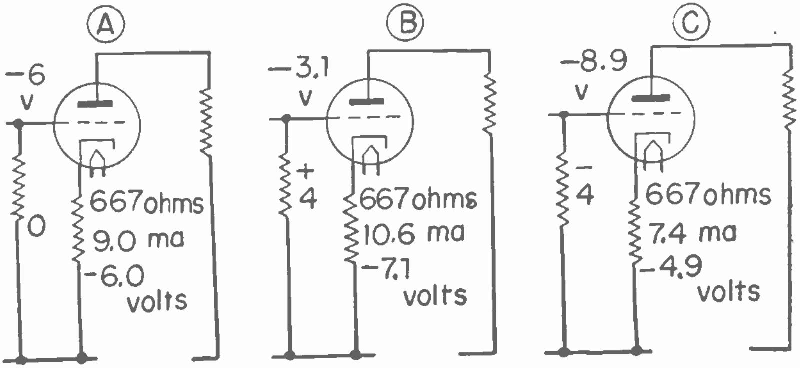


Fig. 17-12.—These potentials and currents actually exist, because cathode-bias alters the values of plate current.

Now what about the amplification with cathode-bias as compared with amplification with a fixed bias of 6 volts negative? To determine the amplifications we first read the plate currents for the signal potentials, then multiply currents by load resistance to find the potential differences across the load, figure the changes of load potential each way from the average potential with a zero signal, and divide these changes by the change of grid potential as caused by the signal. Here are the values with a fixed bias of —6 volts.

Signal potential	Plate current, milliamps.	Volts drop in load resistance	Change of volts in load	Voltage amplification
+ 4 volts	11.25	337.5	67.5	16.9
0 volts	9.0	270.0		
— 4 volts	6.8	204.0	66.0	16.5

Making the same computations for the conditions with our cathode-bias we have,

Signal potential	Plate current, milliamps.	Volts drop in load resistance	Change of volts in load	Voltage amplification
+ 4 volts	10.6	318.0	48.0	12.0
0 volts	9.0	270.0		
— 4 volts	7.4	222.0	48.0	12.0

We find that the cathode-bias has brought about a considerable reduction in voltage amplification; a reduction from an average amplification of 16.7 with fixed bias to 12.0 with our particular cathode-bias. Cathode-bias has made the amplification more uniform in both directions.

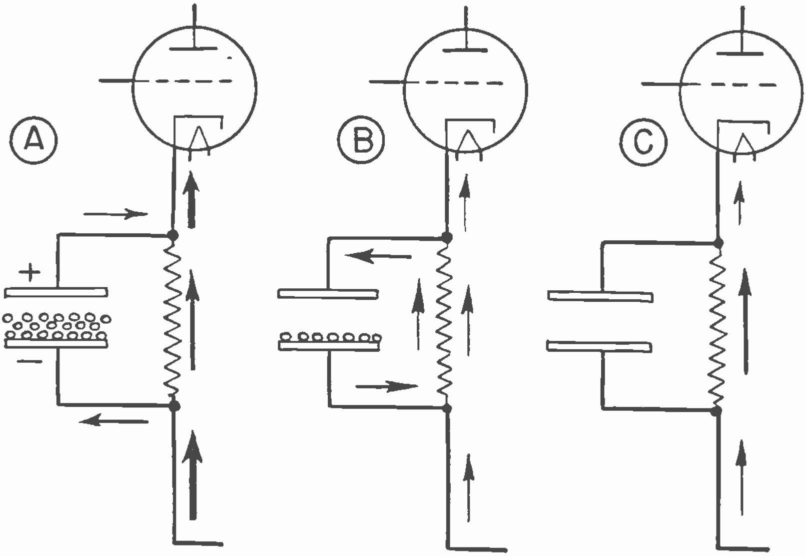


Fig. 17-13.—The action of a smoothing capacitor or bypass capacitor used with the bias resistor.

Degeneration. — The reduction of amplification which results from cathode-bias is a kind of degeneration. *Degeneration* is a name applied to any action whereby changes of potential or current in the plate circuit of a tube so affect the potentials in the grid circuit as to lessen the voltage amplification of the tube. If we desire maximum amplification, then degeneration is undesirable. If we desire the greatest uniformity of amplification with applied signals of widely varying frequencies, then degeneration is desirable.

The degenerative effect of cathode-bias may be lessened by connecting across the bias resistor a smoothing capacitor as in Fig. 17-13. At *A* there is represented a relatively large electron flow to the cathode; such a flow as would result from a large increase of plate current. The accompanying increase of potential difference across the bias resistor acts on the capacitor, and causes the capacitor to take a charge. Part of the electron flow goes through the resistor and the remainder goes to charge the capacitor.

When plate current and cathode current decrease, as in diagram *B*, the reduced electron flow through the bias resistor is accompanied by a reduced difference of potential across the resistor. This leaves the capacitor voltage higher than the resistor potential, and the capacitor discharges through the resistor in the direction of electron flow shown by arrows.

As electron flow in the resistor tends to increase, as in diagram *A*, the increase is lessened by the capacitor. When electron flow through the resistor tends to decrease, as at *B*, the decrease is lessened because of the extra electron flow coming from the capacitor. This latter effect is shown at *C*, where the bias resistor is carrying the sum of the electron flows from the plate circuit and from the capacitor, with this sum being greater than the plate electron flow alone.

The changes of electron flow and potential difference in the bias resistor become smaller than without the capacitor. Since the potential difference across this resistor is the grid bias, the grid bias undergoes relatively small variations as the plate current varies.

The greater the capacitance of the smoothing capacitor the more uniform will be the electron flow in the bias resistor, the more uniform will be the grid bias, and the less will be the degeneration. To secure such results the capacitance should be large enough so that its capacitive reactance at the lowest frequency to be amplified is as low or lower than the resistance of the bias resistor. In the case which we are considering the bias resistor has resistance of 667 ohms. If the amplification is to be of audio frequencies, and if the lowest frequency well amplified is to be 30 cycles, the capacitance of the capacitor would have to be 7.96 or practically 8 microfarads if its resistance is to equal the resistance of the bias resistor. This we learn from the formula,

$$\text{Microfarads} = \frac{159\ 155}{\text{ohms} \times \text{cycles}}$$

The capacitance for any other combination of lowest amplified frequency and resistance of the bias resistor may be similarly computed. For maximum amplification the capacitive reactance should be considerably less than the bias resistance. In our amplifier we might use, instead of 8 mfd., a capacitance of 25 to 50 mfd.

Where some degeneration is desired, about half of the biasing resistance may be fitted with a smoothing capacitor and the other half left without any capacitance across it. A smoothing capacitor may or may not be used with cathode bias for audio-frequency amplifiers, depending on the requirements, but one is used with radio-frequency and intermediate-frequency amplifiers in practically all cases. Because of the relatively high frequencies in these latter classes of amplifiers only small values of capacitance are required to bring their reactances well below the resistances of the bias resistors used. The capacitor which smooths out the variations of potential in the bias resistor often is called a bypass capacitor.

Cathode-bias Circuits.—Cathode-bias circuits for single tubes have been shown in several of the preceding diagrams. If two or more tubes in the same piece of apparatus are to be operated with the same grid bias the one bias resistor may be used for all of the tubes as shown by Fig. 17-14. All of the plate circuits connect to the positive side of the common power supply, and the lower ends of all the grid resistors connect to the negative side of this power supply. Between the negative of the power supply and the cathodes of all the tubes are the bias resistor and its smoothing capacitor. The entire electron flow to all of the cathodes together goes through the resistor. This flow is equal to the sum of all of the cathode currents, and it is the flow used in computing the resistance required in the bias resistor.

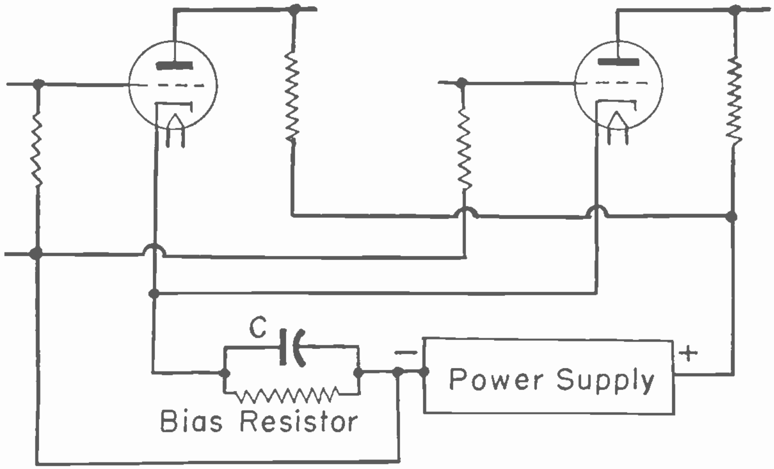


Fig. 17-14.—A single cathode-bias resistor used with several tubes.

A tube having a filament-cathode may be provided with cathode-bias as shown by Fig. 17-15. Here the filament is heated by alternating current from a filament transformer or from a filament winding on any other transformer. The outer ends of the filament winding on the transformer, and the ends of the connected filament, become alternately positive and negative. The center of the winding and the center of the filament remain at a constant average potential. Electron flow from the plate circuit comes through the plate power supply, the bias resistor, and to the center of the transformer winding to which the resistor is connected, thence divides and goes equally to the two ends of the filament. This electron flow then is emitted quite uniformly from the entire length of the filament, and goes to the plate inside the tube.

If the filament winding of the transformer has no center tap, a center-tapped resistor of 20 to 30 ohms value may be connected across the ends of the winding as in the lower left-hand sketch of

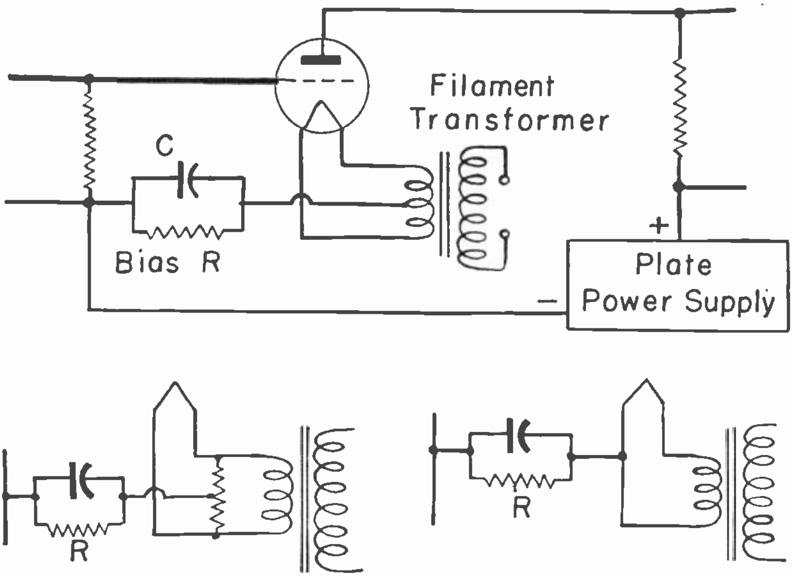


Fig. 17-15.—Obtaining a cathode-bias with a filament-cathode type of tube.

Fig. 17-15, and the bias resistor *R* connected to the center of this tapped resistor. Then electron flow coming back through the bias resistor divides and flows equally through the halves of the tapped resistor to the filament.

Were the bias resistor connected directly to one end of the filament, as in the lower right-hand sketch of Fig. 17-15, the bias potential would be affected by the reversing polarity at that end of the filament, and the bias would increase and decrease with alternations of the filament heating current coming from the transformer. The value of the bias resistor is computed in accordance with the cathode current and the desired bias potential, just as with other applications of cathode-bias. The formula is,

$$\begin{array}{c}\text{Bias resistor,}\\ \text{ohms}\end{array} = \frac{1000 \times \text{required bias, volts}}{\text{cathode current, milliamps}}$$

Bias With Grid Rectification.—When an alternating potential is applied to the control grid circuit of a tube it is possible to obtain a negative grid bias potential by the use of a capacitor called a *grid capacitor* and a resistor called a *grid leak*. This method makes use of what is called grid rectification, so named because the control grid and the cathode of the tube act together as a rectifier to permit electron flow from cathode to grid but not in the reverse direction from grid to cathode. The plate of the tube, and any grids other than the control grid, take no part in this action, and, so far as the securing of bias potential is concerned, those other elements might be omitted from the tube.

Grid bias with grid rectification formerly was employed with many tubes used as demodulators or detectors. It is now used with many oscillators, and the same general principle of securing a fairly steady potential difference from an alternating potential source will appear in many following circuits which we shall study. The principle may be explained as follows.

In diagram *1* of Fig. 17-16 a capacitor is connected between the control grid of a tube and the signal input circuit which includes resistor *R*. Resistor *R* is the one which has been shown in many earlier diagrams as connected between the control grid and the cathode. Here it is assumed that the alternating potential applied to the input is momentarily of such polarity as to make the upper end of *R* positive and the lower end negative. Thus the cathode of the tube is made more negative than the grid, or the grid is more positive than the cathode, and there is an electron flow from cathode to positive grid as indicated by small arrows in the tube. This electron flow can pass only as far as one of the capacitor plates, and the accumulation of electrons on this plate forms a negative charge.

In diagram *2* the direction of applied input potential has reversed. This makes the tube cathode more positive than the control grid, or makes the grid more negative than the cathode. With the grid negative with respect to the cathode there can be no electron flow between these elements. Consequently, the negative charge which has been accumulated on the capacitor plate cannot escape through the tube, and it remains on the capacitor plate. As the alternating input potential continues to reverse its direction, electrons are added to the capacitor plate connected to the grid until the negative potential of this plate and the connected control grid become so negative as to prevent further electron flow from cathode to grid in the tube.

In diagram *3* there has been connected between the grid and

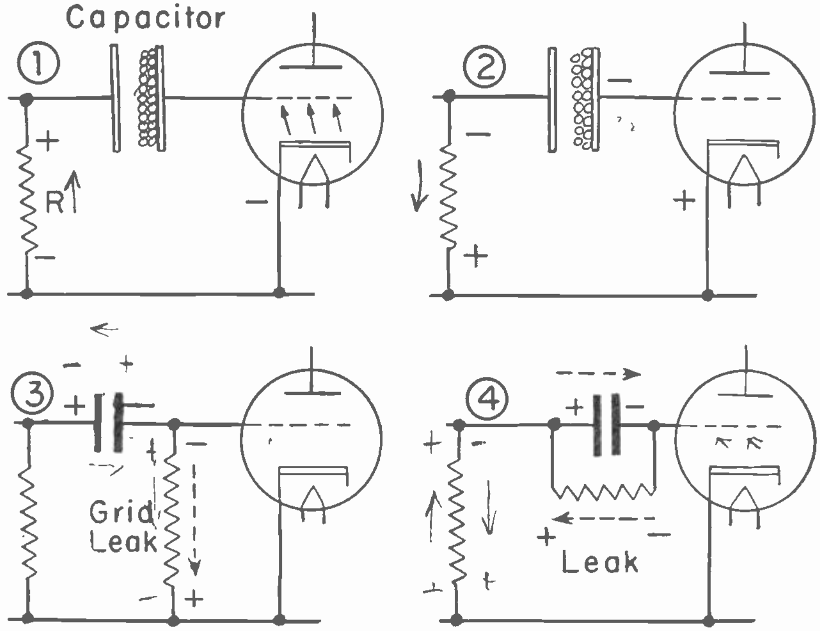


Fig. 17-16.—The principle of grid rectification as used for biasing.

cathode of the tube a *grid leak resistor.* The negative charge which has accumulated on one plate of the capacitor leaks off through this resistor. Since the electron flow through the leak resistor is from top to bottom, the top, and the connected grid, must be negative with respect to the bottom of the resistor, and the connected cathode. Thus the polarity of the leak provides a negative bias for the control grid.

In diagram *4* the grid leak resistor has been connected across the grid capacitor. The negative charge which has accumulated on the side of the capacitor which is toward the grid now flows through the leak resistor as the capacitor discharges. The direction of flow maintains the leak polarity so that the end toward the control grid is negative with respect to the end connected through the input circuit to the cathode. Thus there is provided a negative bias for the control grid.

The grid leak resistor must have resistance great enough so that the capacitor charge can escape only slowly, or so that the charge may be maintained by successive pulses of grid current while it is continually escaping through the leak. The greater the applied potential in the input circuit, and the more frequently the potential alternates in direction, the greater is the total charge given to the capacitor and the smaller may be the capacitance in order to maintain the necessary charge or the necessary potential difference between capacitor plates; this being the value of the grid bias.

The time constant of the grid capacitor and grid leak resistor as measured in fractions of a second should be large in comparison with the time taken for the applied alternating potential to go through one complete set of changes from zero to positive to negative and back to zero. Otherwise the capacitor may discharge almost completely between pulses of grid current. The time constant, in seconds, is equal to the number of microfarads capacitance of the capacitor multiplied by the number of megohms of resistance of the grid leak.

Grid leak bias requires momentary flows of grid current, consequently requires that the applied input potential be positive during its alternations. This method of bias cannot be used for amplifiers where the grid is to be maintained negative at all times. Grid leak bias is used for some types of detector tubes and for some types of radio-frequency power amplifiers, also for many types of oscillators.

Grid Return.—Possibly you have noticed that in all of our circuit diagrams that include a tube having a control grid the grid is connected through some conductive path, such as a resistor, to the cathode of the same tube. The connection of the grid circuit to the cathode is called the grid return. The grid circuit, commencing at the grid itself, includes a grid resistor or some other conductive element which sometimes is in the source of signal potentials. This circuit includes also the source of biasing potential. The other end of the grid circuit is at the cathode.

Every control grid must be conductively connected to the cathode of its tube. That is, there must be some path through which electron flow from cathode to grid could return to the cathode were such a flow to take place. If there is no such conductive connection we have what is called a *free grid.* A free grid accumulates electric charges, which may be either negative or positive according to the operating condition. Then it is these charges, which cannot escape, that determine the grid potential or its state of charge. Under such conditions the grid potential or the grid charge may vary in such erratic manner as to cause highly irregular changes in plate current and in currents of other elements in the tube.

In all of the circuits which we shall work with you will find it possible to trace a conductive path from each control grid around to the cathode of the same tube. It is only by having such a path that we may have control of grid potentials and of grid bias.

REVIEW QUESTIONS

1. What affect does grid bias have on amplitude distortion?
2. What is the name of the battery used for grid bias purposes?
3. How many principal sources of biasing voltage are available for control grid bias?
4. What advantage does battery bias have over other methods of bias?
5. What other name is sometimes given to cathode-bias?
6. How does degeneration affect the voltage amplification of a tube?

Chapter 8

PENTODES AND COMBINATION TUBES

Much of the advancement in radio, and all of our present television systems, have been made possible by development of electronic tubes. First came the diode, followed quickly by the three-element triode. For many years nearly all tubes were triodes, suited as well as possible to all kinds of amplification at all frequencies, and to detection as well. The highest present advances in electronic tubes are found in television camera tubes which change luminous images into corresponding electric voltages, and in the picture tubes for television receivers.

Difficulties arose, especially in the amplification of the higher radio frequencies, and countless intricate circuits were designed and used in efforts to improve the high-frequency performance of the triode. Finally the problem was attacked in the tube itself, and solved with very fair success by the introduction of another grid, called a screen grid, between the control grid and the plate.

But the four-element tube with a screen grid, called a tetrode, developed difficulties of its own. These new difficulties arose when amplifying strong signals and when controlling large powers. Before very long these troubles with the tetrode were eliminated by adding still another grid, this one being placed next to the plate or all around the plate. The added grid, called a suppressor grid, made a tube with five elements which is called a pentode.

Today our basic types of tubes in general use include the diode, the triode, and the pentode. The tetrode has all but disappeared. These are the basic types, but there are almost innumerable combinations and variations of these types to make possible the performance of particular functions with maximum advantage and efficiency. In this chapter we shall examine the reasons for the development of the tetrode, and for its evolution into the pentode, and shall look at many of the more important combinations of the primary types and primary elements. First we shall take up the troubles that occur with a triode used at high frequencies.

Grid-plate Capacitance In a Triode.—At *A* in Fig. 18-1 are represented the grid circuit and the plate circuit of a triode tube. If electron flow in the grid circuit resistor is upward, the bottom of the resistor is more negative than the top, and the top, to which is connected the grid, is more positive than the bottom which goes to the cathode. If the grid is thus made more positive there is an increase of electron flow to the plate and through the plate circuit resistor in such direction as to make the plate end of the resistor and the plate itself less positive or more negative. Considering the *changes* of potentials on grid and plate, as the grid becomes more positive the plate becomes more negative.

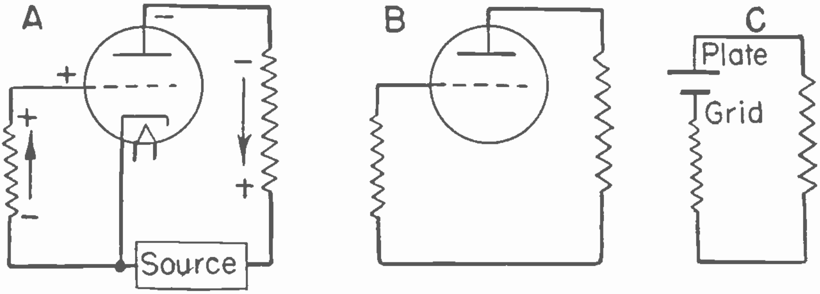


Fig. 18-1.—The grid and the plate, with vacuum between them, act as a capacitor.

Omitting the tube cathode and the plate potential source from the diagram, as at *B*, shows that there is a conductive connection through the resistors all the way from the plate around to the grid. Both the plate and the grid are conductors. Between them is a non-conductor; the vacuum or gas in the tube space. So the plate and grid are, in effect, the two "plates" of a capacitor. The capacitor circuit may be shown as in diagram *C*.

Whenever one plate of a capacitor is charged, the tendency is for the other plate to acquire an equal charge of opposite polarity. When the tube plate becomes more negative (or less positive) there is a tendency for the grid to be made more positive (or less negative). Then the tendency is for changes of potential or charge on the plate, as in diagram *A* of Fig. 18-1, to cause changes of charge or potential on the grid. Furthermore, as the plate becomes more negative the tendency is to make the grid more positive. This change of grid potential makes the plate still more negative, and then the grid is made still more positive. There is a *feedback* of energy from plate circuit to grid circuit, through the grid-plate capacitance, in such direction as to cause a continuing increase of change of plate potential once such a change sets in. This effect limits or may overcome the ability of applied grid circuit potentials to control plate circuit currents; consequently, it is an undesirable effect when the tube is being used as an amplifier.

The more rapid are the changes of potentials, or the higher is the frequency at which the tube is used, the greater is the feedback effect and the more the tube tends to become uncontrollable through applied grid potentials. This feedback effect limits the usefulness of triodes for high-frequency amplification.

Screen Grid.—To prevent or, at least, to greatly reduce the undesirable action of the plate circuit potentials on grid circuit potentials we may place an electrostatic shield between the plate and the grid, as shown in Fig. 18-2. The shield usually consists of many small wires, although sometimes it is of perforated sheet metal or in the form of a woven mesh. The electrostatic shield is called a *screen grid*, because it screens the control grid from the

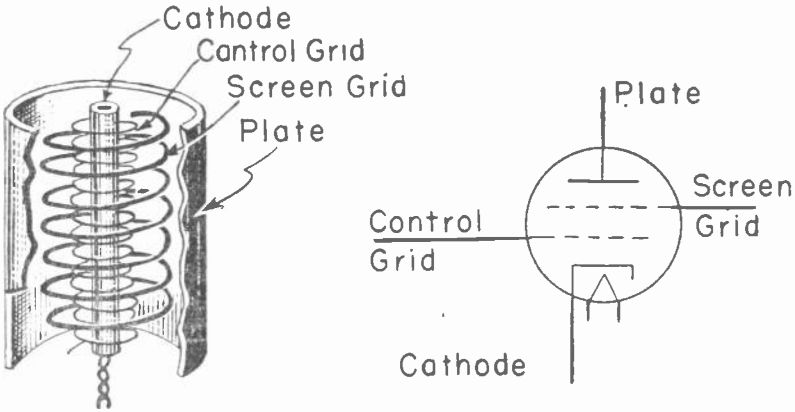


Fig. 18-2.—The screen grid acts as an electrostatic shield between control grid and plate.

effects of changing charges on the plate. Having two grids in one tube, it becomes necessary to distinguish between them by calling one the control grid and the other the screen grid. The screen grid may be only in the space between plate and control grid, as in Fig. 18-2, or it may almost completely enclose the plate on the outside as well as on the inside.

As at the left-hand side of Fig. 18-3, the screen grid is connected directly to the source, so that the screen grid potential with reference to the cathode is maintained at a value equal to the source potential, and does not vary with changes of potential difference across the plate circuit load. The changes of load potential difference affect the plate potential, but not the screen grid potential.

Changes of plate potential, which formerly affected the grid potential, now have their resulting fields intercepted by the screen grid, and since the screen grid is maintained at an almost constant potential by its connection to the source, the changes of plate potential have very little effect on grid potentials. The grid-plate capacitances of triode receiving tubes are in the range of 3 to 8 mmfds., while the grid plate capacitances of screen grid tubes are of an effective value of only 0.01 mmfd. or less.

