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EDUCATIONAL COURSE

PAMPHLET E-4

ELEMENTARY ELECTRICITY

ELECTROMAGNETISM

OFFICE OF
SUPERINTENDENT OF TELEGRAPH
PHILADELPHIA

PAMPHLET E-4

ELEMENTARY ELECTRICITY

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Figs. 19, 20, 21, 23 and 25 are from cuts furnished by the Cutler-Hammer Manufacturing Company.
Figs, 29 and 30 are from "Elements of Electrical Engineering" by Franklin and Esty.

ELECTROMAGNETISM.

1. DISCOVERY AND DEVELOPMENT.—The existence of both magnetism and electricity was known, and the phenomena of both had been studied for many years, before it was thought that there was any relation between the two. However, about 1820, it was discovered that an electric current flowing in a wire affected a neighboring compass needle, and in 1821 that steel needles surrounded by coils of wire carrying current became magnetized. In 1825 the final great discovery was made; namely, that a core of soft iron, surrounded by coils of insulated copper wire, could be made to act not only as a powerful magnet, but as a magnet whose power could be turned on or off at will, and increased or diminished by control of the current in the coils. Since that time, the study of electricity and magnetism has advanced steadily. Laws and rules have been found by means of which electrical and magnetic calculations can be made, and units have been chosen for the measurement of the forces and quantities involved. While there is still much that is mysterious and not easily explained in regard to electromagnetism, so much is known that the performance of a given electromagnet can be predicted, or, in other words, electromagnets can be designed to do definite work and have definite characteristics.

MAGNETIC EFFECTS OF THE ELECTRIC CURRENT.

2. GENERAL STATEMENT.—There is magnetism present wherever an electric current flows. In Pamphlet E-3 it was shown that every magnet has a *magnetic field* about it, in which its *lines of force* are distributed. In a similar way, *every electric current sets up a magnetic field and creates lines of magnetic force.* Every wire or conductor carrying current is surrounded by its own magnetic field, and when a number of such wires are brought close together a resultant field is produced, as when the fields of two ordinary magnets overlap. (See Figs. 4 and 5, Pamphlet E-3.)

3. FIELD ABOUT A STRAIGHT WIRE.—The magnetic field about a straight wire carrying current is circular; that is, the lines of force may be pictured as a series of concentric circles with the wire as a center. A magnetic spectrum or diagram may be made to show this field. A wire is run vertically through a horizontal sheet of cardboard on which iron filings are sprinkled. When current is sent through the wire and the cardboard lightly tapped, the filings arrange themselves in circles as shown in Fig. 1.

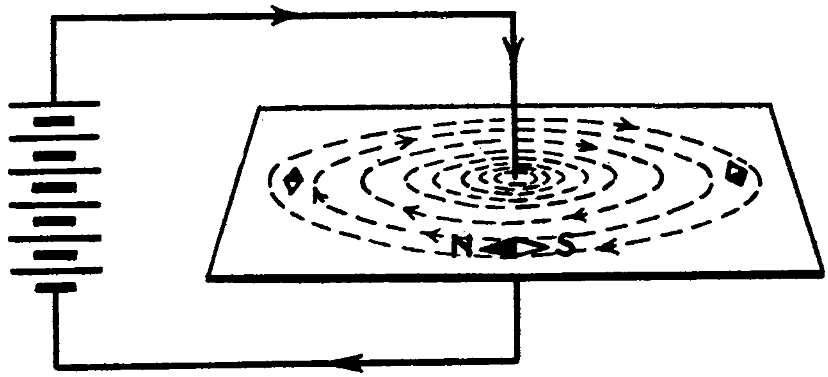

Fig. 1.

If now a pocket compass is brought near the wire, the needle will set itself tangent to the circular lines of force, or at a right angle to a line through its pivot and the center of the wire. It will be found that reversing the current in the wire will cause the compass needle to turn end for end. This is due to the fact that the direction of the magnetic field or lines of force is changed. Fig. 2 illustrates this point. The

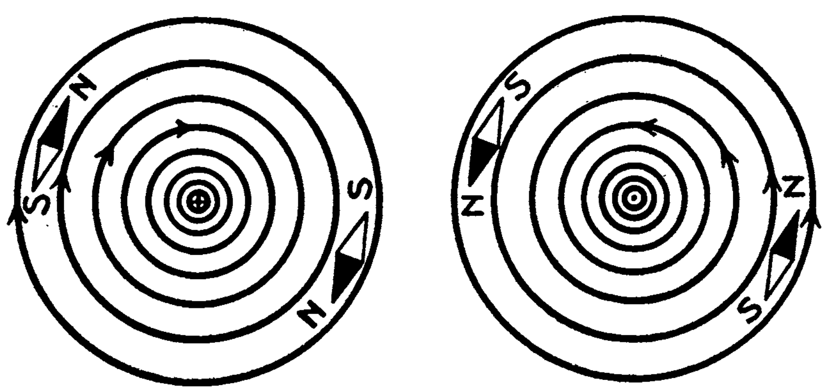

Fig. 2.

left-hand diagram represents conditions when current flows down the wire, or into the page, and the right-hand diagram represents conditions when current flows up the wire, or out of the page. The symbol ⊙ indicates that current is flowing toward the reader, or out of the page, and is the head-on view of an arrow moving in the direction of current. The symbol ⊕ indicates that current is flowing away from the reader, or into the page, and is the rear view of an arrow moving in the direction of current.

A simple rule may be used to aid in remembering the relation of current and direction of magnetic field; namely, *the direction of the magnetic field bears the same relation to the direction of the current as the rotation of an ordinary right-hand screw bears to its lengthwise movement.* Fig. 3 illustrates this rule.

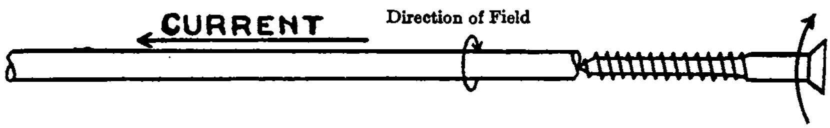

Fig. 3.

4. DIRECTION OF FIELD OR LINES OF FORCE.—In the study of Magnetism, lines of magnetic force were assumed to have direction; that is, they were said to issue from a north pole of a magnet and enter the magnet again only at a south pole. The direction of a magnetic field may be defined in another way, thus: *The positive direction of a magnetic field is the direction in which a free north pole would move along a line of force.* A free north pole, that is, one entirely separate from a corresponding south pole, does not actually exist, but can readily be imagined or assumed for purposes of study and investigation. This definition may be applied in all cases, both in magnetism and electromagnetism, whether considering magnets with definite north and south poles, or magnetic fields where poles are not present; as, for instance, the field about a straight wire as described in Section 3.

5. FIELD ABOUT A STRAIGHT WIRE (Continued).—In Section 3 the deflection of compass needles or magnets in the magnetic field around a straight wire was discussed for a particular case; namely, when the compass needle swung on an axis parallel to the wire. If the distribution of the field about a wire, as before described, is kept in mind, the effect of that field on a compass needle or other magnet in various positions can be predicted. Suppose, for example, that a compass is placed on a table, and a horizontal wire is run directly over it in a North and South direction. With no current flowing, the compass needle will be parallel to the wire. If, now, current is sent through the wire from South to North, application of the rule from Section 3 will show that the direction of the field under the wire is from East to West. Therefore, the north pole of the compass magnet will turn toward the West, and the south pole toward the East. Reversal of the current will reverse the field and, therefore, cause a deflection of the needle in the opposite direction, with the north pole toward the East. Evidently, if the compass is placed above the wire, the deflections will be opposite to those produced

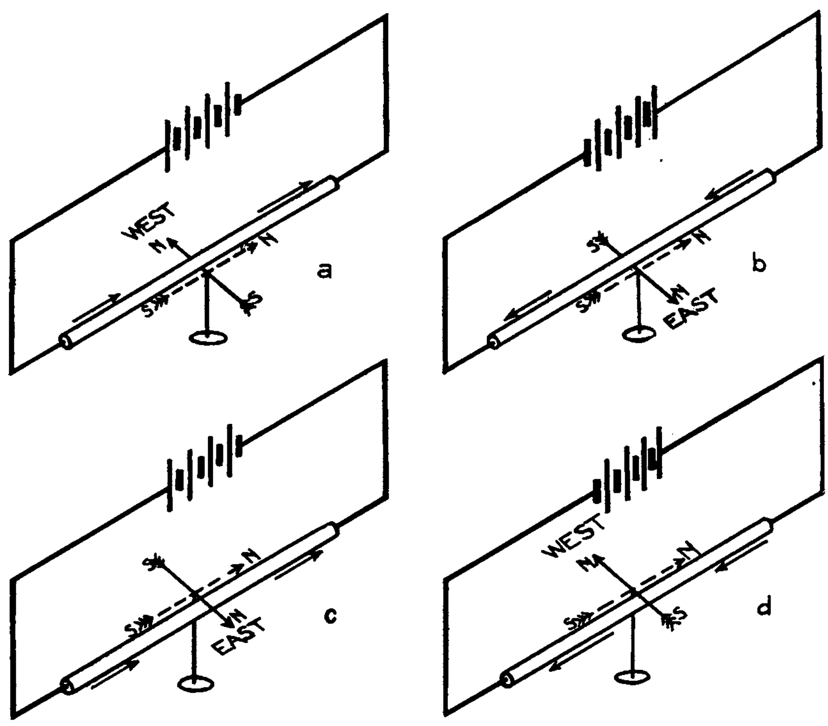

Fig. 4.

when it is below. If the wire and compass are placed side by side the needle will not be deflected. The force of the magnetic field about the wire in this case tends to tilt it vertically on the pivot, as a little thought should make clear. Fig. 4 illustrates the deflection produced in the various cases mentioned above, the dotted lines showing the position of the compass needle with no current flowing.

