Modern Permanent Magnets for Applications in Electro-Technology

By Karl J. Strnat, Professor Emeritus, University of Dayton, Ohio

Abstract

Permanent magnets (PMs) are vital components of many electromechanical machines and electronic devices, but they are usually hidden in subassemblies. System designers and end users often give no thought to how choice and use of the permanent magnet material affect performance, size, and cost of the product. This paper describes the range of materials and properties now at the disposal of design engineers and the place of different magnets in electro-technology, with attention to engineering and economic aspects.

Revolutionary developments have recently occurred in the old field of permanent magnetism. Hard ferrites became an abundant inexpensive magnet material while the rare-earth magnets raised the highest available energy products 4 to 5-fold and coercivity by an order of magnitude. As a consequence, a rapid broadening of magnet uses is now occurring; traditional devices are miniaturized, new applications and design concepts are evolving. Trends and examples are discussed in this paper. A confluence of recent developments in magnets, power semiconductors and microprocessors is particularly fruitful in the area of drives and motion control. We also assess currently evolving permanent magnet materials. production processes, prospects for new, still "better" magnets, as well as ultimate upper limits for permanent magnet properties.

1. Introduction, Some Definitions and a Historical Perspective

Permanent magnets have been used in electrical machinery for over 100 years, but because of recent dramatic improvements in their properties and availability, their application in electro-mechanical and electronic devices is now rapidly growing. They also have many purely mechanical uses, technological as well as trivial. The spectrum of electrical systems that employ magnets is extremely broad. Examples of consumer items are all sound reproduction systems (e.g., loudspeakers), watches, meters, weighing systems, automotive ignitions and starters, microwave ovens, small motors and actuators for computer peripherals (disc drives, printers), typewriters, cameras, and voice and video recorders. Communications uses are in telephones, microwave tubes, and filters. Magnets play an increasing role in particle accelerators and free electron lasers for physics, industry, and defense; also in NMR imagers for medical and industrial applications. They are used in industrial motors, actuators for robotics and flight control, and in some suspension and propulsion units for magnetically levitated vehicles.

The component we call a permanent magnet is a piece of magnetic material which, once magnetized or "charged" by an external magnetic field, retains a usefully large magnetic moment after the magnetizing force is removed. Thus, a permanent magnet (here often just called a magnet or abbreviated as PM) becomes itself a source of a magnetic field which can interact with other magnetizable materials or with electric currents. For a magnet to be technologically useful, this magnetization must persist in the presence of fairly high opposing fields (the permanent magnet must have a high "coercive force"), and not just near room temperature but often at elevated and sometimes also at very cold temperatures; its magnetic properties must be reasonably stable for long periods of time in adverse environments.

Naturally occurring permanent magnet materials have been known for perhaps 5000 years — the "loadstones," rich in magnetite, the ferrimagnetic iron oxide Fe_3O_4. Their only application was in the compass, an instrument first described in Europe around 1200 AD but apparently invented in China at least two millennia before.[1,2] Early and better artificial magnets made of quench hardened iron-carbon alloys (sword steel) were discussed by W. Gilbert in 1600, as were uses of permanent magnets for lifting iron parts. But by today's standards, carbon steel was an extremely poor magnet material: having low coercivity, H_c < 50 Oersted (<4 kA/m), it was easily demagnetized and its energy product — to use a modern term — was small, <0.25 MGOe (2 kJ/m^3).

This remained indeed the quality level until about 1880 when systematic alloying studies commenced. First tungsten and later chromium additions were shown to raise H_c somewhat and the energy density reached 0.3 MGOe by the year 1900. An important discovery followed soon, namely that further additions of a few percent cobalt could triple H_c.

And in 1917, using 35% Co, Kotaro Honda achieved the ultimate properties for steel magnets, about 250 Oe and 1 MGOe. In 1931, Tokuhichi Mishima, also in Japan, patented the first precipitation hardenable magnet alloy based on Fe, Ni and Al ("Alni") — no longer a steel. Thus started the 30-year-long development period of the highly successful Alnico family of magnet materials which also contain cobalt in addition (up to 40%). It ultimately made magnets with coercive forces up to 1900 Oe and energy products to 9.5 MGOe commercially available. *(But in different grades, not combined!)* With high-energy Alnico 5 and high-H_c Alnico 8, permanent magnets had achieved real utility for many electrical uses.

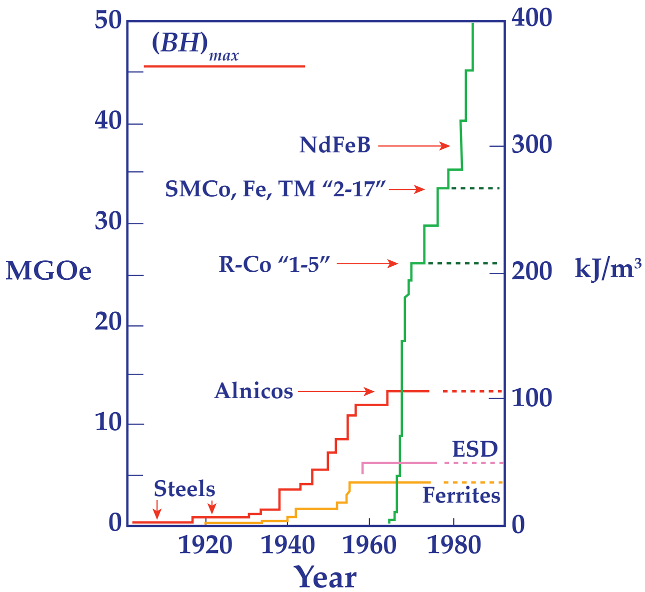


Figure 1a — The development of permanent magnets in the 20th Century using as a measure the laboratory record values of energy product

These and subsequent improvements of permanent magnets have spurred the development of better electro-mechanical and magneto-electric devices and were occasionally inspired by it. Aided by a growing understanding of the physics and metallurgy of magnetic materials, the pace of permanent magnet development has been rapid since World War II — albeit in spurts — and indeed quite hectic in recent years. The resulting variety of magnet materials and the property levels achieved are as impressive as were the concurrent achievements in semiconductor technology (although not nearly as highly publicized).

We have seen that permanent magnets have an extremely long history. On the other hand, practically all the progress that has made them the broadly useful components they now are, and which laid the groundwork for the current rapid expansion of permanent magnet applications and of the magnet producing industry, has occurred after about 1930. Truly amazing material developments took place in the last two decades. Modern permanent magnets are thus definitely high technology creatures of the 20th century. Figure 1 illustrates their chronological evolution, using record values of the static energy product as the yardstick.

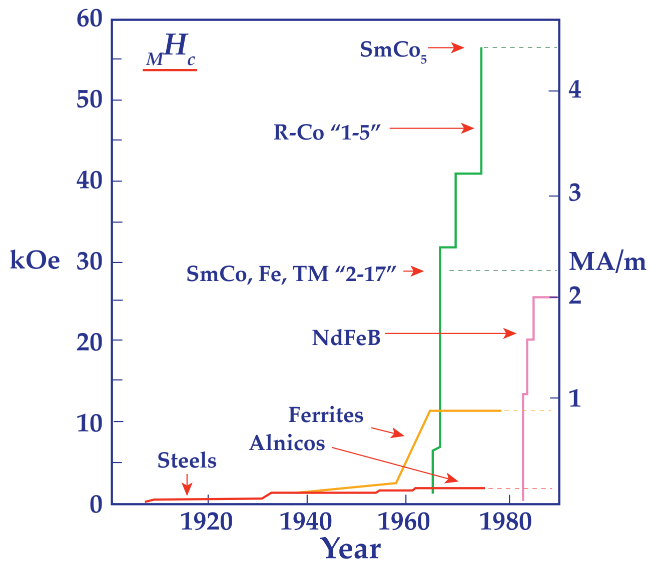


Figure 1b — The development of permanent magnets in the 20th Century using as a measure the laboratory record coercivity.[16]

Schematic magnetization and demagnetization curves shown as Figure 2 will remind the reader of several magnetic terms frequently used in this article. Of the two types of plots, the "intrinsic" M versus H curve is most useful in describing modern magnets. It shows the magnetic moments available under different operating conditions and defines the intrinsic coercive force or "coercivity," ${}_MH_c$ or H_{ci}, as the field strength that can completely demagnetize the magnet.

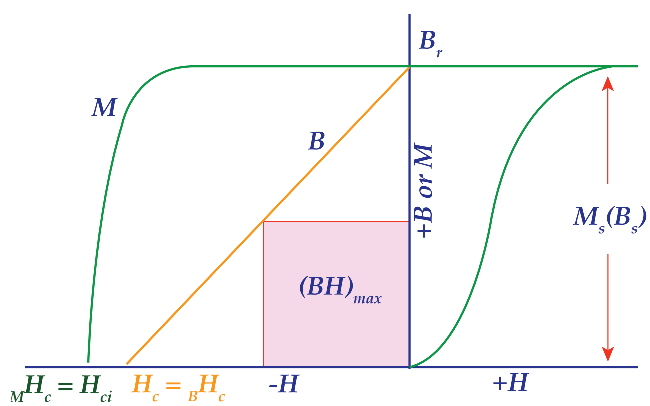


Figure 2 — The "normal" and "intrinsic" demagnetization curves of a modern permanent magnet material, with definitions of some common quantities.

The B versus H curve allows device designers to read off useful flux density levels and it defines a second, "normal" coercive force, ${}_BH_c$ or H_{ci} as the opposing field that reduces the induction flux to zero, often without permanently demagnetizing the magnet. The (maximum static) "energy product" $(BH)_{max}$ represented by the largest rectangle inscribed under the B, H-curve, is a figure of merit often used in comparing different magnet types. For loudspeakers, moving coil meters, voice-coil actuators, etc., where the magnet produces a time-constant field, the volume of permanent magnet material needed for a desired gap-flux density in a given space is inversely proportional to B x H in the magnet; and if one can design for operation at the maximum energy product point, P, then the required magnet volume will decrease inversely with increasing $(BH)_{max}$ values. Note, however, that additional — often economic — considerations influence the choice of a permanent magnet material, and also that there are many other devices for which B x H is not a significant design parameter.

Permanent magnets have a large variety of applications, present and potential, in many diverse areas including several fields of technology as well as non-technical, often trivial uses. Their uses are briefly surveyed below. Then we shall consider in greater detail some engineering applications, selecting them specifically from electro-technology. To put the development of the latter in perspective, let us first briefly consider the history of some important electromechanical machines and electronic devices.

Many of the experiments of Barlow, Franklin, Henry and others in the early 1800s, which demonstrated electromagnetic interactions and thus laid foundations for the later development of machines for the interconversion of mechanical and electric energy, were done with permanent magnets. All early electric generators (magnetos) and motors, as built by inventors around 1850, indeed employed permanent magnets — steel in horseshoe or bar shapes. Some such machines were industrially manufactured and helped start the electric age; but the poor properties of the steel magnets of that time made efficient and large-scale energy conversion impossible. That could only be realized in the later 1800s when dynamo-electric machines were introduced by Siemens, Gramme, Varley, and others. In these, an electromagnetic armature of copper wire wound on a soft magnetic iron core replaced the permanent magnets. This, of course, became the dominant type of electrical machines for the better part of our century.

However, the introduction of the Alnicos made the construction of permanent magnet rotating machines for special purposes reasonable again in the 1940s. The hard magnetic ferrites with their higher coercive force and much lower cost — first becoming available in the 1950s — then proved particularly suitable for electric motor design, and they have indeed found very extensive use in DC motors, especially for battery operation in automobiles, hand tools, etc. The unprecedented properties of rare earth-transition metal alloy permanent magnets (REPM), beginning with sintered $SmCo_5$ introduced in the early 1970s, proved ideal for motors and generators, but these materials are expensive. Sm-Co has indeed found many smaller-volume applications in high performance or miniaturized machines where its high price and limited availability are acceptable. The newest addition to the rare-earth magnet family in the mid-1980s, Nd-Fe-B, has many of the same design advantages and is more abundant and cheaper. It will therefore find widespread use in energy conversion devices.

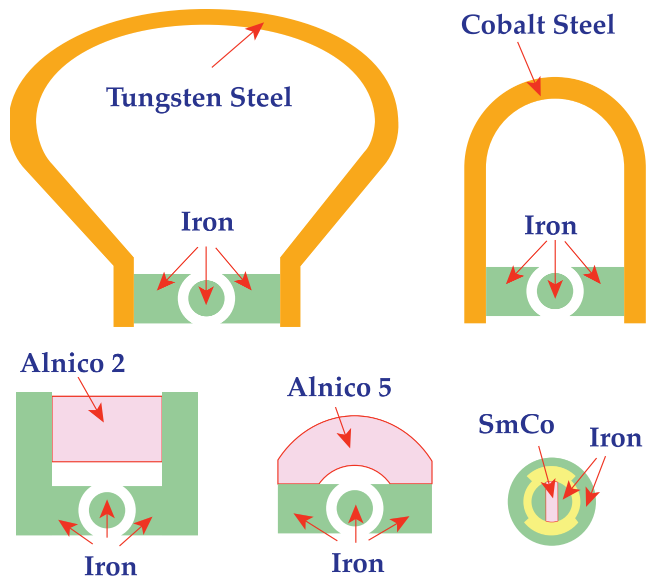


Figure 3 — The evolution of the magnetic circuit of moving coil meters reflects the progress in magnet materials development.

Generally, there is now a strong and accelerating trend toward the use of permanent magnet machines that was made possible by the progress in the permanent magnet materials field. In a sense we are returning to the early energy conversion concepts of over 100 years ago. This trend is strongly aided by a synergy of recent developments: in machine design (internal magnets, axial field, iron-less rotor, linear motors), in power semiconductors which now make it practical to employ new ways of motor operation (brushless with electronic commutation — often in servo loops, variable-frequency synchronous, stepper), and in electronic "motion control" with the aid of position/speed sensors and microprocessors. Another factor favoring permanent magnet motors and actuators in systems where many different motions must be independently performed is the increasing economy of using separate small motors placed where needed instead of the traditional single large machine with purely mechanical power distribution.

Motors and generators are perhaps the most visible of the early electrical applications of magnets, but there are many others. Of those which also have their roots in the late 19th century, several became commercially very important and some remain so to this day, The moving-coil galvanometer (d'Arsonval), long was the most common electrical measuring instrument; it has a permanent magnet circuit which initially comprised a long and bulky steel magnet. As magnet materials improved, the magnetic circuit changed shape and the magnet shrank until it is now often just a segment of the small core inside the coil. (See Figure 3). In electronic communications, telephone receivers, dynamic microphones, audio pickups and, most importantly, loudspeakers usually contain permanent magnets.

Here, too, the shape and size of the device changed drastically as the permanent magnet materials evolved. Figure 4 shows this for speakers.

