MagWeb
Magnetic Material Data

MagWeb - Magnetic Material Database

Your Guide to Magnetic Materials Worldwide

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By

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ABSTRACT

Whether you are designing a hybrid electric vehicle, industrial motor or loud speaker, your product is only as good as the **soft magnetic materials** that you employ. You need to create magnetic property data for their FEM simulation. But your effort to optimally use magnetic materials is handicapped by lack of a comprehensive database of magnetic properties of these materials.

Till now, the magnetic properties were available only as continuous curves on paper or picture files. They need to be converted into smooth data for FEM simulation. But the act of digitization disturbs smoothness. Digitization errors can make FEM simulation fails to converge or prolong computational time. *MagWeb* is a comprehensive database of *smooth B(H) and core loss* curves that do not cause instabilities or increase computational time.

MagWeb database comprises a large number of excel files containing clean B(H) data points. It contains more than 1200 smooth *B(H) and Core Loss Data.* These data is recorded for a variety of magnetic materials. These include: Electrical Steels (both Grain Oriented and Non Grain Oriented), Cobalt Steels, Metglas, NanoCrystalline, Nickel Steels, Stainless Steels, Carbon Steels, Cast Iron and Powder Cores. This revision adds hundreds of coreloss data, as well as complex permeabilities of GHz Ferrites. Wherever available, MagWeb also presents the saturation flux density and electric conductivity of these materials.

Unlike curves in picture files, the smooth data from *MagWeb* can be inputted directly into machine design software. Or it can be used to compare different materials. Once you import the MagWeb database into your FEM software, you are ready to optimally utilize magnetic materials in your design.

DISCLAIMER

The MagWeb database is compiled from open source publications. They include manufacturer’s catalogs, scientific literature, manuals, handbooks, textbooks, websites, etc. MagWeb believes the data to be accurate and reliable to the best of its knowledge. But it is intended to support the user in evaluating and making informed decisions on magnetic materials. MagWeb does not provide any warranty or support. MagWeb is not liable, explicitly or implicitly, for any damages caused by using its database. MagWeb reserves the right to change the data without notice.

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1. INTRODUCTION

Whether you are designing an electric motor, transformer or a wind generator - your product is only as good as **ferromagnetic materials** (aka soft magnetic materials that you employ. They are mainly composed of iron, cobalt or nickel with a little bit of Silicon, Aluminum etc. Modern civilization could not have existed without engineers exploiting their unique ability to conduct magnetic flux more easily than air. In particular, electric motors, which consume over 70% of electric energy produced, depend on them. But, in spite of these magnetic materials being everywhere, there has been no single source of good data of all magnetic materials.

Designers characterize the ability of a magnetic material to carry magnetic flux by *Magnetic Flux Density* B (Tesla). It is the magnetic flux per unit cross-sectional area. It depends on the magnetic field intensity H (A/m) applied to the material. The variation of B with H is shown by a normal magnetization curve - also called B(H) curve. When the magnetic flux alternates, magnetic materials also incur core loss P (w/kg). This loss depends on flux density B and frequency f. So, in addition to B(H) curve, designers also need core loss curves P = P(B,f).

1.1. MagWeb -largest database of soft magnetic materials

MagWeb has 1267 files of B(H) curves and core loss curves. It classifies[1] all soft magnetic materials into 12 categories (or *Folders*). One subfolder stores the smooth B(H) curves and another subfolder stores digital core loss curves. MagWeb identifies each of its files by a unique code. Table 1 lists the *MagWeb* Folders. For example, the Electrical Steel (NGO) Folder has 293 B(H) files and 116 core loss files, or total of 409 files.

Table 1. ***MagWeb Files on Magnetic Materials (1267)***

Category	**MagWeb Folder**	**B(H) Curves**	**Core Loss Curves**	**Total Files**
A	**Electrical Steel – Non Grain Oriented**	**293**	**116**	**409**
B	**Electrical Steel - Grain Oriented**	**141**	**134**	**275**
C	**Metglas & Nanocrystalline**	**23**	**10**	**33**
D	**Cobalt Steel**	**28**	**12**	**40**
E	**Nickel Steel**	**64**	**22**	**86**
F	**Stainless Steel**	**34**	**0**	**34**
G	**Low Carbon Steel**	**89**	**1**	**90**
H	**Castings**	**29**	**0**	**29**
I	**Iron Powder Core**	**49**	**26**	**75**
J	**Alloy Powder Core**	**28**	**43**	**71**
K	**Ferrite**	**51**	**7**	**58**
L	**GHz Ferrite**	**0**	**67**	**67**
	Total Files in MagWeb Database	**829**	**438**	**1267**

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[1] See also, IEC 60404-1:2016, Magnetic materials, part 1, Classification.

So far, a comprehensive database of B(H) curves and core loss curves of magnetic materials produced world wide is not available. With its listing of thousands of B (H) and core loss curves, MagWeb database fills this need. Use of MagWeb database will obviously save time and effort in searching these data.

1.2. Designers need B(H) Curve, but Mfrs supply J(H) curve

Unlike electric materials, the properties of magnetic materials vary with several factors such as annealing, flux direction, specimen shape etc. So, to maintain uniformity, international standards[2] specify standard test conditions under which they should be measured.

Unfortunately, these measurement standards use a different metric, called ***Ferric Flux Density J*** (aka *magnetic polarization)* to characterize a magnetic material. J represents the increase in magnetic flux density B over *vacuum flux density* $\mu_o H$. Thus the ferric flux density J is slightly different[3] from the magnetic flux density B. To calculate the magnetic flux density B from a measured ferric flux density J, one has to add the "vacuum flux density" $\mu_o H$,

$$B = J + \mu_o H \quad \cdots \quad \cdots \quad (1)$$

Electric steel manufacturers follow the international standards to measure variation of J with H. They supply such *ferric flux density curve J(H).* This is a locus of tips of a series of hysteresis loops in the J(H) plane.

But unfortunately, most manufacturers ***mislabel*** their J(H) curve as B(H) curve. And designers input such mislabeled J(H) data as B(H) data into a FEM design software. They neglect to recalculate B(H) using eq. (1). Such usage of *mislabeled J(H) data* as B(H) data is not uncommon, and is a well accepted and prevailing practice. (Even the legendary Steinmetz and ASTM mix up both types of flux densities, and used "B" when they intended to mean "J").

This creates a slight error, called *mislabeling error*. For example when a machine operates at ~ 1.7 T (or say 10,000 A/m), the vacuum carries a flux density of 0.0125 T. Thus, strictly speaking, a measured *ferric flux density* J of 1.7 T must be converted into B of 1.7125 T before inputting into a FEM design software.

The mislabeling error is defined as $\varepsilon_{BJ} = (B-J)/J$. At 10,000 A/m, the mislabeling error is ~ 0.7%. It is so small and harmless that the designers rightly ignore it. But it gets amplified when, under severe duty, parts of a machine (e.g. core-ends or tooth corners) operate beyond the measured data range (i.e. beyond ~ 1.9T). As the overfluxed parts run closer to saturation, they demand lot more H to push a little bit more flux. Then H can be as high as 150 or 300 kA/m. So the mislabeling error increases to 10% or 20%. Such high mislabeling error affects the accuracy of magnetic field solvers. Thus, to accurately analyze overfluxed regions, a designer should use eq. (1) to recalculate B(H) from manufacturer's J(H) data, and input such B(H) data.

This mislabeling has an unfortunate ramification. If you interpret the manufacturer's J(H) curve as B(H) curve – as most software do - it will increase linearly without limit. If you interpret it as J(H) curve, it will eventually reach a saturation limit J_s.

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[2] See e.g., EN10106, Cold rolled nonoriented electrical steel sheet and strip delivered in the fully processed state. 2007

[3] Some researchers express J in terms of *magnetization* M, related to J by $J = \mu_o M$

1.3. B(H) Curve has an Unstable Point of Inflection

The B(H) curve is expressed as $B = \mu H = \mu_o \mu_r H$ where $\mu_o = 4\pi (10^{-7})$ N/A^2 denotes permeability of air. Here μ_r (H) denotes relative permeability as a function of H. So either a B(H) curve, or μ_r(H) curve can be used to characterize a magnetic material. A MagWeb file displays both magnetization curve B(H) and permeability curve μ_r(H).

The **B(H) curve** is needed when one wants the material to carry flux at highest flux density without overheating or saturation. Electric motors, transformers etc fall into this category.

Fig. 1 shows a B(H) curve (**blue**) of the material M250-35A. (It is a part of MagWeb folder AI02). Such B(H) curve has a characteristic *knee*. Below the knee, its tangent curve B'(H) (aka differential permeability = $(1/\mu_o)$ dB/dH) increases with H. Above the knee, it decreases with H. Within the knee, there is a ***Point of Inflection*** Q where the tangent value peaks[4]. It is a natural point of computational instability[5]. Computation of magnetic fields around POI slows convergence and increases computational time. To avoid convergence issues, MagWeb has developed **smooth B(H) data** as described in the next section.

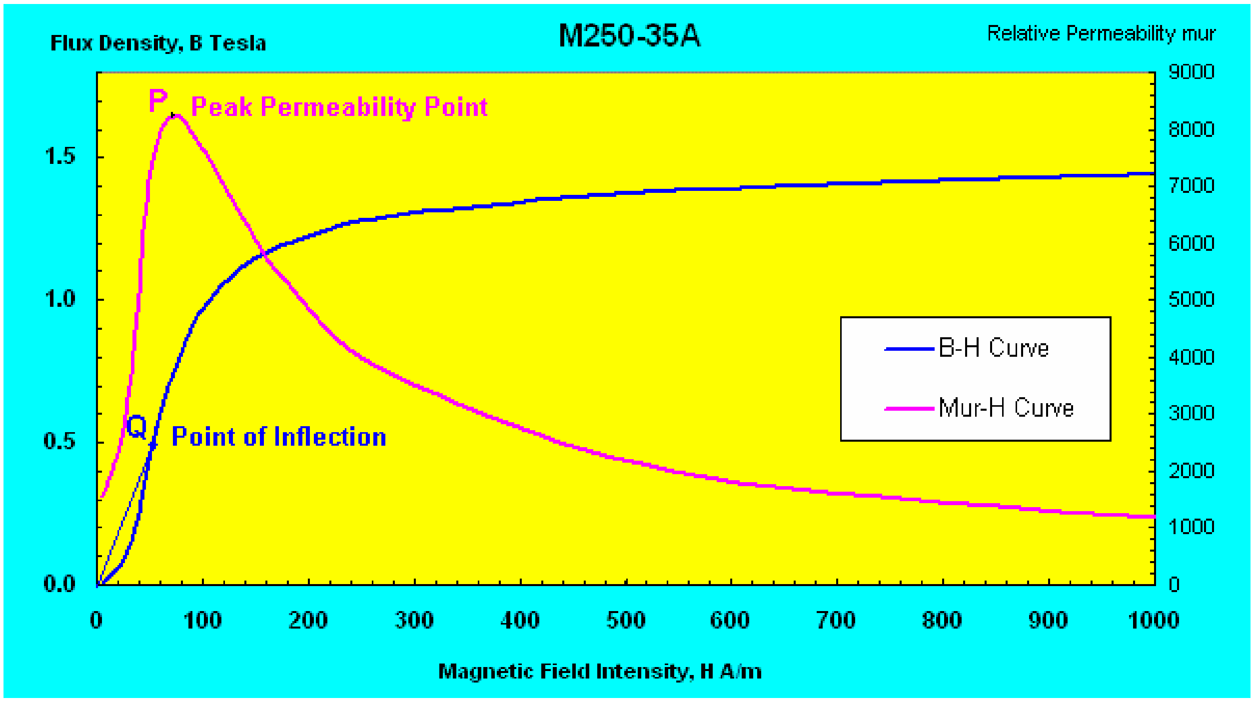

Fig. 1. B-H Curve has a point of inflection that causes poor convergence

The **permeability curve** μ_r(H) is used when one needs a material with highest permeability. Magnetic shields, telecom, GFI etc fall into this category. It is also useful in selecting lamination thickness. Note that AC flux flows only in a thin skin, whose thickness depends on permeability. *So a **too thick lamination detrimentally increases the effective flux density** and simply wastes precious material* (see section.3.1 or 4).

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[4] Spooner, T. *Properties and Testing of Magnetic Materials*, McGraw Hill, 1927, p.10

[5] Kis, P. *Jiles-Atherton model implementation to edge FEM*, Ph.D Thesis,Budapest Univ.Tech., 2006, p.2.

Fig. 1 also shows permeability curve (pink) $\mu_r(H)$ of the material 35HX300. It shows a characteristic ***peak*** permeability point P. Permeability also peaks in the knee region. Below this peak point P, permeability increases with H. Above it, the permeability decreases with H. The peak permeability point P is the ideal point of operation for magnetic shields as it maximizes the shielding effectiveness.

1.4. Smooth B(H) Data

Till now, B(H) curves are plotted as continuous curves on paper; or they are scanned as picture files. But a picture file of B(H) curve cannot be fed into FEM software. The software instead needs B(H) data at discrete points. Digitization is the process of obtaining values of B and H at discrete points from a continuous B(H) curve. But smoothness of digital B(H) data is essential for obtaining convergent solution.

But how does one measure “smoothness”? This is best done by examining the tangent B’(H) curve, which theoretically should have only one peak. A jittery tangent curve B’(H) is one that has more than one peak. It results, for example, when one picks points on a thick B(H) curve that are offset from a mid line. Such jittery tangent curve reflects a non-smooth B(H) data.