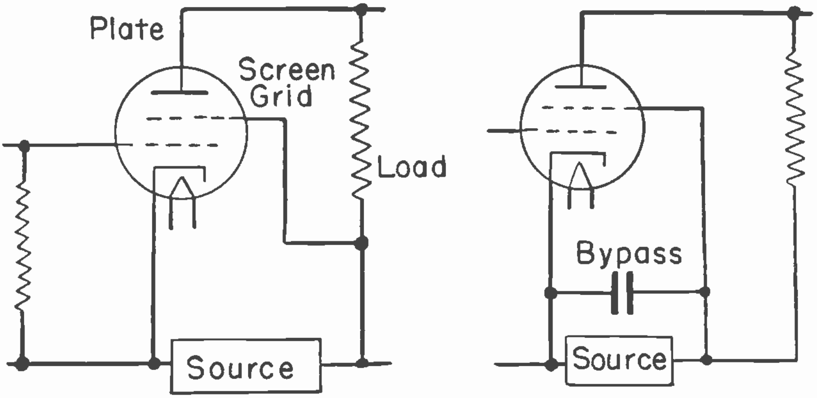


Fig. 18-3.—Connections for the screen grid.

Changes in the rate of electron flow in the plate circuit cause some variations in the terminal potential of the source and these variations affect the potential of the screen grid. To reduce the effect of such variations it is customary to connect a "bypass" capacitor across the source potentials or between the screen grid and cathode of the tube. This is shown at the right in Fig. 18-3. Variations of source potential then cause charging and discharging of the bypass capacitor and, to a great extent, are absorbed by this capacitor rather than being applied to the screen grid.

In Fig. 18-3 the same source potential difference is applied to the screen grid circuit and to the plate circuit. In Fig. 18-4 the source of potentials is divided into two sections. The potential of only one section is applied to the screen circuit, while the sum of the potentials of both sections is applied to the plate circuit. Both methods are used; the choice depending on the type of tube and the purpose for which it is used.

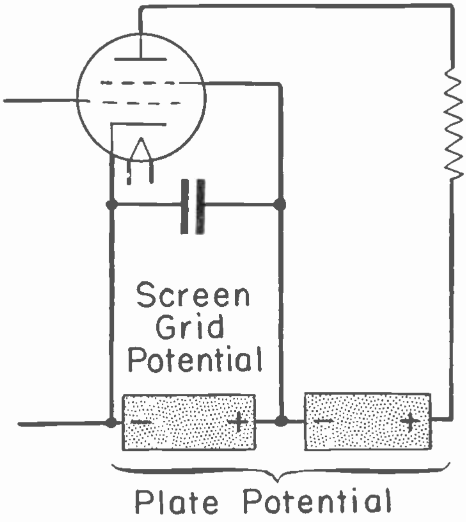


Fig. 18-4.—Different potentials may be applied to the screen grid and the plate.

In any case the screen grid is closer to the cathode than is the plate, and the effect on electron flow drawn from the cathode is greater for a given screen grid potential than for an equal plate potential, and may be as great for a small screen grid potential as for a relatively large plate potential. Actually, the rate of electron flow is controlled almost entirely by screen grid potential and very little by plate potential under usual working conditions.

The screen grid potential greatly increases the speed of the electrons flowing toward it from the cathode. By the time the electrons reach the screen grid they are traveling so fast that most of them fly right on through the spaces between screen grid wires and go on to the plate. The screen grid acts as an accelerator for the electrons. The plate acts chiefly as a collector for the electrons that come through the screen grid.

The control grid, which is in the space between cathode and screen grid, has just as much control over electron flow rate as it has in a triode. The electron flow from cathode to screen grid to plate is varied by variations in control grid potential, just as in a triode. But the average rate of flow is controlled chiefly by screen grid potential, not by plate potential.

Compared with a triode, the screen grid tube may be designed and used for great amplifications. This requires that the control grid be very effective in regulating the rate of electron flow from the cathode. This is accomplished by making the control grid with its wires close together. With the closely spaced wires at a negative potential with reference to the cathode, as ordinarily is the case, there can be but small rates of electron flow. The screen grid tube is characterized by high amplification and small plate

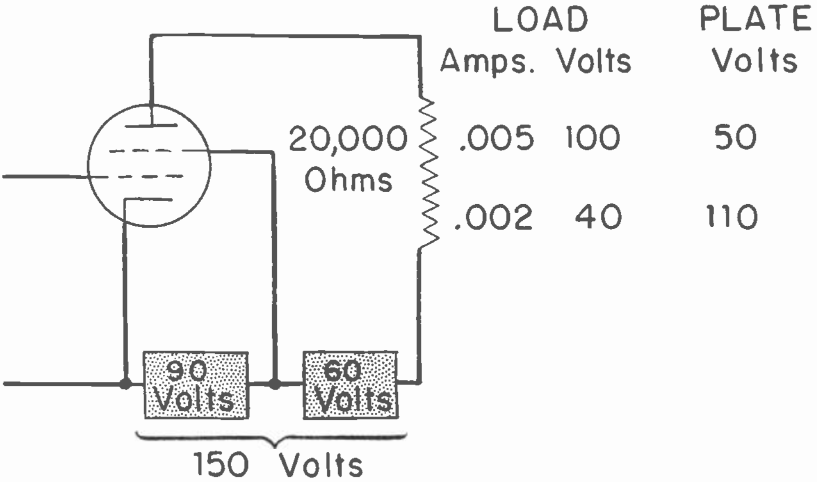


Fig. 18-5.—Changes of current and potential in the plate circuit of a screen-grid tube.

current. These tubes were an important step in the development of amplifiers, but, because they have serious limitations as well as advantages, they seldom are used today.

Secondary Emission.—Fig. 18-5 represents a screen grid tube circuit in which the variations of control grid potential are causing the plate current and load current to vary between 5 milliamperes (0.005 ampere) and 2 milliamperes (0.002 ampere). The load resistance is 20,000 ohms, the screen potential is 90 volts, and the plate supply potential is 150 volts. When the load current is 0.005 ampere there is a drop of 100 volts in the load resistance. This leaves 50 volts for plate potential, since the drop in the load must be subtracted from the supply potential. With a load current of 0.002 ampere there is a drop of only 40 volts in the load resistance, and the plate potential will be 150 minus 40, or will be 110 volts.

The plate potential in the tube varies between 50 and 110 volts. The screen grid potential remains at 90 volts. So the screen becomes 40 volts more positive than the plate when the screen potential is 90 volts and the plate potential 40 volts, and becomes 20 volts less positive than the plate when the plate potential becomes 110 volts.

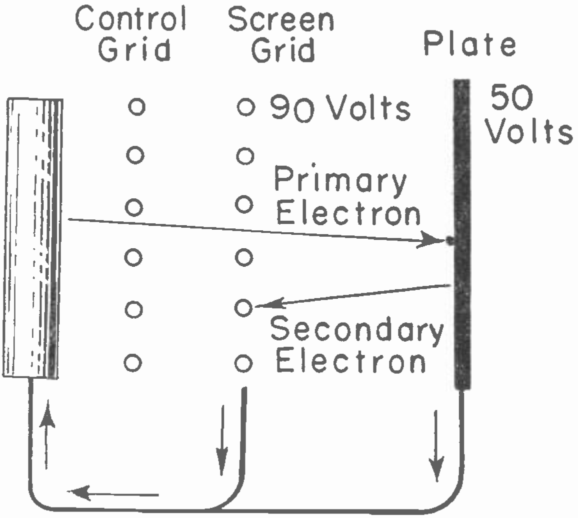


Fig. 18-6.—Secondary emission in a screen grid tube.

Now we shall consider something else that happens in a screen grid tube. Fig. 18-6 represents a cathode, a plate, and in between them the turns of wire that are the control grid and screen grid. An electron emitted from the cathode goes through the control grid, is accelerated to high speed by the screen grid, goes through the screen grid, and strikes the plate surface with considerable force due to its high speed. The impact knocks another electron out of the plate surface. This electron knocked out of the plate is called a *secondary electron.* The one from the cathode is called a *primary electron.*

Assuming that the plate potential is 50 volts and the screen grid potential 90 volts, the secondary electron will leave the plate and go to the more positive screen grid. All these things are happening to billions of electrons. The total electron flow is regulated by the control grid, and it varies with changes of control grid potential. But the changes of total electron flow now are divided between the plate current and a current that appears in the screen circuit due to emission of secondary electrons from the plate. In effect, these secondary electrons are subtracted from the plate current during the period when the plate becomes less positive than the screen. To prevent the effects of secondary emission in screen grid tubes the changes of plate current and load voltage must be kept very small. This limits the power that may be made available from the plate circuit, and is the most serious disadvantage of screen grid tubes.

Secondary emission occurs also from the plates of triodes. But in a triode the plate always is the most positive element, and the

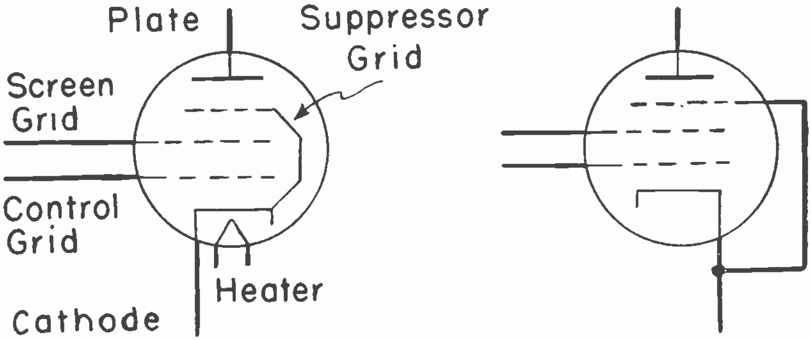


Fig. 18-7.—Symbols for pentodes; showing the five elements.

secondary electrons are drawn back to the plate and form part of the plate current rather than being diverted to another element.

Pentode Tube.—To reduce the effects of secondary emission in a screen grid tube we place still another grid, called a *suppressor grid,* between the screen grid and the plate. The suppressor grid is formed of small wires rather widely spaced. As shown by Fig. 18-7 the suppressor grid is connected to the tube cathode, either by a permanent connection inside the tube or else by connecting together the base pins for the two elements. Now there are five active elements in the tube; cathode, control grid, screen grid, suppressor grid, and plate. A tube with five active elements is called a *pentode.*

With the suppressor grid connected to the cathode this grid always must remain much more negative than the plate. Secondary electrons emitted from the plate may travel a short distance away from the plate and toward the suppressor grid, but are strongly repelled by the relatively negative suppressor grid and are driven back into the plate. Thus nearly all of the electron flow reaching the plate becomes plate circuit current. The suppressor of the pentode tube reduces the effect of secondary emission, while the screen grid of this tube reduces the feedback which otherwise would occur through the grid-plate capacitance. Large changes of voltage and current may occur in the plate circuit without undesirable effects. Pentodes may be designed for either voltage amplification or power amplification.

Typical plate characteristics of a voltage amplifying pentode are shown by Fig. 18-8. As plate potential is increased there is at first a rapid increase of plate current. Then the curves flatten out, showing that further increases of plate potential cause little additional change in plate current. This effect is due to the screen grid, which limits the ability of the plate to vary the rate of electron flow.

In Fig. 18-8 each of the curves applies when the control grid potential is of a certain value, as marked, and when the screen grid potential is maintained at a constant value for all tests. If the control grid potential is maintained at a constant value while tests are run at various screen grid potentials, the resulting set of curves will look about the same as those of Fig. 18-8, but each curve will apply to a certain screen grid potential. This means

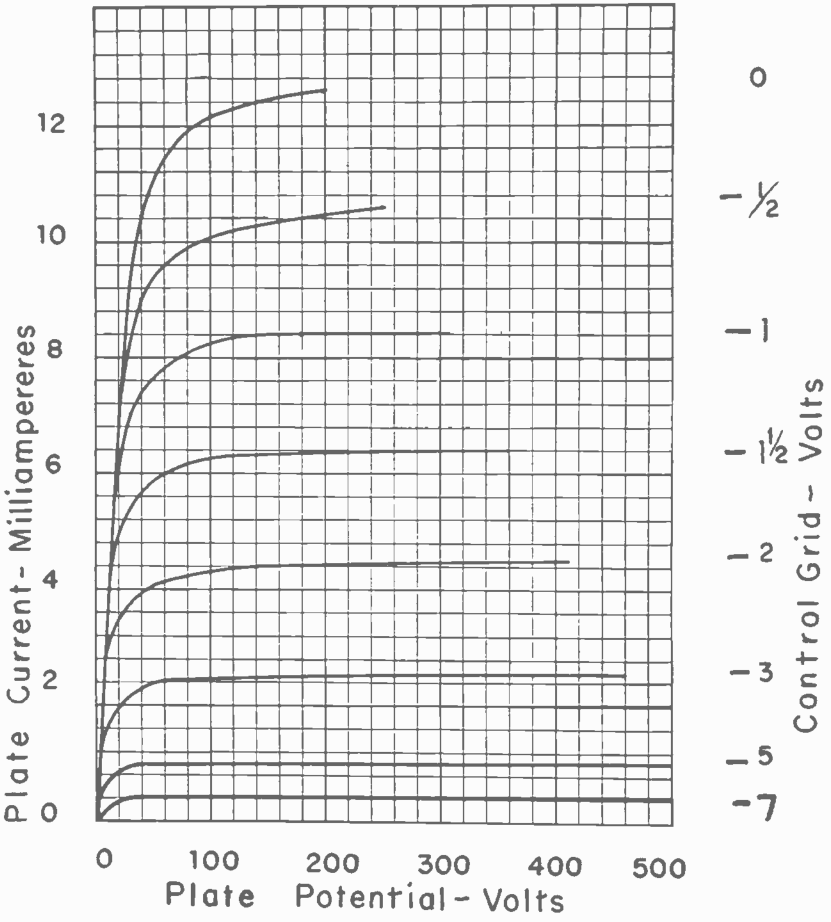


Fig. 18-8.—Typical plate characteristics for voltage amplifying pentodes.

that a controlling potential might be applied either to the regular control grid or to the screen grid in regulating the rate of electron flow, and also that two controlling potentials might be applied simultaneously, one of them to each of the grids. To obtain a given change of plate current the change of control potential applied to the screen grid would have to be many times as great as one applied to the control grid.

Because screen potential is so effective in pulling electrons away from the cathode and in accelerating them toward the plate

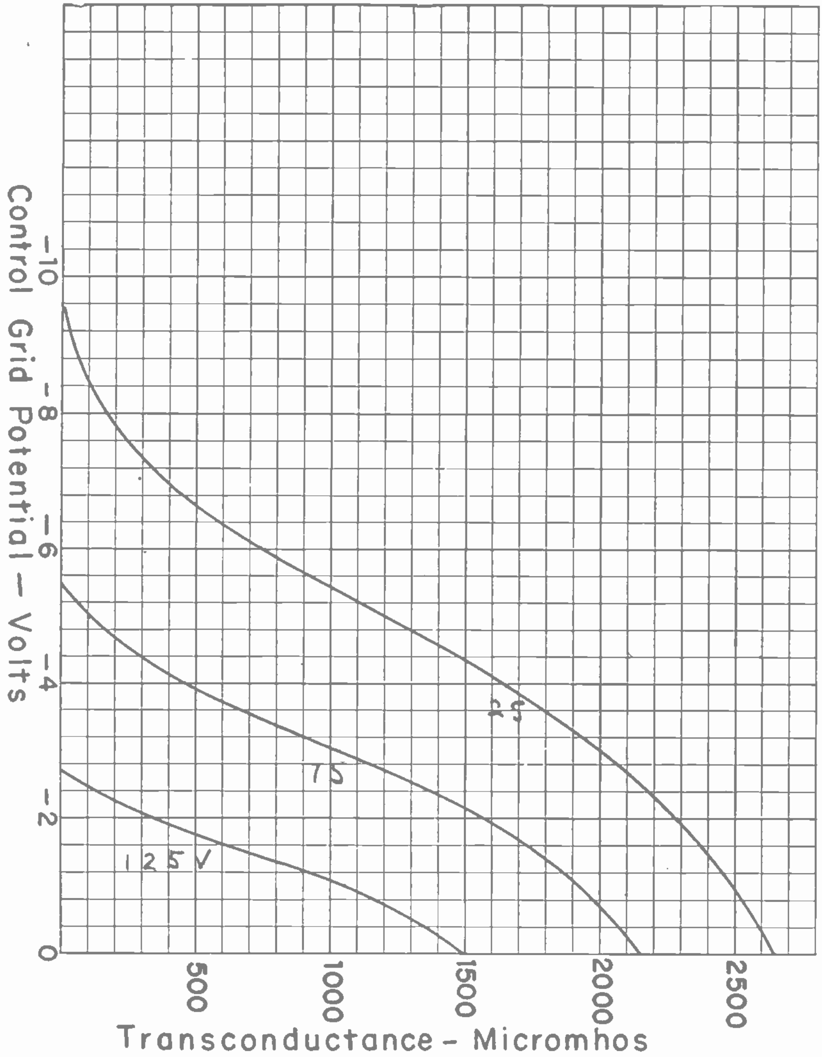


Fig. 18-9.—How transconductance of a pentode varies with different values of screen grid potential.

this potential determines to a large extent the quantities of electrons over which the control grid may exercise its control, and thus determines the changes of plate current that are brought about by given changes of control grid potential. The effect of changes of control grid potential on plate current is measured as transconductance, and so we find that transconductance may be varied within wide limits by changing the screen grid potential. Fig. 18-9 shows transconductances for a voltage amplifying pentode as the control grid potential is changed with three different values of screen grid potential. The left-hand curve is for a screen grid potential of 125 volts, the center one for 75 volts, and the right-hand one for 25 volts. For all three curves the plate potential is maintained at 300 volts.

Variable-mu or Super-control Tubes.—In triodes, in tetrodes, and in many pentodes the control grid wires are uniformly spaced from each other, as at the left in Fig. 18-10. In such tubes the grid potential is uniformly effective in controlling the rate of electron flow from all portions of the cathode surface. If the control grid is made sufficiently negative to stop the electron flow from one portion of the cathode, the flow is stopped from all other portions and we have plate current cutoff. Such tubes are suitable for use where there are no great variations of control grid potential.

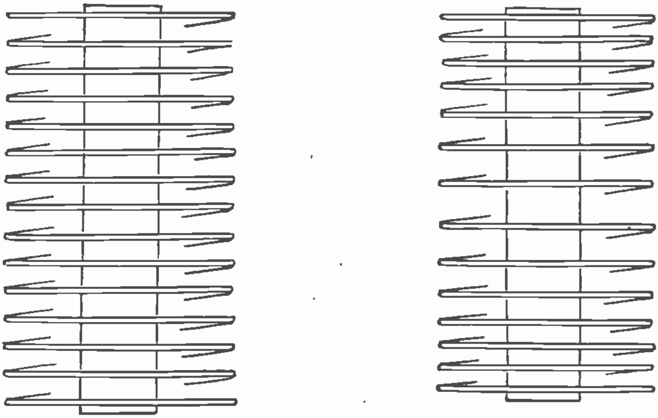


Fig. 18-10.—At the right is the grid wire spacing for a variable-mu pentode.

There are other cases in which it is necessary to handle or amplify great variations of control grid potential, and where it is undesirable that the plate current be completely cut off during any periods. For such amplification we may use a *variable-mu* or *super-control* tube, a type of pentode in which, as at the right in Fig. 18-10, the control grid wires are closely spaced at the ends of the cathode and are more widely spaced toward the center. When the control grid potential becomes so negative as would cause plate current cutoff in other types of tube, the cutoff effect occurs only at the ends of the cathode in the variable-mu or super-control type, and electron flow continues from portions of the cathode surface near the center until the control grid becomes much more negative.

Fig. 18-11 shows how transconductance varies with control grid potential in a super-control or variable-mu tube (broken line curve) and in a pentode otherwise similar except for having its grid wires uniformly spaced (solid line curve). The super-control or variable-mu tube may be called a *remote cutoff* pentode, and the type with uniform grid wire spacing may be called a *sharp cutoff* pentode.

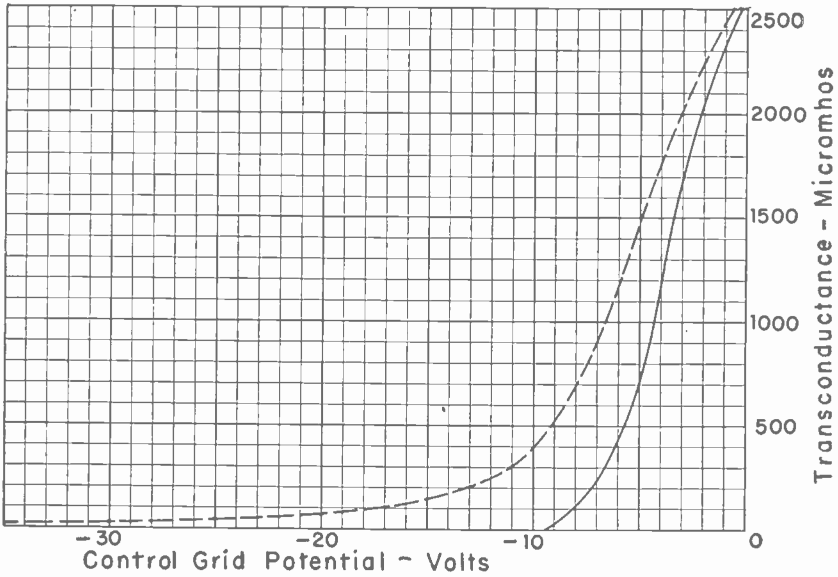


Fig. 18-11.—Transconductance of a remote-cutoff pentode (broken line) and of a sharp-cutoff pentode (full line).

Power Pentodes.—Pentodes designed for handling relatively large plate currents and for controlling considerable amounts of power in their plate circuit loads are called power pentodes. Fig. 18-12 shows a family of plate characteristics for a typical power

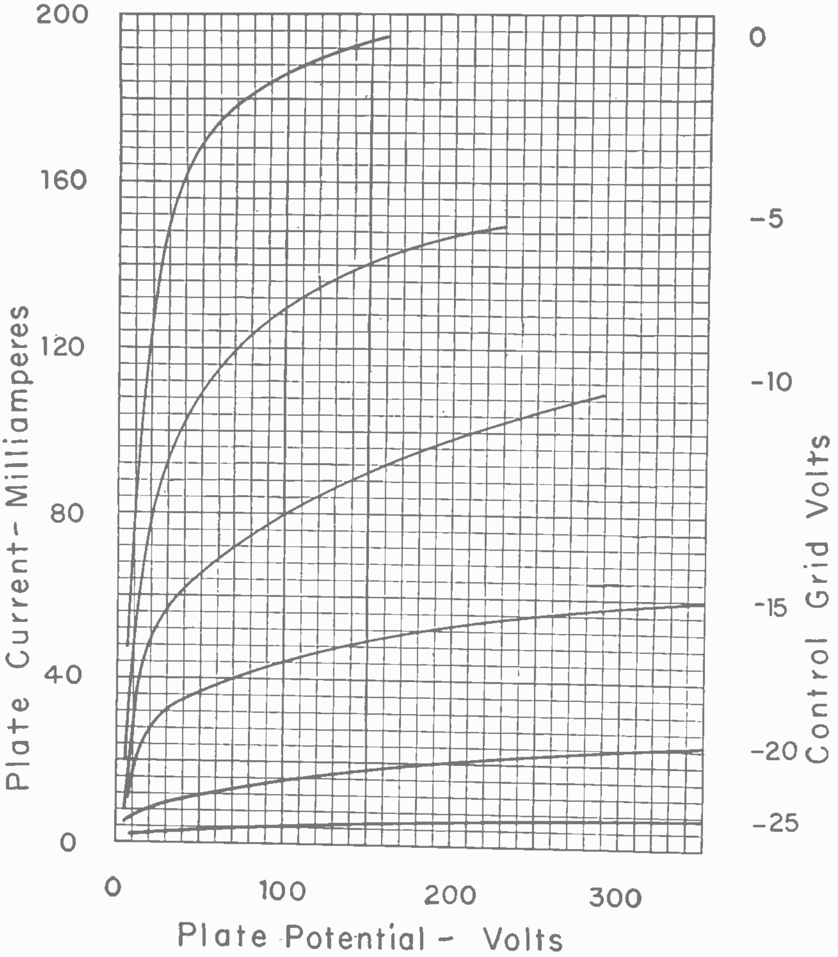


Fig. 18-12.—Plate characteristics for a typical power pentode.

pentode. Whereas the voltage amplifying pentode whose characteristics are shown by Fig. 18-8 handles plate currents up to about 13 milliamperes, the power pentode of Fig. 18-12 handles plate currents up to nearly 200 milliamperes.

The performance of any type of pentode when used with a certain plate load resistance may be determined by drawing load lines on a family of plate characteristics in just the same manner that load lines are drawn on characteristics of triodes.

