BHmag - Magnetic Material Database

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By

Dantam K. Rao
rao@magweb.us
518-382-1699

PRECISION WAFERS, Inc.
2212 Lynnwood Dr., Niskayuna, NY 12309. USA

ABSTRACT

Whether you are designing a MRI, HEV, efficient motor or wind generator, your products are only as good as the magnetic materials that you employ. Even though a wide variety of materials is available, so far there is no comprehensive magnetic material database. Evaluating the impact of different magnetic materials on the performance has been a very tedious trial and error process. Optimal design has thus been handicapped by lack of a comprehensive database of magnetic materials.

We now introduce *BHmag* database that presents about 300 B-H curves of almost all magnetic materials. Use of *BHmag* will greatly aid the optimal magnetic material selection. The magnetic materials include electrical steels (both grain oriented and non-grain oriented), cobalt steels, Metglas and Nanocrystalline materials, nickel steels, stainless steels, low carbon steels, cast iron, powder cores, ferrite cores etc.

BHmag is a compilation of BH Files in Excel containing magnetization and permeability curves of magnetic materials. Each Excel spreadsheet contains digital data on Magnetic Flux Density (B, Tesla) and Relative Permeability (μ_r) at various magnetic field Intensity (H, Amp/m). *BHmag* also presents the saturation flux density B_{sat} and electric conductivity σ for almost all known magnetic materials.

Once *BHmag* is integrated into your design software, it will help you to converge to an optimal magnetic material. This will greatly aid design of wide variety of electric equipment such as HEV, MRI, electric motors, generators, transformers, inductors, EMI shields etc.

DISCLAIMER

All data given in this *BHmag* compilation database is accurate to the best of the provider's knowledge. But it is presented only to assist the user in making informed evaluation and decisions on magnetic materials. No liability is implied, expressed or accepted by the provider for any consequences in usage of the data. The magnetic material data is derived from references listed herein. The provider is not liable for use of any implicit or explicit illegal use of any copyrighted material. The provider is also not liable for loss or damage caused by any error or omission in the data, whether such error or omission is the result of negligence or any other cause. The provider reserves the right to change the contents of *BHmag* without notice.

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1 BHMAG STRUCTURE

1.1 Introduction

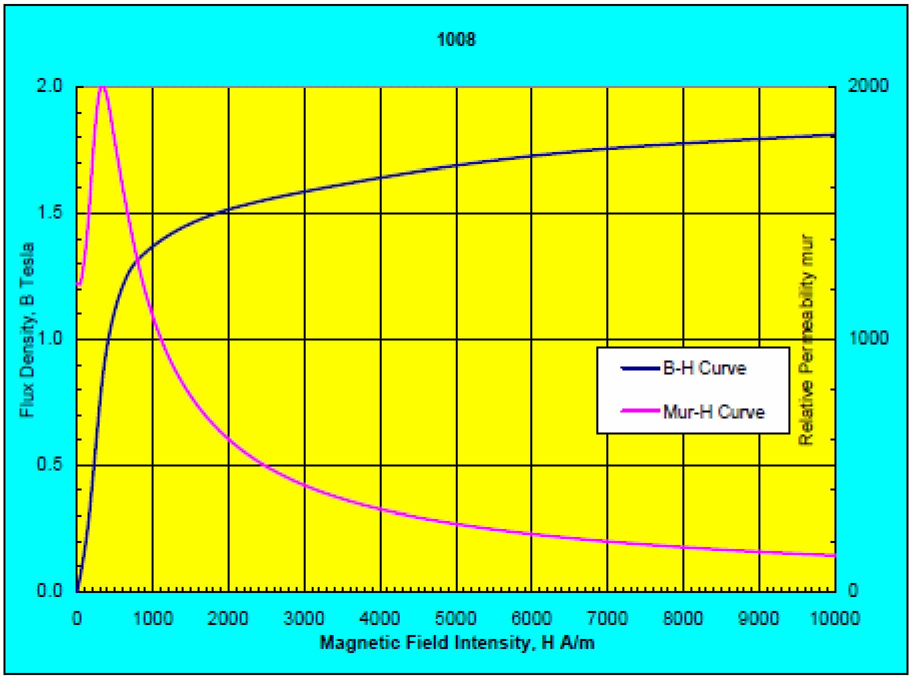

Fig. 1 Typical Magnetization and Permeability curve from BHmag database

The magnetic quality of a material, defined by $B = \mu_o\mu_r H$, is captured by a B-H curve (Normal Magnetization Curve) and μ_r-H curve (Permeability Curve). The B-H Curve plots the variation of Magnetic Flux Density B (Tesla) in the magnetic material due to an applied Magnetic Field Intensity H (A/m). The Permeability Curve plots the variation of Relative Permeability μ_r with the applied Magnetic Field Intensity H. The relative permeability μr signifies the ease with which a magnetic material can be magnetized. μo = 4πx10-7 N/A2 represents the permeability of free space.

Fig. 1 shows typical B-H and μ_r-H curves. Initially as more and more domains of the virgin material are being magnetized, the relative permeability increases. On further magnetization, with availability of fewer domains, the material starts offering more resistance to flow of flux. So the permeability spikes sharply first and then starts reducing rapidly. Beyond the knee, more and more H effort is required to get even slightly higher flux density B. The flux density within iron ($B-\mu_o H$) ultimately reaches a limiting value known as saturation induction B_s. Thus, magnetic materials are highly nonlinear at two places: below the knee where permeability spikes and above the knee during saturation. Digitization should capture both nonlinearities to prevent computational instability.

Digitizing such doubly nonlinear curves by eyeballing is risky as it may miss the spike of permeability below the knee or fail to sense the small change in B above the knee in the saturation regime. Some manufacturers publish digitized data, but it may contain too few data points to capture both nonlinearities. Over years MagWeb has developed a set of precise electronic tools that preserve the nonlinearity during digitization. These tools are used in creating the unique BHmag database of precise digital B-H curves.

