PMAG Handbook
Properties of Hard Magnetic Materials

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Whether you are designing an automotive traction motor, wind power generator, washing machine motor or loudspeaker, your product is only as good as the Permanent Magnet Material that you employ. To gain competitive edge for your product, you need to identify the best quality magnet grade that suits your specific requirements. This requires access to their magnetic properties, called demagnetization curves.

But so far, these demag curves were available only as graphical plots in picture files. But you cannot superpose them to discover a best grade. You cannot input picture files into a design software. You cannot easily locate the maximum energy point to minimize the cost. Reading off values of residual flux density at a temperature using them is prone to errors. What is more, with picture files, it is difficult to estimate a key demagnetization resistance characteristic, called Demag Flux Density (see Chapter 2,3). All these issues made the discovery, design or safe operation of magnets a difficult and non-trivial task.

To address these issues, MagWeb prepared this PMAG database of curated compilation of thousands of digital demagnetization curves of all magnet grades produced by major manufacturers worldwide. The Digital B(H) curves represent properties as a set of carefully digitized data points.

With PMAG, you can estimate the key demagnetization resistance characteristic, termed Demag Flux Density. It is the point beyond which irreversible losses are unacceptably high. The PMAG Database can save you time in discovering the right magnet (and its manufacturer) that meets your specific requirements. You can use it to compare various properties of magnets. You can use it to minimize the cost of a magnet by identifying the maximum energy product point. You can input the digital B(H) data into your design software. You can use it to simplify your magnet sizing calculations.

Magnet grades have several similarities but subtle differences. It is these difference that determine its quality. The quality of a grade varies with the factory that makes it. Different manufacturers use their own secret recipe of ingredients, manufacturing processes and purity control methods to fabricate magnets. So even if two magnets are stamped with the same 'grade label', their demag curves differ subtly. PMAG database lists properties of grades by their manufacturers to help understand these subtle differences.

PMAG aims to help you to discover an optimal permanent magnet and integrate it into your product, thereby gain competitive advantage. It is hoped that this user manual will help you get a deeper insight into the benefits offered by PMAG.

DISCLAIMER

The PMAG database is the result of multi-decade effort to digitize and compile hard-to-find magnetic property data from open sources/publications. They include scientific literature, manuals, handbooks, textbooks, websites, federal databases, university records, old archives, manufacturer’s catalogs etc. MagWeb believes the digitized data to be accurate and reliable. It is intended to support the user in making informed decisions on magnetic materials. MagWeb does not provide any warranty or support. MagWeb is not liable for any damages caused by using its database whether explicitly or implicitly. The sources and methods used to digitize the curves are confidential and proprietary. MagWeb reserves the right to change the data without notice.

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## TABLE OF CONTENTS

1. INTRODUCTION ...................................................................................................... 4  
   1.1. B(H) Curve .................................................................................................... 4  
   1.2. Demag Flux Density (Knee Point) .............................................................. 6  
   1.3. Significance ................................................................................................. 7  

2. IMPROVE PERFORMANCE .................................................................................... 9  
   2.1. Manufacturer ............................................................................................... 9  
   2.2. Grade ......................................................................................................... 10  
   2.3. Energy Product .......................................................................................... 12  
   2.4. Cost ............................................................................................................ 14  

3. IMPROVE DEMAGNETIZATION RESISTANCE .................................................... 15  
   3.1. Manufacturer .............................................................................................. 15  
   3.2. Grade ......................................................................................................... 16  
   3.3. Neo vs SmCo .............................................................................................. 17  

4. NEODYMIUM MAGNETS ....................................................................................... 19  
   4.1. Grades ....................................................................................................... 19  
   4.2. Major Manufacturers ................................................................................. 20  

5. SAMARIUM COBALT MAGNETS ......................................................................... 22  

6. MOLDED/BONDED MAGNETS ............................................................................. 23  

7. FERRITE CERAMIC MAGNETS ........................................................................... 24  

8. ALNICO MAGNETS ............................................................................................. 25  

9. APPENDIX A. PMAG DATABASE FORMAT ....................................................... 26  
   9.1. Category Folders .......................................................................................... 26  
   9.2. Manufacturer Subfolders ............................................................................ 26  
   9.3. Grade Files .................................................................................................. 27  
      9.3.1. Format of Grade Files ........................................................................... 27
1. INTRODUCTION

Permanent Magnets are those that can attract iron\(^1\). They store energy (as in a pre-compressed spring). You use them in your daily life: in your computer disc drives, smart phones, TVs, loudspeakers, automobiles, washing machines and refrigerators. Industry uses them in Automotive Traction Motors, Wind Power Generators, Flight Control Systems, MRI Machines, Maglev Trains, Magnetic Clutches, Brakes, Solenoids etc.

A magnet is made of fine powders of rare earths and metals. Manufacturers use several methods (sintering, molding, casting, pressing etc.) to make them. They measure its magnetic properties as Demagnetization Curve per IEC 60404-5. Major applications need high grade magnets that can withstand high temperatures. So PMAG database centers on those manufacturers that provide temperature-dependent demagnetization curves

1.1. \(B(H)\) Curve

Fig. 1 shows the \(B(H)\) curve of a typical Neo magnet. It shows how flux density \(B\) [tesla] in a magnet varies with magnetic field strength \(H\) [kA/m]). It is broken into ‘reversible’ (green) and ‘irreversible’ (red’) segments; the demagnetization point\(^2\) \(D\) separates both. In the reversible segment, increasing \(H\) decreases \(B\) linearly; removing \(H\) returns the magnet back to initial state. The irreversible segment is waterfall-like\(^3\) and nonlinear.

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\(^1\) Electromagnets also attract iron, but only if energized.
\(^2\) Aka knee point. It will be in \(3^{rd}\) quadrant if the \(B(H)\) curve is a straight-line in the \(2^{nd}\) quadrant.
\(^3\) In this segment, the magnet transitions from ‘hard’ to ‘soft’. It also has an inflection point of numerical instability.
**Residual Flux Density** $B_r$ quantifies a magnet’s ability to create flux. It is the intercept of $B(H)$ curve with the B-axis. It defines the grade of a magnet. The reversible segment terminates at the demagnetization point D (‘demag point’). Beyond D, the magnet *demagnetizes*, viz. on removing H, its $B_r$ reduces by a small *irreversible loss* $\delta B_r$ permanently.

