Magnetic Measuring Techniques for Both Magnets and Assemblies

Roger Allcock
Technical Manager
Arnold Magnetic Technologies Ltd.
Vector 31. Waleswood Way
Wales Bar, Sheffield
S26 5NU
UK

Steve Constantinides
Director of Technology
Arnold Magnetic Technologies Corp.
770 Linden Avenue
Rochester, NY 14625
USA

Summary
Proper device design, fabrication and operation are achieved through a combination of engineering skill, material specification and approved assembly techniques. Specifying permanent magnets with sufficient detail is only part of the task. Production must also measure and verify magnetic performance of stand-alone magnets, magnetic subassemblies and/or of the completed mechanism. Ensuring adequate magnetic performance early in the process maximizes production efficiency and minimizes production and quality assurance costs.

Introduction
Measurement of magnetic properties begins with selection of the most appropriate method. Once the method is determined, equipment capable of providing adequately accurate measurements must be specified and acquired. The equipment must be suitably calibrated, installed and set up for operation. Finally, operators must be trained in using the equipment and interpreting results. It is the objective of this paper to describe magnetic properties measurement options including advantages and disadvantages.

No discussion of measurement can ignore the issues of precision, bias, repeatability and accuracy. Precision, sometimes referred to as resolution, reflects the number of significant digits of measurement output, regardless of accuracy and repeatability.

However, without stable, repeatable readings, additional digits of resolution mislead the viewer.

There are standard methods for determining repeatability of measurements that take into account variations due to operator, time of day, equipment start up versus stable operation, environment (e.g., temperature), and more. These often fall under the name R&R studies or gauge repeatability and reproducibility. If one Googles "R&R studies quality" numerous helpful references are returned.[(1)(2)]

According to quality assurance software and services company, PQ Systems, "The objective of a simple R&R study… is to determine whether the measurement system in use can adequately distinguish between or among units. There are a number of factors that affect the ability of a measurement system to discriminate among the units it measures. These factors may be categorized as those that typically contribute to any process variation: machine (the gage), operator (appraiser), method (method of measurement followed), material (units being measured), and environment.

"In conducting a simple study, an attempt is made to minimize or hold most of these factors constant…"[(3)]

The idea behind today's talk is to consider the wide range of methods available for measuring permanent magnets while:

- Bearing in mind the diversity of interested parties: R&D, material manufacturers, magnet system suppliers and end users
- Explaining the differences and suitability of different methods for each party

Magnetic Characterization

For every application there is a decision to be made on which characteristics of a magnet are to be specified and measured. These target properties are used to gauge magnetic "quality" and therefore will require measurement at one or more points in the supply chain. Table 1 illustrates the most common equipment/method used for each.

Table 1: Key magnetic figures of merit and methods of measurement

Figure of Merit	**Abbreviated Description**	**Measurement Method**
B_r, Residual Induction	Measure of flux density of the magnet in closed circuit and w/o externally applied field	Hysteresisgraph; may be estimated by Helmholtz coil-fluxmeter
H_{cJ} (or H_{ci}), Intrinsic Coercivity	Measure of a magnet's resistance to de-magnetization	Hysteresisgraph, VSM, SQUID, and may also be estimated or measured by pulse de-magnetization
BH_{max}, Maximum Energy Product	Indicative of the energy available for interaction within motors and generators	Hysteresisgraph; may also be estimated from Helmholtz measurements
Flux	Measure of magnetic output; related to magnetic moment	Helmholtz or Search Coil and Fluxmeter

Field Strength, Flux density	Measure of magnetic (flux) output per unit area	Gaussmeter (Hall element or NMR); positional or as part of a fixture (e.g. gap probe)
Reversible Temperature Coefficients, (B_r and H_{cJ})	Indicate how the magnetic characteristics (B_r and H_{cJ}) change with temperature	Hysteresisgraph, VSM or SQUID magnetometer
Field Distribution	Measure of the distribution of the flux	Magnetic Field Scanners: Gauss probe and meter and x-y-z and/or rotational stage

For each of the methods shown in Table 1, there are technical limits to measurement resolution and accuracy. Luca Bottura of CERN produced a chart[4], Figure 1, relating accuracy versus field strength (sensitivity) for numerous field measurement instruments. Probably the most common device for measuring field strength is the gaussmeter, a combination of Hall probe and attached power supply and meter.

Gaussmeter

The Hall effect was discovered in 1879 by Edwin H. Hall at Johns Hopkins University.[5] The availability of semiconductor materials and integrated circuits, spurred development of Hall effect devices in the 1950s, 60s and 70s.[6] The invention of the Hall probe and commercialization[7] led to rapid, inexpensive and adequately accurate readings of field strength that quickly became the preferred method for individual readings and used in combination with search coils for measuring other magnetic characteristics.

