DESIGN, CONSTRUCTION
&
OPERATING PRINCIPLES

OF ELECTROMAGNETS FOR

ATTRACTING COPPER, ALUMINUM
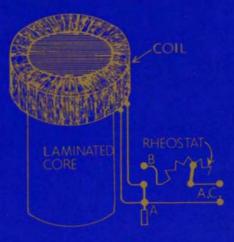# &
OTHER NON-FERROUS METALS

BY

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DESIGN, CONSTRUCTION & OPERATING PRINCIPLES OF ELECTROMAGNETS FOR ATTRACTING COPPER, ALUMINUM & OTHER NON-FERROUS METALS

by

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Disclaimer

Operation of the magnet described herein requires the use of 115 volts AC (Alternating Current) The voltages and currents used are **lethal.**

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PREFACE

Back in 1935 I gave a public lecture demonstration at the physics department of Illinois University in which I used an electrical training aid of my own design and construction to show that an electromagnet could be used to attract non ferromagnetic metals of good electrical conductivity.

In the following five years I devoted much thought, time, and effort to making various types, styles and sizes of electromagnets with which I could produce attraction of non ferrous-metals effectively.

Following is a description of, and basic fundamental operating principles pertaining to the type of electromagnet that I have found most effective for the attraction of non ferrous-metals.

Reprinter's note

I am very interested in communicating with
individuals and or companies that have in the past,
or are currently using this magnet technology.
Should you know of additional articles/books etc. or
individuals that have knowledge relating to this
subject matter please contact me at:

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ELECTROMAGNETS OF SPECIAL CONSTRUCTION FOR THE ATTRACTION OF NON-FERROMAGNETIC METALS

Magnetism is one of the most interesting and mysterious as well as one of the most important physical phenomena known. Through its action we generate and utilize the enormous quantities of electrical power which make possible modern industry and modern living. Many important principles of electromagnetism can be understood from the study of an electromagnet, invented and designed by the author, which attracts non-ferromagnetic metals.

Everyone has experimented with magnets and observed their attraction for iron filings, nails, and other small articles of iron and steel. Some of you will have seen large electromagnets attached to cranes pick up tons of scrap steel and move it about with ease. Tons of iron are held firmly to the magnet with an invisible force and are released by the flip of a switch. You have also observed that while iron is attracted with such force, other metals such as aluminum, copper, and silver are unaffected. This principle is often used to separate iron from non-ferrous metals. No doubt you have used a magnet to determine whether a nickel plated screw had an iron or brass base. You may also have noticed that if alternating current is applied
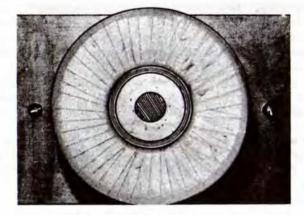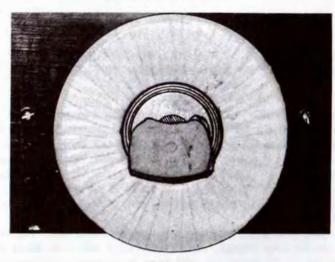

Figure 1

Figure 2

Figure 3

to an ordinary electromagnet, non-magnetic metals of good electrical conductivity will actually be repelled. In view of all of the above it will be most interesting to learn how magnetism can be used to attract non-ferromagnetic metals.

In 1934 the author designed equipment with which it was possible to demonstrate principles whereby non-ferromagnetic metals might be attracted by a special magnet. In 1940 the author completed the development and construction of an electromagnet which would actually attract metals such as aluminum, copper and silver. In fact the magnet would attract any metal of fair or good electrical conductivity. Toward the end of 1947 the author completed the design and construction of a much improved electromagnet for the attraction of non-ferrous metals, the details and description of which are included in this article. The special electromagnet is illustrated in Figure 1. In Figure 2 the magnet, with its axis horizontal, is shown supporting a heavy piece of copper. In Figure 3 two pieces of aluminum have been added to the original piece of copper. Figure 4 shows the magnet supporting two silver dollars. The size of the magnet is illustrated by comparison with the silver dollars. That the magnet may also be used to attract iron is indicated clearly in Figure 5.

Before considering the details of construction and principles of operation of the special electromagnet, let us review some of the basic principles of magnetism and electromagnetism.
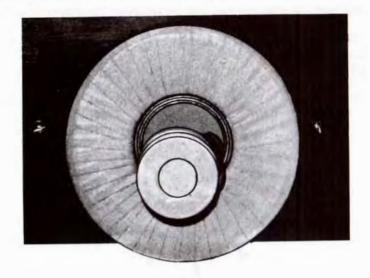
We will not only observe that non-ferromagnetic metals can be attracted to an electromagnet but will also gain the pleasure of understanding its principles of action.

Oersted in 1819 was the first to show that a current carrying wire was surrounded by a magnetic field. He discovered that a compass needle aligns itself at right angles to a wire carrying
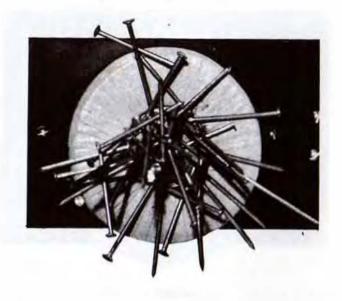

Figure 4

Figure 5

an electric current. Thus it is known that in a circuit similar to that in Figure 6, there will be a magnetic field about the wire in the direction shown. The current direction is in accordance
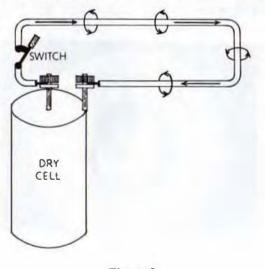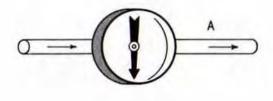

Figure 6

with the conventional explanation that current flow is from positive to negative.