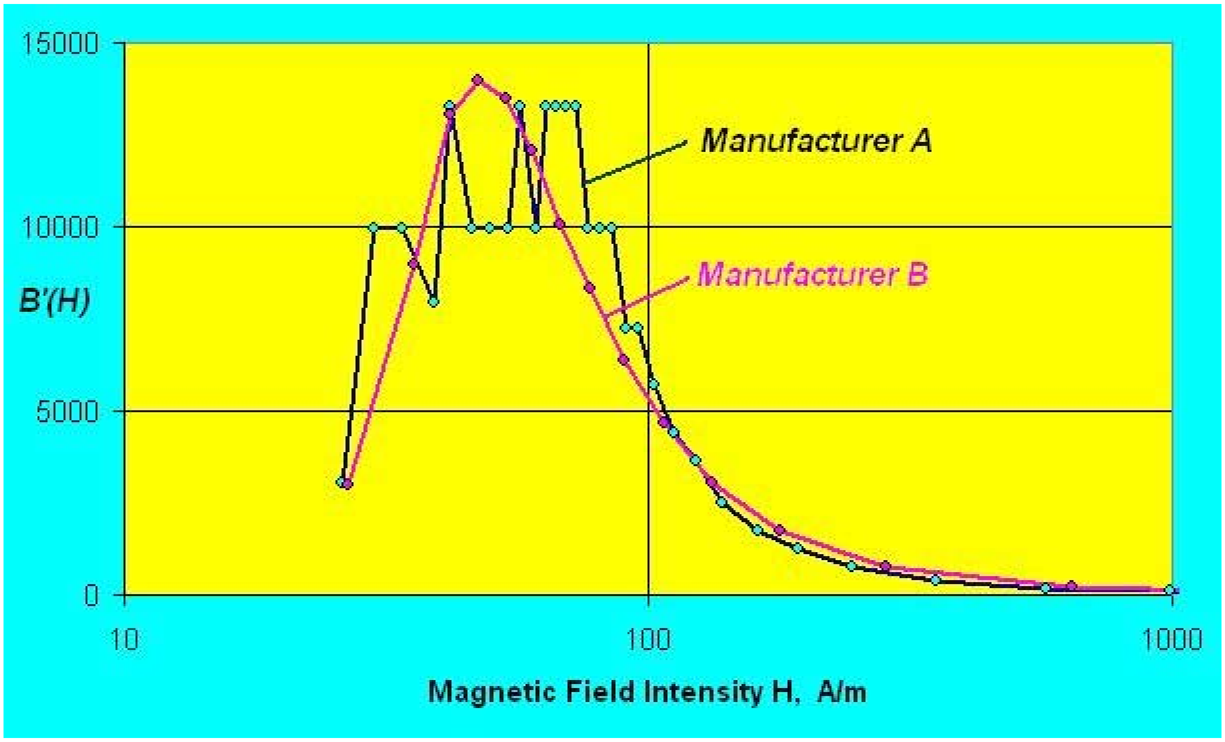

Fig.2. The tangent curve B’(H) for manufacturer A shows jitter.

For example Fig. 2 compares B’(H) tangent curves for NGO steel M250-35A, derived from B(H) curves of two manufacturers A and B. The B’(H) tangent curve from the manufacturer A is seen to have multiple peaks, i.e., its tangent curve is jittery. In contrast, the B’(H) curve from manufacturer B shows only one peak. Such data is free of jitter. Thus the quality of B(H) curves varies with manufacturers. Some have jittery tangent, some are smooth.

A jittery tangent confuses the Newton iteration used in FEM software. The computer struggles to find the real peak buried in the jittery data. This in turn creates computational instability. The solver may fail to converge, causing instability. Or the convergence can be slow, increasing computer time [6,7]. To avoid them, one needs to plot B'(H) curve and eliminate "spurious" peaks.

Obviously there is a need to develop B(H) data that does not have jittery tangent[8]. B(H) data is said to be ***smooth*** when its tangent curve B'(H) has only one peak, that too, at the point of inflection only. A *smooth* B(H) data obviously will not cause convergence issues or computational instability, so is desirable.

Over several years, MagWeb developed several tools needed to derive *smooth* B(H) data for a variety of materials. Its digitization tools include, precision scanning a picture file, converting B and H units, picking points on B(H) curve that are on mid-line of B(H) curve, plotting B'(H) curve, eliminating multiple peaks if discovered, equi-spacing the data points etc. Of these, plotting B'(H) curve and removing spurious peaks is a most tedious step. MagWeb database contains the resulting smooth B(H) data. So its usage does not cause computational instability or convergence issues.

1.5. Organization of MagWeb Files

A BH file contains BH curve, permeability curve plus (B, H, mur, B'(H)) data points. In addition, it lists Manufacturer, brand name, thickness, annealing schedule, Saturation Flux Density and Resistivity etc if available. Top two rows contain this information. row 1 contains data while row 2 contains descriptors of the data. These two rows, respective 11 columns, and their description are shown below.

Table 2. ***Header Rows in each data file***.

C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
Electrical Steel GO	Posco, South Korea	Posco		0.009	0.23	Fully Processed	DC	2.020	2.083	B002
	Manufacturer	***Brand***	***gage***	***inch***	***mm***	***Annealing***	***Hz***	***Bsat***	***MS/m***	*Curve*

C1 - Material Category (electrical steel, metglas etc)
C2 - Manufacturer
C3 – Material Name given by the manufacturer
C4, C5, C6 - Thickness in gage, inches and mm respectively. .
C7 - Annealing condition. For example
    "Fully Processed": Manufacturer delivers steel in fully annealed condition.
    "Semi-Processed": Manufacturer expects user to anneal steel.
    "732C anneal": steel is annealed per a 732 C anneal schedule.
C8 - frequency in Hz. For example, 50 Hz means B-H data is measured at 50 Hz.
C9 - Saturation Flux Density J_s of the material (Tesla) if available.
C10 – Electric Resistivity in $\mu\Omega$m.
C11 - MagWeb Id. It is a unique 4-digit code assigned to each file.

The digital B(H) data is tabulated in four columns C1-C4. They contain H (A/m), B (tesla), μ_r and B'(H) respectively. Each B-H curve is digitized with 20 to 25 noise-free data points. This ensures stability and fast convergence. *MagWeb* stores data with 8-decimal digits, but displays only 2 or 3 decimal digits. If greater accuracy is needed, one can display more decimal digits through excel facility.

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[6] Rao, D. K, Kuptsov, V., Effective use of magnetization data in the design of electric machines with overfluxed regions, IEEE Trans. Magnetics, Vol. 51, No. 7, July 1015, paper no. 6100709

[7] Hameyar, *Numerical Modeling and Design of Electric Machines*, WIT Press, 1997, p. 93

[8] To avoid convergence issues, some FEM software replace measured B(H) with an "artificial" one that has constant slope below POI. Essentially they "remove" the POI. But if operating is below POI, it leads to large errors. See e.g. https://www.jmag-international.com/library/jmag_atoz/03.html. or https://www.emetor.com/blog/post/influence-b-h-curve-convergence-finite-element-solution/

2. ELECTRICAL STEELS – NON-GRAIN ORIENTED

“Electrical Steels” (also called *Silicon Steels*) are thin sheets of ultra low carbon steel, with silicon added (upto 4%) to reduce core loss. Carbon is removed to stabilize core loss (it prevents “aging” i.e., degradation of permeability and core loss with time). Non Grain-Oriented (NGO) steel may have Carbon less than 30[9], 50[10,11], 200[12], 800[13] ppm - depending on whom you ask. (Carbon is magnetically harmless below its solubility limit of 70 ppm). Electrical steels tend to be more brittle than structural steels. But they offer higher permeability and consistent magnetic properties. (Structural steels add Carbon to improve mechanical strength while Electrical Steels remove Carbon to improve its magnetic properties).

Manufacturers supply electrical steels as fully annealed sheet rolls. Thickness ranges 0.009” to 0.040” (<1 mm) and width up to 4 ft (1250 mm). They have a smooth surface finish, with tightly adherent surface oxide coating (often called as C-0). All electrical steels invariably have an additional insulative coating (C-2 to C-6). Such coatings are not really insulative. They are resistive and only increase the surface resistance, so reduce interlaminar loss. (Un-annealed or uncoated electrical steels can be procured only as special order.)

Electrical steels are sold in two major groups - Grain-Oriented (GO) or Non Grain Oriented (NGO) steel. GO steels offer superior properties in rolling direction, and therefore are mainly used in transformers or large generators. In contrast, NGO steels offer magnetic properties that are more or less independent of direction, and therefore are mainly used in electric motors. NGO steels are less expensive than GO Steels.

This section deals with NGO Steels only. They go by other names, e.g., Cold Rolled Non-Oriented Steels (CRNO), Non-Oriented Electrical Steels (NOES) or Non-Oriented Silicon Steels (NO). They are used in several markets, e.g., industrial motors, fans, pumps, rolling mills, oil/gas, machine tools etc. Their grain size is smaller (50 to 200 μm) compared to GO steels. They are used mainly at line frequencies (50, 60) or even at aviation frequency 400 Hz.

The peak permeability of NGO steel ranges 4000 to 8000. It can be an order of magnitude lower than that of GO steels. Therefore they require higher excitation current to reach same core loss. Their saturation magnetization J_s is 2.05 T.

Core loss of NGO steels ranges 2 to 9 w/kg at 1.5 T, 50 Hz. That for GO steel ranges 0.5 to 1 w/kg. So core loss of NGO steel can be a factor of 2 to 18 higher than that of GO steel.

In top grade NGO steels (with 2.5 to 3.2% Si) core loss ranges 2.2 to 3 w/kg. That for medium grades (with 1.5 to 2.5% Si) it ranges 3 to 6 w/kg. That for low grades (with 0.5 to 1.5% Si) ranges 6 to 9 w/kg. Medium grade steels thicker than 1mm are called relay steels. Some vendors offer a “high strength” (HS) grade steel, for use in hybrid vehicle motors.

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[9] AK Steel, Selection of Electrical Steel for Magnetic Cores, Product Data Bulletin, 2007, p. 7

[10] Electrical steel, https://en.wikipedia.org/wiki/Electrical_steel

[11] Dorner, D., Non-Oriented electrical steel sheet for electric vehicle drives, ThyssenKrupp Techforum, Issue 1, 2009.

[12] ASTM A677, Standard Spec. for NonOriented Electrical Steel.

[13] US Govt, Non-Oriented Electrical Steel CVD, http://enforcement.trade.gov/download/factsheets/factsheet-multiple-non-oriented-electrical-steel-cvd-prelime-031914.pdf

2.1. NGO Steels are not fully isotropic

Contrary to common belief, NGO steels are not completely isotropic. Nonetheless, they are more isotropic than GO steels. The European Standard EN 10106 defines *anisotropy* T of electrical steels as

$$T = \frac{P_1 - P_2}{P_1 + P_2}$$

where P_1 and P_2 are losses in samples cut in Transverse Direction (TD) and Rolling Direction (RD) respectively. Anisotropy of NGO steels can vary from 6 to 30% depending on thickness and vendor. One needs to contact the vendor for its value.

Fig. 3 (reproduced from MagWeb folder AI04) shows how the flux angle (angle of flux relative to Rolling Direction) affects B(H) curve of NGO steel[14]. To neutralize such variation, a motor designer should use their properties that are measured in a 50/50 Epstein frame. In this, 50% of test specimens are cut along the rolling direction, 50% are cut along the transverse direction.

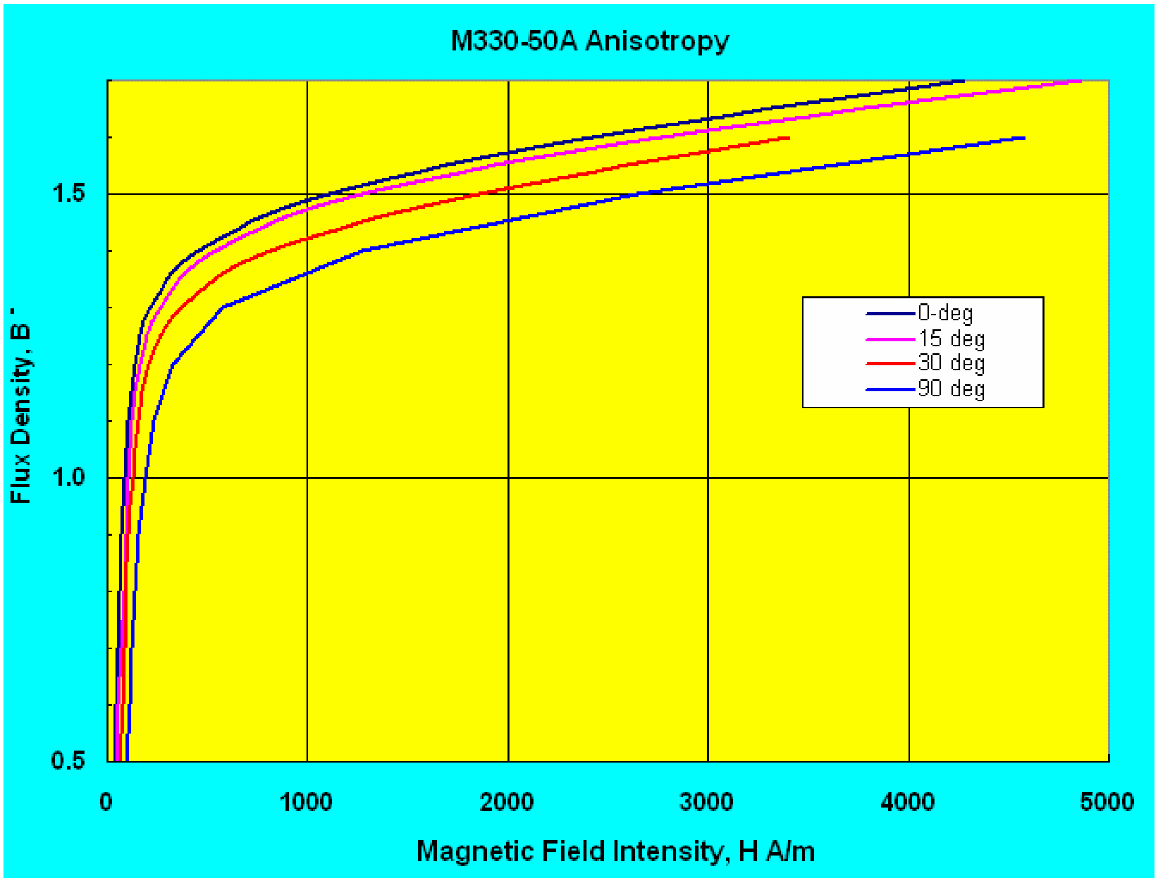

Fig. 3 Magnetic Properties of NGO steels do vary with direction.