Beam Power Tubes.—In the beam type of power tubes the advantages of a pentode are secured without the use of a suppressor grid. The construction and action of an RCA beam power tube are shown by Fig. 18-13. Around the cathode is the control grid, and outside the control grid is the screen grid. Each wire of the control grid is directly between the cathode and one of the wires in the screen grid. Electrons which are attracted to and accelerated by the screen grid flow between the turns of the

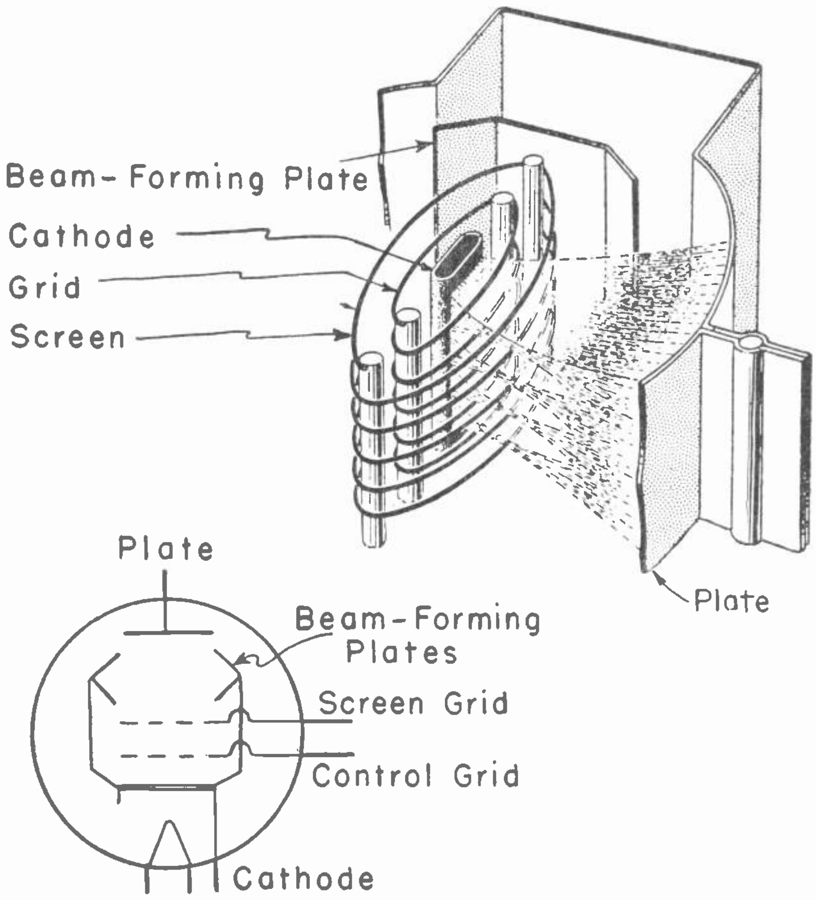


Fig. 18-13.—The action in a beam power tube and a symbol for such a tube.

control grid, thus traveling in paths that carry them between the screen grid wires. The result is a very small screen grid current.

During periods in which the potential of the plate becomes lower than that of the screen there is a decreasing field intensity or a decreasing potential from the screen to the plate, and because of the lessening accelerating force the electrons slow down in the space between screen and plate. The slowing down of the electrons means that there is a greater concentration of electrons at a point between screen and plate than in other parts of the tube space. Because the electrons are negative there occurs a concentrated negative space charge between the screen and plate. This negative space charge repels secondary electrons emitted from the plate and drives them back to the plate rather than allowing them to go to the higher-potential screen. Thus the negative space charge suppresses the effects of secondary emission in the beam tube just as the suppressor grid suppresses the effects in a pentode.

In the beam power tube there are beam forming plates partially enclosing the cathode, grid, and screen. These plates are internally connected to the cathode, as indicated by the tube symbol of Fig. 18-13. With the plates maintained at cathode potential, which is negative with respect to the screen and plate, the electron streams are confined into beams traveling between cathode and plate. Secondary electrons from the plate cannot get around the beam plates and go to the screen.

Multiple-purpose Tubes.—There are many tubes which have, in a single envelope, various combinations of pentodes, triodes, and diodes. A few of them are represented by symbols in Fig. 18-14. Base pins are shown in their relative positions on the sockets. Number *6* is a 6-pin type and number *8* is a 7-pin type. All the others have 8-pin bases, although not all eight pins always are used for element connections. Elements are indicated by letters on the pin positions, as follows: *F*, filament-cathode; *K*, heater-cathode; *H*, heater for heater-cathode; *G*, control grid; *Sc*, screen grid; *P*, plate; *D*, diode plate; and *E*, connection to metal envelope. The control grid of numbers *1, 2, 7, 8* and *10* is connected to a cap on top of the tube rather than to a base pin.

Number *1* represents a triode and a single diode, while *2* represents a triode and two diode plates, with only a single cathode in each case. Number *3* is a combination triode with two control grids and a single plate, *4* has two plates but only a single control grid, and *5* is two complete triodes with separate control grids and plates but only one cathode. Number *6* is a direct-coupled power amplifier consisting of a voltage amplifier triode and a power amplifier triode with the input unit coupled to the output unit within the tube.

Number *7* represents a pentode combined with two diode plates. As in following symbols, the suppressor grid is connected to the cathode within the tube. Number *8* shows a pentode combined with a diode which acts as a rectifier. Number *9* shows a pentode and a triode working with a single cathode, while *10* shows a pentode, a triode, and single diode plate, all within a single envelope. Number *11* shows two complete pentodes. Number *12* shows a beam power amplifier combined with a diode which acts as a rectifier.

Combination tubes are used to save in costs of material and assembly labor, since they not only reduce the number of separate tubes required, but also simplify the circuit connections and wiring. Each section in such a tube performs in accordance with the principles which previously have been explained for tubes of the same general type as the section being considered.

The tubes represented by diagrams *1*, *10* and *11* of Fig. 18-14 have filament-cathodes. All of the others have heater-cathodes. Any of the types shown with one kind of cathode might be constructed also with the other kind of cathode. Most types of tubes are available with either kind of cathode.

Tubes represented by diagrams *3*, *8* and *12* have two cathodes with separate base pin connections to each cathode. Such types are used where the circuits for the two sections of the tubes are to be insulated from each other so far as the cathode connections are concerned, or where the two cathodes are to be operated at different potentials. In all of the other types represented there is but a single cathode for both sections or for all the sections in the tube. A single cathode will furnish emission for two or more sections; part of the total emission going to one section and part to others. Then all of the circuits come together in the common cathode, but may be entirely separate and may carry their own electron flows everywhere except in the cathode.

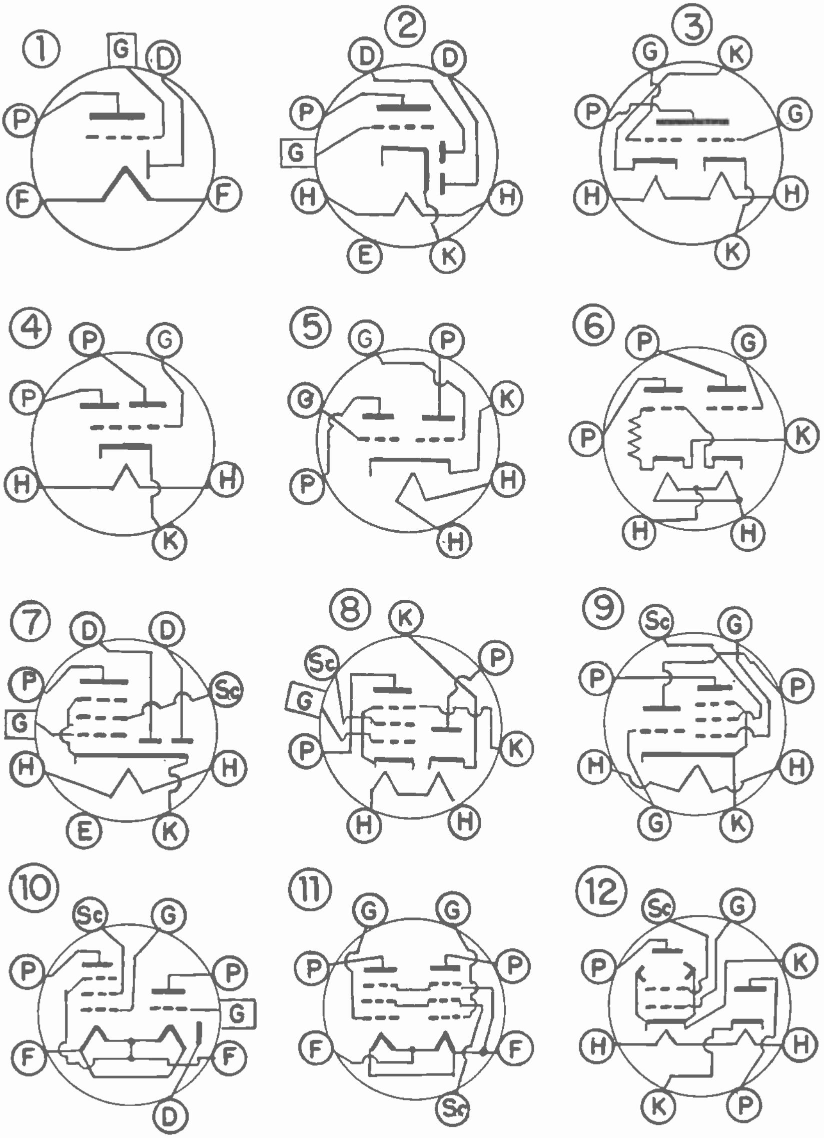


Fig. 18-14.—Symbols showing the elements and their base pin connections in some multi-purpose tubes.

The output of the tube shown by diagram *3* is used to control two following tubes of the power amplifier type which operate together to actuate a loud speaker. The connections to the power tube circuits are taken from the two cathodes of the tube shown here, with the electron flows in these cathodes controlled by the two separate control grids.

The tube shown by diagram *4* is used to control two tuning indicator tubes, which are tubes showing by means of visible shadows whether or not a radio receiver is correctly tuned to a signal being received. The indicator circuits are connected to the two plates of the tube shown here. With one of these plates the action is that of a remote cutoff triode, and with the other it is that of a sharp cutoff triode. One of the tuning indicators then is effective with strong signals and the other is effective with weak signals.

The tube of diagram *6* acts as a voltage amplifying triode in the section on the right in the diagram, and as a power amplifying triode in the section on the left. A weak signal is applied between the right-hand grid and the cathode; it is amplified and applied within the tube itself to the control grid of the left-hand section, and in this section there is controlled enough power to operate a large loud speaker.

In diagrams *8* and *12* there are rectifier diodes in addition to the amplifying sections which are, respectively, a power pentode and a beam power assembly of elements. The rectifier sections are used for obtaining direct current from the alternating potential of the line power supply, just as separate rectifiers would be used, and the direct current and potentials from these rectifier circuits are used for plate, screen, and control grid bias circuits of all of the tubes in the receiver. Here we have cases of placing two independent tubes in a single envelope with no particular dependence of either section on the other.

In diagrams *9* and *10* there are separate base pin connections for all of the elements in the triodes and pentodes except the cathode connection, which is common to both sections. Consequently, the two sections may be operated quite independently. In diagram *11* there are two pentodes with separate base pin connections for only the control grids and the plates. Both screen grids are connected to the same base pin, consequently both screens must be operated at the same potential. Both suppressor grids are connected to the filament-cathode which is common to both sections.

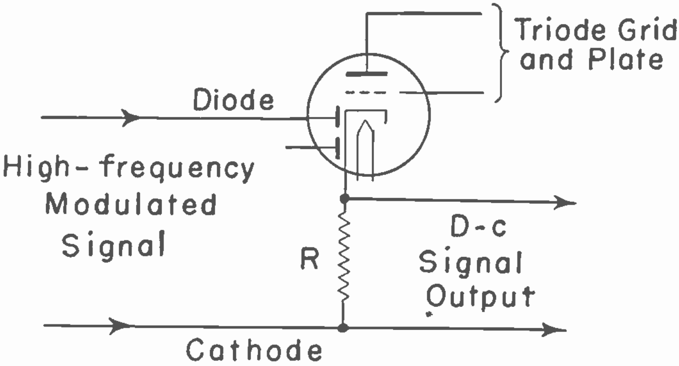


Fig. 18-15.—Connections to a diode used as a detector.

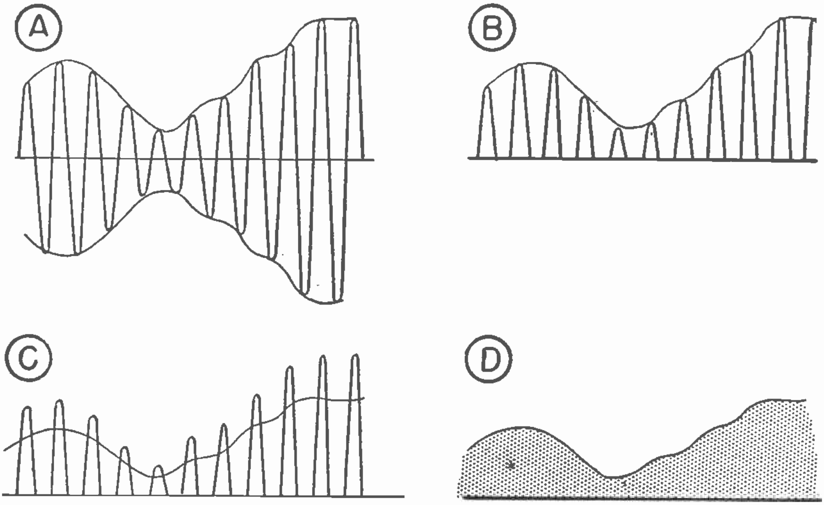


Fig. 18-16.—How a diode detector separates the low-frequency modulation from the high-frequency signal.

Diodes in Combination Tubes.—In diagrams *1*, *2*, *7* and *10* of Fig. 18-14 small diode plates are shown near the cathodes, with separate base pin connections for these plates. These diode sections are used as demodulators or detectors, also are used in circuits for automatic control of volume. They have very small current handling capacities, whereas the rectifier diodes such as shown in diagrams *8* and *12* are designed for handling large currents at high voltages.

The operation of a diode as a detector or demodulator is simple. Connections may be made as shown by Fig. 18-15. Here the symbol shows the same tube that is shown by diagram *2* of Fig. 18-14, but now we are using a simpler form of symbol which does not indicate the connections of the elements to base pins but which shows only the elements and the envelope. Only one of the two small diode plates is being used in the circuit diagram. In series with the cathode is a resistor *R*. A high-frequency modulated signal is applied between the diode plate and the lower end of the resistor. This applied signal may be of radio frequency or it may be of intermediate frequency. In either case the frequency is far higher than anything which would produce an audible sound, or it is higher than any audio frequency. A direct current, varying at the audio-frequency or other low frequency corresponding to the modulation, will appear across the resistor *R* in the cathode circuit. The triode grid and plate, or any elements other than those for the diode, do not enter into the detector action.

How the d-c audio-frequency current is produced is shown by Fig. 18-16. At *A* is represented the modulated high-frequency signal in which amplitudes above and below the zero potential vary in accordance with the signal modulation. The diode acts as a rectifier, passing an electron flow or current only during the half-cycles of high frequency in which the diode plate is made positive with reference to the cathode. The result is a series of high-frequency pulses of electron flow as shown at *B*. The effective value of the one-way high-frequency pulses is shown by the wavy line drawn through them at *C*. The average effective value of the pulses is the direct current indicated at *D*. This is the direct current in resistor *R* of Fig. 18-15. It increases and decreases just as does the modulation of the high-frequency signal

This direct current really is made up of successive pulses occurring at the frequency of the applied signal, but the frequency of these pulses is so far above audibility that the result, after suitable amplification, will affect our ears only at the low-frequency or audio-frequency rate. We simply do not hear the high-frequency pulses, but hear only the average variations which are at audio frequency.

Instead of using only one of the diodes, when there are two in the tube, both may be connected together to increase the current. It is possible also to use the two diodes in a different kind of circuit, called a full-wave detector circuit, with which both positive and negative alternations of the high-frequency signal cause electron flows in the diode sections. One of the diode plates may be used as a detector and the other used in a circuit for automatic control of volume; this being discussed under the heading of volume controls.

Connecting Elements Together.—It has been mentioned in connection with the diode detectors that two diode plates may be connected together to increase the rate of electron flow. The same thing may be done with rectifier tubes in which there are two plates. Such rectifiers are designed for operation in "full-wave" rectifier circuits with which both positive and negative alternations of applied potential are made to produce electron flows in the same direction in the output circuit. Such full-wave arrangements are described in detail under the subject of rectifiers and power supply systems.

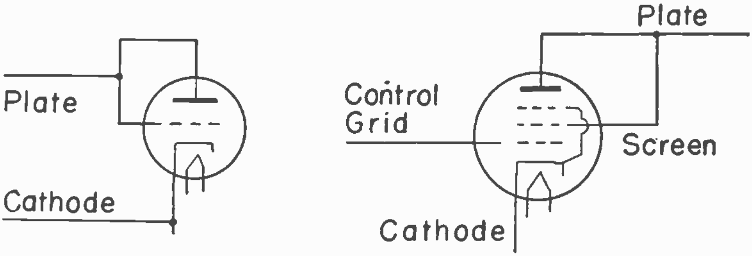


Fig. 18-17.—A triode connected as a diode (left), and a pentode connected as a triode (right).

A triode may be operated as a diode by connecting the plate and the control grid together at the socket terminals and by using the combination as the plate of a diode. The connections are shown in Fig. 18-17. This sometimes is done in experimental work when we have a triode but have no regular rectifier diode. The current-handling capacity of a triode used in this manner is no greater than when the same tube is used in the regular way as a triode.

Tubes which are designed and constructed as pentodes quite often are operated as triodes by connecting together the plate and the screen grid at the socket terminals and by using the combination as the plate of a triode. When operated with similar potentials there are no great differences between total cathode currents and between transconductances with the two connections. The plate resistance with the triode connection is but a small fraction of that with the pentode connection, and the triode load resistance is made considerably less than for the pentode operation. The power output with the pentode connection usually is about four times as great as the output with the triode connection. The connections are shown in Fig. 18-17.

Converters. — There are many combination tubes of a type called a *converter*, none of which are represented by the diagrams in Fig. 18-14. These tubes are used in superheterodyne receivers to convert the radio-frequency of the received signal into a signal having a much lower frequency, called the intermediate frequency, which is amplified in stages following the converter much more effectively than the original high-frequency signal could be amplified. The modulation of the original signal remains in the intermediate-frequency signal.

The lower intermediate frequency is obtained by combining in the converter tube the original radio-frequency potentials with potentials which are at a frequency either somewhat higher or lower than that of the received signal. This "mixing" of the two frequencies produces a third frequency which is equal to their difference, and this difference frequency is the intermediate frequency. Just how all of this takes place is fully explained in connection with superheterodyne receivers, but right here we need to understand some things about the action in order to talk about the converters.

The frequency which is combined with or mixed with the received radio-frequency potentials is produced by an oscillator which is part of the receiver. In some superheterodyne receivers one tube is used as an oscillator and a separate tube is used as a mixer in which the frequencies are combined. But when a converter tube is used this one tube acts as an oscillator and as a mixer; some of the elements acting in one capacity and others in the second capacity.

The parts of the converter which act as an oscillator form the elements of a triode; a cathode, a control grid which we shall call the oscillator grid, and a plate which we shall call the oscillator plate or the oscillator anode, which means the same thing as a plate.

Earlier in this chapter it was explained that, due to grid-plate capacitance in a triode, there is a feedback of energy from plate to grid in such polarity that the changes of grid potential, once started, are continued in the same direction. That is the basic action of a type of oscillator employing capacitance feedback through the tube itself. But at the frequencies used in broadcast reception that type of oscillator does not operate energetically enough to serve our purpose, and so a similar but greater feedback is provided in circuits external to the tube.

Briefly, the action of a feedback oscillator is as follows: Assuming to begin with that the control grid potential is becoming more negative, the feedback potential makes the grid still more negative until its potential reaches the value for plate current cutoff. Then, with no current in the plate circuit and, of course, with no further change of plate current, the feedback has to stop and the grid recovers its normal or average potential.

As the grid potential becomes less negative or more positive as it changes from the cutoff value this change allows plate current to again flow, and to increase. The effect of this change of plate current is to produce feedback of energy to the grid circuit, but now the direction of the feedback is such as to make the grid less and less negative, or more positive. This change of grid potential makes the plate current still greater, and the increasing plate current continues to react on the grid circuit. Finally, in this stage of operation, the grid bias changes to stop the changes of grid potential and plate current, and the grid goes back to its average potential.

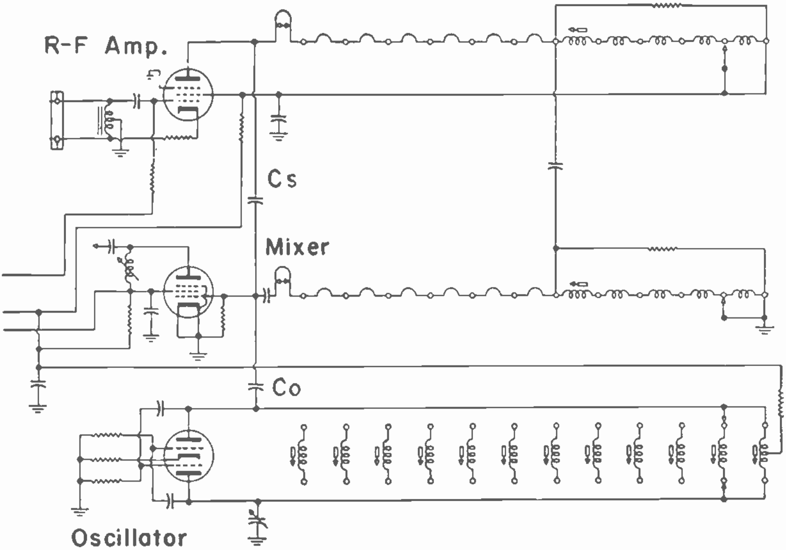


Fig. 18-18.—A television tuner with separate amplifier, mixer, and oscillator tubes.

The return of the grid to its average potential causes a reduction of plate current. The decreasing plate current causes a feedback of energy in such direction as to drive the grid still more negative, and we are right back in the conditions where this explanation started. So the action continues; forcing the plate current to rise and fall between the limits set by the values of parts used in the oscillator circuit. We have then an alternating plate current which increases and decreases above and below its average value. By using suitable values of inductance, capacitance, and resistance in the circuits connected to the oscillator, the frequency of the alternating plate current may be made whatever is required for production of the intermediate frequency.

Television Mixers and Oscillators.—In television receivers and in some f-m sound receivers the mixer and oscillator functions are performed in separate tubes rather rather than in a single converter type. This separation is employed principally because at the very-high frequencies of television and f-m reception the oscillator frequency may suffer "pulling" away from its correct value when both functions are carried out with a single set of elements and a single stream of electrons acted upon by the received signal and by the oscillator voltages, as in a converter.

Fig. 18-18 shows the circuits of a television tuner in which the center tube is a mixer, the bottom one is an oscillator, and the one at the top is an r-f amplifier for strengthening signals received at carrier frequencies, before these signals go to the mixer. Circuits extending toward the right from each tube are for tuning to the several television channels.

In this and many other television tuners the frequency of resonance is not continuously varied in going from channel to channel, but is altered in steps. As the selector switch is shifted from channel to channel, contact is made along the tuning inductors to bring more or less of the total inductance into the active circuits at each step. Successive values of inductance are such as cause resonance at frequencies of the channel to which the switch is turned at any one time. Moving the switch to another position either adds or cuts out enough inductance to cause resonance at frequencies in another channel. There is no gradual change of resonant response or resonant frequency between channels.

Signal voltages from the r-f amplifier tube go to the control grid of the mixer through capacitor *Cs*, while oscillator voltages go to the mixer grid through capacitor *Co*. The two voltages combine in the mixer to produce at its output a voltage at the desired inter-

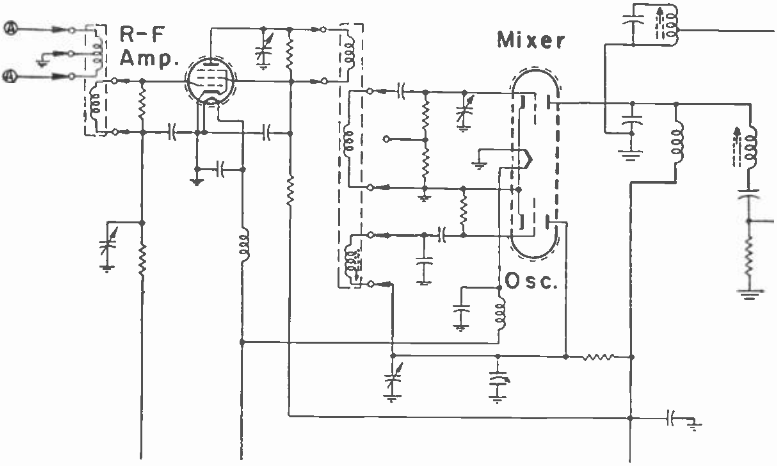


Fig. 18-19.—A television tuner in which a twin triode tube acts as mixer and oscillator.

mediate frequency, which still carries the received signal in the form of modulation.

Fig. 18-19 shows the circuits in a television tuner having a pentode as the r-f amplifier for received signals, and having a twin triode in which one section acts as mixer and the other as oscillator. Voltages from the r-f amplifier and from the oscillator are coupled into the mixer grid circuit through the three coils shown in the center of the diagram. One coil is in the plate circuit of the r-f amplifier, a second is in the plate and grid circuit of the oscillator, and the third is in the grid circuit of the mixer.