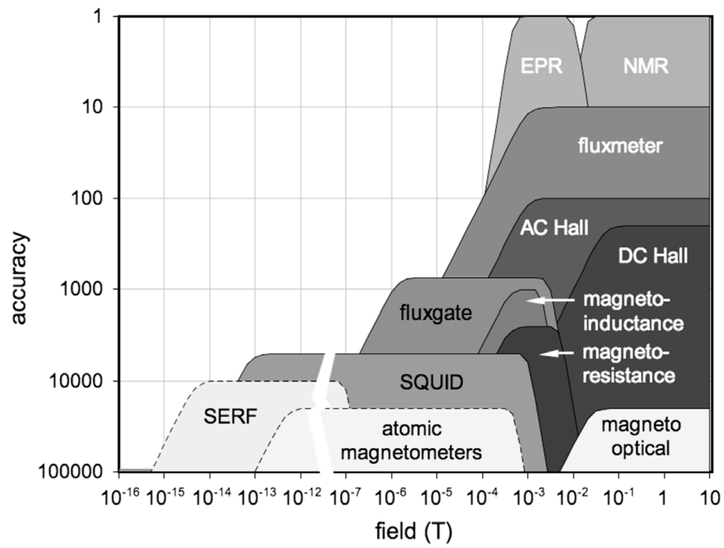

Figure 1. Accuracy and sensitivity of magnetic field measuring devices

The Hall probe is made with a small, ceramic chip of conducting material. One common material is indium-arsenide. Leads are soldered on each of the four sides as shown in Figure 2. The electron flow is partially diverted by the magnetic field vector perpendicular to the flat face of the chip. By controlling the electron flow and measuring the potential difference across the side electrodes, the magnitude of the field can be inferred. When the system is calibrated and the calibration constants entered into firmware, the output is field strength (field density) perpendicular to the chip and is indicated on the meter or communicated to a computer for processing. Hall devices are corrected for temperature effects on output and the output is linearized versus actual field strength.

The Hall element (chip) is brittle and physically weak and can be easily damaged. Therefore, it is mounted on a rigid substrate and (usually) encased in a protective sheath. Hall element (chip) position within the holder presents the potential for inaccuracy. This error is small for fields with low gradient but can be excessive for high gradient fields such as those near a magnet or magnet-air interface. Probe manufacturers often specify the location of the chip within the holder; many do not. In either case, it may be necessary to establish the precise chip position in order to guaranty accuracy. Furthermore, the solder connections on the chip are not perfectly symmetrical, so the "magnetic neutral plane" of the chip may not agree with the physical neutral plane. Also, the chip may not sit perfectly flat on the supporting substrate and the substrate may not have parallel faces. A preferred method for locating the chip is to use a very fine, small magnet assembly with precision dimensions to establish the switching point of the probe relative to its external dimensions. Such a device is the Hall Probe Element Locator (HPEL) used by Arnold and shown in Figure 3. The HPEL utilizes a 0.0020" (0.05 mm) thick FeCrCo magnetic strip to generate the field for neutral point sensing as shown in Figure 4.

$$V_H = R_H \, I \, B \, \mathrm{Sin}\, \Phi / t = R_H \, I \, B \, \mathrm{Cos}\, \alpha / t$$

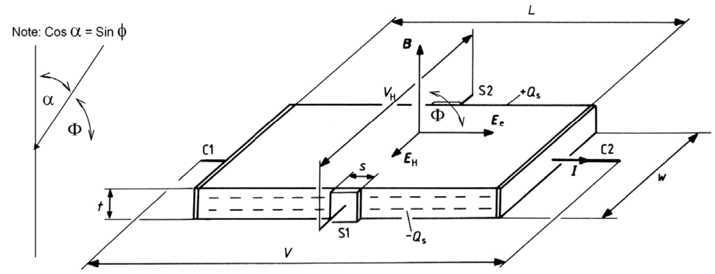

Figure 2. Schematic of a Hall chip(7)

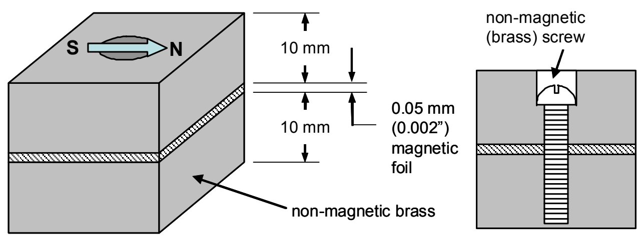

Figure 3. Hall Probe Element Locator

Hall probes come in a variety of sizes, shapes and range output. The two principle types are axial, with the plane of the chip perpendicular to the end of the probe, and transverse, with the plane of the chip parallel to the side of the probe.

Measurements using a Hall probe vary depending on angle of incidence of the magnetic field vector and the face of the Hall chip. It is possible with three chips mounted on three orthogonal axes to