Wherever a compass is used to explore a magnetic field, there are two forces acting on the magnetic needle: one due to the earth's magnetic field, and the other due to the field which is being explored, and the position of the needle is determined by the direction of the resultant field due to the overlapping of the two fields. The great majority of electromagnets produce fields which near their poles are so strong that the effect of the earth's field on an exploring compass needle is inappreciable. There are, however, certain electrical instruments in which the earth's magnetic field is made use of as a controlling force.

From the previous explanations of the effect of the field about a current-carrying wire, on a pivoted magnet, it becomes evident that a magnet or compass needle can be used to determine; first, whether or not current is flowing in a wire; and second, the direction of such current as is found to exist. If current is flowing, a compass set on the wire will have its needle deflected toward a position at right angles to the wire, and the direction of the current can be determined by consideration of the direction in which the north pole of the needle is moved, and by application of the "screw rule" illustrated in Fig. 3.

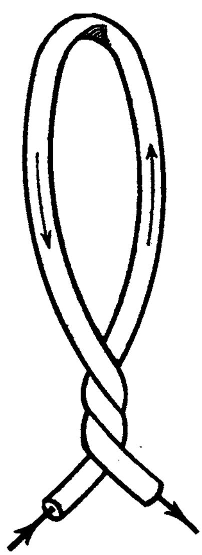

Fig. 5 (a).

6. FIELD ABOUT A LOOP.—The magnetic field surrounding a loop of wire will next be considered.

The loop of insulated wire in Fig. 5 (a) has current flowing through it in the direction shown by the arrows. Suppose this loop were run through a glass plate: ⊕ indicates where the wire and the current go down through the plate and ⊙ indicates where the wire and current come up out of the plate. The field which results is shown in Fig. 5 (b), and a spectrum could be obtained by the use of iron filings as before.

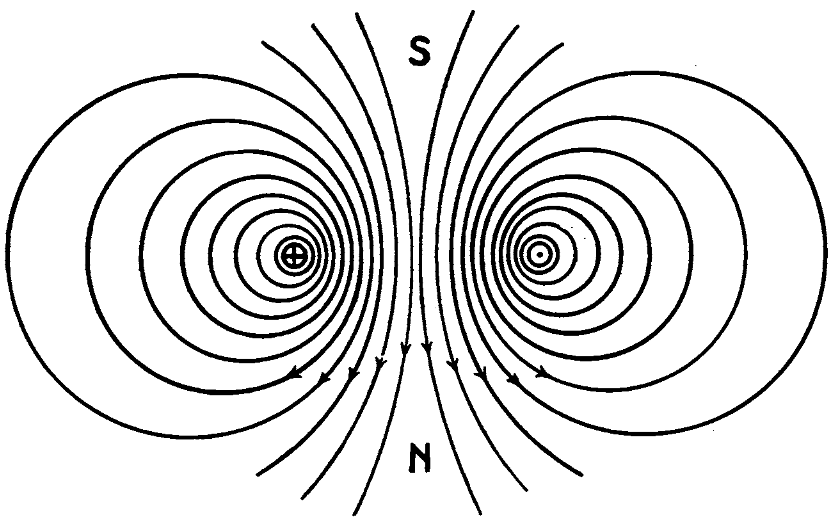

Fig. 5 (b).

The side from which the lines of force issue is called the north or N face of the loop, and the side where they enter the loop is called the south or S face; and the loop will, in fact, act in every respect as if it were a short magnet, circular in cross-section. It will repel or attract other magnets, depending upon whether the face which is presented to them is of the same or opposite polarity.

7. FIELD OF A SOLENOID.—Suppose several of these loops of wire are placed face to face in line; or better, a helical coil of insulated wire wound as shown in Fig. 6. Coils of this type are known as *solenoids*.

When current passes through this coil, a magnetic field is set up about each loop, and these fields combined produce a resultant field with lines of force distributed as shown in Fig. 7, which is a sectional view of a coil similar to that shown in Fig. 6.

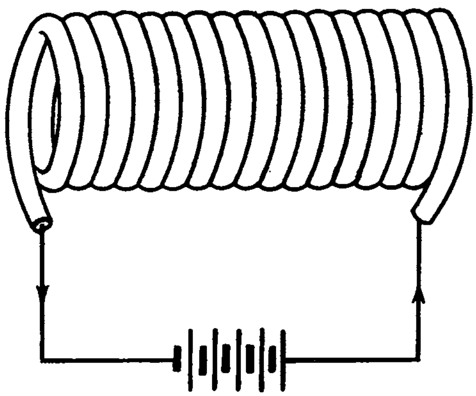

Fig. 6.

A comparison of this diagram with one showing the field of a bar magnet will show that the two are practically the same. The lines of force pass inside the solenoid from one end to the other just as they go through the magnet from pole to pole, and the circuit is completed through the air in the same way.

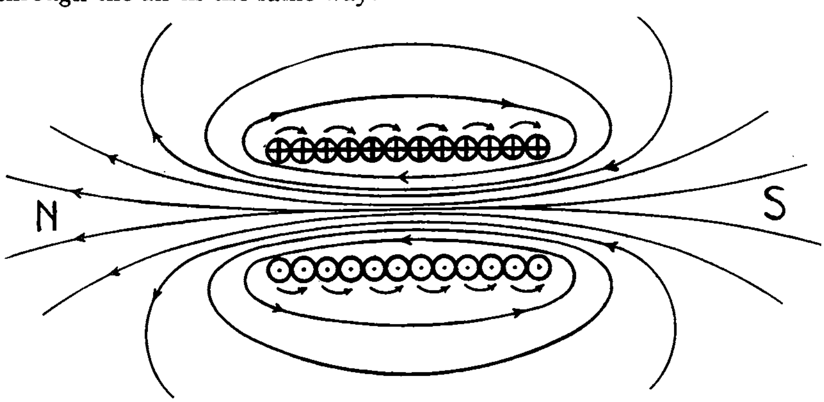

Fig. 7.

8. POLARITY OF A LOOP OR SOLENOID.—The face of a loop or the end of a solenoid where the lines of magnetic force pass out is a *north pole*, and oppositely, the face of the loop or end of the solenoid where the lines enter is a *south pole*. As in the case of a straight wire, the direction of the field depends on the direction of the current. A convenient rule for determining the polarity is as follows: *Curve the* **RIGHT** *hand around the outside of the loop, keeping the palm toward its axis, so that the direction of the flow of current is from the wrist to the tips of the fingers; then the outstretched thumb will point along the positive direction of the lines within the loop; that is, toward the end or face of north polarity.* The face from which the lines of force issue is, therefore, on the same side of the hand as the thumb; hence, the thumb points to the **NORTH** pole of the magnet. Fig. 8 illustrates this rule.

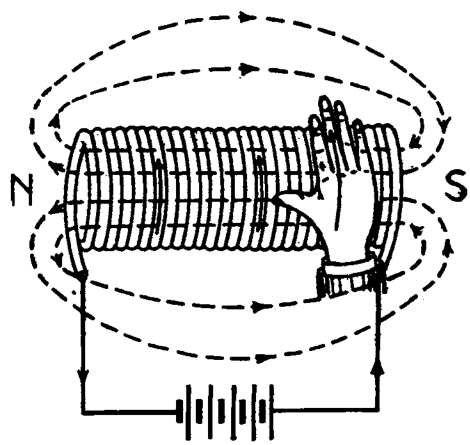

Fig. 8.

Suppose an observer stands to the right of the solenoid in Fig. 8 and looks at the nearer end, or south pole. The direction of current around the coil is from left to right, or *clockwise;* that is, in the same direction as the rotation of the hands of a clock. To an observer on the left of the solenoid, who looks on the end of north polarity, the direction of the current is from right to left, or *counter-clockwise;* that is, opposite to the rotation of the hands of a clock. These facts may be stated in the form of a rule as follows: *Look on the end of a coil. If the direction of current around the coil is clockwise, the end viewed is a* **SOUTH** *pole. If the direction of current is counter-clockwise, the end viewed is a* **NORTH** *pole.*

9. INSERTION OF AN IRON CORE WITHIN A SOLENOID.—A simple solenoid, such as shown in Figs. 6 and 8, is an electromagnet, but of comparatively little power or strength. If an iron center or *core* is inserted in a solenoid, the strength of the magnetic field produced by the current in the winding will be changed. Iron is a better conductor of magnetism than air. This fact is stated in Pamphlet E-3, and is illustrated there by Fig. 6. Iron is so much superior to air as a magnetic conductor that the magnetizing force of the current in the solenoid winding is sufficient to send many more lines of force through it, and the strength of the magnetic field is greatly increased. Because of these facts, a solenoid with an iron core, such as shown in Fig. 11, will be a much stronger magnet than the same coil, carrying the same current, but without the iron core. The distribution of the lines of force around a solenoid will be changed but very little by the insertion of an iron core. The magnetic spectrum will be practically unaltered, and similar to Fig. 7, except that the number of lines of force will be greater.

