# Soft Magnetics Application Guide

## Basics of Magnetics

ARNOLD®
THE MAGNETIC PRODUCTS GROUP OF SPS TECHNOLOGIES

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## Magnetism…

The earth itself has magnetism. Ages ago, seagoing navigators learned how to use this phenomenon to sail their ships accurately from one port to another.

All of us are aware that the earth spins on an axis, the opposite ends of which have been designated as the geographic north and south poles. These geographic poles are near the earth's magnetic poles.

Invisible magnetic lines of force completely surround the earth. Oversimplified (but adequate for this discussion), these lines enter the earth at one pole, pass through the earth, exit at the other pole, and then loop back to the first pole. They are useful not only to the mariner on the high seas but also to the airplane pilot aloft.

Ancient mariners learned that certain substances, known as lodestones, would always point approximately north or south when suspended on a string. If the lodestone was deliberately moved from this position, it would slowly return to its original orientation. This gave evidence of a strange force which man could use.

Long after the mariner's compass became a universally useful navigational instrument, other pioneering scientists observed that a voltage could be measured between the ends of a piece of wire moved across magnetic lines of force. They also learned that, if the ends of a long enough wire were touched together, a tiny spark could be seen when the wire was moved very rapidly. Gradually, as these phenomenon were observed by scientists and word of their observations was circulated, the relationship between electricity and magnetism was discovered.

Although they did not understand the causes at first, they eventually developed the idea that something was flowing in the wire. In due course, new words such as voltage, current, resistance, and impedance began to creep into the strange, new jargon of science. Each new discovery added to the previous knowledge and, through such evolution, order developed out of conflicting opinions. That process continues today, although the points of discussion and discovery are now many times more specific in nature than the general concepts developed in the past.

Virtually everyone has an intuitive understanding of simple magnetic devices like the lodestone. However, an individual designing today's sophisticated magnetic products for the commercial market place must have a deeper knowledge and understanding of the subject.

The following training document provides some of the information and understanding needed to use magnetic products successfully. You'll find general information on magnetic theory and specific information on magnetic core types and applications. It requires a modest understanding of electrical circuits and basic principles of electronics, so some preparatory study would be beneficial for anyone without such background.

There are many ways to get up to speed in this subject. The possibilities include a basic electronics course of study or one of the programmed learning packages on the market. For example, the Heath Company offers a variety of electronics educational products.

## Energy

Arnold serves industries and individuals deeply involved with conversion and utilization of magnetic energy. Their actual final products can range anywhere from computers to electrical power distribution to automobiles. This manual provides an understanding of the basic phenomenon of magnetics and how Arnold products allow it to be put to practical use.

Any energy form—be it electrical, thermal, chemical, or mechanical—is only of value to us if it can be used in our everyday life. This is called doing work. To do work for us, energy must be converted from one form to another. The products that Arnold manufactures facilitate this conversion and make it efficient enough to be of practical use. It is certainly possible to make permanent magnet (PM) motors with lodestone motor arcs and transformers from cut-up tin cans. But, how efficient would they be, and would they allow the design of the everyday electromagnetic devices that have become necessities to us?

Understanding the formation and utilization of energy is very important.

## Units of Measurement

Before getting too involved in a discussion of magnetics, you should spend some time on one of the most controversial subjects you will encounter: the system of units that information/literature/design documentation should be using. Arnold Engineering has traditionally used the **CGS** (centimeter-gram-second) system. Its principal advantages are that the units are nicely “sized” for real-world magnetic materials, and that the permeability of free space is equal to one. (This last point will be defined more clearly later in this document.)

Unfortunately, CGS units receive only passing mention in formal training in electromagnetic theory. The system of choice in academic and scientific communities is the MKS (meter-kilogram-second) system or, as it is often called, the **SI** (System International) system. These units tend to be a little more awkward in size, and the permeability of free space is an exponential number. On the other hand, mathematical operations are much simpler when going from energy to power to flux density, etc.

## Simple Magnetic Theory

Fundamental to **all** magnetic theory is the concept that a magnetic field is produced when a current passes through a conductor. The direction and intensity of this magnetic field is a funtion of the direction and amplitude of the current.