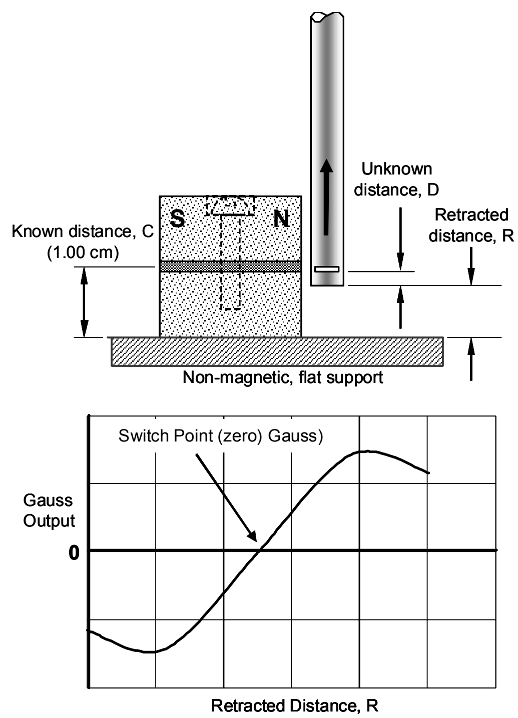

Figure 4. Finding Hall chip neutral plane by change in polarity of the field

measure not only magnitude, but also the direction of the field vector. The three chips cannot be co-located – a small offset is a physical necessity – so high field gradients will produce an error proportional to the gradient. This can be eliminated by precisely moving the probe prior to measuring each axis so that the chips would have been in the “same” location. This would have been exceedingly tedious prior to computerization. Now stepper motors and computers can automate the task to produce accuracy at or near the limit accuracy of the Hall chips.

Stepper motors and computers also provide for field scans, that is, the continuous or near continuous measurement of field strength (magnetic field density) as a function of position of the probe relative to a field source. These scans can be linear, planar, or multi-planar (x-y-z scans). The inclusion of a rotating stage allows rotational scans. Precision of probe relative to the magnet or source of field is managed through precision of the physical stage assembly. The three orthogonal axes must reside at 90.0 degrees mutually from each other and be true over the range of movement in the x, y, and z axis directions.(12)

Likewise, the rotational stage and probe position are critical for close-in measurements. It may be beneficial to fasten a non-magnetic spacer to the probe or to the item being measured and spring-load the Hall sensor holder against the spacer.

NMR, or Nuclear Magnetic Resonance, is another technique for quantifying magnetic field strength. It was first described and measured in molecular beams by Isidor Rabi in 1938,(8) and in 1944, Rabi was awarded the Nobel Prize in physics for this work. Nuclear magnetic resonance (NMR) is a physical phenomenon in which magnetic nuclei in a magnetic field absorb and re-emit electromagnetic radiation. A key feature of NMR is that the resonant frequency of a particular substance is directly proportional to the strength of the applied magnetic field.

Advantages of NMR magnetometers include: extremely precise measurements, no drift, not directionally sensitive – reads vector sum of magnetic field. Constraints of NMR include: requires uniform, DC or slowly varying fields and low-field NMR requires a large sample size (strong field). Additional disadvantages of NMR magnetometers are high price – about 10x a typical gaussmeter – and large probe restricting measurements in small spaces.(10)

Fluxmeter

A fluxmeter measures the effect of a magnetic field on surrounding materials – there is no flow of physical matter. The measurement is voltage generated by the presence of a changing magnetic field and a receiving coil. The source of the magnetic field and the coil must move relative to each other to generate a changing potential across the coil(s) and measurable “flux” output. The fluxmeter can provide instantaneous output or integrate the change in potential difference over time. Output can be via analog meter, but is increasingly via digital display and digital output to computerized data collection.

A search coil is one or more turns of wire either free-standing (heavy gauge) or in a support structure (paddle or probe, thin gauge wire). The coil will have calibration in area-turns provided by the manufacturer and usually written on or affixed to the probe. More turns provides greater sensitivity for detection and measurement of weak fields. The leads running from the coil to the fluxmeter must be twisted to prevent them from acting as part of the coil.

Single turn coils are suitable for direct measurement of a magnet's Bd. By positioning the coil at the neutral plane of a simple-shaped magnet, zeroing the fluxmeter and extracting the magnet from the coil (or slipping the coil from around the magnet), and integrating the voltage generated, the total magnetic field output can be calculated. The coil must conform closely to the size and shape of the magnet being tested. It is possible with computer manipulation of the data to zero the integrating fluxmeter, pass the magnet completely through the coil to a point far on the other side and to compute the flux contributed by passage to the neutral zone, reverse the sign of the signal and compute the flux from the opposite end of the magnet. This avoids having to find the neutral cross-section.

Purchased coils are of nominal cost and include calibration/certification. In-house made coils are very simple to make but should be calibrated or "quantified" via measuring of a gold standard.

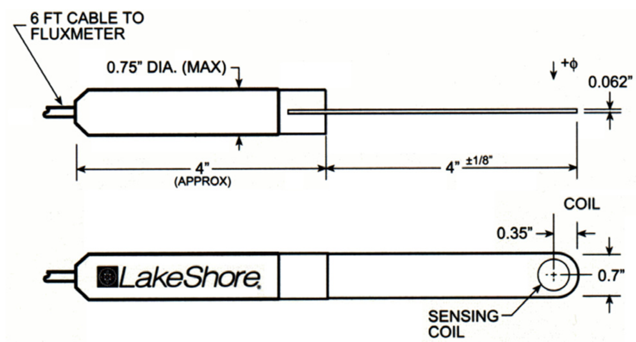

Figure 5. Typical search coil

When current flows in a wire, a magnetic field is generated around the wire. If a spiral of wire is formed – many turns next to each other – the result is an axial field aligned with the coil central axis. This arrangement is called a solenoid. In c.1871 Hermann von Helmholtz calculated that a pair of coils separated by a certain distance related to the coil diameter would produce a region within the boundary of the coils with relatively uniform magnetic field strength when a current was caused to flow through the coils. (The coils are connected in series). While it is difficult to work within the central region of a solenoid, the open, separated arrangement of the pair of coils makes physically working within the uniform field region relatively easy to do. The pair of coils constructed with appropriate dimensional control is referred to today as a Helmholtz coil. They can be purchased from many companies or constructed in-house following the mathematical constraints discussed in reference texts or on-line (http://en.wikipedia.org/wiki/Helmholtz_coil).