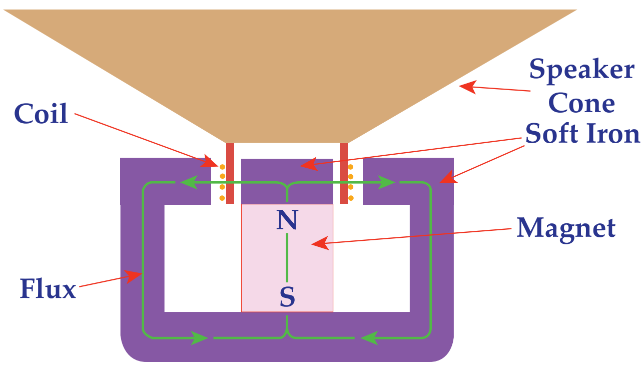


Figure 4a — Typical Alnico speaker design

The devices mentioned so far are historically the most important consumers of permanent magnets. Around 1960, three-quarters of the magnet production (then still mostly Alnico) went into motors, meters, and speakers in approximately equal proportions.[3]

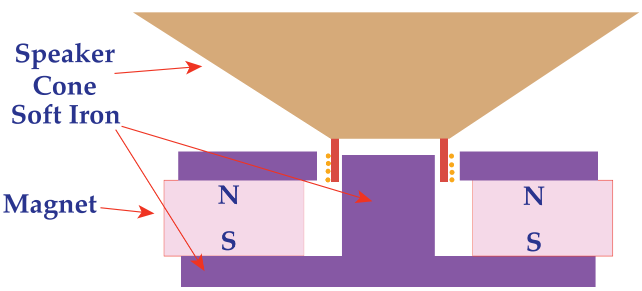


Figure 4b — Typical ferrite speaker system The evolution of the design of loudspeaker permanent magnet systems with improving permanent magnet materials properties, Clegg in [B-6], is shown in Figures 4a, 4b, and 4c.

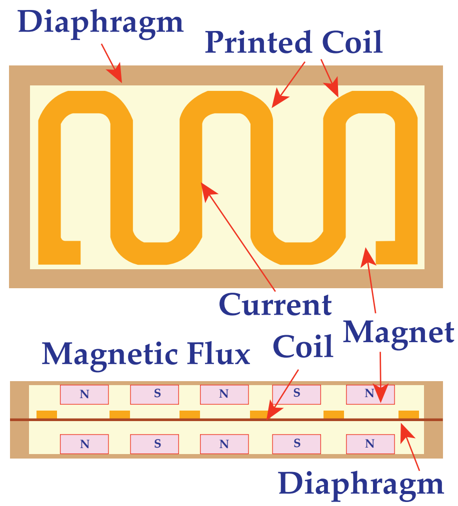


Figure 4c — Flat speaker with REPM.

2. Permanent Magnets in Current Use — Characteristics and Economics

A. Commercial Magnet Materials and their Economic Significance

A bewildering variety of magnet materials has been developed over the years and many of them are still produced today. Table 1 lists most of these in the chronological order of their introduction and with comments about present consumption and its trends.

Table 1 — Permanent Magnet Materials In Use Today

Material Type	First Introduced	Consumption (Product Value)	Use Trend
A. Principal Magnet Materials			
Alnico Alloys	1932	Medium	Slow decline
Ferrites (oxides)	1952	Largest	Medium growth
Rare Earth-Cobalt Alloys (Sm-Co Base)	1970	Medium	Slow growth
Rare Earth-Iron Alloys (Nd-Fe-B Base)	1983	Medium	Rapid growth
B. Materials of Minor Significance			
Co, Cr-Steels	1900	Very small	Declining
Fe-Co-Mo (Remalloy)	1934	Very small	Declining
Fe-Ni-Cu (Cunife)	1935	Very small	Steady
Pt-Co	1936	Extremely small	Steady
Co-Fe-V (Vicalloy)	1940	Very small	Steady
Fe-Co ESD (Lodex)	1954	Discontinued in 1988	
Fe-Cr-Co	1979	Small	Steady
Mn-Al-C (Almax)	1979	Very small	Steady

Notes: Polymer bonded versions exist for Alnico (small, declining), Ferrite (medium, steady) and the Rare Earth-Co/Fe magnets. Bonded REPM have small uses at this time but the largest growth rate of all magnets. The total market share of all specialty magnets in group B is only ~1%.

Only the four basic types in group A (three if we combine Rare Earth-Co and RE-Fe-B alloys as rare earth permanent magnets) are economically important; together they constitute almost 99% of the total magnet market.

“Global” permanent magnet sales (excluding the Comecon countries and China) were estimated as about $1.46 billion in 1987, and $1.755 billion in 1988. The growth rate in 1987 over 1986 was 12.4%, from 1987 to 1988 it was 20%. These estimates are based on the value of finished magnets and ready-to-press powders only, not of subassemblies or devices. (Off-shore currencies converted to US $ at average rates for 1986, 1987, and 1988, respectively).[B-15] The geographic distribution of the 1987 magnet production was said to be as follows:

	1987	1988
Japan	52.2%	53.9%
United States	19.9%	20.2%
Western Europe	16.5%	17.1%
All Others	11.4%	8.8%

Japanese companies continue to strengthen their position, with at least 25% of the US magnet needs now being supplied by them. Additional magnets are imported as components of consumer goods in quantities for which no public statistics exist. Generally, the magnet market is not yet a truly global one and the distribution of the different magnet types produced varies between regions.

Wheeler [B-15] and Hennig[4] cite statistics for 1987 and 1988 that form the basis of Table 2. We see that in 1987, the ferrites accounted for nearly two-thirds of all magnet sales worldwide and in the major regions. In 1988 their relative market share began to shrink, but total ferrite sales continued to increase. The rare earth permanent magnet share is rapidly growing: it had almost reached that of alnico in 1987 overall, exceeded it in the USA (19.1 versus 15.2%) and dramatically so in Japan (32.2 versus 7.0%). This trend continues: in 1988, global rare earth permanent magnet sales exceeded those of all magnets except the ferrites for the first time. (Note that in these statistics Alnico production was shown separately in 1987, but for 1988 it is lumped together with "other magnets.")

Table 2 — Distribution of Production within Regions in 1987 and 1988

	US		Japan		Europe		Others		Global	
Material	1987	1988	1987	1988	1987	1988	1987	1988	1987	1988
Ferrite	64.4%	66.2%	60.5%	56.1%	62.5%	60%	84.0%	83.9%	64.3%	61.3%
Sm-Co	8.9%	8.5%	27.6%	25.4%	12.5%	15.0%	—	—	4.8%	18.0%
Nd-Fe-B	10.2%	11.2%	4.6%	11.6%	2.1%	3.3%	—	—	11.5%	9.0%
Alnico	15.2%	14.1%	7.0%	6.9%	18.7%	21.7%	16.0%	16.1%	18.3%	11.7%
Other Magnets	1.3%		0.3%		4.2%		—		1.1%	
Sales of all PM	$300	$355	$760	$945	$240	$300	$160	$155	$1460	$1755
1 Year Gain	18.3%		24.3%		25.0%		-3.0%		20.2%	

Looking at the tonnage quantities of magnets produced during 1987 in all these regions ("globally") gives an even more extreme picture of the distribution between the magnet types. (See Table 3). The predominance of ferrite is overwhelming: ~97% of the total produced magnet mass! Alnico was just 2% anymore, and Sm-Co and Nd-Fe-B together were only 0.55%. However, the rare earth permanent magnets can do the same job as a much larger quantity of Alnico or ferrite; they also command a much higher price.

Table 3 — Estimated "Global" Production Quantities of Magnets

	1987		1988	
Material	Metric tons	Rounded	Metric tons	Rounded
Alnico	4700	2.0%	4900	1.9%
Ferrite	225,000	97.4%	245,000	97.4%
Sm-Co	900	0.4%	900	0.4%
Nd-Fe-B	350	0.15%	725	0.3%
Other permanent magnets	20	0.01%	25	0.01%
Total mass of magnet materials produced (approximately)	231K tons		252K tons	

B. "Specialty Magnets" of Minor Significance

The materials listed in Table 1.B are mostly older and largely obsolete magnet types. Their permanent magnet properties are mostly poor by today's standards, yet they are often expensive because of the small production volume. It is noteworthy that very few of the permanent magnet materials that were once in production have ever completely disappeared.

One reason is that some have unique properties deemed necessary for certain applications. For instance, Cunife and Vicalloy are ductile in the unfinished state, and somewhat flexible even when magnetically hardened, while most magnets are hard and brittle. They can be formed by rolling or wire drawing, further shaped by punching and bending. The extremely expensive Pt-Co (78% weight platinum!) is also ductile and chemically quite inert; it is produced in very small quantities mostly for medical implants. But the main reason for the persistence of some old materials is simply the conservatism of a few users, perhaps also a lack of information about the newer alternatives. Even some steel magnets are still produced, for devices such as hysteresis motors where semi-hard materials are needed.

Two of the specialty materials, Fe-Cr-Co and Mn-Al-C, are modern; their commercial production began just 10 years ago when cobalt was in short supply and became temporarily very expensive. They were intended to replace the high-Co alnicos. But restoration of the cobalt supply and the rapid substitution of ferrite for alnico on the low cost and property end of the permanent magnet spectrum, and of the rare earth permanent magnets in high-performance applications, removed again the economic pressures favoring Fe-Cr-Co and Mn-Al-C even as their production began. So they have remained commercially fairly unimportant although Fe-Cr-Co is now offered by major PM manufacturers in several countries.[5]

The Fe-Co-based ESD (Elongated Single Domain) fine particle magnets are a special case. They were the first attempt to develop a strictly synthetic magnet based on theoretical concepts.[6] This partially successful development resulted in a commercial magnet, the lead-bonded "Lodex", which found a significant niche market and was manufactured for about 30 years, by General Electric and later Hitachi Magnetics. Since its production involved handling large quantities of mercury it was discontinued two years ago because of environmental concerns. Its advantages of easy net-shape pressing and machinability are shared by newer bonded magnets based on ferrite or REPM powders which should take their place in former Lodex applications.

Some materials with coercive forces in the 50 to 200 Oe range, which we no longer consider true permanent magnets, continue to be used as "semi-hard" magnetic materials for small hysteresis motors, clutches, latching relays, and more recently anti-theft tags and identification cards. Co, Cr-steels and Vicalloy are employed there along with other Co-Fe-based alloys. Some older permanent magnet materials with modest H_c are now also used as special magnetic recording media: Vicalloy wires for aircraft in-flight recorders (for crash survivability), Ba-ferrite particles and films on bank cards, etc. Such applications are outside the scope of this article.

C. Today's Principal Commercial Magnet Materials

Listed in Table 1.A are the magnet types which resulted from the "three magnet revolutions" previously mentioned: the Alnico alloys, the hexaferrites, and the Rare earth permanent magnets. Because of their great importance they shall now be discussed in more detail.

1. The Alnico Magnet Family

Chemically, the Alnicos are iron-cobalt-nickel based alloys with minor additions of aluminum and copper, and in some grades titanium. Typical compositions for today's main commercial grades are shown in Figure 5. Alnico is usually produced by casting, but small precision shapes are also made by sintering, especially in Europe. Coercive force is developed by a sequence of heat-treating steps which cause a finely dispersed precipitate of a strongly magnetic Fe-Co phase to grow in a weakly magnetic Ni-Al-rich matrix. By ESD-like behavior, the smallness of these elongated precipitates combined with their shape anisotropy brings about H_{ci} values between 500 Oe and almost 2000 Oe (in high-Co alloys with Ti). Cheaper grades such as Alnico 2 are isotropic, i.e., their magnetic properties are nearly the same in all directions. While this is desirable in some components like small, multipole motor rotors, it also means low remanence and energy product and thus an inefficient use of a fairly expensive material.

Anisotropy with a single preferred axis can be achieved in two ways: annealing in a magnetic field orients all precipitate particles parallel, and close thermal control of the solidification process can produce a crystal texture, i.e., a common orientation of the coarse matrix grains. The field anneal alone gives the standard Alnico 5 its enhanced remanence and improved demagnetization curve, and a combination of both measures produces the best results possible with this composition in the so-called columnar Alnico 5 ($B_r \approx 13.5$ kG, $BH_m \approx 7.5$ MGOe, $H_c \approx 750$ Oe). Of the high-Co alloys with Ti, Alnico 8 is field-treated but not columnar; it has the highest H_c (up to 1.9 kOe), but a much lower B_r (7 to 8 kG) than Alnico 5 and only ~5 MGOe. A slightly different alloy, with a little sulfur added, allows the growth of columnar crystals, yielding the high-energy magnet known as Alnico 9 (10.5 kG, ~9MGOe, ~1500 Oe) which is very costly. Detailed accounts of the production metallurgy can, e.g., be found in.[7,8]

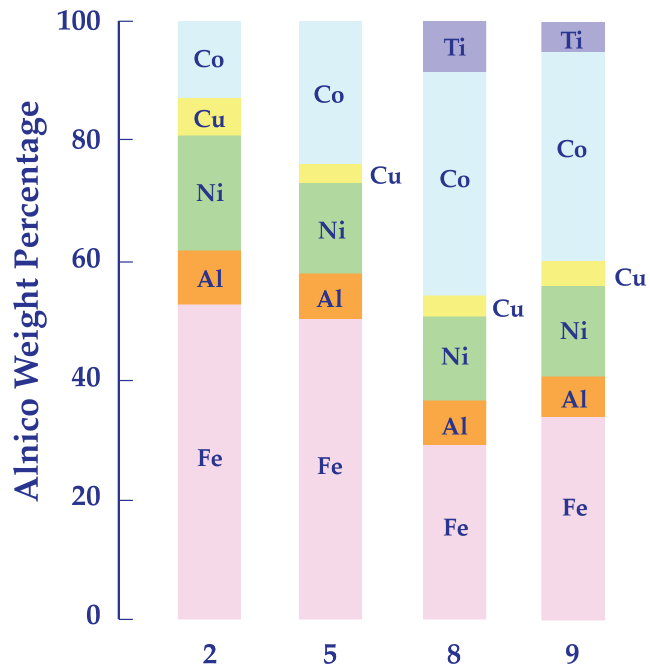


Figure 5 — Typical compositions of important Alnico grades in the chronological order of their development [B-11].

Other important magnetic characteristics of the Alnicos are their very high Curie temperatures (700 to 850°C); a small negative reversible temperature coefficient, $\alpha(B_r) \approx$ -0.02% per °C; and their excellent flux stability at elevated temperatures. These alloys are also chemically and metallurgically quite stable, and Alnico 5 is the only magnet material that has some long-term utility at temperatures up to 500°C. Mechanically, all Alnicos are hard and brittle; the high-H_c grades are worst, sintered versions relatively better than the cast. The magnets must be finished by surface grinding and must not be put under tensile stress. The mass density is 6.9 to 7.4 g/cm^3. Alnico alloys are quite corrosion resistant, even at high temperature, resembling stainless steels in this respect.

Figure 6 shows typical demagnetization curves for representative magnets of all currently used PM types, including Alnico 5 and 8. We see that the Alnico coercive forces are very low in comparison to more modern materials. This is a disadvantage in device design and dynamic operation, and it limits the attainable energy product in spite of high remanence. There appears to be no way to significantly increase H_c over the values achieved some 25 years ago. The alnico development has long ago run its course.

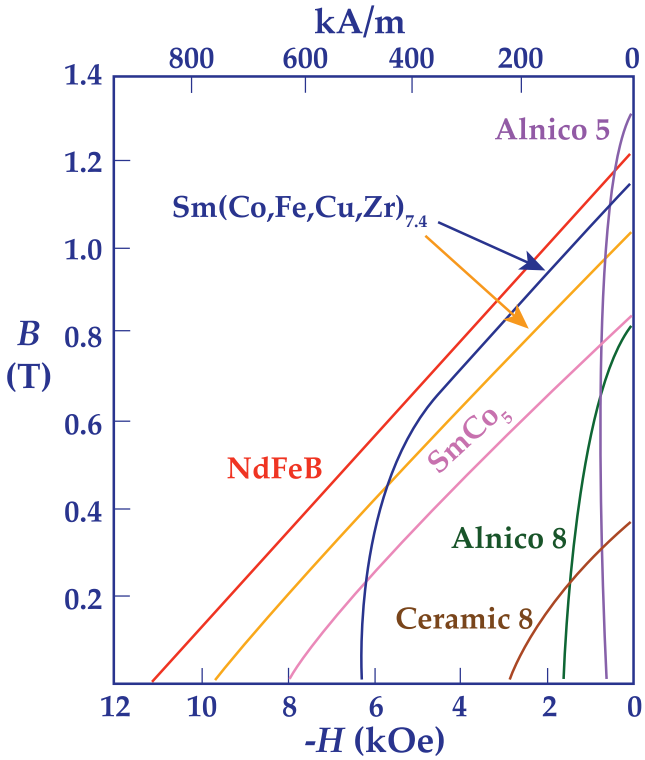


Figure 6 — Comparison of rare-earth magnets with some older magnet types. *B*,*H* demagnetization curves of average commercial magnets.