BHmag is the resulting database of ~ 300 B-H curves. The database comprises 11 BH folders. Each BH folder corresponds to a material category and comprises dozens of BH files. Each BH file is an electronic file (with .xls or .pdf extension) that contains the Magnetization Curve as well as the Permeability Curve, digital data points of (H, B, μ_r) of the curves plus hard to find metrics such as Saturation Flux Density Bsat and electrical conductivity. *BHmag* is literally a warehouse of BH files of almost all magnetic materials in the world. Such unique digital database of magnetic materials with curves, digital data and critical metrics in one place is useful in computerized design of electrical equipment such as MRI, HEV, wind generators, efficient motors, transformers, inductors etc.

BHmag database presents B-H curves of wide categories of magnetic materials with permeability ranging 10 to 10,000. So it is useful in the design of a broad range of electrical equipment such as electric motors, generators, transformers, solenoids, inductors, relays etc. The most frequently used B-H curve, called DC or Normal Magnetization Curve refers to one measured at DC (0 Hz). In this database, wherever available, the B-H curve is given at other frequencies ranging from 50 to 2000 Hz. Unless otherwise stated, the data refers to one at room temperature of 25 C.

The user can easily integrate the database into any commercial Magnetic Field Software. Such integration relieves the designer the burden of collecting B-H curves, normalizing them into standard units, digitizing them and manually entering the data into the software. A magnetic field software with built-in *BHmag* database can be used to quickly run the "what-if" simulations to analyze how change of materials affects the performance of machines. With few clicks, the designer can change a magnetic material and evaluate the impact of changed material on the performance. Such fast what-if simulations greatly reduce the time for selection of optimal magnetic materials, significantly reducing the design cycle time.

The B-H curve itself is measured typically by using Epstein test samples in accordance with some standard. There are several standards though, e.g., ASTM A341, ASTM A867, ASTM A726, IEC 404, BS 6404, BS EN60404. The test apparatus and test procedures are very expensive and require considerable skill and expertise. Besides there are only few test houses around the world with facilities to accurately measure the B-H curve. As a result, designers tend to rely on published B-H curves.

1.2 Magnetic Material Categories (BH Folders)

BHmag classifies all magnetic materials into 11 categories. ***BH File*** is an electronic file containing magnetic properties of a magnetic material. ***BH Folder*** is a collection of BH files of all magnetic materials in a specific category. Table 1 lists the Material Categories (BH Folders) and magnetic materials (BH files) in each category. The material categories are listed in accordance with permeability, starting from high permeability materials ending with low permeability materials.

Table 1. Categories (BH Folders) and Magnetic Materials (BH Files)

Symbol	*Material Category (BH Folder)*	*Magnetic Materials (BH Files)*
A	Electrical Steel NGO	96
B	Electrical Steel GO	37
C	Metglas & Nano	11
D	Cobalt Steel	15
E	Nickel Steel	37
F	Stainless Steel	16
G	Low Carbon Steel	25
H	Castings	15
I	Iron Powder Core	14
J	Alloy Powder Core	27
K	Ferrite Powder Core	7
Total Nr. of BH files		**300**

1.3 Magnetic Materials (BH Files)

BHmag database is extensive collection of BH files on a variety of magnetic materials.

- 196 of these BH files define "electrical steels" which are in the form of 1D thin laminations and are characterized by high relative permeability, ranging 1000 to 10000. These include 133 for Electrical Steels, 11 for Metglas and Nanocrystalline materials, 15 for Cobalt Steels, 37 for Nickel Steels.

- 56 of these BH files define "industrial steels" which are in the form of 2D bulk solids such as plates, rounds and are characterized by medium permeability ranging 500 to 2000. These include 16 for Stainless Steels, 25 for Low Carbon Steels, 15 for Castings.

- 48 of these BH files define "powder cores" which are in specific 3D shapes and are characterized by permeability ranging 10 to 500. These include 14 for Iron Powder Cores and 34 for Alloy Powder Cores.

Electrical steels are used make motors, generators and transformers in the 50 to 400 Hz range. Metglas is used for inductors and transformers in the 500 to 5000 Hz range. Nanocrystalline materials are used for inductors in the 1000 to 20000 Hz range. Cobalt Steels are used primarily in aircraft applications where size and weight is critical. Nickel Steels are used in high frequency ranging 500 to 50000 Hz in inductors, transformers and communication equipment. Stainless Steels are used in low-frequency or near DC applications where high corrosion resistance is required. Low Carbon Steels, including Forged Steels, are also used in low frequency application such as rotor shafts and solenoids. Cast Iron is used for large components, which required inexpensive materials with low saturation flux density. Powder Iron is used as cores for transformers and inductors.

Electrical Steels (also called *Silicon Steels*) are used in electric machines and transformers at commercial line frequencies in the 60 to 120 Hz range in industrial applications and in the 400 to 500 Hz range in the aerospace applications. They come in Grain-Oriented (GO) and Non Grain Oriented (NGO) grades meeting magnetic properties per certain standards such as ASTM A677, JIS C2552. The steel foundries produce them as long thin sheets ranging 0.009 to 0.040 inches with widths of up to about 47 inches (1200 mm) and usually anneal them for optimal magnetic properties before shipping.

BH Files A001 - A096 in Electrical Steels NGO Folder contain B-H data of 96 Non Grain Oriented Electrical Steels. *Electrical Steel NGO* (Non-Grain Oriented) contains 1-3.5 % silicon to iron to reduce core loss. The group also includes Cold Rolled Magnetic Lamination quality steel (CRML) per ASTM 726-2010. They are useful in applications ranging 50 to120 Hz line frequencies (they have relatively lower core loss in this frequency range). NGO steels have nearly isotropic magnetic properties. Their permeability in cross direction is at most 10% lower than that in rolling direction. Their saturation flux density, permeability and core loss are generally inferior to GO steels. However, they are far less expensive than GO steels. So majority of electric motors are made from NGO steel laminations.

BH Files B001 - B037 in Electrical Steels GO Folder contain B-H data of 37 Grain Oriented Electrical Steels. *Electrical Steels GO* (Grain-Oriented) contains 3 to 4% Silicon. Grain-Oriented steel has higher permeability, higher saturation and lower core loss than Non-Grain Oriented steel and usually come in thickness ranging 0.012 to 0.014 inches. However, is more expensive. However, their permeability in the cross direction can be as much as 50% lower. Recently thinner steels (thickness less than 0.012", termed grade H or laser-scribed sheets) with lower losses are offered by leading steel mills. Traditional Grain Oriented steels are used to build large electric machines. Thinner laser-scribed Grain Oriented steels are used to build large transformers where the premium of lower core loss is justified.