When the coils are connected to a fluxmeter and a magnet moved relative to the coils in a specific way described below, we create a very simple generator whose output is a function of the strength of the magnet. By incorporating the coils' physical information (number of turns of wire, resistance, physical size) and information about the size and shape of the magnet, it is possible to calculate the B_{di} of the magnet and its magnetic moment and dipole moment. With a precisely constructed system, it is also possible to measure flux generated in each of the orthogonal axes and the deviation of the vector sum of flux output from the physical structure of the magnet – something often referred to as error-angle.

Error angle = ATAN $((Mx^2 + My^2)^{0.5} / Mz)$ (Eq 1)
where Mz is the direction of magnetization; error angle in degrees

Helmholtz coil-fluxmeter systems are calibrated to produce accurate output when a magnet is either introduced from afar into the center of the coil system or removed from the center to a point outside the Helmholtz coil. However, the integrated output generated by rotating a magnet in the center of the coil is exactly twice as much. Rotating a magnet is often more easily accomplished and in producing twice the output also increases the sensitivity (resolution) of the system. Rotating the magnet requires a “stage” or holder for fixing the magnet in the center and along the axis of the coil. Then, either using the fixture or human hand, the magnet is rotated 180 degrees to produce the output.

The measurement is affected by the presence of ferromagnetic material within or near the coils. The magnet’s field will be distorted by the ferromagnetic material and the produced values will be in error. Presence of ferromagnetic materials on the operator will also affect the readings. Such items as pens with a pocket clip made of spring steel, key rings, cell phones with speaker magnets, and signal generating equipment including radios will all contribute to variation in signal output. A general rule is to keep the coil at least five coil diameters away from ferromagnetic material. More sensitive systems will benefit from additional spacing requiring consideration of building construction elements (rebar in the floor, electrical wiring, electrical transformers). Moving equipment will also affect readings. Items such as fork lift trucks, metal work carts, and metal trays and racks can influence the readings. It is advised to test movement of items within 15 to as much as 50 feet (5 to 15 meters) from the coil to verify that readings are not being unduly influenced.

The combination of a slip coil flux value and a Helmholtz coil flux value allow calculation of both B_d and B_{di}. These in turn provide estimates of B_r and energy product. Assuming negligible spontaneous knockdown after pulse magnetizing in open circuit, the value of energy product (BH) can be also be assumed to approximate $(BH)_{max}$.

Magnetic properties vary with temperature. The greater the desired accuracy of test output, the more sensitive we must be to the temperature of the magnets and the test environment. For example, it may be necessary to specify the temperature of the room where the test is conducted and how long the magnet or magnetic components have been in that environment before they can be tested.

Handling of magnets can alter their temperature (hand contact). Suitable precautions must be instituted to minimize handling time. Even the length of time to re-measure a sample, when it involves a human pick-and-place activity can be enough to affect the output. Ferrite is worst in this regard, but the effect can be observed with Neo magnets as well. Alnico is the most stable and SmCo magnets are only slightly affected. See Figure 6 for estimates of the affect of temperature on HH flux measurements.

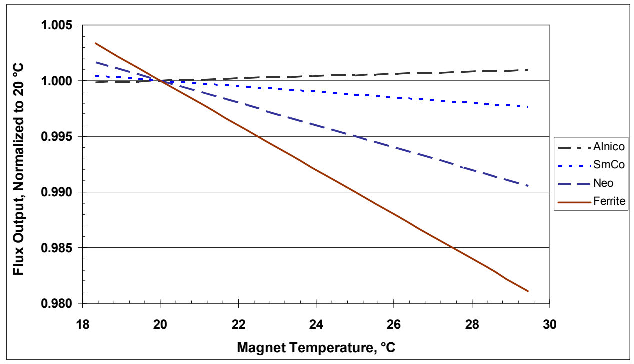

Figure 6 chart of normalized flux change as function of temperature

Hysteresisgraph

A magnetometer is any device used to measure a magnetic field. We've discussed Gaussmeters and fluxmeters. Now we will discuss a system using multiple measurement devices combined in a system so as to establish the direct measurement of the intrinsic magnetic characteristics of a permanent magnet. There are several types of magnetometers that can do this: hysteresisgraph, VSM, SQUID magnetometer, and the pulsed field magnetometer.

What information does the hysteresisgraph provide? Magnetic materials react to the presence of external magnetic fields. The external fields induce a field within the magnetic material. When we relate the magnitude of the applied field to the induced field we obtain measurements useful for designing devices such as motors, torque-coupled pumps, sensors, actuators, etc. (The key characteristics may be seen in Table 1).