**Demag Flux Density** $B_d$ quantifies the ability of a magnet to resist demagnetization. It is the point where the magnet will lose 1% of $B_r$ permanently. Thus the ability of a magnet to create flux and simultaneously resist its destruction are quantified by the two end points ($B_d, B_r$) of the reversible segment. Both properties are needed to *force* a magnet to operate in the safe reversible segment.

In a pre-compressed spring analogy, $B_r$ refers to ‘compressed height’, indicating a spring with stored energy. $B_d$ refers to its ‘free height’, indicating a spring with no stored energy.

**Figure 2.** Typical Demagnetization Chart from a manufacturer. It shows $J(H)$ curves plus $B(H)$ curves. But both intersect at umpteen spots, making it difficult to define precisely the safe operating region of magnets.
1.2. **Demag Flux Density (Knee Point)**

Fig.1 (B(H) curve for a particular temperature), extended over wide temperature range, defines a demagnetization chart. Fig. 2 shows a typical demagnetization chart provided by manufacturers. It shows both B(H) and legacy J(H) curve. But both intersect each other at umpteen places. These intersections obscure the usable safe operating segment and unsafe reversible segment of a magnet.

Fig. 3 shows MagWeb’s alternative representation. It contains only B(H) curves. It clearly displays the key **Demag Flux Density** $B_d$ that separates the Safe Operating Area (green) and unsafe demagnetized range (red). $B_d$ increases as temperatures increases. This narrowing a magnet’s SOA. This reflects a magnet’s increasing vulnerability to demagnetization at higher temperatures.

![Figure 3. Typical B(H) Demagnetization Curves in PMAG database](image)

For example, consider a PM motor using Arnold N52M grade. At 100C, its SOR is $(B_d, B_r) = (0.698, 1.312)T = 1.005 \pm 0.307 \text{ T}$.

If its temperature rises to 150C, its SOR shifts to $(0.908, 1.22)T = 1.064 \pm 0.156 \text{ T}$. So increasing magnet’s temperature from 100C to 150C halves the dynamic load capacity (from $\pm 0.307$ to $\pm 0.156$T).
The PMAG Database stores the B(H) data points in excel files. Appendix A, Fig. 14 describe the format used by MagWeb to store the B(H) data. Note: B-H curve in the second quadrant, as specified by most commercial manufacturers, is sufficient to express the properties of magnets if the knee appears in the second quadrant (e.g., magnet operating at high temperatures). However, it is insufficient if the knee falls in 3rd quadrant (e.g. at room temperature).

1.3. Significance

MagWeb’s PMAG database is a large and unique compilation of digital demagnetization curves. It contains about 5000 temperature-dependent digital demagnetization curves of hundreds of grades that are made by dozens of manufacturers. It puts vital magnet’s properties of all permanent magnets at your finger-tips. Typical benefits of using PMAG database are:

- Improve Performance:
  - Compare properties of same-grade magnets by various manufacturers
  - Discover Optimal Grade that best suits your requirements.
  - Determine BH\(_{\text{max}}\) of any grade
  - Save on cost by choosing the right operating point

- Improve Demagnetization Resistance:
  - Limit irreversible loss and develop optimal fault diagnostics.
  - Identify B\(_{r}\) of a magnet at your machine temperature.
  - Superpose B(H) Curves to compare same grades.
  - Input digital B(H) data into your Computer software.
  - Assist in Detail Design

Largest Database. Different manufacturers offer magnets at various grades. The quality of their grades depends on several factors e.g. impurities, particle sizes, shapes, composition, quality control practices. PMAG database lists B(H) data of each grade produced by each manufacturers. With it, the users can thus make their own assessment of the quality of grades (carrying same grade label) produced by different manufacturers.

Demag Flux Density B\(_d\). It quantifies the resistance of a magnet to demagnetize. PMAG database lists the Demag Flux Density of any grade. Operating a magnet beyond its demag point produces unacceptably large irreversible loss. (see Ch. 2, 3).

Computer Input. Demag curves supplied by manufacturers as picture files cannot be inputted into computer software. MagWeb’s (H\(_i\), B\(_i\)) digital data tables can be inputted into

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4 See section 2.2 on how B(H) curves of same-grade Neo magnets vary with manufacturers.
8 Quality Control, Magfine Corp., https://www.magfine.co.jp/eng/magnet/quality.html
simulation software. The demag point data is included in it, so the software can display precisely any demagnetized region of magnets so increase the accuracy of simulation.\textsuperscript{9,10}

**Superpose B(H) Curves.** In the past, demag curves were created in diverse units, scales and formats. This made it very difficult to discover which manufacturer makes a better grade. The digital demag curves in PMAG Database are created in standard SI units. This enables one to superpose B(H) curves from different manufacturers. Such superposition can help you to identify a better quality grade (see sec. 2.1).

**Discover Best Grade.** Designer uses several parameters (such as $B_r$, $B_d$, $BH_{\text{max}}$) to discover the best quality magnet grade. The PMAG Database can thus be used to investigate how various grades compare from such diverse perspectives.

**Residual Flux Density $B_r$.** It varies nonlinearly with temperature. Operating magnets require precise value of residual flux density $B_r$ at the continuous duty and overload duty temperatures. The PMAG allows you to determine $B_r$ precisely at any temperature.

**Reversible Segment.** The interval $(B_d, B_r)$ defines the lower and upper bounds of the reversible segment within which a magnet should operate to prevent demagnetization. The PMAG database allows you to match the reversible segment of a magnet with the SOR of your machine.

**Maximum Energy Product $BH_{\text{max}}$.** This is useful in minimizing the volume and hence the cost of a magnet. The PMAG database can determine its location and how it changes with temperature. This allows you to minimize the cost of magnets.

In summary, this PMAG Database allows you to limit the irreversible demagnetization of the magnet, to determine their safe operating range, to compare B(H) curves, to discover the best quality magnet grade and to minimize their cost. All these benefits simplify your task of discovering a best quality magnet and designing it into your machine, thereby allowing you to gain competitive edge of your product.