Electrical steels are available as thin laminations of "standard" thicknesses as shown in Table 4. The "standard" is really not standard, as thickness varies slightly between inch-based or mm based steels. For example 0.0185 inch steel from US is 0.47mm thick. But equivalent 0.5 mm steel from Europe is 0.0195 inch thick. The European steel is 1 mil or 5% thicker. Both are referred as gage 26 steels though. Strips thinner than 0.006 inch are used to make toroidal cores, those in the 0.008 to 0.012 inch are usually employed in low-loss transformers while ones that are 0.014 inch or thicker are used in motor laminations.

Table 2. "Standard" thickness of Electrical Steels

Inch	Mm	Steel gage
0.001	0.025	
0.002	0.050	
0.004	0.10	
0.006	0.15	
0.009	0.23	
0.010	0.25	
0.011	0.27	
0.012	0.30	
0.014	0.35	29
0.019	0.50	26
0.025	0.63	24

BH Files C009 - C011 in Metglas Folder contain B-H data of 3 Metglas materials. *Metglas* strips contain 9% - 13 % Silicon and offers low loss at high frequencies. This category also includes nanocrystalline materials. They also feature low or near zero magnetostiction. *Metglas* is an Amorphous Steel that contains 9% silicon. They are also produced as long thin strips that are tape-wound. They are available at about 0.001" thick with widths of up to about 9 inches. They are useful in applications in medium frequencies ranging 100 Hz to 5000 Hz as they offer relatively lower loss in this range. They are generally used to build transformers and inductors, not motors. Metglas can be iron-based, Nickel-based or Cobalt-based. There are 4 Iron-based Metglas: 2605CO has Bs of 1.8T while 2605SA1, 2605HB1M has Bs of 1.6T and 2605S3A has Bs of 1.4 T, all offer lower core losses at 50-60Hz compared to electrical steels. Recently the price for iron-based 2605S3A Metglas has decreased significantly to an unbelievable level. Ni-based Metglas has Bs is much lower at 0.8T, but its very low loss makes it suitable for high frequency applications; but it is much more expensive.

BH Files C001 - C008 contain B-H data of 8 Nanocrystalline tapes. *Nanocrystalline* materials are non-amorphous steels that contain 13 to 15% silicon. They are available as tapes, 0.001" or less thickness. They have limited widths of up to about 4 inches. They are useful in high frequency applications ranging 1000 Hz to 100,000 Hz as they produce relatively low core loss in this range compared to electrical steels.

BH Files D001 - D015 in Cobalt Steels Folder contain B-H data of 15 Cobalt Steels. *Cobalt Steels* contain ~12 to 50% Cobalt to offer highest possible saturation flux density of about 2.4 Tesla. They go by various tradenames such as Supermendur. Sometimes Vanadium is added to increase ductility and are known as 2V-Permendur. They are rather expensive and used mostly in the aircraft industry where size is important.

BH Files E001 - E037 in Nickel Steels Folder contain B-H data of 37 Nickel Steels. *Nickel Steels* contain 30 to 80% Nickel to produce high permeability and low loss, but they suffer from low saturation flux density. They are useful in high frequencies ranging 1000 to 50000 Hz and are used primarily in the EMI and shielding industry.

BH Files F001 - F016 in the BH Folder named Stainless Steels contain B-H data of 16 stainless steels. *Stainless Steels* (aka Chromium Steels) contain 12 to 30% Chromium to offer high corrosion resistance. They are primarily used in low frequency applications that require high corrosion resistance. Their magnetic properties are poor relative to Electrical Steels.

BH Files G001 - G025 in Low Carbon Steels Folder contain B-H data of 25 low carbon steels. *Low Carbon Steels* contain 0.01% - 0.2% Carbon to produce high saturation at low DC frequencies. This includes low carbon forgings used to construct large rotors. They are available in solid form as bars, slabs and rounds. Forged Steels generally refer to large sizes, those with diameters above 10 inches. They offer high strength and low permeability of less than 2500. They are useful in low frequency applications as they are very loss above about 5 Hz. They are mainly used in solenoids and actuator industries. Materials in which Carbon is almost completely removed are called pure iron and have high saturation flux density.

BH Files H001 – H015 inCastings Folder contain B-H data of 15 steel castings. *Castings* include several types malleable iron castings, ductile iron castings, gray iron castings, Ingot iron or steel castings. It contains several impurities so have relatively inferior magnetic properties. They are used in applications requiring inexpensive magnetic materials with relatively low flux density at relatively low frequencies.

BH Files I001 – I014 in Iron Powder Cores Folder contain B-H data of 14 Iron powder core materials. *Iron Powder Cores* are built from insulated iron powder in resin to achieve low permeability at high frequencies. Unlike laminations, they are characterized by low relative permeability that ranges 30 to 600. They are produced as relatively thick bulk solids in custom shapes such as toroids, blocks, pot cores etc. They are mainly used for energy storage such as inductors in power electronics industry.

BH Files J001 – J027 in Alloy Powder Cores Folder contain B-H data of 27 alloy powder cores. *Alloy Powder Core* refers to ones made of iron alloy powders in resin. Unlike laminations, they are characterized by low permeability that ranges 10 to 600. They are mainly used for energy storage such as inductors and transformers in power electronics industry. This group excludes *Ferrite* cores that offer low core loss and high permeability at high frequencies.

BH Files K001 – K007 in Ferrite Cores Folder contain B-H data of 7 ferrite cores. Ferrite powder cores refer to those made of ferrite material. They are produced as relatively thick bulk solids in toroids, pot cores etc. They are used as inductors and transformers and chokes in the power electronics industry.

1.4 List of all Magnetic Materials

The *BHmag* database also contains a pdf file named *Index* that lists key material information. This index file contains the saturation induction, electrical conductivity of all 300 materials in the format shown in Table 2. The *BHmag* database also contains a pdf file of this *BHmag* User Manual.