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[14] Influence of flux angle on the magnetic properties varies with manufacturer.

2.2. Quality varies with the Manufacturer

Several manufacturers produce NGO steel of the “same-grade” (per international standards). But in reality, their properties vary with the manufacturer, even if they are “same-grade”.

For example, Fig. 4 (reproduced from MagWeb Folder AI02) compares the core loss curves of several M-15 grade steels from manufacturers A, B, C and D. It shows that, even if the grade designation is same, core loss from a “best” steel producer can be 30% lower than that from a “worst” steel producer.

The reason for such variation is that (in addition to C and Si), the core loss depends subtly on how strictly trace impurities are controlled. They are: Oxygen, Sulphur, and Nitrogen[15]. When they vary from 10 to 50 ppm, the core loss can vary by 30%!

These trace impurities differ from manufacturer to manufacturer, depending on their quality control. So the magnetic properties of electrical steel vary with the manufacturer, even if the composition is same. So MagWeb lists the properties of steels by each manufacturer, *irrespective of their grade.* Such manufacturer-based database can assist designers in making informed decisions and in comparing electrical steels from different manufacturers.

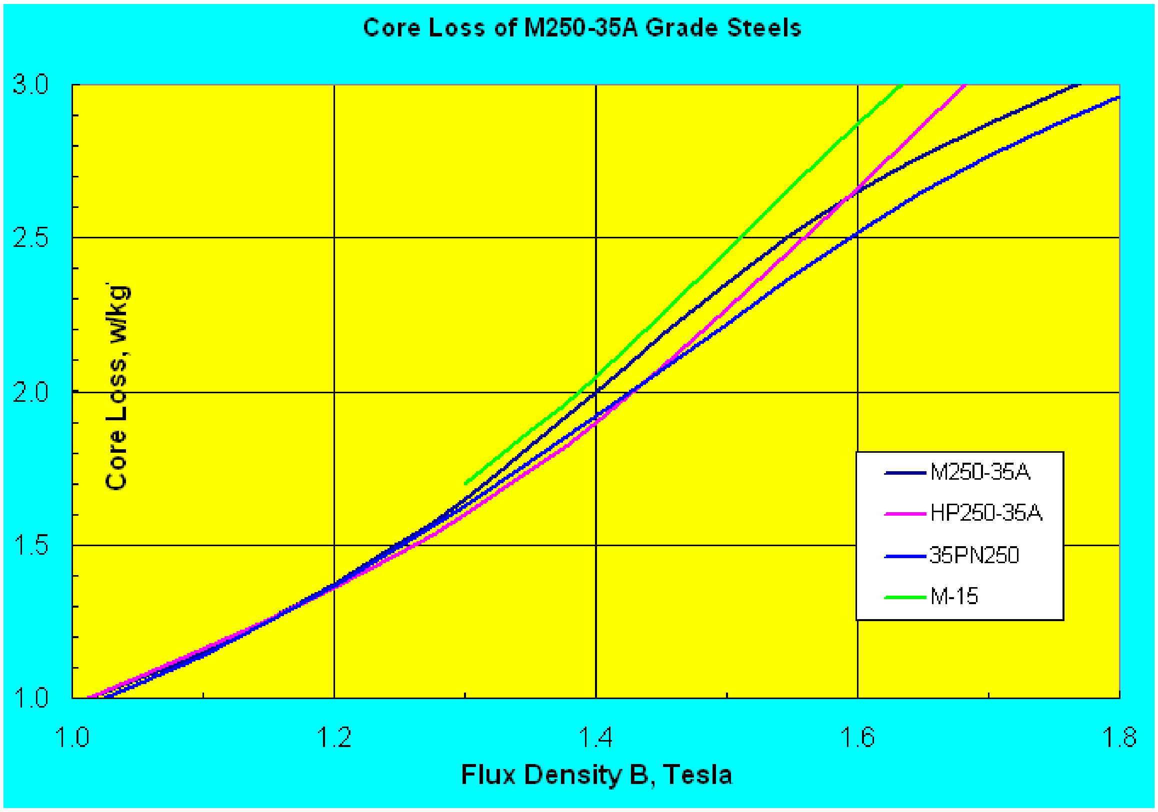

Fig. 4. Same-grade NGO steels from various manufacturers differ in quality.

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[15] Bozorth, R. M., Ferromagnetism, Van Nostrand Co., New York, 1951. p. 52

2.3. ASTM and IEC steels are not equivalent

Another misconception is that inch-based electrical steels (primarily from USA, based on ASTM standards) can be interchanged with mm-based other steels of identical thickness (from other countries based on international standards, viz IEC/EN/JS). The mm-based steels are produced outside USA with 0.35 mm, 0.50 and 0.65 mm thickness. The inch-based laminations from USA are produced with 0.014”, 0.0185” and 0.025” thickness. But the 0.35 mm (0.01378”) thick IEC steel is 1.6% thinner than its 0.014” thick ASTM counter part. The 0.5 mm (0.0197”) thick IEC steel is 6.4% thicker than its 0.0185” ASTM counter part. The 0.65 mm (0.0256”) thick IEC steel is 2.4% thicker than its 0.025” thick ASTM counterpart. These minute differences in thickness can affect the number of laminations required to build a stack. For example, a 10” stack requires (theoretically) 726 laminations of 0.35 mm thick steel, but only 714 laminations of 0.014” thick steel. Thus they can impact the stacking factor and overall length of a machine! They apparently affect the cost of a core. The “Electrical Steels (NGO)” folder contains total of 409 MagWeb excel files as shown below.

Table 3. “Electrical Steel (NGO)” Folder – B(H) Curves (293)

"Electrical Steel (NGO)" Folder – B(H) Curves (293)		
No.	**ID**	**Material Name**
1	AB01	HF-10 As Sheared
2	AB02	HF-10 Stress Relief Annealed
3	AB03	HF-10X As Sheared
4	AB04	HF-10X Stress Relief Annealed
5	AB05	HF-12 As Sheared
6	AB06	HF-12 Stress Relief Annealed
7	AB07	M-10 DC
8	AB08	M-10X 50/50
9	AB09	M-10X parallel
10	AB10	M-13 50 Hz
11	AB11	M-13 60 Hz
12	AB12	M-13 100 Hz
13	AB13	M-13 150 Hz
14	AB14	M-13 200 Hz
15	AB15	M-13 300 Hz
16	AB16	M-13 400 Hz
17	AB17	M-13 600 Hz
18	AB18	M-13 1000 Hz
19	AB19	M-13 1500 Hz
20	AB20	M-13 2000 Hz
21	AB21	M-13 DC
22	AB22	M-14
23	AB23	M-15 14 mil 0Hz
24	AB24	M-15 14 mil 60 Hz
25	AB25	M-15 19 mil 60 Hz
26	AB26	M-19 14 mil 0 Hz
27	AB27	M-19 14 mil 50 Hz
28	AB28	M-19 14 mil 60 Hz
29	AB29	M-19 14 mil 100 Hz
30	AB30	M-19 14 mil 150 Hz
31	AB31	M-19 14 mil 200 Hz
32	AB32	M-19 14 mil 300 Hz
33	AB33	M-19 14 mil 400 Hz
34	AB34	M-19 14 mil 600 Hz
35	AB35	M-19 14 mil 1000 Hz
36	AB36	M-19 14 mil 1500 Hz
37	AB37	M-19 14 mil 2000 Hz
38	AB38	M-19 19 mil 0 Hz
39	AB39	M-19 19 mil 50 Hz
40	AB40	M-19 19 mil 60 Hz
41	AB41	M-19 19 mil 100 Hz
42	AB42	M-19 19 mil 150 Hz
43	AB43	M-19 19 mil 200 Hz
44	AB44	M-19 19 mil 300 Hz
45	AB45	M-19 19 mil 400 Hz
46	AB46	M-19 19 mil 600 Hz
47	AB47	M-19 19 mil 1000 Hz
48	AB48	M-19 19 mil 1500 Hz
49	AB49	M-19 19 mil 2000 Hz
50	AB50	M-22
51	AB51	M-27 14 mil 0 Hz
52	AB52	M-27 14 mil 60 Hz
53	AB53	M-27 19 mil 0Hz
54	AB54	M-27 19 mil 60 Hz
55	AB55	M-27 25 mil 60 Hz
56	AB56	M-36
57	AB57	M-43 Fully Processed
58	AB58	M-43 Semi Processed
59	AB59	M-45
60	AB60	M-47 Fully Processed
61	AB61	M-47 Semi Processed
62	AC01	E230

No.	ID	Material Name
63	AC02	M195-35A
64	AC03	M400XP-35A
65	AD01	Arnon 5
66	AD02	Arnon 7 400 Hz
67	AD03	Arnon 7 800 Hz
68	AD04	Arnon 7
69	AG01	Silicon Core Iron A (732 C Anneal)
70	AG02	Silicon Core Iron A (843C Anneal)
71	AG03	Silicon Core Iron A (954C Anneal)
72	AG04	Silicon Core Iron A (1066C Anneal)
73	AG05	Silicon Core Iron A-FM (732C Anneal)
74	AG06	Silicon Core Iron A-FM (843C Anneal)
75	AG07	Silicon Core Iron A-FM (954C Anneal)
76	AG08	Silicon Core Iron A-FM (1066C Anneal)
77	AG09	Silicon Core Iron B (732C Anneal)
78	AG10	Silicon Core Iron B (843C Anneal)
79	AG11	Silicon Core Iron B (954C Anneal)
80	AG12	Silicon Core Iron B (1066C Anneal)
81	AG13	Silicon Core Iron B-FM (732C Anneal)
82	AG14	Silicon Core Iron B-FM (843C Anneal)
83	AG15	Silicon Core Iron B-FM (954C Anneal)
84	AG16	Silicon Core Iron B-FM (1066C Anneal)
85	AG17	Silicon Core Iron C (843C Anneal)
86	AG18	Silicon Core Iron C (954C Anneal)
87	AG19	Silicon Core Iron C (1066C Anneal)
88	AI01	M235-35A
89	AI02	M250-35A
90	AI03	M250-35HS
91	AI04	M250-50 Anisotropy
92	AI05	M250-50A
93	AI06	M270-35A
94	AI07	M270-50A
95	AI08	M290-50A
96	AI09	M300-35A
97	AI10	M310-50A
98	AI11	M310-65A
99	AI12	M330-35A
100	AI13	M330-35HP 50 Hz
101	AI14	M330-35HP 100 Hz
102	AI15	M330-35HP 200 Hz
103	AI16	M330-35HP 400 Hz
104	AI17	M330-35HP 1000 Hz
105	AI18	M330-35HP 2500 Hz
106	AI19	M330-35HS
107	AI20	M330-35HT
108	AI21	M330-50A Anisotropy
109	AI22	M330-50A 50 Hz
110	AI23	M330-50A 100 Hz
111	AI24	M330-50A 200Hz
112	AI25	M330-50A 400 Hz
113	AI26	M330-50A 1000 Hz
114	AI27	M330-50A 2500 Hz
115	AI28	M330-65A
116	AI29	M350-50A
117	AI30	M350-65A
118	AI31	M400-50A
119	AI32	M400-65A
120	AI33	M470-50A
121	AI34	M470-65A
122	AI35	M530-50A
123	AI36	M530-50HP
124	AI37	M530-65A
125	AI38	M600-50A
126	AI39	M600-65A
127	AI40	M600-65HP
128	AI41	M600-100A
129	AI42	M700-50A
130	AI43	M700-65A
131	AI44	M700-100A
132	AI45	M800-50A
133	AI46	M800-65A

No.	ID	Material Name
134	AI47	M800-100A
135	AI48	M1000-100A
136	AI49	NO10
137	AI50	NO12 50 Hz
138	AI51	NO12 400 Hz
139	AI52	NO12 2500 Hz
140	AI53	NO12 5000 Hz
141	AI54	NO12 10000 Hz
142	AI55	NO15 50 Hz
143	AI56	NO15 400 Hz
144	AI57	NO15 2500 Hz
145	AI58	NO15 5000 Hz
146	AI59	NO15 10000 Hz
147	AI60	NO18 50 Hz
148	AI61	NO18 400 Hz
149	AI62	NO18 2500 Hz
150	AI63	NO18 5000 Hz
151	AI64	NO18 10000 Hz
152	AI65	NO20 50 Hz
153	AI66	NO20 400 Hz
154	AI67	NO20 2500 Hz
155	AI68	NO20 5000 Hz
156	AI69	NO20 10000 Hz
157	AI70	NO27 50 Hz
158	AI71	NO27 400 Hz
159	AI72	NO27 2500 Hz
160	AI73	NO27 5000 Hz
161	AI74	NO27 10000 Hz
162	AI75	NO30 50 Hz
163	AI76	NO30 400 Hz
164	AI77	NO30 2500 Hz
165	AI78	NO30 5000 Hz
166	AI79	NO30 10000 Hz
167	AK01	10JNEX900 50 Hz
168	AK02	10JNEX900 400 Hz
169	AK03	10JNEX900 1000Hz
170	AK04	10JNEX900 2000 Hz
171	AK05	10JNEX900 5000Hz
172	AK06	10JNEX900 10000 Hz
173	AK07	10JNEX900 20000 Hz
174	AK08	10JNEX900 30000 Hz
175	AK09	10JNEX900 50000 Hz
176	AK10	10JNEX900 DC
177	AK11	10JNHF600 50 Hz
178	AK12	10JNHF600 100 Hz
179	AK13	10JNHF600 2000Hz
180	AK14	10JNHF600 10000Hz
181	AK15	10JNHF600 20000 Hz
182	AK16	10JNHF600 30000 Hz
183	AK17	10JNHF600 50000 Hz
184	AK18	10JNHF600 100000 Hz
185	AK19	10JNHF600 DC
186	AK20	20JNHF1300 50 Hz
187	AK21	20JNHF1300 100 Hz
188	AK22	20JNHF1300 2000 Hz
189	AK23	20JNHF1300 10000 Hz
190	AK24	20JNHF1300 20000 Hz
191	AK25	20JNHF1300 DC
192	AK26	35JN200
193	AP01	15HX1000
194	AP02	20HX1200
195	AP03	20HX1300
196	AP04	27HX1500
197	AP05	27HX1800
198	AP06	30HX1600
199	AP07	30HX1800
200	AP08	35H210
201	AP09	35H230
202	AP10	35H230
203	AP11	35H250
204	AP12	35H270