Radio Converters.—In Fig. 18-20 all elements for oscillator and mixer are in one tube, with only a single stream of electrons acted upon by both signal and oscillator voltages. This type is called a *pentagrid converter,* because there are five grids between the cathode and the plate. Grid number *1,* which always is the grid nearest to the cathode in any tube having several grids, is here used as the oscillator grid. The second grid or grid number 2 is used as the oscillator plate, and may be called the oscillator

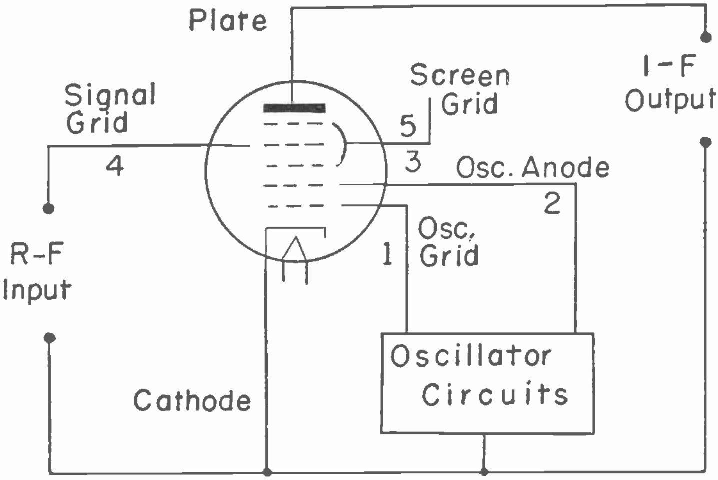


Fig. 18-20.—Connections for one kind of pentagrid converter

anode. The oscillator grid and anode are connected to the oscillator circuits in which the feedback is produced and controlled.

The signal grid of our pentagrid converter is grid number *4*, which is enclosed by the two parts of the screen grid which form grids number *3* and number *5* as we count away from the cathode and toward the plate. The radio-frequency signal is applied between the signal grid and the cathode, while the oscillator frequency appears in the oscillator grid and anode. As in the other converters, the electron stream flowing from cathode to plate is acted upon by the oscillator frequency and also by the signal frequency to produce in the output the intermediate frequency which is the difference.

There is another type of converter in which the grids are used similarly to those of Fig. 18-20, but in which there is an additional suppressor grid between the plate and the screen grid with the suppressor connected to the cathode within the tube. This other type is called an *octode converter*, because it has eight elements in all. The five grids of the converter of Fig. 18-20, together with the cathode and plate, make a total of seven elements. The addition of a suppressor grid makes a total of eight elements.

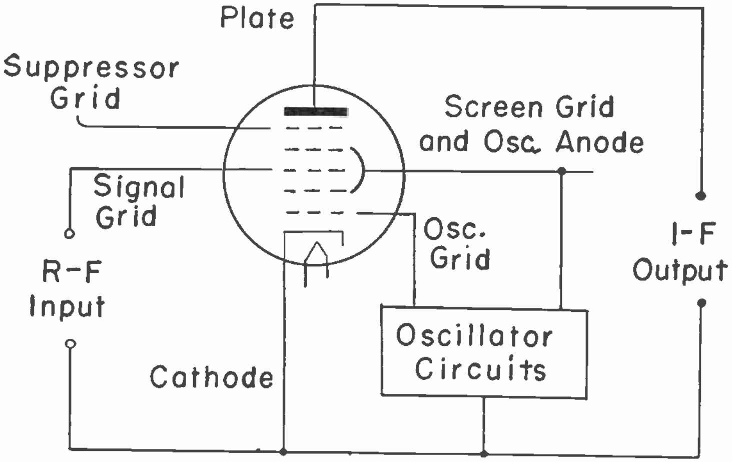
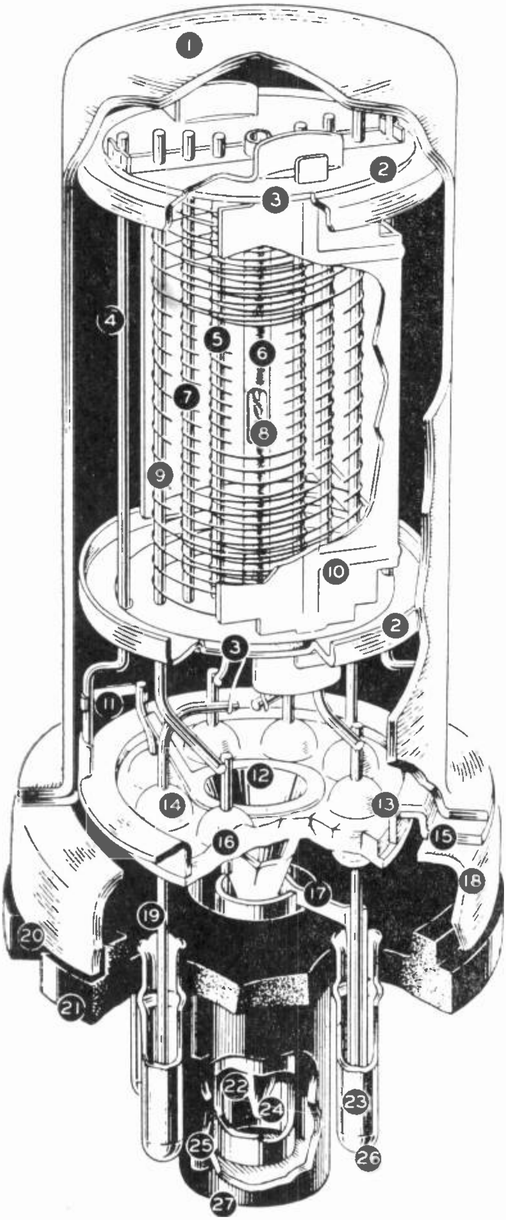


Fig. 18-21.—Connections for another type of pentagrid converter.



1, metal envelope
2, spacer shield
3, insulating spacer
4, support for mount
5, control grid
6, coated cathode
7, screen grid
8, heater
9, suppressor grid
10, plate
11, getter for gases
12, shield for stem
13, header insert
14, glass seal
15, header
16, steam seal
17, shield for base
18, header skirt
19, lead wire
20, lock for base
21, base
22, tube for withdrawing gases
23, base pin
24, tip on exhaust tube
25, aligning key on base
26, solder on base pin
27, aligning plug on base

Fig. 18-22.—Structure of an RCA single-ended metal tube of the pentode type

Still another kind of converter is shown by Fig. 18-21. This one has five grids between its cathode and plate, and so it is called a *pentagrid converter* as is also the type of Fig. 18-20. But now we have no one grid or no separate grid acting as the oscillator anode, rather this function is served by grid number *2* which is part of the screen grid assembly. A suppressor grid, which is connected to a separate base pin, is placed between the plate and the screen grid of the tube represented by the diagram. In other similar types the suppressor is connected to the cathode inside of the tube.

Just as with all of the other converters, the electron stream flowing from cathode to plate in the tube of Fig. 18-21 is acted upon simultaneously by the oscillator frequency and by the signal frequency to produce the intermediate frequency which appears in the output. It might be mentioned that the tube which is like the one of Fig. 18-21 except for having the suppressor internally connected to the cathode may be called a *pentagrid mixer* instead of a pentagrid converter.

Tube Structures and Sizes.—We have examined enough different kinds of tubes to cover quite thoroughly the purposes of the various elements and the behavior of most of the generally used combinations. All of the tubes contain as their elements certain combinations of cathodes, control grids, screen grids, suppressor grids, and plates or anodes. Knowing what each of these five elements is supposed to do, it is not difficult to figure out the intended performance of almost any possible combination of them.

It is the kind of elements used in a tube, and their arrangement, that determine the purposes which may best be served. The kind of mechanical structure and the overall dimensions have no direct effect on tube performance so far as the electronic action is concerned, but help to adapt the tube to the mechanical requirements of design and assembly of receivers.

In Fig. 18-22 are shown all of the details of construction of an RCA metal-envelope pentode tube. Here it may be seen that the arrangement of the elements, from cathode to plate, is like that of the glass-envelope pentode tube whose construction we examined in the first of these chapters on tubes. The differences between glass- and metal-envelope construction are such as required by the mechanical characteristics; the differences are not electronic.

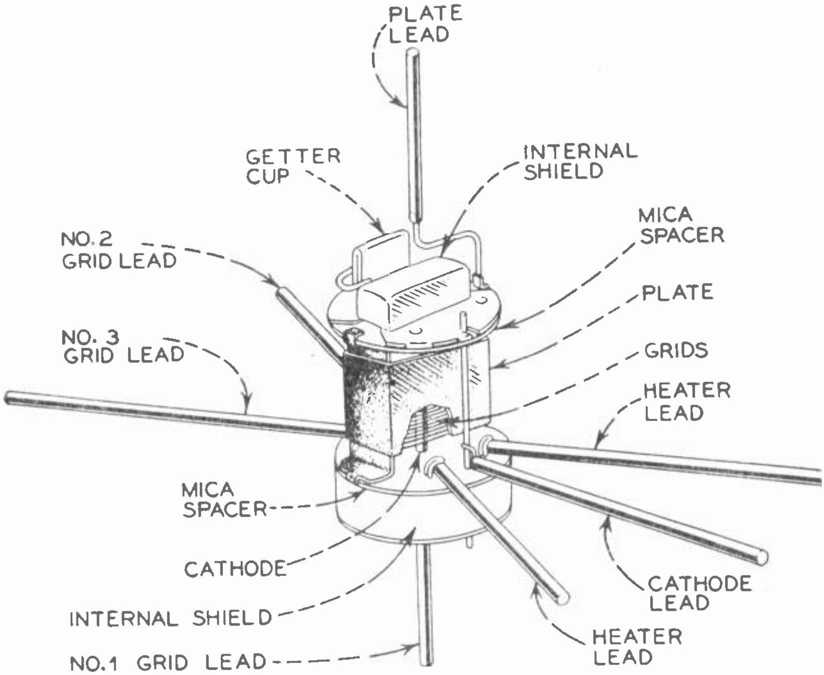


Fig. 18-23.—Internal structure of an RCA acorn pentode.

Tubes may be of small size and still perform all of the functions of the larger varieties. In a series of tubes which are designated as *miniature* types the maximum overall diameter is ¾ inch and the overall heights, including the base pins, are between 1¾ and 2⅝ inches. In the miniature tubes we find all of the types which have been discussed; including converters, beam power tubes, rectifiers, and all the others. The use of such tubes in all positions permits the building of complete receivers in very small sizes.

Another interesting type of small tube is the *acorn* style, for which a pentode with its glass envelope removed is shown by Fig. 18-23. Connections to the elements are made by means of leads extending from the envelope rather than to base pins. The acorn tubes are especially designed for operation at wavelengths as short as 0.7 meter, which is a frequency of about 430 millions of cycles per second.

Tubes for Ultrahigh Frequencies.—Ultrahigh frequencies are those between 300 and 3,000 megacycles, and include all of the ultrahigh-frequency television channels. The original channels, 2 through 13, are in the very-high frequency range of 30 to 300 megacycles. Only r-f amplifiers, oscillators, and mixers of television sets must handle ultrahigh frequencies during formation of the lower intermediate frequencies.

A major difficulty in ultrahigh-frequency operation results from internal capacitances and inductances of conductors within the tubes. Only a short, straight conductor and a very small capacitance are needed for resonance at ultrahigh frequencies. Inductances of leads within the tubes may be lessened by providing two or more connections to some of the elements. Using these leads in parallel decreases inductance, because the inductance of any paralleled inductors is less than that of any one of them alone. Energy losses in socket materials may be avoided by omitting the sockets and making connections directly to leads extending out of the tube envelope.

At ultrahigh frequencies there may be difficulties due to transit time in tubes. Transit time is the time required for an electron to pass from cathode to plate. It is measured in fractions of a millionth of a second yet may be long enough for reversal of plate and grid voltages which are alternating at ultrahigh frequencies. An electron which leaves the cathode under the influence of a positive charge on the plate may be driven backward by a reversed polarity of the charge before ever reaching the plate. Transit time effects may throw signal voltages in a plate circuit out of phase with grid signals, because electrons arriving at the plate will be those released by a grid voltage which occurred a fraction of a cycle earlier in time.

In spite of all the problems, tubes are available which perform well as either amplifiers or oscillators at frequencies as high as 1,500 to 3,000 megacycles.

Chapter 9

COUPLINGS FOR TRANSFER OF ENERGY

In nearly all of our practical applications of radio it is necessary to take energy or power from some circuits and put it into other circuits. In a receiver or sound reproducer we take the exceedingly weak energy from the antenna, phonograph, or microphone and put it into the circuits containing the control grids of amplifier tubes, so that the weak energy may control greater energy and power. Then we transfer energy or power from the output of one amplifier tube to the input of the following tube, and finally transfer the output power of the final

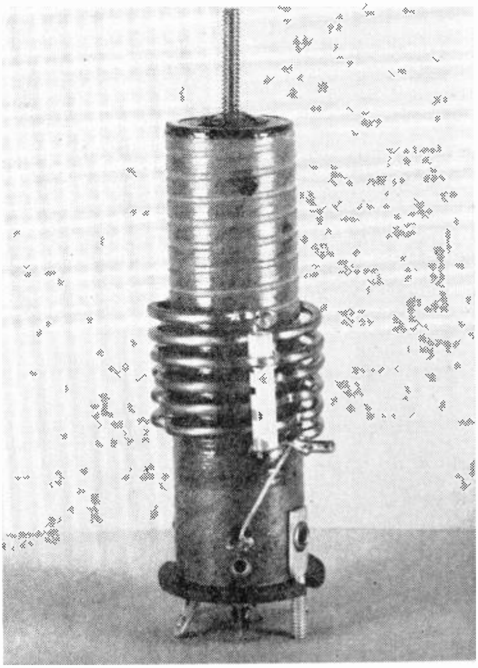


Fig. 19-1.—This unit couples the sound section to the tuner in a television receiver.

amplifier tube or tubes into the loud speaker. At the same time, in receivers operated from a-c line power, that power has to be transferred into the heater and filament-cathode circuits for the tubes, and into the rectifier system which produces direct currents and potentials from the a-c power.

At a transmitter there are similar requirements. The weak energy from microphones and recordings is transferred to and through the amplifier circuits, modulation circuits, oscillator circuits, and control circuits. Finally we have the relatively great power output from the transmitting antenna. At the same time the a-c line power has to be transferred into rectifier circuits and other circuits.

All of the transfers of energy or power from circuit to circuit take place through arrangements which we call *couplings*, and the circuits are said to be *coupled.* In a sound reproducer we *couple* the antenna, the microphone, or a phonograph to the amplifiers, we couple the amplifier to the loud speaker, and we couple various circuits to their controls.

We may define coupling as a means by which changes of potential or of current in one circuit cause related changes of potential or current, or both, in another circuit to which the first one is coupled.

There are many ways in which circuits may be coupled, but they all have this in common: There will be some one element that exists in both circuits or that acts on both circuits at the same time. This common element may be a resistance, it may be an inductance, it may be a capacitance. Or it may be a magnetic field or else an electric or electrostatic field.

Resistance Couplings.—In Fig. 19-2 are two circuits. One circuit consists of the a-c source, the inductance coil *La*, and resistor *R*. The other circuits consists of resistor *R* and inductance coil *Lb*. Resistor *R* is a part of both circuits. The emf of the a-c source provides a total potential drop that divides between coil *La* and resistor *R*. The portion of the potential drop that exists across *R* is applied to the second circuit and causes an alternating potential and current in inductance coil *Lb*. The two circuits are coupled through their common resistor *R*. This method of coupling is called *resistance coupling.*

The simple system of resistance coupling shown by Fig. 19-2

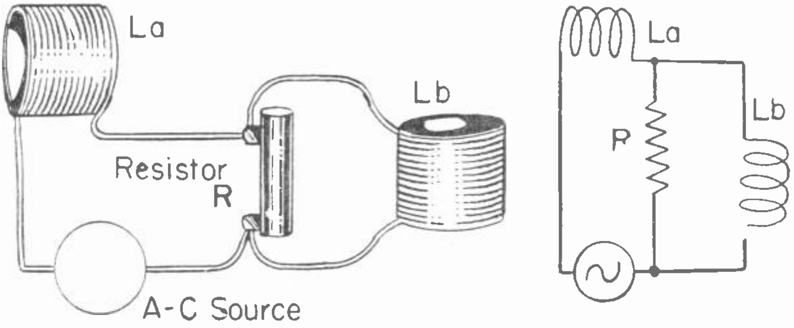


Fig. 19-2.—The resistor provides resistance coupling between two circuits.

finds little practical use other than in some types of measuring instruments, but it illustrates a general principle of which modifications find wide application in radio circuits. As an example, the two amplifier tubes shown at the left in Fig. 19-3 are coupled through resistance *R* which is common to the plate circuit of the first tube and the grid circuit of the second tube. Variations of potential in the resistor, which accompany changes of plate potential and current, are applied between the grid and cathode of the second tube, and so form the varying grid potential for the second tube.

The principal fault with the circuit at the left in Fig. 19-3 is that the resistor carries the direct current for the plate circuit of the left hand tube as well as the variations of this current

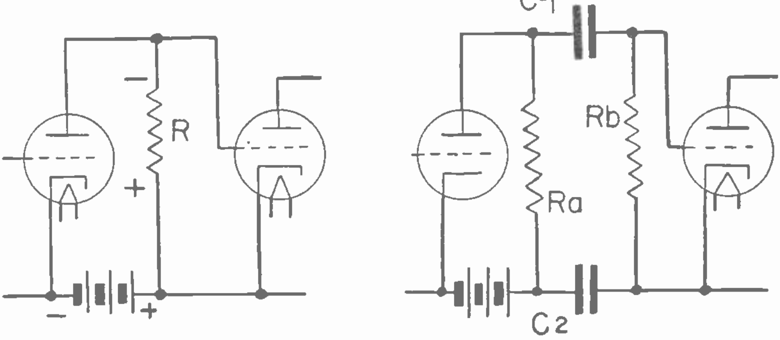


Fig. 19-3.—Resistance coupling between amplifier tubes.

which are the alternating component. The average potential at the top of resistor *R* is highly negative with reference to the bottom, and with these ends connected to the grid and cathode of the right-hand tube this tube has an excessively high negative grid bias.

In the right-hand diagram of Fig. 19-3 the resistor *Ra*, in the plate circuit of the first tube, is not directly connected to the grid and cathode of the second tube but is connected through capacitors *C-1* and *C-2*. To permit the grid of the second tube to be biased with reference to its cathode, the resistor *Rb* is connected between these elements. Because of the high insulation value of the dielectric in the capacitors no electrons from the plate circuit of the first tube can flow in resistor *Rb*. However, changes of potential across *Ra* cause corresponding changes in the charges on the plates of the capacitors, and the variations of charge cause electron flow in *Rb* which correspond to the changes of potential in *Ra*. The system at the right in Fig. 19-3, called *resistance-capacitance* coupling or resistance-capacity coupling, is widely used in radio apparatus. Capacitor *C-2* usually is replaced by a "bypass" capacitor in practical circuits.

Impedance Couplings.—Instead of using resistors in the plate circuit of one tube and in the grid circuit of a following tube, air-core inductance coils may be used for both circuits as shown in Fig. 19-4, at the left. The combined inductance and resistance of the coils form impedances, so this method is a form of im-

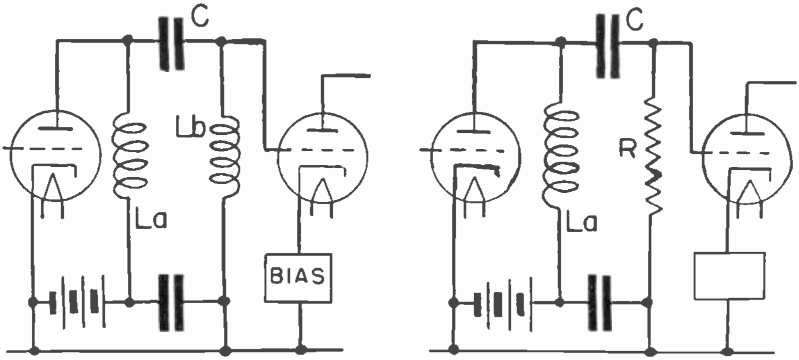


Fig. 19-4.—Impedance coupling with air-core coils.

pedance coupling. Changes of potential across the impedance of *La* pass through capacitor *C*, and corresponding changes of potential appear across the impedance of coil *Lb* or across the resistance of resistor *R* in the following grid circuit.

The reactances and impedances of the coils increase with increase of frequency, so that given changes of current in the coils is accompanied by increasing potential drops across the coils. However, the reactance or impedance of capacitor *C* decreases as the frequency increases. The two effects may compensate in some degree, and provide fairly uniform transfer of power from the plate circuit of the first tube to the grid circuit of the second tube when there are moderate variations in frequency. At best, the methods shown by Fig. 19-4 would be satisfactory for high-frequency coupling only when there are relatively minor variations in frequency.

For impedance coupling at audio frequencies an inductance coil with an iron core may be used in the plate circuit of the first tube, as indicated at the left in Fig. 19-5. The inductance of the coil usually is between 50 and 200 henrys. Its impedance remains quite high throughout the range of audio frequencies usually amplified.

In Figs. 19-4 and 19-5 the capacitance of the capacitor *C* and the inductance of the coil in the plate circuit of the first tube may produce a resonant peak of impedance within the range of operating frequencies. If the inductance and capacitance are so

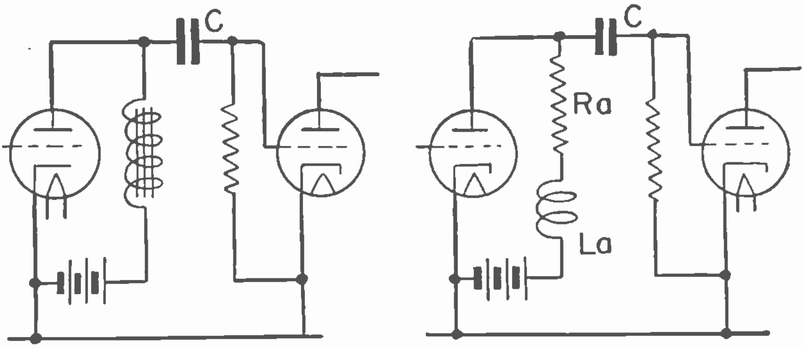


Fig. 19-5.—An audio-frequency impedance coupling (left) and a coupling with compensation for high frequencies (right).

chosen as to be resonant at a frequency above the operating range, the power transfer of the coupling circuit may be made to increase more or less with increase of frequency. At the right in Fig. 19-5 the plate circuit of the first tube contains a resistance *Ra* in series with an inductance *La*. The impedance of the inductance increases with frequency, and tends to maintain the transfer of power at the higher frequencies where it otherwise falls off with the more usual resistance-capacitance coupling shown at the right in Fig. 19-3.

Fig. 19-6 shows a *tuned impedance* coupling such as sometimes used in amplifiers operating at radio frequencies. In the plate circuit of the first tube is a parallel resonant circuit consisting of inductance coil *La* and tuning capacitor *Ca*. This circuit is tuned to resonance at whatever frequency is to be amplified. Then the potential drop across the tuned parallel circuit is maximum at this frequency, while being relatively small at other frequencies, and the potential variations at the tuned frequency are transferred to resistor *Rb* in the grid circuit of the following tube.

Capacitor *C* of Figs. 19-3 to 19-6 sometimes is called a *coupling capacitor*, because it transfers power from the first to the second circuit, and sometimes is called a *blocking capacitor* or a stopping capacitor, because it keeps direct currents from the first (plate) circuit out of the second (grid) circuit. The primary function of this capacitor is to provide a connection of low impedance to

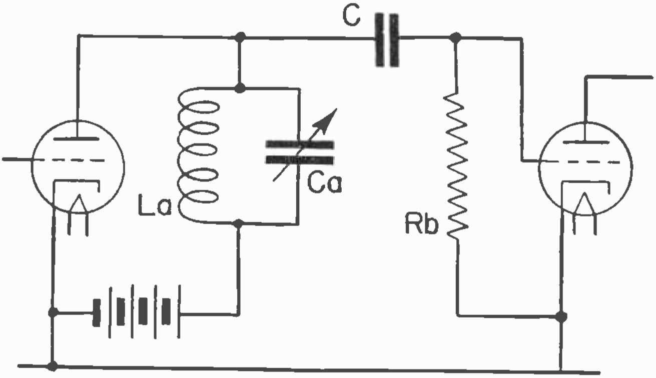


Fig. 19-6.—A tuned impedance coupling for radio frequencies.

alternating currents and of high resistance to direct currents between the two circuits. The greater the capacitance of *C*, and the less its impedance, the greater is the power transfer. The effect may be modified in case the capacitance of *C* tunes with some of the inductances at a frequency within or close to the operating range of frequencies. The capacitance of *C* always adds in some degree to the total of capacitance in circuits on either side of it. If these circuits are of resonant types their response at various frequencies will be affected to some extent by this additional capacitance.

Direct Inductive Coupling.—Fig. 19-7 shows two coupled circuits. In one circuit is the source of alternating potential, also the coil *La* and the coil *Lc*. In the second circuit are coils *Lc* and *Lb*. Coil *Lc* is in both circuits, or is common to both circuits. Alternating potential differences that appear across coil *Lc* are in both circuits. Power from the first circuit is transferred to the second circuit through coil *Lc*, or through the inductance of *Lc*. Such coupling through a common inductance is called *direct inductive coupling*. This method seldom is found in practice.

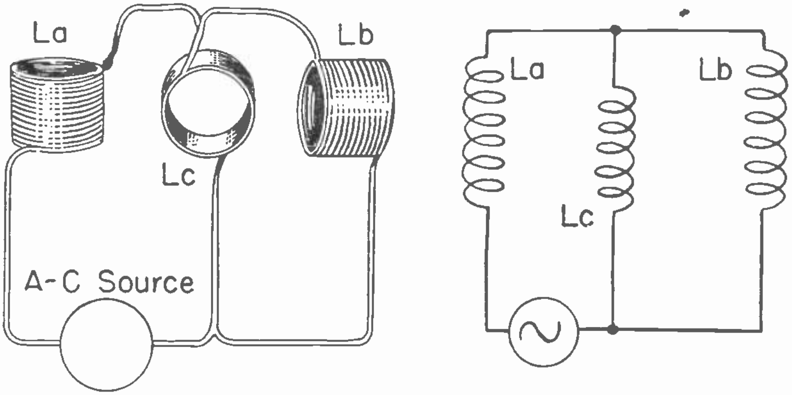


Fig. 19-7.—A direct inductive coupling.