The simple circuit shown in Figure 1 depicts how electrical energy is converted to magnetic energy. A current source, in this case a battery, is attached to a length of conducting wire. Because the electrical circuit is closed, current flows. This current is called the excitation current and, when used with a certain coil geometry, results in what is referred to as the **Magnetizing Force,** or **MMF per unit length,** or the **H** of the coil. The unit of the measure is **Oersted** in CGS units and **AMP-turn per meter** in SI units. Units of MMF (magneto-motive force) are **Gilbert** in CGS and **AMP-turn** in SI systems.

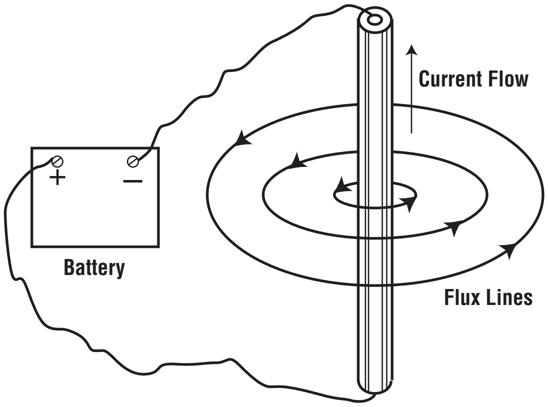

*Fig. 1*

1 AMP-TURN per METER = .0125 OERSTED

The flow of current creates a “force field” that is concentric to the conductor. This field was arbitrarily called a magnetic field by 19th century researchers, and a measure of its magnitude was called **Flux,** or lines of flux, or **B**. In other words, some amount of amps of current creates some amount of lines of flux. The resulting magnetic field is a pool of potential energy. The unit of flux is the **Weber** or the **Volt-second** in the SI system, and the **Maxwell** in CGS.

1 WEBER = 1 VOLT-SECOND

1 WEBER = $10^8$ MAXWELLS

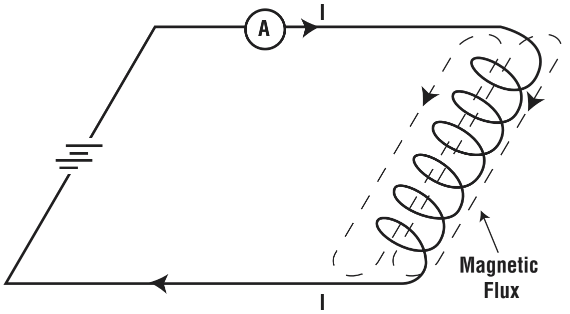

*Fig. 2* *Schematic representation of magnetic flux resulting from current flow in a coil.*

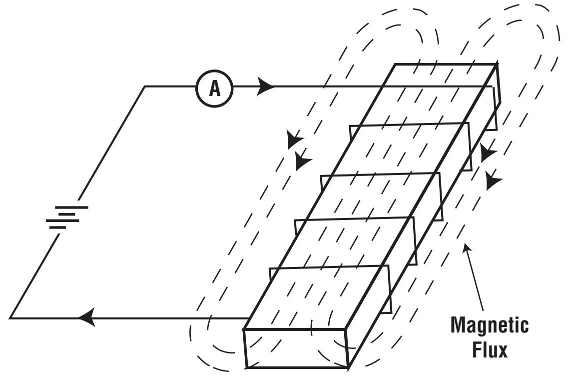

*Fig. 3* *Schematic representation of increased magnetic flux with a ferromagnetic core.*

From this simple beginning, scientists manipulated the phenomenon to perform work more efficiently. The single loop of wire was made into a multiple-turn coil (see Figure 2), proportionately increasing the amount of lines of flux produced by a limited amount of current. Many times the only way early researchers had to measure the amount of flux produced by a certain configuration was to observe the amount of attractive force a coil exhibited. It was only a matter of time before someone came upon the idea of putting an iron "core" inside the coil conductors (see Figure 3) and, naturally enough, the amount of force produced increased drastically over all previous experiments.

Two important concepts began to evolve from this early research.

The first is that the presence of an iron "core" obviously increased the concentration of lines of flux within the coil of wire. This further solidified the notion of flux density, or the number of lines of flux per unit of cross-sectional area. Flux density is also sometimes referred to as induction. The unit of measure of flux density is **Gauss** in CGS units and **Tesla** in SI units. Occasionally an engineer will use "lines per square inch" as a unit of induction, but this is not common.

1 TESLA = 10,000 GAUSS

1 TESLA = 1 WEBER PER METER$^2$

1 GAUSS = 1 MAXWELL PER CM$^2$

Flux density is one of the components used to determine the amount of magnetic energy stored in a given geometry. The other component is the MMF, described previously.