2. IMPROVE PERFORMANCE

This section describes how PMAG database can be used to improve the performance of your machine. It shows how to discover an optimal magnet that best suits your specific requirements, thereby improving the performance of your machine.

Auto-traction motors expose magnets to high temperatures ranging 100C to 200C. The primary requirement for a magnet is that it should have widest safe operating range at rated temperatures. That is, they should offer highest \(B_r\) and lowest \(B_d\). So designing traction motors needs accurate \((B_d, B_r)\) at rated temperatures, which PMAG provides.

2.1. Manufacturer

In the early 1990’s, the quality of Neo magnets produced by China used to vary widely. But over the past 10 years, the Chinese magnet industry has come of age. Today, many Chinese firms offer grades with reasonably consistent properties at competitive prices. So users have come to ‘expect’ that the same grade magnets, procured from different manufacturers, to have same properties within published tolerances.

But unfortunately even now the quality of a grade varies with manufacturers. This is hidden in their demagnetization curves – they vary with manufacturers – even in magnets labeled as of same-grade. Hence magnets from some major manufacturers perform better than others.

For example, till 2012, manufacturers used Dysprosium (Dy) up to 12% to improve the demagnetization resistance (i.e. Demag Flux Density) of UH, EH and AH grades (sourced in EV motors). But at ~$300/kg, Dy is very expensive. Recently, to combat its high cost, different manufacturers developed different methods, which lowered the Dy to 7.5%.

These methods include grain boundary diffusion\(^{11}\), grain size refinement, solid solution strengthening etc. But they that differ in the % Dy used to produce same grade. Using different % Dy caused difference in the degree of demagnetization resistance they achieved. As a result, the quality of high grades continues to differ with manufacturers.

Demag Flux Density Differences

For example, Fig. 4 compares the Demag Flux Density of same N40UH grade at 180C from 3 different manufacturers – TDK, Arnold and HPMG. It shows that TDK’s N40UH grade has \(B_d\) of 0.291T, while HPMG’s N40UH grade has \(B_d\) of 0.393T.

This shows that HPMG’s N40UH grade has 35% lower demagnetization resistance than TDK’s N40UH grade. It demonstrates that even if manufacturers use the same grade label, one of them will have higher demagnetization resistance, so is the preferable

choice. One can use the Demag Flux Density available in PMAG in this fashion to discover the manufacturer that offers a higher quality grade.

**Figure 4. Demag Flux Density of N40UH varies significantly with its manufacturer.**

### 2.2. Grade

PMAG database reveals that the energy product BH_{max} varies by as much as 20% in the same grade magnets produced by different manufacturers. That is, there will be a manufacturer whose grade offers 20% higher energy than others. Discovering and switching to such manufacturer (without changing the grade) adds an extra ‘cushion’ that can benefit your design!

Fig. 5 shows the effect of temperature class of a N40 magnet on the Demag Flux Density. All carry same energy but have different temperature capability. It shows that for N40, N40M grades (with lower ~100C capability) B_d clusters around ~ 0.65T. In contrast, that for N40H, N40SH (with higher ~150C capability) B_d clusters around ~0.3T. Thus using high temperature magnets doubles the demagnetization resistance.
Figure 5. Demag Flux Density variation with Letter Grade.

Fig. 6 shows the effect of energy of magnets (with different temperature rating) on the Demag Flux Density. It shows that increase in energy stored increases both residual flux density and demag flux density proportionately.

Figure 6. Demag Flux Density dependency on Numeral Grade.
Figure 7. Coercivity Degradation of a Magnet Grade varies with the manufacturer.

Fig. 7 shows the effect of manufacturer on $H_{cb}$ temperature coefficient. The y-axis shows the percentage degradation relative to a reference $H_{cb}$ (-1000 kA/m for TDK at 20°C). Thus PMAG database indicates that a $H_{cb}$ temperature coefficient is highly nonlinear; this nonlinearity varies with the manufacturer. It reveals that using the linear temperature coefficients (provided by manufacturers) can produce misleading results.

2.3. Energy Product

BH Energy Product is the product of B [G] and H [Oersted]). It is expressed in MGOe; 1 MGOe equals 7.958 kJ/m$^3$. It characterizes energy density (the energy stored per unit volume) at a given H. A high $BH_{max}$ indicates the smaller volume of the magnet is needed to store same energy.

Review of BH(H) Curves of hundreds of magnets revealed that magnets from only handful of reputed manufacturers met their maximum energy product specification. The PMAG database will help you spot such reputed manufacturers.
Unfortunately, manufacturers do not publish the maximum energy product \( BH_{\text{max}} \) at elevated temperatures. You can use the digital \((B_r, H_c)\) data in \textit{PMAG} to calculate \( BH \) at any temperature. \textit{The PMAG is the only database that helps you calculate \( BH_{\text{max}} \) for any magnet and any manufacturer at specific temperature.}

In a PM motor, the energy product \( BH \) of a magnet at its rated temperature determines its size\textsuperscript{12}. To minimize the magnet cost, locate a magnet that needs smallest volume to store same maximum energy. Then operate it close to this max. energy \( BH_{\text{max}} \) point \textsuperscript{13}.

\textit{Figure 8. Energy Product Curve \( BH(H) \) indicate the point at which the magnet stores maximum energy. Operating it at \( BH_{\text{max}} \) point minimizes the cost.}

The BH can be plotted against \( H \). Fig. 8 shows the BH(\( H \)) curve for the N40UH magnet from TDK at 180C. At the point M the magnet attains maximum energy product. It corresponds to P on B(\( H \)) curve. This \( BH_{\text{max}} \) reduces with the temperature. A N40UH magnet at room temperature has \( BH_{\text{max}} = 40 \) MGOe. Fig. 8 shows that the same magnet at 180C, it reduces to \( BH_{\text{max}} = 24.7 \) MGOe. Thus the magnet degrades energy wise by \(~40\%\) when the temperature increases from 25 C to 180 C.