If a compass is placed above the wire it will point in the direction shown in Figure 7-A, pointing at right angles to the current carrying conductor. The compass needle will point in the direction that the flux lines are moving. If the current is reversed as in Figure 7-B the compass will point in the opposite direction as shown and we know the flux lines have reversed their direction.
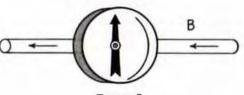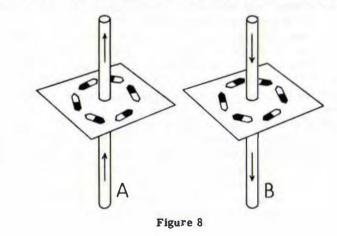

Figure 7

If we place a number of magnetic needles or compasses about a current carrying conductor in the manner shown in Figure 8 the compass needles will point in the directions illustrated.

Figure 8

This indicates very clearly that the magnetic lines of force are directed in a circular path around the conductor and that their direction reverses with a reversal of current in the conductor.

To determine the direction of the flux lines we grasp the conductor in the right hand with the thumb pointing in the direction of the current. Then the fingers encircle the wire in the direction of the flux lines (see Figure 9). This is known as the Right Hand Rule.

CONDUCTOR →

THUMB POINTED IN DIRECTION OF CURRENT
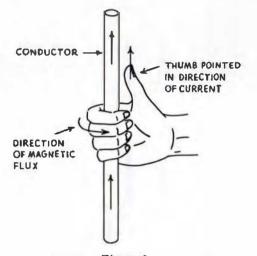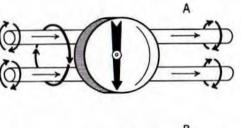
DIRECTION OF MAGNETIC FLUX

Figure 9

Now let two parallel wires carrying current in the same direction be placed near each other as in Figure 10. The compass will point in the direction shown in Figure 10-A if placed above either wire and will also point in the same direction if shifted to any position above the two wires. However, it will reverse its direction when placed underneath either or both of the wires (Figure 10-B). Thus we conclude that flux lines encircle each wire and also that there are lines extending around or encircling both wires.

We can now deduce two important properties of flux lines. It is to be observed by experiment that parallel wires such as those illustrated in Figure 11 are attracted by the magnetic action of the two currents flowing in the same direction. This attraction can be explained by saying that the lines of flux are under tension like stretched rubber bands, that is, they tend to shorten. Those lines which encircle both wires will, then, tend
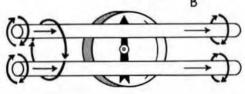
A

B

Figure 10

to pull the wires together. Note that the flux lines <u>between</u> the wires are opposite in direction. We may also say that in a region such as the space between the wires where the lines of flux are in opposite directions, there is attraction between the conductors.

Now let the two parallel wires carry currents in opposite directions as in Figure 12. The flux lines about No. 1 conductor
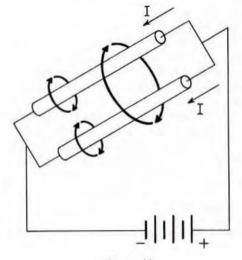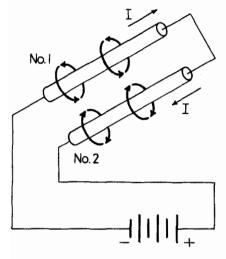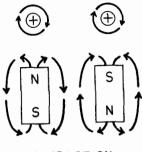

I

I

Figure 11

Figure 12

will be opposite to the flux lines about No. 2 conductor and there are no flux lines encircling both conductors. The two conductors will repel each other. Thus we see that flux lines which travel in the same direction, as in the space between the wires, produce repulsion.

From the foregoing we see that such non-ferromagnetic metals as copper conductors can be moved about in magnetic fields because of the magnetic lines of force that are produced by currents flowing in the conductors (metals) themselves. This does not, necessarily, indicate that it is possible to magnetize non-ferromagnetic metals (such as copper or aluminum) in the manner that we do a piece of steel or other ferromagnetic metal; however, it is quite interesting to note the striking similarity of attraction and repulsion as shown by Figures 13 and 14.

In Figure 13, by the use of conventional symbols, two conductors are shown carrying current. The circles with a plus (+) at their centers represent the cross section of two conductors carrying current away from the observer. The direction of the magnetic flux about the conductors is also shown in relation to the direction of current flow. Just below the two conductors are two permanent magnets with an indication of the direction of flux lines of each magnet in relation to its' polarity. Note the similarity in the direction of the flux lines between the
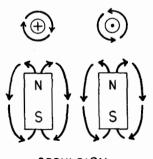
ATTRACTION

Figure 13

magnets and between the conductors carrying current. It is shown in the drawing and can easily be demonstrated that there is attraction between the two copper (non-ferrous) conductors when the flux lines between them are in opposite directions; likewise, there is attraction between the two pieces of steel (permanent magnets) when the flux lines between them are in opposite directions.

In Figure 14, illustration is made of the same two conductors and permanent magnets except here the current in the right hand conductor is represented as flowing toward the observer, such designation being a dot (·) at the center of the circle (conductor). Also, it is to be noted that the right hand permanent magnet has its polarity reversed to that of Figure 13. Here the magnetic lines of force between the two conductors are in the same direction thereby producing repulsion between the two copper
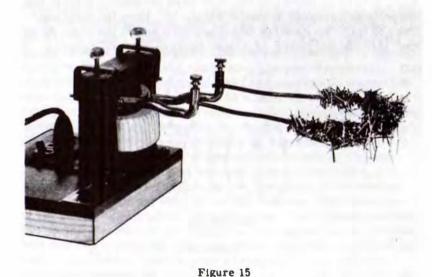

REPULSION

Figure 14

(non-ferrous) conductors. Likewise the magnetic lines of force between the two permanent magnets are in the same direction and <u>repulsion</u> is produced between the two (ferrous) steel magnets.

From the foregoing illustrations we see that magnetic lines of force flowing in opposite directions between current carrying conductors or between magnets (between non-ferrous or between ferrous metals) produce attraction. And that magnetic lines of force flowing in the same direction between current carrying conductors or between magnets (between non-ferrous or between ferrous metals) produce repulsion.