Most Alnico alloys contain rather large amounts of the expensive, strategic metal cobalt, and they make relatively poor use of it in terms of energy density due to their low coercivity. There are now newer Co-free magnets that are either cheaper (ferrite) or much better in terms of H_c and *BH*-product (Nd-Fe-B). And then there are the Sm-Co based magnets which — while having even higher Co contents — make much better use of the cobalt. This is the main reason why Alnico consumption has severely declined in the last decade and will drop further. However, in some applications the good magnetic stability at high temperature, the low $|\alpha|$ and good corrosion resistance are important, so it is likely that a small but still significant alnico production will continue for a long time.

2. The Ferrite or Ceramic Magnets

These materials are oxides of the generic formula $MO.6Fe_2O_3 = MFe_{12}O_{19}$, where the metal M is barium or strontium or a mixture, sometimes with Pb, Al or S as minor additives.[9] Sr-ferrite yields slightly higher coercivity and is now the preferred product. These oxides are ferrimagnetic, have a hexagonal crystal structure and a fairly large single-easy-axis crystal anisotropy. Because of the latter these "hexaferrites" can be given a high coercive force by milling the compound into submicron particles, then compacting these and sintering them into a dense "ceramic" body. Being mixed oxides in which only the iron atoms carry a magnetiC moment, the ferrites have a much lower saturation magnetization ($B_s \approx 4.7$ kG) and Curie temperature (450°C) than the metallic Alnicos or REPMs. As a consequence, they are limited to comparatively low remanence values (2.0 to 4.3 kG) and energy products (1 to 4.5 MGOe). The room-temperature H_{ci} can reach ~4 kOe, but as with other magnets, there is always a trade-off to make: highest B_r and BH_{max} is combined with lower H_c and vice versa.

The ferrites have some peculiar properties setting them apart from other magnets, for better and worse. As oxides, they are electrical insulators, which eliminates eddy currents. (Most permanent magnet materials, being metals, are fairly good conductors.) This is advantageous under dynamic operating conditions as in electric motors and also facilitates pulsed field charging. They are chemically inert, so the production steps of milling, pressing and surface grinding can be done in air and with water lubrication; they also have no corrosion problems in use even at high temperatures, But the lower T_c causes the magnetization to drop more rapidly on heating, $\alpha(B_r) \geq +0.2\%$ per °C around r.t. is about 10 times greater than for Alnico. Unique among magnets, the intrinsic coercive force has a positive temperature coefficient, $\beta(H_{ci}) \geq +0.2\%$ per °C. This means that the resistance to demagnetization is reduced on cooling, which can cause problems at the lowest environmental temperatures and must be taken into account in the design of certain devices such as automotive cranking motors,

The ferrites were the first magnets with a straight-line demagnetization curve far into the second quadrant, which for some grades extends beyond $_BH_c$, As a consequence, they may operate at very low permeance values, they can (and should) be used in shapes very short in the magnetization direction, and they can be pre-magnetized before device assembly without significant flux loss in transfer. (No more "keepers.") Because of the low remanence, the magnet cross section must be much larger than for Alnico to achieve comparable flux.

Although most magnetic properties of the ferrites are rather modest, they have one great advantage over all other permanent magnet types, which explains their enormous competitive success: the raw materials are cheap and plentiful. And now that large-scale, efficient, and highly automated production facilities have been established, this translates into low prices for finished magnets, particularly for simple shapes needed in large quantities. In the latter category are loudspeaker rings and arc segments for small DC motors, especially for the auto industry. Like the Alnicos and rare earth permanent magnets, sintered ferrites can be made with isotropic properties (low B_r, but very cheap), or anisotropic with varying degrees of grain alignment achieved by compaction in a field. Contrary to the situation with Alnico and, especially, the rare earth permanent magnets, the material fraction of the magnet cost is small and there is no concern about conserving raw materials, so it is perfectly reasonable to use isotropic ferrites where the low flux density is sufficient.

The mechanical properties are again undesirable: sintered ferrites are very hard and very brittle; machining requires surface grinders and diamond cutting tools, so it should be minimized. However, easily machinable rigid or flexible bonded magnets can be made by consolidating ferrite powder with a polymer matrix, Their B_r (1 - 3 kG) and BH_m (0.3 - 2 MGOe) are at the very low end of the permanent magnet property scale. Nevertheless, these "rubber ferrites" have also enjoyed enormous economic success, e,g., in such applications as refrigerator door seals, magnetically adhering signs, and toys, but also very small electric motors and shaft-position encoders. The general subject of bonded magnets is further discussed below.

3. The Rare-Earth Magnet Family

a. Fundamentals and General Features

This newest and still growing family of hard magnetic alloys includes the well-known samarium-cobalt and neodymium-iron-boron magnets, but also many other related materials, All are based on intermetallic compounds formed when 3d-transition metals (TM), notably the strongly magnetic Co and Fe, are alloyed with rare-earth elements (RE) of the 4f-transition series, i.e., the "lanthanides" Ce, Pr, Nd, Sm, Gd, Dy and others, or their close chemical relatives La and Y. Addition of still another element, such as B, C, Si, or Ti, often helps form ternary compounds, The systematic study of these synthetic metallic substances and their properties is relatively young; it began in earnest in the 1950s and continues today.[10,11] A large number of such binary and ternary intermetallics are ferro- or ferrimagnetic, and at least 50 combine a substantial saturation magnetization, B_s, with a sufficiently high Curie point, T_c, to possibly qualify them for some magnetic application. Several combine these features with a very large single-easy-axis magneto-crystalline anisotropy which makes them potential permanent magnet materials.[12] Three subgroups in particular — the compound types RECos, RE_2CO_7 and $RE_2Fe_{14}B$ — were thoroughly studied and a few members of these have been developed into useful permanent magnets.[13]

The large crystal anisotropy of the principal metallurgical phases present in the rare earth permanent magnets was the key and a necessary condition for developing very high intrinsic coercive forces. Early single-domain particle theories had suggested that all that was necessary to obtain a large H_{ci} was to comminute a high-anisotropy compound into small particles below a critical size, here on the order of one micron. But in fact, making good magnets is a much more difficult process, and the fine-particle theory that guided the early rare earth permanent magnet research proved quite inadequate for explaining the permanent magnet behavior. Real rare-earth magnets are not simply the respective intermetallic compound; rather, they are multi-phase, often multi-component and non-equilibrium metallurgical systems and their magnetization curve behavior is controlled by submicroscopic details of the microstructure. The actual origins of the coercivity are still not fully understood and at present the subject of much theoretical effort and argument. A detailed discussion of these physical mechanisms is outside the scope of this article; the interested reader is directed to references.[8,14,15,16]

Room temperature H_{ci} values for the rare earth permanent magnets are in the range of 5,000 to > 30,000 Oe (0.4 to > 2.4 MA/m). They are much higher than those of the ferrites and even of Pt-Co, and in magnet alloys like Sm-Co or Nd-Fe-B a high H_c is combined with B_s-values comparable to those of the Alnicos. As a consequence, the *B, H*-demagnetization curves at least at room temperature (r.t.) — are nearly straight lines through most or all of the second quadrant. This means that the theoretical maximum energy product of $(B_s^2)/4$ can be closely approached, something that was previously possible only for the low-B_s ferrites. Figure 6 shows representative r.t. *B, H*-curves for the main rare earth permanent magnet types now in production, contrasting them with characteristic demagnetization curves for some good Alnico and ferrite magnets. A magnet is "best" for most purposes when it combines high B_r and H_c, so all the rare earth permanent magnets with curves extending far to the left and upward in the plot are clearly superior. What this plot cannot show is the very high intrinsic coercivity of most of the Nd(Dy)-Fe-B, of the high-H_c 2-17 Sm-TM and the $SmCo_5$ magnets, which can be an enormous additional advantage in dynamic applications as in certain motors and actuators, or the high spatial rigidity of their magnetization vector which is now consciously exploited in some designs of electron-beam devices or material separators.

The other magnetic properties important for the device engineer vary widely for the many different subtypes of the rare earth permanent magnets. Table 4 is an attempt to summarize important design parameters in a manner that allows a quick orientation. (For the exact properties of a specific magnet type the manufacturer's product sheets must be consulted.)

Table 4 Magnetic Properties of Dense Rare Earth Permanent Magnets in or Near Commercial Production in 1989

Compositional Families Structure Types and Basic Magnet Processing Methods		d (g/cm³)	T_c °C	at Room Temperature					Max. Use Temp. °C	Min. Field to Charge [kOe]
				B_r	$_MH_c$	$(BH)_m$	B_r	MH_c		
Sm(Ce, Pr)-Co(Fe, Cu) "1-5"	Sintered	7.7-8.4	500-750	5-10.3	5->25	6-26	-0.45	-0.2	200-250	15-20
							-0.09	-0.44		
SM(Ce, ND, Y) - Co, Fe, Cu, Zr(Hf, Ti) "2-17"	Sintered	8.3-8.6	780-850	9.5-12	6->25	20-31	-0.03	-0.2	300-350	10-40
							-0.06	-0.4		
ND(Dy) - Fe-B R/Q, Hot Pressed "2-14-1"	Sintered isotropic R/Q, Hot-Deformed, Anisotropic	~7.4	~310	11-12.8	10-24	25-40	-0.12	-0.70	80-120	~20
				8-9	15-17	12-14	to	-0.5	150	~45
				10-12	12-14	22-32	-0.13	-0.63	100	~25
ND(Dy) Fe, Co-B	Sintered	~7.4	300-500	12-12.4	8-18	32-36	-0.07	-0.55	150-160	15-20
Nd-Fe(Co)-B-Ga "2-14-1"	Sintered R/Q, Hot-Deformed, Anisotropic	~7.4	300-500	10-12.7	10-20	23-36	~0.09	-0.53	140-160	~20
				11-12.2	18-20	28-35				~25
Pr-Fe-Cu-B "2-14-1"	Hot Rolled Anisotropic	~7.4	~300	10.8-12.6	10-11.2	27-30	-0.11	-0.60	~90	~20

(Numbers are approximate. Compositional and property variations in each family can be very extensive.)

b. Classification of the Rare-Earth Magnets

We now usually distinguish three groups of rare earth permanent magnets, by the nominal stoichiometric composition of their main phase which provides the useful magnetic flux:

(1) The "1-5" magnets based on $RECo_5$ intermetallics (these include $SmCo_5$); they are now often called the first generation of rare earth permanent magnets.

(2) The second generation "2-17" magnets, which in fact usually have Rare Earth TM_x compositions in which $x < 8.5$ (= 17/2); they use mostly Sm as the rare earth and the TM is primarily Co, but increasingly with Fe substitutions up to 25% weight.

(3) Finally the "2-14-1" magnets, the "third generation" of rare earth permanent magnets.

In these, the principal rare earth component is Nd (but now often partially replaced by Dy, Pr, and soon perhaps Ce); the TM is mostly Fe, but often with substantial Co substitution, up to 20% weight.

The feature used in this common classification of the rare earth permanent magnets into three groups, then, is the crystallographic type and corresponding stoichiometry of the principal phase. But within each of these groups, and cutting across them, there are almost infinite possibilities for compositional variations, and corresponding to them many different combinations of the basic magnetic properties such as T_c and B_s. There are also several options for influencing the magnetization reversal behavior and coercivity, ways of modifying the temperature dependence of B_s and H_{ci}, and finally many possible economic trade-offs involving properties, cost, and material availability. As the composition and microstructure are varied, secondary properties such as the corrosion behavior and magnetic property stability are also strongly affected. And there are by now several alternative ways of producing magnets from these different RE-TM alloys.

The main reason for this great variety is the fact that there are 15 rare-earth elements, many of which can playa useful role in permanent magnet alloys. They can be used not only singly but in various combinations of 2, 3, or more rare earths. (An example of the latter is "mischmetal", a blend of most of the rare earths — dominated by Ce, La, and Nd-corresponding to their natural mixture in common ores.) On the transition metal side there are also possibilities of mixing and substituting — although much more limited-notably some Fe for Co and vice versa, but also a little Ni, Mn, Cr, Cu, Zr, etc. And then there is the possibility of varying x in the RE-Co-based alloys $(RE)TM_x$. This yields useful magnets at several x-values in the range ~4.2 < x < ~9 which includes the 1-5 and the 2-17 stoichiometries. Of these almost unlimited possible combinations, many have been explored in the laboratory, and potentially useful magnets of many compositions were prepared and described in the literature.

Only a limited selection has so far been developed into commercial products. But even these offer such a variety of property and behavior combinations, and a wide price spread as well, that it can be very confusing to the magnet user. The qualitative compositions and property value ranges given in Table 4 suggest this large choice in the current rare earth permanent magnet production, (Some specialty magnets are indeed left out of the table.) And as more options are explored, the breadth of the offering is likely to increase. However, there is another side to the coin: a magnet user who makes the effort to become well informed can find magnets optimally matched to his application. It is even possible to tailor-make rare earth permanent magnet for a specific use. This is, of course, reasonable only when either very large quantities of the material will be needed, or for devices demanding highest performance of the magnet and where cost is secondary.

It is obviously impossible to do the subject of the rare earth permanent magnet full justice in this paper. Our further discussion will be restricted to the main types of commercial magnets. We shall consider their typical compositions, methods by which they are produced, properties and features they have in common and others that distinguish them, and also some economic aspects.

c) Commercial Rare Earth Permanent Magnet Types and Properties

The "1-5" Magnets

The original and still most-used commercial rare earth permanent magnet is sintered $SmCo_5$, now produced with energy products of about 16 to 23 MGOe and typically very high coercivity (15 to > 30 kOe). Its Curie point of ~750°C is almost as high as that of Alnico. But upon heating, the intrinsic coercive force drops off much more rapidly than B_s, does, to near zero at ~475°C, thus limiting the upper use temperature of $SmCo_5$ magnets to about 250°, probably less for very low-permeance operating points, The magnet contains about 66% Co and 34% Sm by weight. $SmCo_5$ is the most expensive of the three basic rare earth permanent magnet alloys. It has been modified in various ways for different reasons: Praseodymium (Pr) additions can raise the energy product and slightly reduce the cost (at the expense of lower H_c and poorer stability); cerium (Ce) or mischmetal (MM) broaden the raw material base and reduce the cost per unit mass, but they also reduce BH_m (to ~14 MGOe) and T_c (Ce to as low as 450°C); gadolinium (Gd) and other heavy rare earths (HRE) with high atomic magnetic moments can be added for temperature compensation, the trade-offs being a reduced B_r, lower BH_m (9 to 14 MGOe) and higher cost. Replacing some of the Co in $SmCo_5$ or $CeCo_5$ by copper and proper heat treatment changes the magnetization reversal mechanisms from "nucleation controlled" to "pinning controlled" (general wall pinning by precipitate particles). This has advantages in certain applications and also allows the introduction of some iron in the alloy, thus lowering the cost. The Curie point is again reduced by the Cu addition; B_r and BH_m are lower, but the Fe can partly offset that. The mechanical properties of all Sm-Co-based magnets are at least as bad as those of ferrites; most REPM are brittle as glass and machining is restricted to cutting and grinding with diamond tools.