2.4. Cost

**Figure 9. Energy Product curve can be used to minimize the cost of a magnet.**

A BH(H) curve can help you achieve a minimal magnet cost design. Fig. 9 shows BH(H) curve for an N52 magnet at 40°C. What working point E minimize its cost without damaging it?

Fig. 9’s BH(H) curve shows max energy BH\(_{\text{max}}\) = 48.4 MGOe occurs at M. Its B(H) curve shows that its Demag Flux Density B\(_d\) = 0.44 T. Allowing a 20% safety margin establishes a **Safe Floor Point A (0.53T)**. The magnet should always operate above this point A to prevent demagnetization.

One can use PMAG database to locate the working point E that minimizes the cost as follows:

- Draw vertical line from point A(0.53T). It intersects BH curve at point A'(45MGOe).
- Draw a horizontal line from A’. It intersects BH curve again at point E'(45MGOe).
- Draw vertical line from E’. Its intersection with B(H) curve locates point E (0.9T).

Then extreme loads can demagnetize the magnet from E (0.9T) to A(0.53T) – causing 70% drop in B. But the energy in it fluctuates from E’ (45 MGOe) to M (48.4 MGOe), i.e. energy stored drops only 7%. Thus the magnet operates near its maximum energy product point M, thereby needs minimal volume. The PMAG database can be used this way to minimize the cost of a magnet without demagnetization.
3. IMPROVE DEMAGNETIZATION RESISTANCE

3.1. Manufacturer

In section 2.1 we have shown that there will be some manufacturer whose grade offers a higher demagnetization resistance advantage. How high this advantage is, depends on the operating temperature.

Fig. 10 compares the variation of Demag Flux Density $B_d(T)$ for N40M grade produced by 3 firms (Ankey, Arnold and K&J). It shows that Ankey’s N40M grade offers highest demag resistance compared to that of K&J. But such comparison between those of Ankey and Arnold is more complex. It shows that magnets from Ankey have superior demag resistance only at either low or higher temperatures. This shows the need to compare $B_d(T)$ plots of same grade magnets from different manufacturers in order to locate the manufacturer with superior demag resistance advantage.

*Figure 10 Demag Flux Density varies non linearly with temperature. Such nonlinearity depends on manufacturer*
3.2. Grade

Fig. 11 plots the variation of \( B_d(T) \) with the temperature. It shows that both N40 can be operated above 0.5T without demagnetization only up to 80°C. In contrast, N40H extends the demag-free range to 140°C. This figure shows that variation of \( B_d \) with temperature in highly nonlinear, and this nonlinearity depends on the grade.

Design of permanent magnets often require demag flux densities at a specific operating temperature \( T \). We estimate it by fitting a quadratic model

\[
B_d(T) = B_d(T_o)[1 + \alpha_1(T - T_o) + \alpha_2(T - T_o)^2] = B_d(T_o)P(T)
\]

Where \( T_o \) is a reference room temperature. The coefficients \( \alpha_1, \alpha_2 \) are obtained by fitting the model to the data.

![Figure 11. Demag Flux Density varies nonlinearly with temperature. Such nonlinearity depends on grade.](image)

In a similar fashion, a plot showing how \( H_d \) varies with temperature (for several grades) will be useful to determine the grade required to operate a magnet at a rated temperature up to a given demag field strength.
Figure 11a. Variation of demag field strength $H_d$ with temperature. Its nonlinearity depends on the grade.

Fig. 11a show how $H_d$ typically varies with the temperature [57]. It shows that $H_d$ decreases linearly with temperature for some grades, but is highly nonlinear with other grades. For example, if one is looking for a grade that can withstand 500 kA/m at 100°C, this figure shows that N40M is the most suitable grade. It also shows that N40H grade can also withstand similar operating conditions, but will also protect it at far higher temperatures of 130°C, so might be a overkill.

3.3. Neo vs SmCo

At present most engineers believe\(^\text{14}\)\(^\text{15}\) that Neo magnets max out and are preferable for operation below 150°C. Both Neo and Samarium magnets are usable in the 140°C to 250°C range. The choice depends on cost vs. performance tradeoff. Demag Flux Density is one major consideration in the selection.

Fig. 12 compares the linear portions of B(H) curves of Neo Grade Vac 992TP with Samarium Cobalt Vacomax 240 in the temperature range of 200-250°C. It shows that even though Samarium magnets offer slightly higher Br, they suffer from substantially


poorer Demag Flux Density, resulting in smaller safe operating range. Specifically, demag flux densities are:

- at 210C: Neo = 0.113T; Samarium = 0.425T – so Neo has a 0.312T higher demag resistance.
- At 240C: Neo = 0.320T; Samarium = 0.489T - so Neo has a 0.169T higher demag resistance.

Thus, for a 240C application, the higher demagnetization resistance of Neo 921TP make it a better choice than the samarium magnet Vacmax 240. Of course, Samarium Cobalt magnets continue to be the only option for operation above 250C.

Figure 12. At 240C, Neo magnet offers higher demagnetization resistance than SmCo magnet, making it a better choice.
4. NEODYMIUM MAGNETS

PMAG Database Folder AM for Neodymium Magnets lists 3351 B(H) Demagnetization Curves of 707 grades, produced by more than 35 manufacturers worldwide. For names of all these grades, please click on PMAG, Materials.

Neo magnets were developed by Hitachi in 1980’s. They are also called Neo or NdFeB magnets. They are produced by sintering ~4µm size fine powders. They can be made only in simple blocks, ring or arc shapes. They are made of ~66% Fe, 30% Neo, 1% B,0.7% Nb, 0.3% Al. 7 to 12% dysprosium is added to improve high temperature performance, but it increases their cost. Neo magnets have poorer thermal stability than SmCo magnets (~0.1%/C). So currently most engineers prefer to use them below 150C. It can corrode easily, so needs coatings. Their energy product ranges 28 to 54 MGOe. Their residual flux density ranges 1 to 1.45T. Their maximum service temperature ranges 80 to 250C.