The magnetic force about a current carrying conductor is quite small unless a very large current is set up in it. In order to produce quite striking demonstrations to further illustrate basic laws of magnetism and their relation to and association with electrical currents we shall utilize a conveniently arranged electrical training aid as an efficient and inexpensive means of supplying a very large current to a single conductor at a low voltage and low power consumption.

This device (shown in Figure 15) is a specially designed dissectible transformer. The two turn secondary provides a current source of more than 400 amperes at less than 3 volts potential and when short circuited by the single copper loop (U conductor), provides the conductor with an extremely heavy current.

Figure 15

This U conductor when carrying a current of approximately 400 amperes can be used to produce (with small power consumption) some striking experiments to illustrate important basic magnetic phenomena.

Figure 15 illustrates how a current of 400 amperes will produce a very strong magnetic field about a conductor. In fact, the magnetic field about the conductor in this instance is so great that a layman might easily mistake the conductor for a magnet. Although it does actually look like the copper conductor has become a magnet, we know, of course, that the small nails are magnetized by the strong magnetic field produced as a result of the large current flow through the copper (U) wire.
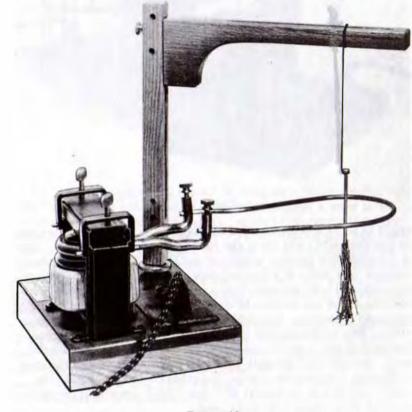

Figure 16

To further illustrate the effect of the magnetic field produced by the current flow through this U loop conductor, Figure 16 shows a large nail suspended within and at the center of the loop. The large current flow through the loop conductor produces a magnetic field about the loop which magnetizes the large nail. Visual proof that the large nail is magnetized is shown by the fact that it attracts and holds in suspension a large number of small nails.

To proceed a step further, we shall now study Figure 17. Here a few large nails are shown within the loop of copper wire
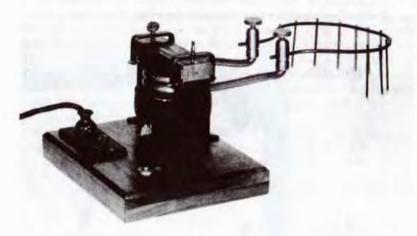

Figure 17

and it is to be noted that all these nails have become magnetized by the magnetic field about the current carrying conductor. Each of the nails has become a magnet and they all repel each other because like poles of a magnet repel. These nail magnets have the same polarity because they are all on the same side of the conductor and are subject to lines of force that are flowing in the same direction. Although the current flowing through the copper loop is alternating it nevertheless produces a magnetic flux that at any instant is in the same direction through all the nails. As the field strength and polarity of any one nail changes, it likewise changes through all the others. Consequently, the nails have like polarities at all times which results in repulsion between them since like poles repel.

Let us assume that the magnetic flux for a given alternation is flowing downward on the inside of the copper loop conductor.

As the magnetic flux circles about the conductor it will flow upward on the outside of the loop. Therefore, a nail placed on the outside of the loop will have the opposite polarity to one on the inside and attraction will result between a nail on the outside and one on the inside since unlike poles attract. Figure 18 shows this very clearly where several nails on the inside of the loop cling to the nails on the outside of the loop.
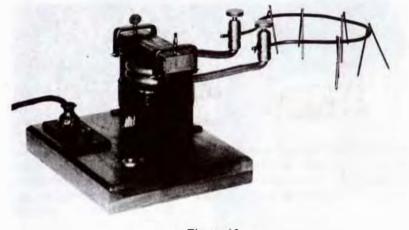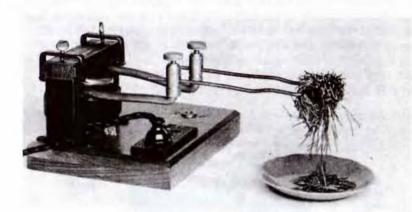

Figure 18

As has previously been stated the magnetic force about a current carrying conductor is quite small unless a very large current is made to flow through it. In order to concentrate the action and increase the force, the wire may be formed into several turns as shown in Figure 19. Here there are three turns forming the coil (helix) thereby concentrating the magnetic lines of force along several inches of the conductor into a small space, which shows how the magnetic strength produced by a given current flow can be concentrated.

It is a well established fact that the magnetic force (strength) of a coil is directly proportional to the ampere turns of the coil. To find the ampere turns of a coil it is necessary to multiply the number of turns in the coil by the current flow, in amperes, through the coil. For example, a coil of 100 turns carrying 10 amperes is equivalent to a coil of 10 turns carrying 100 amperes, assuming of course that all other factors could be made equal in each coil.

The magnetic force between two parallel conductors may be

Figure 19

augmented by concentrating the magnetic field and thereby increasing the force by forming the conductors into coils as shown in Figure 20. Here there would be many flux lines linking both coils and thus pulling them together so long as the currents
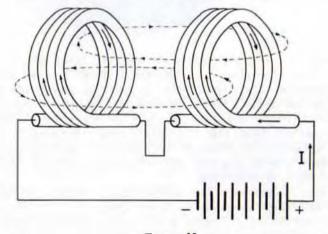

Figure 20

through both coils were in the same direction. If the leads to one of the coils were reversed thereby reversing the direction of current flow through that coil, the two coils would repel each other.