No.	ID	Material Name
205	AP13	35H300
206	AP14	35H360
207	AP15	35H440
208	AP16	35HX230
209	AP17	35HX250
210	AP18	35HX300
211	AP19	50H230
212	AP20	50H250
213	AP21	50H270
214	AP22	50H290
215	AP23	50H310
216	AP24	50H350
217	AP25	50H400
218	AP26	50H470
219	AP27	50H600
220	AP28	50H700
221	AP29	50H800
222	AP30	50H1000
223	AP31	50H1300
224	AP32	50HX290
225	AP33	50HX350
226	AP34	50HX470
227	AP35	50HX600
228	AQ01	35PN210
229	AQ02	35PN230
230	AQ03	35PN250
231	AQ04	35PN270
232	AQ05	35PN300
233	AQ06	35PN360
234	AQ07	35PN440
235	AQ08	50PN250
236	AQ09	50PN270
237	AQ10	50PN290
238	AQ11	50PN310
239	AQ12	50PN350
240	AQ13	50PN400
241	AQ14	50PN470
242	AQ15	50PN600
243	AQ16	50PN700
244	AQ17	50PN800
245	AQ18	50PN1300
246	AR01	2112 50 Hz Along
247	AR03	2112 50 Hz Mix
248	AR02	2112 50 Hz Traverse
249	AR04	2212 50 Hz Along
250	AR06	2212 50 Hz Mix

No.	ID	Material Name
251	AR05	2212 50 Hz Transverse
252	AR07	2312 50 Hz Along
253	AR09	2312 50 Hz Mix
254	AR08	2312 50 Hz Transverse
255	AR10	2412 50 Hz Along
256	AR12	2412 50 Hz Mix
257	AR11	2412 50 Hz Transverse
258	AR13	2413 50 Hz Along
259	AR15	2413 50 Hz Mix
260	AR14	2413 50 Hz Transverse
261	AR16	M530 50 Hz Along
262	AR18	M530 50 Hz Mix
263	AR17	M530 50 Hz Transverse
264	AR19	M700 50 Hz Along
265	AR21	M700 50 Hz Mix
266	AR20	M700 50 Hz Transverse
267	AR22	M800 50 Hz Along
268	AR24	M800 50 Hz Mix
269	AR23	M800 50 Hz Transverse
270	AT01	MES3F
271	AV01	USS Q-core P19
272	AV02	USS Q-core P21
273	AX01	Isovac 270-35A
274	AX02	Isovac 290-35A
275	AX03	Isovac 330-35A
276	AX04	Isovac 330-50A
277	AX05	Isovac 400-50A
278	AX06	Isovac 400-65A
279	AX07	Isovac 470-50A
280	AX08	Isovac 470-65A
281	AX09	Isovac 530-50A
282	AX10	Isovac 600-50A
283	AX11	Isovac 600-65A
284	AX12	Isovac 700-50A
285	AX13	Isovac 700-65A
286	AX14	Isovac 800-50A
287	AX15	Isovac 800-65-A
288	AX16	Isovac 900-50A
289	AX17	Isovac 1000-65A
290	AX18	Isovac 1000-65K
291	AX19	Isovac HP 250-35A
292	AX20	Isovac HP 350-65A
293	AX21	Isovac HP 1400-100A

Table 4. “Electrical Steel (NGO)” Folder – Core Loss Curves (116)

Digital Core Loss Curves in "Electrical Steel (NGO)" Folder (116)

No.	ID	Material Name
1	aB01	HF-10 As Sheared
2	aB02	HF-10 Stress Relieve Annealed
3	aB03	HF-10X As Sheared
4	aB04	HF-10X Stress Relieve Annealed
5	aB05	HF-12 As Sheared
6	aB06	HF-12 Stress Relieve Annealed
7	aB07	M-10X
8	aB08	M-13
9	aB09	M-15 14 MIL
10	aB10	M-19 14 mil
11	aB11	M-19 19 mil
12	aB12	M-27 14 mil
13	aB13	M-27 14 mil
14	aB14	M-27 14 mil
15	aB15	M-36 14 mil
16	aB16	M-36 19 mil
17	aB17	M-36 25 mil
18	aB18	M-43 19 mil
19	aB19	M-43 25 mil
20	aB20	M-45 14 mil
21	aB21	M-47 19 mil
22	aC01	195-35A
23	aD01	Arnon 5
24	aD02	Arnon 7
25	aI01	M235-35A
26	aI02	M250-35A
27	aI03	M250-35A eqvt
28	aI04	M250-35HS
29	aI05	M250-50A
30	aI06	M270-35A
31	aI07	M270-50A
32	aI08	M290-50A
33	aI09	M300-35A
34	aI10	M310-50A
35	aI11	M310-65A
36	aI12	M330-35A
37	aI13	M330-35HP
38	aI14	M330-35HS
39	aI15	M330-35HT
40	aI16	M330-50A
41	aI17	M330-65A
42	aI18	M350-50A
43	aI19	M350-65A
44	aI20	M400-50A
45	aI21	M400-65A
46	aI22	M470-50A
47	aI23	M470-65A
48	aI24	M530-50A
49	aI25	M530-50HP
50	aI26	M530-65A
51	aI27	M600-100A
52	aI28	M600-50A
53	aI29	M600-65A
54	aI30	M600-65HP
55	aI31	M700-100A
56	aI32	M700-50A
57	aI33	M700-65A
58	aI34	M800-100A
59	aI35	M800-50A
60	aI36	M800-65A
61	aI37	M1000-100A
62	aI38	NO10
63	aI39	NO12
64	aI40	NO15
65	aI41	NO18
66	aI42	NO20
67	aI43	NO27
68	aI44	NO30
69	aK01	10JNEX900 50 Hz
70	aK02	10JNEX900 50 kHz
71	aK03	10JNHF600 50Hz
72	aK04	10JNHF600 50 kHz
73	aK05	20JNHF600 50 Hz
74	aK06	20JNHF1300 20 kHz
75	aQ01	35PN210
76	aQ02	35PN230
77	aQ03	35PN250
78	aQ04	35PN270
79	aQ05	35PN300
80	aQ06	35PN360
81	aQ07	35PN440
82	aQ08	50PN250
83	aQ09	50PN270
84	aQ10	50PN290
85	aQ11	50PN310
86	aQ12	50PN350
87	aQ13	50PN400
88	aQ14	50PN470
89	aQ15	50PN600
90	aQ16	50PN700
91	aQ17	50PN800
92	aQ18	50PN1300
93	aX01	Isovac 270-35A
94	aX02	Isovac 290-35A
95	aX03	Isovac 330-35A
96	aX04	Isovac 330-50A
97	aX05	Isovac 400-50A
98	aX06	Isovac 400-65A
99	aX07	Isovac 470-50A
100	aX08	Isovac 470-65A
101	aX09	Isovac 530-50A
102	aX10	Isovac 530-65A
103	aX11	Isovac 600-50A
104	aX12	Isovac 600-65A
105	aX13	Isovac 700-50A
106	aX14	Isovac 700-65A
107	aX15	Isovac 800-50A
108	aX16	Isovac 800-65A
109	aX17	Isovac 940-50A
110	aX18	Isovac 1000-65A
111	aX19	Isovac 1000-65K
112	aX20	Isovac HP 235-35A
113	aX21	Isovac HP 250-35A
114	aX22	Isovac HP 350-65A
115	aX23	Isovac HP 1400-100A
116	aZ01	CRML 25 mil

2.4. CRML Steels for Fractional Horse Power motors

CRML (Cold Rolled Magnetic Laminations) Steels are uninsulated low carbon steel laminations, with no or little silicon, as defined in ASTM 726. Low grades have carbon <0.06%, high grades < 0.02%, while best grades have <0.005%. They are temper-rolled which produces roughened surface. In a stack such rough surfaced laminations contact only at high points. Few such high points increase surface-to surface resistivity, so they reduce eddy loss even without an insulation coating. And they are less expensive than NGO steels. When properly annealed, their magnetic properties rival that of low grade NGO steels.

CRML steels come in two classes – un-annealed and annealed. Un-annealed CRML is easy to stamp and offers low tool wear. But the user almost always does a decarburizing anneal after stamping to restore magnetic properties. This reduces C to <0.005%, reduces core loss and prevents aging. They are used where cost is more important than efficiency or overheating. An unannealed 0.018 inch CRML dissipates (at 1.5 T, 50 Hz) 8 to 12 w/kg. After decarburizing annealing its core loss reduces to about 3 w/kg. Many suppliers, such as JFE and Arcelor. offer annealed CRML with core loss of ~2.6 w/kg – competing with low/medium grade NGO steel at lower cost.

CRML is used in small FHP motors that have intermittent duty cycles. They generally can tolerate large core loss (~10 w/kg). Examples include household motors (appliances, vacuum cleaners, hair dryers, handheld mixers, garage door openers, sump pumps, power tools, toys etc) and automotive (engine fan, seat adjuster, starter-motor, power windows etc.). They are also used in lifting magnets and holding electromagnets etc. Unfortunately magnetic properties of CRML steels are not in public domain and therefore not included here.

3. ELECTRICAL STEELS - GRAIN-ORIENTED

These steels (also called GO steels) employ ~ 4% Silicon to reduce losses. They have ultra low carbon (<0.001%)[16]. In addition they are made by a complex process that increases the peak permeability (in the Rolling Direction) by an order of magnitude to 60,000 or higher. At 1.5T, 50 Hz, their core loss ranges from 0.5 to 1 w/kg. Their saturation magnetization J_s is ~2.03 T. The GO steels are more expensive than the NGO steels. As with NGO steels, trace impurities impact the coreloss and B(H) curves, even if the composition is same. So MagWeb lists the properties of steels by each manufacturer, *irrespective of their grade.*

3.1. GO Steels are dominantly anisotropic

These steels are highly anisotropic. Their magnetic properties are best along the Rolling Direction (RD or easy axis). If by any chance the flux flows in Transverse Direction (TD or hard axis), the core loss could triple! If the flux deviates even as little as 10^o from RD, the permeability can drop sharply. What is worse, under TD conditions, its permeability could reduce by an order of magnitude. So GO steels are really characterized by two B(H) curves, one for RD and other for TD. An example MagWeb file Bo12 shows B(H) data for TD and RD conditions.

GO steels are used mainly in applications where the flux primarily flows along the Rolling Direction, e.g., transformers. GO steels should never be used in motors, since flux flows in all directions. So called high-permeability steels also concentrate magnetic flux to a skin depth that may be thinner than thickness of lamination, thereby detrimentally increasing effective flux density. For example, a 0.35 mm thick GO steel lamination with 60,000 relative permeability concentrates a 60 Hz flux in ~0.2 mm skin depth, thereby detrimentally increasing the flux density by ~40%!.

Exceptions are the large utility generators (which have low pole count) and hydro and wind units (which have high pole count). Their cores are built with segments such that flux flows mostly along the Rolling Direction. But even in such machines, flux flows inefficiently, in Transverse Direction in some areas. For example in teeth of low pole count utility generators and in the back iron of high pole count hydro units flux flows in Transverse Direction. . Such parts with poorer permeability can choke the flow of flux. Thus, to accurately analyze such overfluxed regions, a designer should use one B(H) curve to model RD regions, another B(H) curve to model TD regions (a two-curve approach).

European standards use the nomenclature “Mccc-tt-x” for these steels. Here, “M” is for electrical steel, “ccc” is for core loss (w/kg x 100) at 1.5T or 1.7T, “tt” is for thickness (mm x 100) and “x” is for “type” – equal to N for core loss measured at 1.5T, S for core loss measured at 1.7T and P for a high permeability material with loss measured at 1.7T. For example, M105-30P refers to 0.3 mm thick high permeability steel with the 1.7T/50 Hz core loss not exceeding 1.05 w/kg.

GO steels come in three tiers – conventional, high permeability (HiB) and laser scribed. Japanese steels reflect these tiers by using the nomenclature “tt-xx- ccc”. Here, “tt” denotes

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[16] Ramanathan, S., Study of dislocations...on magnetic properties of grain oriented electrical steel, Ph. D Thesis, Cardiff University, 2013, p. 2

thickness (mm x 100), “xx” denotes the “type” – with Z for normal, ZH for HiB steel, ZDKH for HiB steel with laser scribing and “ccc” is for core loss (w/kg x 100) at 1.5 or 1.7T, 50 Hz. For example 27ZDKH95 refers to 0.27 mm thick laser scribed HiB steel with 1.7/50Hz core loss not exceeding 0.95w/kg.

3.2. Quality varies with the manufacturer

Dozens of manufacturers world wide are known to produce GO steel of “same-grade”. But in reality, core losses in such “same-grade” steels vary from one manufacturer to the other due to variations in composition, manufacturing processes and overall quality control.

For example, Fig. 5 compares the core loss curves of different M-6 grade steels, produced by different firms (AK Steel, ATI, Cogent, Nippon and Posco). It shows that, within the same-grade steels, core loss could vary by as much as 30%!

In view of this, MagWeb lists the properties of GO steels produced by each firm, *irrespective of whether they are of the same grade*. It is hoped that such vendor-based data can assist designers in choosing the right GO steel from the right manufacturer depending on their specific performance needs, cost, availability, delivery schedule, import duty etc.