In basic principle, direct inductive coupling is similar to the resistance coupling shown by Fig. 19-2. With resistance coupling there is a power transfer through the common resistance. With direct inductive coupling there is a power transfer through the common inductance.

Mutual Inductive Coupling. — Most of the couplings used in radio receiving and transmitting apparatus are either of the resistance-capacitance type shown at the right-hand sides of Figs. 19-3 to 19-5, or else of the *mutual inductive* type which is shown in principle by Fig. 19-8. With mutual inductive coupling the two coupled circuits have no coils, resistors, or other physical parts in common, and there is no conductive connection between them. The coupling occurs because of mutual induction between coils which are in the two circuits and which are so placed in relation to each other as to permit the action of mutual induction.

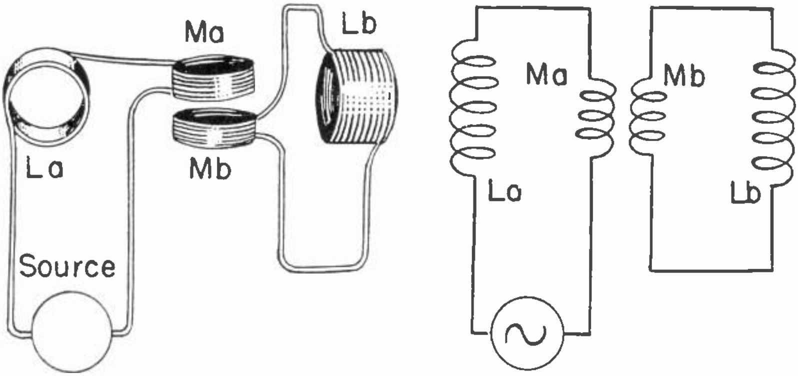


Fig. 19-8.—The principal of mutual inductive coupling.

In Fig. 19-8 the first circuit consists of the source of alternating potential, of coil *La*, and of coil *Ma*. The second circuit consists of coils *Mb* and *Lb*. Coil *Ma* in the first circuit and coil *Mb* in the second circuit are so placed that the magnetic field of either will cut through the conductors of the other. Changes of current in either coil will cause changes of the magnetic field of that coil. These magnetic field changes, acting on the other coil, induce emf's in that other coil. The induced emf's cause corresponding currents in the other coil and in the circuit of which it is a part. Thus there is a transfer of energy from one circuit to the other through the action of mutual induction.

In Fig. 19-8 only part of the inductance in each circuit takes part in the action of mutual induction. The self-inductance of the left-hand circuit consists of the self-inductances of coils *La* and *Ma*, and in the right-hand circuit it consists of the self-inductances of coils *Lb* and *Mb*. But it is only between the coupled coils, *Ma* and *Mb*, that there is mutual inductance. In other types of mutual inductive coupling the coupling may be between the entire self-inductance of one circuit and the entire self-inductance of the other circuit. This is what occurs with iron-cored transformers such as shown by Fig. 19-9. The entire winding or coil *La* connected to the source is active in producing changes of magnetic flux in the iron of the core, and the changes of flux in the core induce emf's in the entire winding or coil *Lb* which is connected to the load. Here the mutual inductance and the coupling are very great, because nearly all of the magnetic lines cut the conductors of both coils.

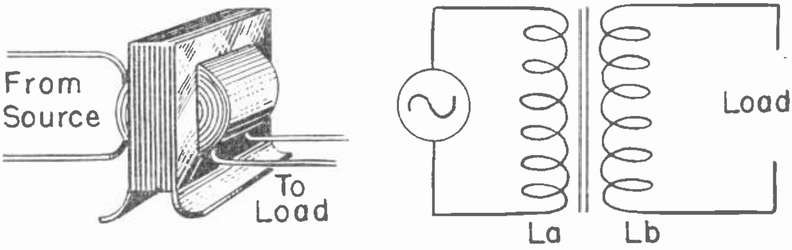


Fig. 19-9.—Mutual inductive coupling in an iron-core transformer.

Of the two coils between which there is coupling, the one which is in the circuit connected to the source is called the *primary* coil or *primary* winding. The one to which power is transferred, or the one connected to a load circuit, is called the *secondary* coil or the *secondary* winding.

In many coupled circuits the secondary may be tuned to resonance by means of a variable capacitor. Such an arrangement is shown by Fig. 19-10. Here the primary coil *La* is con-

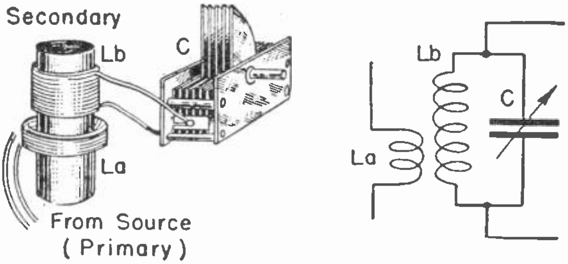


Fig. 19-10.—Mutual inductive coupling with tuned secondary winding.

nected to the source of alternating potential or current. The primary is coupled by mutual induction to the secondary coil *Lb*, which may be tuned to resonance by variable capacitor *C*. Coil *Lb* and capacitor *C* form a resonant circuit into which energy is transferred, and in which emf's are induced, through mutual inductive coupling with the primary *La*.

The coupling method of Fig. 19-10 may be used between the antenna-ground circuit and the grid circuit of the first amplifying tube of a radio receiver as shown by Fig. 19-11, also between the plate circuit of one tube and the grid circuit of a following tube as shown in the same diagram. The primary *La* is in the antenna circuit which receives energy from the radio waves. This

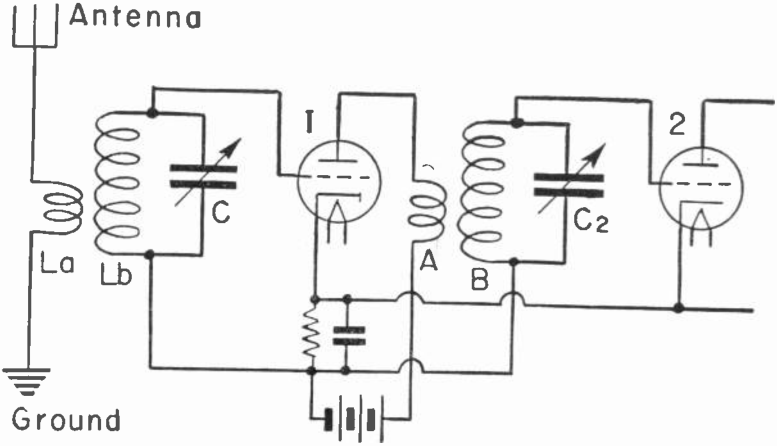


Fig. 19-11.—Tuned inductive couplings between antenna and first tube, and between the two tubes.

energy is transferred by mutual inductive coupling to secondary *Lb*, with which variable capacitor *C* allows tuning to resonance at the frequency to be received and amplified. Potential differences in the tuned circuit *Lb-C* are applied to the grid-cathode circuit of tube *1*. Variations of plate current in the plate circuit of this tube pass through primary winding *A*, which is coupled by mutual induction to secondary winding *B*. This secondary winding and variable capacitor *C2* are tuned to resonance at the frequency being received. Potential changes across the resonant circuit *B-C2* are applied to the grid-cathode circuit of tube *2*. The amplified output of this second tube is applied to following circuits in the receiving apparatus.

When one or both circuits which are coupled by mutual induction may be tuned to resonance, the method may be called *tuned transformer coupling*. The coupling from the antenna circuit to the first circuit of the receiver is called *antenna coupling*. Any coupling used between amplifying tubes may be called *interstage coupling*. An amplifying tube with its associated grid, plate, cathode, and other directly connected circuits is called a *stage* of amplification.

When there are changes of (current) electron flow in the primary winding there are accompanying changes of its magnetic field. During any given half-cycle these changes of magnetic field induce emf's in the secondary winding which cause an electron

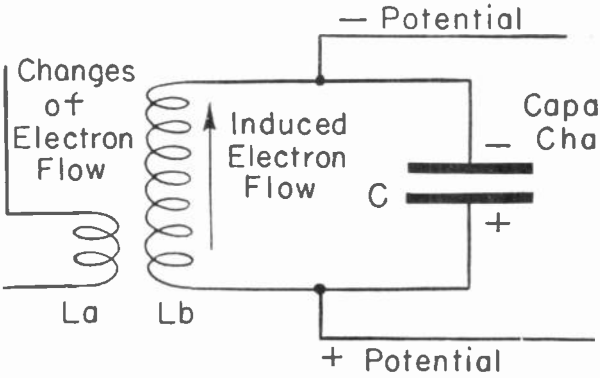


Fig. 19-12.—The induced electron flow and the accompanying potentials in a tuned coupled circuit.

flow in the secondary. This is shown by Fig. 19-12. The electron flow charges the capacitor, and builds up a difference of potential between the plates of the capacitor. These potential differences are applied to any circuit connected to the tuned secondary, which might be the grid circuits of Fig. 19-11. It should be noted that the induced emf appears in the secondary winding. Therefore, this emf which is applied to the tuned secondary circuit is effectively in series with the coil and capacitor in this circuit. But, because the coil and capacitor are connected together in parallel so far as the load circuit or grid circuit is concerned, the potential differences produced on the capacitor plates, which must be the same as those at the ends of the coil at each instant, are applied to the connected load circuit as shown by Fig. 19-12.

Fig. 19-13 shows two tuned circuits coupled by mutual induction. This is a coupling method employed between certain tubes in superheterodyne radio receivers. The primary circuit consists of coil *La* and tuning capacitor *Ca*. The secondary circuit consists of coil *Lb* and tuning capacitor *Cb*. The two coils are placed with reference to each other so that there is mutual induction and mutual inductive coupling between them. Both circuits are tuned to the same frequency, which is the frequency being amplified. As explained in connection with superheterodyne receivers, this frequency is not that of the signal coming to the antenna, but is a lower frequency, called the intermediate frequency, at which most of the amplification is carried out.

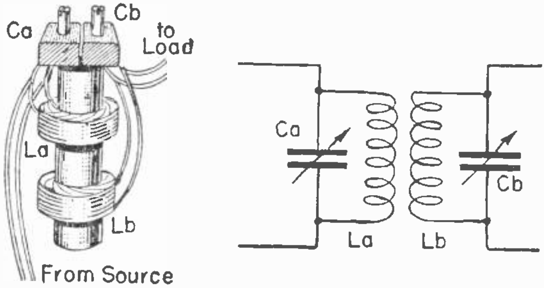


Fig. 19-13.—Two tuned circuits having mutual inductive coupling.

Mutual Inductance.—The rate of energy transfer between circuits having mutual inductive coupling is increased by increasing the mutual inductance in proportion to the self-inductance of the circuits. Mutual inductance, like self-inductance, is measured in henrys, millihenrys or microhenrys. Mutual inductance is defined as the increase in the total inductance of the circuits when the increase is due to coupling between them. The symbol for mutual inductance is the letter *M*, for self-inductance it is the letter *L*.

The amount of mutual induction and of mutual inductance of two coils depends on many factors. Among the most important factors are the relative positions and the relative sizes of the coils. To illustrate, it may be assumed that the two coils shown at *1* in Fig. 19-14 have some certain amount of mutual inductance when separated endwise as shown, and when the axis of one coil is in line with that of the other. The mutual inductance is lessened when the coils are moved farther apart as at *2*, still with their axes in line, and it is lessened much more when they are moved still farther apart, as at *3*. If, as at *4*, the axes of the coils remain parallel but they are moved out of line, the mutual inductance is reduced. If, as at *5*, the axes are not parallel, although still intersecting each other, the mutual inductance is reduced. If the axes are at right angles and intersecting, as at 6, the mutual inductance is of the least value for the given separation of the coils.

In examples *2* to *6* of Fig. 19-14 the self-inductances of the two coils remain unchanged from the values assumed at *1*. In examples *7* to *9* the self-inductances are changed in relative values. At *7* one of the self-inductances has been reduced. This lessens the mutual inductance. A decrease of the self-inductance of either or both coils lessens the mutual inductance, while an increase of the self-inductance of either or both coils adds to the mutual inductance. At *8* one of the coils is of smaller diameter than the other, which reduces the self-inductance of the smaller coil if its general construction is unchanged, and also reduces the mutual inductance. At *9* a sheet of iron or steel has been placed between the coils in such position that the magnetic lines from either coil expend their energy in the metal rather than passing through the turns of the other coil. This, of course, causes a great reduction of mutual inductance. Anything that lessens the number of magnetic lines of force from one coil that cut the turns of the

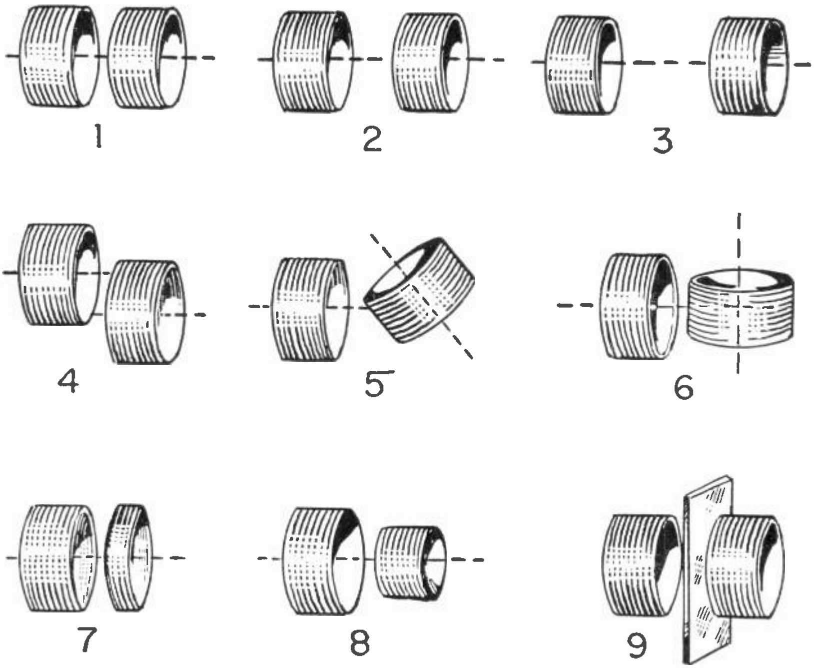


Fig. 19-14.—Mutual inductance is affected by the relative positions and sizes of coils, and by intervening objects.

other coil when there is a change in field strength will reduce the mutual inductance, and anything that increases the number will increase the mutual inductance.

It is possible to compute the changes of mutual inductance brought about by such variations of position as shown at *2*, *3*, *5* and *6* of Fig. 19-14, but any formulas that give fairly accurate values are exceedingly complicated in form, and simplified formulas usually give large errors except in a limited number of cases.

Mutual inductance usually is determined by measurement. One method is as follows: The two coils are placed in the relative positions that they are to occupy in service. The two coils, an a-c source, and a meter which indicates values of alternating current are connected in series, as at the left in Fig. 19-15. Assuming that the opposition of the coils to flow of current is due chiefly

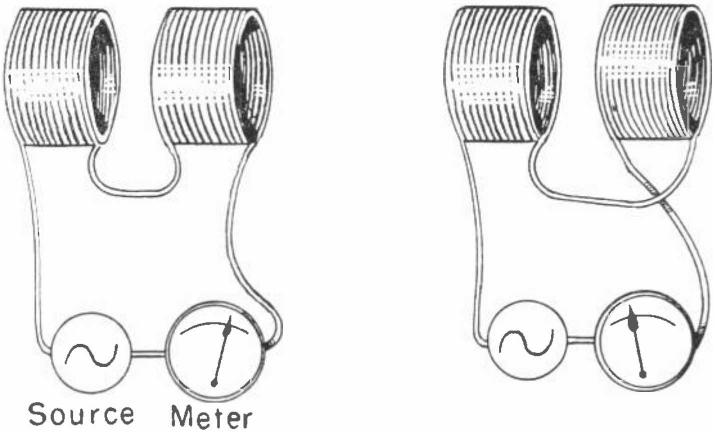


Fig. 19-15.—A method of measuring mutual inductance.

to reactance and but little to resistance, it is easy to compute the reactance from the known voltage of the source and the observed current, for $X = E/I$. Knowing the reactance and the frequency of the source it is easy to compute the inductance, which is equal to the reactance divided by the product of 6.2834 and the frequency in cycles.

Now the connections to one of the coils are reversed, as at the right in Fig. 19-15, and the inductance is again computed. In one case the mutual inductance is adding to the self-inductances, and in the other case it is subtracting from the self-inductances, because in one case the magnetic fields of both coils act in the same direction at the same time and in the other case they are in opposite directions and oppose each other. Then the mutual inductance is found from the formula,

$$M = \frac{\text{1st inductance} - \text{2nd inductance}}{4}$$

Coefficient of Coupling.—The effectiveness of the coupling, or the degree of coupling, between two coupled circuits is measured as a fraction which is called the *coefficient of coupling* or the *coupling factor.* If we had two coils precisely alike in length, diameter, number of turns, and method of winding, the two could have a mutual inductance of 1.0 were it possible for them to occupy the same space at the same time. That is to say, 1.0 or "unity" is the maximum coefficient of coupling which is theoretically possible. In all practical cases the coefficient or the factor is less than 1.0. With air-core coils such as shown in some of the preceding illustrations the coefficient usually is somewhere between 0.02 and 0.10, or is between 1/50 and 1/10 of the theoretical maximum. With iron-core transformers we may have a coupling coefficient of 0.90 or even greater.

If we know the total self-inductances in each of two coupled circuits, and know also their mutual inductance, it becomes possible to compute the coefficient of coupling with this formula.

$$k = \frac{M}{\sqrt{La \times Lb}}$$

In the formula *k* is the coupling coefficient, *M* is the mutual inductance of the circuits, and *La* and *Lb* are the self-inductances of the two circuits. The self-inductances are those of the entire circuit in each case, which may be greater than the self-inductances of the two coils which furnish the coupling. The inductances, self- and mutual, are to be in the same units; which may be henrys, millihenrys, or microhenrys.

As an example, supposing that we have circuits in which the self-inductances are 120 microhenrys and 30 microhenrys, and which have a mutual inductance of 6 microhenrys. With these values in the formula we have,

$$k = \frac{6}{\sqrt{120 \times 30}} = \frac{6}{60} = 0.10$$

Now supposing that the circuit containing the 30 microhenrys of self-inductance were to have inserted in it another coil having a self-inductance of 40 microhenrys so that the total self-inductance in this circuit would be 70 microhenrys. Using the new value in the formula would show that the coupling coefficient has dropped to 0.065. Here we have less of the total self-inductance acting to form the coupling. We may conclude that the less of the total self-inductance that is coupled the smaller will be the coupling coefficient, and that we shall have maximum coupling coefficient when all of the self-inductances in both circuits are acting as the coupling.

Coils which may be connected into a circuit for the sole purpose of increasing the self-inductance of the circuit, or which may be cut out of the circuit to lessen its total self-inductance, are called *loading coils.*

Couplings between circuits cause many rather peculiar effects, whose extent usually varies with changes of coupling coefficient. Couplings in which the coefficient is less than 0.5 may be said to have *loose coupling,* while those in which the coefficient is 0.5 or more may be said to have tight coupling or *close coupling.*

Couplings often are given as percentages rather than as decimal fractions. Multiplying the fraction by 100 gives the equivalent number of per cent. For instance, a coupling coefficient of 0.5 is the same as a coupling of 50 per cent. Formulas always make use of coefficients in the form of a fraction rather than as a percentage.

If two circuits are coupled, and if the resistance of one of them is increased, the other circuit will behave as though its own resistance had been increased. This effect exists with all kinds of high-frequency resistances as well as with ordinary ohmic resistances of conductors. If the resistance of one circuit is lessened, the other circuit will act as though its own resistance were lessened. To what degree the resistance of one coupled circuit affects the other circuit increases with increase in the coefficient of coupling; that is, the effect is greater with close coupling than with loose coupling.

Either an inductive reactance or a capacitive reactance which is in one of two coupled circuits will make the other circuit act as though it too had additional inductive or capacitive reactance. Here again the effect increases with increase of the coupling coefficient. When either of the coupled circuits are tunable to resonance, the inductance or capacitance in the other circuit will affect the tuning if the first inductance or capacitance is changed, and the second circuit will have to be retuned to overcome the effect. If either or both of the coupled circuits are tuned to resonance, and if the degree of coupling is changed, the tuning will have to be readjusted because more or less of the inductive or capacitive effect of one circuit is then carried over into the other circuit.

Double-hump Resonance.—Coupling, or the degree of coupling, has important effects on the behavior of tuned circuits in radio. To observe one of the effects, consider the conditions of Fig. 19-16. Here we have two tunable circuits, each of which is separately tuned to a frequency of 470 kilocycles while the two are so far removed from each other as to have zero coupling. If the two circuits now are brought close enough together so that they have a coupling coefficient of 0.02, and if the original tuning adjustments are not disturbed, resonance will not occur at a frequency of 470 kilocycles, but there will be resonant peaks somewhat above and somewhat below that original frequency.

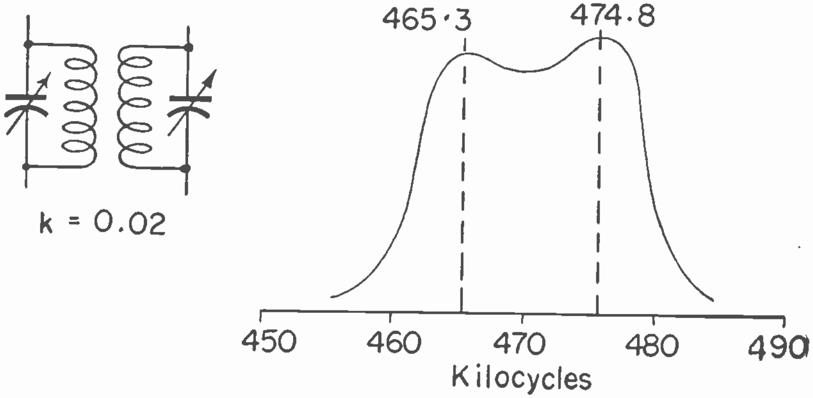


Fig. 19-16.—Double-hump resonance with coupled tuned circuits.

There will be a peak of current and potential at a higher frequency of about 474.8 kilocycles, and another peak at about 465.3 kilocycles. We have two peaks or humps on the resonance curve, and have the condition called double-hump resonance. Instead of maximum response at and close to the frequency of 470 kilocycles we now have a response which remains high over a band of frequencies from somewhat above 460 kilocycles to somewhat below 480 kilocycles. This effect is not always objectionable. In fact, the effect of double hump resonance as employed in certain transformers of superheterodyne receivers allows good amplification over the entire band of frequencies to be handled by the intermediate-frequency amplifier, while providing quite sharp cutoff or reduction of all frequencies outside of this band.

Now supposing that we increase the coupling until the coefficient is 0.10. The result is shown by Fig. 19-17. Instead of resonance at the original frequency of 470 kilocycles, we have one peak at 448.0 kilocycles and another at 495.4 kilocycles. The lower peak is 22.0 kilocycles below the original value, and the higher one is 25.4 kilocycles above. At the frequency of 470 kilocycles we have a negligible response.

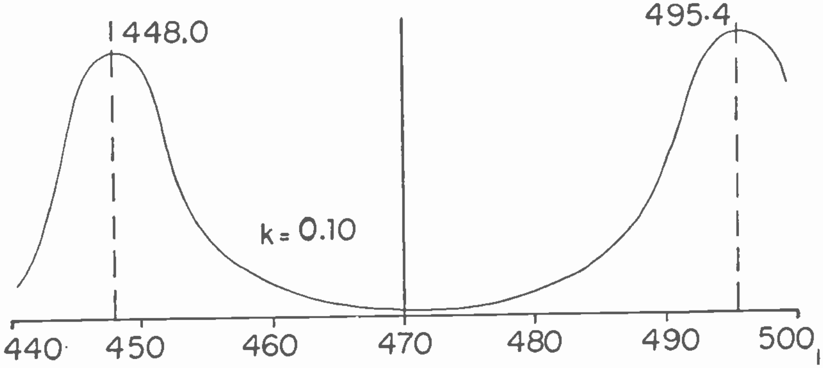


Fig. 19-17.—Close coupling causes the resonant peaks to move apart.

Were the coupling to be made even looser than indicated by Fig. 19-16 the two peaks would come still closer together, and they might be made to nearly merge into one peak. On the other hand, as the coupling is made closer and closer the peaks move farther and farther apart, and the dip of response in between them becomes lower and lower until we reach the condition of Fig. 19-17.

The two coupled circuits behave as though each contained a value of inductance different from that in the other circuit. One of these inductances appears equal to the actual self-inductance minus the mutual inductance, and the other appears equal to the self-inductance plus the mutual inductance. As an example, assume that our 470-kilocycle tuned circuits contain 190 mmfd of capacitance and 603.5 microhenrys of inductance; a combination which is resonant at this frequency. With a coupling coefficient of 0.10, and equal self-inductances, the mutual inductance is 0.10

times the self-inductance, or is 60.35 microhenrys. Subtracting and adding the mutual gives apparent inductances of 543.15 and of 663.85 microhenrys. Using these two apparent inductances with our capacitance of 190 mmfd, and computing the resonant frequencies, gives those frequencies as 495.4 and 448.0 kilocycles, just as shown by Fig. 19-17.