The other important concept that became apparent was that, in a situation where a magnetic material was inserted into a coil (see Figure 3), the flux (or flux density) was actually the result of two constituents—one being the contribution of the coil itself, the other the contribution of the iron core. These two parts are additive, and the total flux is the sum of the two.

$$\text{FLUX}_{\text{core}} + \text{FLUX}_{\text{coil}} = \text{FLUX}_{\text{total}}$$

The significance of this is best demonstrated by the use of normal and intrinsic demagnetization curves in Arnold's permanent magnet literature. The intrinsic curve is representative of the magnet's contribution, and the normal curve is the magnet plus the coil. There will be further discussion of this later in this document.

## Permeability

Not all magnetic materials respond equally to the applied MMF. In other words, different materials exhibit different flux densities when subjected to the same magnetization levels. To account for this, scientists developed a term to describe the mathematical ratio of flux density to magnetizing force. This ratio, called **Permeability,** is a measure of the magnetic sensitivity of the material.

Every magnetic material has a permeability that is numerically greater than the value of the permeability of free space. This means that magnetic materials are more responsive to the applied MMF than the "air" that they occupy. Since the value of a magnetic material's permeability is expressed relative to the permeability of free space, it will be numerically the same in either CGS or SI systems. The value of the permeability of free space, however, is quite different in the two systems.

Absolute permeability of free space = 1 (CGS) or $4\pi \times 10^{-7}$ (MKS)

The relative permeability of hard ferrite is slightly greater than 1

Relative permeability of neo-fe = slightly greater than 1

Relative permeability of samarium-co. = slightly greater than 1

Relative perm. of alnico = 3 - 7
"   "   "   MPP = 14 - 350
"   "   "   powdered iron = 8 - 75
"   "   "   Silectron = up to 30,000
"   "   "   Supermalloy = up to 300,000

Unfortunately, the permeability of magnetic materials is not constant. It is observed that permeabilities will change over a several-decade range as the excitation level is varied. Also, real-world materials are affected by their environment, and things like temperature and mechanical shock can have a profound effect on the actual value of permeability.

## Saturation

Although magnetic materials are more susceptible to excitation than air, they have the drawback of limited flux capacity. As the applied excitation becomes higher and higher, the material reaches a point where its permeability approaches the permeability of free space and it cannot hold any more magnetic energy. This point is referred to as **Saturation** and is characterized by the material's **Saturation Flux Density.**

Saturation is strictly a material property; it is not a function of the excitation current. Many engineers tend to be misguided on this point. A material's saturation flux density is only a result of its metallurgy and its operating temperature. (However, the excitation level at which this saturation occurs is a function of just about everything.)

Most materials do not have a well-defined saturation flux density. If an engineer specifies that a material have a minimum saturation flux density, he should also specify at what excitation level this flux density is to be measured. There are no hard and fast rules as to where a material is, by definition, saturated.

## BH Loop

In order to differentiate the properties of specific materials more easily, a measurement technique was devised that clearly shows all the phenomenon described above. This is the hysteresisgram, or as it is more commonly called, the **Hysteresis Loop** or **BH Loop**. Since it is of such basic importance to magnetic designers, some explanation of its features will be given.

The BH loop is obtained by exciting the magnetic material sample with a controlled, and varied, MMF and simultaneously recording the resulting flux density induced in the sample. Generally the format is to excite the sample to saturation in the positive direction and then instantaneously reverse direction and excite it in the negative direction. The final step is to reverse direction again and return to the positive saturation point.

The sample may or may not be driven into saturation during the test sequence. This point is of particular significance in permanent magnets, where the full potential of a material can only be realized if it is completely saturated when magnetized. As a practical footnote, it should be mentioned that, in the case of all permanent magnet materials and a few soft magnetic materials, the excitation source is actually an electromagnet where the amp-turns are indirectly applied to the sample.

Figure 4 shows a typical BH or hysteresis loop. Flux density, B, is displayed on the vertical axis and magnetizing force, H, is on the horizontal axis. Note that positive and negative values of both parameters are utilized. One variation of the BH loop is the demagnetization curve commonly used to display the properties of permanent magnet materials. The "demag" curve only represents the second quadrant of the full BH loop. This is where the material has been magnetized and now a gradual demagnetizing MMF is being applied (and thus the term demag).