4.1. Grades

Manufacturers identify the Neo magnets by “N”. They offer it in several “grades” which follow Chinese conventions. 64 of them are called “standard” grades, with two codes:

- A letter code, which refer to their Maximum Service Temperature $T_{\text{max}}$.
- A numeral code, which prescribes their Max. Energy Product $BH_{\text{max}}$ (MGOe).

Table 4 lists these grades, their maximum service temperatures, maximum energy product. It shows that $Br$ of Neo magnets spans 1T to 1.45T. Grades between 30 to 40MGOe are spaced at 0.05T, while those between 40 to 55 are spaced at ~0.025T.

Table 1. “Standard” Grades of Neodymium Magnets

16 How Neo magnets are made, e-magnetsuk.com
Of these, UH, EH and AH grades are used primarily in automotive traction motors, wigglers and wind power generators.

American standards identify a grade as xx/yy where xx refers to maximum energy product $BH_{\text{max}}$ in MGOe and yy refers to intrinsic coercivity $H_{cJ}$ in Oe. European standard IEC 60404-8-1 uses same symbols, but with xx for $BH_{\text{max}}$ in kJ/m$^3$ and yy for $H_{cJ}$ in 10kA/m. European and Japanese firms do not follow the Chinese naming conventions, so it is difficult to identify their equivalent grades.

**Coating.** Neo magnets need coating as their corrosion resistance is poor. All manufacturers offer a wide variety of coatings\(^\text{18}\). Electrolytic nickel coating is a common choice as it is least expensive and provides a hermetic seal against, air, moisture and gases. The user should select the coating that best suits his application. The thickness of coating varies from 7 to 28 $\mu$m. The thickness of the uncoated magnet should be plugged into a design software (instead of its nominal thickness) for more accurate design of a machine.

### 4.2. Major Manufacturers

Neo magnets are offered in several grades. Fig. 13 ranks some these major manufacturers by the number of grades they produce. It shows that **Arnold Magnetic Technology** offers the largest number (79) of grades, followed by Dexter Magnetics (60). Three European firms - Sura Magnets (51), Neorem (48) and Vacuumschmelze (44) - also offer more than 40 grades. One Chinese firm Ankey offers ~ 50 grades.

However, few reputed firms such as Hitachi, Shin-Etsu, TDK however produce smaller number of higher grades. So producing large number of grades need not necessarily imply that it is a source of high quality grades.

Highest Temperature Magnets: 230-240 C class Neo magnets are offered by Vacuumschmelze, Arnold Magnetics and Integrated Magnetics with demag curves. They are also offered by Schramberg and Ningbo YinZhou UpMagnet, but without demagnetization curves. 220C Class are offered by Sura Magnets, Arnold Magnetics, Eclipse Magnetics, Hitachi etc.

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\(^\text{18}\)For comparison of various coatings, see for example e-magnetsuk.com.
Strongest Magnets: 55 MGOe grade Neo magnets are produced by Arnold Magnetics, Dexter Magnetics, Smart Magnet and Yantai Shougang Magnetic. Their residual flux density can be as high as 1.49T.

Figure 13. Number of Grades Produced by Major Manufacturers.

![Bar chart showing number of grades produced by major manufacturers.](image-url)
5. SAMARIUM COBALT MAGNETS

PMAG Database Folder BM lists 694 B(H) Demagnetization Curves of their 159 grades, produced by 23 manufacturers worldwide. For names of all these grades, please click on PMAG, Materials.

Samarium Cobalt Magnets were developed for US Air Force by University of Dayton Research Institute (UDRI) in 1970s. They are also called Samarium or SMCO Magnets. They are composed of Sm, Co, balance Cu, Zi and Fe. The powders are pressed, sintered, machined and magnetized. They can be only made in simple shapes. To prevent chipping, customers are advised to tumble them which rounds their edges to 0.005-inch radius. Untumbled magnets can chip and create “dirty” magnets. They are expensive, so mainly used in applications that demand exemplary performance at high temperatures. Their energy product ranges 15 to 32 MGOe. Their residual flux density ranges 0.9 to 1.2 T. It is the preferred choice for operation above 150°C, up to 550 °C.

Electron Energy Corp (EEC) produces SMCO magnets that can operate at 550C. Both EEC, Dexter and Arnold Magnetic offer strongest SMCO magnets (BH\text{max} = 33 MGOe, B_r = 1.19T). Tianhe Magnets offers 52 grades without demag curves. Dexter Magnetic offers 38 grades with demag curves. Ningbo Ningang Permanent Magnet also offers 33 grades but without demag curves. Two subcategories:

Sm1Co5: Also called 1:5. It has one Samarium atom per 5 Cobalt atoms. It has 35% Samarium. It has no iron, so does not corrode with water. Its Energy Product ranges 15 – 25 MGOe. In the PMAG database, they can be identified by its T_{\text{max}} of 250°C and lower electrical resistance of 55 µΩcm.

Sm2Co17: Also called 2:17. It has two Samarium atoms for 14 – 17 Cobalt atoms. It is less expensive (has only 25% Samarium) and carries more energy (21-32 MGOe). Its B_r ranges 0.9 to 1.16T. So most new designs use 2:17 magnets as it is less expensive and reduces the size of magnets. But it uses iron, so may corrode slightly in water. It has high demag resistance. It comes in three styles:

- **Normal.** Their T_{\text{max}} ranges 350C. They offer higher resistivity of 85 µΩcm.
- **Ultra High Temperature (UHT).** Their T_{\text{max}} ranges 400 to 550C. PMAG database contains their hard to find demag curves. They should be plated, however.
- **Low Temperature Coefficient (LTC).** They offer near zero thermal temperature coefficients. So their thermal stability is very high.

SMCO store less energy than Neo and more expensive. But:

- Cooling restores its magnetic properties (reversible thermal degradation).
- Above 180C their B_r is higher than Neo – so they are the preferred choice.\(^{19}\)
- It can operate up to 550C (but its B_r falls to 0.54T) Neo is limited to 250C.
- Its demag resistance is higher than Neo.
- It degrades less with temperature (.035%/C).
- It is more resistant to corrosion.
- It can be abrassively machined only with coolant.
- Its abrassive machining does not degrade its properties.
- But it is more brittle than Neo magnets.