10. THE MAGNETIC CIRCUIT.—In the study of direct current electricity, one becomes familiar with the idea of the electric circuit, and the fundamental quantities of electromotive force, current, and resistance. The same idea of a continuous circuit holds true in the study of electromagnetism. An electromotive force acts to force an electric current through a resistance, and in a similar way a *magnetomotive force* acts to force a magnetic current through a magnetic resistance. In place of the cumbersome terms "magnetic current" and "magnetic resistance," which might be confused with electric current and resistance, use is made of the terms *magnetic flux*, or simply *flux* (flux means flow) and *reluctance*. The statement made above that "a magnetomotive force acts to force a magnetic current through a magnetic resistance" is better expressed: *a magnetomotive force acts to force flux through reluctance.*

A consideration of each of these three quantities, and a comparison with the similar electrical quantities will help one to understand the magnetic circuit more clearly.

11. MAGNETOMOTIVE FORCE.—The magnetic pressure, or magnetomotive force which forces the flux around a magnetic circuit is furnished by the current in the electromagnet winding, and has been found to be directly proportional to the amount of current flowing and the number of turns through which this current flows. The unit of pressure in the electric circuit is the volt; the unit of pressure in the magnetic circuit is the *ampere turn.* One turn of wire with one ampere flowing in it produces one *ampere turn.* Two turns of wire with one ampere flowing produce two ampere turns of magnetomotive force. Two turns with two amperes flowing produce four ampere turns. In other words, *magnetic pressure is expressed in ampere turns, which is the product of the number of turns of wire and the current flowing in the turns.* An electric pressure or difference of potential causes current to flow between points in a closed electric circuit. In the same way, a magnetic difference of potential causes magnetic flux to flow between points in a a magnetic circuit. The source of magnetomotive force in natural and in permanent magnets is not known.

12. FLUX.—Flux in a magnetic circuit corresponds closely to current in an electric circuit. The expressions "lines of magnetic force," "lines of force," "magnetic lines," etc., have been previously used in speaking of the magnetic current. The flux is the same as these lines of force; the total flux in a magnetic circuit is the total number of lines of force there.

Flux density is the total flux per unit area, and is usually expressed as so many lines of force per square inch or per square centimeter.

13. RELUCTANCE.—The reluctance of a magnetic circuit corresponds to the resistance of an electric circuit. There are, however, a number of important differences between reluctance and resistance; and owing to these differences, the calculation of magnetic circuits is somewhat more difficult than the calculation of electric circuits. The specific electric resistance, or resistivity, of any ordinary material can be accurately measured, and, except for slight changes due to temperature, is constant. It is not affected by the amount of current flowing through the material, except as the amount of current affects the temperature. The *specific reluctance*, or *reluctivity*, of all non-magnetic materials (practically everything except iron and steel) is also constant, and non-magnetic materials all have the same reluctivity. Therefore, the reluctance of a body of given dimensions is the same no matter what its composition—air, water, wood, metal, stone, glass—practically everything except iron and steel. The reluctivity of iron and steel is, in general, much lower than the reluctivity of non-magnetic materials, but it is also a very variable quantity, and depends upon the density of the flux. In general, the more flux sent through a given piece of iron or steel, the greater its reluctance becomes. Doubling the electromotive force applied to a resistance will double the current through the resistance, but doubling the magnetomotive force applied to a reluctance composed of iron or steel will not double the flux through the reluctance, and the greater the flux density in the iron, the less proportionately will be the increase in flux when the magnetomotive force is increased. The variations in reluctance of iron and steel will be more fully discussed under the heading *permeability*.

There are many materials, such as air, oil, rubber, slate, mica, etc., which have a resistivity so high that, for all practical purposes, they are insulators of electricity, and no appreciable current will pass through them. It is known that copper is one of the best conductors of electricity, and its specific resistance is about 1.59 microhms, or .00000159 ohms. The specific resistances of various insulating materials are given in Pamphlet E-2, and the figure set down for rubber compound such as is used for insulating wire is 1,770,000,000 megohms = 1,770,000,000,000,000 ohms, or more than 1,100,000,000,000,000,000,000 = 11×10^{20} times the resistivity of copper.

Very soft, carefully annealed wrought iron, and special grades of steel developed for the purpose are the best conductors of magnetic flux known, yet even with low flux density, the reluctivity of these materials is never less than $\frac{1}{2500}$ of that of non-magnetic materials. In other words, the poorest conductors of magnetic flux never have more than 2500 times the reluctivity of the best conductors. This means that there is no insulator for magnetism and that flux passes through air or any other material with comparative freedom. A magnetic circuit is, therefore, a leaky circuit; that is, all the flux cannot be confined to the desired path, but some of it will flow wherever a difference of magnetic potential exists, regardless of the composition of the material between the places having different magnetic potential.

Another important difference between resistance and reluctance is that no power or energy is expended in a reluctance when magnetic flux is forced through it. The passage of current through a resistance causes heating of the conducting material, and the electrical energy is transformed into heat, but the passage of flux through a reluctance causes no heating. Electric power is required to excite an electromagnet, but all of this power is expended in the I^2R or copper loss of the magnet winding, and does not appear in the magnetic circuit. In later pamphlets, it will be shown that there is energy stored in a magnetic field, although it does not become evident as long as the flux is constant and the field unchanged.

14. PERMEABILITY.—Permeability was defined in Pamphlet E-3 as the relative ease with which the molecules of a piece of iron or steel could be turned to act together magnetically. It can also be used to express the ability of a magnetic conductor to carry flux. Consider, for example, the solenoid of Fig. 7. There are twelve turns, and say five amperes flowing through them. The magnetomotive force is 5×12 or 60 ampere turns. This magnetomotive force causes a flux of ten lines when the magnetic circuit is wholly of air. If the complete path of the flux could now be changed from air to iron, with the same number of turns and the same current strength, about 20,000 lines of force would go through the iron, due to the fact that the iron has a much lower reluctance than air. The ratio of the flux when the circuit is of iron, to the flux when the circuit is of air, is called the *permeability* of the iron. In this case, the permeability is $\frac{20000}{10}$, or 2000. *Permeability, in its true sense, is a ratio expressing the relation between the flux in a magnetic circuit of any material at any particular flux density, and the flux in a circuit of the same dimensions with the same magnetomotive force, with nothing but air in the magnetic path.* Permeability, like reluctance, is not constant. Just as reluctance increases, permeability decreases when the flux is increased.

15. MAGNETIC PROPERTIES OF IRON.—Suppose an ampere turn of magnetomotive force is impressed on a magnetic circuit of wrought iron. Assume that it produces 1000 lines of force. Two ampere turns will produce 2000 lines, and so on until a flux of 10,000 lines is reached with a magnetomotive force of ten ampere turns. Eleven ampere turns produce 10,500 lines (only 500 additional); and twelve ampere turns produce 10,900 lines (only 400 additional), and so on. From this point on, the increase in lines becomes proportionately less as the magnetomotive force is increased. At the point where an increase in magnetomotive force fails to give a corresponding increase in flux (between 10,000 and 11,000 lines in this case) the iron is said to have reached its *point of saturation.* This explains further the idea of saturation obtained in Pamphlet E-3. An increase of magnetomotive force, after the point of saturation of the iron is reached, will produce a comparatively small increase in flux.

When similar pieces of steel and good wrought iron are subjected to the same magnetomotive force, a greater number of lines of force will be produced in the wrought iron than in the steel because the permeability of the wrought iron is higher than that of the steel. Thus, in Fig. 9, curve No. 1 is the *magnetization curve* of the sample of wrought

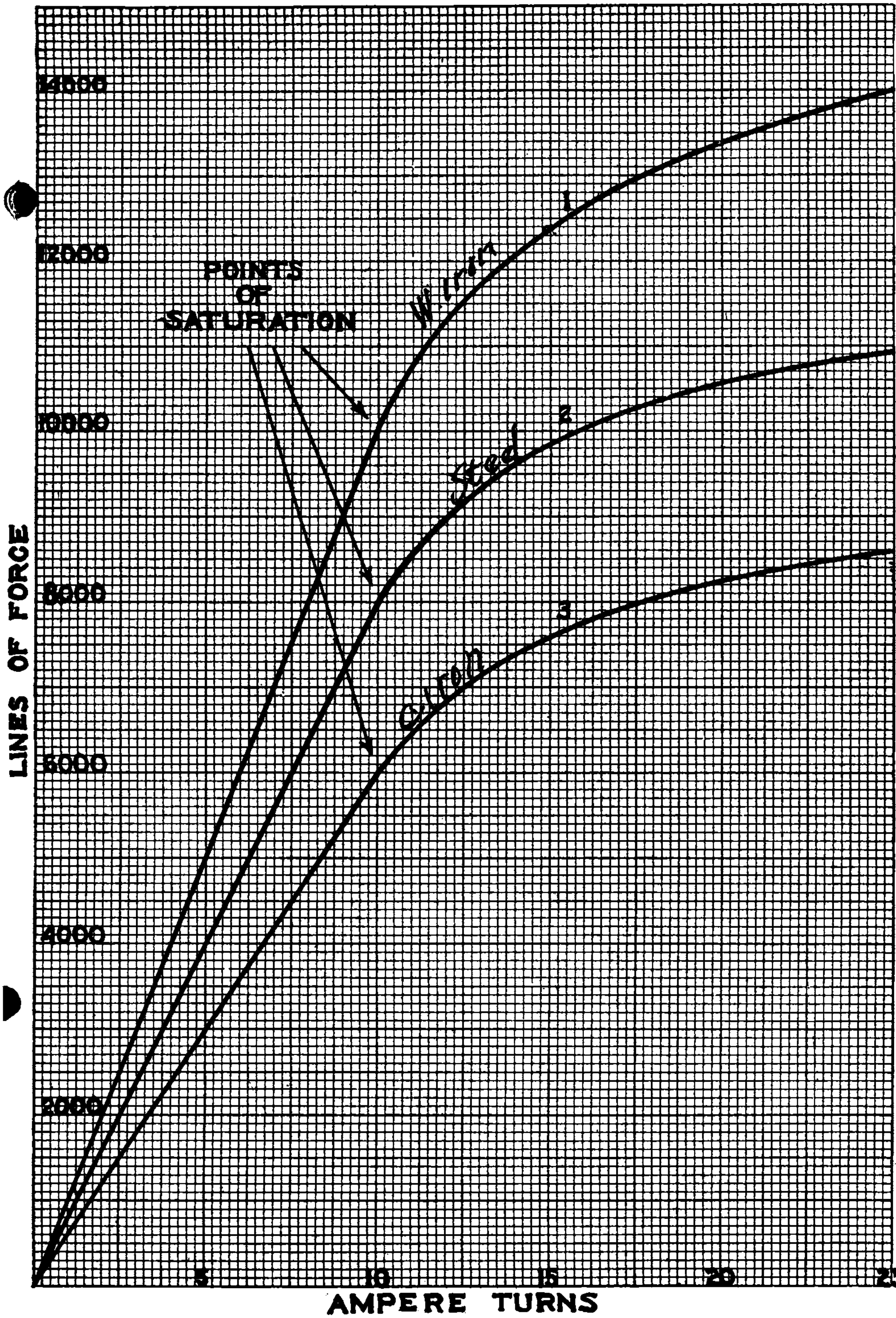
14000
12000
10000
8000
6000
4000
2000
POINTS OF SATURATION
Wr'i'n 1
Steel 2
C.Iron 3
LINES OF FORCE
5
10
15
20
25
AMPERE TURNS