The most common industrial device for obtaining this information is the hysteresisgraph. It is a system in which the magnet to be tested is placed in a closed magnetic circuit. This is accomplished by having at least one of the poles adjustable with regard to the opposing pole to create a gap of varying length. The magnet is introduced into the gap and the pole(s) adjusted to close the gap. This requires that the two pole faces be flat, parallel and perpendicular to the direction of magnetization. In order to measure the induction (induced field) within the magnet, a coil surrounds the magnet during the test. During the test an external field is applied by electromagnets that are part of the closed magnetic circuit. To separately measure the applied field, we use either a second coil (that may go around the magnet but which does not enclose the magnet) or a Hall probe placed within the gap and next to the magnet.

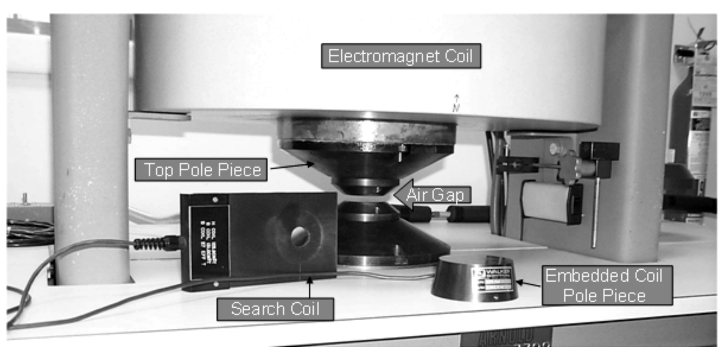

Figure 7. Hysteresisgraph showing search coil, pole caps and electromagnet. Embedded pole cap can be substituted for standard pole cap.

A Hall probe measures the field strength on a continuous basis. Coil-fluxmeter combinations measure changing field strength. Accuracy of the hysteresisgraph measurements benefits from minimizing meter drift ("nulling") and zeroing of the metering system both before and after testing to remove residual drift from the output. The magnetic circuit is not constructed of perfectly soft magnetic material and so retains some small degree of induction which must also be measured both before and after the test and used to correct the measured values. Corrections due to drift and retained magnetism are applied to the entire test loop.

The lower the B_r and H_{cJ} of the magnet being tested, the more sensitive the measurements become to the condition of the hysteresisgraph components. A practical lower limit for H_c is between 25 and 50 oersteds depending on construction materials. Materials with H_c below 25 oersteds is considered a soft magnetic material and requires different measurement methods.

The majority of search coil systems measure both the induction and applied fields with coils. Both coils are contained in a structure called the “search coil” or “paddle”. The “B” coil is wound, many turns, continuously around the sample opening. The “H” coil is wound around the general area of the opening, but so that it does not form a closed loop around the magnet. In many systems there is an additional “H” coil that can be connected, externally, to the B coil but in reverse polarity so that its H signal is subtracted from the B signal producing just the magnetic contribution of the sample being tested. This has the advantage of reducing noise – what affects the B coil affects the H coil equally. However, it requires that coils be very accurately balanced. Imbalanced coils will produce an error in H_c, $(BH)_{max}$ and Recoil Permeability.

Instead of a surrounding “search” coil, it is also possible to embed a coil in the pole piece. Since there is often a pole-to-pole difference in magnetic output of a magnet, using two embedded coils, opposite each other within the pole caps and averaging the output produces more accurate results for the average properties of the magnet sample. The field being measured is that which passes through the Supermendur pole cap within the coil. This region of the pole cap is adjacent to the pole of the magnet being tested. It is essential that the magnet totally cover the coil area which is typically ½” (12 mm) in diameter. Embedded coils allow testing magnets of varying size and shape without the inconvenience of changing search coils.

When embedded coils are used, the H field is measured with a Hall probe placed in the gap midway between the poles and as close to the magnet as reasonably possible.

The requirement to use a search coil around the magnet and/or a Hall probe in the gap requires that the magnet thickness (its magnetic length) be larger so that the pole caps can be closed into contact with the magnet. During the test on high coercivity rare earth magnets, the magnitude of the demagnetizing field is so large as to elastically deform the steel return path. It is necessary for the pole caps to simultaneously be in close contact yet to have removed backlash from the adjusting system to ensure minimal applied stress on the magnet during the test.

Alnico and ferrite magnets can be saturated in the hysteresisgraph in the first quadrant by means of the applied electromagnetic field, thus they do not need pre-magnetization. Rare earth magnets require pre-magnetization, accomplished by a pulse field ranging from 35 to 55 kOe (2800 to 4400 kA/m) depending on magnet type and grade. Even the best rare earth magnet can experience minor spontaneous demagnetization when magnetized in "open circuit". A decision must be made whether to test the magnet in this very slightly demagnetized condition or apply a magnetizing (1st quadrant) field to the magnet in the hysteresisgraph just prior to obtaining 2nd quadrant data. Testing the magnet as-is represents what a customer is likely to see; testing after re-saturation obtains the maximum intrinsic magnetic values. Spontaneous knockdown can be less than 0.1% but may be as high as several percent depending on size of the magnet, rounding of edges, (ferromagnetic) nickel plating, permeance coefficient, H_{cJ} and loop squareness.