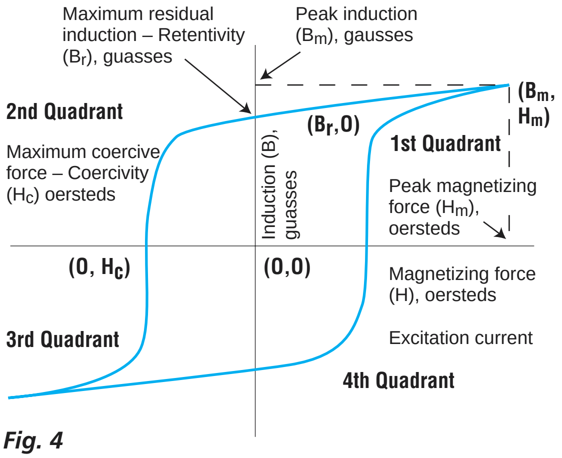

*Fig. 4*

For accurate results, the magnetic material sample being measured should start out completely demagnetized. This would be the axis point (0,0) on the BH loop in Figure 4. At that point the excitation current is zero and the sample contains no flux. As excitation is increased slowly in the positive direction, flux builds up in the material, also in the positive direction. Generally, the excitation is increased until saturation occurs; but, since this is not always the case, we will assume in this discussion that the material is not saturated. (The occurrence of saturation does not change the following test sequence.) This point of maximum excitation is signified on Figure 4 by ($+B_m$,$+H_m$), where $+B_m$ is the maximum flux density observed and $+H_m$ is the maximum MMF applied. Current then is slowly decreased to zero, to the point on the curve labeled ($+B_r$,0). But, as indicated in Figure 4, the flux does not return to zero. Instead flux density assumes what is called the residual flux of the sample. The symbol for **Residual Flux** is $B_r$.

One of the distinguishing characteristics of real-world magnetic materials is that they have "memory" of their previous excitation condition. This results in a "lag"in the response of the material when excitation is varied. The residual flux is a manifestation of this phenomenon. (It should be noted that **all** magnetic materials, including core products, have residual flux values.) This lag is referred to as **Hysteresis,** from which the name hyteresisgram or hysteresis loop is taken.

Now the excitation is increased in the negative direction, and a demagnetizing force is applied against the sample's inherent residual flux. Eventually the magnetic energy, in the form of flux, is forced out of the sample and the flux density returns to zero. This is point (0,$-H_c$). The amount of negative MMF required to demagnetize a material from $B_r$ is called the **Coercivity** of the sample material. Obviously, the coercive force is designated by $H_c$. The unit for coercivity is the same as that for magnetizing force, either amp-turn per meter or oersted.

This parameter differentiates "hard," or permanent, magnetic materials from "soft", or core type, materials. Soft magnetic materials are quite easily demagnetized. Hard magnetic materials are quite difficult to demagnetize, so they are able to retain the magnetic energy stored in them better. In either case, unless something comes along to demagnetize them, magnetic energy will be stored in magnetic materials indefinitely. More discussion on this point will follow in later sections.

The remainder of the BH loop is simply a mirror image of the first two quadrants. The sample is driven to ($-B_m$,$-H_m$), then ($-B_r$, 0) then (0, $+H_c$) and finally back to ($+B_m$,$+H_m$).

As mentioned earlier, the flux in the "air space" within the exciting coil does contribute to the total, or normal, flux observed or measured in the BH loop. Some hysteresisgraphs, as the instruments are called, are equipped to correct for this and display the intrinsic BH loop of the material. Other instruments do not. This additional flux contribution is only of significance in those situations (such as Arnox and Neo-Fe) where it takes a large MMF to magnetize and demagnetize the material, or for materials such as low-permeability powder cores where it takes a significant amount of MMF to saturate the material. This subject is dealt with only rarely in the case of soft magnetic products but, in PM literature, both the normal and intrinsic demagnetization curves usually are given for high-coercivity materials (see Figure 5). For intrinsic BH loops, an additional "i" subscript is added to all the defining parameters described above. In other words, $H_{ci}$ is the intrinsic coercivity of the sample, whereas $H_c$ is the normal coercivity. Both normal and intrinsic demagnetization curves are of significance to the PM circuit designer.