Table 3. Index of the BHmag Database

No.	***Name of Magnetic Material***	***Category***	***Manufacturer***	***Bsat***	***MS/m***	***Curve***
1	35JN200	Silicon Steel, NGO	JFE Steel Corp., Japan	1.734	1.695	A001

The following section list all 300 Magnetic Materials in the BHmag database along with corresponding curve numbers. Obviously this amounts to the list of all BH Files in the database.

1.4.1 Electrical Steels, Non-Grain Oriented

Curve Nr.	Material Name/BH File Name
A001	35JN200
A002	35PN210
A003	35PN230
A004	35PN250
A005	35PN270
A006	35PN300
A007	35PN360
A008	35PN440
A009	50PN250
A010	50PN270
A011	50PN290
A012	50PN310
A013	50PN350
A014	50PN400
A015	50PN470
A016	50PN600
A017	50PN700
A018	50PN800
A019	50PN1300
A020	Arnon 5
A021	Arnon 7
A022	HF-10 FP
A023	HF-10 SRA
A024	M-10 14 mil 0 Hz
A025	M-13 19 mil 50 Hz
A026	M-13 19 mil 60 Hz
A027	M-13 19 mil 100 Hz
A028	M-13 19 mil 150 Hz
A029	M-13 19 mil 200 Hz
A030	M-13 19 mil 300 Hz
A031	M-13 19 mil 400 Hz
A032	M-13 19 mil 600 Hz
A033	M-13 19 mil 1000 Hz
A034	M-13 19 mil 1500 Hz
A035	M-13 19 mil 2000 Hz
A036	M-14
A037	M-15 14 mil 0Hz
A038	M-15 14 mil 60 Hz
A039	M-15 19 mil 60 Hz

A040	M-19 14 mil 0 Hz
A041	M-19 14 mil 50 Hz
A042	M-19 14 mil 60 Hz
A043	M-19 14 mil 100 Hz
A044	M-19 14 mil 150 Hz
A045	M-19 14 mil 200 Hz
A046	M-19 14 mil 300 Hz
A047	M-19 14 mil 400 Hz
A048	M-19 14 mil 600 Hz
A049	M-19 14 mil 1000 Hz
A050	M-19 14 mil 1500 Hz
A051	M-19 14 mil 2000 Hz
A052	M-19 19 mil 0 Hz
A053	M-19 19 mil 50 Hz
A054	M-19 19 mil 60 Hz
A055	M-19 19 mil 100 Hz
A056	M-19 19 mil 150 Hz
A057	M-19 19 mil 200 Hz
A058	M-19 19 mil 300 Hz
A059	M-19 19 mil 400 Hz
A060	M-19 19 mil 600 Hz
A061	M-19 19 mil 1000 Hz
A062	M-19 19 mil 1500 Hz
A063	M-19 19 mil 2000 Hz
A064	M-22
A065	M-27 14 mil 0 Hz
A066	M-27 14 mil 60 Hz
A067	M-27 19 mil 0Hz
A068	M-27 19 mil 60 Hz
A069	M-27 25 mil 60 Hz
A070	M-36
A071	M-43 Fully Processed
A072	M-43 Semi Processed
A073	M-45
A074	M-47 Fully Processed
A075	M-47 Semi Processed
A076	Silicon Core Iron A (732 C Anneal)
A077	Silicon Core Iron A (843C Anneal)
A078	Silicon Core Iron A (954C Anneal)
A079	Silicon Core Iron A (1066C Anneal)
A080	Silicon Core Iron A-FM (732C Anneal)
A081	Silicon Core Iron A-FM (843C Anneal)
A082	Silicon Core Iron A-FM (954C Anneal)
A083	Silicon Core Iron A-FM (1066C Anneal)

A084	Silicon Core Iron B (732C Anneal)
A085	Silicon Core Iron B (843C Anneal)
A086	Silicon Core Iron B (954C Anneal)
A087	Silicon Core Iron B (1066C Anneal)
A088	Silicon Core Iron B-FM (732C Anneal)
A089	Silicon Core Iron B-FM (843C Anneal)
A090	Silicon Core Iron B-FM (954C Anneal)
A091	Silicon Core Iron B-FM (1066C Anneal)
A092	Silicon Core Iron C (1066C Anneal)
A093	Silicon Core Iron C (843C Anneal)
A094	Silicon Core Iron C (954C Anneal)
A095	USS Q-core P19
A096	USS Q-core P21

1.4.2 Electrical Steels, Grain Oriented

Curve Nr.	Material Name/BH File Name
B001	3% Si Steel GO
B002	23PH090
B003	23PH095
B004	23PHD085
B005	27PG130
B006	27PH100
B007	27PHD090
B008	30PG120
B009	30PG130
B010	30PG140
B011	30PH105
B012	35PG145
B013	35PG155
B014	3408
B015	3411
B016	3413
B017	3423
B018	H-0
B019	H-0 DR
B020	H-1
B021	H-1 DR
B022	H-2
B023	H-2 DR
B024	M-2
B025	M-3
B026	M-4
B027	M-5
B028	M-6
B029	M-6 Cross
B030	M-6 Rolling
B031	Microsil 4 mil
B032	Silectron 2 mil
B033	Silectron 4 mil cross
B034	Silectron 4 mil rolling
B035	Silectron 6 mil
B036	Silectron 12 mil
B037	Trafoperm N3

1.4.3 Metglas, Nano

Curve Nr.	Material Name/BH File Name
C001	Finemet 50Hz NFA
C002	Finemet 50Hz TFA
C003	Finemet FT3M
C004	Nanocrystalline
C005	Vitroperm 50Hz LFA
C006	Vitroperm 50Hz NFA
C007	Vitroperm 50Hz TFA
C008	Vitroperm 400
C009	Metglas 2605HB1M 50Hz
C010	Metglas 2605SA1
C011	Metglas 2605SA1 50Hz

1.4.4 Cobalt Steels

Curve Nr.	Material Name/ BH File Name
D001	2V Permendur
D002	Cast Cobalt
D003	Cobalt
D004	Hiperco 15
D005	Hiperco 27
D006	Hiperco 50
D007	Hiperco 50A Bar (820C Anneal)
D008	Hiperco 50A Bar (871 C Anneal)
D009	Hiperco 50A Bar (1010C Anneal)
D010	Hiperco 50A Strip (871C Anneal)
D011	Hiperco 50HS
D012	Supermendur
D013	Vacoflux 17
D014	Vacoflux 50
D015	Vanadium Permendur