6. MOLDED/BONDED MAGNETS

**PMAG** Database Folder CM for Molded magnets lists 554 B(H) Demagnetization Curves of 49 grades, produced by 19 manufacturers worldwide. For names of all these grades, please click on **PMAG, Materials**.

Also called plastic magnets or polymer magnets, the molded/bonded magnets are made by mixing magnetic powders with nonmagnetic binders. They are made into intricate shapes by either injection molding or compression bonding. Molding avoids additional machining and assembly cost. It reduced per part cost in large volumes, but needs high tooling cost investment. They use Neo, Samarium or Ferrite magnetic powders. Those made of Ferrite are inferior to others. Their magnetic strength is reduced by the binding agent. Injection Molded magnets are limited to 6 MGOe. Bonded magnets can go up to 13 MGOe. Their residual flux density ranges 0.6 to 1T. Their service temperature ranges 100 to 220 C.

Aichi Steel's bonded magnets can reach 21 MGOe (Br ~ 1T). They are generally small (<125 gm). Their density is less than 6 gm/cc.

**Arnold Magnetic Technology** offers 40 grades, followed by Kollektor and Schramberg (~30). Schramberg and Max Baerman also makes ones that can operate up to 220C. Magnequench has the largest number of patents. Their names do not follow any standard conventions. MagWeb’s magnetization curves can help you to find the best grade vendor that matches your specific needs.

**Injection molding** mix ~65% magnetic powders with ~35% *thermoplastic* “resin”. It squeezes the heated cavity into a cavity, applying pressure in multiple directions. They can produce complex intricate shapes (compression bonding produces only blocks, rings). Insert injection molding can mold magnets over pre-manufactured parts. They can produce shafts for micromotors with multipole magnets to be mass produced inexpensively. They are less dense than compression molded ones, so store less energy.

Their maximum service temperature T<sub>max</sub> is limited by that of the binders. PPS resins can offer T<sub>max</sub> up to 220 C. They also offer better resistance against oils, grease. Other popular resins are: Nylon 6, 12, PA6, PA12 and Polyamide; their T<sub>max</sub> 150C or 180C.

**Compression bonding** mix ~80% magnet powders with ~20% *thermoset* “epoxy”. The mix is fed into a die cavity and compacted punches; the green part is then cured. This process applies pressure in one direction, so they can produce only rings, blocks or segments. They are best suited to make thin wall rings. But the height is limited by the compression pressure. Its tooling is less complex and hence less expensive than injection molding. So their energy product ranges 7 to 13 MGOe (Br <0.8T).
7. FERRITE CERAMIC MAGNETS

**PMAG** Database DM lists 430 B(H) Demagnetization Curves of 134 grades, produced by 19 manufacturers worldwide. For names of all these grades, please click on **PMAG, Materials**.

Ferrite Magnets were first engineered by Philips, Netherland in late 50’s. They are made of 85% iron oxide plus oxides of Barium or Strontium Ferrites. They are mixed with a ceramic binder which are compressed and sintered. Dry-pressing results in isotropic magnets. Wet pressing results in anisotropic magnets which store far more energy. Ferrite magnets are the cheapest magnets. But they are lot weaker. They are very hard but brittle. They are resistant to water, salt, petrol, but not to acids. They are used in toys, speakers and motors. They suffer from low energy (1 to 5 MGOe) and low flux density \( B_r \sim 0.25 \) to 0.4 T. Their maximum service temperature is 350°C.

**Dexing Magnetics** offers 63 grades, followed by Kaiven Magnets (52). Alliance Magnetics makes ferrite magnets with \( T_{\text{max}} \) of 350C. Kaiven Magnets makes strongest magnets \( (B_r \sim 0.88T) \). Several manufacturers (China Rare Earth Magnet, Dexing Magnet, Kaiven Magnet, Ningbo Bestway) can produce these magnets to any standards.

But, their quality controls differ. So their magnetic properties differ. Such difference is most noticeable at elevated temperatures. **PMAG** furnishes demagnetization curves of all grades produced by different manufacturers. It helps in identifying one that produces best rated Ferrite magnets. Different standards use different symbols to identify their ferrite magnets as follows.

<table>
<thead>
<tr>
<th>Standard</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chinese standard SJ/T 10410</td>
<td>Y</td>
</tr>
<tr>
<td>USA</td>
<td>C</td>
</tr>
<tr>
<td>Europe Standards (IEC404-8-1)</td>
<td>HF</td>
</tr>
<tr>
<td>Japan TDK</td>
<td>FB</td>
</tr>
</tbody>
</table>

HF20/19 refers to ferrite magnet with minimum energy product of 20 kJ/m\(^3\) and minimum \( HcJ \) of 190 kA/m. All standards specify \( BH_{\text{max}}, B_r, H_{\text{CB}} \) and \( H_{\text{CJ}} \), but not \( T_{\text{max}} \).

**Properties.** Ferrites are valued for their low cost, high resistivity (>10M\( \Omega \)cm) and high corrosion resistance. Their demagnetization resistance is moderate (~250 kA/m).

Most Ferrite magnets can operate up to 250°C. But some firms produce ferrite magnets that can operate up to 400°C. \( Hc \) of Ferrites need not decrease monotonically with temperature; in some, it may be limited to ~60°C. Their thermal stability is an order of magnitude worse than Alnico (0.2%/C). For anisotropic materials, coercivity decreases at +0.35 %/°C. Their thermal conductivity is ~ 12 w/mK.
8. ALNICO MAGNETS

*PMAG* Database contains 82 B(H) Demagnetization Curves of 75 Alnico Magnets grades, produced by 12 manufacturers worldwide. For names of all these grades, please click on *PMAG, Materials*.

*Alnico Magnets* were first developed for USA military in 1940’s. Alnico magnets are composed of Al (8-12%), Ni (13-20%), Co (3-24%), Cu (3-6%), balance Fe, plus trace elements such as Ti, Si, Zi. Different grades are obtained by combing them in different strengths. They are formed by casting or sintering. Alnico is best in long pencil shaped magnet applications. They are very hard and brittle. Their energy product is limited to 10MGOe. Their $B_r$ varies from 0.55 to 1.37 tesla. They can operate up to 600°C. They are valued for their high temperature stability (0.02%/C).