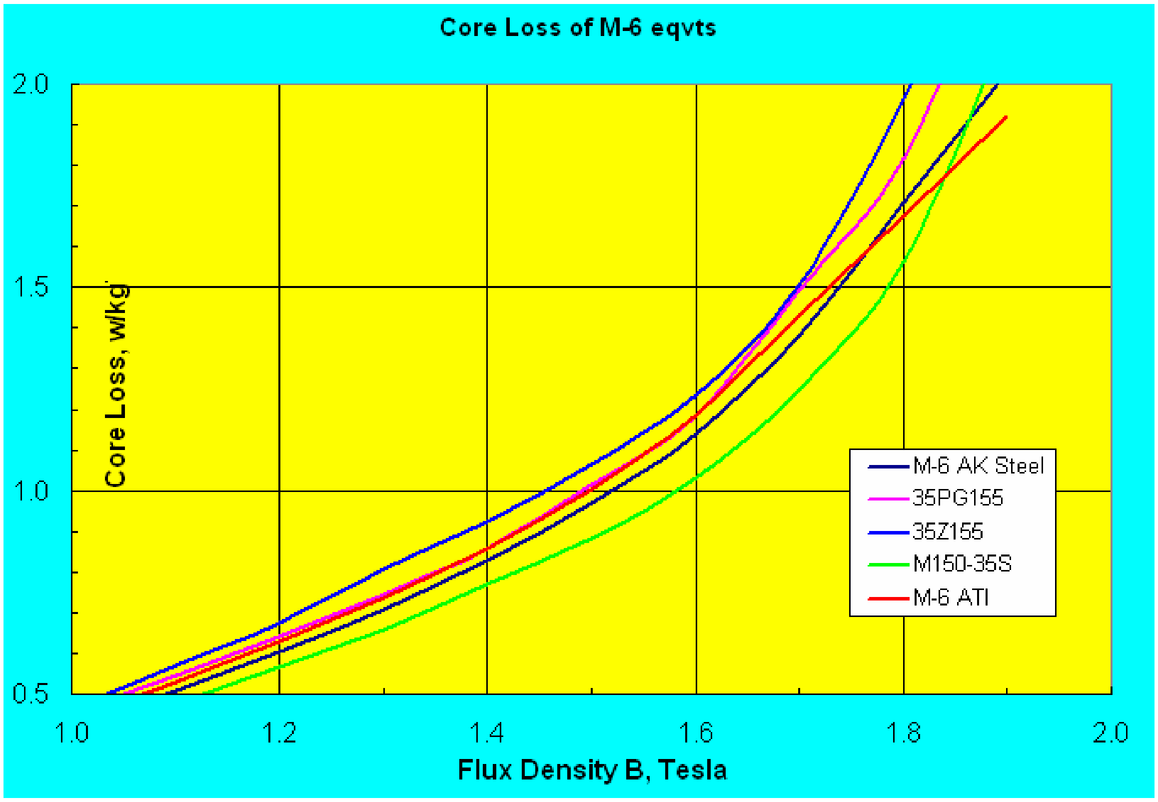

Fig. 5 M-6 grade steels from various manufacturers differs in quality.

The “Electrical Steels (GO)” folder contains 141 smooth B(H) Curves and 134 Digital Core Loss Curves (total of 275 excel files). Tables below names all materials in these files.

Table 5. ***“Electrical Steel (GO)” Folder – B(H) Curves (141)***

Digital B(H) Curves in "Electrical Steel (GO)" Folder (141)

No.	ID	Material Name
1	BB01	3% Si Steel GO
2	BB02	H-0 DR
3	BB03	H-0
4	BB04	H-1 DR
5	BB05	H-1
6	BB06	H-2 DR
7	BB07	H-2
8	BB08	M-2 Lite Carlite
9	BB09	M-2 Mill-Anneal
10	BB10	M-3 Carlite
11	BB11	M-3 Lite Carlite
12	BB12	M-3 Mill-Anneal
13	BB13	M-3X Lite Carlite
14	BB14	M-4 Carlite
15	BB15	M-4 Mill-Anneal
16	BB16	M-5 Carlite
17	BB17	M-5 Mill-Anneal
18	BB18	M-6 Carlite
19	BB19	M-6 Mill Anneal
20	BE01	M-2
21	BE02	M-3
22	BE03	M-4
23	BE04	M-5
24	BE05	M-6
25	BE06	M-6 Cross
26	BE07	M-6 Rolling
27	BF01	B27G120
28	BF02	B27G130
29	BF03	B27P100
30	BF04	B27P110
31	BF05	B30G120
32	BF06	B30G130
33	BF07	B30G140
34	BF08	B30P105
35	BF09	B30P110
36	BF10	B30P120
37	BI01	M085-23P
38	BI02	M090-23P
39	BI03	M090-27P
40	BI04	M095-23P
41	BI05	M095-27P
42	BI06	M100-23P
43	BI07	M100-30P
44	BI08	M103-27P
45	BI09	M105-30P
46	BI10	M110-23S
47	BI11	M110-27S
48	BI12	M111-30P
49	BI13	M115-27S
50	BI14	M115-30S
51	BI15	M120-23S
52	BI16	M120-27S
53	BI17	M120-30S
54	BI18	M127-23S
55	BI19	M130-27S
56	BI20	M130-30S
57	BI21	M140-27S
58	BI22	M140-30S
59	BI23	M140-35S
60	BI24	M150-30S
61	BI25	M150-35S
62	BL01	Microsil 4 mil
63	BL02	Silectron 2 mil
64	BL03	Silectron 4 mil cross
65	BL04	Silectron 4 mil rolling
66	BL05	Silectron 6 mil
67	BL06	Silectron 12 mil
68	BP01	23ZDKH75
69	BP02	23ZDKH80
70	BP03	23ZDKH85
71	BP04	23ZDKH90
72	BP05	23ZDMH80
73	BP06	23ZDMH85
74	BP07	23ZDMH90
75	BP08	23ZH85
76	BP09	23ZH90
77	BP10	23ZH95
78	BP11	23ZH100
79	BP12	27Z120
80	BP13	27Z130
81	BP14	27ZDKH85
82	BP15	27ZDKH90
83	BP16	27ZDKH95
84	BP17	27ZH90
85	BP18	27ZH95
86	BP19	27ZH100
87	BP20	27ZH110
88	BP21	30Z120
89	BP22	30Z130
90	BP23	30ZH95
91	BP24	30ZH100
92	BP25	30ZH105
93	BP26	30ZH110
94	BP27	35Z135
95	BP28	35Z145
96	BP29	35Z155
97	BP30	35ZH110
98	BP31	35ZH115
99	BP32	35ZH125
100	BP33	35ZH135
101	BO01	3407 0.27mm
102	BO02	3407 0.3 mm
103	BO03	3407 0.35 mm
104	BO04	3408 0.27mm
105	BO05	3408 0.3mm
106	BO06	3408 0.35 mm
107	BO07	3408
108	BO08	3409 0.27 mm
109	BO09	3409 0.3mm
110	BO10	3411
111	BO11	3413
112	BO12	3414 anisotropy
113	BO13	3423
114	BQ01	23PH090
115	BQ02	23PH095
116	BQ03	23PHD085
117	BQ04	27PG130
118	BQ05	27PH100
119	BQ06	27PHD090
120	BQ07	30PG120
121	BQ08	30PG130
122	BQ09	30PG140
123	BQ10	30PH105
124	BQ11	35PG145
125	BQ12	35PG155
126	BS01	110-23
127	BS02	120-23
128	BS03	114-27
129	BS04	120-27
130	BS05	130-27
131	BS06	140-27
132	BS07	117-30
133	BS08	122-30
134	BS09	130-30
135	BS10	140-30
136	BS11	150-30
137	BS12	130-35
138	BS13	140-35
139	BS14	150-35
140	BS15	160-35
141	BW01	Trafoperm N3

Table 6. “Electrical Steel (GO)” Folder – Core Loss Curves (134).

Digital Core Loss Curves in "Electrical Steel (GO)" Folder (134)					
No.	**ID**	**Material Name**	**No.**	**ID**	**Material Name**
1	bB01	H-0 0.23 mm	68	bP06	23ZDMH85
2	bB02	H-0 DR 0.23 mm	69	bP07	23ZDMH90
3	bB03	H-1 0.27 mm	70	bP08	23ZH85
4	bB04	H-1 DR 0.27 mm	71	bP09	23ZH90
5	bB05	H-2 0.30 mm	72	bP10	23ZH95
6	bB06	H-2 DR 0.30 mm	73	bP11	23ZH100
7	bB07	M-2 Lite Carlite	74	bP12	27Z120
8	bB08	M-2 Mill Anneal	75	bP13	27Z130
9	bB09	M-3 Carlite	76	bP14	27ZDKH85
10	bB10	M-3 Lite Carlite	77	bP15	27ZDKH90
11	bB11	M-3 Mill Anneal	78	bP16	27ZDKH95
12	bB12	M-3X Lite Carlite	79	bP17	27ZH90
13	bB13	M-4 120 Carlite	80	bP18	27ZH95
14	bB14	M-4 125 Carlite	81	bP19	27ZH100
15	bB15	M-4 Mill Anneal	82	bP20	27ZH110
16	bB16	M-5 125 Carlite	83	bP21	30Z120
17	bB17	M-5 130 Carlite	84	bP22	30Z130
18	bB18	M-5 140 Carlite	85	bP23	30ZH95
19	bB19	M-5 Mill Anneal	86	bP24	30ZH100
20	bB20	M-6 Carlite	87	bP25	30ZH105
21	bB21	M-6 Mill Anneal	88	bP26	30ZH110
22	bB22	M-6 Equivalent Steels	89	bP27	35Z135
23	bE01	M-2	90	bP28	35Z145
24	bE02	M-3	91	bP29	35Z155
25	bE03	M-4	92	bP30	35ZH110
26	bE04	M-5	93	bP31	35ZH115
27	bE05	M-6	94	bP32	35ZH125
28	bF01	B27G120	95	bP33	35ZH135
29	bF02	B27G130	96	bO01	3407 0.27mm
30	bF03	B27P100	97	bO02	3407 0.3 mm
31	bF04	B27P110	98	bO03	3407 0.35 mm
32	bF05	B30G120	99	bO04	3408 0.27mm
33	bF06	B30G130	100	bO05	3408 0.3mm
34	bF07	B30G140	101	bO06	3408 0.35 mm
35	bF08	B30P105	102	bO07	3409 0.27 mm
36	bF09	B30P110	103	bO08	3409 0.3mm
37	bF10	B30P120	104	bQ01	23PH090
38	bI01	M080-23P	105	bQ02	23PH095
39	bI02	M085-23P	106	bQ03	23PHD085
40	bI03	M090-23P	107	bQ04	27PG130
41	bI04	M090-27P	108	bQ05	27PH100
42	bI05	M095-23P	109	bQ06	27PHD090
43	bI06	M095-27P	110	bQ07	30PG120
44	bI07	M100-23P	111	bQ08	30PG130
45	bI08	M100-30P	112	bQ09	30PG140
46	bI09	M103-27P	113	bQ10	30PH105
47	bI10	M105-30P	114	bQ11	35PG145
48	bI11	M110-23S	115	bQ12	35PG155
49	bI12	M110-27S	116	bS01	110-23
50	bI13	M111-30P	117	bS02	120-23
51	bI14	M115-27S	118	bS03	114-27
52	bI15	M115-30S	119	bS04	120-27
53	bI16	M120-23S	120	bS05	130-27
54	bI17	M120-27S	121	bS06	140-27
55	bI18	M120-30S	122	bS07	117-30
56	bI19	M127-23S	123	bS08	122-30
57	bI20	M130-27S	124	bS09	130-30
58	bI21	M130-30S	125	bS10	140-30
59	bI22	M140-30S	126	bS11	150-30
60	bI23	M140-35S	127	bS12	130-35
61	bI24	M150-35S	128	bS13	140-35
62	bI25	M175-50N	129	bS14	150-35
63	bP01	23ZDKH75	130	bS15	160-35
64	bP02	23ZDKH80	131	bZ01	Magnesil 2 mil
65	bP03	23ZDKH85	132	bZ02	Magnesil 4 mil
66	bP04	23ZDKH90	133	bZ03	Orthonol 0.5 mil
67	bP05	23ZDMH80	134	b037	Trafoperm N3

4. METGLAS & NANOCRYSTALLINE

These materials are thin ribbons that use more Silicon (9% - 15 %) than electrical steels to reduce core loss and increase permeability. But they saturate earlier. They also feature low or near zero magnetostiction. Unlike electrical steels, they have no grain or crystalline structure and no domain structure (i.e. amorphous).

Their magnetic property is most often measured by a multi-valued hysteresis loop (instead of a single value magnetization curve). For a given H, such loop has two values of flux densities for each H - one in the lower segment, another in the upper segment of the hysteresis loop. MagWeb estimates a B(H) curve from a hysteresis loop using the *Elenbass Rule*[17]*.* Per this rule, the flux density B for a given H equals average of these two flux densities.

Magnetic properties of both amorphous and nanocrystalline materials are sensitive to stress. So designers should preferably use them as toroids or C-cores supplied by a vendor.

(a) Amorphous Ribbons
They are produced by cooling a molten metal over a rotating copper drum. They use Boron to improve the viscosity of the molten metal. The drum rotates at such high speed that the melt does not have time to form crystalline structure. The high speed limits their thickness to 25 μm (1 mil). The drum size limits width to 200 mm (8”). Because they are paper-thin and have limited width, they are called *ribbons*.

Amorphous cores are useful in frequencies ranging 100 Hz to 100,000 Hz. They are used in inductors, transformers (single phase or power converter), shields etc. But because the ribbons are very thin and narrow, making three phase transformers or motors using these ribbons is still a challenge. But in a 25 μm thick ribbon with 200,000 relative permeability, a 100 kHz flux flows only through a skin 5μm deep. This not only wastes lot of material, but detrimentally increases flux density!.

Metglas is the world’s leading producer of amorphous steel ribbons and cores. So “amorphous” and “Metglas” are often used interchangeably. But several other firms (e.g. Vacuumschmelz, Amotech, Toshiba, NanoAmor etc) also produce amorphous cores. Metglas manufactures several grades of amorphous ribbons as shown in the table below.