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1.4.5 Nickel Steels

Curve Nr.	Material Name/BH File Name
E001	4750
E002	4750 cross
E003	AD-MU-80 60 Hz
E004	AD-MU-80 DC
E005	Carpenter 49
E006	Carpenter 49 (788C Anneal)
E007	Carpenter 49 (871C Anneal)
E008	Carpenter 49 (954C Anneal)
E009	Carpenter 49 (1121C Anneal)
E010	Carpenter 49 Rotor Grade (843C Anneal)
E011	Carpenter 49 Rotor Grade (954C Anneal)
E012	Carpenter 49 Rotor Grade (1066C Anneal)
E013	Carpenter 49 Rotor Grade (1177C Anneal)
E014	Carpenter 49 Transformer Grade 60 Hz
E015	Carpenter 49 Transformer Grade 400 Hz
E016	Carpenter Hymu 80
E017	Deltamax GO
E018	MolyPermalloy
E019	Monel Annealed
E020	Monimax Nonorieted
E021	Monimax Oriented
E022	MuMetal
E023	Mumetal 77% Ni
E024	Mumetal 80% Ni
E025	Ni 30% Temp. Compensated Alloy
E026	Nickel
E027	Permalloy GO 78%
E028	Permalloy Nonoriented
E029	Permalloy Oriented
E030	Permivar
E031	Sinimax
E032	Square 50
E033	Square 80
E034	Supermalloy
E035	Superperm 49
E036	Superperm 80
E037	Supersquare 80

1.4.6 Stainless Steels

Curve Nr.	Material Name/BH File Name
F001	35% Chrome Steel
F002	405 Annealed
F003	410 Annealed
F004	416 Annealed
F005	430 Annealed
F006	430F Annealed
F007	455 Annealed
F008	430F B75
F009	430F B82
F010	430FR
F011	13-XP
F012	12-FM
F013	Chromium Steel
F014	SUS 403
F015	SUS 405
F016	TAF

MagWeb
Magnetic Material Data

1.4.7 Low Carbon Steels

Curve Nr.	Material Name/BH File Name
G001	12L14
G002	50H470
G003	1002
G004	1006
G005	1008
G006	1010
G007	1018
G008	1020
G009	1030
G010	1117
G011	Cold Rolled Annealed
G012	Cold Rolled Low Carbon Strip
G013	Consumet Electrical Iron (843 C Anneal)
G014	Consumet Electrical Iron (954 C Anneal)
G015	D6ac
G016	Hot Rolled Low Carbon Steel
G017	M-50
G018	Magnet steel
G019	Magnetite
G020	Pure Iron
G021	Pure Iron Annealed
G022	Soft iron
G023	Steel Forging, Annealed
G024	Tungsten Steel
G025	Vacofer S1

1.4.8 Castings

Curve Nr.	Material Name/BH File Name
H001	Cast Iron
H002	Cast Iron Nodular
H003	Cast Steel
H004	Ductile Iron
H005	Magtiz
H006	Malleable Cast Iron
H007	Malleable Iron
H008	Ductile Iron Annealed
H009	Ductile Iron Silal
H010	Gray Iron Annealed
H011	Gray Iron As Cast
H012	Ingot Iron
H013	Ingot Iron Annealed
H014	Malleable Iron As Cast
H015	Steel Castings As Cast

1.4.9 Iron Powder Core

Curve Nr.	Material Name/BH File Name
I001	-2 Material
I002	-8 Material
I003	Ferrotron 559H
I004	Fluxtrol A
I005	Fluxtrol LRM
I006	Powder Iron Annealed
I007	SMP 1171
I008	SMP 1172
I009	SMP 1182
I010	SMP 1192
I011	SMP 1220
I012	SMP 1230
I013	SMP 1331
I014	Vetroferrit

1.4.10 Alloy Powder Cores

Curve Nr.	Material Name/BH File Name
J001	Amoflux
J002	HiFlux 14 mu
J003	HiFlux 26 mu
J004	HiFlux 60 mu
J005	HiFlux 125 mu
J006	HiFlux 147 mu
J007	HiFlux 160 mu
J008	Koolmu 26 mu
J009	Koolmu 40 mu
J010	Koolmu 60 mu
J011	Koolmu 75 mu
J012	Koolmu 90 mu
J013	Koolmu 125 mu
J014	MPP 14 mu
J015	MPP 26 mu
J016	MPP 60 mu
J017	MPP 125 mu
J018	MPP 147 mu
J019	MPP 160 mu
J020	MPP 173 mu
J021	MPP 200 mu
J022	MPP 300 mu
J023	MPP 550 mu
J024	SuperMSS
J025	SuperMSS 26 mu
J026	SuperMSS 60 mu
J027	Xflux

1.4.11 Ferrite Powder Cores

K001	Ferrite
K002	FerriteF 3000 mu
K003	FerriteH 15000 mu
K004	FerriteJ 5000 mu

K005	FerriteK 1500 mu
K006	FerriteP 2500 mu
K007	FerriteR 2300 mu

1.5 References

This *BHmag* database is developed over a period of 25 years. The information is collected from public and non-proprietary sources. The information is drawn from internet, Manufacturer's Catalog, Handbooks, Textbooks, Published Articles, and Scientific Reports etc. An internet website or book may contain a continuous B-H curve, plotted in a variety of units, in a variety of logarithmic and linear scales over a variety of ranges. Considerable effort is expended to digitize these B-H curves and bring them to electronic forms so that a B-H curve can be inputted directly into a magnetic field software.

2 APPENDIX 1 - NONLINEARITY OF B-H CURVES

To fight the extreme nonlinearities in magnetization and permeability curves, one had to use large number of points in their digitization. Otherwise too few points may misrepresent their nonlinear behavior as discussed below.

Fig. 2 shows the magnetization curve and permeability curve of typical electrical steel from BHmag database.