A very striking demonstration of the attractive and repulsive forces produced by the magnetic fields of two coils is illustrated by Figures 21 and 22. In Figure 21-A two coils are shown suspended and separated a considerable distance before current was
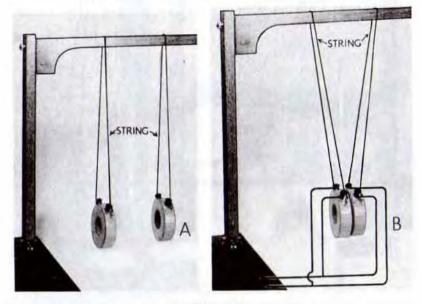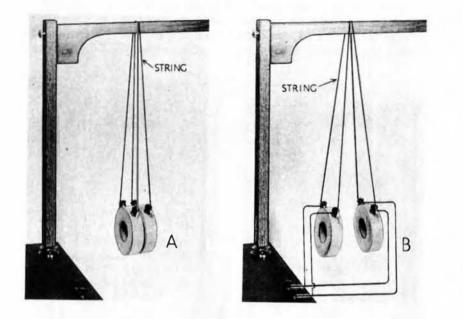

Figure 21

made to flow through them. A current flow through the two coils in the same direction caused the attractive force to be so great that the coils jumped together through several inches as shown in Figure 21-B.

By suspending the two coils so that they touched each other before passing current through them, they were as shown in Figure 22-A. But as soon as current was made to flow through the two coils in opposite directions they repelled each other in the manner shown in Figure 22-B.

In order to concentrate and utilize effectively the magnetic lines of force that are produced by a current flow through a conductor, for most applications it is advisable to use ferromagnetic metals such as steel to conduct the flux, because air is a very poor conductor of magnetism and ferromagnetic metals such as steel are exceptionally good magnetic conductors. That is, air offers a high reluctance while ferromagnetic metals offer

Figure 22

low reluctance. How a ferromagnetic metal may be used to illustrate this fact is clearly shown by the use of the soft steel cores shown in Figures 23 and 24.

The foregoing experiments should be sufficient to give a very clear picture of how magnetic flux is produced by current flow
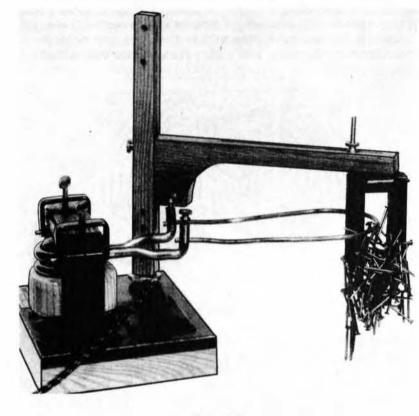

Figure 23

Figure 24

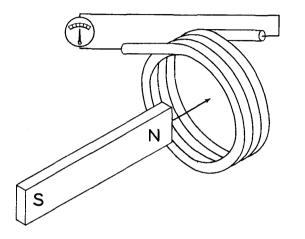and something of the relation of the flux to the current flow.

The discussion thus far has been concerned with the mechanical force produced by magnetism. We must also study the effect of magnetism in inducing a voltage or current if we are to understand the attraction of non-magnetic metals by the special electromagnet.

After Oersted discovered the magnetic field about a conductor carrying current in 1819, many experimenters attempted to produce the inverse effect. That is, they tried to produce a current by means of a magnetic field. All were unsuccessful until Faraday's historic experiments in 1831. Faraday showed that a current, or more correctly an electromotive force, was induced when the amount of flux threading a coil was changing,

but that no voltage was induced by a steady magnetic field re-
gardless of how strong it might be made. Let us consider a few
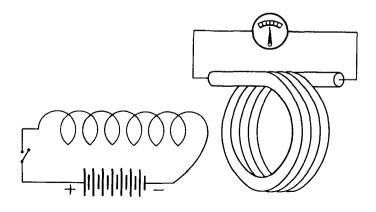simple experiments concerning induced electromotive force.

Let the bar magnet of Figure 25 be thrust quickly into the
coil. The d-c voltmeter with a zero center scale will deflect

Figure 25

momentarily either to the right or left depending upon the po-
larity of the connections. Let us say it deflects to the right.
Next, if the magnet is withdrawn quickly the voltmeter will de-
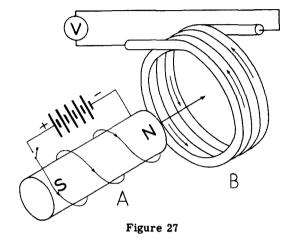flect momentarily to the left.

Now let the bar magnet be replaced by a coil or solenoid and
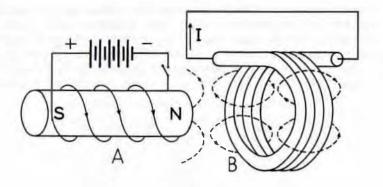a battery as in Figure 26. Upon closing the battery circuit the

Figure 26

voltmeter will show a deflection, and will deflect in the opposite
direction upon opening the circuit. The magnitude of the voltage
induced with the arrangement of Figure 26 would be quite small.
However, the magnitude of the induced voltage can be greatly
increased by inserting a laminated iron core in the solenoid as
in Figure 27. The introduction of an airon core causes a great

Figure 27

deal more flux to be set up in coil B for a given current in the
coil A, thus increasing the induced voltage. We say the iron
carries flux more readily than air because it has a higher per-
meability.

Let us consider the direction of the induced electromotive
force in Figure 27. Upon closing the switch, current will flow
in the direction of the arrows on the solenoid winding and thus
produce a north pole at the right hand end of the iron core. Now
we must use a law discovered by Lenz in 1834 which is called
Lenz' Law. The law may be stated as follows: Any induced
electromotive force tends to set up a current in such a direction
as to oppose the action which produced the electromotive force.
Thus, upon closing the switch in Figure 27, a current would be
induced in coil B in the direction indicated because such a cur-
rent would set up a magnetic flux which opposes the flux set up
by a north pole at the right hand end of the electromagnet core.
Figure 28 shows that coil B will be repelled since flux lines in
the same direction repel. We might also consider that the cur-
rent in coil A is producing a north pole at the left side of coil B
which is repelled by the adjacent north pole of coil A. Upon
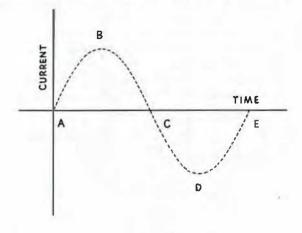opening the switch, the current in coil A would be reversed

Figure 28

(decreasing). According to Lenz' law, the induced current in coil B would set up a magnetic flux which would tend to prevent the decrease of the existing flux. Under this condition, the flux in coil B would be reversed, and coil B would be attracted toward the electromagnet A. Figures 26 and 27 show turns of wire having voltages induced in them because of a changing current in the solenoid. It is evident that a conducting non-ferromagnetic washer would behave in a similar manner.