Fig. 9.

iron mentioned, and curves No. 2 and No. 3 are the magnetization curves of similar samples of steel and cast iron respectively. These curves show that the same magnetomotive force will produce different amounts of flux in the different kinds of iron.

From the foregoing, the following conclusions may be drawn: Air is not a good conductor of flux, for, a given magnetomotive force, which produces only one line of force in air, might produce 2500 lines in iron; in an iron circuit, an increase in magnetomotive force will produce a corresponding increase in flux up until the iron reaches its point of saturation; beyond this point, an increase in magnetomotive force, however large, will produce only a relatively small increase in flux.

It is readily seen that it is advantageous to use iron in a magnetic circuit at the point of saturation; because, below this point the iron is not carrying as much flux as it can, and above this point there is an expenditure of magnetomotive force (requiring an expenditure of current) which does not produce a corresponding increase in flux.

The variation of permeability can be illustrated from Fig. 9. Ten ampere turns produce 10,000 lines in the wrought iron circuit; the same magnetomotive force in a circuit of air would produce, say, five lines. The permeability of this sample of iron with a magnetomotive force of ten ampere turns is $\frac{10000}{5}$, or 2000. According to curve No. 1, twenty ampere turns produce 13400 lines in the iron. Ten lines are produced in air, since the lines produced in air are directly proportional to the magnetomotive force. With a magnetomotive force of twenty ampere turns, the permeability is $\frac{13400}{10}$, or 1340. This illustrates the fact that permeability decreases as the flux is increased beyond the point of saturation.

16. FORCE EXERTED BY ELECTROMAGNETS.—A line of force may be compared to a stretched rubber band, and like such a band, it tends to draw up or shorten. In Fig. 10, which shows a horseshoe magnet and its armature or keeper, the dotted line represents a line of force. It passes through the magnet, through the two air spaces, generally called "*air gaps*," and through the armature. If this line were a stretched rubber band, it would tend to shorten and draw up the armature. The line of force shown acts very much as the rubber band would act. Two bands would increase the force of attraction, and three bands would increase the pull still more, and so on. Reasoning similarly with lines of force, it is seen that the more lines there are, the greater is the pull or lifting power.

A coil of wire with current going through it would act as a magnet; but electromagnets are designed to lift or pull, and the amount of pull exerted depends on the number of lines of force in the magnetic circuit. By inserting iron in the circuit of flux, the lines are increased, say 1500 times, hence the advantage of an iron core for lifting purposes is readily seen. As was mentioned before, the amount of flux is dependent upon the magnetomotive force, which in turn depends on two things—the

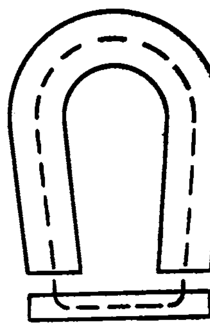

Fig. 10.

number of turns and the current flowing through these turns. Therefore, *the pull that an electromagnet will exert is dependent upon the number of turns of wire on the magnet and the amount of current flowing in the turns, but is not directly proportional to these quantities.* Air gaps and the kind of material in the magnetic circuit are also factors which influence the pull.

17. FACTS ABOUT ELECTROMAGNETS.—1. Doubling the number of turns of wire on the magnet increases the force exerted, but in most cases does not double the force. The same can be said of the current through these turns.

2. The amount of current is limited by the size and kind of wire used.

3. If the iron is being operated considerably above the point of saturation, an increase in core area will increase the pull.

4. Increasing the length of the iron circuit decreases the pull.

5. It is very important to have the air gaps in the magnetic circuit as short as possible. Air gaps compared with iron have high reluctance.

An air gap of $\frac{1}{8}$ inch is equivalent to about twenty feet of iron in reducing the amount of flux.

6. The strength of an electromagnet is not diminished by the removal of its armature.

18. TYPES OF ELECTROMAGNETS.—All forms of electromagnets may be classed in one, or a combination of two or more of four types.

1. The simplest type is the plain *solenoid* with an iron core, shown in Fig. 11.

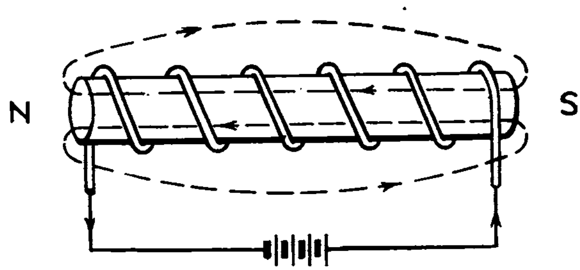

Fig. 11.

It is seen that a little less than half of the flux path is through the iron, most of the path being through the air. When this magnet is used commercially, it is generally stationary and is used to draw up movable armatures, which armatures, in most cases, are a centimeter or less away from the core.

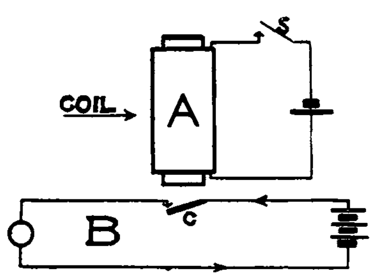

Fig. 12.

In Fig. 12 the solenoid, A, could be used to close the circuit, B, by drawing up the armature, C. When A is de-energized (that is, when the switch, S, is opened) the armature, C, will, by the force of gravity, fall and open the circuit, B.

2. The solenoid of Fig. 11 may be bent into a U or horseshoe shape as shown in Fig. 13, and for many purposes the *horseshoe* magnet is

superior to the straight solenoid. Its advantage lies in the fact that the air gap is short. If this gap is increased to any extent the pull of the magnet is very materially reduced; because the reluctance of the path through the air gaps and armature becomes so great that most of the flux jumps directly across from leg to leg of the magnet instead of going through the armature and drawing it up. Horseshoe magnets should be used, therefore, where the air gaps are small, if high efficiency is desired.

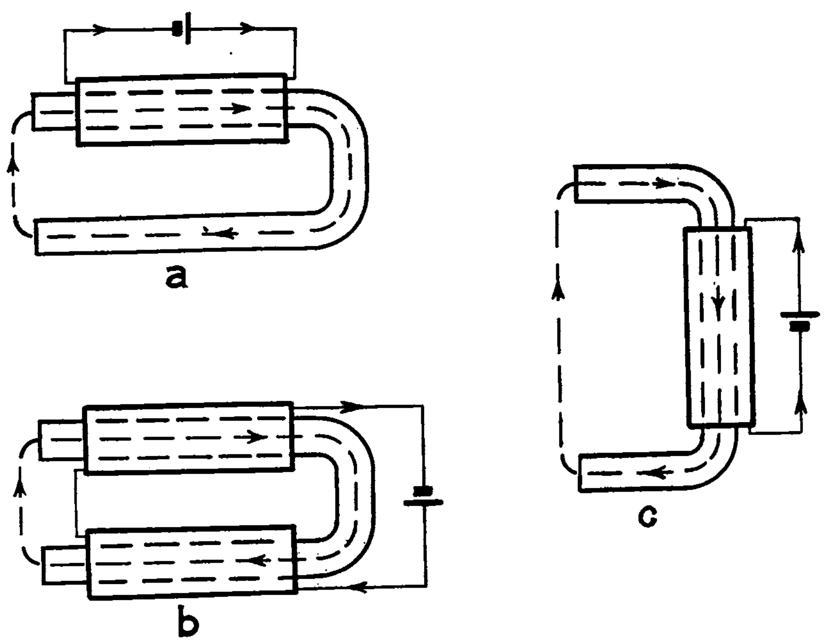

Fig. 13.

An ampere turn on the horseshoe magnets of Fig. 13 will give a much greater lifting power than an ampere turn on the solenoid magnet of Fig. 11. The horseshoe type may be used as illustrated in Fig. 12, substituting a horseshoe magnet for the solenoid magnet, and may also be used in any place where the armature, or part to be operated, can be located near the magnet, such as in electric bells, automatic gas lighting burners, electric locks, etc.