The "2-17" Magnets

Sm-Co-based magnets of this type have been in production since about 1980, a typical commercial composition being $Sm(Co, Fe, Cu, Zr)_{7.4}$. Initially they could be made only with a relatively low coercivity (5 - 6 kOe) and therefore a knee in the demagnetization curve (see Figure 6), but now they are also available with H_{ci} = 10 - 25 kOe, equivalent to $SmCo_5$. B_r and therefore the energy products are higher than for 1-5 magnets, 20 to 30 MGOe (lab, record 34);[17,18] T_s is very high (750 to 850°C), and the temperature coefficient of B_r is smaller in magnitude. Upper use temperatures to 350°C are quoted. At the same time their Sm content is lower (18 to 27 weight %) and so is the cobalt content (40-50%), Co being partially replaced by Fe (10-20%). Thus, the newer 2-17 magnets are superior in all respects to $SmCo_5$ and seem destined to replace it in those applications where rare earth permanent magnet properties are essential but Nd-Fe-B will not do. Here, too, a further reduction of α (B_r) is possible by alloying-in a HRE such as Gd or Er (internal temperature compensation). Some commercial 2-17 magnets also contain Ce, Y, or Nd. It should be mentioned that all currently used 2-17 magnets derive their coercivity from domain-wall pinning by a fine metallurgical precipitate and that the Cu addition is essential for that. Forming the appropriate microstructure requires relatively complicated and prolonged heat treatments which keep the cost of the 2-17 magnets higher than the raw material savings would suggest.

The "2-14-1" Magnets

The possibility of making permanent magnets with the ternary intermetallic compound $Nd_2Fe_{14}B$ as the main phase was first announced in 1983.[19,20] In the years since then this newest type of rare earth permanent magnet has received an unprecedented amount of attention, and as a commercial product it is now experiencing very rapid growth. The reason is economic: Here, finally, was a magnet offering properties largely equivalent and in some respects superior to those of the best Sm-Co magnets; but it has a much broader raw material base, promising fewer restrictions on availability and also a lower magnet cost (per kg and especially per unit of stored magnetic energy), Nd is perhaps ten times more abundant in nature than Sm and the supply of cheap iron is virtually unlimited. $Nd_2Fe_{14}B$ has a slightly higher B_s (16 kG) than even $Sm_2(Co, Fe)_{17}$ and its density, at 7.4 g/cm³, is 12% lower. Even the mechanical properties are somewhat better: it is less brittle and has somewhat greater compressive and tensile strength. It must still be machined by grinding but there is less breakage.

However, Nd-Fe-B magnets also have some serious disadvantages that have so far restricted their applications to near room temperature. The Curie point of the 2-14-1 compound is only about 300°C, making the (negative) temperature coefficient, $\alpha(B_r) \approx -0.15\%/°C$, five times greater than that of 2-17. The H_{ci} drops off even more rapidly on heating, to near zero at 250°; its T.C. at room temperature is $\beta \approx -0.6\%/°C$. This limited the upper use temperature initially to less than 100°. Various alloy modifications — resulting from an intense global research effort — have improved these figures somewhat, but at the price of increasing the alloy complexity and cost. Cobalt was re-introduced to raise the $\underline{T_c}$ (up to 500°C at 25% Co substitution for Fe). and several percent of the HRE dysprosium were found to strongly increase H_{ci} while decreasing |α|. In magnets meant for applications up to 150 - 200°C these Co and Dy substitutions are now combined and small additions of still other elements, such as gallium, are used.[21] These measures increase again both cost and the dependence on scarce materials, thus they are not desirable for large-volume applications.

Still another problem is the strong propensity of Nd-Fe based alloys for atmospheric corrosion; it is several times greater than that of $SmCo_5$. This has caused severe difficulties for manufacturers of disc-drive actuators who began using the insufficiently characterized Nd-Fe-B magnets in large quantities in the last few years. Depending on the amount present of a necessary Nd-rich phase, its microstructural distribution and the average grain size, any exposed surfaces of these magnets corrode and spall more or less rapidly, even at room temperature. Coating with polymers slows the deterioration but cannot completely prevent it. Combining metal plating of the magnets with an epoxy coating can apparently yield satisfactory results, but only if it is done with great care. Magnet manufacturers and users are now still struggling with this problem, The need for corrosion protection also adds to the cost of the finished magnets, and so the "neo-iron" may not be able to live up to early, optimistic predictions of a truly inexpensive rare earth permanent magnet costing a fraction of Sm-Co. However, this does net change the fact that Nd-Fe is magnetically excellent; it is also cheaper and can certainly become much more available than Sm-Co. As a consequence it is now rapidly replacing the latter in many applications where the magnet operates always near room temperature and where ultimate flux stability is not required.

In the laboratory, Nd-Fe-B-based magnets have been made with properties fairly closely approaching the theoretical limit of remanence and energy product; a $(BH)_{max}$ = 50.6 MGOe was reported.[22] Commercial products now have typically 14 to 36 MGOe, with over 40 MGOe offered by at least two manufacturers. B_r values range from 8 to > 13 kG, H_{ci} at 25°C is typically 10-12 kOe for the high-energy sintered magnets and 17-20 for the Dy-modified versions which have somewhat lower B_r and BH_m. The magnetizing behavior is generally similar to that of $SmCo_5$ ("nucleation controlled") and charging requires fields of at least 20 - 25 kOe. Only the fine-grained isotropic magnets made by rapid quenching and hot pressing have much higher coercivity and require double these charging fields, 40-50 kOe.

Manufacturing Methods for Rare Earth Magnets

The alloys for any rare earth permanent magnet type are commercially made by one of two techniques:

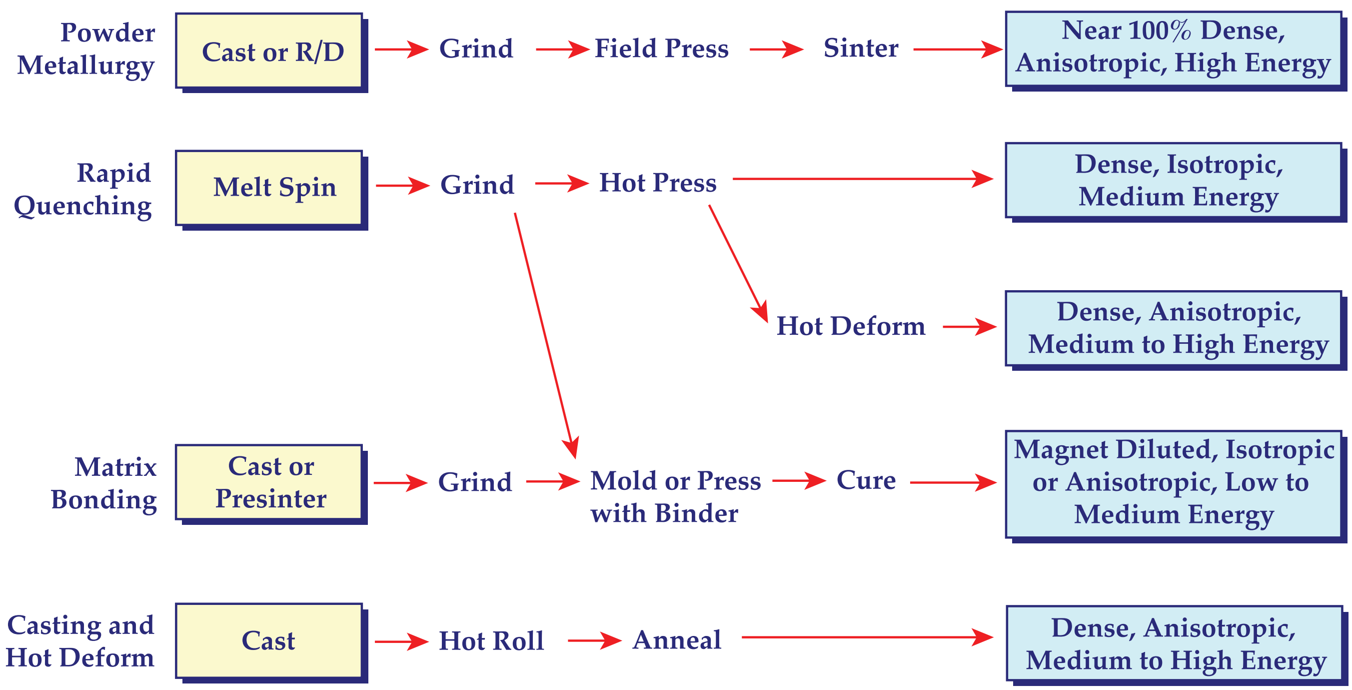
(1) By induction melting the metallic constituents together in a crucible and chill-casting, or

(2) By the method known as reduction-diffusion (R-D) or core duction (KOR).

In the latter, the RE and sometimes a part of the TM are introduced as oxide powders, together with most of the Co or Fe as metal powders; the oxides are reduced with calcium in molten or vapor form, and a spongy alloy powder is formed by simultaneous diffusion.[23,24] This calcio-thermic reduction process was an important factor in lowering the cost of $SmCo_5$ by eliminating several steps; it was later successfully modified for the 2-17 alloys, and recently for Nd-Fe-B and its derivatives. But the latter alloy is much more difficult to handle and there are still considerable problems with the commercial production of NdFe-B by R-D/KOR methods. The alloys are then commonly processed into magnets by powder-metallurgical techniques. They are ground into micron-size particles in several mechanical milling steps; the powder is magnetized and oriented by means of a magnetic field (if anisotropic magnets are desired), compacted in a die or isostatic press, the compacts sintered to near 100% density and heat treated. Cutting or grinding to final shape and remagnetizing complete the production process. This sequence of steps is generally analogous to the one used for ferrite magnets, except that the high chemical reactivity of the RE and alloy powders calls for much greater care and the use of vacuum or an inert atmosphere at most steps. Table 5 schematically outlines this method and three others discussed in the following.

For the Nd-Fe-B a radically different alternative production method[25] was developed by the General Motors Corp., generally known by the GMC brand name, Magnequench (MQ), a term used for the method, the powders, and finished magnets. The first step is modeled after the rapid quenching (R/Q) technique of making amorphous metals in ribbon form. The molten alloy is squirted onto a rotating metal wheel where it solidifies as flakes comprising extremely small crystallites of some 10 nm diameter. This "spin casting" is followed by mechanical milling into platelet-shaped particles which are annealed to a very high-coercivity state.

Table 5 — Basic Processing Methods For Rare-Earth Magnets



These are still finely polycrystalline, magnetically isotropic and cannot be aligned by a magnetic field. They can be processed into isotropic bonded magnets ("MQ-1", see below), or full densification without alignment is achieved by hot pressing ("MQ-2"). An additional hot-deforming step can produce a deformation texture (crystal orientation) which results in a magnetic anisotropy without the help of a magnetic field. Initially, only moderate alignment was achieved by the so-called die-upsetting procedure, but recently improved hot-deformation methods have been developed which now can yield well-oriented magnets with 40 MGOe, essentially equivalent to the best sintered magnets. These "MQ-3" magnets do, however, retain a much finer metallurgical grain that sintered magnets, and as a consequence they are more corrosion resistant and may have better long-term magnetic stability.

As was done earlier with chipped alnico and ferrite powders, it is also possible to make bonded or "matrix" magnets from different rare earth permanent magnet alloys. In these, the binder dilutes the magnetic constituent so that remanence and energy product are significantly reduced. But most of the RE- TM alloys have such high B_r-values that even in diluted form they are superior to most non-RE magnets.[26] Some bonded rare earth permanent magnets have been available since the mid-70s, but they were long ignored by most magnet users. Only in the last few years have bonded rare earth magnets been strongly promoted by several Japanese magnet manufacturers and they are now becoming quite popular. Early versions, based on fine $SmCo_5$ powder in a rigid plastic or a flexible rubber matrix, have been offered with energy products of 3-10 MGOe, but most had a stability problem. When coarser particles are used, particularly of the bulk-hardened 2-17 alloys, much more stable bonded magnets of up to 17 MGOe can be produced.[27] A soft metal matrix instead of a polymer binder also offers improved elevated temperature stability,[28] a method not yet used commercially. Either cast ingots or presintered, oriented blocks are recrushed to produce the powders. Nd-Fe-B presents special difficulties: sintered materials lose much of their coercivity when crushed and the powders are subject to severe corrosion. However, the R/Q-flakes lend themselves to making fairly stable, isotropic epoxy-matrix magnets (MQ-1 and similar products), also with 3-10 MGOe. And the hot pressed and die-upset "MQ-3," being very fine-grained and oriented, can be successfully crushed, field-pressed, and rebonded into matrix magnets. BH_m > 20 MGOe has been achieved in laboratory samples. Such anisotropic bonded Nd-Fe-B magnets are now beginning to be marketed, but little is known as yet about their stability and cost.

Finally, recent papers from Japan[29][30] announced yet another processing method, initially applicable only to the praseodymium equivalent of Nd-Fe-B. A cast ingot of an alloy based on $Pr_2Fe_{14}B$ can be given a favorable crystal texture — and hence magnetic anisotropy — by hot deformation, particularly hot rolling. This process avoids powdering and compaction altogether. It is now in development as a commercial process and could become an economical magnet production method for the alloys and simple magnet shapes to which it proves applicable.

e. Rare Earth Permanent Magnet Raw Materials and Economic Considerations

Let us first quantify somewhat better the chemical makeup of the different rare earth permanent magnet alloys discussed. Figure 7 shows the approximate compositions of several important magnet types. They all contain a large weight fraction of one or more rare earth elements.

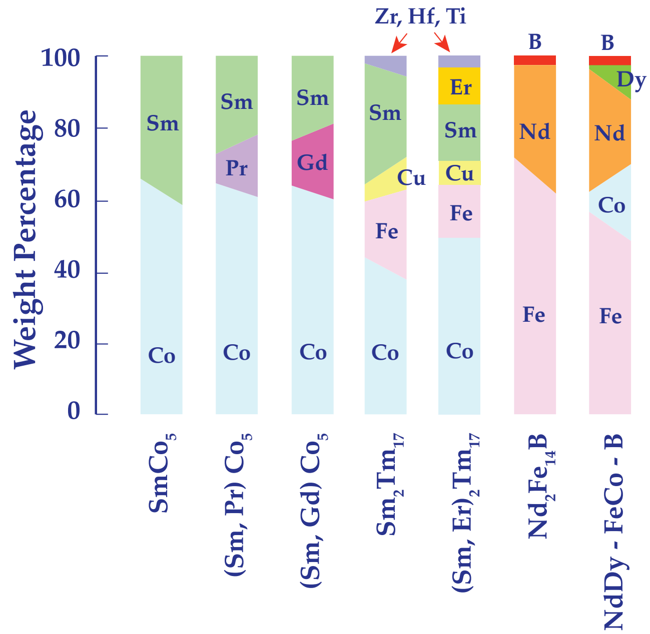


Figure 7 — Typical compositions of commercially available REPM (c. 1989).

In view of the growing commercial importance of the rare earth permanent magnet and the anticipated growth of the market, particularly for Nd-Fe-B, it seems appropriate to take a closer look at the rare earth supply situation. The "rare earths," despite their unfortunate traditional name, are indeed metals, and they are not particularly rare. They are, however, always thoroughly intermixed with each other in the ore bodies, and it is expensive to separate them and to reduce them to the metallic state. The most common minerals now mined, bastnaesite and monazite, yield mostly the "light" rare earths (LRE), in the approximate proportions 45-55% Ce, 25-30% La, 12-20% Nd and ~5% Pr; Sm is 0.5-3% depending on the ore source. There are other, less common ores that yield primarily Y and the HRE, including Gd, Dy, and Er. The total abundance of the LRE is estimated to be more than that of copper; Ce is comparable to tin, Nd to Co and Sm to Be. These are all metals that are not very common, yet they have found extensive technological uses. There is only slightly less Gd and Dy in nature than Sm. Thus, an ample overall rare earth supply seems assured. Ore bodies are widely distributed, but with about 80% of the known global reserves located in China! The US share is about 10%, much of it developed and actively mined.