Magnetic properties change with temperature. To quantify these changes it is necessary to test magnets over a range of temperatures. In a hysteresisgraph this is accomplished by either heating/cooling the pole caps or by introducing an enclosed temperature controlled structure in the gap between the pole caps and then sliding the magnet and search coil into this structure. Heated pole caps are simple, however, the enclosed structure provides better temperature control especially at higher test temperatures. The enclosed structure also allows cooling while the heated pole caps do not. The normal procedure is to introduce the magnet three minutes prior to starting the measurement to allow the magnet to stabilize at temperature. The adequacy of this brief residence time can be verified by both noting changes in temperature immediately adjacent to the magnet being tested and observing the 1st quadrant trace during re-magnetization and the relaxation back to zero field: the two traces should overlay during the majority of the trace, that is over the portion subsequent to re-saturation of the magnet.

An advantage of the hysteresisgraph, is that the test is conducted in closed circuit and no correction needs to be made for the self-demagnetizing stress internal to the magnet. VSM measurements require this correction calculation which introduces another variable and potential source of error. VSM samples are also small in size which makes accuracy of dimensional measurement and precision of shape important issues. A small sample is also dependent on uniformity of the bulk magnet material so that the small sample size fairly represents the larger magnet structures.

A VSM measures the magnetic response of a sample to the imposed field of an electromagnet. The sample is affixed to the tip of a holder which is movable via rotation and sinusoidal vibration. A distinct advantage of a VSM lies in the ability to place the end of the holder with the magnet into a chamber for heating or cooling. A standard chilled chamber can be controlled from room temperature down to 4.2 K. Heated chambers operate up to 1000 degrees Celsius.

Design of motors and sensors require estimates of magnetic flux output over the application temperature range. Furthermore, magnets in motors are subject to demagnetizing stress and it is necessary to ensure adequate resistance to this stress as indicated by H_{cJ} and H_k at the maximum use temperature. A correlation between temperature and B_r and temperature and H_{cJ} can be obtained by testing samples at a range of temperatures and calculating an average rate of change as a function of temperature between specified temperature limits. These values are called Reversible Temperature Coefficients of Induction (B_r) and of (Intrinsic)

Coercivity (H_{cJ}). By making a sufficient number of measurements, a polynomial regression fit can be obtained to freely calculate magnetic properties at any temperature within the tested range or even by extrapolation outside that range. Most materials are accurately described using a 2nd order polynomial though some may require a 3rd order fit.

A significant shortcoming of the hysteresisgraph is experienced when testing rare earth magnets: the intrinsic coercivity can be greater than the flux-carrying capability of the pole caps. Supermendur pole caps will saturate between 22.0 and 22.5 kOe (1790 kA/m). When this happens, the pole caps behave like air resulting in rapid spreading of the field parallel to the faces of the pole caps and extending into the region around the caps. In a well-constructed and close-fitting search coil, the curve shape will become distorted but the final value of H_{cJ} will be close to actual. This curve distortion prevents accurate reporting of H_k and loop squareness. H_k is important to the design engineer as a predictor of the onset of demagnetization in the application. It is possible to run the test at high fields without a magnet in the coil and use the resulting data to correct the with-magnet test data. However, this is a tedious process and seldom done. The problem in a VSM is that the size of the electromagnet to generate these high fields can be substantial (expensive).

A pulse demag test technique has been used for several decades to estimate the 2nd quadrant hysteresis loop. D.L. Martin and M. Benz[13] described the technique shortly after the discovery of SmCo magnets in the 1960s when the problem of large H_{cJ} values first occurred. The method is to saturate the magnet to be tested using a pulse magnetizer. Measure the Helmholtz flux output. Expose the magnet to a reverse pulse of low magnitude and re-measure flux output then reverse pulse at a slightly high field and re-measure. This process is continued until the magnet reverses polarity (H_{cJ} has been exceeded).

While the test appears straightforward two issues arise. First the magnet has an internal demagnetizing stress that is a function of magnet dimensions and B_r. Second, metal magnets generate eddy currents when pulsed. These currents generate a reverse magnetic field which impedes field penetration of the magnet and must be accounted for. Equipment using the method of increasing reverse pulse is called a PFM, Pulsed Field Magnetometer.

A laboratory tool for quantifying magnetic properties is the superconducting quantum interference device or SQUID. These are expensive to purchase and to operate and the sample size is too small for them to be practical as a production tool.

Secondary Tests

Academia, laboratories and Industry perform many additional material and product evaluations based on the measurement tools mentioned earlier. These tests can be used to gauge non-magnetic characteristics using magnetic measurements as the gauging tool. The test can also be an evaluation of estimated in-service product performance. In some cases, the test may be part of a procedure to modify or select product from the entire batch. Three of these tests will be discussed here.

Thermal and/or Magnetic Knockdown

There are two common reasons for knocking a magnet down from saturation: 1) to stabilize it against partial demagnetization in-service and 2) to adjust magnetic output to within tighter limits than normal production variation provides. Adjustment of magnetic output by partial knockdown can be achieved with either a reverse magnetic field or by exposure to elevated temperatures (rare earth magnets). Activation energies for domain reversal due to thermal exposure differ from those associated with a reverse pulse. Thus a magnet knocked back using one method may experience additional knockdown when exposed to the alternate method. It is highly advised to knockdown magnets with the mechanism expected in product use.