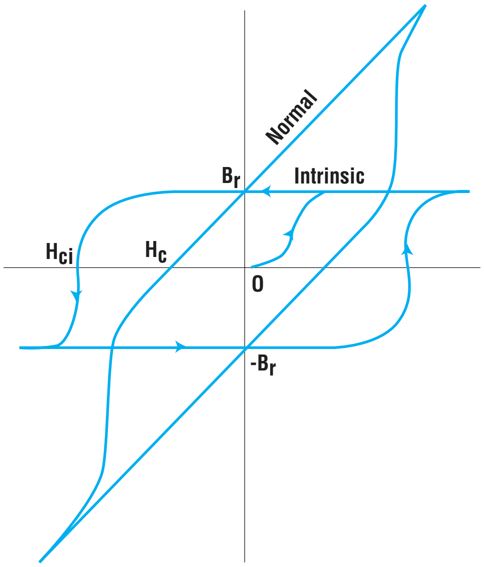

*Fig. 5*

## Magnetic Energy

As originally stated, the intent and purpose of high-performance magnetic materials is to convert, store and utilize magnetic energy more efficiently.

By definition, magnetic energy is the product of the flux density in the magnetic circuit and the magnetizing force it took to excite the material to that flux level.

$$\text{Energy} = B \times H$$

The unit of energy in the SI system is the **Joule,** in the CGS system it is the **ERG**. In permanent magnet design a special energy density, or energy product, is also used to indicate energy and storage properties per unit volume. The CGS unit of energy product is the **Gauss-Oersted**. The SI unit is the **Joule Per Meter$^3$**.

$$1 \text{ joule} = 10^7 \text{ ergs}$$

$$1 \text{ joule per meter}^3 = 125.63 \text{ gauss-oersted}$$

Now the differences between permanent magnets and core products start to become more apparent.

Soft magnetic materials, or core products, do have the ability to store magnetic energy that has been converted from electrical energy; but it is normally short-term in nature because of the ease with which these types of materials are demagnetized. This is desirable in electronic and electrical circuits where cores are normally used because it allows magnetic energy to be converted easily back into electrical energy and reintroduced to the electrical circuit.

Hard magnetic materials (PMs) are comparatively difficult to demagnetize, so the energy storage time frame should be quite long. The portion of the BH loop that shows the sample's normal state of energy storage is, as already described, the demagnetization portion of the curve from $(+B_r,0)$ to $(0,-H_C)$.

If hard magnetic materials dissipated their stored energy back into the magnetizing electrical circuit quickly, as do soft materials, they would be of no value to us. Instead, they use this energy to establish a magnetic field external to the magnet itself. This external field does work for us by interacting with, for instance, the conductor current in a PM motor. Presumably, unless something causes it to become demagnetized, the permanent magnet will maintain this external field indefinitely. One of the common misconceptions of novice PM motor designers is that, somehow, the energy stored in the magnet is being consumed as the motor is operated normally. This is not true.

As explained before, the product of the flux density and the magnetizing force is a measure of the magnetic energy stored in the permanent magnet.

## Magnetic Circuits

It is quite convenient to draw an analogy between the more common electrical circuit and something called a **Magnetic Circuit**. A magnetic circuit is essentially a schematic of the magnetic path, arranged in a closed loop, where the MMF sources (PMs and windings with applied currents) and MMF drops (areas with low permeability) are represented. To complete the analogy, "resistances" are against the applied MMF instead of the applied current, as is the case in the electrical circuit (see Figure 6).

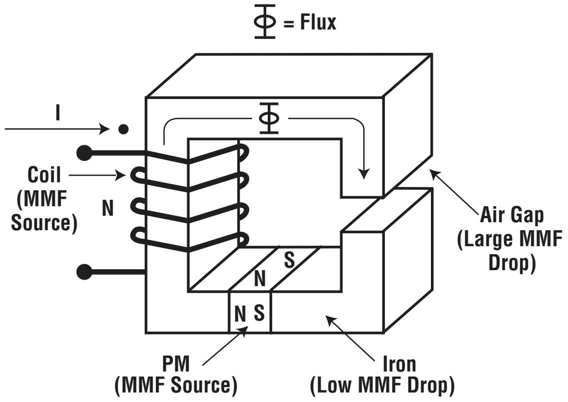

***Fig. 6*** *Typical Magnetic Circuit*

To facilitate the analysis of magnetic devices, the concept of **Reluctance** was introduced. This is the magnetic circuit "resistance" referred to above. This mathematical tool not only considers the permeability of that section of the magnetic circuit, but also its dimensions and shape.