While the natural abundance would be adequate for any of the rare earths needed by the magnet industry, there are indeed limitations for the quantities of Sm, Nd, etc., which can be produced at reasonable cost. The problem is that we are now using for permanent magnet production only a small portion of the spectrum of all the rare earth that must be extracted from the ores together and must then be largely separated. If the dominant elements, Ce, La, Nd, and Y cannot be sold in adequate quantities, the materials that are used must bear the total cost burden and would become unreasonably expensive. Alas, all markets for the different rare earths are thus coupled, and the total rare earth market grows only very slowly. Several years ago the point was reached where the magnet industry now uses virtually all Sm available as a byproduct, and as a consequence, the Sm price kept climbing and the Sm-Co magnet production can increase only incrementally now. The supply situation for Nd is clearly better, but only by a factor five to ten. From this we must draw several conclusions: Any larger-scale new REPM uses should be based on Nd-Fe where possible to reduce the pressure on SmCo and preserve Sm for those applications where it is absolutely needed. Similarly, Dy-substituted Nd-Fe-B should only be used where the higher temperature stability is required. Development efforts should continue to try and broaden the range of LRE used in magnet alloys, especially Ce, La, or better yet, mischmetal. And neither Sm nor Nd should be squandered by the extensive use of isotropic magnets.

A few more words regarding the last recommendation: The initial R/Q versions of Nd-Fe-B in bonded and hot pressed form were isotropic, and yet they were considered for large-quantity applications in automobiles. While isotropic magnets may sometimes offer a design convenience, they make very inefficient use of the alloy. The isotropic magnet has only 1/2 the remanence and 1/4 the energy product of a perfectly aligned one. So one can argue that its use requires four times the really necessary magnet weight for the same device function. Aside from the added expense, this amounts to throwing away most of the supply advantage that Nd has over Sm, and an extensive use of isotropic Nd-Fe-B could soon lead to a neodymium shortage.

D. Summary and Comparison of Permanent Magnet Material Properties

Having discussed many individual magnet types in some detail, we shall now compare their salient magnetic properties in a series of summary graphs. Again, the emphasis will be on the newest types, the rare earth permanent magnet, but we shall also put them in perspective relative to all commercial magnets.

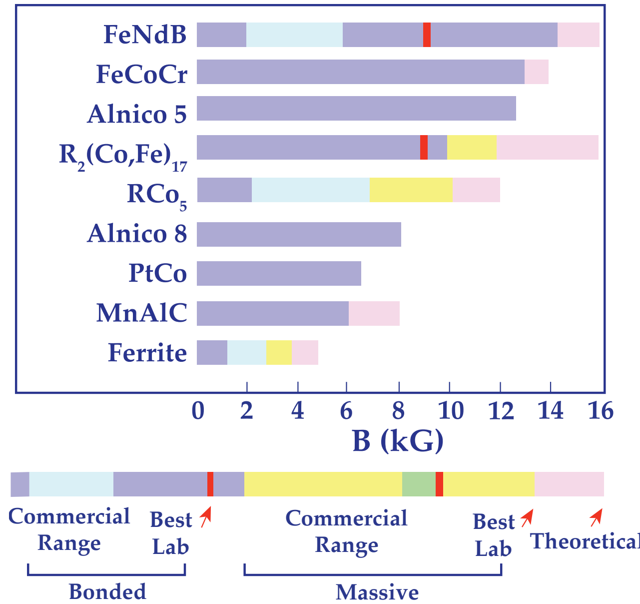


Figure 8a — Remanence of commercial magnet materials. (Arranged in order of decreasing remanence.)

Figure 8 shows remanence and static energy products for representative members of different commercial magnet families. The materials are arranged in descending order of their B_r values. Theoretical maxima "potential," shown in dashed lines where meaningful, are based on reported room temperature saturation magnetization values of the main intermetallic or oxide phases. The different marks and shadings of the bars indicate production property ranges and laboratory record values as explained in the key bar.

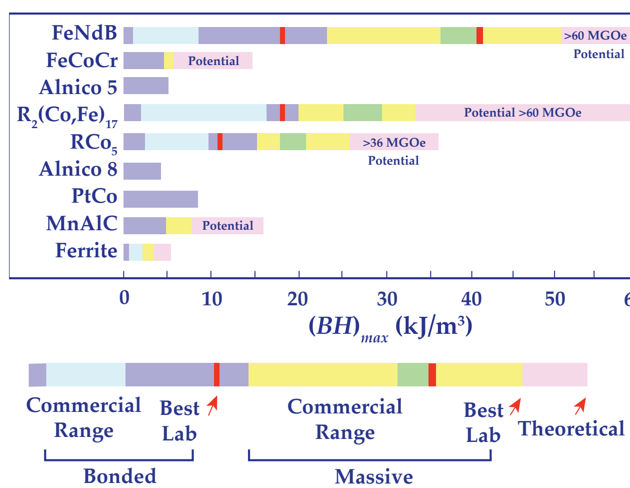


Figure 8b — Energy product of commercial magnet materials. (Arranged in order of decreasing remanence.)

Figure 9 is a similar bar graph detailing the energy product ranges now available from different subtypes of the rare-earth magnets.

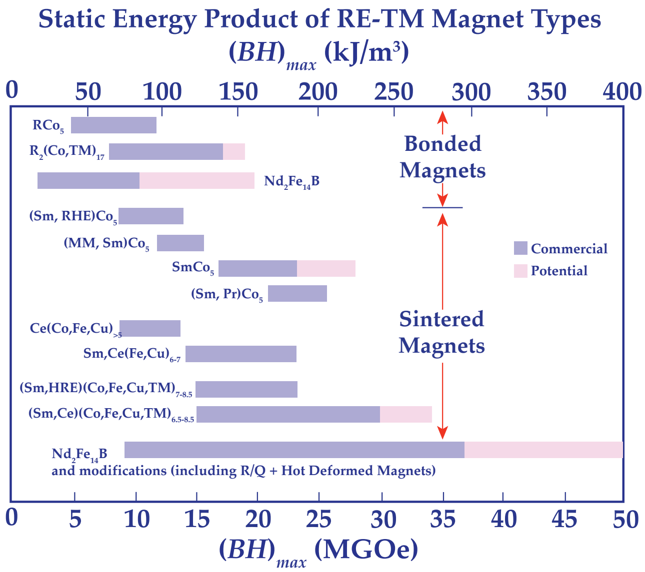


Figure 9 — Energy products available from different rare-earth magnet types in production in 1989.

Examples of the reversible behavior of the useful flux at elevated temperatures are given in Figure 10 for representative rare earth permanent magnets up to their respective limits of utility. As mentioned before, this temperature dependence can be reduced by judicious HRE alloying additions.

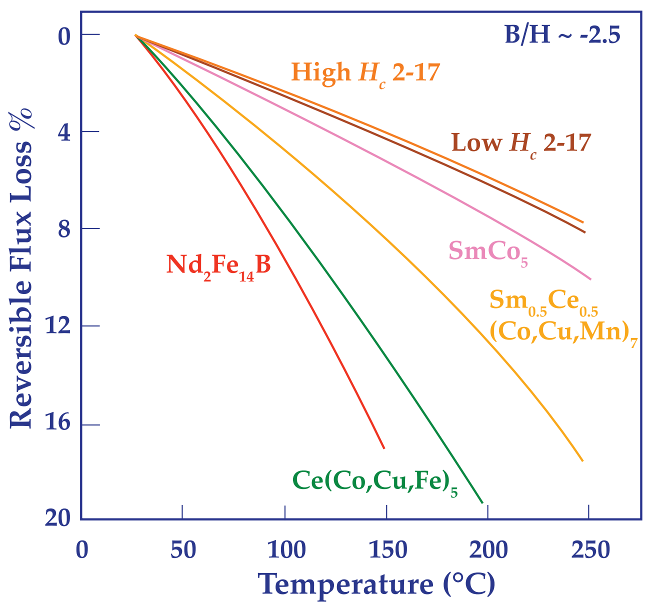


Figure 10 — Reversible flux versus temperature plots for several Rare Earth Permanent Magnet materials. (Measured in open circuit at B/H ≈ -2.5 after thermal pre-stabilization. D. Li *et al.*, 1988.)

Figure 11 illustrates the principle of this internal temperature compensation which is unique to the rare earth permanent magnet.

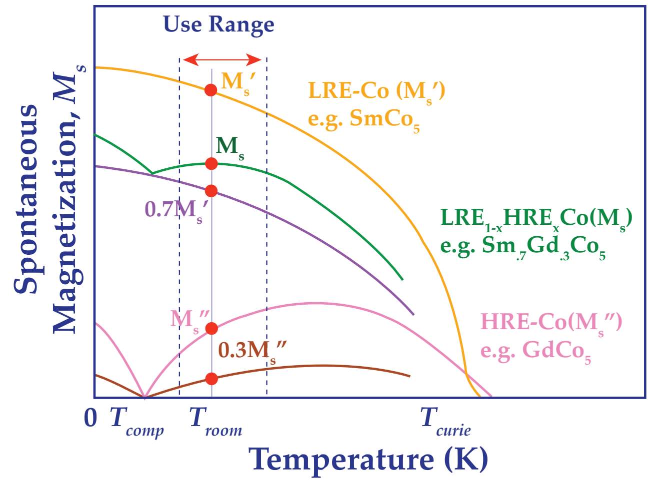


Figure 11 — The principle of temperature compensation by heavy RE additions

One plays out the strong positive temperature coefficient of the spontaneous magnetization of a (ferrimagnetic) HRE-TM metal alloy (e.g., Gd-Co) above its compensation point against the smaller negative T.C. of a ferromagnetic LRE-TM compound such as Sm-Co. It is possible to achieve a near-zero or other low T.C. for the remanence of the magnet around room temperature or in another desired operating temperature range.

The variety of coercivity mechanisms active in different rare earth permanent magnets is reflected in the different shapes of the initial magnetization curves shown in Figure 12. The behavior type A is typical of sintered $SmCo_5$ and Nd-Fe-B: these are fairly easy to magnetize to saturation from the thermally demagnetized state, although full development of their second quadrant curve demands 15-20 kOe; however, once they have been magnetized and then field-demagnetized, re-saturating requires much higher fields yet. (Not shown in Figure 12.)

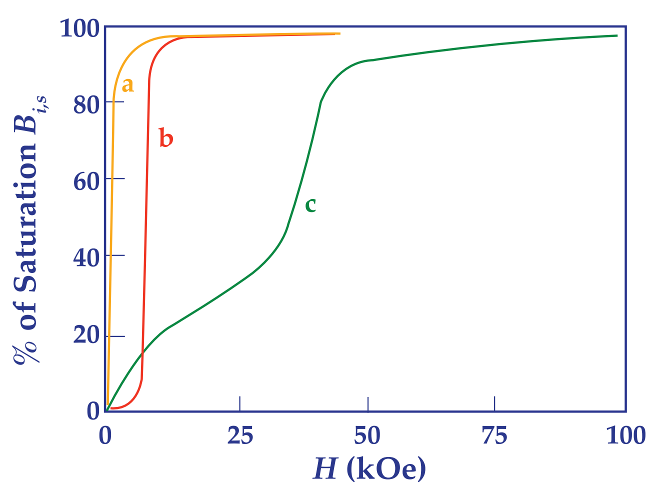


Figure 12 — Typical initial magnetization curves for different REPM types: (a) Sintered $SmCo_5$, Nd-Fe-B and derivatives ("nucleation controlled" = domain walls pinned at grain

boundaries only.) (b) Bulk hardened magnets like Sm(Co, Cu)$_5$ or the low-H_c 2-17 magnets ("pinning controlled" by homogeneous precipitate) (c) High coercivity 2-17 and R/Q type Nd-Fe-B magnets (pinning controlled, with very non-uniform pin strength) (After W. Ervens in [B-22].)

The precipitation hardened, Cu-containing 1-5 and low coercivity 2-17 magnets exhibit behavior type B: fully charging them requires only 10-12 kOe, about 1.5 to 2 times their modest H_{ci} values, independent of the magnetic history. The very high-coercivity 2-17 magnets and the Nd-FeB prepared by the R/Q-route show behavior type C: these magnets typically require extremely high charging fields in the 40 to 50 kOe range under all circumstances.

Finally we shall return to the topic of bonded magnets once more. While these magnets are inferior to their fully dense parent permanent magnets in terms of B_r, energy density, demagnetization curve shape, and stability, they offer very important economic advantages in manufacture and handling. It is possible to mold them to their final shape with close dimensional tolerances by die pressing or such cheap methods as injection molding, extrusion, or calendering.

In mass production this brings significant savings of processing costs, and since there is virtually no waste in the form of cutting scrap or grinding swart, it also helps conserve supply-limited magnet alloys. Smaller or more delicate, as well as larger parts can be made than are producible by casting or sintering. It is also possible to produce, in a single molding operation, whole subassemblies incorporating iron or nonmagnetic structural parts. If machining should be required, it can often be done with a drill or lathe using hard-faced tool bits. Plastic or soft-metal matrix magnets are also much easier to handle so that there is less danger of breakage or injury in device assembly. For all these reasons, bonded ferrites are already, and bonded rare earth permanent magnets are expected to become, a significant portion of total magnet production. Figure 13 summarizes the types of matrix magnets now commercially available and compares their properties in terms of the ranges in which their *B,H*-demagnetization curves fall. (For reference, the figure still includes the ESD (Lodex) magnets although their production was recently discontinued.)

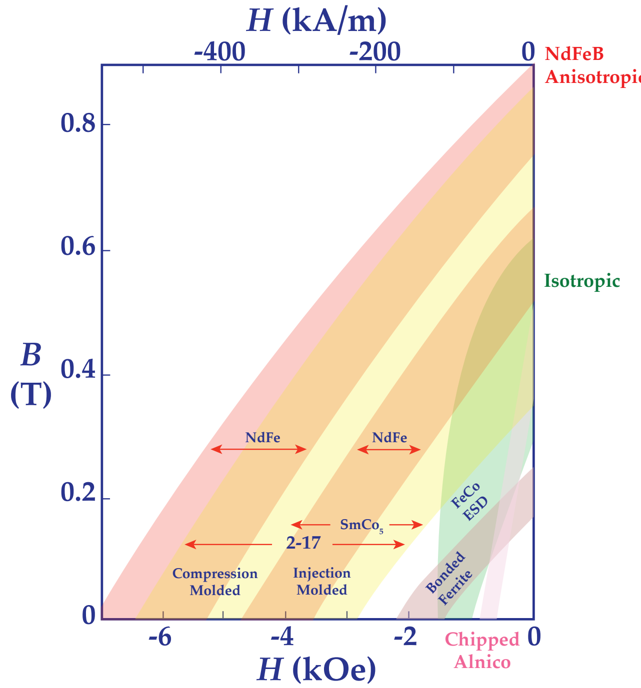


Figure 13 — Comparison of the second-quadrant demagnetization curves of polymer-bonded magnets in or near commercial production (1989).

3. Applications of Permanent Magnets

A. General Survey of Permanent Magnet Application Areas

As was mentioned in the introduction, magnets are used in many different areas of human activity and for many different functions. Any enumeration of these uses must be incomplete and any classification of permanent magnet devices somewhat arbitrary. Having said this, I shall nevertheless attempt now to list most applications, technological and otherwise, grouping them as much as possible by the physical principle utilized and giving a number of specific examples for each generic device class.