Table 7. Amorphous Ribbons by Metglas (graded by Core Loss)

Name	**Base Element**	**Composition**	**J_s, Tesla**	**Core Loss w/kg At 0.75T, 50Hz**
2705M	Cobalt	$Fe_4 Si_{12} Co_{69} B_{12} Ni_1 Mo_2$	0.77	-
2714A	Cobalt	$Fe_4 Si_{15} Co_{66} B_{14} Ni_1$	0.57	-
2605SC	Iron	$Fe_{81} Si_{3.5} B_{13.5} C_2$	1.61	**0.011**
2605HB1M	Iron	$Fe_{90} Si_5 B_5$	1.63	**0.028**
2605S3A	Iron	$Fe_{90} Si_3 B_3 Cr_3$	1.4	**0.036**
2605SA1	Iron	$Fe_{78} Si_9 B_{13}$	1.56	**0.055**

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[17] Bozorth, *Ferromagnetism*, Van Nostrand Co., 1951, p. 511

2826MB	Nickel	$Fe_{40} Ni_{38} Mo_4 B_{18}$	0.88	**0.057**
2605CO	Iron	$Fe_{66} Co_{18} Si_1 B_{15}$	1.8	**0.178**

The iron-based Metglas offer core losses far lower than those of electrical steels. So it is used at high frequencies. The price of 2605S3A has drastically reduced recently, allowing its wider usage. The Cobalt-based Metglas offer lower core loss and at higher frequencies, but are more expensive. Cores made of powdered amorphous ribbons are sold under trade names amoflux, optialloy). Their properties are listed in the alloy powder core folder.

(b) Nanocrystalline Ribbons

These materials employ more silicon (13 to 16%) than amorphous materials to reduce loss further. Trace Cu, Nb is added to improve magnetic properties. The molten amorphous material is subjected to annealing under intense magnetic field. This process produces 10nm sized particles, hence the name. It also reduces core loss further, thereby allowing them to be used at frequencies of 100 kHz or higher. They are available as ribbons with thickness less than 0.001" and width less than 4".

Nanocrystalline ribbons are sold in several grades. Most grades use ~ 15% Si, but saturate by ~1.2 T. One grade (Nanoperm) is usable upto 1.5T, but at the expense of higher loss. High temperature grades use Cobalt (which also increases saturation flux density to 1.8T), but they are not yet commercially available.

Hitachi and Vacuumschmelz are world leaders of nanocrystalline materials. But several other firms (Magnetec, Arcelor Mecagis, ATM, NanoAmor etc.) also produce this material.

Table 8. NanoCrystalline Ribbons (graded by Core Loss)

Name	**Firm**	**Composition**	**J_s, Tesla**	**Core Loss w/Kg At 0.2T, 100kHz**
VITROPERM	Vacuumschmelz	$Fe_{73.5} Si_{15.5} B_7 Cu_1 Nb_3$	1.23	**35**
FINEMET	Hitachi	$Fe_{73.5} Si_{13.5} B_9 Cu_1 Nb_3$	1.24	**38**
NANOPHY	ArcelorAperam	$Fe_{74.1} Si_{15.7} B_{6.1} Cu_1 Nb_{3.1}$	1.24	
NANOPERM	Magnetec	$Fe_{86} B_6 Cu_1 Zr_7$	1.52	**116**
HiTPERMa	Carnegie Mellon	$Fe_{67} Co_{18} Si_1 B_{14}$	1.8	**-**
HiTPERMb	Carnegie Mellon	$Fe_{44} Co_{44} B_4 Zr_7 Cu_1$	1.8	**-**

The "Metglas&Nano" folder contains 23 smooth B(H) Curves and 10 Digital Core Loss Curves (total of 33 excel files). Tables below names all materials in these files.

Table 9. *"Metglas" Folder – B(H) and Core Loss Curves (33)*

Digital B(H) Curves in "Metglas" Folder(23)		
No.	**Id**	**Material Name**
1	CJ01	Finemet 50Hz NFA
2	CJ02	Finemet 50Hz TFA
3	CJ03	Finemet FT3M
4	CJ04	Nanocrystalline
5	CN01	2605 HB1M
6	CN02	2605 S3A LFA
7	CN03	2605 S3A HFA
8	CN04	2605 SA1 50Hz
9	CN05	2605 SA1 DC
10	CN06	2705M Sheared Loop
11	CN07	2705M Sq Loop 60 Hz
12	CN08	2705M Sq Loop DC
13	CN09	2714A NFA
14	CN10	2714A LFA
15	CN09	Nanoperm 8000 Mu
16	CN10	Nanoperm 30000 Mu
17	CN11	Nanoperm 80000 Mu
18	CW01	Vitroperm 10Hz
19	CW02	Vitroperm 50Hz LFA
20	CW03	Vitroperm 50Hz NFA
21	CW04	Vitroperm 50Hz TFA
22	CW05	Vitroperm 400
23	CW06	Nano Powder Composite

Digital Core Loss Curves in "Metglas" Folder (10)		
No	**Id**	**Material Name**
1	cJ01	Finemet
2	cW01	Vitroperm
3	cN01	2605CO
4	cN02	2605HB1M
5	cN03	2605S3A
6	cN04	2605SC
7	cN05	2605SA1
8	cN06	2705M
9	cN07	2714A
10	cN08	2826MB

5. COBALT STEELS

Cobalt Steels employ 12 to 50% of Cobalt to significantly increase saturation flux density to about 2.4 Tesla. Sometimes Vanadium is added to increase ductility and is known as 2V-Permendur. They are sold under a variety of trade names such as Supermendur, Vacodur, each having slightly different properties. Specific annealing procedures, recommended by a manufacturer, should be used to attain their high flux density capability. Those with higher cobalt are rather expensive; they are used in aerospace industry where small size and light weight is more important than cost. Those with lower cobalt are less expensive; but their magnetic properties are less attractive.

The "Cobalt Steels" folder contains 28 smooth B(H) Curves and 12 Digital Core Loss Curves (total of 40 excel files). Tables 10 and 11 below lists all Cobalt Steels in these files.

Table 10 and 11. Cobalt Steel Folder – B(H) Curves (28) and Core Loss Curves (12)

Digital B(H) Curves in "Cobalt Steel" Folder (28)		
No.	**Id**	**Material Name**
1	DC01	AFK 1
2	DC02	AFK 18
3	DC03	AFK 502
4	DG01	Hiperco 15
5	DG02	Hiperco 27
6	DG03	Hiperco 27HS
7	DG04	Hiperco 50
8	DG05	Hiperco 50A Bar (820C Anneal)
9	DG06	Hiperco 50A Bar (871 C Anneal)
10	DG07	Hiperco 50A Bar (1010C Anneal)
11	DG08	Hiperco 50A Strip (871C Anneal)
12	DG09	Hiperco 50HS
13	DG10	HS50
14	DG11	Permendur 24
15	DG12	Permendur 49
16	DG13	Rotelloy 3
17	DG14	Rotelloy 5
18	DG15	Rotelloy 8
19	DW01	Vacoflux 17
20	DW02	Vacoflux 48
21	DW03	Vacodur 49 Magnetic
22	DW04	Vacodur 50 Magnetic
23	DW05	Vacodur Splus
24	DZ01	2V Permendur
25	DZ02	Cast Cobalt
26	DZ03	Cobalt
27	DZ04	Supermendur
28	DZ05	Vanadium Permendur

Digital Core Loss Curves in "Cobalt Steel" Folder (12)		
No.	**Id**	**Material Name**
1	dG01	Hiperco 27
2	dG02	Hiperco 50 0.006 in
3	dG03	Hiperco 50 0.010 in
4	dG04	Hiperco 50 9.014 in
5	dG05	Hiperco 50A 0.006in
6	dG06	Hiperco 50A .010in
7	dG07	Hiperco 50A .014in
8	dG08	Hiperco 50HS 0.006 in
9	dG09	Supermendur 2 mil
10	dG10	Supermendur 4 mil
11	dW01	Vacoflux 48
12	dW02	Vacoflux 50

6. NICKEL STEELS

Nickel Steels use 30, 50 or 80% Nickel to greatly reduce the core loss and increase permeability compared to Grain Oriented steels. Because of their low core loss, they are used at high frequencies ranging 1000 to 100,000 Hz. But their saturation flux density is lower than that of electrical steels. The 80% Nickel steels offer highest permeability but lower saturation (~0.8 to 1.1T). The 50% Nickel steels offer higher saturation (~1.6T), but have lower resistivity. But as with electrical steels, trace impurities (that impact magnetic properties) differ from manufacturer to manufacturer. So their properties depend on the manufacturer, irrespective of materials being of same composition. They are employed in inductors, transformers used in communication, EMI Shielding and anti-shop lifting industries.

Steels containing same percentage of Nickel are sold under a variety of trade names (e.g., Mumetal, ultraperm for 80% nickel steels; or 4750, Carpenter 49 for 50% nickel steels).
In particular, Carpenter 49 is available as non-grain oriented grade (aka “rotor” grade) or grain-oriented grade (aka “transformer grade) They are also available as ribbons. Cores made of 50% Ni-Steel powders are known as MPP cores.

Unfortunately, because they are thin, (1 to 0.25 mil) they are delicate, prone to create large stresses. These stresses can easily alter their magnetic properties. So they require careful stress-relieving anneal by the user, even if they are annealed by the manufacturer. So even though a 50% Ni offer lower loss than Metglas 2605SC, amorphous or nanocrystalline are eroding their market share, perhaps because their properties are less sensitive to stress.

The “Nickel Steels” folder contains 64 smooth B(H) Curves and 22 Digital Core Loss Curves (total of 88 excel files). Tables below names all materials in these files.

Table 10. “ Nickel Steel” Folder – B(H) Curves (64).

Digital B(H) Curves in "Nickel Steel" Folder (64)

No.	Id	Material Name
1	Eb01	AD-MU-80 60 Hz
2	Eb02	AD-MU-80 DC
3	EC01	Supra 50
4	EC02	Supra 50 150 C
5	EC03	Supra 50 -25 C
6	EC04	Supra 510
7	EE01	4750 60Hz
8	EE02	4750 400 Hz
9	EE03	4750 1000 Hz
10	EE04	4750 cross
11	EE05	4750
12	EG01	55 Ni-Fe
13	EG02	Carpenter 49 (788C Anneal)
14	EG03	Carpenter 49 (871C Anneal)
15	EG04	Carpenter 49 (954C Anneal)
16	EG05	Carpenter 49 (1121C Anneal)
17	EG06	Carpenter 49 Rotor Grade (843C Anneal)
18	EG07	Carpenter 49 Rotor Grade (954C Anneal)
19	EG08	Carpenter 49 Rotor Grade (1066C Anneal)
20	EG09	Carpenter 49 Rotor Grade (1177C Anneal)
33	Ej02	Netic
34	Em01	Nilomag Alloy 77 50Hz
35	Em02	Nilomag Alloy 77 400Hz
36	Em03	Nilomag Alloy 77 1000 Hz
37	Em04	Nilomag Alloy 77 DC
38	EW01	Megaperm40L (35%Ni)
39	EW02	MuMetall (80% Ni)
40	EW03	Permax M (65% Ni)
41	EW04	Permenorm 3601 K5 (50% Ni)
42	EW05	Permenorm 5000 H2 (50% Ni)
43	EW06	Permenorm 5000 S4 (50%Ni)
44	EW07	Permenorm 5000 V5 (50%Ni)
45	EW08	Ultrperm 10 (80%Ni)
46	EW09	Ultraperm 200 (80% Ni)
47	EW10	Ultrvac 44V6 (44%Ni)
48	EW11	Vacoperm 100 (80%Ni)
49	EZ02	Deltamax GO
50	EZ03	MolyPermalloy
51	EZ04	Monel Annealed
52	EZ05	Monimax Non-Oriented

21	EG10	Carpenter 49 Transformer Gr 60 Hz
22	EG11	Carpenter 49 Transformer Gr 400 Hz
23	EG12	Carpenter 49
24	EG13	Hymu 80
25	EG14	Hymu 800
26	EL01	Square 50
27	EL02	Square 80
28	EL03	Supermalloy
29	EL04	Superperm 49
30	EL05	Superperm 80
31	EL06	Supersquare 80
32	Ej01	Conetic

53	EZ06	Monimax Oriented
54	EZ07	MuMetal
55	EZ08	Mumetal 77% Ni
56	EZ09	Mumetal 80% Ni
57	EZ10	Ni 30% Temp. Compensated Alloy
58	EZ11	Nickel
59	Ei01	Permalloy 80% Ni
60	EZ12	Permalloy GO 78% Ni
61	EZ13	Permalloy Nonoriented
62	EZ14	Permalloy Oriented
63	EZ15	Perminvar
64	EZ16	Sinimax

Table 11. "Nickel Steel" Folder – Core Loss Curves (22)

Digital Core Loss Curves in "Nickel Steel" Folder (22)		
No.	**Id**	**Material Name**
1	eG01	Carpenter 49 GO .006in
2	eG02	Carpenter 49 GO .014in
3	eG03	Carpenter 49 NGO
4	eG04	Hymu 80 .004in
5	eG05	Hymu 80 .006in
6	eG06	Hymu 80 .014in
7	eW01	MuMetall (80% Ni)
8	el01	Nilomag Alloy 77 0.1 mm
9	el02	Nilomag Alloy 77 0.2 mm
10	eW02	Perenorm 3605 (50% Ni)
11	eW03	Perenorm 5002
12	eG07	Permalloy 80 1mil
13	eG08	Permalloy 80 2 mil
14	eG09	Permalloy 80 .5 mil
15	eW04	Permax M (65% Ni)
16	eG10	Supermalloy 1mil
17	eG11	Supermalloy 2mil
18	eG12	Supermalloy .5mil
19	eG13	Superperm 48
20	eW05	Ultraperm 10 (80%Ni)
21	eW06	Vacoperm 100 (80%Ni)
22	eW07	Vacoperm 85 (35%Ni)

7. STAINLESS STEELS

Stainless Steels (aka Chromium Steels) are those that add 12 to 30% Chromium. The 400 series are magnetic. They are available as plates, slabs, and rounds etc, some of which are machinable. Their core loss is high, so they are used only in DC or low frequency applications where high corrosion resistance is required. Their permeability is low, ranging 500 to 2000. Applications include rotors and solenoids. The "Stainless Steels" folder contains 34 B(H) Curves.