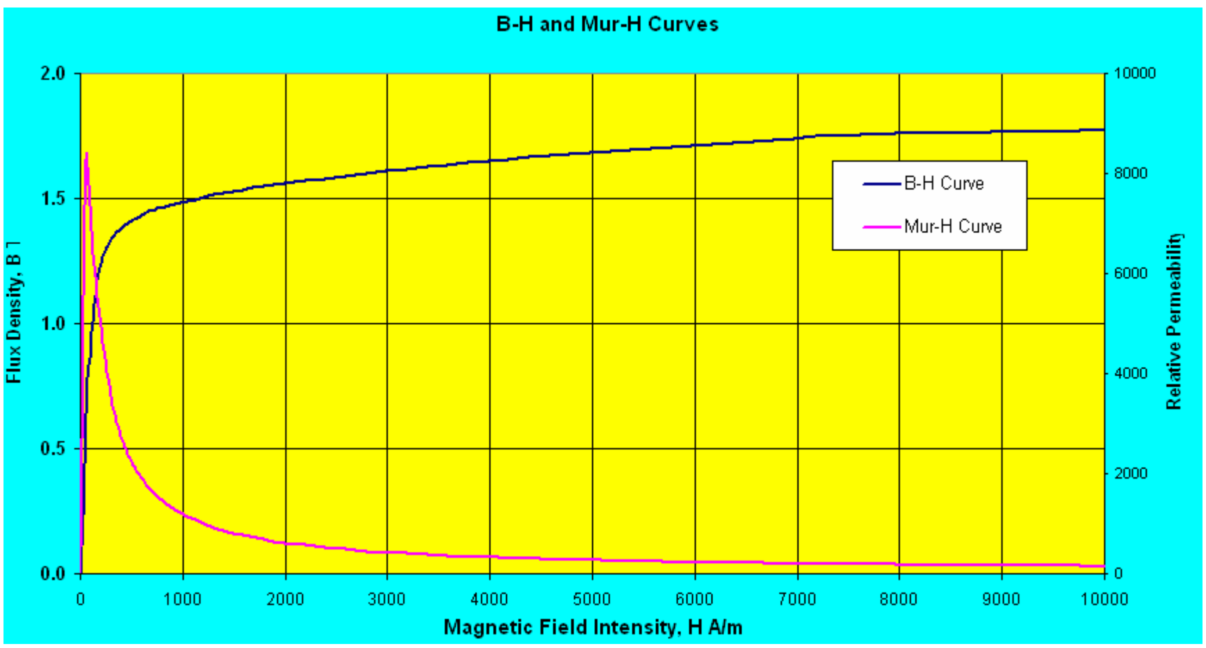


Figure 2 Magnetization and Permeability Curves of a typical electrical steel.

Examination of these highly nonlinear curves indicate that

- Below the knee (<1.2 T), relative permeability mur spikes sharply, changing by an order of magnitude (8000 to 1000), mainly due to too many unmagnetized domains.
- Above the knee (1.5 to 1.8 T), the flux density B increases very slowly when field intensity H increases by an order of magnitude (1000 to 10000 A/m), mainly due to too few unmagnetized domains.

Below the knee, capturing the permeability spike and subsequent rapid falling of permeability requires large number of data points. Above the knee, capturing small change in the flux density B when H increases by an order of magnitude also requires large number of data points.

But most other sources use very few points (some times less than 15) to digitize the entire magnetization curve. Too few data points may not catch faithfully the double nonlinearity inherent in the magnetic materials and can seriously impact the digital computations.

Thus the number of data points used in digitizing the doubly nonlinear magnetic materials has a major impact on modern digital usage. MagWeb recommends using large number of digital data points to digitize these nonlinear curves. Most digital B-H curves within the BHmag database use more than 100 digital points to characterize the double nonlinearity. Such high data density provides best insurance against numerical instability and ensures rapid and reliable estimation of magnetic fields.

But since non-convergence can be caused by several other factors, no guarantee can be given that using such large number of points alone will ensure convergence. Extreme caution should be exercised in extrapolation as sometimes finite element solution may fail to converge due to several other factors. Thus, one has to investigate numerical instability on a case-to-case basis.

Following additional tests might be needed to ensure fidelity of the BH curves: a) test that incremental permeability dB/dH increases always, b) test that intrinsic magnetization $B_i = B - \mu_o H$ monotonically converges to saturation induction B_s to third decimal place without oscillations.

The Becker-Doring model described in Umenei, A. E. et al "Models for Extrapolation of Magnetization Data on Magnetic Cores to High Fields" at IEEE Trans. Magnetics, Dec.

2011, Vol. 47, No. 12, pp. 4707-4711 is sometimes recommended in cases where extreme caution is required in extrapolation.

3 APPENDIX 2 - SATURATION INDUCTION

BH files list saturation flux density Bsat. Normally the designers can use the material up to Saturation Flux Density Bsat, but unfortunately, most sources publish only saturation induction Bs. Bs is always smaller than saturation flux density Bsat. Designers can better utilize the magnetic materials by basing on saturation flux density Bsat instead of saturation induction Bs. Magnetic materials can be used upto a design limit of Saturation Flux Density Bsat multiplied by stack factor.

As field intensity H increases, domains of magnetic materials progressively are saturated. Engineers use several ways to characterize saturation. Saturation Induction Bs and Saturation Flux Density Bsat are two most popular metrics. Various metrics used to characterize saturation are as follows:

(a) *Saturation Induction* B_s. As intensity H is increased, the fraction of flux density B carried by the magnetic material alone - termed intrinsic induction $B_i = B - \mu_o H$ - monotonically converges to a finite limit. The limiting value of intrinsic induction is called “Saturation Induction B_s”. In the *BHmag* database, the Saturation Induction B_s is defined as the intrinsic induction B_i that converges to the 3rd decimal place (i.e. converges within 0.05%). The iron is said to saturate at the saturation induction B_s. Any flux exceeding B_s is said to be carried by the “void” or air space occupied by iron.

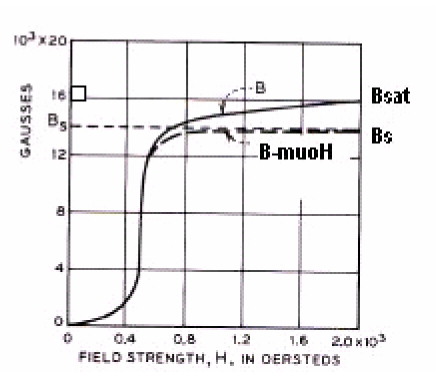


Fig. 1 Distinction between Saturation Induction B_s and Saturation Flux Density B_{sat}

(b) *Saturation Flux Density* B_{sat}. It is defined as the flux density carried by the magnetic material (that is limited by B_s) plus that carried by the void space it occupies. Saturation flux density B_{sat} is calculated from $B_{sat} = B_s + \mu_o H$. The Saturation Flux Density B_{sat} is always greater than Saturation Induction B_s. Fig. 1 shows the difference between B_s and B_{sat}.