Both magnetic and thermal knockdown are sensitive to the permeance coefficient of the magnet. If the magnet is placed on a ferromagnetic support (steel sheet) to facilitate close stacking of magnets in thermal knockdown, the temperature of knockdown will be higher than if the magnets were in open circuit. Further, not all of the magnet is at the same permeance coefficient, so local regions of the magnet reverse prior to other regions. The intent of thermal knockdown is to stabilize the magnet from additional knockdown due to elevated temperature exposure in use.

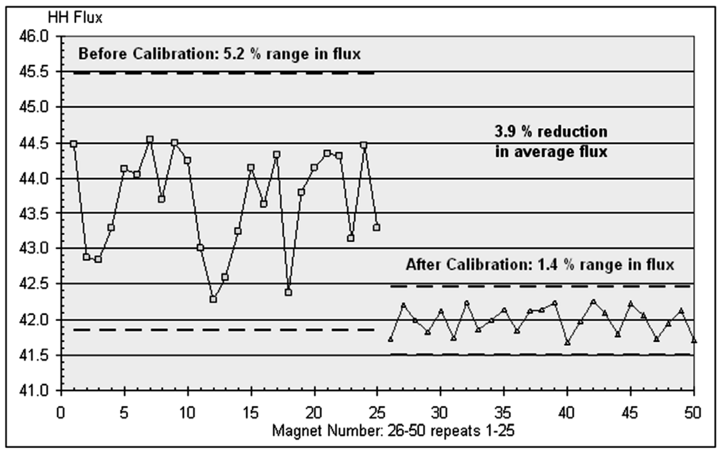

Figure 8. Distribution of flux before and after magnetic calibration

Magnetic knockdown, on the other hand, is most often used to narrow the distribution of flux output from a batch or batches of magnets. Magnets are knocked back to a target value +/- a tight tolerance. A priori, this value of output is lower than the spec limits of the grade of material. Figure 8 shows both the tightening of distribution and the drop in Flux output as a result of magnetic knockdown.

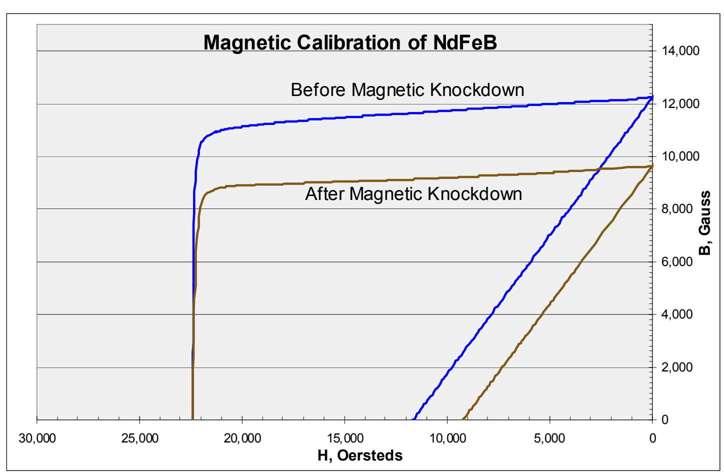

Figure 9. Hysteresisgraph curves showing drop in Br with magnetic knockdown while HcJ remains unchanged

It is counterintuitive, but the effects of thermal and magnetic knockdown are a drop in B_r and flux output, but with no measurable loss in intrinsic coercivity. Figure 9 demonstrates this: a magnet knocked down by

20% has the same H_{cJ}. Although it is possible to knock a magnet down continuously from 0 to 100%, generally accepted limits are between 10 and 20% maximum. Greater knockdown exaggerates localized variation in output. It can in a motor, for example, cause increased vibration and electrical noise.

Irreversible Loss Testing

The same procedures used to stabilize a magnet can be used to evaluate a magnets' resistance to knockdown. When carried out for short duration at increasingly higher temperatures, we call the test: STILT (Short Term Irreversible Loss Test). For extended testing, it is necessary to select a temperature and place magnets on test for times ranging from 96 to many thousands of hours. The longer duration test is called LTILT (Long Term Irreversible Loss Test).

These tests are not meant to evaluate a magnet's resistance to corrosion, but they will often highlight loss due to chemical reactivity, especially the LTILT, where magnets are on test for extended periods.

The STILT procedure can be performed on an absolute basis by fabricating magnets of a defined permeance coefficient, 2 for example, and always testing this same size/shape of magnet. The test can also be performed on a comparative basis with literally any size magnet. But comparison is only possible for same size/shape magnets.

Prior to testing, it is imperative that the magnets be magnetically saturated to develop both maximum B_r, but more importantly, maximum H_{cJ}. Equipment required for the STILT test are: an oven capable of heating the magnets from just above room temperature to the maximum specified for the test. Non-magnetic trays capable of withstanding the highest temperature will be used to hold and separate the magnets at least 75 mm (3 inches) from the next nearest magnet. Thin aluminum sheet is one suitable material which will also assist in rapid heating and cooling.