The path that the lines of flux will take in a given geometry is analogous to current in an electrical circuit. Electrical current tends to take the path of least resistance. Magnetic flux tends to take the course of least resistance. Reluctance is inversely proportional to permeability and directly proportional to the length of the magnetic circuit.

Minimum reluctance is realized when the permeability of the magnetic materials are high, when the **Air Gap** in the magnetic path is reduced, and the configuration tends toward the material forming a closed loop (see Figure 7). In a PM circuit, the effect of reluctance is to demagnetize the material. Higher operating flux densities can be realized if the air gap (reluctance) in the PM circuit is reduced.

Generally, air gap is introduced into magnetic circuits in two ways: a **Discrete** air gap and a **Distributed** air gap (see Figures 8 and 9, respectively). Discrete air gaps are significant in both PM and soft magnetic circuits; distributed air gap is only applicable to powder core products.

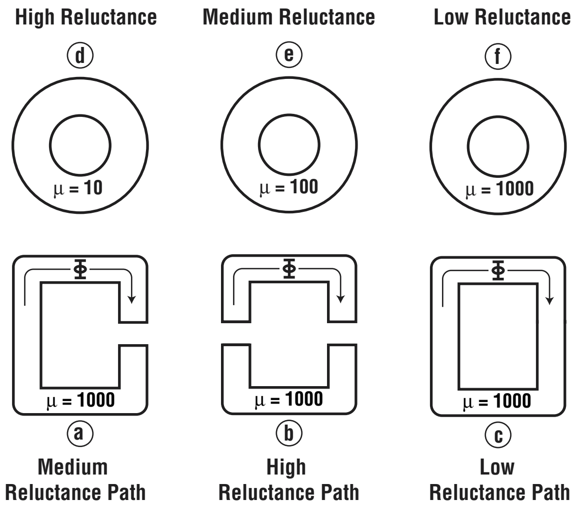

*Fig. 7*

A discrete air gap, as used in a gapped C-Core or in a PM motor, is best described by a situation where a very few (usually one or two) comparatively large air gaps are introduced into a basically high-permeability material that is part of the path of the circuit.

A distributed air gap actually refers to a very large number of small air gaps throughout the core. Examples of distributed air gap are Molybdenum Permalloy Powder (MPP) and powdered iron cores. Because it minimizes second-order effects such as leakage and fringing flux, distributed air gap allows the opportunity to obtain much larger effective air gaps in the magnetic path.

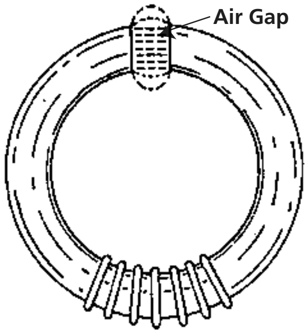

***Fig. 8*** *Cutting a small section out of an iron ring to make an air gap increases the total reluctance and therefore reduces the total flux.*

There are other ways to obtain an air gap without introducing a physical space into the circuit. One common occurrence is in a C-core where the normal manufacturing process (specifically the impregnation system) tends to lower the permeability of the material, creating an effective air gap. Additionally, dynamic effects such as core loss tend to create an effective air gap by reducing the net permeability of the material.

## Electrical Properties of the Magnetic Circuit

Devices made with Arnold magnetic materials generally are used in conjunction with electrical current to perform useful work. This is almost always true of soft magnetic products and quite often true of hard magnetics as well (as in a PM motor, for instance). Whenever the device is connected to a circuit that provides current, it will exhibit certain electrical properties in that circuit. The most significant of these is **Inductance**.

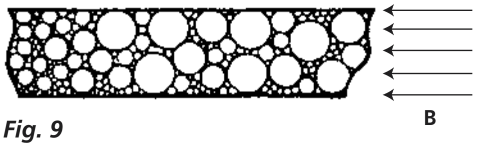

*Fig. 9*

Inductance, along with resistance and capacitance, is one of the three basic parameters of any electrical circuit. Inductance determines the electrical **Impedance** that the device presents to the electrical circuit. This, in turn, dictates the electrical current that will flow. The unit of inductance in both SI and CGS systems is the **Henry**. The unit of impedance in both systems is the **Ohm**.

Mathematically, inductance is inversely proportional to the reluctance of the magnetic circuit of the device. Thus a core with a large air gap (a high-reluctance magnetic circuit) will provide very little impedance to the electrical circuit. Likewise, a PM motor designed with a very large clearance between the rotor and the arc magnet will tend to provide less impedance to the circuit supplying the electrical power.