*PMAG* database lists their properties by each manufacturer as their properties differ. Alnico magnets exhibit a ‘knee’ beyond which irreversible demagnetization occurs. So great care must be used in using them beyond their knee point. This sort of demag can occur during assembly or startup of motors causing it to run below the ‘virgin’ B(H) curve, so great care must be taken for proper design and handling. They suffer from low resistance to demagnetization ($HcB \sim 40-150$ kA/m). They also can leak significant flux. USA, Europe and China use different ways to name “standard” grades as listed in Table 3.

### Table 3. Equivalent Grades of Alnico Magnets.

<table>
<thead>
<tr>
<th>CHINA</th>
<th>USA</th>
<th>Europe</th>
<th>$Br$, tesla</th>
</tr>
</thead>
<tbody>
<tr>
<td>MMPA 0100-00</td>
<td>IEC 60404-8-1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LN10</td>
<td>Alnico 3</td>
<td>Alnico 9/3</td>
<td>0.65</td>
</tr>
<tr>
<td>LNG11</td>
<td>Alnico 1</td>
<td>Alnico 8/4</td>
<td>0.72</td>
</tr>
<tr>
<td>LNG13</td>
<td>Alnico 2</td>
<td>Alnico 12/6</td>
<td>0.7</td>
</tr>
<tr>
<td>LNGT18</td>
<td>Alnico 8</td>
<td>Alnico 17/9</td>
<td>0.58</td>
</tr>
<tr>
<td>LNG16</td>
<td>Alnico 4</td>
<td></td>
<td>0.8</td>
</tr>
<tr>
<td>LNG34</td>
<td>Alnico 5C</td>
<td></td>
<td>1.18</td>
</tr>
<tr>
<td>LNG37</td>
<td>Alnico 5C</td>
<td>Alnico 37/5</td>
<td>1.18</td>
</tr>
<tr>
<td>LNG40</td>
<td>Alnico 5</td>
<td></td>
<td>1.22</td>
</tr>
<tr>
<td>LNG44</td>
<td>Alnico 5</td>
<td>Alnico 44/5</td>
<td>1.22</td>
</tr>
<tr>
<td>LNG52</td>
<td>Alnico 5 DG</td>
<td>Alnico 52/6</td>
<td>1.25</td>
</tr>
<tr>
<td>LNG60</td>
<td>Alnico 5-7</td>
<td></td>
<td>1.3</td>
</tr>
<tr>
<td>LNGT28</td>
<td>Alnico 6</td>
<td>Alnico 26/6</td>
<td>1.05</td>
</tr>
<tr>
<td>LNGT32</td>
<td>Alnico 8</td>
<td>Alnico 38/11</td>
<td>0.8</td>
</tr>
<tr>
<td>LNGT38</td>
<td>Alnico 8</td>
<td>Alnico 38/11</td>
<td>0.82</td>
</tr>
<tr>
<td>LNGT44</td>
<td>Alnico 8</td>
<td></td>
<td>0.88</td>
</tr>
<tr>
<td>LNGT60</td>
<td>Alnico 8</td>
<td>Alnico 60/11</td>
<td>0.9</td>
</tr>
<tr>
<td>LNGT72</td>
<td>Alnico 9</td>
<td></td>
<td>1.05</td>
</tr>
<tr>
<td>LNGT36J</td>
<td>Alnico 8 HC</td>
<td>Alnico 36/15</td>
<td>0.7</td>
</tr>
</tbody>
</table>

*Datayo Magnet*, *Dexing Magnet* offer largest number of grades (32) Magnets from AIC Magnetics can operate up to 550°C. Thomas Skinner, Arnold and AIC Magnetics make Alnico magnets with highest $Br$ of 1.37 T.

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9. APPENDIX A. PMAG DATABASE FORMAT

9.1. Category Folders

PMAG Database groups all permanent magnets into 5 Category Folders, labeled AM to EM. For example, AM Folder stores B(H) digital demagnetization curves of all Neodymium Magnets type.

Table 1 shows these 5 category folders. Its Col. 3 lists the maximum energy product (in MGOe) while rest list the number of firms, grades and demagnetization curves in each folder. It shows that the PMAG database comprises nearly 5000 digital demagnetization curves.

Example: Category AM Folder contains 3351 digital demagnetization curves. This data is stored in 696 excel files, each file corresponding to a specific grade produced by 35 firms worldwide.

These magnets operate over a wide temperature range of -40C to 550C. Neo magnets can operate between -125C to 250C. The Samarium magnets can operate up to 550C, but are expensive. The molded/bonded magnets can withstand 180C. The weaker Alnico and Ceramic magnets can go up to 520C and 400C respectively.

Table 4. Demagnetization Digital Curves in the PMAG Database (5111)

<table>
<thead>
<tr>
<th>Folder</th>
<th>Category Folder Name</th>
<th>MGOe</th>
<th>Firms</th>
<th>Grades</th>
<th>Curves</th>
</tr>
</thead>
<tbody>
<tr>
<td>AM</td>
<td>Neodymium Magnets</td>
<td>55</td>
<td>35</td>
<td>696</td>
<td>3351</td>
</tr>
<tr>
<td>BM</td>
<td>Samarium Cobalt Magnets</td>
<td>34</td>
<td>23</td>
<td>165</td>
<td>694</td>
</tr>
<tr>
<td>CM</td>
<td>Molded/Bonded Magnets</td>
<td>12</td>
<td>19</td>
<td>145</td>
<td>554</td>
</tr>
<tr>
<td>DM</td>
<td>Ferrite Ceramic Magnets</td>
<td>4</td>
<td>18</td>
<td>126</td>
<td>430</td>
</tr>
<tr>
<td>EM</td>
<td>Alnico Magnets</td>
<td>4</td>
<td>12</td>
<td>75</td>
<td>82</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>62</td>
<td>1207</td>
<td>5111</td>
<td></td>
</tr>
</tbody>
</table>

9.2. Manufacturer Subfolders

Each Category Folder comprises several Manufacturer Subfolders. Its label refers to a specific manufacturer. Example: ‘Hitachi’ subfolder contains data files of all the grades.
If a Manufacturer furnishes J(H) curves it is converted into B(H) curves using $B = J - \mu_0 H$. PMAG stores all data with 8-decimal digits. But it displays only 3 decimal digits. One can use excel format to display more digits if desired.