Magnets are tested using the Helmholtz flux test. The value of flux output becomes the baseline for the test. Each magnet is then placed on the tray and inserted in the oven at the first incremental test temperature, 50 °C for example. After one hour, the tray is removed and the magnets allowed to cool to ambient temperature. After cooling, they are re-tested for flux output, replaced on the tray, placed in the oven at the next higher temperature, 75 °C, for example. This process is continued until the magnets have been tested at the highest temperature. If there

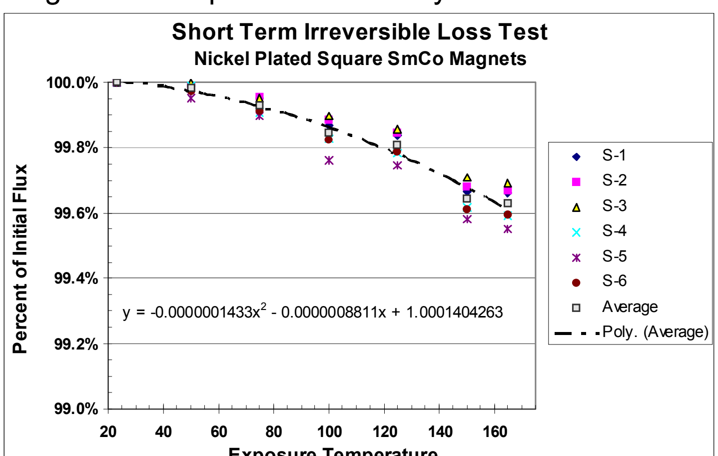

Figure 10. STILT results on SmCo disk magnets with Pc=3.65

is suspicion of chemical reaction or corrosion occurring, it may be desirable to re-saturate and re-measure the magnets. The amount by which they fail to return to 100% of initial output represents irreversible loss, most likely from structural damage.

Values of flux output are normalized as percent of initial flux. This allows comparison of magnets with greatly varying flux output, though permeance coefficient must be the same for direct comparison. The normalized data can then be plotted as shown in Figure 10.

For evaluation of a magnet's permanency, as resistance to oxidation, corrosion or fundamental metallurgical change, it may be necessary to test magnets for extended periods at one or more elevated temperatures. This LTILT test is performed much the same as the STILT is except that magnets are placed in only one temperature and periodically removed for measuring. The interval between measurements usually starts small and then lengthens. Typical intervals are for measurements at 0, 24, 48, 96, 168 hours and weekly thereafter.

Coated, high performance magnets may show little-to-no change over time so measurements must be performed as consistently as possible. Laboratory temperature should be +/-0.5 °C and recorded as part of the measurement data. Magnets must be uniformly at room temperature when measured. Magnets should be handled minimally to avoid picking up body heat. The Helmholtz test system must be in the same location and orientation. Other equipment in or near the lab must be in consistent locations over time. It may be useful to have a set of equivalent magnets that are carefully stored for comparison measurements. Measurement data can be corrected for slight room temperature differences or for variation noted in the un-tested magnets used for reference.

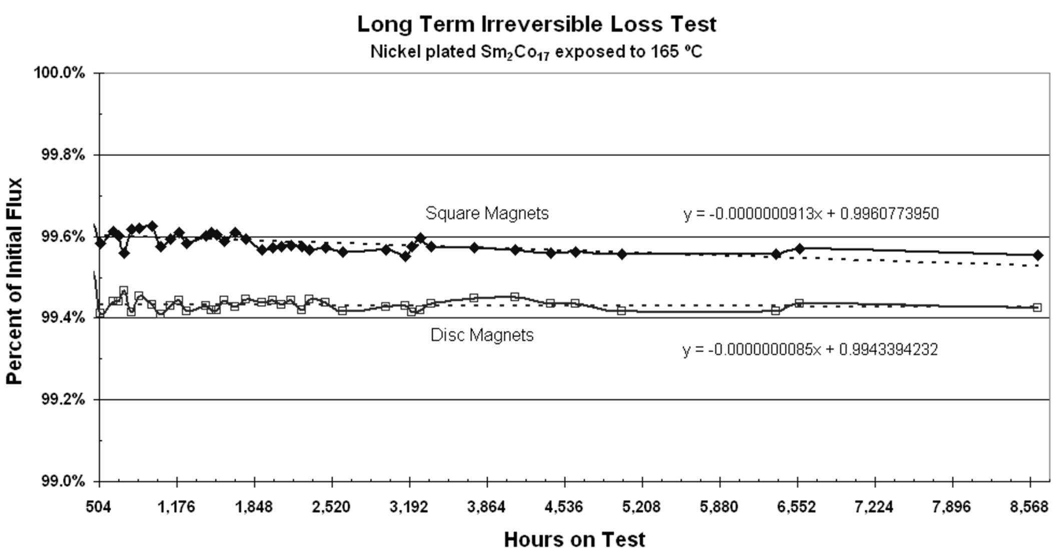

Figure 11. LTILT of nickel plated SmCo exposed to 165 °C for several thousand hours

It is normal for magnets to lose a percentage of flux output during the first one to four hours on test. After this initial period of loss, additional loss may occur until the outside surface of the magnet stabilizes. The third stage of aging is an extended period of nearly linear flux loss. Some materials have been reported to suffer more dramatic losses near end of life. Our own tests have ended between 5,000 and 8,000 hours while still nearly linear in loss per unit time as shown in this example test (Figure 11) of nickel plated Sm_2Co_{17} evaluated at 165 °C.

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