(c) *μ--limited Flux density* B_μ defined as the flux density which has specified relative permeability μ_r. μ_r could range 10 to 500 depending on the application. For example, $B_{100\mu}$ defines the flux density that reaches permeability of 100. This is typically used in the American powder core community.

(d) *H-limited Flux Density* $B_{H\ defined}$ as the flux density, which has specified magnetic field intensity H in A/m. For example, B_{H50} defines the flux density that demands 50 A/m of field intensity. This is typically used in Europe and Japan.

For example for M-15 (A037),

- Saturation Induction B_s = 1.89 Tesla.
- Saturation Flux Density B_{sat} = 1.96 Tesla.
- μ-limited Flux Density at μ_r = 100, $B_{100\mu}$ = 1.79 Tesla
- H-limited Flux Density B_{5000H} = 1.685 Tesla

References:

1. Bozorth, R. M., Ferromagnetism, D. Van Nostrand Co., Princeton, 1951, p. 7.
2. Roters, H. C., Electromagnetic Devices, John Wiley & Sons, New York, 1941, p. 23.
3. Allegheny Ludlum Corp., Electrical Materials Handbook, Electrical Materials Handbook, Pittsburgh, p.I/3.
4. "Misconceptions regarding the meaning of the saturation induction," in p. 8 of New Developments in Ferromagnetism Research edited by V.N. Murray, Nova Science Publishers, 2006.

4 APPENDIX 3- BH FILE FORMAT

Material Name. This name is identical to the Name of the BH file. The material name can include following:

- Thickness (in mils or 1/1000ths of an inch). e.g., 14 mil means 0.014 inch thickness
- Frequency. For example, 2000 Hz means B-H data is at 2000 Hz.
- Heat treatment. For example
  - "Fully Processed": steel is delivered as fully annealed by the steel manufacturer.
  - "Semi-Processed": steel is delivered partially annealed. stress annealing needed
  - "732C anneal": data when annealed at 732 C anneal schedule on source website.

Headers

All B-H curves are headed by 2 rows; row 1 contains data while row 2 contains descriptors of the data. For a typical 23PH90 material. these two and respective 11 columns are shown below.

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*

The information in 11 Columns C1 to C11 is described below.

C1 - Material Category. It is identical to those listed in the home page. The magnetic properties are greatly influenced by the material category.

C2 - Manufacturer of the material

C3 - Brand name of the material given by the manufacturer

C4, C5, C6 - Thickness in gage, inches and mm respectively. Generally provided if the steel is a thin lamination. For Non-laminated materials, it lists available forms such as slabs, billets, rounds etc.

C7 - Annealing condition as described under material name.

C8 -frequency at which B-H curve is obtained

C9 - Saturation Flux Density Bsat of the material in Tesla

C10 - Electrical Conductivity in Ms/m.

C11 -B-H Curve number. It is a unique number assigned to each curve. It is given in Xyyy format where X is the symbol for the material category and yyy is a serial number.

For highly permeable materials such as Metglas or nanocrystalline, only hysteresis loop is sometimes available instead of magnetization curve. The B-H curve is then extracted from it by the Elenbass rule, as explained in Bozorth, Ferromagnetic Materials, Fig. 11-27 and p. 511. This rule states that, for a specific H, the B on the normal magnetization curve equals average of vertical ordinates of the hysteresis loop.

B-H Data

The B-H data is headed by third row with H, B, μ_r data labels in columns C1, C2, C3:

C1 *H A/m*. It refers to column 1 label for Magnetic Field Intensity H in A/m, usually expressed as round numbers.

C2 B *Tesla*. It refers to column 2 label for Magnetic Flux Density B in Tesla, usually shown to 3 decimal digits.

C3 *Mur*. It refers to column 3 label for relative permeability (μ_r) .

The data points on the magnetization and permeability curves are presented from row 4. Each row defines a (H, B, μ_r) data point. The numbers refer to DC or peak values (not rms).

The user can convert the B-H curve into other units using following relations: 1 Tesla = 1 N/Am = 1 Weber/m2 = 1 volt-sec/m2 = 10,000 gauss = 64.52 kilo-lines/in2. 1 A/m = 1/79.577 oersted = 0.01 A/cm = 0.025 A/in.

The B-H data is contained in Col. A and B. The units refer to DC or peak values (not rms). The μ-H data is contained in Col. A and C. The μ-B data is contained in Col. B and C. Data in a row corresponds to one data point of B-H curve. Each B-H curve is digitized with more than 100 data points. Such large number of data points results in high data density. As B-H curve is highly nonlinear, a B-H data with high data density is essential for convergence of nonlinear field equations.

The *BHmag* database store the values of B, H, μ_r as numbers with 8-decimal digits. But for simplicity, the database shows only 3 decimal digits of B and none for H and μ_r.

5 APPENDIX 4 - SAMPLE BH FILE

Next few pages present a sample BH File. This file is for a Grain Oriented Steel from Posco Electrical Steel named 23PH090. B-H curves as well as permeability curves are included in the database. For example, the designer can identify maximum permeability point and saturation flux density point and decide to operate the machine within this range. For this material, maximum permeability point is (15 A/m, 1.349 T, 73568) and saturation point is (8000A/m, 2.002 T, 199). Alternatively, the designer can choose to operate at the maximum relative permeability of 73000, which occurs at 1.349 Tesla. Alternatively, he can limit to the worst-case to the Saturation Flux Density of 2 Tesla. The data can thus help designer to choose not only an optimal material, but also an optimal design point for operation of the machine.