9.3. **Grade Files**

Each Manufacturer subfolder comprises several Grade Files. Each Grade File is an excel file that contain the B(H) and Core Loss datasets (at several frequencies and temperatures) for a particular Grade. For example, ‘N2717’ excel grade file contains demagnetization datasets og grade N2717.

9.3.1. **Format of Grade Files**

Fig. 14 shows the format of datasets in a Grade File. In each Grade File,

- Header Row 1: Grade in col. 2, its Manufacturer in col. 4.
- Header Row 2: Data Labels
- Header Row 3: Units, H kA/m, B tesla.

Remaining rows stores the demagnetization datasets in H and B columns.
Figure 14. Format of PMAG database. Header Row 2 lists Data Labels. Header Row 3 lists Units. Within the Data Label, BH denotes B(H) Data, 20C denotes data at 20°C. Data in green Zone refers to Safe Operating Range. Operating a Magnet in this Range will protect it from degenerating to a lower grade permanently.

Data Labels
The Data Label defines the type of curve plus plus temperature at which it is measured. It is highlighted yellow. Its format is:

\[ BHttC \]

where

- \(BH\) = B(H) demagnetization Curve
- \(ttC\) = Temperature numerals ttt followed by ‘C’

Example: BH50C - B(H) demagnetization data at 50 C.

Data
It equi-spaces all data at 0.05T. It shows points in reversible segment (viz. Safe Operating Range) in green color. Demag point \(D\) \((H_d, B_d)\) is the last point in this green zone.
segment. It highlights and stores this point with 4 decimals. It displays other (H, B) points to 3 decimals. It also shows those in unsafe operating range in red color.

**DIGEST Files**

Each Category Folder also contains a DIGEST file. It is a single searchable excel file that lists discrete properties of most grades at room temperature. For example, the DIGEST AM for Neo Magnet Folder AM lists the magnetic properties of 1379 Neo magnet grades, out of which only 633 contain temperature-dependent demagnetization curves.

In it, the 5 columns (A to D, L) contain magnet/manufacturer descriptors. These include Manufacturer, Country, Material Category, Material Name (Grade) and Source) as shown in Table 1.

**Table 1. DIGEST File - Manufacturers, Grade, and Source**

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer</td>
<td>Country</td>
<td>Material Category</td>
<td>Material Name</td>
<td>Source</td>
</tr>
<tr>
<td>AIC Magnetic</td>
<td>China</td>
<td>Alnico, Cast</td>
<td>CLNG12</td>
<td><a href="http://www.aicmag.com/wp-">http://www.aicmag.com/wp-</a></td>
</tr>
<tr>
<td>AIC Magnetic</td>
<td>China</td>
<td>Alnico, Cast</td>
<td>CLNG82</td>
<td><a href="http://www.aicmag.com/wp-">http://www.aicmag.com/wp-</a></td>
</tr>
</tbody>
</table>

The balance columns (E to K) contain 7 searchable magnetic properties listed below.

**Table 5. DIGEST File – Discrete Properties of Magnets.**

<table>
<thead>
<tr>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{max}}$ [°C]</td>
<td>$BH_{\text{max}}$ [MGOe] @ 20°C</td>
<td>$B_r$ [tesla] @ 20°C</td>
<td>$H_{\text{cb}}$ [kA/m] @ 20°C</td>
<td>$H_{\text{cb}}$ [kA/m] @ 20°C</td>
<td>$\rho$ [$\mu\Omega$ cm]</td>
<td>$\gamma$ [gm/cm$^3$]</td>
</tr>
<tr>
<td>3</td>
<td>48</td>
<td>1.413</td>
<td>1000</td>
<td>1036</td>
<td>114</td>
<td>7.3</td>
</tr>
<tr>
<td>4</td>
<td>120</td>
<td>42</td>
<td>1.359</td>
<td>997</td>
<td>1497</td>
<td>114</td>
</tr>
<tr>
<td>100</td>
<td>38</td>
<td>1.346</td>
<td>906</td>
<td>1182</td>
<td>114</td>
<td>7.3</td>
</tr>
</tbody>
</table>

**Column** | **Symbol** | **Property**
---|---|---
E | $T_{\text{max}}$ | Maximum Service Temperature [°C]
F | $BH_{\text{max}}$ | Maximum Energy Product [MGOe]
G | $B_r$ | Remnant Flux Density [T]
H | $H_{\text{cb}}$ | Normal Coercivity [kA/m]
I | $H_{\text{cb}}$ | Intrinsic Coercivity [kA/m]
J | $\rho$ | Resistivity [$\mu\Omega$ cm]
K | $\gamma$ | Density (gm/cm$^3$)

$T_{\text{max}}$ can be that temperature beyond which B(H) shows curvature (a “knee”) in the second quadrant; but this definition is not adapted as a standard. With the DIGEST file,
you can search or compare the magnetic properties of same grade magnets from different manufacturers. You can also shortlist those magnets which can withstand your specific service temperature.

The magnetic properties in the DIGEST refer mostly to “typical" values listed by manufacturers. But manufacturers list mostly minimum values of $H_{cb}$ and $H_{cj}$ to be listed instead of typical value. So the magnetic data in the digest should not be used for design. In contrast, the temperature-dependent B(H) curves in the PMAG database consistently refer to typical values. In most machines, magnets operate between 50 to 150C. So for consistency, they should be used in designing magnets.

Properties of magnets vary slightly from batch to batch, grade and firm. Reputed firms offer magnets with $\pm 2\%$ tolerance on $B_r$. Others offer with $\pm 5\%$ tolerance.

**Free Magnet B(H) Data**

The MagWeb website also furnishes 10 sample B(H) data files (2 from each of the 5 categories of magnets). You can review them to get a ‘feel ‘for the diverse capabilities of the PMAG database.