3. When the part to be operated cannot be located near the magnet, a third type of magnet may be used; namely, the *plunger* type.

The coil shown in cross section in Fig. 14 is wound on a hollow spool, and an iron plunger fits easily into the center of the spool. The action depends on the fact that the flux, in seeking the path of least reluctance, will tend to draw the plunger into the center of the spool. It

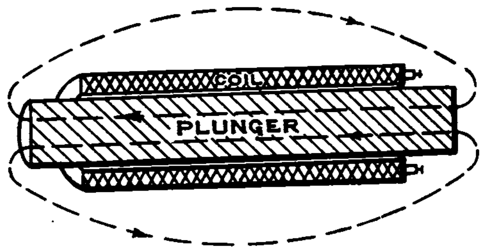

Fig. 14.

will be noticed that considerably over half of the magnetic path is through air. The plunger can be taken completely out without doubling the air gap; hence, without doubling the reluctance of the magnetic path. It is evident, therefore, that the flux through a plunger type electromagnet is not altered to such a degree as to destroy its pulling power, by moving the plunger in and out of its jacket. A twelve inch

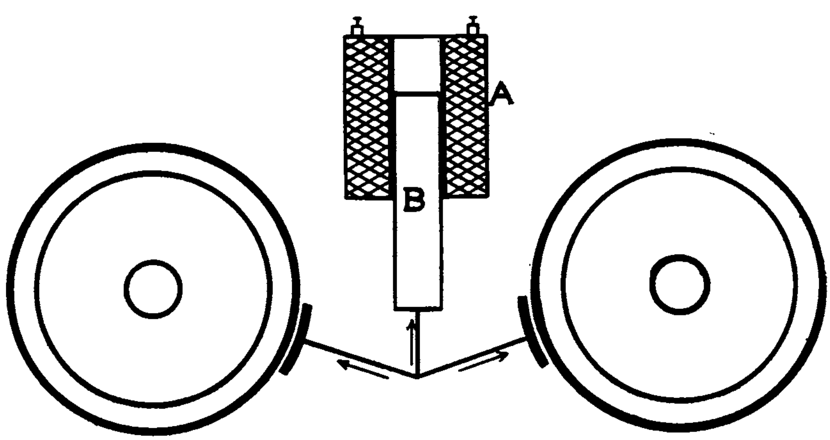

Fig. 15.

magnet of this type will exert considerable pull on its plunger while this plunger moves a distance of eight inches. Such a magnet is very useful to pull or push, as is illustrated in Fig. 15. By energizing the coil, A, the plunger, B, is drawn up and forces the brake shoes against the wheels. This is a form of magnetic brake. In a much modified form it is used as a rail brake on some street cars.

4. A better form of plunger magnet is the *iron clad* magnet shown in Fig. 16. A double advantage is gained in this type, for it is evident

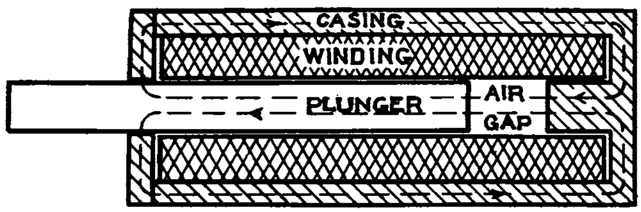

Fig. 16.

that the air gap is greatly shortened, and the coil is protected from injury by the iron casing which surrounds it. The iron clad type is the most efficient, and mechanically the best protected from injury of all long range magnets.

The plunger type of magnet has many uses, among which are: the operation of high voltage switches, magnetic brakes, circuit breakers, arc lamps and countless other electrical devices. In large power plants,

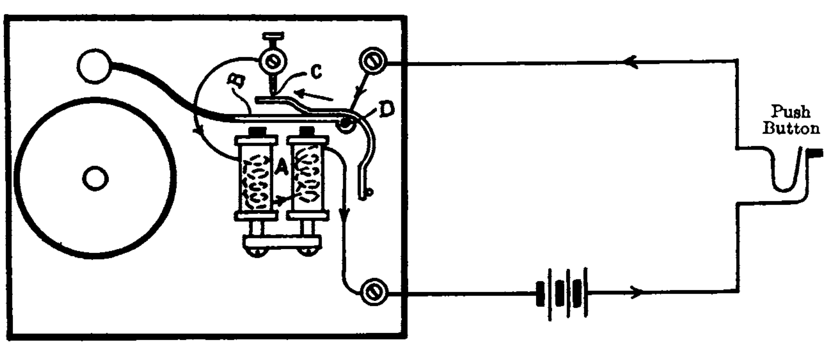

Fig. 17.

one man in a small room can operate large switches all over the plant by merely closing low voltage circuits which operate magnets that in turn operate the switches.

19. SOME COMMERCIAL ELECTROMAGNETS.—In the following pages, some of the common uses of electromagnets are illustrated and explained. Possibly the simplest and most common use is found in door bells, as shown in Fig. 17.

A is a pair of coils making up an electromagnet very similar to a horseshoe magnet. B is an armature pivoted at D to which one wire of the circuit is attached. The bell tapper is fixed rigidly to B. When the push botton is pressed, the current will flow through the circuit as indicated by the arrows, and the electromagnet, A, will exercise enough force on armature, B, to pull it away from C against the action of the spring, causing the tapper to strike the gong. When B is drawn up to A, the electric circuit is broken at C, and A no longer holds B; hence, B is forced back by the action of the spring. The action is repeated rapidly and the tapper will continue to vibrate and ring the bell as long as the push botton is pressed.

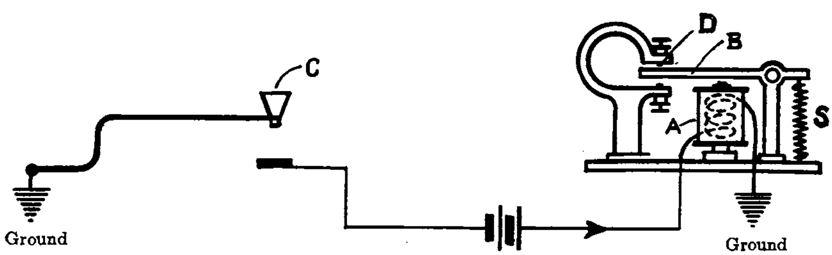

Fig. 18.

Fig. 18 is a sketch of a simple telegraph system. It consists of a magnet at A, over which is placed an armature or sounder, B. When the key at C is pressed, the circuit is completed and current flows in the direction indicated by the arrow. In this figure the return circuit from the sounder to the key is through the earth from the ground connection shown at the right to the ground connection shown at the left. The current will cause the iron core in the magnet coil to be magnetized and draw down the armature, B. When the key is released, the current will stop flowing and the magnet will lose its power of attraction. This will release the armature; the spring, S, will pull it away; and the armature will make a clicking sound when it strikes the upper contact, D. The key, C, may be miles away from the sounder, B.

A very simple electromagnet is used on a motor starter to hold the starter arm, which is the longer arm shown in Fig. 20. In starting

Fig. 19.

the motor, this arm is moved to the right until the small iron armature mounted on it strikes the poles of the electromagnet which is shown at the right of the figure. As soon as the line switch is closed, before the motor is started, this magnet is energized, and when the starter arm is at the extreme right, it is held by the electromagnet as long as the line switch is closed. When the line switch is opened the magnet becomes de-energized, and the starter arm is pulled back by a spring to the position shown.

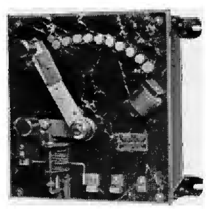

Fig. 20.

A magnet like the above but of large dimensions is shown in Fig. 19. The cylinder in the middle contains a large coil of wire with an iron core in its center. The magnetic circuit is completed from the core by the large triangular shaped flanges on the sides and by the iron which the magnet is lifting. The whole load of iron drops almost instantly when the current is cut off the coil. The connections from the coil are carried to a point from which an operator controls the magnet and the crane on which it is mounted.

A very ingenious electromagnet is the one used in magnetic separators, as shown in Fig. 21. The magnetic pulley is made up of a series of disks, or circular magnets, mounted on a shaft, as shown in Fig. 22. Current is led into the coils through the carbon brush, B, which slides on a metallic ring, C. This ring is thoroughly insulated from, but revolves with, the shaft. A wire runs from the slip ring, C, to the coils in the first compartment; from thence to the second compartment, and so on. The circuit is completed from the last compartment by a wire which leads to the slip ring, D; from thence to the brush, A, and finally to the negative line wire. The current going through the coils causes flux to flow as indicated by the dotted lines. The circular disks, therefore, become magnets with poles as indicated in the figure.

Magnetic material such as iron filings will be attracted by these magnets and carried around on the belt until the magnetic force becomes so

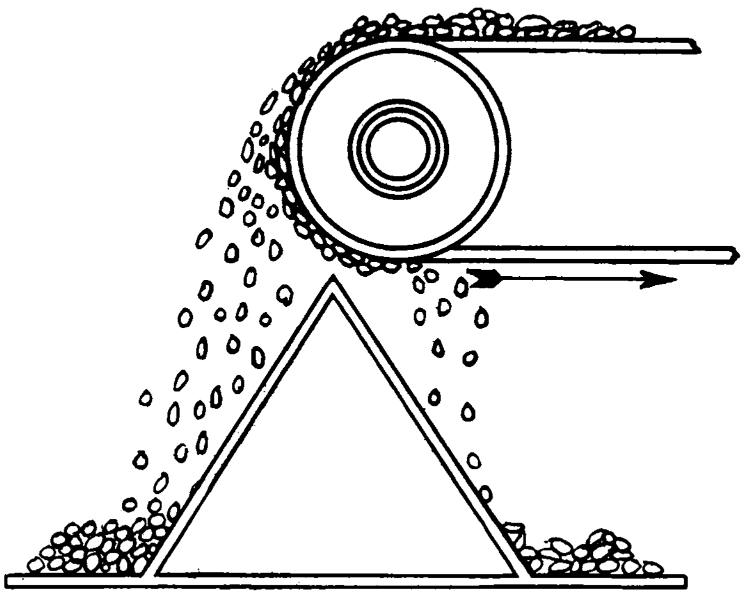

Fig. 21.

weak, because of the particles moving farther from the magnetic pulley, that the magnetic material will fall as indicated in Fig. 21. All non-magnetic material will thus be separated from magnetic material.