1. Electro-Mechanical Machines and Devices

a) Electric Motors

Types-DC (commutator and brush less), synchronous, induction start/synchronous run, hysteresis; rotary and linear; continuous, servo, torque, or stepping operation.

Geometries — permanent magnet stator (conventional and iron less armatures), permanent magnet rotor; inner or outer rotor; radial or axial field (disc) motors.

b) Generators

Types — Magnetos, ignition or other pulse generators, tachometers, auxiliary exciters, alternators, multiphase synchronous machines, homopolar DC machines.

Geometries-permanent magnet rotor; radial or axial field; stator winding with or without iron.

c) Electro-Mechanical Actuators

Linear — Force motors for valves, etc.; printer hammer mechanisms; computer disc-drive head actuators (VCM); laser focusing and tracking (optic/magneto-optic recording: audio CDs, video, data); recorder pen positioners. Rotary-Disc drive VCMs; aircraft control-surface actuators; materials handling robots.

d) Measuring Instruments

Moving-coil (d'Arsonval and long scale geometries) and moving-magnet meters for many functions.

e) Electric Current Control

Circuit breakers, reed switches, miniature biased relays, thermostats, automotive ignition, eddy. current motor overspeed switch, arc blow-out magnets.

2. Acoustic Transducers

a) Sound Generators:

Loudspeakers, earphones, telephone receivers, ringers, buzzers, ultrasonic generators.

b) Sound Receivers:

Dynamic microphones, ultrasound pickups.

c) Other Audio Frequency Transducers

Phonograph pickups.

3. Mechanical Force and Torque Applications

a) Contact Holding and Lifting

Machine-tool chucks, grippers, load-lifting magnets (electrically switchable), tool holders, door catches, refrigerator seals, advertising signs, toys, and many more.

b) Traction Devices

Conveyers, separators for ores and other materials, field-gradient water purifiers, photocopier rollers.

c) Couplings and Brakes

Synchronous torque couplings, linear followers, eddy current and hysteresis couplers and brakes, rotary-to-linear motion converter.

d) Magnetic Bearings and Suspensions

Passive-watt-hour meters, ultra-centrifuges, record player tone-arm support, textile spinning turbines. Partly active servoed systems-gyros, satellite momentum and energy wheels, laser beam scanner, turbo-molecular pumps, electro-magnetic tracked vehicle levitation.

e) Electro-Balances

Modern weighing devices from analytical balances to supermarket scales and truck weigh stations.

4. Microwave/MM-Wave Devices, Electron Ion Beam Control

a) Power Tubes:

Magnetrons (radar, kitchen ovens); PPM focusing for TWTs and klystrons; crossed-field amplifiers, gyrotrons, etc.

b) Waveguide Devices:

Biasing ferrite or YIG elements in resonance filters, switches, and isolators.

c) Particle Accelerators, Synchrotron Radiation Sources. free Electron Lasers

Lenses, deflecting magnets, wigglers, undulators.

d) Mass Spectrometers:

Deflecting magnets

e) Cathode Ray Tubes:

Ion trap, focusing, pin-cushion correction

5. Sensors, Electric Signal Transducers

a) Transducers Using Permanent Magnetss

Inductive, Hall effect, magnetoresistive, temperature sensitive elements.

b) Quantities Measured

Position, velocity, acceleration, fluid and heat flow, pressure, vibration, temperature, etc.

c) Use Areas

Automotive, industrial, aerospace, computer peripherals (keyboards, read/write head sensors), office equipment.

6. Medical Electronics and Bioengineering

a) NMR Imaging Devices:

DC field source for MRI tomographs

b) Mechanical Prostheses:

Eyelid muscle assist, dental prostheses, stoma seals, valves, heart-assist pumps, artificial limbs.

c) Surgical Clamps:

For incisions and severed blood vessels.

d) Diagnostic Aids:

Catheters; sensors/transducers.

e) Miniature Hearing Aids:

External devices and implants.

7. Miscellaneous Applications

a) Magnetic Locks

Key and cylinder with encoded magnets

b) Magnetic Jewelry

Necklaces, clasps, earrings

c) Electronic Choke

Steady bias field for core

d) Magnetic Bubble Memory

Bias field for bubble element

e) Vacuum Technology

ton getter pumps, vacuum gauges.

B. Comments on the Design with Permanent Magnets

Due to the nonlinear, hysteretic and widely varying behavior of magnetic materials the mathematical modeling of magnetic components is generally difficult. Magnetization curves and magnetic flux patterns can seldom be accurately described by algebraic equations. The concepts of "magnetic circuit" and "demagnetizing factor" work well only for the simplest situations. In most cases they yield very incorrect results unless they are heavily modified with experience factors, and extensive prototype building and testing are often necessary. This is especially true for permanent magnet circuits containing the older, low-H_c magnets such as Alnico in combination with iron parts for flux conduction. [B-6, Chapter 6, or B-7, Chapter 4]. For these reasons, the design of permanent magnet circuits containing the older, low-H_c magnet based devices has traditionally been a "black art" largely perpetuated within companies for their products,

In recent years the situation has been dramatically improved, at least in principle. Mathematical methods are now available which allow the numerical solution of Maxwell's equations, notably the finite element analysis (FEA) and finite difference methods. They rely heavily on the great speed and memory capacity of modern digital computers. If one can adequately describe the properties of the magnetic materials used, and if a reasonable geometry is specified for the magnetic assembly, it is possible to get quite accurate results for field values, flux distribution, mechanical forces, etc. The program cannot invent a new and better basic device — that still has to come from the engineer's intuition and experience — but one can use it effectively to optimize a given design, compare several alternative design concepts, and explore the effects of choosing different materials, The one great disadvantage of this new analytical approach is its high cost. It is, however, often used when mass production is contemplated, or to shorten product development time when otherwise several prototype stages would be required. In the design of electric motors and other machines, FEA is extensively applied and appears to be a valuable analytical aid.[31]

When the use of an expensive magnet material such as Sm-Co is considered, careful design optimization becomes very important — to use the permanent magnet material most efficiently; to compare device cost, bulk and performance for alternative magnet choices; to weigh the effects of properties deviating from specifications; to minimize device size, operating expenses, etc. In this case the use of costly mathematical analysis can be justified. However, it is also often not really necessary, thanks to the unique properties of many modern magnet materials which facilitate a simple circuit analysis, We shall briefly discuss this now with reference to typical rare earth permanent magnet properties, although some of the arguments given apply equally to high-H_c square-loop (but low-B_r) ferrites.

Good Sm-Co and Nd-Fe-B magnets combine the following features:

(1) A high saturation (hence high remanence and useful flux density)

(2) High intrinsic coercivity-they strongly resist demagnetization

(3) A very "square" M versus H loop shape, often without a knee in the second quadrant. (High H_k, straight-line B versus H, $\mu_r \approx 1$.)

(4) A spatially very rigid magnetization vector. (Due to the large anisotropy field, which is especially high for $SmCo_5$)

This has several remarkable and pleasant consequences for the device designer: The magnets can be considered "magnetic batteries" with a high and fixed MMF; as long as the combined applied and self-demagnetizing fields do not exceed the knee field, H_k, the MMF is almost field independent. They can also generally be placed right at or near the air gap where the flux is needed, thus minimizing stray flux. This means that a simple circuit analysis method based on the Ohm's law analog works well.[32] The magnets can be used in short and sometimes strange shapes while keeping their uniform magnetization. Fairly high external magnetic fields, perhaps produced by coils wound right over the permanent magnet, can be superimposed to change or modulate the gap field without changing the magnetic moment of the permanent magnet. More generally, several rare earth permanent magnet and current-carrying coils may be put in close proximity; their fields will simply add up vectorially without significantly affecting other members of the array, again allowing a simple theoretical description.[33]

But these unique properties of the rare earth permanent magnet have not only simplified design and circuit analysis; more importantly, their thoughtful and aggressive exploitation has brought forth many novel magnet structures that were impractical or impossible before the advent of the REPM. They include several classes of ingenious multipolar devices pioneered by Klaus Halbach who designed wigglers, undulators, and multipole lenses for synchrotron light sources with Sm-Co magnets.[34] (See cover story in Physics Today, June 1983.) These can be pure permanent magnet structures or hybrids employing some iron parts.

Herbert Leupold and coworkers used similar ideas to create a large variety of novel static magnetic field sources for TWT tube-focusing, other ion-beam devices, and MRI magnets[35] They also make extensive use of a "cladding" concept in which high-H_c permanent magnets are placed over the field-source magnets with perpendicular moment orientation in such a way that an equipotential surface is created over the entire surface of the magnetic circuit. This suppresses all stray flux and confines the magnetic field to the volume in which it is needed.

Partial-circle multipolar rare earth permanent magnet structures have been applied to magnetic ore separators by M. and N. Marinescu.[36] Extremely uniform high transverse fields can also be achieved in cylindrical and square cavities with flux confinement, for possible application in medical NMR magnets.[37,38] The papers referenced here also illustrate the modern analytical methods used for permanent magnet device design.

For calculating the fields produced by freestanding magnets and the forces between them, the uniformly and rigidly magnetized ferrites and rare earth permanent magnets can often be modeled either as pairs of charge sheets located at the end faces, or as uniform surface current sheets on the circumference. This is a particularly fruitful mathematical approach in the design of magnetic torque couplers[39] or passive magnetic bearings.[40,41] In these cases, closed-form analytical solutions can also often be formulated, although a numerical execution of the integrals is usually required.

Finally, a general warning for the user of the new magnet materials seems in order: The rare earth permanent magnet in particular have indeed wonderful properties. But the magnet manufacturer will often speak only about the advantages and let the user discover drawbacks for himself. Also, the advertised properties are often the best that have been achieved in the laboratory, and samples provided initially may be from a small and carefully controlled pilot line. The materials are quite expensive, so the temptation is great to design for the advertised best performance. But the average properties in later mass production are invariably poorer; nor can very close property tolerances be maintained at reasonable cost.

The application engineer is therefore well advised not to use the best values listed in the manufacturers' literature for design calculations. It can also be dangerous to base critical devices on the newest magnet material offered without insisting on detailed and reliable test results for the effects of the pertinent environmental parameters. (Temperature coefficients, flux losses on heating and cooling, long-term stability, corrosion resistance, radiation effects, etc., may be important.)

There have been two strongly negative episodes in the history of the rare-earth magnets attributable to mistakes in this respect-one with the instability of early plastic-matrix $SmCo_5$ in the mid-1970s, the other recently with the corrosion problems of Nd-Fe-B in disc-drive actuators. Such problems will generally be overcome with time, or the limitations of a material will be fully known and can be taken into account; but caution and extensive testing is initially advised.

C. Some Selected Applications of Modern Magnets

In this section we discuss several applications of magnets in electro-technology in a little more detail. The selection is rather arbitrary, but all examples involve the use of ferrites, Sm-Co or Nd-Fe-B. They are either in areas that are now economically important (e.g., electric motors, computer peripherals) or may become so in the near future (magnetic imaging systems, maglev vehicles), or they are chosen for their novelty. Some illustrate how the unique properties of the rare earth permanent magnet can be imaginatively used. In any case, these examples are intended more to titillate the reader's mind than to systematically educate. The figures show primarily the magnetic circuits and the location of the permanent magnet. Brief descriptions of the devices also emphasize the function of the magnets in them. The order of presentation approximately follows the preceding survey.

Electric Motors

Many types of motors can use permanent magnets [B-2, p. 279 ff]. Permanent magnet-excited, brush-type DC motors with the magnet in the external stator are still the most used. Many million units are produced annually, particularly for automotive applications. In cars they operate auxiliary devices like windshield wipers, blowers, cooling fans; window, seat, mirror and roof actuators; fuel and windshield washer pumps. Increasingly, starter motors also use magnets. For economic reasons, the permanent magnet material in most small motors is sintered ferrite, although bonded rare earth permanent magnet are of increasing importance. When the smallest possible weight and volume are desired, as in aerospace applications, dense Sm-Co and Nd-Fe-B are also used. Figure 14 shows how the replacement of the wound-field stator by Alnico, then the switch to anisotropic ferrite, and finally the use of an rare earth permanent magnet influence the stator geometry and relative size of functionally comparable motors, here using the same wound rotor.[42]

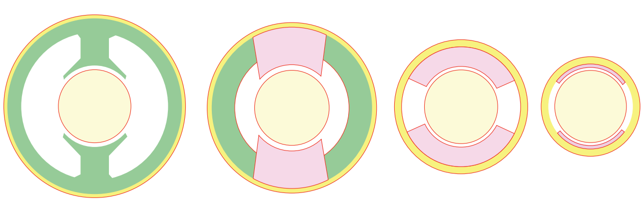


Figure 14 — Evolution of stator magnet geometry in small DC motors. (Based on 2-pole motors of comparable power using identical wound rotors.)

An increasingly important small motor type are the stepping motors. They permit precise incremental position or speed adjustment with electric pulses from digital controllers, They have many applications (in watches and clocks, timer switches, cameras, for flight control, etc.), but the largest numbers are now used in computer peripherals[43] (floppy-disc head positioners, paper and ribbon advance, daisy-wheel rotation in printers), typewriters, and office machines of all kinds. Modern step motors use mostly permanent magnet rotors, either of a hybrid type (permanent magnet plus toothed iron wheels) or pure permanent magnet construction, with ferrites or rare earth permanent magnet. Figure 15 shows two examples of the latter:[31]

(a) This motor has a simple, diametrically magnetized 2-pole rotor that moves 180° with each pulse; the asymmetric airgap determines the sense of rotation. Such steppers drive most quartz-controlled dial type wrist watches; they must be extremely small and use rare earth permanent magnets.

(b) This motor also has a pure permanent magnet rotor comprising a disc of high-H_c $SmCo_5$ axially magnetized through the thickness with up to 100 poles on the circumference; this allows step angles down to 1.8° in two-phase operation, with high torques and very low inertia.[44]

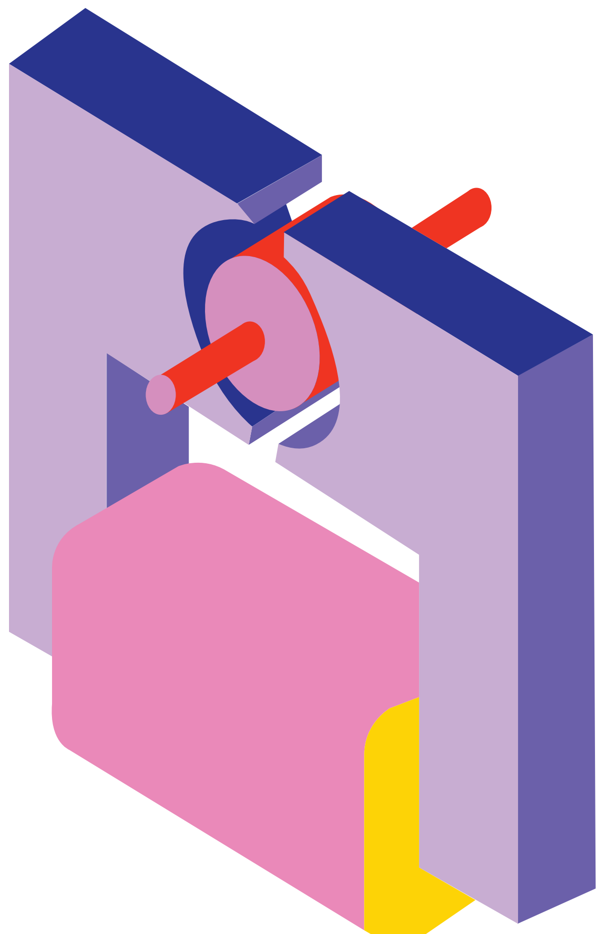


Figure 15a — Pure permanent magnet stepping motor geometry — Asymmetric airgap, 2-pole cylinder permanent magnet rotor, diametrically magnetized, 180° step angle.