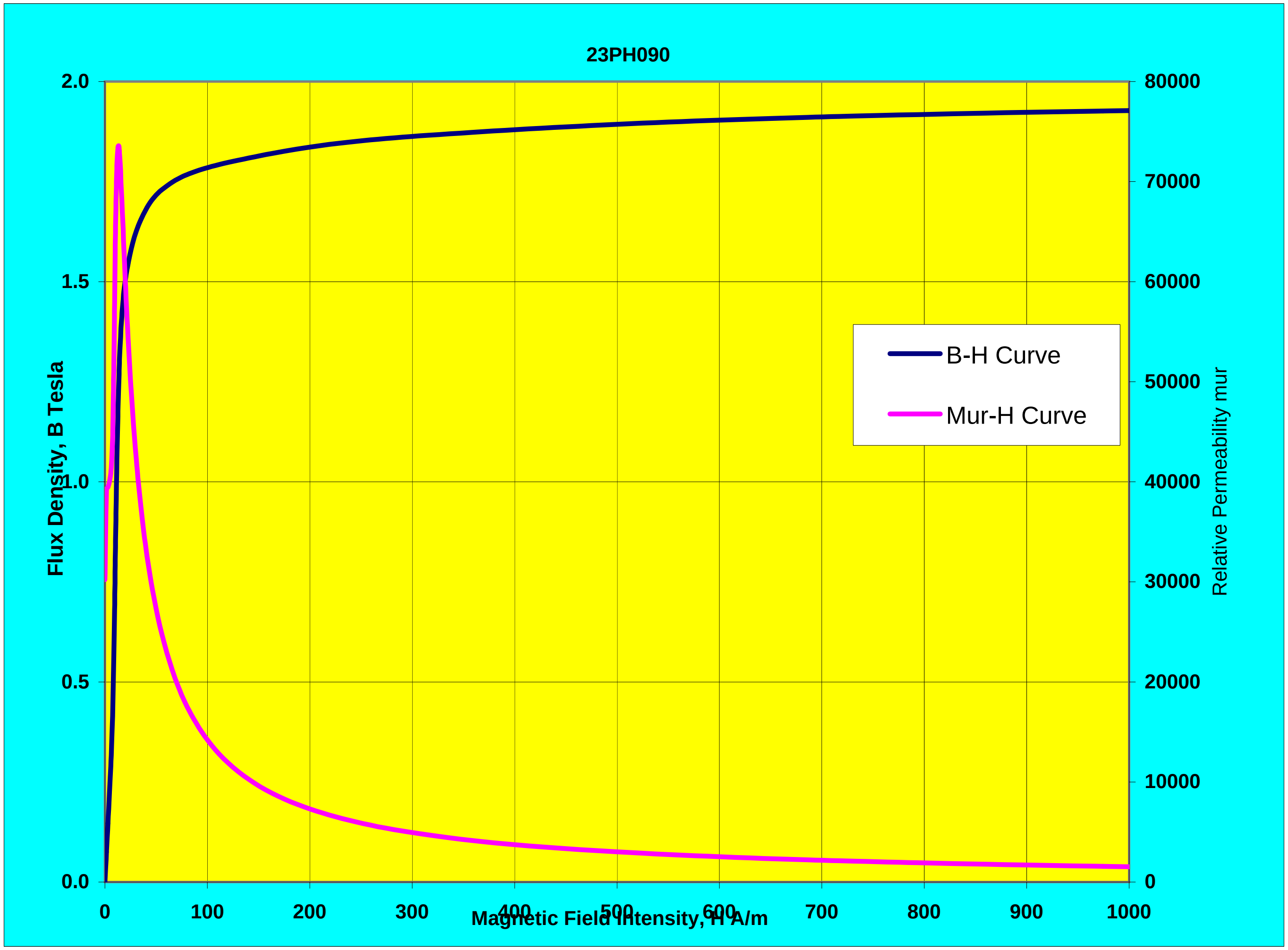
MagWeb
Magnetic Material Data

23PH090

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*

H A/m	***B Tesla***	***Mur***
0	0.000	30221
2	0.075	39221
3	0.147	39479
4	0.215	39935
5	0.276	40635
6	0.328	41626
7	0.374	42866
7	0.415	44319
8	0.453	45950
8	0.491	47724
8	0.529	49654
9	0.569	51756
9	0.611	54036
9	0.657	56481
10	0.706	59045
10	0.761	61663
10	0.821	64264
11	0.887	66751
11	0.955	68982
12	1.024	70838
12	1.089	72233
13	1.149	73125
13	1.202	73551
14	1.248	73561



14	1.288	73194
15	1.321	72501
15	1.349	71569
16	1.373	70488
16	1.394	69336
17	1.413	68170
17	1.431	67001
18	1.448	65825
18	1.462	64641
19	1.475	63434
19	1.487	62147
20	1.499	60724
20	1.511	59125
21	1.524	57340
22	1.537	55403
23	1.552	53357
24	1.567	51239
26	1.582	49075
27	1.597	46853
29	1.612	44564
31	1.627	42215
33	1.641	39840
35	1.655	37538
38	1.668	35385
40	1.680	33423
43	1.691	31645
45	1.701	29949

48	1.711	28249
52	1.721	26501
56	1.730	24704
60	1.739	22910
66	1.748	21168
72	1.757	19512
78	1.766	17925
87	1.774	16290
97	1.783	14560
112	1.793	12775
130	1.803	11047
151	1.815	9535
175	1.826	8295
200	1.836	7306
225	1.845	6517
252	1.852	5847
282	1.859	5246
317	1.866	4689
357	1.873	4175
402	1.880	3721
450	1.887	3335
500	1.893	3013
550	1.899	2746
602	1.904	2516
657	1.908	2311
717	1.913	2124
784	1.917	1946

23PH090

867	1.922	1764
974	1.926	1573
1117	1.932	1377
1299	1.937	1187
1515	1.944	1021
1752	1.950	886
2000	1.955	778
2253	1.960	692
2521	1.964	620
2820	1.968	555
3167	1.972	495
3568	1.976	441
4000	1.980	394
4432	1.983	356
4833	1.987	327
5188	1.989	305
5542	1.992	286
5958	1.994	266
6500	1.996	244
7203	1.999	221
8000	2.002	199
8797	2.005	181
9500	2.007	168
10086	2.008	158
10813	2.010	148
12008	2.011	133
14000	2.014	114

23PH090

17016	2.018	94
20875	2.022	77
25297	2.028	64
30000	2.034	54