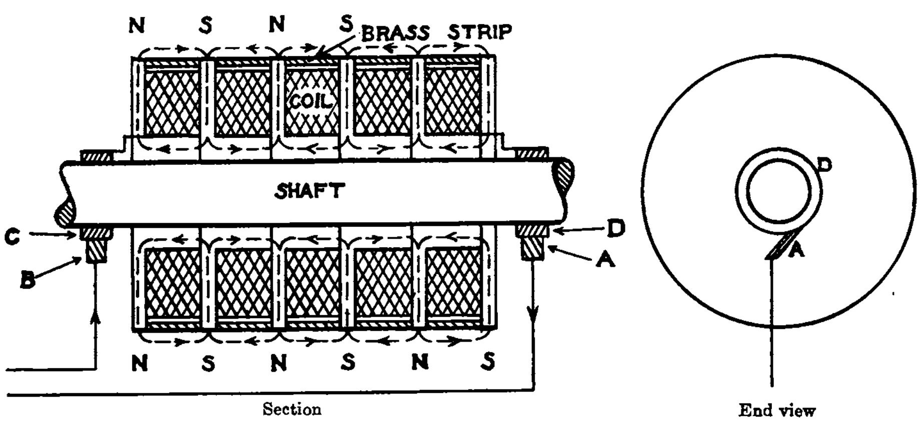

Fig. 22.

Probably the largest magnets made are the circular lifting magnets such as shown in Fig. 23.

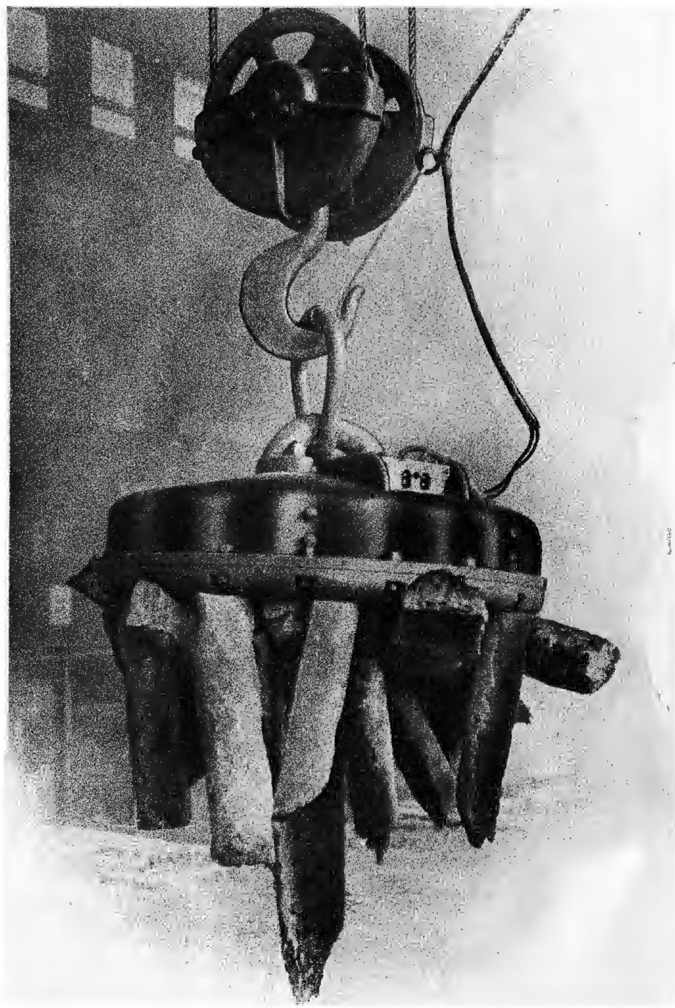

Fig. 23.

A coil is wound horizontally around the center, as shown in Fig. 24, which is a sectional view of a lifting magnet. The flux takes the path of the dotted lines. The outside ring forms one pole and the inside ring the opposite pole. The connecting wires of the coil are carried to the cage or cab from which the operator controls the magnet

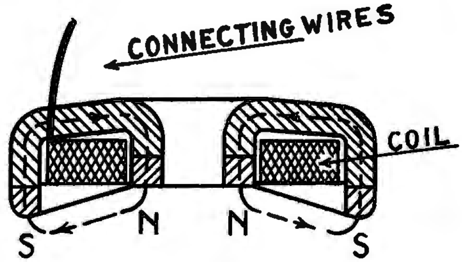

Fig. 24.

and the derrick or crane which carries it. Some of these magnets are made strong enough to lift 50,000 pounds of iron or steel in the form of slabs. Such a magnet, in making a heavy lift, uses about 47 amperes on 220 volts. It has a diameter of 61 inches and weighs 6660 pounds. It will be seen that this apparatus lifts seven or eight times its own weight.

Fig. 25.

Another use of magnets is illustrated in the hand lifting magnet, shown in Fig. 25. Its usefulness is readily seen. This is merely a form of horseshoe magnet with the windings on the legs. The magnetic circuit is completed by the nails which are being lifted.

An electromagnet can be used as a *current-limiting device* because its pull is dependent upon the current in its winding. This is well illustrated in the common circuit breaker, the purpose of which is to open an electric circuit when the current increases to such a value that it might damage either conductors or apparatus. Circuit breakers are

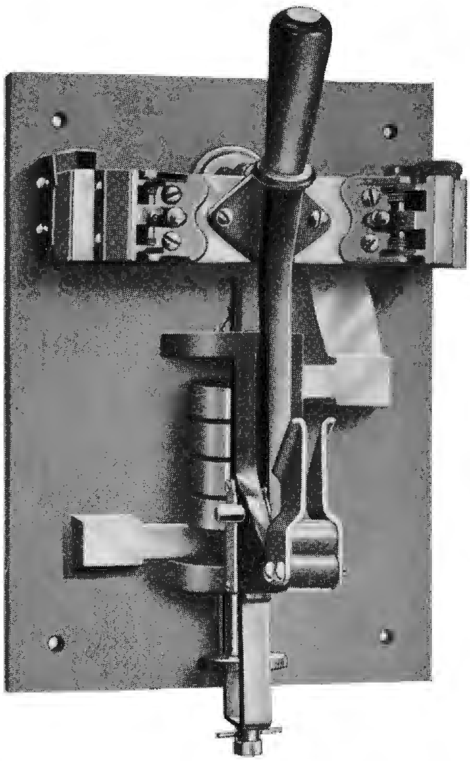

Fig. 26.

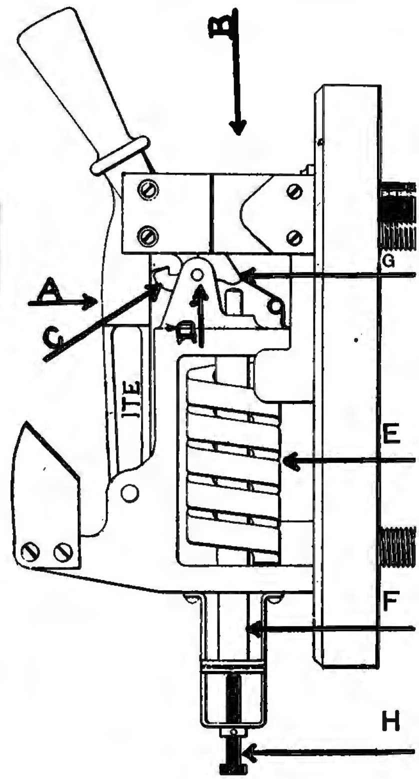

Fig. 27.

also made to open circuits when the current falls below a certain value or when the direction of the current flow is reversed. One form of single pole, overload circuit breaker is shown in Figs. 26 and 27.

The switch blade, A, is forced into the knife receptacle, B, against the action of a spring which tends to push the blade out. The knife blade is held in place by the catch, C, which catch is pivoted at D. The main current of the line goes through the coil, E, which tends to draw up the plunger, F. When the current reaches a certain value, the force on the plunger will be sufficient to draw it up until it hits the trigger, G, which pushes C down and releases the knife blade switch, which in turn is forced out by action of the spring, and breaks the circuit. The farther down the plunger is, the more force, that is, the more current, will be required to raise it. The plunger can be raised or lowered by the screw, H, and the circuit breaker can, therefore, be made to open at any desired current value within certain limits.

Another use of electromagnets is found in telephone receivers. Telephone phenomena will not be explained here except to say that voice currents go through the coil of an electromagnet which acts on a metal diaphragm and causes it to vibrate so as to reproduce the sounds impinged on the transmitter at the other end of the line. Telephone apparatus is almost wholly made up of electromagnets in various forms.