Table 12. "Stainless Steel" Folder – B(H) Curves (34)

Digital B(H) Curves in "Stainless Steel" Folder (34)		
No.	**ID**	**Material Name**
1	FE01	405
2	FE02	410
3	FE03	416
4	FE04	430
5	FE05	430F
6	FG01	12-FM
6	FG02	13-XP
7	FG03	430F B75
8	FG04	430F B82
9	FG05	430FR
10	FG06	430FR IMRE
11	FT01	KM31
12	FT02	KM35FL
13	FT03	KM38
14	FT04	KMH50
15	FT05	KMH60
16	FZ01	9% Cr Steel at 25C
17	FZ02	9% Cr Steel at 600C
18	FZ03	17-4 PH/ 630
19	FZ04	17-7 PH
20	FZ05	20cb-3
21	FZ06	35% Cr Steel
22	FZ07	310S
23	FZ08	316LN
24	FZ09	400
25	FZ10	440
26	FZ11	455
27	FZ12	Chromium Steel
28	FZ13	Duplex Stainless Steel
29	FZ14	Nitronic 33
30	FZ15	Nitronic 40
31	FZ16	SUS 403
32	FZ17	SUS 405
33	FZ18	TAF
34	FZ19	SUS304L

8. LOW CARBON STEELS

Low Carbon Steels (aka mild steel) are those with relatively more carbon than electrical steels (usually 0.05% to 0.3% C). They are very lossy above ~ 5 Hz. So they are used mostly in applications that carry large flux at low frequencies. These include rotors, pole pieces, solenoids, actuators, lifting magnets etc. They are more ductile and machinable than electrical steels. Because of higher carbon content, they are prone to aging. That is as time progresses, their core loss increases and permeability decreases. Their magnetic properties can vary with manufacturer, heat and form. They are available as sheets, rods, tubes etc in fully annealed or hardened condition.

This folder contains 89 BH curves for a variety of carbon steels, e.g., 10xx series steels, 4340 etc in cold/hot rolled, annealed/ un-annealed conditions. It also lists six grades of pure iron (ie.carbon completely removed, so does not suffer from aging). It also has hard-to-find core loss curves for mild steel in 0 -250 Hz.

Table 13. ***"Low Carbon Steel" Folder – B(H) Curves (89)***

Digital B(H) Curves in "Carbon Steel" Folder (89)		
No.	**ID**	**Material Name**
1	GZ01	0.31% Carbon Steel
2	GZ02	1% Carbon Steel
3	GZ03	1.44% Carbon Steel
4	GZ04	12L14 Steel
5	GZ05	50H470 Steel
6	GZ06	1002 Steel
7	GZ07	1006 Annealed
8	GZ08	1006 Steel
9	GZ09	1008 Steel
10	GZ10	1010 Cold Rolled Annealed
11	GZ11	1010 Cold Rolled
12	GZ12	1010 Hot Rolled 1300F Anneal
13	GZ13	1010 Hot Rolled 1400F Anneal
14	GZ14	1010 Hot Rolled 1500 F Anneal
15	GZ15	1010 Steel
16	GZ16	1016 Steel
17	GZ17	1018 Steel
18	GZ18	1020 Cold Rolled Annealed
19	GZ19	1020 Cold Rolled
20	GZ20	1020 Hot Rolled 1300F Anneal
21	GZ21	1020 Hot Rolled 1400F Anneal
22	GZ22	1020 Hot Rolled 1500F Anneal
23	GZ23	1020 SAE
24	GZ24	1020 Steel
25	GZ25	1030 Annealed
26	GZ26	1030 Cold Rolled
27	GZ27	1030 Steel
28	GZ28	1035 Steel
29	GZ29	1045 Steel
30	GZ30	1050 Steel
31	GZ31	1095 Steel
32	GZ32	1117 Steel
33	GZ33	1215 Steel
34	GZ34	4130 Steel
35	GZ35	4140 Steel
36	GZ36	4340 Steel
37	GZ37	6302 Steel
38	GZ38	6427 Steel
39	GZ39	A36 Steel
40	GZ40	A80
41	GZ41	A90
42	GZ42	A284 Grade D
43	GZ43	A633 Steel
44	GZ44	D6ac Steel
45	GZ45	Galvanized Wire
46	GZ46	Gr. 36 Steel
47	GZ47	HSLA 80 Steel
48	GZ48	HY 100 Steel
49	GZ49	HyTuf Steel
50	GZ50	Low Carbon Strip Cold Rolled
51	GZ51	Low Carbon Strip Cold Rolled Annealed
52	GZ52	Low Carbon Strip Hot Rolled
53	GZ53	M-50
54	GZ54	Magnet steel
55	GZ55	Magnetic Rubber
56	GZ56	Magnetil
57	GZ57	Magnetite
58	GZ58	Mild Steel 1 Hz
59	GZ59	Mild Steel 50 Hz
60	GZ60	Mild Steel 100 Hz
61	GZ61	Mild Steel 150 Hz
62	GZ62	Mild Steel 200 Hz
63	GZ63	Mild Steel 250 Hz
64	GZ64	Mild Steel
65	GZ65	P-6 Steel, 577C Anneal
66	GZ66	P-6 Steel, 625C Anneal
67	GZ67	P-6 Steel
68	GZ68	P-9 Steel
69	GZ69	Pure Iron Annealed
70	GZ70	Pure Iron Armco (99.85% Fe)
71	GZ71	Pure Iron Consumet (99.58% Fe, 843 C Anneal)
72	GZ72	Pure Iron Consumet (99.58% Fe, 954 C Anneal)
73	GZ73	Pure Iron ME1 Free Cutting
74	GZ74	Pure Iron Gr 19991
75	GZ75	Pure Iron Vacofer S1 (99.98%Fe)
76	GZ76	Pure Iron
77	GZ77	SAE 52100
78	GZ78	Soft iron
79	GZ79	St 1860 Steel
80	GZ80	St 37-2 Steel
81	GZ81	Steel Forging Annealed
82	GZ82	Terfenol - D
83	GZ83	Tool Steel
84	GZ84	Tungsten Steel
85	GZ85	Tungsten Steel MT17F
86	GZ86	Tungsten Steel MT185
87	GZ87	Tungsten Steel MT18F
88	GZ88	Tungsten Steel Varian MLC
89	GZ89	Vascojet Steel

9. CASTINGS

Castings are steels with more than 1% Carbon, made by casting. They are available as malleable iron castings, ductile iron castings, gray iron castings, Ingot iron and steel castings etc. The have low saturation flux density. They contain several impurities - so repeatability of magnetic properties is poor and permeability is low. Cast Iron is used in large components that require inexpensive magnetic material. They produce large core loss at line frequencies. So they are used in near DC applications. The “Castings” folder contains 29 smooth B(H) Curves. Table below names all materials in these files.

Table 14. “Castings” Folder - B(H) Curves (29)

Digital B(H) Curves in "Castings" Folder (29)		
No.	**Id.**	**Material Name**
1	HZ01	Cast Iron 3% C
2	HZ02	Cast Iron Ductile
3	HZ03	Cast Iron GJL 250
4	HZ04	Cast Iron GJS 400-15
5	HZ05	Cast Iron GJS 500-7
6	HZ06	Cast Iron GJS 700-2
7	HZ07	Cast Iron Malleable
8	HZ08	Cast Iron Nodular
9	HZ09	Cast Iron
10	HZ10	Cast Steel A148 80-50
11	HZ11	Cast Steel Annealed
12	HZ12	Cast Steel GS-52
13	HZ13	Cast Steel Hardened
14	HZ14	Cast Steel
15	HZ15	Cast Steel a
16	HZ16	Ductile Iron Annealed
17	HZ17	Ductile Iron Silal
18	HZ18	Ductile Iron
19	HZ19	Gray Iron Annealed
20	HZ20	Gray Iron As Cast
21	HZ21	Ingot Iron Annealed
22	HZ22	Ingot Iron
23	HZ23	Magtiz
24	HZ24	Malleable Iron 2.24%C
25	HZ25	Malleable Iron As Cast
26	HZ26	Malleable Iron
27	HZ27	Steel Castings As Cast
28	HZ28	Wrought Iron Annealed
29	HZ29	Wrought Iron

10. IRON POWDER CORES

Iron Powder Cores are made of high purity iron powder, mixed with insulating epoxy resins and compressed at extremely high pressures to form toroids, blocks, pot cores etc. This results in a magnetic material with distributed gap. Glass fibres are sometimes added to increase strength. They offer low permeability (30 to 600) and produce low core loss at high frequencies (up to 20 kHz). These materials are primarily used as cores of transformers and inductors by power electronics industry. The trace impurities (that impact the coreloss and B(H) curves) differ with manufacturers, even if the composition is same. So MagWeb lists the properties of steels by each manufacturer, *irrespective of their grade* .The powder core community expresses core loss in mW/cm^3. It has to be divided by density (gm/cm^3) in order to convert it into w/kg. This folder contains 49 B(H) data and 28 Core Loss Curves.

Table 15. "Iron Powder Core" Folder- B(H) Curves (49), Core Loss Curves (26)

Digital B(H) Curves in "Iron Powder" Folder (49)		
No.	**Id.**	**Material Name**
1	lf01	Alphaform LF
2	lf02	Alphaform MF
3	lf03	Ferrotron 559H
4	lf04	Fluxtrol 25
5	lf05	Fluxtrol 50
6	lf06	Fluxtrol 100
7	lf07	Fluxrol 119
8	lf08	Fluxtrol A
9	lf09	Fluxtrol LRM
10	lh01	Somaloy 500A
11	lh02	Somaloy 500B
12	lh03	Somaloy 500C
13	lh04	Somaloy 700 3p
14	lk01	-1 Material
15	lk02	-2 Material
16	lk03	-3 Material
17	lk04	-6 Material
18	lk05	-7 Material
19	lk06	-8 Material
20	lk07	-10 Material
21	lk08	-12 Material
22	lk09	-14 Material
23	lk10	-15 Material
24	lk11	-17 Material
25	lk12	-18 Material
26	lk13	-26 Material
27	lk14	-30 Material
28	lk15	-35 Material
29	lk16	-38 Material
30	lk17	-40 Material
31	lk18	-45 Material
32	lk19	- 52 Material
33	lk20	-60 Material
34	lk21	-61 Material
35	lk22	-63 Material
36	lk23	-66 Material
37	lk24	-70 Material
38	lk25	LM085 Material
39	lk26	M125 Material
40	ln01	SMP 1171
41	ln02	SMP 1172
42	ln03	SMP 1182
43	ln04	SMP 1192
44	ln05	SMP 1220
45	ln06	SMP 1230
46	ln07	SMP 1321
47	la03	Accucore
48	lr01	Vetroferrit
49	lz01	Powder Iron Annealed

Digital Core Loss Curves in "Iron Powder" Folder (26)		
No.	**Id.**	**Material Name**
1	ig01	-2 Material
2	ig02	-8 Material
3	ig03	-14 Material
4	ig04	-18 Material
5	ig05	-19 Material
6	ig06	-26 Material
7	ig07	-30 Material
8	ig08	-34 Material
9	ig09	-35 Material
10	ig10	-38 Material
11	ig11	-40 Material
12	ig12	-45 Material
13	ig13	- 52 Material
14	ig14	-60 Material
15	ig15	-61 Material
16	ig16	-63 Material
17	ig17	-65 Material
18	ig18	-66 Material
19	ig19	-70 Material
20	ig20	M125 Material
21	iq01	Accucore
22	if01	Fluxtrol 559H
23	if02	Fluxtrol 50
24	if03	Fluxtrol 100
25	if04	Fluxtrol A
26	ih01	Somaloy 500

11. ALLOY POWDER CORES

Alloy Powder cores are made of iron alloy powders mixed with epoxy resins, which is compressed at high pressure to form toroids, pot cores etc. Their permeability ranges 10 to 600 and saturation flux density ranges 0.7 to 1.6 T.

Of these, MPP (made from 80% Ni Steel powders) offers lowest core losses, but has lower flux capacity (J_s ~0.75T). Xflux (made from high Si steel) has the highest saturation flux density ($J_{s\sim}$ 1.6T), but produces highest losses. Amoflux (made by powdering Metglas ribbon) offers 50% lower loss than HiFlux (made from 50% Ni Steel). Most alloy powder cores can operate up to 200 C, excepting Amoflux which is limited to 155 C.

Several firms produce powder cores of same composition. But the coreloss and B(H) curves are sensitive to trace impurities, even if the composition is same. So MagWeb lists the properties of alloy powder cores produced by each firm, irrespective of they being of same composition.

They are mainly used in inductors and transformers in power electronics industry when they carry high dc bias currents with a high frequency ripple current (e.g. 0.1T, 100 kHz ripple over 0.4 T DC bias). Table 18 lists salient properties of several alloy powder cores.

Table 16. Properties of Major Alloy Powder Cores (graded per core Loss)

Name	**Composition**	**Density gm/cc**	**J_s, Tesla**	**Core Loss w/kg At 0.1T, 100kHz**
MPP	$Fe_{20}\,Ni_{80}Mo$	8.7	0.75	**68**
Sendust	$Fe_{85}\,Si_{9.5}\,Al_6$	7.0	1.	**100**
KoolMu	$Fe_{85}\,Si_{9.5}\,Al_6$	7.0	1	**100**
Amoflux	$Fe_{81}\,Si_{3.5}\,B_{13.5}\,C_2$	6.5	1.5	**108**
High Flux	$Fe_{50}\,Ni_{50}$	5.8	1.5	**224**
Xflux	$Fe_{93.5}\,Si_{6.5}$	7	1.6	**286**
OptiAlloy	$Fe_{81}\,Si_{3.5}\,B_{13.5}\,C_2$	6.5		**292**
Fluxscan	$Fe_{93.5}\,Si_{6.5}$	7		**314**
Iron Powder	Fe_{100}	5 to 7.2	1.4	**1000**

The “Alloy Powder Cores” folder contains 28 smooth B(H) Curves and 43 Digital Core Loss Curves (total of 71 excel files).