Instead of tuning the two circuits to the same frequency we might tune them to slightly different frequencies. Naturally we should expect to have two resonant peaks due to the two different tunings, and this actually is the case. But coupling still has its effect, and one of the actual peaks will be at a frequency somewhat higher than the higher tuned frequency, and the other peak will be at a frequency somewhat lower than the lower of the tuned frequencies. Thus tuning of the circuits to different frequencies moves the resonant peaks still farther apart than as though both circuits were tuned to the same frequency, and widens the band of response when the peaks remain close enough together to cover a band of frequencies rather than two separated peaks.

Whether the two circuits are tuned to the same or different frequencies to begin with, any change of inductance or capacitance in either circuit will result in a shifting of the frequency of both peaks, not only in one of them. Truly, we find strange performances in radio circuits.

Induced Currents.—The emf which is induced in a secondary circuit by changes of current in the primary circuit causes elec-

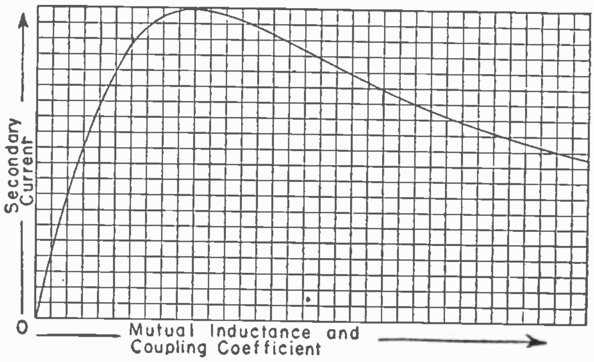


Fig 19-18—The effect of coupling and mutual inductance on secondary current

tron flow (current) in the secondary when the secondary is part of a closed circuit through which such a flow may take place. With the impedance of the primary circuit remaining constant, the power used in that circuit will be practically proportional to the square of the induced current, just as other powers are proportional to the square of the current. As a consequence, what we have to say about induced current applies generally to the power put into the secondary circuit from the primary.

As we should expect, the induced secondary flow and the power put into the secondary circuit are affected by the coupling. When conditions in the primary circuit remain constant, the current induced in the secondary varies about as shown by Fig. 19-18 when the coupling coefficient is changed from zero to greater values. The coupling coefficient is directly proportional to the mutual inductance, so the curve shows the effect of increasing the mutual inductance as well as of increasing the coupling.

With zero mutual inductance and coupling there is, of course, no induced emf and no induced electron flow in the secondary winding. As the coupling is increased there is a rapid rise of secondary current until it reaches a maximum value at some certain coefficient of coupling. With still closer coupling there is a gradual drop in secondary current. However, no matter how close the coupling is made there always will be some current induced in the secondary circuit. The curve shows that we may increase the secondary current and power transfer by increasing the coupling up to a certain value, but that couplings which are too close result in a decrease.

The value of mutual inductance or coupling at which we obtain the maximum secondary current depends on several factors, but especially on the operating frequency and on the resistance (high-frequency) of the circuits. The greater the high-frequency resistances the closer must be the coupling. This is the same as saying that the lower the Q-factor the closer must be the coupling for maximum secondary current. The higher the operating frequency the looser must be the coupling for maximum secondary current. To summarize; we may say that poorly constructed or designed coils having low Q-factors, also operation at low frequencies, will call for closer couplings than will better coils and higher frequencies. All of this refers to the conditions for maximum secondary flow. With couplings either less or greater that the "optimum" value there will be a decrease of current no matter what kind of coils are used and no matter what the frequency.

For any given electron flow in the primary, the flow in the secondary winding may be increased in either of two ways. It may be increased by lessening the high-frequency resistance in the secondary circuit, or it may be increased by increasing the high-frequency resistance of the primary circuit. Of course, an increase of resistance in the primary is going to reduce the primary current, and the overall effect may be a dropping off in secondary current in spite of the fact that the secondary would be greater in proportion to the primary—the trouble being that we have a smaller primary current than originally assumed.

REVIEW QUESTIONS

1. How does the transfer of energy from circuit to circuit take place in a radio circuit?
2. For what purpose are loading coils used?
3. What is the difference between loose coupling and close coupling?
4. How is the rate of energy transfer between circuits having mutual inductive coupling affected by an increase of mutual inductance in proportion to the self-inductance of the circuits?
5. With a given primary current, in what two ways may the current be increased in the secondary of a coupling transformer?

TO FIND WHAT FREQ A CERTAIN IND. & CAP. WILL BE RESONANT IS THE FORMULA FOR X_L & X_C - EACH OTHE

Chapter 10

RADIO TRANSFORMERS

TELEVISION AND RADIO TRANSFORMERS

Of all the kinds of couplings which we have studied, transformers serve more different purposes in television and radio than do any of the other types. The transformer, which operates because of mutual induction, has two great advantages over other kinds of couplings. First, in the secondary circuit we may have higher voltages and smaller currents than in the primary, or we may have lower voltage and greater current. Second, there is no conductive connection between the primary and secondary circuits; that is, no current can flow directly from one circuit into the other through a conductor, because there is no conductor connecting secondary and primary so far as the transformer itself is concerned. The primary and secondary circuits are insulated from each other, yet energy may be transferred.

The uses of various types of transformers in a radio receiver are illustrated by Fig. 20-1, which is a diagram showing control-grid circuits and plate circuits of a superheterodyne set. In the upper part of the diagram are the audio-frequency amplifiers, the detector, and the loud speaker. In the center part are the converter and the intermediate-frequency amplifier. In the lower part is the power supply system with its rectifier and filter.

Following the high-frequency or radio-frequency signal that enters the system between the antenna, *Ant*, and ground, *Gnd*, we come first to transformer number *1* which is a radio-frequency transformer with primary winding *P* in the antenna-ground circuit and with secondary winding *S* in the control grid circuit of the converter tube. The secondary winding is tuned to resonance with the received frequency by adjustment of capacitor *C*.

The intermediate-frequency output of the converter goes to primary *P* of transformer *2*, which is an intermediate-frequency transformer having both primary and secondary tuned to resonance at the intermediate frequency by adjustment of the small capacitors connected across these windings. This is the type of transformer in which may be produced the double-hump resonance response which we examined in an earlier chapter.

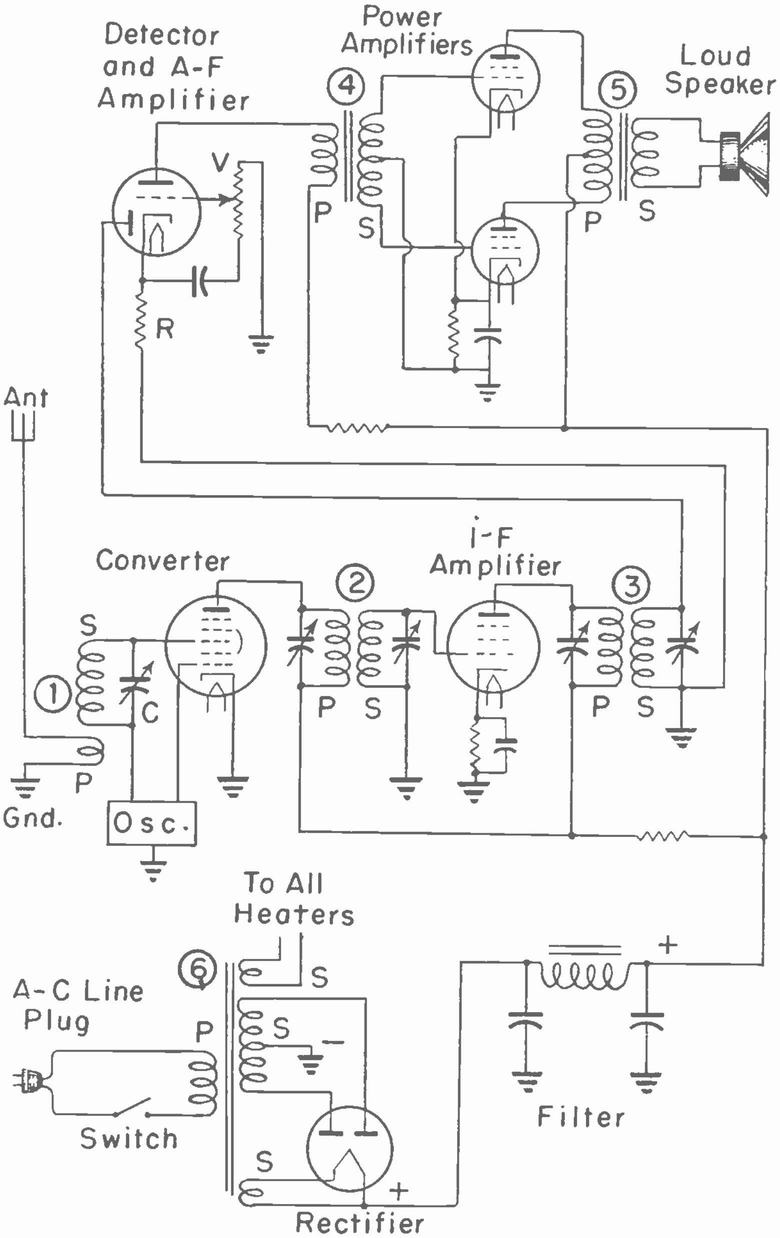


Fig. 20-1.—Points at which transformers may be used in a superheterodyne radio receiver.

The secondary of the i-f transformer *2* is in the control grid circuit of the i-f amplifier tube. The output of this tube goes to the primary of transformer *3*, which is another double-tuned i-f transformer similar to number *2*.

The secondary of transformer *3* is connected between the diode plate and the cathode of the diode-triode tube which is at the left in the upper part of the diagram. The diode plate and the cathode act together as a detector or demodulator, rectifying the intermediate-frequency potentials and producing in resistor *R* the average direct current which follows the modulation of the incoming signal. From the upper end of resistor *R* a connection is made through a capacitor to the voltage divider resistor *V*, which is the adjustable volume control.

The control grid of the triode section of the diode-triode tube is connected to the slider on volume control *V*, so that varying strengths of a-f potential may be applied to this grid. The output of the triode section of the triode, which is acting as an audio-frequency voltage amplifier, goes to the primary winding *P* of transformer *4*. This transformer, operating at the relatively low audio frequency, is shown as having an iron core, whereas the r-f and i-f transformers have air cores which are suitable for high-frequency operation.

The secondary winding of transformer *4* is tapped at its electrical center. The outer ends of this winding go to the control grids of the two power amplifier tubes. The cathodes of these tubes are connected together and through a biasing resistor to ground and to the center-tap of the transformer secondary. The power tubes are being used in what is called a push-pull system of amplification.

The outputs of the two power tubes go to the outer ends of the center-tapped primary winding of transformer *5*, with the tap connected to the source of plate potential and current. The secondary of transformer *5* connects to the loud speaker. Transformer *4* may be called a push-pull input transformer, and number *5* a push-pull output transformer. Transformer *5* may be called also a speaker coupling transformer, because it delivers audio-frequency power from the amplifiers to the loud speaker.

Going to the bottom portion of Fig. 20-1 we start from the a-c line plug which provides connection to any convenient lighting or power line. The plug connects through a switch, that turns the receiver on and off, to the primary winding of transformer *6*. This transformer is the power transformer for the receiver. It is of the iron-core type because it operates at the low frequency of the a-c power line. From the upper secondary winding of the power transformer alternating current at a suitable low voltage goes to the heaters of all the amplifying tubes. The heaters are connected in parallel to this winding, although the connections are not shown in the diagram.

The outer ends of the center-tapped secondary winding of the power transformer are connected to the two plates of the full-wave rectifier tube. The center tap, which is the negative terminal of the power supply system, is connected to ground. The positive terminal is at the filament-cathode of the rectifier tube. From here a lead goes to the filter, which consists of a choke coil and two capacitors. The smooth direct current from the output of the filter goes to the plate circuits of all the amplifier tubes. All of the cathodes of the amplifier tubes are directly or indirectly grounded, thus completing the plate circuits back to the negative ground on the plate-power supply system.

In the receiver whose circuits have been traced we find the following types of transformers.

1. Radio-frequency transformer with secondary tuned. This unit sometimes is called an antenna coupler or an antenna transformer when used in the antenna circuit.

2 and **3.** Intermediate-frequency transformers of the double-tuned type.

4. Audio-frequency transformer with center-tapped secondary, an iron-core type.

5. Speaker coupling transformer, another iron-core type.

6. Power transformer, an iron-core type.

Air-core Transformers.—Between the performances of air-core and iron-core transformers there are such differences that it is impossible to use the same rules and formulas in both cases. One of the differences is in the degree of coupling; with air-core windings it is very small in comparison with the coupling when using an iron core. The second difference is that one or both windings of the air-core unit usually are tuned to resonance at or near the operating frequency, while the windings of iron-core transformers seldom are so tuned. At resonance the currents circulating in tuned windings are large, and the potential differences across the inductance and capacitance are high compared to the applied potentials. In air-core transformers used at high frequencies the performance depends to a great extent on the high-frequency resistance or energy losses, and we are much interested in Q-factors. But in iron-core transformers used at lower audio and power frequencies we do not have the same kinds of losses, instead having other kinds associated with the iron.

Fig. 20-2 shows several air-core transformers mounted inside of metallic "cans" which provide electrostatic shielding. The

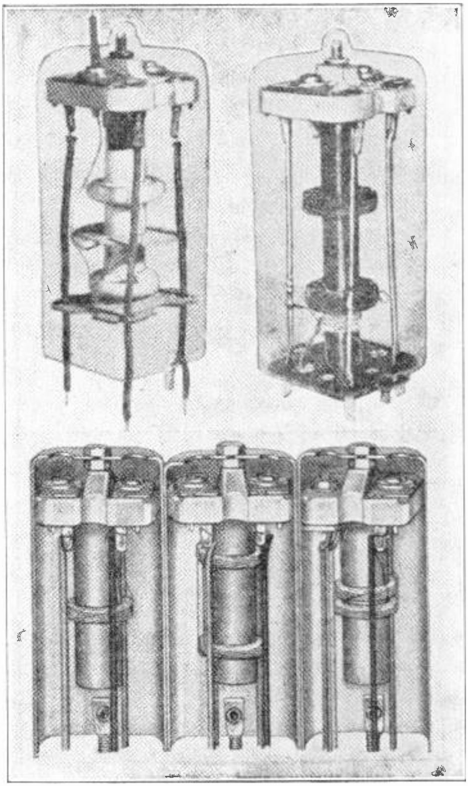


Fig. 20-2.—Intermediate-frequency transformers with their tuning capacitors in shielding cans.

types illustrated are intermediate-frequency transformers in which the windings are tuned to resonance by means of small adjustable "trimmer" capacitors located beneath the adjusting screws on the porcelain pieces which are in the tops of the cans. The primary and secondary windings of these transformers are carried on insulating tubes and are separated by various distances in accordance with the degree of coupling desired.

Transformers such as are used in antenna circuits, also those used between one radio-frequency amplifying tube and another, appear generally similar to the i-f types pictured except for having no tuning capacitors mounted in the cans. For the radio-frequency transformers the capacitor for tuning the secondary winding is a separate unit operated from the tuning dials of the receiver. The primary windings of the r-f transformers are not tuned.

When an r-f transformer with tuned secondary and untuned primary is used for interstage coupling as in Fig. 20-3 there always is a loss of voltage in the transformer itself, which reduces the gain due to the amplification of the preceding tube. Factors which lessen the transformer loss are marked on the diagram. The loss is decreased directly with increase of coupling factor or coefficient so long as the coupling does not exceed the value at which secondary current commences to drop off. The transformer loss decreases directly also with increase of secon-

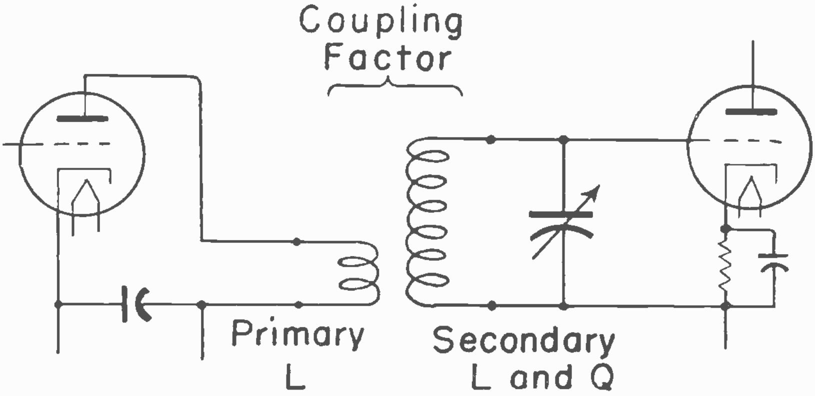


Fig. 20-3.—Factors affecting loss of signal voltage in a tuned transformer

dary inductance, *L*, and with the Q-factor of the tuned secondary circuit. Finally, the loss decreases as the square root of the ratio of primary inductance to secondary inductance.

The primary winding ordinarily has fewer turns and consequently less inductance than the secondary winding. As a result, the ratio of primary to secondary inductance is a fraction and the square root is a fraction. The greater the inductance of the primary in comparison with that of the secondary, the larger will be the fraction and the smaller will be the loss.

As an example, we might assume a transformer with a coupling coefficient of 0.05, a secondary inductance of 270 microhenrys, a *Q* of 400, and a primary inductance of 30 microhenrys. We change the inductance values from microhenrys to henrys, then multiply together the coupling coefficient, the secondary inductance, and the secondary *Q*, to get the fraction 0.054. The ratio of primary to secondary inductance is 1/9 and the square root of 1/9 is 1/3. Multiplying 0.054 by 1/3 gives 0.018, which is the fraction representing the loss of the transformer, or the "negative gain" as it may be called. Now supposing that the amplifier tube has a mutual conductance or grid-plate transconductance of 2,000. Multiplying 2,000 by 0.018 shows that the overall gain of the stage (tube and transformer together) will be 36. That is, the signal voltage applied at the control grid of the tube will be amplified 36 times in the signal potential which is the output of this stage.

If the transconductance of the amplifier tube were 55.6 the product of 55.6 and the negative gain of 0.018 would be approximately 1.0, and the output of the stage would be equal to the input. Were the transconductance less than 55.6 the output of the stage would be less than the input, and there would be a net loss of voltage. Such stages sometimes are used for the purpose of tuning to the desired signal, and excluding undesired ones, with signal strength restored and increased by following stages.

In order to make the preceding amplifier tube work hard enough to deliver a strong signal it is necessary that the impedance in the plate circuit load be quite high. Taken by itself, the impedance of the primary winding of an r-f transformer would be small, but when the primary is coupled to a tuned secondary circuit in which the resonant impedance is high, the secondary impedance is "reflected" back into the primary circuit.

The effective impedance which the transformer places in the plate circuit of the amplifier tube is directly proportional to the Q of the secondary circuit and also to the square of the mutual inductance between primary and secondary. Increasing either of these factors increases the effective impedance in the plate circuit. The effective primary impedance varies with variation of the secondary inductance; more of this inductance increasing the primary impedance.

In Fig. 20-4 we have an air-core transformer with both primary and secondary tunable. If we assume that the tuned circuits have no high-frequency resistance, and that both are tuned to the same frequency, the ratio of secondary voltage to primary voltage would be proportional to the square root of the ratio of secondary inductance to primary inductance. For example, we might have a secondary inductance of 300 microhenrys and a primary inductance of 75 microhenrys. The ratio is 300/75 or 4/1, which is equal to 4. The square root of 4 is 2, so the ratio of secondary to primary voltage would be 2 and the secondary voltage would be twice that across the primary.

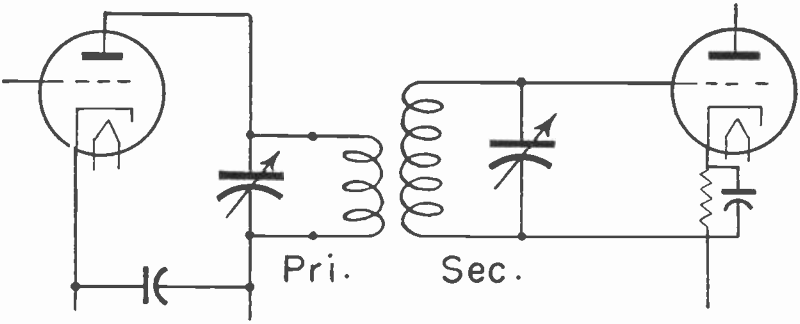


Fig. 20-4.—Coupling by means of a double-tuned transformer between amplifier tubes.

If the two tuned windings are closely coupled, but are not tuned to the same frequency, and if we assume no high-frequency resistance in either circuit, the ratio of voltages is about the same as the ratio of numbers of turns on the two windings. That is, if the secondary has twice as many turns as the primary the secondary voltage will be about twice the primary voltage. Of course, we cannot have circuits without high-frequency resistance, and the actual performance is always affected by such resistance. Our examples simply illustrate the best possible theoretical performance of double-tuned air-core transformers.

IRON-CORE TRANSFORMERS

To get acquainted with the construction and operation of iron-core transformers in general we shall make a detailed examination of one particular type which utilizes most of the principles employed in the majority of iron-core radio transformers. The type which we shall examine is a power transformer pictured in Fig. 20-5. This is a unit such as would be used at position *6* in Fig. 20-1. The primary winding connects to the a-c supply line. There is one secondary winding for the plates of the full-wave rectifier tube, another for the filament of the rectifier, and a third for the heaters of all the other tubes. The leads or external connections for the primary and the three secondaries may be seen in Fig. 20-5 extending from the right-hand side of the housing or shell which covers the windings on that side.

On the left-hand side of the transformer in Fig. 20-5 is a shell enclosing the windings on that side. Between the two shells may be seen the *core*. The core consists of many thin sheets of steel. These thin sheets are called *laminations*.

In Fig. 20-6 the transformer has been turned to show the leads coming through two openings in the shell. At the upper left are two black-covered wires which connect internally to the primary winding. At the upper right are three green-covered wires which connect to the secondary winding for the rectifier filament. In the unit we are looking at this rectifier filament winding is center tapped as shown schematically in Fig. 20-7. The high-voltage positive output of the rectifier goes to the filter through the tap, and thus is unaffected by the variations of alternating potential existing at the ends of the winding.

At the lower right in Fig. 20-6 are three yellow-covered leads which connect to the heater winding. This winding, like that for the rectifier filament, is center tapped as indicated schematically

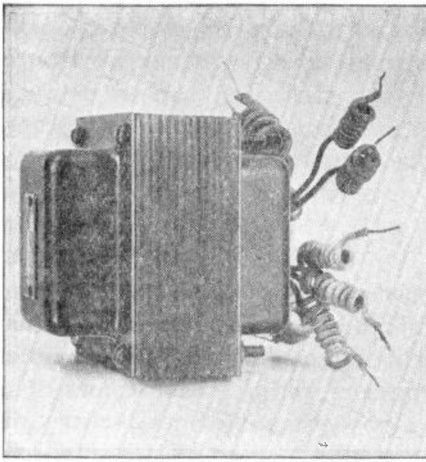


Fig. 20-5.—A power transformer for a radio receiver.

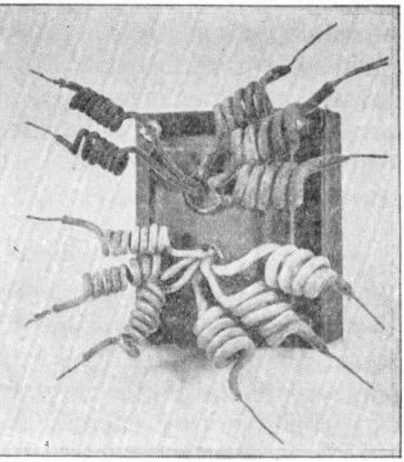


Fig. 20-6.—The leads extending through openings in the transformer shell.

in Fig. 20-7. This center tap may be connected to whatever point is at a potential which is desired for the average potential of the heaters in the tubes. This permits maintaining the heaters at some certain potential, or at some certain potential difference, with reference to the cathodes. For example, the cathodes may be connected to the center tap of the heater winding to maintain a zero potential difference. In some types of amplifiers the heaters

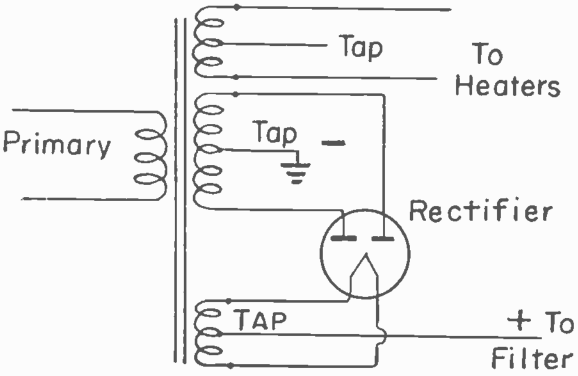


Fig. 20-7.—The center tap connections on the secondary windings of the power transformer.

are maintained at about 10 volts positive with reference to the cathodes in order to prevent electron emission from the heater going to the cathode. Such emission would cause hum in the sound reproduction. The desired potential difference is maintained by connecting the heater center tap to a point 10 volts more positive than the point (often ground) to which the cathodes are connected. That is, the heaters are "biased" 10 volts positive with reference to the cathodes.