You recall that for direct current, induced voltages and currents appear only during switching operations and that there is no induced voltage during steady current flow regardless of how strong the fields may be. However, the author's special electromagnet utilizes alternating current, and if we are to understand the operation of the electromagnet we must consider a few of the characteristics of alternating current.

As you already know alternating current has the property of reversing its direction of flow many times a second. For the usual 60 cycle current it flows in one direction for 1/120th of a second, and then in the opposite direction for the next 1/120th second. However, it does not change abruptly from say 10 amperes in one direction to 10 amperes in the other direction. This would require a very rapid change in current at the reversals and consequently induce high voltages. Instead it changes in the gradual manner illustrated in Figure 29. This curve is called a sine wave and represents many natural motions as well as alternating current. For example, it represents the velocity-time relation of a weight suspended from a spring and set into oscillation. Considering alternating current, the point A
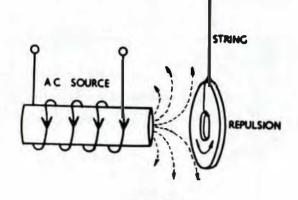
Figure 29

represents zero current, but the current is increasing. In fact, it is increasing most rapidly at this point of the wave. The point B represents maximum current, but the current has stopped increasing. Beyond point B the current decreases. At point C the current is zero and decreasing most rapidly. From C to D and E the effect is repeated but in the opposite direction. Thus we see that with alternating currents, the current is changing continuously except at the peaks of the wave, that is, except at points like B and D. Since changing current produces changing flux, and changing flux produces induced voltages and current in conductors linked by the changing flux, then alternating currents produce similar alternating induced electromotive forces.
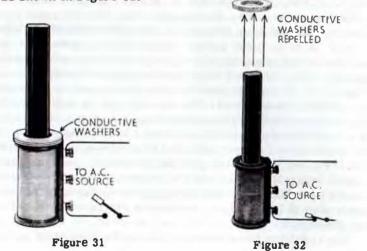
Now let us consider an iron core solenoid connected to an alternating current source with a non-ferromagnetic conducting washer (short circuited secondary) suspended before it as in Figure 30. At some instant the solenoid current is increasing in the direction indicated. The direction of the induced current in the washer will be as indicated because an induced voltage is always in the opposite direction to the inducing voltage. Thus the washer will be repelled from the electromagnet because the flux lines produced by the current flow in the washer produces a north pole adjacent the end of the electromagnet nearest the washer, and the current flow through the electromagnet produces a north pole adjacent the face of the washer nearest the electromagnet.

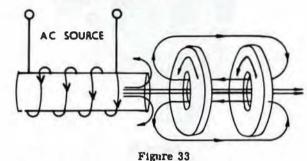The repulsive force exerted between the field of an a.c.

Figure 30

electromagnet and the field of a short circuited secondary (washer) is strikingly shown by a study of Figures 31 and 32. Figure 31 shows an electromagnet and with a means provided for connecting it to a source of alternating current. The electromagnet has an extended core over which are placed three aluminum washers resting on the end of the magnet coil (primary winding). When the magnet winding is energized by the alternating current the magnetic field produced by the coil winding and that set up by the (secondary) aluminum washer current produce repulsion and the washers are thrown violently into the air, as shown in Figure 32.

Figure 31

Figure 32

Let two washers be placed near the end of the electromagnet as in Figure 33. Some of the flux from the electromagnet will thread or cut through both of the washers, and at a particular instant currents in the two washers and in the electromagnet winding will have the directions indicated. Here we have one of the most important operating principles of the special electromagnet for attracting non-magnetic metals.

Figure 33

Compare the situation of the currents in the two washers of Figure 33 with the currents in the two coils of Figures 20 and 21. The currents are flowing in the same direction and as indicated in Figure 33, there will be flux lines linking the two washers which will tend to pull them together. However, since the force of repulsion between the a.c. electromagnet and both washers is very strong it is difficult to show by the arrangement of Figure 33 that there is an attraction between the two washers. If the currents in the two washers were sufficiently large the washers would be pulled together with considerable force. The hole in either washer is immaterial since flux passes through non-ferromagnetic materials just as it does through air.

With this fundamental principle in mind, (that there is attraction between the two washers of Figure 33), let us now consider the construction and fields of the special electromagnet which will attract non-ferrous materials. The electromagnet is shown diagramatically in Figure 34. The few turns shown represent the entire winding of the electromagnet. Figure 35 is a cross section of the inner and outer laminated iron cores which extend the entire axial length of the electromagnet. Figure 36 shows the inner core and the group of copper washers which partially fill the annular space between the inner and outer cores. These copper washers occupy this space in only the face end of the magnet. The top washer shows clearly in the photograph of Figure 1. The complete electromagnet is

LAMINATED CYLINDRICAL CORE

COPPER WASHERS

AC WINDING
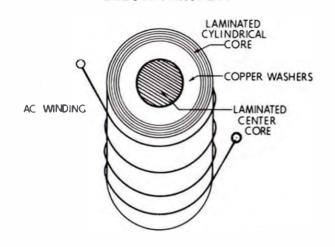
LAMINATED CENTER CORE

Figure 34

mounted on a supporting stand for convenience in demonstrating its unique ability to attract non-ferromagnetic metals.

We now know the construction of the electromagnet and have studied the essential magnetic theory involved in its operation.
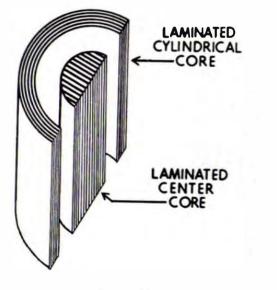

LAMINATED CYLINDRICAL CORE

LAMINATED CENTER CORE

Figure 35

LAMINATED CENTER CORE

COPPER WASHERS

Figure 36
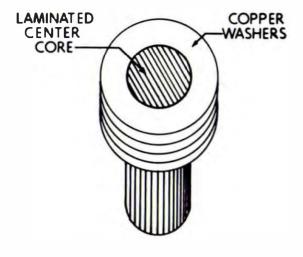
With this information it will not be difficult to explain its performance.