When a magnetic material saturates, permeability decreases and reluctance increases rapidly. Consequently, the impedance of that device tends toward zero and it begins to disappear from the electrical circuit.

## Soft Magnetic Materials

Soft magnetic products (or core products, as they're more commonly called at Arnold) offered by Arnold consist of the **Molybdenum Permalloy Powder (MPP), HI-FLUX™ and SUPER-MSS™ cores**. In addition, a wide variety of tape wound products are available from National-Arnold Magnetics. Additional soft magnetic materials, in unfinished form, are sold through the Rolled Products Division of Arnold. Discussion will be restricted to finished cores in this document.

## Core Loss

Core loss is of minimal importance in hard magnetic materials but is extremely important in soft magnetics. Core loss represents an inefficiency, so it is highly disdained by the designer. In many instances, core loss will render a particular material unusable in an application. The most glaring example would be the high-frequency power-conversion transformer industry, which is dominated by soft ferrites. In general, the products offered by Arnold are too lossy, however there are many important exceptions. For example, flyback transformers operated in a lower range of high switching frequency. Arnold powder core products are quite useful for high-frequency power conversion inductors. The reason for this will be explained in a later section. The unit of core loss in both SI and CGS systems is the **Watt**.

1 watt = 1 joule per second

Core loss is realized by two major components: **Hysteresis Loss** and **Eddy Current Loss**.

Hysteresis loss results from the fact that not all energy required to magnetize a material is recoverable when it is demagnetized. The wider and taller the hysteresis loop, the more hysteresis loss a material has.

Eddy current loss is the result of small circulating currents (eddy currents, not unlike eddy currents produced in the wake of a boat) that are induced when the flux density changes in the magnetic material (see Figure 10). The amplitude of these small currents is dependent on the **Electrical Resistivity** of the material. Products produced by Arnold have low resistivities. As a point of comparison, soft ferrites, while having large hysteresis losses, have very high resistivities and quite low eddy current losses. This is the reason they are the material of choice at high-frequency.

## Energy Storage vs. Energy Transfer

As discussed previously, energy storage is a fundamental mechanism in magnetic theory. In soft magnetic materials this is exploited to introduce "time delay" into electrical currents. For instance, this time delay can be used to differentiate between frequencies or filter out unwanted frequencies in the excitation current. As a rule, cores used for this application require basic alterations to the magnetic circuit to enhance its energy storage.

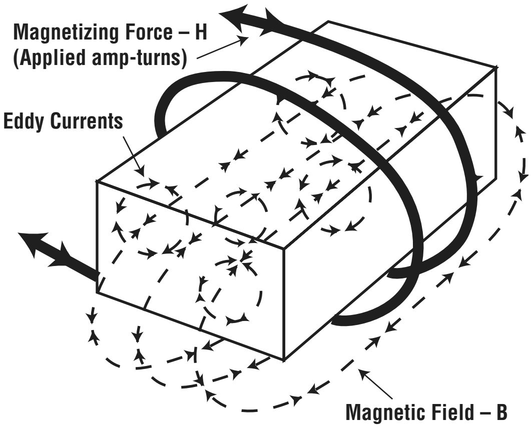

*Fig. 10* *Energy Loss in form of heat*

The **Inductor** or the **Choke** explicitly utilizes the concept of storing electrical energy in the form of magnetic energy. The flux build-up in the core is proportional to the applied current and to the effective permeability of the core material. The magnetic energy is converted back into electrical energy as soon as the exciting current is removed.

It was stated previously that energy stored in a magnetic circuit (or core) is proportional to the applied excitation current multiplied by the resulting flux. Consequently, to increase the amount of energy stored in a given core (assuming that the basic dimensions don't change), there are only two possible alternatives: increase the flux or increase the applied amp-turns. Since all materials have an inherent and unchangeable saturation flux that limits the obtainable flux density, the only possibility is to somehow increase the applied current necessary to force the core into saturation: in other words, to "desensitize" the core to the magnetizing current. This is quite easy to accomplish simply by mechanically lowering the effective permeability (increasing the reluctance) of the device. This is almost always done by introducing an air gap into the magnetic circuit.

**Energy Transfer** is a special case of energy storage that is somewhat more difficult to understand than energy storage, which is basic to all magnetic devices.