Table 17. “Alloy Powder Core” Folder- B(H) Curves (28), Core Loss Curves (43)

Smooth B(H) Curves in "Alloy Powder" Folder (28)		
No.	**Id**	**Material Name**
1	Ji01	Amoflux
2	Ji02	HiFlux 14 mu
3	Ji03	HiFlux 26 mu
4	Ji04	HiFlux 60 mu
5	Ji05	HiFlux 125 mu
6	Ji06	HiFlux 147 mu
7	Ji07	HiFlux 160 mu
8	Ji08	Koolmu 26 mu
9	Ji09	Koolmu 40 mu
10	Ji10	Koolmu 60 mu
11	Ji11	Koolmu 75 mu
12	Ji12	Koolmu 90 mu
13	Ji13	Koolmu 125 mu
14	Ji14	MPP 14 mu
15	Ji15	MPP 26 mu
16	Ji16	MPP 60 mu
17	Ji17	MPP 125 mu
18	Ji18	MPP 147 mu
19	Ji19	MPP 160 mu
20	Ji20	MPP 173 mu
21	Ji21	MPP 200 mu
22	Ji22	MPP 300 mu
23	Ji23	MPP 550 mu
24	Ji24	Xflux 26mu
25	Ji25	Xflux 60mu
26	Jl01	SuperMSS
27	Jl02	SuperMSS 26 mu
28	Jl03	SuperMSS 60 mu

Digital Core Loss Curves in "Alloy Powder" Folder (43)		
No.	**Id**	**Material Name**
1	jj01	Amoflux
2	jj02	HiFlux 14 mu
3	jj03	HiFlux 26 mu
4	jj04	HiFlux 60 mu
5	jj05	HiFlux 125 mu
6	jj06	HiFlux 160 mu
7	jj07	Koolmu 40 mu
8	jj08	Koolmu 90 mu
9	jj09	Koolmu 125 mu
10	jj10	MPP 14 mu
11	jj11	MPP 26 mu
12	jj12	MPP 60 mu
13	jj13	MPP 125 mu
14	jj14	MPP 173 mu
15	jj15	MPP 300 mu
16	jj16	MPP 550 mu
17	jj17	Xflux 26mu
18	jj18	Xflux 60mu
19	jk01	Fluxsan 14mu
20	jk02	Fluxsan 26mu
21	jk03	Fluxsan 40mu
22	jk04	Fluxsan 60mu
23	jk05	Fluxsan 75mu
24	jk06	Fluxsan 90mu
25	jk07	OptiAlloy 14mu
26	jk08	OptiAlloy 26mu
27	jk09	OptiAlloy 40mu
28	jk10	OptiAlloy 60mu
29	jk11	OptiAlloy 75mu
30	jk12	OptiAlloy 90mu
31	jk13	OptiAlloy 125mu
32	jk14	Sendust 14mu
33	jk15	Sendust 26mu
34	jk16	Sendust 40mu
35	jk17	Sendust 60mu
36	jk18	Sendust 75mu
37	jk19	Sendust 90mu
38	jk20	Sendust 125mu
39	jk21	Sendust 147mu
40	jk22	Sendust 160mu
41	jk23	Sendust HF 26mu
42	jk24	Sendust HF 60mu
43	jk25	Sendust HF 125mu

12. FERRITES

Ferrites are high resistivity materials made of MnZn or NiZn plus iron oxides. They derive their magnetic properties by complex interaction of metallic and nonmetallic elements. They are available as bars, toroids, pot cores etc. They are used in inductors, transformers, etc by power electronics industry.

MnZn ($Mn_xZn_{1-x}Fe_2O_4$) ferrites saturate at higher flux density (0.3 to 0.5 T). Their permeability is high (μ_i = 500 to 20,000). But their resistivity is low. So Mn Zn ferrites are used upto 1 MHz.

NiZn ($Ni_xZn_{1-x}Fe_2O_4$) ferrites offer lower saturation (<0.35T). Their permeability is low (μ_i = 10 to 2000). But their resistivity is high. So NiZn Ferrites are used in 1 MHz to 0.5 GHz range. (Ferrites used in the 1 to 150 GHz range are described in the next folder.)

The “Ferrites” folder lists 51 B(H) Curves and 7 Core Loss Curves as shown below. Ferroxcube for example uses “3” to denote MnZn Ferrites and “4” to denote NiZn Ferrites.

Table 18. “Ferrites”Folder - B(H) Curves (51), Core Loss Curves (7)

Digital B(H) Curves in "Ferrite" Folder (51)

No.	Id	Material Name
1	Kd01	78 Material at 25 C
2	Kd02	78 Material at 100 C
3	Kd03	79 Material at 25C
4	Kd04	79 Material at 100 C
5	Kd05	95 Material at 25C
6	Kd06	95 Material at 100 C
7	Kd07	97 Material at 25C
8	Kd08	97 Material at 100C
9	Kd09	98 Material at 25C
10	Kd10	98 Material at 100 C
11	Ke01	3C34 25C
12	Ke02	3C34 100C
13	Ke03	3C81 25C
14	Ke04	3C81 100C
15	Ke05	3C90 25C
16	Ke06	3C90 100C
17	Ke07	3C91 25C
18	Ke08	3C91 100C
19	Ke09	3C92 25C
20	Ke10	3C92 100C
21	Ke11	3C93 25C
22	Ke12	3C93100C
23	Ke13	3C94 25C
24	Ke14	3C94 100C
25	Ke15	3C96 25C
26	Ke16	3C96 100C
27	KJ01	MP70D 23C
28	KJ02	MP70D 100C
29	KJ03	MQ40D 23C
30	KJ04	MQ40D 80C
31	KJ05	MQ53D 25C
32	KJ06	MQ53D 80C
33	KJ07	NL12D 25C
34	KJ08	NL12D 100C
35	KJ09	NL16D 25C
36	KJ10	NL16D 100C
37	KJ11	NL30S 25C
38	KJ12	NL30S 100C
39	KJ13	NL40S 25C
40	KJ14	NL40S 100C
41	KJ15	NL80S 23C
42	KJ16	NL80S 100C
43	Ki01	F Material 100 C
44	Ki02	Ferrite
45	Ki03	H Material 100 C
46	Ki04	J Material 100 C
47	Ki05	K Material 100 C
48	Ki06	P Material 100 C
49	Ki07	R Material 100 C
50	Ki08	W Material 25C
51	Ki09	W Material 100 C

Digital Core Loss Curves in "Ferrite" Folder (7)

No.	Id	Material Name
1	ki01	F Material
2	ki02	H Material
3	ki03	J Material
4	ki04	K Material
5	ki05	P Material
6	ki06	R Material
7	ki07	W Material

13. GHZ FERRITES

GHz Ferrites are high-resistivity materials made of non metallics plus oxides. Their chemical composition is XFe_yO_z. Changing X, y, z changes their magnetic properties. The materials are grouped into: Garnet ferrites (1-10 GHz), spinnel ferrites (3-30 GHz) and hexagonal ferrites (1-100 GHz).

GHz ferrites are used in GHz devices in Autos, TV, cable modem etc. These include GPS, satellite digital radio, Bluetooth, Wi-Fi, cellphone, digital FM, remote keyless entry, security systems, tire pressure monitoring systems etc. They are used in antennas, filters, phase shifters etc.

But when multiple GHz devices are close, they can interfere with each other. To fine-tune them, engineers use FEM software such as CST, HFSS, FEKO etc. Such FEM software require core loss data in terms of *complex permeability* μ^*. Some engineers specify it by *loss tangent* tan δ, or its inverse, called *quality factor* Q. All these metrics for core loss are related by

$$\mu^* = \mu' - j\mu''$$

$$\tan\delta = \frac{\mu''}{\mu'} = \frac{1}{Q}$$

where μ' = real part and μ'' = imaginary part. Both vary widely with frequency. The core loss P can then be calculated using

$$P = \pi JH \frac{\tan\delta}{\sqrt{1+\tan^2\delta}}$$

Table 21 presents the core loss curves of 67 GHz Ferrites. They are given in terms of real and imaginary parts μ', μ'' (as well as tan δ).

Table 19. “GHz Ferrites” Folder Core Loss Curves (67)

Digital Core Loss Curves in "GHz Ferrite" Folder (67)

No.	Id	Material Name
1	le01	3B1
2	le02	3B7
3	le03	3B46
4	le04	3C11
5	le05	3C30
6	le06	3C34
7	le07	3C81
8	le08	3C90
9	le09	3C91
10	le10	3C92
11	le11	3C93
12	le12	3C94
13	le13	3C96
14	le14	3D3
15	le15	3E5
16	le16	3E6
17	le17	3E7
18	le18	3E8
19	le19	3E9
20	le20	3E25
21	le21	3E26
22	le22	3E27
23	le23	3E28
24	le24	3E55
25	le25	3F3
26	le26	3F4
27	le27	3F5
28	le28	3F35
29	le29	3F45
30	le30	3H3
31	le31	3R1
32	le32	3S1
33	le33	3S3
34	le34	3S4
35	le35	3S5
36	le36	4A11
37	le37	4A15
38	le38	4A20
39	le39	4B1
40	le40	4B2
41	le41	4B3
42	le42	4C65
43	le43	4D2
44	le44	4E1
45	le45	4E2
46	le46	4F1
47	le47	4M2
48	le48	4S2
49	le49	4S3
50	le50	4S60
51	le51	8C11
52	le52	8C12
53	lJ01	MP70D
54	lJ02	MQ40D
55	lJ03	MQ53D
56	lJ04	NB12D
57	lJ05	NB25S
58	lJ06	NB50S
59	lJ07	NB65S
60	lJ08	NB90S
61	lJ09	NL12D
62	lJ10	NL16D
63	lJ11	NL30S
64	lJ12	NL40S
65	lJ13	NL80S
66	lp01	IBF10
67	lp02	IBF15

14. APPENDICES

14.1. *Electrical Machine Design Software Sources*

Table below list all FEM software used to design electric machines. It categorizes into Free, Commercial/FEM, Motor Design and Inductor Design.

	Software	**Firm**	**Website**
FREE SOFTWARE	**FEMM**	**FEMM, USA**	**femm.info/wiki/Download**
	EMETOR	**Emetor, USA**	**emetor.com**
	MotorAnalysis	**VepcoTech, Russia**	**motoranalysis.com**
	KOIL	**Free Univ, Italy**	**Koil.sourceforge.net**
	Lambertus	**Lambertus**	**Lambertus.info**
	MAXFEM	**Univ. Santiago**	**usc.es/en/proxectos/maxfem/download.html**
	FEMAG	**ETH, Switzerland**	**elmocad.de profemag.ch**
	POISSON	**LANL, USA**	**laacg.lanl.gov/laacg/services/download_sf.phtml**
	VIZIMAG	**VIZIMAG, USA**	**vizimag.software.informer.com/3.1**
	ELMER	**CSC, Finland**	**https://sourceforge.net/projects/elmerfem/**
	GETDP	**GETDP, Finland**	**http://onelab.info/wiki/GetDP**
	BIOT	**Ripplon, Canada**	**ripplon.com/software.html**

FEM SOFTWARE	**COMSOL**	**COMSOL, Sweden**	**comsol.com**
	CST	**CST, Germany**	**cst.com**
	EMWORKS	**EM Works, Canada**	**emworks.com**
	FEKO	**Elec.Mag., South Africa**	**feko.info**
	FLUX	**Altair, France**	**cedrat.com/software/flux/**
	Motor Rewind	**EASA, USA**	**http://www.easa.com/resources/software**
	JMAG	**Jmag Intnl, Japan**	**jmag-international.com/products**
	MAGNET	**Infolytica, Canada**	**infolytica.com**
	MAGNETO	**Integ. Engg , Canada**	**integratedsoft.com**
	MAGNUM	**Field Precision, USA**	**fieldp.com**
	MAXWELL	**Ansys Inc, USA**	**ansys.com/products/electronics/ansys-maxwell**
	OPERA	**Cobham Tech., UK**	**operafea.com**
	QUICKFIELD	**Tera Anal., Denmark**	**quickfield.com**
	SAMARIUM	**Vitatech, India**	**vitatechindia.com/welcome.php**

	AC Elec Motor	**SoftbitOnline**	**Softbitonline.com**
MOTOR SOFTWARE	**BLDC**	**Magneforce, USA**	**magneforcess.com**
	BLDC	**Yeadon Energy, USA**	**yeadoninc.com**
	FLUX	**Altair, France**	**cedrat.com/software/flux/flux-rotating-machines-package/**
	MANATEE	**EoMYS, France**	**eomys.com**
	MotorCAD	**Motor Design Ltd, UK**	**motor-design.com/motor-cad-software**
	Motorsolve	**Infolytica, Canada**	**infolytica.com**
	RMXPRT	**ANSYS, USA**	**ansys.com/products/electronics/ansys-rmxprt**
	SPEED	**Siemens/CD-Adapco**	**speed-emachine-design.com**

INDUCTOR SOFTWARE	**Micrometals**	**Micrometals**	micrometals.com/software.html
	Magnetics	**Magnetics**	mag-inc.com/design/software
	INTUSOFT	**Intusoft**	www.intusoft.com/mag.htm
	PEXPRT	**ANSYS**	**ansys.com/products/electronics/ansys-pexprt**
	Choke	**Rale**	rale.ch/
	Power	**Ridley Engg**	ridleyengineering.com/software.html

14.2. *Electrical Steel Manufacturers worldwide*

Code	FIRM	Country
A	Advanced Technology Materials	China
B	AK Steel	USA
C	Arcelor Mittal	Belgium
D	Arnold Magnetic Technologies	USA
E	Allegheny Technology Inc (ATI Metals)	USA
F	Baoshan Iron & Steel Co Ltd (BaoSteel)	China
G	Carpenter Technology Corp; Telcon	USA
H	China Steel Corp (CSC)	China
I	Cogent Power (Tata Steel)	Sweden
J	Hitachi Metals	Japan
K	JFE Steel	Japan
L	Magnetic Metals	USA
M	Magnitogorsk Iron Steel Works (MMK)	Russia
N	Metglas Inc, USA; Magnetec, Germany	USA
O	Novolipetsk Metullurgical Plant	Russia
P	Nippon Steel & Sumitomo Metal (NSSMC)	Japan
Q	Posco	Korea
R	RuSteel	Russia
S	Stalprodukt SA	Poland
T	Taiyuan Iron & Steel (TISCO); Tohuku Steel	China
U	Thyssen Krupp AG (TKS)	Germany
V	US Steel, FrySteel	USA
W	Vacuum Schmelze GmBH & Co KG	Germany
X	Voestalpine Stahl GmbH	Austria
Y	Wuhan Iron and Steel (WISCO)	China
Z	Multiple Sources/Other	