Figure 37 is a cross section of the magnet with the four copper washers removed. The circles at the top and bottom represent the winding. The dots and crosses indicate that current is directed out of the paper above and into the paper below at the instant considered. We know from the right hand rule that
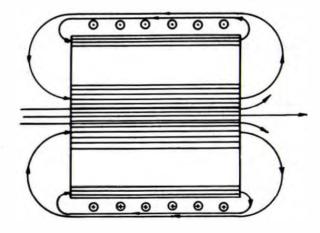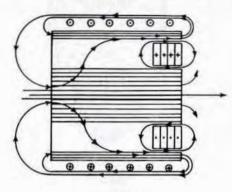

Figure 37

the flux lines are directed toward the right within the coil. We also know that practically all of the flux is concentrated in the iron because of its high relative permeability.

Now let the copper washers be replaced as indicated in the cross section of Figure 38. Again let us consider an instant when the alternating current is increasing and directed out of

Figure 38

the paper above as indicated by the dots. Referring to the theory presented in connection with Figures 25, 26, and 27, we know that the induced currents in the copper washers will be directed in the opposite direction to those in the coil as indicated by the dots in the lower half of the washers. Lenz' law states that the current in the washers will produce a flux which will oppose the flux produced by the primary. Thus the current in the washers produces a flux directed toward the left through the center of the washers. Note that the action of the induced current in the washers is such that the flux it produces tends to crowd the flux out of the center core and into the outer core.

Now let a piece of copper be brought near the face of the magnet as shown in Figure 39. The flux lines passing through the piece of copper will induce a voltage which will cause a current in the piece of copper in the same direction as the current in the copper washers of the electromagnet. This current will cause the piece of copper to be attracted to the copper washers just as the two wires were attracted in Figure 11, the two coils in Figure 20, the two coils in Figure 21-B, and the two washers in Figure 33.

The currents in the washers and in the piece of copper produce magnetic flux lines threading both the washers and piece of copper. These flux lines tend to act as stretched rubber bands
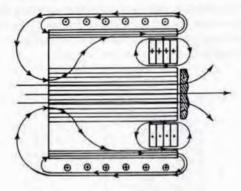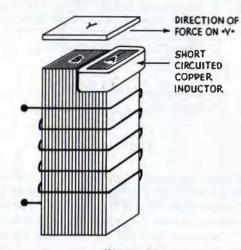
Figure 39

pulling the two parts together. The alternating current in the copper washers is sufficiently large that the copper piece is pulled forcibly against the face of the magnet. Additional conductive pieces are attracted, but with decreasing force. Each added piece will have less induced current than the preceding one and will thus be attracted less forcibly toward the copper washers. However, the electro-magnet shown is powerful enough to readily support two silver dollars or several discs of aluminum.

In this type of electromagnet there is another force involved which is of interest and importance. This force is one concerned with the effect produced by a traveling magnetic field. By this we simply mean that due to the particular construction of this electromagnet there are two magnetic flux fields produced at the end of the magnet. The first of these is the field produced by the primary coil which is a sinusoidal varying field set up by the primary current. The second is a field in the central core which lags the first field by a few degrees (less than one half cycle). The interaction of the two fields over the face of the magnet produces a magnetic field which appears to move from the outer core of the magnet in toward the central core. The traveling magnetic field is utilized in this electromagnet in a manner which produces strong centering action in the mass being attracted by the magnet.

The traveling magnetic field is produced in this electromagnet in exactly the same manner as in many commercial single-phase induction motors. These motors are called "shaded pole" motors and the principle involved is called the "shaded pole"

principle. The shaded pole provides the rotating field required to start the rotor of the single-phase induction motor. To explain what is meant by a "shaded pole" let us study the electromagnet of Figure 40.
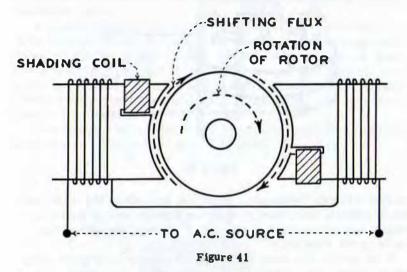

Figure 40

Here we have a laminated core electromagnet in which a short circuited copper ring is embedded in the pole face. The portion of the pole face inside the short circuited turn is said to be shaded, while that portion external to it is unshaded. So the pole itself is called a "shaded pole" and the short circuited turn (conductor) is known as the "shading coil."

With alternating current in the primary winding, there is an alternating magnetic field in the unshaded portion of the pole which is in time phase with the alternating current producing it. The magnetic field in the shaded portion of the pole lags the above mentioned field due to the action of the "shading coil." Let us assume that at a given instant, the flux in the unshaded portion is a certain value and increasing. The flux in the shaded portion due to the primary coil is that same value, but in the shaded portion the flux set up by the current induced in the "shading coil" is in the opposite direction (Lenz' Law) so the net flux is some smaller value. This would mean that given values of flux would occur first in the unshaded portion of the pole and at a slightly later time, in the shaded portion of the pole. Hence, the appearance of a shifting or moving magnetic field results. The direction of the shifting flux is across the

pole face from the unshaded portion toward the shaded portion.

Figure 41 is a schematic drawing of a shaded pole motor. Here we see the direction of the shifting flux and the direction of rotation of the rotor. Note that the flux shifts in a direction

Figure 41

from the unshaded toward the shaded portion of either motor pole. It is a well established fact that a conductor in a rotating magnetic field will have a force exerted on it tending to make the conductor follow the rotating field. Therefore, the force on the conductors in the rotor face cause it to move from the unshaded toward the shaded pole section as illustrated in Figure 41.