20. ACTION OF ELECTROMAGNETS ON CURRENT-CARRYING WIRES.— Probably the greatest field for the use of electromagnets is in generators and motors. In Pamphlet E-3 the following statement occurs: "Like

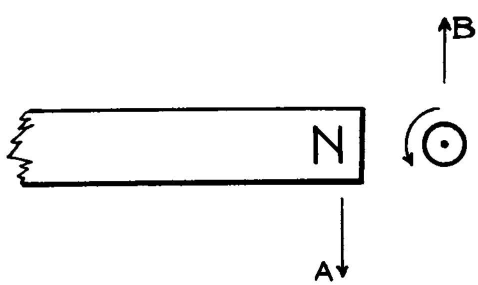

Fig. 28.

poles repel and unlike poles attract each other." The poles mentioned are really centers of magnetic fields. When two magnets are brought close together their fields act on each other and produce either attraction or repulsion. Furthermore, two fields, whether produced by electromagnets or current-carrying wires, will interact and produce a force of attraction or repulsion. The effect on a compass produced by the field surrounding a current-carrying wire has been discussed and illustrated. In reality, the field of the compass magnet interacts with the field of the wire, the north pole of the compass following the direction of the stronger field. Whether the magnet is a compass, or a large bar magnet freely suspended, the same action will take place.

In Fig. 28, ⊙ represents the cross section of a wire in which current is flowing toward the reader, or out of the page. The N pole of the bar magnet will attempt to follow the direction of the field, and, if the force is strong enough, will move in the direction indicated by arrow, A. If the bar is held stationary, and the wire allowed to move, it will move in the direction indicated by arrow, B.

The resultant field due to magnet poles and a current-carrying wire is shown in Fig. 29.

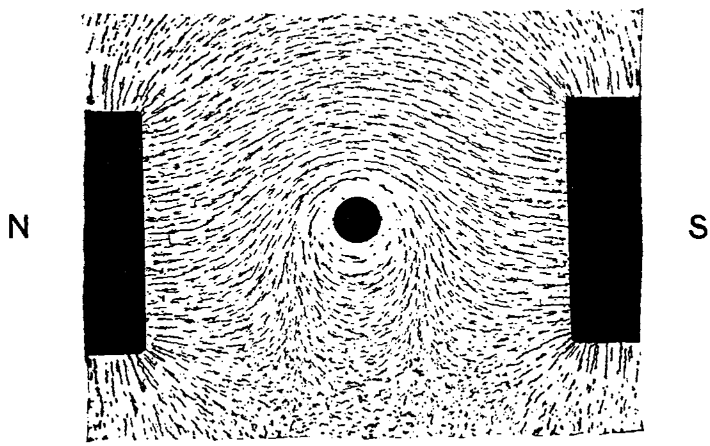

Fig. 29.

Such a magnetic field is obtained when the north and south poles are as indicated and the current in the wire is flowing away from the reader. An enlarged section of the center of this figure may aid in giving a conception of the resultant field and forces. Fig. 30 shows plainly the existing conditions.

Below the wire, the field of the magnets and the field of the wire are in opposite directions. The field of the magnets is said to be moving from the north pole to the south pole and is, therefore, moving from left to right; while the field of the wire below the conductor is moving from right to left. Hence the two fields below the wire buck or neutralize each other to a great extent and the resultant field is weak at that point. Above the wire the field of the magnets and the field of the wire are in the same direction. These fields combine and form a strong field above the wire The strong field above, and the weak field below, produce unequal forces on the two sides of the wire, and tend to move it toward the weaker field or downward, as indicated by the arrow, F. If either the direction of the current in the wire or the polarity of the magnet poles is reversed, the wire will tend to move in the opposite direction. If both the direction of the current in the wire and the magnetic field are reversed, the wire will move in the same direction as at first. A consideration of the respective fields produced will make the above statements clear.

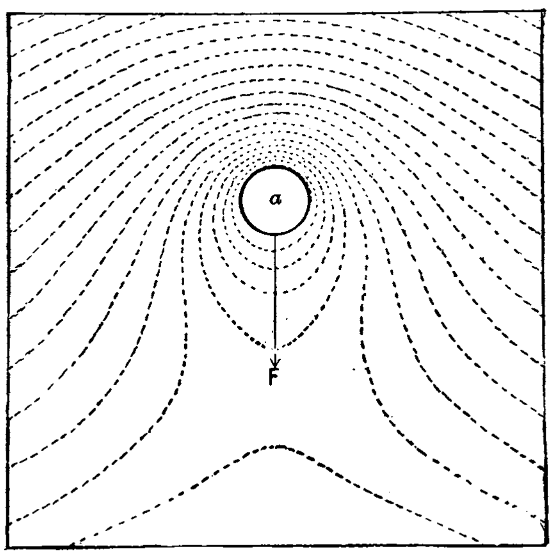

Fig. 30.

21. DIRECTION OF SIDE PUSH ON ELECTRIC WIRE.—Simply by reasoning as above, one can predict which way a wire will move when the direction of current and the direction of the field are known. However, a simple rule will enable one to tell easily and quickly which way a current-carrying wire placed in a magnetic field will tend to move. Fig. 31 illustrates what is commonly known as *the left-hand motor rule.*

The thumb, first, and second fingers are extended at right angles to each other as shown. The *first finger* is pointed in the direction of the *field* of the magnet, the *second finger* is pointed in the direction the *current* is flowing, and the *thumb* will then be pointed in the direction the *wire will tend to move*. Having any two directions, the third may be found by the aid of this rule.

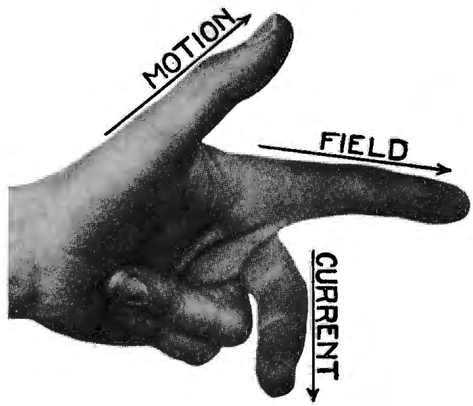

Fig. 31.

The action of a field on a current-carrying wire is often spoken of as the *side push* on the wire. The amount of this side push is proportional to three things: first, the strength of current flowing in the wire; second, the strength of the magnetic field; and third, the length of wire in the field. Increasing or decreasing any one of these three quantities increases or decreases proportionately the side push on the wire.

22. FUNDAMENTAL ACTION OF A MOTOR.—Suppose a piece of stiff wire, W, is bent as shown in Fig. 32. Let current be supplied through wires, A and B, to the brushes, C and D, in contact with metallic rings to which the ends of the stiff wire are connected. The current in the wire flows in the direction indicated by the arrows. Applying the *left-hand motor rule,* it will be seen that the top part of the wire will move to the left and the bottom part will move to the right. A cross-section of this figure, illustrated in Fig. 33, shows plainly the direction of the field and the direction of the motion. If the current flows in at A and out at B as shown in Fig. 33, the flux will be weakened below A and above B, and the loop will tend to rotate as indicated by the arrows, C and D.

The modern direct current motor is simply the development and perfection of the above idea. A great number of coils similar to the one shown in Fig. 32 are wound on a drum and suitable provisions are made to bring current into the coils and to reverse the direction of the current in the coils at proper intervals. The drum is thus made to revolve continuously, and to give out mechanical power at a pulley or gear attached

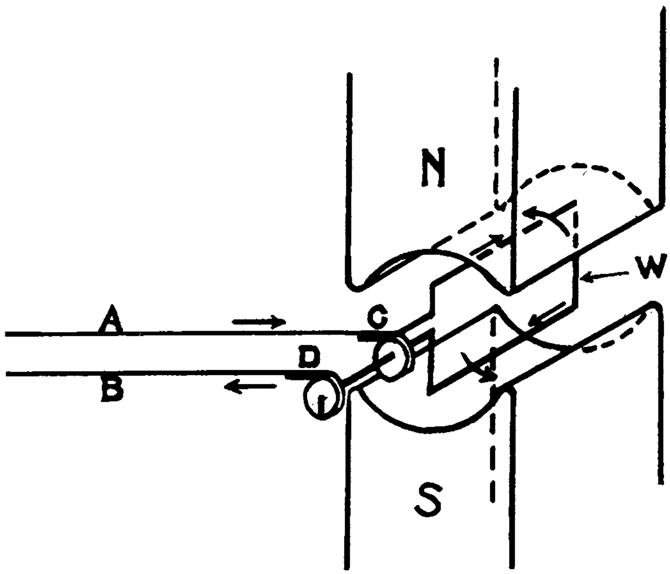

Fig. 32.

to the revolving shaft. The motor is, therefore, a machine which transforms electrical power to mechanical power. The complete development and principles of operation of the electric motor will be taken up in later pamphlets. The fundamental principle is merely outlined here to illustrate the important part that electromagnets play in electrical machinery.

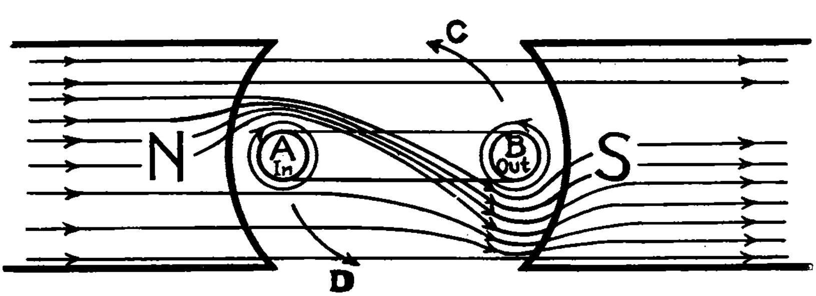

Fig. 33.