Energy transfer in a magnetic device is most typically represented by a two-winding **Transformer,** where excitation current flows in one winding and an induced voltage appears in the other winding. At first glimpse, you might be tempted to say that no energy storage is taking place in a typical transformer. This is not the case. In fact, two energy conversion/storage mechanisms are taking place.

The first is the familiar "time delay" energy storage already described. This is generally undesirable in a transformer because it detracts from the efficiency of the transfer. Usually every attempt is made to minimize exciting energy. The user wants maximum permeability in the core of a transformer, so air gap—either real or apparent—is minimized.

The desirable conversion/storage mechanism is where magnetic energy stored in the core is almost instantaneously transferred to the secondary winding and the electrical load attached to it. The core never really "sees" this magnetic energy, and the magnetic circuit does not have to support any flux created by the conversion. The energy consumption of the load attached to the secondary winding is said to be "reflected" into the primary circuit.

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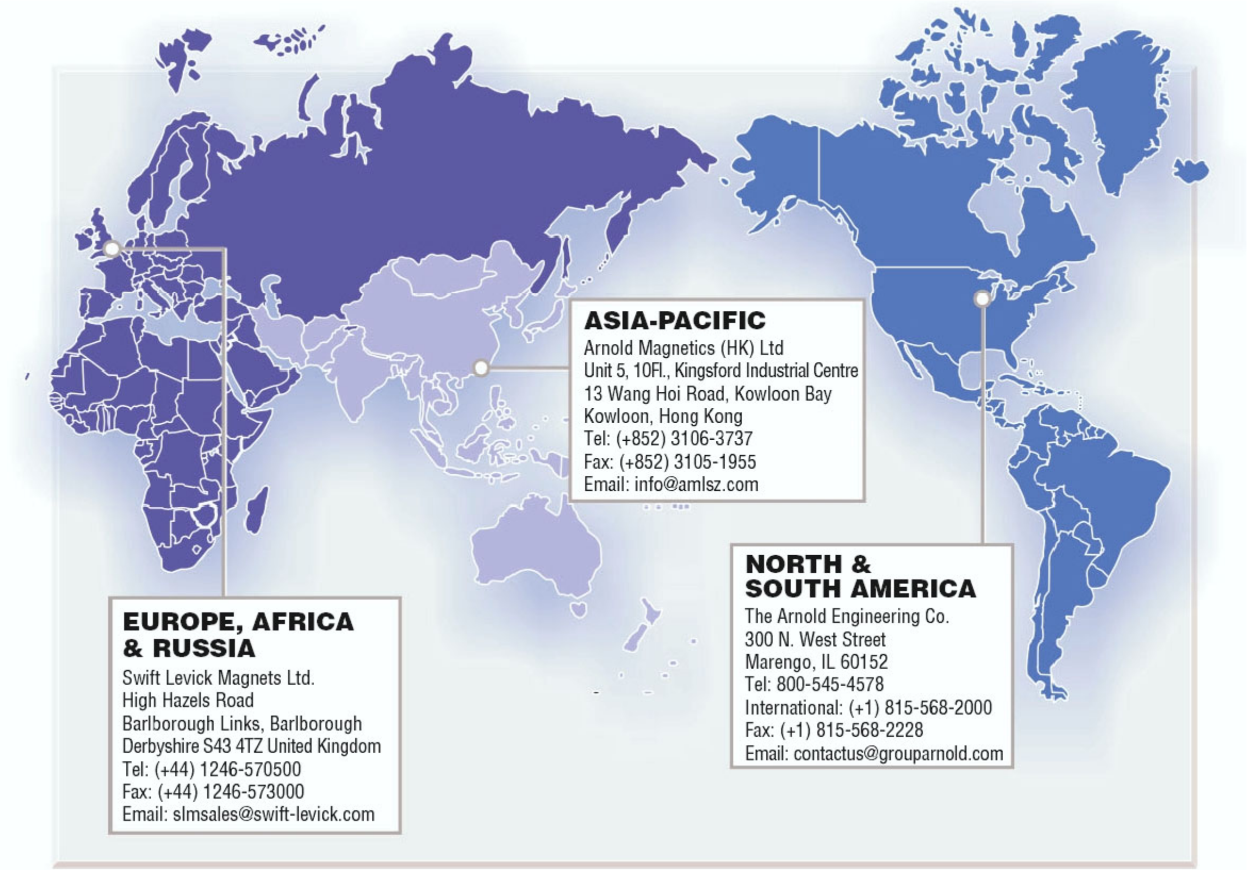

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