At the lower left in Fig. 20-6 are three leads, with red insulation, which connect to the rectifier plate winding or high-voltage winding. The center tap of this winding is the most negative point in the d-c power supply system which includes the rectifier tube. The tap may be connected to ground, as in Figs. 20-1 and 20-7, or to any other point in the receiver circuits which is to be the most negative point.

Core and Magnetic Circuit.—By removing all of the windings, their leads, and all of the insulation from the power transformer we finally will come to the core which is shown by Fig. 20-8. On the left in this picture you will see the edges of the steel laminations which are visible in Fig. 20-5, but now we see also the flat surfaces. Although the core laminations are made of steel alloys which have magnetic properties suitable for use in a transformer, we commonly speak of the core as the "iron" or speak of it as though made of iron.

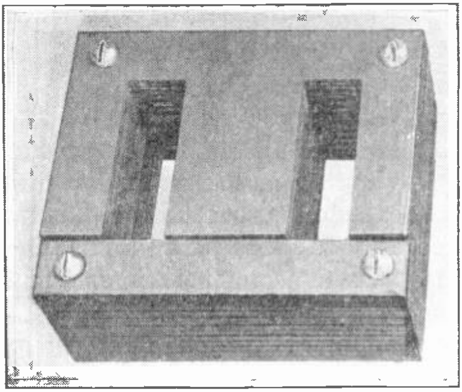


Fig. 20-8.—The core of the power transformer.

The core is made up of two kinds of laminations whose shapes are shown at *A* in Fig. 20-9. One is called the *E-iron* because it is shaped like a capital letter "E" and the other may be called the *I-iron* because it is straight, like a capital "I". In the complete core there are as many I-irons as E-irons. Half of the E-irons are pointed as at *A* and the other half as at *B*. In our power transformer the irons are in groups of three pointing in one direction, then three in the opposite direction, and so on until all are assembled. The result is as shown at *C*, where we have two openings which are called the *windows* completely surrounded by the iron. Using pieces of E-shape permits pushing them together with the previously assembled windings or coil in the window spaces.

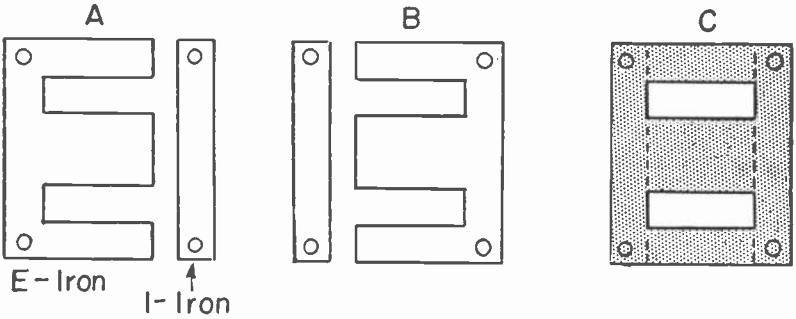


Fig. 20-9.—The shapes of the core irons, and how they are placed together.

When all of the groups of E-irons have been pushed into the coil, with alternate groups facing opposite directions, groups of I-irons are pushed into the remaining spaces at the open ends of the E-irons to make the core, in effect, a mass of magnetic steel having no open spaces other than the windows. The core of Fig. 20-8 has all of the I-irons in place except the last group which will go at the right of the last group of E-irons whose open edges are visible in the picture.

Fig. 20-10 shows, in principle, how a winding is placed in the windows of the core. The winding, also as many other windings as may be used, goes around and around the section of the core called the center leg. When electrons (current) flows in the winding, magnetic lines of force flow as shown by broken lines and arrows, through the center leg and around through the two outer legs to complete the magnetic circuit. The center leg has twice the cross sectional area of one of the outer legs. Then with all of the magnetic lines flowing in the center leg, and half of them going through each outer leg, we have the same flux density or the same number of lines per square inch of cross section in all parts of the core.

We may consider the winding of Fig. 20-10 as representing the primary winding of our transformer. When there are variations in the rate of electron flow in this winding there will be corresponding changes in flux density in the core iron. When the direction of flow reverses, as it does with alternating current, there will be corresponding reversals of magnetic flux direction.

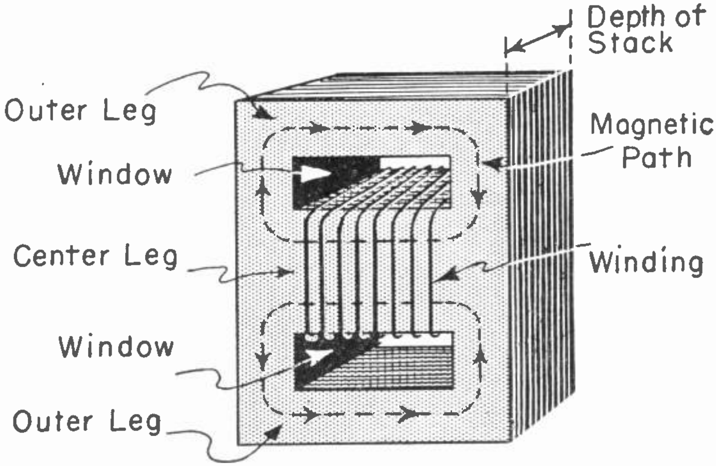


Fig. 20-10.—How the windings are placed on the center leg of the core.

If we place in the same window space with the primary winding another winding and use this other winding for a secondary, every change of magnetic flux in the core will pass also through the turns of the secondary winding. Because of electromagnetic induction these changes of flux will induce in the secondary corresponding emf's and changes of emf. If the secondary forms a part of a closed electric circuit the emf's will cause corresponding flows of current in that circuit. Thus, by having a magnetic core which is common to both primary and secondary, we transfer energy and power from the primary circuit to the secondary circuit.

The core is made with thin laminations, rather than with thick and solid sections, to reduce the loss of power which is due to eddy currents caused to flow in the iron. Eddy currents tend to flow in directions which are at right angles to the direction of the magnetic lines. From Fig. 20-10 it is plain that eddy currents would tend to flow from front to back, and from back to front, of the core. But to flow in these directions the eddy currents would have to pass from one lamination to another, and the laminations are effectively insulated from one another by their coatings of iron oxide, or sometimes by coatings of shellac or varnish. Thus the eddy currents are kept very small, and little power is wasted in causing them to flow. In our power transformer the individual laminations are 0.0188 inch thick. Thicknesses usually are anywhere from 0.010 to 0.030 inch in various types of transformers.

Primary and Secondary Windings.—Now we may proceed to build up the windings for the power transformer just as though the unit were being constructed step by step. The complete assembly of all the separate windings, when ready for insertion of the core iron, usually is called the coil.

The first step is to prepare a form, called the bobbin, such as shown by Fig. 20-11. This bobbin is made of spirally wound heavy-weight kraft paper, later impregnated with wax. It will fit snugly over the center leg of the core iron, providing a support for the coil as well as insulation between core and coil.

On the bobbin we wind the primary winding which is shown in its completed form by Fig. 20-12. For the transformer we are examining the primary consists of 340 turns of number 24 gage plain enameled wire wound in six layers of about 57 turns each. This primary is designed for use on a 60-cycle 117-volt a-c supply line, and with all secondaries carrying their full rated electron flow (currents), the primary flow will be about 0.65 ampere as taken from the supply line. Between successive layers of the primary winding are sheets of insulating paper which is about

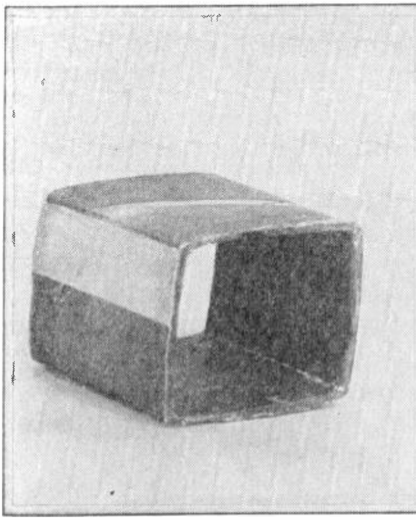


Fig. 20-11.—The bobbin on which the windings are placed.

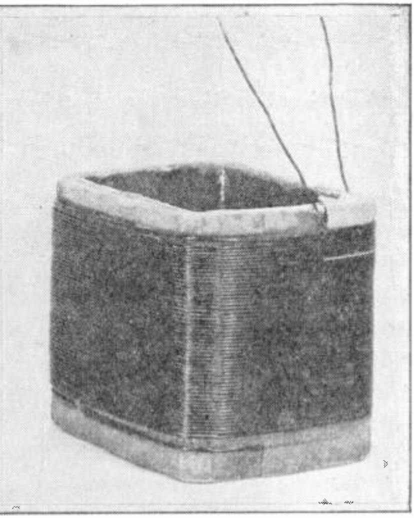


Fig. 20-12.—The completed primary winding.

0.006 inch thick. Around the outside of the primary is placed a wrapping of heavier paper, or sometimes of oiled linen, to provide plenty of insulation between the primary and the following secondary windings.

The power supply lines to which the primary winding will be connected often are subjected to sudden brief pulses or surges of potential and electron flow entirely distinct from the regular alternations. These pulses result from turning on and off the lamps and various electric appliances connected to the same lines, and they may result from the kinds of atmospheric electrical disturbances which we class under the general name of "static."

To reduce the effect of the primary "static" pulses on potentials and currents induced in the secondaries we place around the primary winding an electrostatic shield which is shown by Fig. 20-13. This shield consists of a strip of copper which, in our power transformer, is only 0.0015 inch in thickness, and is long enough and wide enough to go all the way around the primary. To the copper is soldered a lead which later will be held in contact with the core iron, and which will provide a connection to ground when the core and transformer shells are grounded.

The ends of the shield are separated from each other with a piece of fibre, as shown in Fig. 20-14. Were this not done the copper would form a continuous conductive ring around the primary winding. Due to the very low electrical resistance of the copper there would be induced in a continuous ring very large currents which would produce much heat at the expense of a considerable waste of power. The copper strip with its ends separated and insulated from each other does not carry circulating currents, yet forms an effective electrostatic shield which reduces energy transfer through capacitance between the windings.

Fig. 20-13.—The electrostatic shield and its connection lead.

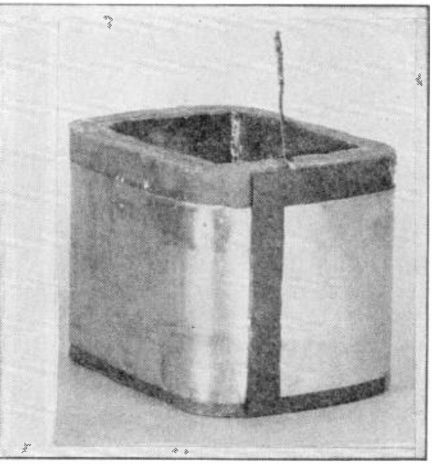


Fig. 20-14.—The shield with its ends insulated from each other.

The next step will be to cover the copper shield with insulating paper or cloth. Then we apply the secondary winding which is the high-voltage winding whose ends are to be connected to the plates of the rectifier tube, and whose center tap forms the most negative point of the d-c power supply system. The completed high-voltage winding is shown by Fig. 20-15.

The center-tap connection may be seen extending downward in front of the light-colored strip of tape. At the bottom, and on either side, are the leads from the start and finish of the secondary, these being the leads for the rectifier plates. Over toward the left may be seen the two leads for the primary winding, and at the back of the winding appears the lead which is attached to the electrostatic shield.

The high-voltage winding consists of 2,140 turns of number 33 gage plain enameled copper wire wound in 14 layers of about 153 turns each. It is not necessary to have exactly the same number of turns in each of the layers of any winding. Usually the number is about the same so that all layers will extend for approximately the same length of winding. In the transformer being examined, half of the total secondary turns are put into the first seven layers, and an extended length of the wire is left at the finish end. Then, commencing with another extended end, the remaining turns are put into the following seven layers. When the finish end of the first section is connected to the beginning of the second section, their connection forms the center tap for the entire winding.

Now for some information about how the primary and secondary windings operate together. In the primary we have 340 turns. To the ends of this primary will be applied the 117-volt potential difference of the power supply. Dividing 117 (volts) by 340 (turns) shows that the potential difference per turn of winding will be 0.344 volt. We shall assume, which is very nearly the case, that the same changes of magnetic flux (in the core) pass through both the primary and the secondary. Then the emf induced in each turn of the secondary will be equal to the potential difference in each turn of the primary, and, in the present example, will be 0.344 volt. There are 2,140 turns in the secondary winding. Multiplying 2,140 by 0.344 (volts per turn) shows that the total emf induced in the secondary will be about 736 volts.

The relations between primary voltage, secondary induced emf, and the numbers of turns in the two windings may be stated thus: The ratio of secondary emf to primary voltage is equal to the ratio of secondary turns to primary turns, or,

$$\frac{\text{secondary emf}}{\text{primary voltage}}\;\frac{\text{secondary turns}}{\text{primary turns}}$$

The secondary emf may be found from the following formula,

$$\begin{array}{c}\text{Secondary}\\ \text{emf, volts}\end{array} = \begin{array}{c}\text{primary}\\ \text{applied volts}\end{array} \times \frac{\text{secondary turns}}{\text{primary turns}}$$

This latter formula shows that we may determine the secondary emf by multiplying the number of volts applied to the primary by the ratio of secondary turns to primary turns. When there are more secondary turns than primary turns the secondary emf will be greater than the primary voltage, and we shall have what is called a *step-up* transformer. If there are fewer secondary than primary turns the secondary emf will be less than the primary voltage, and we have a *step-down* transformer.

The formula for required potential difference applied to the primary, or primary voltage, is as follows when we know the required secondary emf and the turns numbers.

$$\begin{array}{c}\text{Primary}\\ \text{applied volts}\end{array} = \begin{array}{c}\text{secondary}\\ \text{emf, volts}\end{array} \times \frac{\text{primary turns}}{\text{secondary turns}}$$

We cannot take more power out of a transformer than we put into it. In fact, we cannot take as much, because there are some losses of energy and power in the operation of any transformer. For the time being we shall neglect these losses, and then may say that the power in volt-amperes taken from the secondary or secondaries must be equalled by the power in volt-amperes put into the primary.

Let's consider our high-voltage secondary and the primary with reference to power. The two halves of the secondary work alternately on opposite half-cycles of their alternating potential; this because current flows first through one plate of the rectifier tube and then through the other plate. Each half of the winding is designed to deliver an output potential of 350 volts when the current is 90 milliamperes or 0.090 ampere. Volt-amperes are equal to the product of volts and amperes, and 350 times 0.090 equals 31.5 volt-amperes. Then, to supply energy for the high-voltage secondary, the primary must be supplied with 31.5 volt-amperes of power. To find the primary electron flow (current) we divide the primary volt-amperes (31.5) by the applied primary voltage (117), which shows the primary current to be 0.269 ampere.

Here we note that with a secondary emf greater than the primary voltage, the secondary current is less than the primary current. Whenever we step up the voltage, primary to secondary, we will get a step-down of electron flow, primary to secondary.

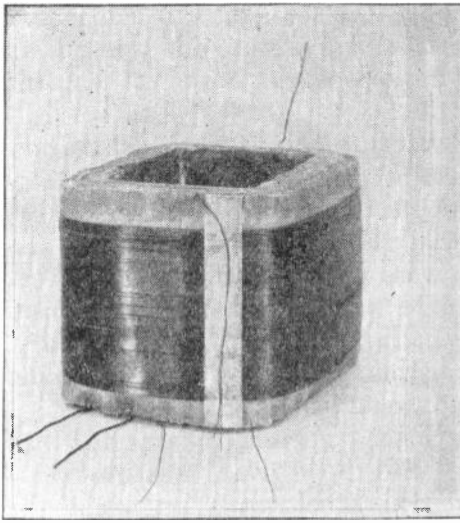


Fig. 20-15.—The completed high-voltage winding.

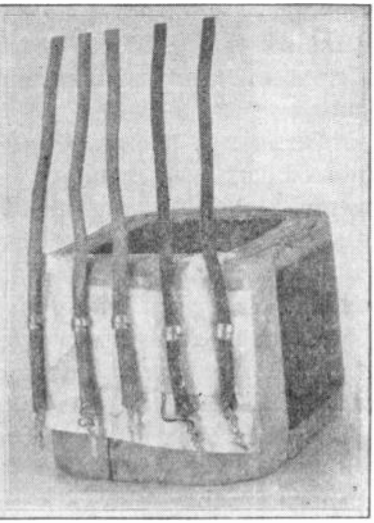


Fig. 20-16.—How the external leads for the high-voltage and primary windings are supported.

Only in this way will the primary and secondary volt-amperes remain equal. Were the secondary emf to be less than the primary voltage, the secondary current would be greater than the primary current.

Probably you have noticed that earlier we computed the total secondary emf to be about 736 volts, which would mean 368 volts across each half, then later said that each half is rated to deliver only 350 volts output. The difference, about 18 volts of emf, is used up in forcing the 90 milliamperes of current through half of the secondary winding. The great length of small wire in the secondary has considerable resistance in ohms, and it is in this resistance that we lose 18 volts of emf, leaving an output potential difference of 350 volts.

The actual voltage ratio of a transformer never is quite so great as the turns ratio, when we consider the secondary *output voltage* or terminal voltage. It is very nearly the same when we consider the total *emf* induced in the secondary. It is not quite the same because some of the flux lines produced by current in the primary pass through the space around the core and the windings, and do not pass through the secondary to induce emf in the secondary. There is some leakage of flux, and this has an effect similar to resistance in the secondary. The effect is called *leakage reactance.*

Now let's go back to the 18-volt difference between secondary induced emf and secondary terminal voltage when the secondary current is 90 milliamperes, which is the rated load current or the full-load current. Supposing that the secondary were open circuited, that one or both ends were disconnected from all other conductors so that there could be no current. With no current there would be no voltage drop in the resistance of the secondary. Then the open-circuit or no-load voltage of the secondary would be equal to the induced emf, and would be 368 volts.

The difference between the no-load voltage and the full-load voltage from the secondary is called the *regulation* of the transformer, or the voltage regulation. The regulation usually is specified as the ratio of the difference between no-load and full-load voltage to the voltage at full load. In the transformer we are discussing, the difference is 18 volts and the full-load voltage is 350. The ratio is 18/350 which is approximately 0.0514 when expressed as a decimal fraction. The regulation often is given as a percentage, which is equal to 100 times the fraction, and in our power transformer high-voltage secondary would be 5.14 per cent. When there is a large difference between no-load and full-load voltages we say that the transformer has *poor regulation,* and when there is a small difference we say that there is *good regulation.* Five per cent is entirely satisfactory regulation in a high-voltage winding for rectifier plates in a receiver d-c power supply.

Additional Secondary Windings.—Proceeding with the construction of the coil for our power transformer, the next step is to secure the ends of the rather small wires used for primary and high-voltage secondary windings, and attach to these small wires the relatively heavy leads that will come out of the transformer shell. The arrangement is illustrated by Fig. 20-16. Here, at the left, are the three heavy leads for the secondary winding; two leads for the start and finish of the winding, and one more for the center tap. These leads are covered with insulating sleeving colored red, which is the standard color for high-voltage secondaries. The lead for the center tap is identified by having part of the threads in the sleeve colored yellow, so the center tap lead is really red with a yellow tracer.

At the right are the two leads for the primary. They are covered with sleeving which is colored black; the standard color for primaries of power transformers. All of the leads are securely clipped to a piece of heavy fabric which is bound in place by the insulating wrappings.

After applying suitable insulating wrappings over the leads for the primary and high-voltage secondary we wind on the turns for the heater winding as shown by Fig. 20-17. This winding is designed to furnish a full-load current of 3.5 amperes at a potential difference of 6.3 volts when the current reaches the heaters in the various tubes. The winding consists of 20 turns of number 18 gage plain enameled copper wire. At the end of the tenth turn is attached a lead forming a center tap. Wire of the gage used here is so large and strong that the ends and the attached leads require no support other than provided by the insulating wrappings.

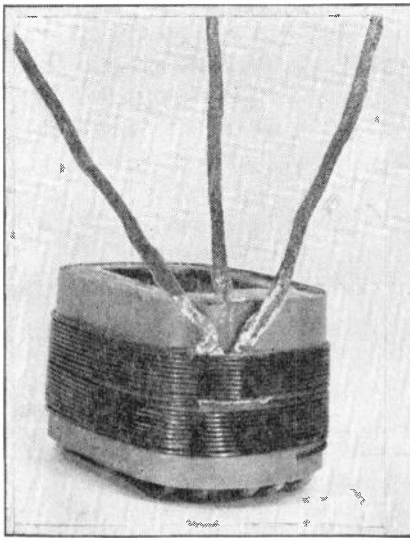


Fig. 20-17.—The center-tapped winding for the tube heaters.

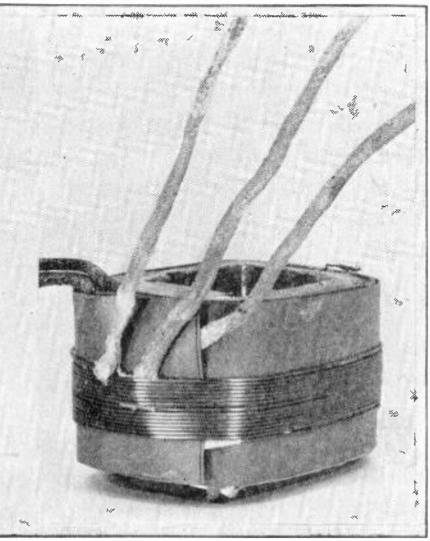


Fig. 20-18.—The center-tapped winding for the rectifier filament.

All of the secondary windings on the one transformer are subjected to the same changes of magnetic flux so far as this flux travels in the iron core. Consequently, we have the same volts per turn in all of the secondaries, and we may apply the earlier formulas showing relations between voltages and numbers of turns or turns ratios. In 20 turns of the heater winding, with 0.344 volts per turn, we will have a total emf of 6.88 volts. After the voltage drop in the winding and in the connections going from the winding to the tube heaters, we still will have at least 6.3 volts at the heaters themselves even when the total heater current is the rated value of 3.5 amperes.

For this winding we might use the formula for secondary emf in volts, inserting the known values of primary applied volts and numbers of primary and secondary turns as follows.

$$\begin{array}{c}\text{Secondary}\\ \text{emf, volts}\end{array} = 117 \times \frac{20}{340} = 6.88 \text{ volts}$$

We should keep in mind that the number of volts given by such formulas is the same as the induced emf, consequently is the same as the no-load voltage without allowance for voltage regulation which occurs when load current flows.

As in the cases of all the windings so far applied, we again apply a wrapping of insulation over the heater winding and then put on the winding for the rectifier filament as shown by Fig. 20-18. This is another center-tapped winding. It has a total of 16 turns of number 20 gage plain enameled copper wire, with the tap at the end of the eighth turn. This winding is rated to deliver a full-load of 3.0 amperes with a potential difference of 5.0 volts at the rectifier filament. Using the value of 0.344 volt per turn, and multiplying by 16 (turns), we find that the induced emf is about 5.5 volts. This would be the no-load potential difference, which would be dropped somewhat by the voltage lost in the resistance of the winding and its external connections when current flows.

Transformer Losses.—There are several causes for wastes or losses of energy and power in iron-core transformers. One loss already has been mentioned; the one incurred in forcing current to flow in the secondary winding against the resistance of this winding. There is a similar loss in the primary. The combined effect of these losses which occur in the conductors of the windings is called the *copper loss*. Measured in watts, the copper loss is equal to I^2R or to the square of the current in amperes multiplied by the winding resistance in ohms.

There is another loss due to production of eddy currents in the core iron. This loss is proportional to the square of the thickness of the laminations; so thin laminations reduce the eddy current loss. This loss is proportional also to the square of the frequency in cycles. Being proportional to the square of the frequency, the eddy current loss becomes so great at radio frequencies as to prohibit the use of ordinary laminated iron cores at such frequencies.

Still another loss that occurs in the core is caused by hysteresis; by the changing and reversal of magnetic flux in the core iron. Hysteresis loss increases directly with operating frequency, and increases also with flux density in the iron. The combined effect of the eddy current loss and the hysteresis loss is called the *iron loss*. All of the power used in overcoming the copper loss and the iron loss produces heat and acts to raise the operating temperature of the transformer as well as being a useless load on the line power supply connected to the primary.

All of the heat produced in the transformer must be dissipated into surrounding air and other materials. The temperature of the transformer will rise until it is far enough above the temperatures of surrounding materials to allow this rate of heat dissipation.

So far as the windings are concerned, heat is lost least readily from the primary, which is in between the core and all the secondaries, and is radiated most easily from the outer secondary which is the rectifier filament winding in our power transformer. If you look up the cross sectional areas in circular mils of the gage sizes of wire used in the several windings, and divide these areas by the currents in amperes, you will find the following values.

Primary winding	629 circ. mils per amp.
High-voltage secondary	557 circ. mils per amp.
Heater secondary	464 circ. mils per amp.
Rectifier filament secondary	341 circ. mils per amp.

In the primary, from which heat is hardest to get rid of, we use the greatest wire size per unit of current and consequently have the lowest rate of heat production due to resistance. Then, going outward from the core, we use smaller and smaller wire sizes or sections per unit of current until, in the outside winding for the rectifier filament we have the smallest wire section in proportion to current.