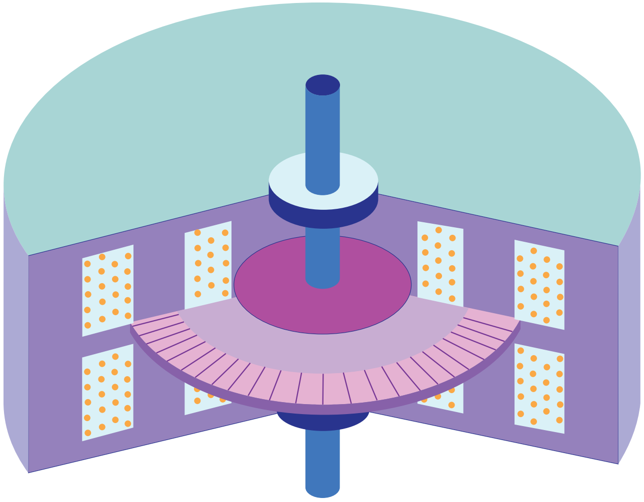


Figure 15b — Pure permanent magnet stepping motor geometry — Axially magnetized rare earth permanent magnet disc rotor, down to 1.8° step angle.

Limited-Travel Actuators

We shall discuss two examples of computer peripheral devices presently in very wide use. Figure 16 shows the arrangement of magnets and moving coil for one of several basic types of head positioners used in winchester disc drives.[45] Here, a set of four Sm-Co magnets in an iron flux-closure frame sets up the steady field with which the current in the flat, self-supporting coil of low inertia can interact to produce a rotary motion through a limited angle. Disc-drive actuators are built with alnico, ferrite, and rare-earth magnets, with accordingly varying geometries. The use of rare earth permanent magnets assures minimum weight, high torque, and short access time, so that many disc-drive manufacturers switched rapidly to Nd-Fe-B when it became available.

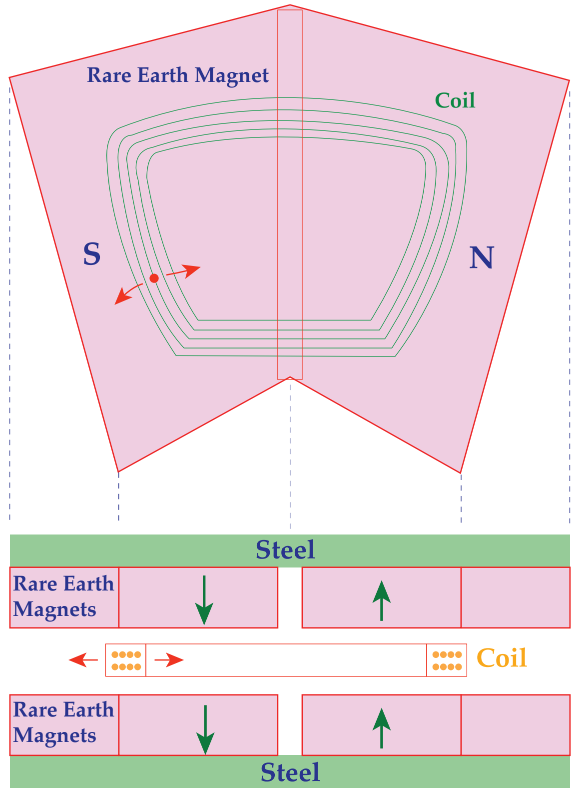


Figure 16 — Rotary actuator with moving coil for disc-drive head positioner.

The second example is the hammer mechanism of a dot matrix printer. Figure 17 shows the design of an individual drive unit for a print wire, one of 24 in a Kanji character print head from Toshiba.[46] This is a pulse-operated, short stroke linear actuator. The steady flux from the permanent magnet (here again $SmCo_5$) holds back the armature and tensions the leaf spring. A current pulse through the coil temporarily displaces the flux from the core, releasing the armature to push the wire forward under the spring force. The hammer completes one cycle in ~400 µsec, at a 0.3 mm stroke. Again, similar print mechanisms are built in many different designs, employing Alnico, ferrite, and rare earth magnets. Fast mechanical line printers for alphanumeric type or hybrid (dot-composed line) printing also make extensive use of permanent magnets.

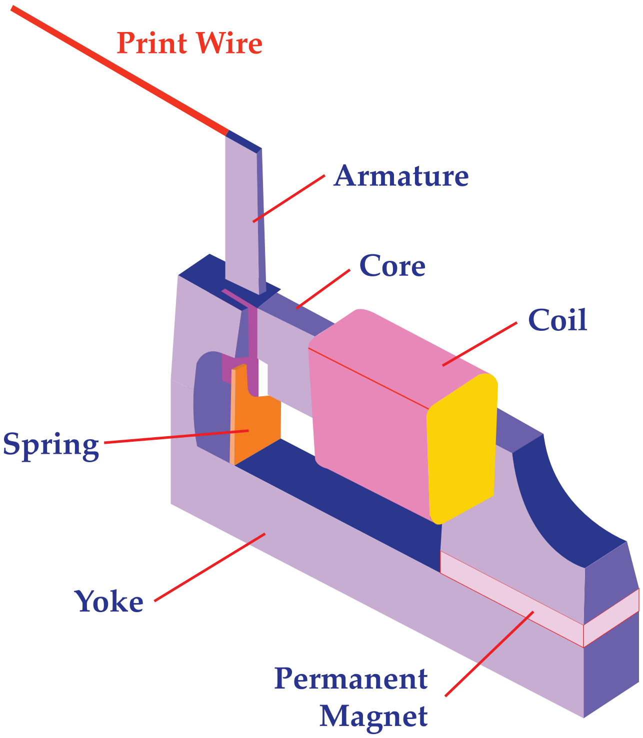


Figure 17 — Hammer mechanism for a dot-matrix printer.[46]

Microwave Power Tubes

Many kinds of microwave and mm-wave generators or amplifiers need a steady magnetic field. (The "magnetron" is named after its prominent magnet!) We shall consider the traveling wave tube (TWT) in which an extended axial "focusing" field is needed to keep electrons traveling in a narrow, pencil-like beam over the considerable length of the tube.[47] The original focusing method was to generate a uniform axial field with a solenoidal electromagnet. (Figure 18a.)

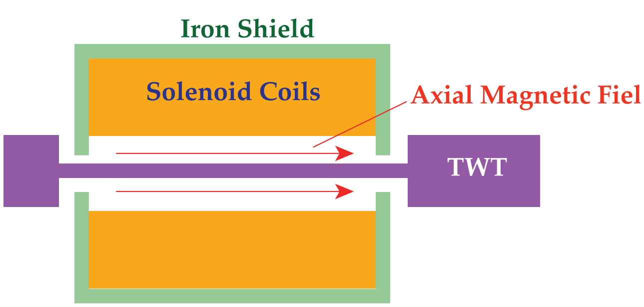


Figure 18a — Traveling wave tube with focusing solenoid that requires power source and cooling.[47]

Not only is this coil bulky and heavy — much bigger than the tube itself — but it requires a power supply, consumes energy, and usually has to be cooled. The coil can be replaced by a single Alnico magnet (Figure 18b) which is similarly bulky but no longer consumes power.

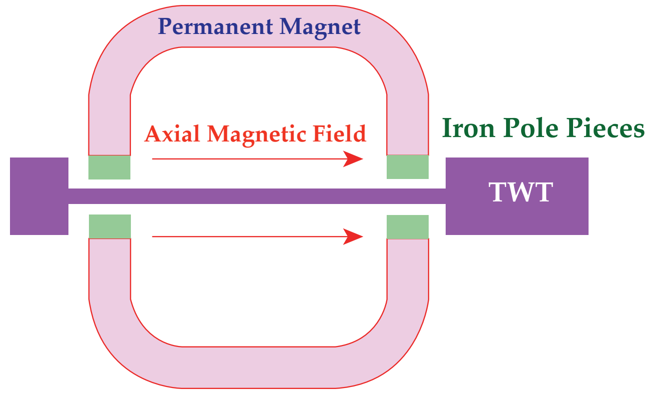


Figure 18b — Traveling wave tube with uniform axial field from permanent magnet.

But then it was discovered that the field need not even be uniform; it may vary in a periodic fashion along the beam axis as long as it is essentially axially oriented over the beam volume. This can be achieved with a periodic permanent magnet (PPM) structure of which an example is shown in Figure 18c.

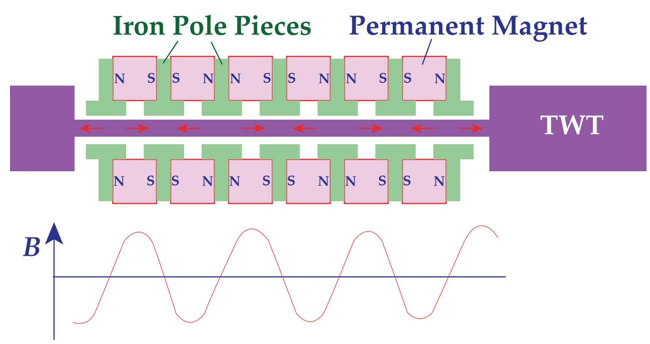


Figure 18c — Modern traveling wave tube with periodic permanent magnet focusing.

While PPM structures have been built with Alnicos and ferrites, they become very compact and light with the rare earth permanent magnet. In this application, good stability at elevated temperature and a small reversible temperature coefficient are often desired. This favors Sm-Co based magnets that can also be internally temperature compensated, and argues against the use of Nd-Fe-B or ferrite.

Some newer millimeter-wave devices require linearly varying axial magnetic fields. These can be achieved with rare earth permanent magnet structures like those shown in Figure 19.[35]

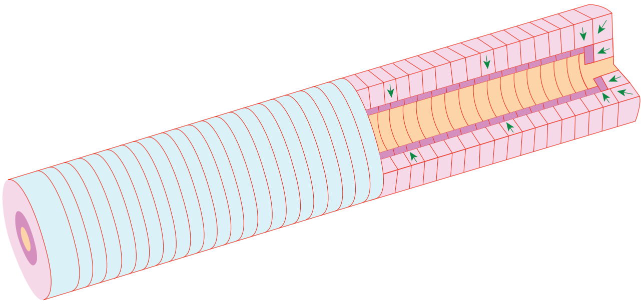


Figure 19a — Pure permanent magnet structures for linearly varying axial field source.[35] Parametric structure (magnet properties vary).

Here the properties of the permanent magnet rings must also vary along the tube axis. The use of cladding with a judiciously designed second shell of radially magnetized magnets confines the flux to the interior cylindrical volume. In this outer shell, each magnet must have a different remanence (but a straight demagnetization line), shown as Figure 19a, or a different diameter as in Figure 19b. The simpler case, Figure 19a is readily achievable with bonded Sm-Co magnets.[48]

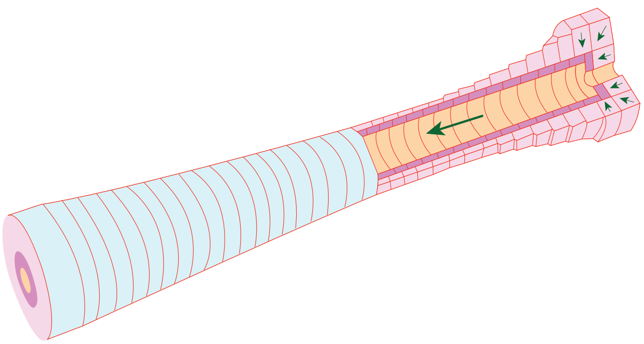


Figure 19b — Pure permanent magnet structures for linearly varying axial field source. Geometric structure (magnet diameter varies). Cladding magnets confine field to inner working space.

Beam Insertion Devices for Particle Accelerators

Figure 20 shows the principle of the "insertion" devices called undulators and wigglers, and below, three of the many possible geometries of permanent magnet structures that can be used in these.

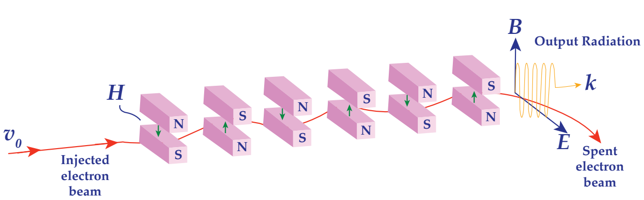


Figure 20a — Beam insertion devices for generating synchrotron radiation. Principle of beam interaction with magnetic field.

When a relativistic electron or ion beam is forced into a snake-like path by means of a spatially periodic magnetic field, it emits a very intense, focused beam of gamma radiation.

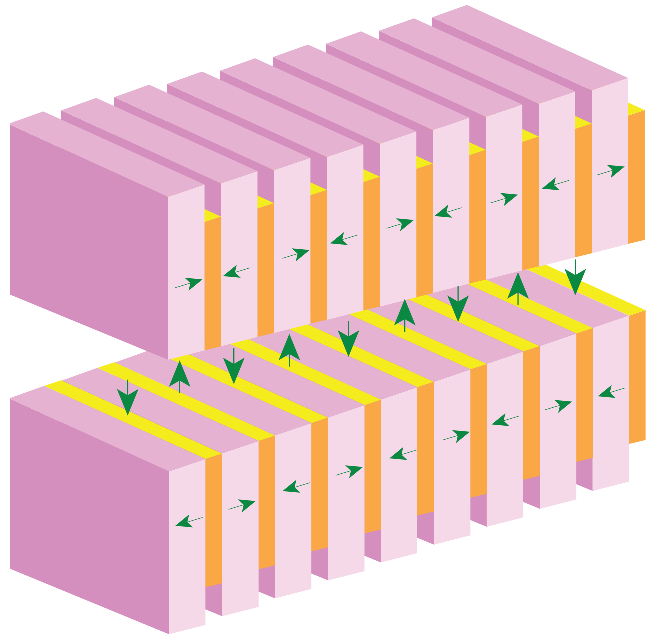


Figure 20b — Beam insertion devices for generating synchrotron radiation. Hybrid wiggler structure with axially oriented magnets (fine arrows) and iron pole pieces to produce B_y (fat arrows).

Such "synchrotron light sources" and related "free electron lasers" are now by far the most powerful generators of x-rays and ultraviolet radiation. Insertion devices have been built at all large accelerator facilities, initially using conventional or superconducting electromagnets.

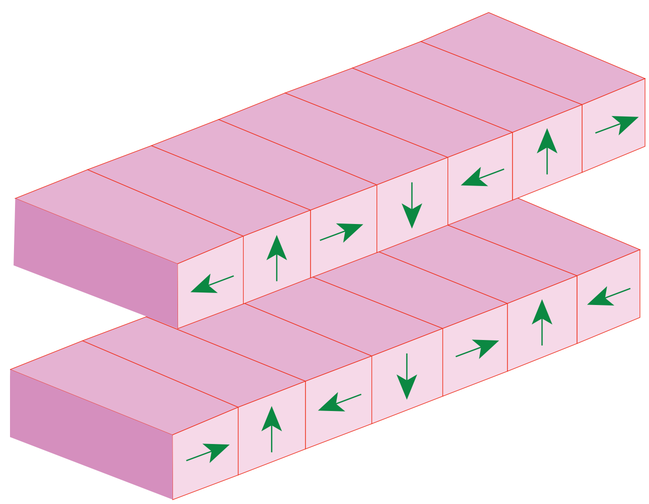


Figure 20c — Beam insertion devices for generating synchrotron radiation. Pure REPM structure with 90% magnet angle.