From the foregoing explanations it is obvious that the copper conductor (Y) of Figure 40 will have a force exerted on it that will move it in the direction indicated toward the shaded portion of the pole.

If a three legged core as shown in Figure 42 is wound with a coil and excited by a source of alternating current the three pole pieces will all become (N) north poles at some instantaneous value of the impressed voltage which will result in repulsion between the flux lines as illustrated. The flux of the two outer poles will tend to repel the flux lines of the center pole to crowd them toward the center and the flux from the center pole will tend to repel the flux of the two outer poles. Here now we have exactly the condition existing in the authors special electromagnet except that in the electromagnet the two outer poles are
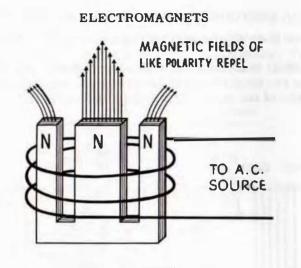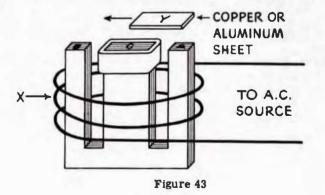
MAGNETIC FIELDS OF
LIKE POLARITY REPEL

TO A.C.
SOURCE

Figure 42

formed into one continuous cylindrical pole about the inner pole.
But in addition the center pole of the authors special electro-
magnet has a short circuited (copper washer) secondary sur-
rounding the pole end.

If we modify the three legged electromagnet of Figure 42 by
adding a short circuited copper secondary on the center core
leg the modified electromagnet will look like Figure 43. This
device will therefore become a compound shaded pole electro-
magnet. In this electromagnet a (second secondary) tertiary
piece of copper Y will have a force exerted on it in the direction
shown if it is placed over poles A and C but will have a force
exerted on it in the opposite direction if placed over poles B

← COPPER OR
ALUMINUM
SHEET

TO A.C.
SOURCE

Figure 43

and C. This means that the tertiary Y will have forces exerted
on it from poles A and B which will cause a strong centering
action of the tertiary over pole C. Here again we have the same
condition in the authors special electromagnet, except that poles
A and B are formed into one continuous (cylindrical) pole about
the center pole.

A graphic illustration of the existence of the travelling mag-
netic field produced by the special electromagnet is illustrated
by an actual photograph (Figure 44). Here two aluminum balls
are placed upon the face of the electromagnet and with the pri-
mary current turned on the aluminum balls rotate very rapidly.
The curved arrow above each ball indicates the direction of ro-
tation of the ball.

Several interesting things are to be noted about the attractive
properties of this special electromagnet. The mass to be
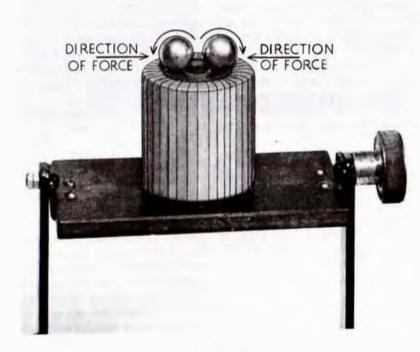

DIRECTION
OF FORCE

DIRECTION
OF FORCE

Figure 44

attracted may be subject to a repulsive force from the primary field and therefore should be of a size not larger than the space within the cylindrical pole. Since the current in the primary winding is generally opposite to the current in the mass to be attracted, that mass should be of a general size and shape to lie within the cylindrical pole piece boundary and should not extend over into the influence of the primary coil.

When the circumference of the mass to be attracted is larger than the circumference of the cylindrical pole, the repulsive force exerted upon it by the primary winding increases very rapidly with an increase in its size. The non-ferrous mass is also repelled if it is approximately of the same peripheral dimensions as the inside dimension of the cylindrical core but is not closely adjacent thereto. The object to be attracted should be adapted to the field and should generally be placed fairly close to the magnet unless it is quite a bit smaller than the inside dimension of the cylindrical pole face. It is possible to make the conductive mass to be attracted "jump" a considerable distance to affix itself to the attractor by having the non-ferrous mass of considerably smaller diameter than the cylindrical core.

By experimenting with armatures of different sizes suspended at various distances from the attractor face it has been found that a region or zone of attraction exists which is conical in shape. A conductive object placed with its principal conducting path within this cone is attracted. The base of this cone
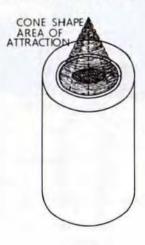

CONE SHAPE
AREA OF
ATTRACTION

Figure 45

substantially coincides with the face of the attractor and has its vertex on the axis at a distance from the attractor as illustrated in Figure 45.

Figure 46 shows a silver half dollar suspended near the attractor face. In this figure the half dollar is suspended so as to have its plane perpendicular to the plane of the attractor face
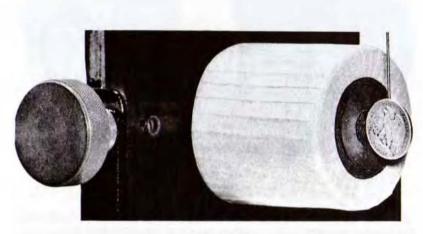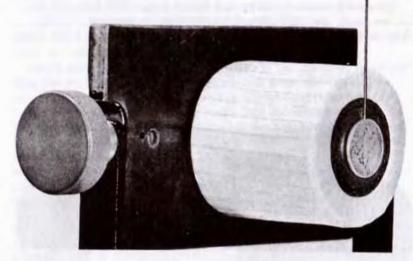

Figure 46

before the magnet is energized. But the instant current flows through the primary winding of the electromagnet the half dollar turns so that its plane is parallel with the plane of the attractor face as shown in Figure 47 and is attracted with considerable force. This result is exactly opposite to the result to be expected if the silver dollar were placed in the field of an ordinary alternating current electromagnet. If the attractor in this special electromagnet were not present to exercise its influence, the coin would then turn with its plane perpendicular to the plane of the electromagnet face.