23. MAGNETIC BLOW-OUTS.—Electromagnets are used in some devices to blow out or quench electrical arcs. If a circuit in which there is a heavy current flowing is suddenly broken, the current will continue to flow for an instant across the open gap in the form of an intense arc

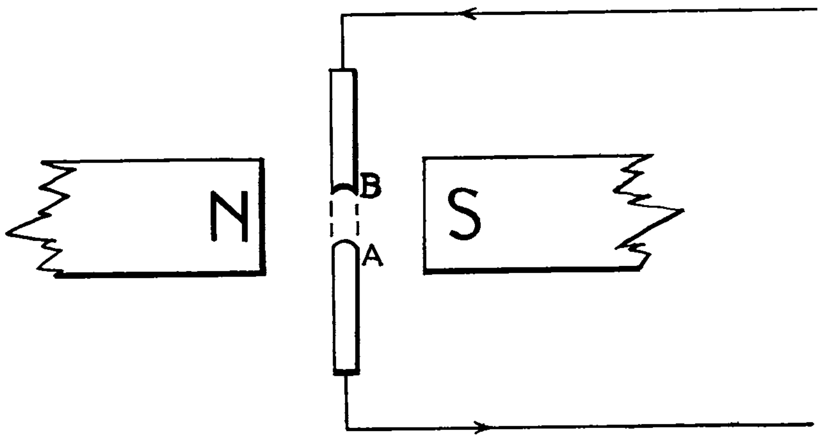

Fig. 34.

or flame, exemplified in the familiar flash which occurs when a street car trolley flies off the trolley wire. This flame is very hot and consists of vaporized metal taken from the points where the circuit is broken,

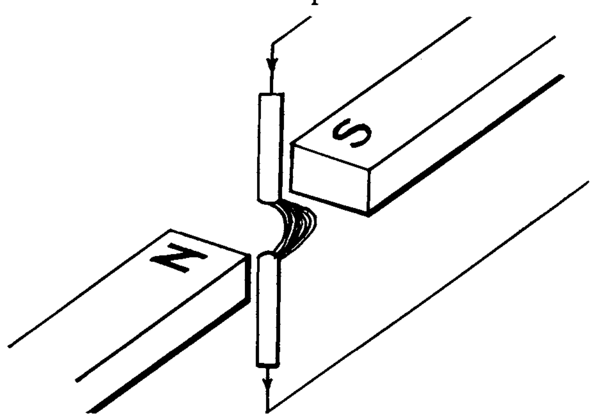

Fig. 35.

which forms a conductor for the current. Just as an electromagnet pushes a current-carrying wire aside, it will also push aside such an arc as described above. Figs. 34 and 35 will make this clear.

Assume that the contacts, A and B, are together, with a current of about fifteen amperes flowing. A and B are then moved apart as shown. With no magnets present, an arc having the appearance of a very brilliant flame will be drawn between A and B and will burn the ends of these contacts. If this arc is placed in a strong magnetic field, as illustrated, it will be pushed toward the reader as shown in Fig. 35 (apply left-hand motor rule). This deflection of the arc makes the path of the current between the electrodes so much longer that the resistance of the arc is increased, thereby reducing the current to such an extent that the arc finally goes out. In reality all this takes place very quickly, and herein lies the advantage of the *magnetic blow-out.* A company could not well afford to be continually replacing burned electric switches and contacts because of arcs; hence the magnetic blow-out is finding a large field of service in work where heavy currents are frequently interrupted.

PROBLEMS.

NOTE.—These problems should be answered one or more complete lessons at a time.

FIRST LESSON.

1.—Air has no point of saturation. If the magnetomotive force of a solenoid is doubled, what can you say of the flux of the solenoid?

2.—What is the magnetomotive force in ampere turns in a coil of 100 turns if $2\frac{1}{2}$ amperes are flowing?

3.—Show the path, direction of flux, and mark the polarity of the poles in the following electromagnet, Fig. 36. The direction of current in the windings is indicated by the arrows.

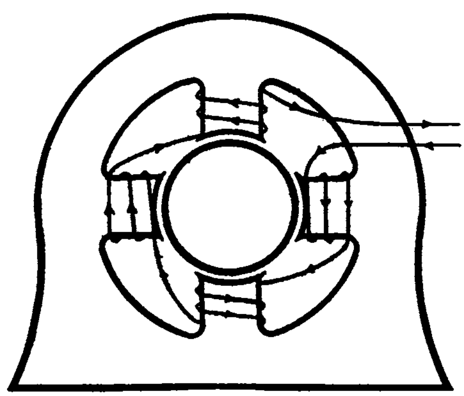

Fig. 36.

4.—(*a*) To what is the magnetomotive force of a coil proportional?

(*b*) What effect does the insertion of an iron core in a magnetic circuit have on the magnetomotive force and flux?

(*c*) When the core in a solenoid is operated above saturation and the number of turns is doubled, the flux is not doubled, if the current remains the same. Is the magnetomotive force doubled?

5.—What are three expressions which mean the same as flux?

SECOND LESSON.

6.—It is difficult to magnetize heated iron or steel. What rule could be stated concerning the relation between the reluctance and temperature of these materials?

7.—Resistance is practically constant for all values of current, so long as the temperature does not change. Is reluctance constant, no matter what the flux may be?

8.—Compare magnetic reluctance with electrical resistance, stating fully—(*a*) In what respects reluctance is unlike resistance, and (*b*) In what respects reluctance resembles resistance.

9.—Twelve turns of insulated wire are wound on a vertical iron rod. Beginning at the upper end of the rod, the first six turns are wound in a clockwise direction, and the remaining turns in the opposite direction. Current flows through the coil from top to bottom. Make a sketch showing the rod and wire and indicate the magnetic poles produced.

10.—A current is sent through a coil of wire wrapped around a tumbler in the same direction that the fingers of the right hand point when clasping it to drink. What is the polarity of the end of the coil observed while drinking?

11.—A coil of wire is wound on a vertical rod and the current flows clockwise and downward. Will a north pole be attracted or repelled by the top of the rod?

Third Lesson.

12.—What is meant by the expression "point of saturation" as used in this pamphlet?

13.—(*a*) According to Fig. 9 how many lines of force go through the piece of cast iron before the point of saturation is reached?

(*b*) How many through the piece of steel?

14.—Why is it advantageous to operate iron in an electromagnet at the point of saturation?

15.—The pole of an electromagnet having a steel core deflects a certain compass needle 44 degrees when held at a distance of one foot. A wrought iron core is substituted for the steel and the deflection is now 85 degrees. How do you account for this, since the distance and the current strength remain the same?

16.—Which magnet core in the above problem possesses the greater permeability?

17.—If 10 ampere turns produce 5 lines of force in air:

(*a*) What is the permeability of the wrought iron in Fig. 9 with a magnetomotive force of 15 ampere turns?

(*b*) What is the permeability of the steel in Fig. 9 with a magnetomotive force of 20 ampere turns?

(*c*) What is the permeability of the cast iron in Fig. 9 with a magnetomotive force of 25 ampere turns?

FOURTH LESSON.

18.—Suppose a certain magnet lifts 50 pounds with 5 amperes flowing in its turns; how much will the magnet lift if 8 amperes are flowing, assuming the pull exerted is proportional to the square of the current? (Approximately true up until the point of saturation is reached.)

19.—Why does a solenoid tend to draw its plunger into its center?

20.—If the current in Fig. 15 is reversed, will the plunger still be drawn up or will it be pushed down? Explain your answer.

21.—Name four things which influence the amount of pull an electromagnet will exert.

22.—A certain magnet requires 3000 ampere turns of magnetomotive force. (*a*) If there are 500 turns in the coil, what must be the current capacity of the winding? (*b*) What, if there are 1200 turns in the coil?

23.—An electromagnet is to be attached to one end of a lever which applies a friction clutch on a hoist. To release the clutch the magnet must move the end of the lever a distance of 6 inches against the pull of a spring. The hoist is exposed to the weather, and the magnet coil must be protected mechanically and against dampness.

What type of electromagnet would be suitable for use in this case? Give reasons for your choice.

24.—Give two reasons why hard steel is not used for lifting magnets. (Remember that steel retains considerable magnetism after it is once magnetized.)

25.—(*a*) What four types of electromagnets are mentioned in this pamphlet?

(*b*) Which type produces the most flux per ampere turn of magnetomotive force?

Fifth Lesson.

26.—Suppose current is flowing in a wire from East to West; (*a*) Is there a side push on the wire? (*b*) If there is, what is its direction? Explain your answers.

27.—A feed wire for an overhead direct current trolley line is run up a wooden pole from an underground duct. When the pole is approached from the South, the N end of a compass needle held in the hand is deflected East. Is the current flowing up or down the wire on the pole? How do you get your answer?

28.—If the wire in Fig. 29 is covered with rubber insulation, will the wire have a side push on it?

29.—In a certain magnetic field the side push on a wire 10 centimeters long with 5 amperes flowing, is 4 ounces. What is the side push in ounces in a field twice as strong, when the wire is 16 centimeters long with 14 amperes flowing?

30.—(*a*) If, in Fig. 29, the N pole were placed where the S pole is, and the S pole placed where the N pole is, which way would the wire be pushed and why? (*b*) If the direction of current in the wire is also changed, which way will the wire then be pushed and why?

31.—(*a*) Two insulated wires are placed side by side. If current in both is flowing in the same direction, will they attract or repel each other?

(*b*) If their currents are flowing in opposite directions, what will be the action? Explain the reason for your answers.