Power in Transformer Windings. — The power put into the transformer through its primary winding must equal the sum of the powers taken from all the secondaries, plus the power required to overcome all of the transformer losses. For the transformer which we have been examining, you can compute the volt-amperes of power for each secondary by multiplying together its rated output voltage and its rated full-load current in amperes. For the high-voltage secondary the volt-amperes are 31.50, for the heater secondary 22.05, and for the rectifier filament secondary 15.00. The sum of these secondary powers is 68.55 volt-amperes. At full load the primary will take from the line a power of about 75.15 volt-amperes. The difference between primary input power and secondary output power at full load is 6.60 volt-amperes, which is the power used in overcoming transformer losses.

The power efficiency of a transformer is the ratio of output power to input power. For the unit being examined this ratio is 68.55/75.15 (in volt-amperes) which is equal to the fraction 0.912. Changing this to a percentage shows that this transformer has a power efficiency of 91.2 per cent. The difference between this and 100 per cent, which is 8.8 per cent of the input power, is wasted in overcoming losses and goes into the production of heat.

When the primary winding of a transformer is connected to the a-c supply line, and when the secondary or secondaries are left open circuited and disconnected from all external circuits, only a small current from the supply line flows in the primary. The primary flow is only enough to maintain flux changes sufficient to produce a counter-emf equal to the supply voltage. That is, the primary flow increases only to a value at which the counter-emf induced in the primary balances the supply voltage. This primary flow, called *magnetizing current*, may be as little as 1/50 of the full-load flow in the primary.

When power is taken from a secondary winding there is a reduction in the density of the magnetic flux in the core. Then there is a smaller counter-emf in the primary and the primary current increases to a value that permits supplying the power being taken from the secondary winding. As mentioned before, there are copper losses in the secondary only while the secondary carries current. But there are copper losses in the primary during all of the time it is connected to the a-c supply, because then the primary is carrying current. Also, so long as the primary is connected to the supply line there are iron losses in the core because there is a varying magnetic flux. These losses which occur whenever the primary is "excited" must be compensated for by some small primary current in addition to the current that causes the counter-emf.

Full-wave Power Transformer. — The high-voltage secondary winding of the power transformer which has been examined is of the center-tapped variety designed for use with a full-wave rectifier tube. Electrons (current) flow through only one rectifier plate at one time, flowing alternately in the two plates during opposite half-cycles of the alternating potential. Consequently, only half of the high-voltage secondary carries current at one time.

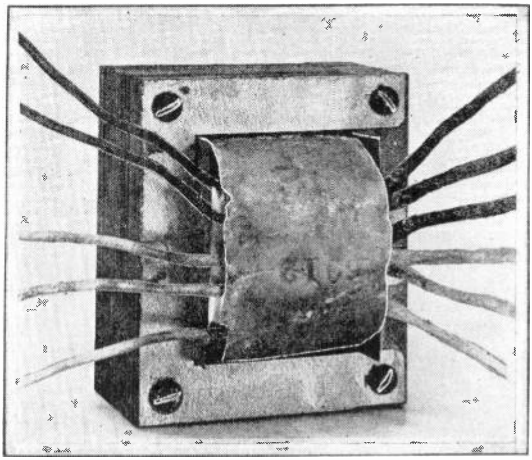


Fig. 20-19.—Here the core iron has been inserted into the completed coil.

Our high-voltage secondary winding would have a terminal potential difference of 700 volts across the entire winding. But with only half of the winding working at one time the actual effective output potential from the secondary is the potential across half of the winding, or is 350 volts. Then the transformer output, as applied to the rectifier, is 350 volts when the electron flow is 90 milliamperes.

When all of the windings have been built up to form the complete coil an outer insulating wrapping is applied, the entire coil is impregnated with insulating waxes and oils, and the core iron is inserted. Then we have the assembly shown by Fig. 20-19. This is a complete power transformer, and might be used just as pictured. However, for the sake of appearance and also to provide a certain amount of magnetic shielding, the exposed sides of the coil may be enclosed by steel shells or housings. When the housings are fastened to the core iron, with the leads brought through suitable openings, we have the completed unit as illustrated by Figs. 20-5 and 20-6.

Power Transformer Formulas.—There are four rather simple formulas which allow determining the terminal potential difference, the number of turns required, the required cross sectional area of the core iron, and the flux density in the core of small power transformers operated from single-phase power lines. All lighting lines in residences, offices, and most commercial establishments are single-phase.

The meanings of the letter symbols used in the formulas are,

E Terminal potential difference of the winding being considered, either primary or secondary. In effective or r-m-s a-c volts.

N Number of turns in the winding considered.

A Cross sectional area of portion of core on which windings are placed. This is the center leg of the transformer shown in preceding pictures. Area is in square inches.

B Flux density, in magnetic lines per square inch of cross sectional area of the core. This is the area defined for A above.

f Operating frequency, in cycles per second.

The four formula are,

$$E = \frac{N\,A\,B\,f}{22\ 500\ 000} \qquad N = \frac{22\ 500\ 000\ E}{A\,B\,f}$$

$$A = \frac{22\ 500\ 000\ E}{N\,B\,f} \qquad B = \frac{22\ 500\ 000\ E}{N\,A\,f}$$

Most small power transformers are worked with flux densities between 70,000 and 90,000 lines per square inch of core cross section. The unit which we have been examining is worked at a flux density of about 83,100 lines per square inch.

In the formulas for core area (A), number of turns (N), and flux density (B), the frequency term (f) is below the line. Then if the frequency is decreased, as from 60 to 50 or 25 cycles, and the potential difference and other values on the right are kept unchanged, it will be necessary to increase either the core area, the number of turns, or the flux density. That is, working out any of the formulas first for 60 cycle frequency and then for one of the lower frequencies, will give more area, more turns, or more flux density for the lower frequency than for the higher one. Any one, two or three of these factors may be increased. This is the reason that 50-cycle and 25-cycle transformers are larger than 60-cycle types of the same power and voltage rating.

If we use the formula for number of turns (N) and apply it to the primary winding we would have the following. The center leg of the core in our power transformer measures 1⅛ by 1-7/16 inches, which makes a cross sectional area of 1.617 square inches.

$$N = \frac{22\ 500\ 000 \times 117}{1.617 \times 83100 \times 60} = 326.5 \text{ turns}$$

This computed number of turns is smaller than the actual number, which is 340. The additional turns are required to care for iron and copper losses, and to insure the desired voltage regulation. If we apply the same formula to the high-voltage secondary winding the computation will indicate about 1,953 turns, while the actual number is 2,140. The additional secondary turns are required to maintain the desired voltage ratio which, primary to secondary, is 117/700. That is, when we add more turns than computed for the primary we have to add more on the secondaries to maintain the secondary voltages. While the formulas are basic, and are correct so far as they go, it is necessary to modify the results in the practice of transformer design.

Phase Relations in a Transformer. — Fig. 20-20 shows the simultaneous variations of the alternating potentials and currents in the primary and secondary windings of a transformer. Conditions in the primary are shown by the upper curves, and in the secondary by the lower curves.

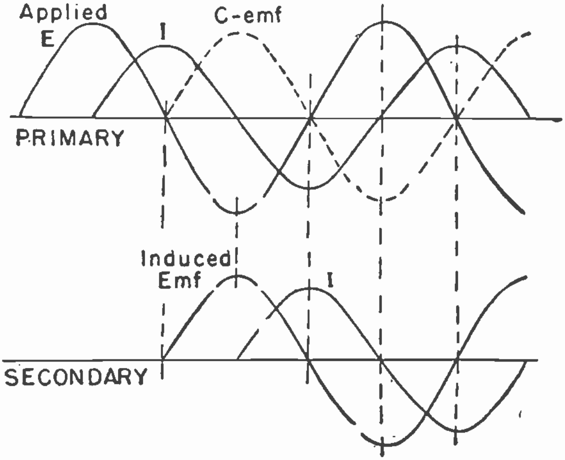


Fig. 20-20.—Phase relations in primary and secondary windings.

The upper full-line curve represents the alternating potential applied from the line to the primary. The counter-emf, represented by the broken line curve, is in opposite phase or is exactly 180 degrees out of phase with the applied potential. The primary current lags the applied potential by 90 degrees.

It is the changes of primary electron flow (current) that induce the emf in the secondary winding. As shown by the lower curve for induced emf, it is in opposite phase or is 180 degrees out of phase with the primary applied potential. The secondary flow lags the secondary induced emf by 90 degrees as shown by the lower curve *I*. Then the secondary flow is of opposite phase in relation to the primary flow shown by the upper curve *I*. Note these facts: At any one instant the primary and secondary voltages are in opposite phase, and the primary and secondary currents are in opposite phase.

Transformers in Series and in Parallel.—If certain precautions are observed the primaries or the secondaries, or both, of two or more transformers may be connected together in series or in parallel. In general, any two or more transformers so connected must have the same turns ratios, the same voltage ratings, the same impedances in their respective windings, and should have very nearly the same voltage regulation. In other words, the transformers should be practically identical with certain exceptions which we shall note.

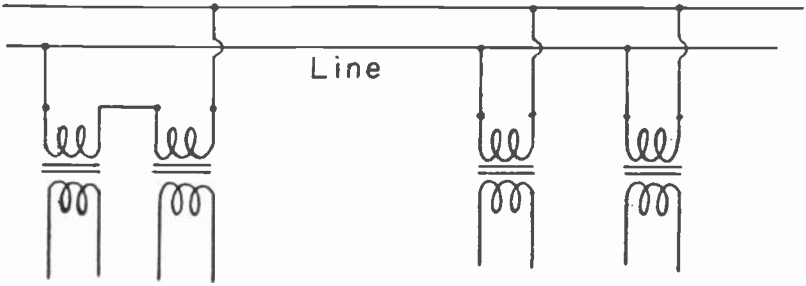


Fig. 20-21.—Primaries in series and in parallel on the line.

If the primaries of several transformers are connected in series across a supply line, as at the left in Fig. 20-21, the line voltage will divide between the primaries in proportion to the primary impedances. The effective impedances of the primaries vary with the loads on their respective secondary windings, consequently the division of voltage will vary with changes in loads. If the primary impedances are equal and the secondary loads are equal, the line voltage will divide equally. Thus two 115-volt transformers might be used in series on a 230-volt line.

The primaries of any number of transformers may be connected in parallel to the same supply line, as at the right in Fig. 20-21, provided the rated primary voltages are suited to the supply voltage. Each transformer operates independently of the others on the same line so long as line voltage remains reasonably constant. An overload on one transformer sometimes reduces line voltage and thereby affects the performance of the other transformers.

If the secondaries of two transformers, or if two secondaries of one transformer, are connected together in series as at the left in Fig. 20-22, the secondary voltages will combine. If the connections are such that the phases of potentials and currents are the same, or are in phase, for both windings the total voltage from the two will be the sum of the separate voltages. If the connections are such that the phases are opposite, as indicated in the right-hand diagram, the total voltage will be the difference between the separate voltages.

As an example, if two secondaries have output voltages of 100 and 50, and if they are series connected in phase, the total output will be at 150 volts. But if they are in opposite phase the total will be 100 minus 50, or will be 50 volts. It is easy to determine whether series windings are in phase or in opposite phase by measuring the combined output with a suitable a-c voltmeter. The connection which gives the higher output is the one with which the voltages are in phase.

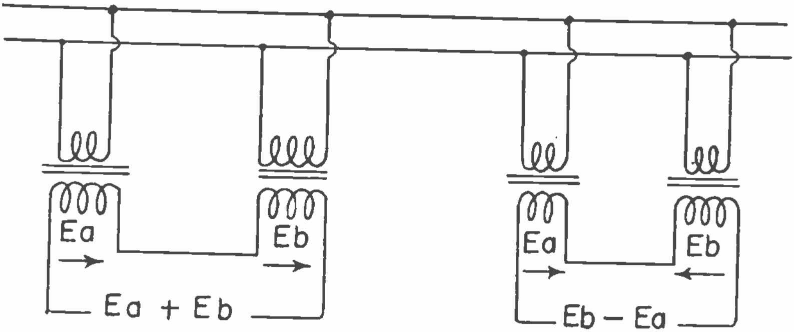


Fig. 20-22.—Secondaries in series with each other.

The same current flows in two windings connected together in series. Therefore, the total current must not exceed the current-carrying capacity of the winding having the smallest capacity. With series secondaries rated at something like 90 milliamperes for one and 200 milliamperes for the other, the maximum current must not exceed 90 milliamperes or else the winding of this capacity may be burned out. Windings of any different voltage ratings may be series connected so long as we do not exceed the current limit just mentioned.

Secondary windings connected together in parallel must have identical ratings for both voltage and current. Then the output from the group will be at the same voltage as that from one unit, and the current may be equal to the rated current of one unit times the number of units. Differences between voltages of secondaries in parallel would mean that the unit of higher voltage would force current through the one of lower voltage rating in addition to the current normally flowing in the latter unit, and it would be overloaded. If transformers have different current ratings, but equal voltage ratings, it means that when operated in series and with equal currents their voltages would be different. This is true because rated voltages are based on certain rated currents, as was explained in connection with the subject of voltage regulation.

Voltage Taps.—Sometimes a transformer is adapted for connection to any one of several different supply line voltages. This may be done by placing voltage taps on the primary winding as in the left-hand diagram of Fig. 20-23. The common lead always is connected to one side of the line, and one of the voltage taps to the other side. Assume that the line furnishes 110 volts, that we connect the tap marked *110*, and that the ratio of the number of primary turns thus connected across the line to the number of turns in the secondary winding gives the desired secondary voltage. If now we have to operate from a 120-volt line we connect the tap marked *120*. Then we have more active turns in the pri-

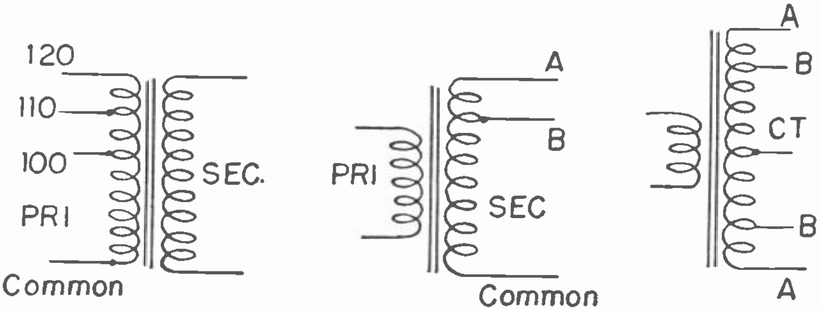


Fig. 20-23.—Voltage taps on primary and secondary windings.

mary, and the turns ratio of primary to secondary is changed so that the secondary voltage is the same for this 120-volt line as for the 110-volt line. Were the transformer connected to a 100-volt line we would use the tap marked *100*, which would reduce the number of active primary turns and change the turns ratio to again permit the same secondary voltage as before. Taps may be provided to suit any certain line voltages while maintaining the same secondary voltage or very nearly the same voltage.

A similar scheme may be used for a secondary winding, as in the center diagram. The common connection always is connected to the load. Because there are more secondary turns between the common and tap *A* than between the common and tap *B*, a connection to *A* will provide a higher secondary voltage than will one to *B*. Any number of such voltage taps may be provided. It is entirely possible to have in the same transformer various numbers of voltage taps on both primary and secondary windings.

If the secondary winding has a center tap, *CT* in the right-hand diagram, it is necessary to provide voltage taps equally spaced as to numbers of turns at both ends of the secondary. Then for a lower output voltage we would use the center tap and end taps *B* and *B*, while for a higher voltage we would use the center tap and end taps *A* and *A*.

Auto-transformers.—An auto-transformer is a type of transformer in which the primary and secondary windings form a continuous conductor and coil, and in which only a portion of the entire winding is used for one of the windings, with the entire winding used for the other winding. Auto-transformers

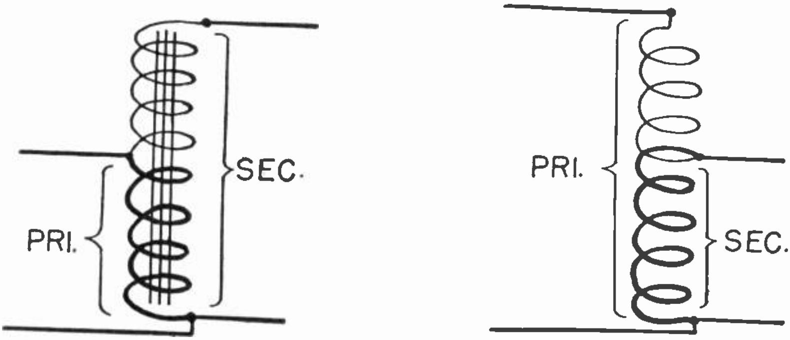


Fig. 20-24.—The principle of auto-transformers.

may be represented by the symbols in Fig. 20-24. In radio they are used chiefly for raising or lowering supply line voltages by small amounts so that apparatus of higher or lower voltage rating than the actual line voltage may be operated.

The left-hand diagram represents a step-up auto-transformer. Part of the winding is used as the primary and all of the winding as the secondary. Then there are more turns in the secondary than in the primary, and the secondary voltage is greater than the voltage applied to the primary. The right-hand diagram represents a step-down auto-transformer. Here the entire winding is used as the primary and only part of it as the secondary, so that there are more primary than secondary turns, and the secondary voltage is lower than that applied to the primary.

Both primary current and secondary current flow together in the portion of the coil which is used in both windings. Therefore, this portion usually is made of larger wire than the remainder, which carries only the primary current or only the secondary current.

Audio-frequency Transformers.—Audio-frequency transformers or audio transformers are indicated at positions *4* and *5* in the diagram of Fig. 20-1. They are iron-core transformers used for transferring alternating-current power at audio frequencies from tube to tube and from the final power tube or tubes to the loud speaker. Fig. 20-25 illustrates the appearance of one style

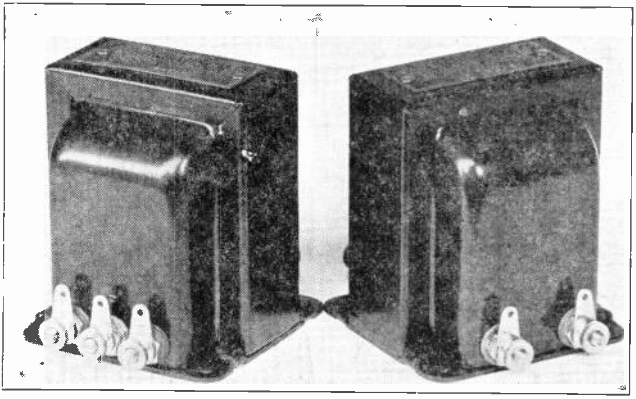


Fig. 20-25.—Audio-frequency transformers for a push-pull amplifier.

of audio transformers such as indicated in the circuit diagram mentioned above. On one side of the housing are three terminals; one for the center tap and two for the outer ends of one winding. On the other side are the two terminals for the other winding.

The cores of audio transformers are constructed similarly to the core of the power transformer which we examined earlier in this chapter. The laminations may be thinner for audio transformers than for power types, and sometimes are made from iron having greater permeability than used in power types. When a secondary winding of an audio transformer is to be connected in the grid circuit of an amplifying tube, the secondary carries practically no current (because any such current would be grid current) and as a consequence may be made of very small wire; usually of number 40 gage or even smaller. When the secondary winding is for connection to a loud speaker, as at position *5* of Fig. 20-1, the secondary carries a considerable current and is made with wire of suitably large size.

When the primary winding of an audio transformer is connected in the plate circuit of a tube, as shown by Fig. 20-26, this winding carries the entire plate current of the tube. The plate current consists of a steady d-c current which flows when the tube is handling no signal, and combined with this current is the alternating current which represents the audio signal. Thus the primary winding carries a direct current with an alternating or audio-frequency component.

It is only the changes of primary current that induce emf's in

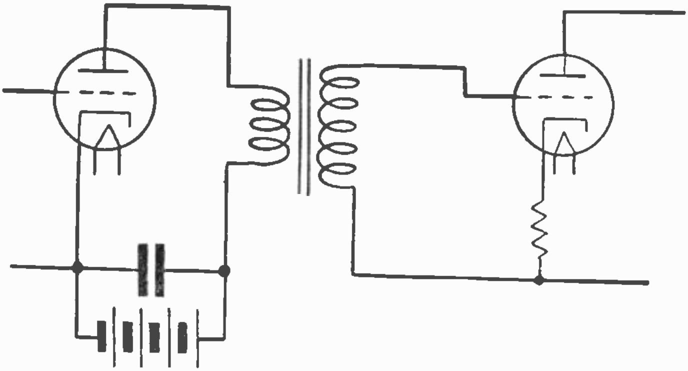


Fig. 20-26.—An audio transformer for coupling between amplifier tubes.

the secondary winding. A steady direct current undergoes no changes, and no matter how large such a current may be it induces no emf's in a secondary winding. In the audio transformer of Fig. 20-26, and in any transformer connected in a generally similar manner, the only emf's induced in the secondary are those corresponding to the audio-frequency signal variations of the primary current. The direct component of the primary current does not affect the secondary emf's so long as the direct component is not too great.

If the direct current in the primary is greater than the maximum value for which the transformer is designed and rated, this excessive current partially or wholly saturates the core iron. As an example, we might have a transformer whose core iron has a magnetization curve somewhat like that of Fig. 20-27. So long as the primary current does not exceed six to eight milliamperes the iron is worked on the steeply sloped part of the curve, and there are large changes of magnetic flux for all of the changes of current in the winding. But with greater currents we get onto

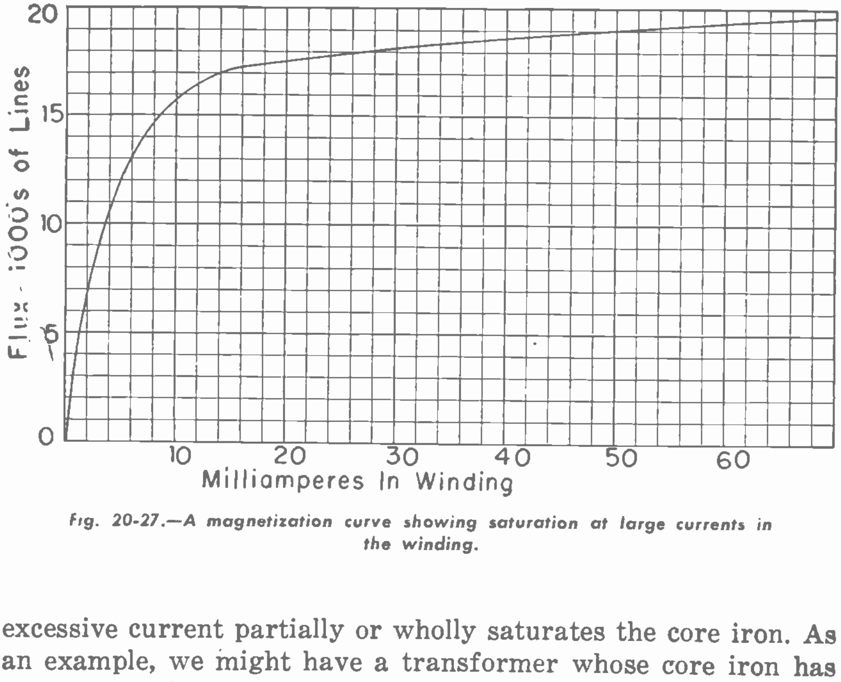


Fig. 20-27.—A magnetization curve showing saturation at large currents in the winding.

the knee of the curve, and then onto the flattened upper portion. Here we would find that changes of current in the winding produce very small changes of flux and, consequently, induce very small emf's in a secondary.

Audio-frequency transformers often are of the step-up type with which emf's induced in the secondary are greater by from two to six or more times than the a-f voltages applied to the primary. The transformer provides the only type of coupling between tubes with which there is an increase of signal voltage in the coupling as well as in the tubes.

Audio transformers are limited as to the lowest frequency with which there is uniform transfer of signal voltages; this being because the impedance of the primary winding decreases with lowering of frequency, and with reduced impedance the tube in whose plate circuit is the primary is not forced to work hard enough to have a good power output. These transformers are limited at the high audio frequencies by the distributed capacitances of the windings. These capacitances have lower and lower capacitive reactances as the frequency increases, and then tend to bypass part of the signal potentials so that they are not amplified.

Powdered Iron Cores.—It has been mentioned that energy and power losses in laminated iron cores are due to the formation of eddy currents and to magnetic hysteresis and the flux varies and reverses. These losses increase so rapidly with rise of frequency that laminated iron cores can be used efficiently at frequencies only somewhat higher than the high end of the audio range. Air-core transformers and coils used at radio- and intermediate-frequencies are not subject to these iron losses, but the inductance for a winding of given dimensions and number of turns is far less than were the same winding to be used with an iron core. A compromise may be effected by employing a core of finely divided particles or iron or of iron alloys with the particles insulated from one another.

For a given inductance with a winding having a powdered iron core the winding may be small compared to one for use with an air core. The smaller winding has smaller high-frequency losses than a larger one, and this, combined with the high inductance, makes a transformer or a coil having a relatively high Q-factor. These cores are used in both radio-frequency and intermediate-frequency transformers, also in choke coils or reactors designed for high-frequency service.

Intermediate-frequency transformers having molded iron cores often are tuned to resonance by moving the core into and out of the windings to vary the inductance while the capacitance remains constant, instead of having a constant inductance and a variable capacitance which is adjusted by means of a capacitor. In many transformers of this tunable type the tuning capacitance is provided by the distributed capacitance in the winding and in the connections, without the need for any added lumped capacitance in the form of a capacitor.

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