If a non-ferrous ring, washer, or disc with a plane dimension considerably in excess of the cylindrical pole face dimension is placed near the face of this special electromagnet, then the object is out in the influence of the primary coil and, as in the case of a conventional electromagnet, the object would be repelled.

Figure 47

In Figure 48 a large aluminum disc is suspended in front of the electromagnet with its plane parallel with the attractor face before the electromagnet winding is energized with current. But the instant that current flows through the electromagnet's primary winding the large disc is repelled with great force and finally comes to rest with its plane perpendicular to the face of the electromagnet (see Figure 49) and remains in this position as long as the current continues to flow through the primary winding of the electromagnet.

It is altogether possible to modify the secondary (attractor) element by substituting a winding in place of the copper washers. Such an arrangement is shown by Figure 50.

Here a means is provided for short circuiting the secondary coil by closing the switch to position A as illustrated. By this arrangement the switch may be closed, causing the short circuited winding to act like the copper washers, producing attraction of a non-ferrous mass when used in conjunction with the primary winding and cylindrical core. Then the switch may be opened causing the non-ferrous mass to be repelled since the only flux lines now produced by the electromagnet are those
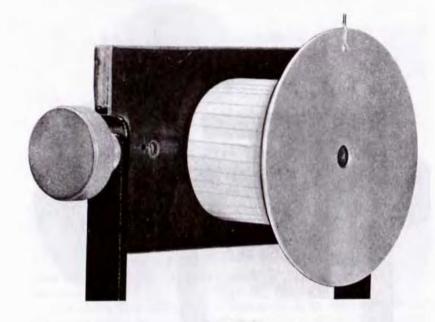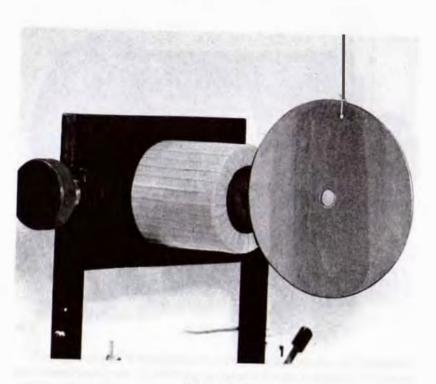
Figure 48

produced by the primary. By the arrangement shown in this figure the switch may be closed to position B thereby connecting the winding to the same alternating current source to which the primary winding is connected but in a manner so as to oppose the primary winding. By this means attraction of the non-ferrous mass can also be accomplished. This arrangement in which the secondary (attractor) is connected so as to be in phase opposition to the primary is inferior to the form in which the secondary (attractor) has current induced in it. The reason for this is to be attributed to the fact that the current induced in the mass to be attracted (tertiary) is not exactly opposite in phase to the primary current and therefore will not be exactly in phase with the current in the secondary where the secondary is fed in exact opposition to the primary. When current in the secondary is induced, it is more nearly exactly in phase with the current in the armature which results in maximum attraction.

In the instance where the primary and secondary (attractor)

Figure 49

are connected in phase opposition to the same alternating current source, the secondary (attractor) circuit may be modified so as to afford some phase lag. An arrangement for this modification is shown in Figure 50 where a resistor may be connected in series with the attractor winding by closing the switch to position B. This circuit can be connected in parallel opposition with the primary and by adjustment of the variable rheostat, a fairly comparable phase lag may be produced. However, this form of construction (even with a resistor) in which the secondary (attractor) is connected in phase opposition to the primary is inferior to the form in which the secondary has current induced in it.

The arrangement shown in Figure 50 has some advantages for educational demonstrations even though it is not as efficient as the copper washer type. The switching system allows a much greater flexibility in its use since the equipment may be
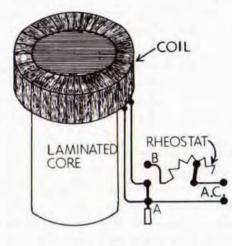
Figure 50

used both as a special electromagnet for non-ferrous materials and as a conventional electromagnet.

Due to the fact that this electromagnet is an open core device its power factor is not unity. This results in rather large power consumption and in heating of the winding although the heating may be reduced considerably by using very large wire. For large electromagnets of this kind it may be necessary to provide means for circulating a cooling medium through both primary and secondary. Hollow copper tubing could be used in the construction of extremely large electromagnets of this type. Generally speaking, capacitors may be used in correcting the power factor of this type electromagnet thereby relieving the power supply line of much of its wattless current burden and thus helping to keep the electromagnet primary winding cool.

Figure 51 is a graph showing amount of power factor correction that was obtained with static capacitors of 100 microfarads used in conjuction with one of the authors' electromagnets for the attraction of non-ferrous metals.

Table I shows the change in current, line voltage, power factor, and phase angle obtained through the use of static capacitors in conjunction with the electromagnet. The electromagnet and capacitors were those used to obtain the graph shown in Figure 51. In order to correct the power factor by use of static capacitors the capacitors are, of course, shunted across the input terminals of the primary winding of the electromagnet.
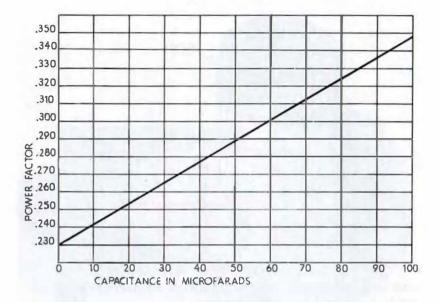
Figure 51

Table I

CAPACITORS USED FOR POWER FACTOR CORRECTION

Capacitance in Mfd.	Line I	Line E	Power Factor P E.I.	Phase Angle
0	16.5	110	.230	77°
50	13.8	110	.289	72° 58'
100	11.5	110	.348	69° 42'

An electromagnet for attraction of non-ferrous metals such as has been described cannot be made effective for the attraction of small pieces of non-ferrous metals when used on a low frequency power source. In order to use this type electromagnet for the attraction of small particles or pieces of non-ferrous metals, it is necessary that it be designed and constructed for operation on a supply of high frequency current. The frequency required will depend on the size of the pieces or particles to be attracted.