Since Halbach[34] showed that permanent magnets, specifically the rare earth permanent magnet, have great advantages over electromagnets, many permanent magnet-based variations of such devices have been constructed; some are pure Sm-Co structures, others incorporate iron parts, and still others use additional current-carrying coils for field enhancement and tuning.

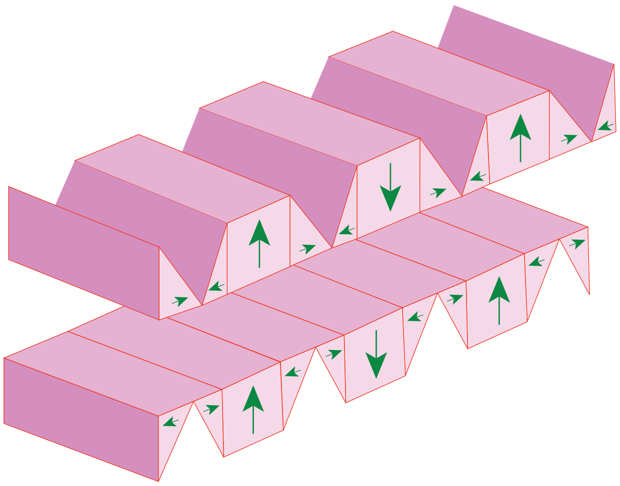


Figure 20d — Beam insertion devices for generating synchrotron radiation. Pure REPM wiggler as in 20a, but with longitudinally oriented magnets cladding the transverse field source magnets to reduce flux leakage.[33,35]

Magnetic Resonance Imaging

Imaging systems based on nuclear magnetic resonance are used for medical diagnosis and increasingly also for inspection purposes in the food industry. They require very uniform and steady magnetic fields, often in large volumes. Initially, good image quality could only be achieved with very high fields, in the 5 to 15 kG range, that are usually produced by superconducting magnets. Such medical MRI systems now cost as much as $2.5 million, plus up to $2 million more for magnetically shielding the exam room and accommodating the liquid helium cryogenic unit.[49] Recent advances have made it possible to get satisfactory images with lower fields of 1 to 3 kG, and these can be produced with permanent magnets. Permanent magnet units have been built using ferrites (weights: magnet alone ~21 tons; magnet assembly ~70 tons), Sm-Co (5 tons; 27 tons) and Nd-Fe-B (2.6 tons; 24 tons).[50,51] As in other magnetic systems, the use of permanent magnets eliminates the need for a power source and cooling, no cryosystem and liquid helium are required, and the MRI system becomes smaller and cheaper to build and operate. There are also yokeless, largely self-shielding permanent magnet systems under development which would eliminate most of the stray flux and the need for shielding.[37,51]

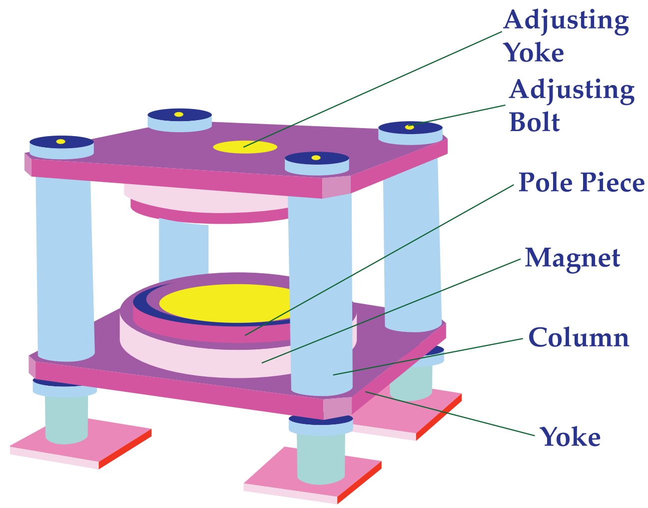


Figure 21a — Conventional hybrid dipole using Nd-Fe-B magnets.[50] for magnetic resonance imaging.

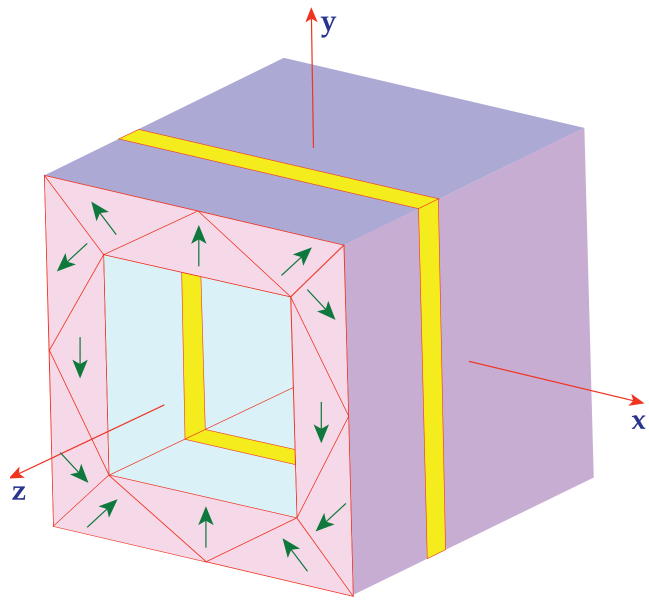


Figure 21b — Yokeless pure-permanent magnet dipole magnet design (REPM or ferrite)[51] for magnetic resonance imaging

It appears that the use of permanent magnet MRI systems should have a bright future. Figure 21(a) shows a magnet employing Nd-Fe-B as the permanent magnet material that is now a commercial product in japan. Figure 21(b) depicts a very unconventional self-shielded system without any iron now under development in the USA; it could be built with rare earth permanent magnets or ferrite magnets.

Maglev Vehicles

As our final example we shall consider the utility of permanent magnets in magnetically supported and propelled "maglev" transport systems. Many schemes for levitating tracked vehicles by magnetic fields, usually combined with propulsion by a linear electric motor that does not require contact between vehicle and guideway, have been proposed in the last 30 years.[52] Some projects would involve large quantities of magnet material. Lining the tracks with ferrite blocks repelling other permanent magnets in the vehicle works in principle, but the idea was abandoned for economic reasons. However, another German system that uses attractive-force levitation and a linear synchronous long-stator motor is now in public transport operation — the "M-Bahn" in the city of Berlin — and an equivalent system is being built in the USA, the Las Vegas People Mover. These are not the high-speed railroads usually associated with maglev, but local transit systems operating at top speeds around 120 km/h with frequent stops. The M-Bahn principle[52,53] uses rare earth permanent magnets in the vehicle undercarriage in a dual function, as part of the levitation and of the propulsion systems (Figures 22 and 23).

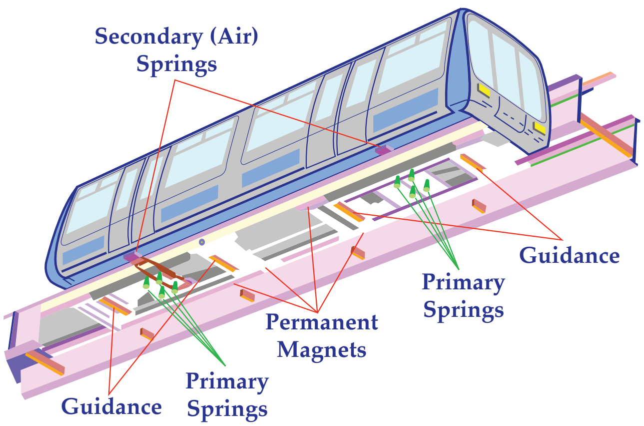


Figure 22 — Magnetic vehicle levitation and propulsion: View of M-Bahn cabin from underneath, showing support structure and bogies.[53]

The weight of vehicle and load is supported by the attractive force between four sets of permanent magnets and the iron of the motor stator. The needed force control is provided by varying the air gap, between 11 and 24 mm, with an ingenious mechanical device involving spacer wheels that see only small forces and thus have long lifetime, Figure 23a.

In the propulsion system, a 3-phase winding in a slotted laminated iron core on each side of the guideway sets up a traveling electro-magnetic field which interacts with the permanent magnets and pulls the vehicle along, Figure 23b. The frequency of the current is varied and with it the travel speed of the magnetic wave and the vehicle. 512 kg of $SmCo_5$ are used in each car. Replacement of the Sm-Co by Nd-Fe-B is anticipated, but the greater thermal and chemical instability of the latter may present unforeseen problems in the rough operating environment of a "railroad."

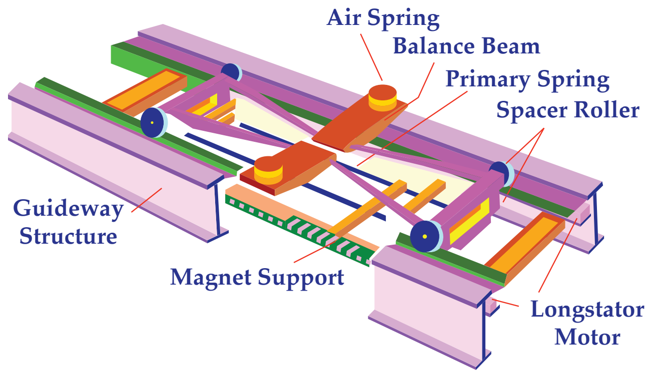


Figure 23a — Maglev M-Bahn vehicle: Air gap control system, showing location of Sm-Co permanent magnets in the bogie structure.[53]

H. Weh[52,54] described various possibilities of completely contact-free magnetic suspension, combining permanent magnets (to carry the empty vehicle weight) with electromagnets to provide extra lift for the cargo and for dynamic force control. They are under development for use in the German Transrapid high-speed vehicles. Here, too, lift and thrust functions are combined, and the scheme can be extended to use the same magnets also for lateral stabilization.

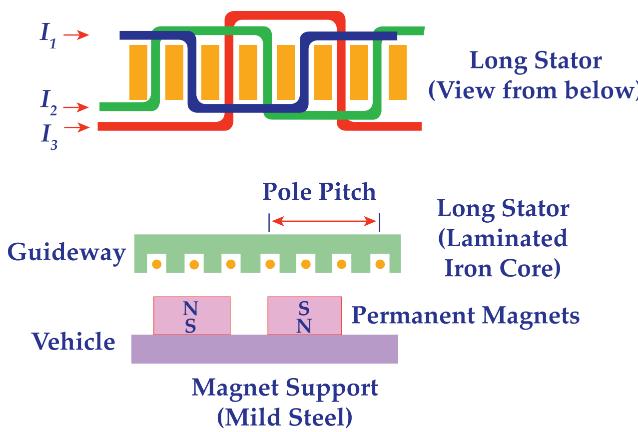


Figure 23b — Maglev M-Bahn vehicle: Schematic of synchronous long stator motor.

The methods described are equally suitable for the transport of materials in coal mines because they are intrinsically explosion proof and the vehicles can climb steep gradients.[53] An "integrated transportation system" for men, material, coal, and rock is said to be under development for a large German mining company.

There are now at least two types of fully developed maglev transport systems using permanent magnets, one being installed for commercial operation. If they prove successful, this will open up a completely new market for large quantities of the rare earth permanent magnet materials.

4. Future Prospects for Permanent Magnet Materials

Avenues for Further Improvement of Magnets

In order to assess the prospects for further improving permanent magnets, we must define what we mean by better. It is obvious that different groups of magnet users will have divergent views of the developments they would like to see pursued. This author attempted a systematic analysis of such user requirements and of the possibilities of satisfying them, done specifically with view to the rare earth permanent magnets.[13] The reader is referred to that paper for details. Table 6 lists various attributes of magnets considered important in different application areas and it correlates them with device categories.

With these requirements in mind, we can see several broad avenues along which magnet R&D can proceed. Aside from the long-shot search for totally new materials-discussed separately and last-four general development areas are identified, as we shall consider the prospects for the main magnet types within this framework.

(a) Improving existing magnetic material types

For the Alnicos, no significant property improvement is likely any more. Increased H_c would be the key to any progress here. And while it is still not fully understood why the coercivity should be limited to present values, the absence of H_c-enhancements in nearly 30 years, despite continuing research, strongly suggests that further gains are improbable.

Table 6 — Magnetic Property Requirements for Different Applications

Higher B_r, $(BH)_{max}$ near RT	Miniature devices
Extremely high MH_c near RT	Bearings, lenses
Straight line B vs. H to > 250°C, Good B_r	Microwave tubes, accelerometers
Temperature independent B_r, ${}_BH_c$	
Low cost, plentiful raw materials	Speakers, motors for appliances, business machines
Easy, cheap fabrication methods	
Easy magnetizing and "calibrating"	Many permanent magnet devices
Good at very low temperatures	Space, cyro-technology
These are often conflicting and call for different compromises	

The Fe-Cr-Co magnets are subject to similar limitations regarding coercivity. But since this technology is much younger and the best Alnico properties have not yet been matched in commercial production, further improvements toward full equivalence to all Alnico grades can eventually be expected. With declining markets it is uncertain whether the necessary efforts will be made.

For the hexaferrites, too, the possibilities for any major property improvement seem exhausted. Materials science and technology are in a mature state. All recent efforts were aimed at translating laboratory achievements into mass production and to improve the means for the latter by factory modernization and automation. The polymer bonded versions have some room for improvement; current work with these concentrates on newer production techniques such as injection molding.

There is still much need for improvement of the rare earth magnets. Each subgroup has its specific shortcomings; some concern magnetic properties, some the undesirable mechanical or chemical behavior, and others are economical. Examples of current efforts are:

(1) With "Nd-Fe-B" raising its upper use temperature; improving its long term magnetic stability;

reducing corrosion problems by alloy modifications, by refining the grains and applying protective coatings; a precipitation-hardened version might be developed.

(2) Bringing the 2-17 magnets closer to their full potential of B_r and $(BH)_{max}$ by maximizing the Fe and total TM contents and minimizing Cu, Zr, etc. As the Fe content of 2-17 is increased and more Co is added to the 2-14-1 compositions, the distinction between RE-Co and RE-Fe based REPMs becomes increasingly blurred.

(3) Applying the concept of internal temperature compensation through the use of heavy rare earths to additional rare earth permanent magnet alloys. Good possibilities have been demonstrated in laboratory work and are waiting to be implemented in production.

(4) Broadening the range of bonded rare earth permanent magnet, especially now by perfecting the Nd-Fe-based varieties, making those strongly anisotropic and chemically more stable.

(b) Modifying Materials to Meet Specific Application Requirements

Here again, little more can be done with regard to the Alnicos. For Fe-Cr-Co, one remaining objective is to create an equivalent to the high-H_c Alnico 8.

With the ferrites, too, few further useful composition modifications appear possible. Work in the last decade moved some higher-H_{ci} materials from laboratory into production, especially for automotive starter-motor applications, and composite magnets of two different ferrite materials were introduced for the same use.

In the rare earth permanent magnet area, some application-driven alloy development work is in progress, and much more is possible:

(1) Broadening the rare earth raw materials base by adding more Ce, Pr, La, and Y to the alloys is becoming increasingly important as large-volume applications develop. This is possible in Sm-Co and Nd-Fe-based magnets. The time may have come to reconsider using mischmetal in 2-17 magnets, an idea that was largely abandoned during the cobalt supply crisis of 1978-80.

(2) It is possible to tailor-make magnets close to specified temperature functions of the flux for applications such as accelerometers, TWTs or measuring instruments.

(3) Many alloying additions to Nd-Fe-B are being explored with a view to the better stability needed in many uses.

(4) Special alloy modifications and heat treatments are needed for making low-cost or otherwise optimized bonded magnets.

(5) Similarly, alloys for producing the best possible magnets by sintering, or by rapid quenching and post-processing into dense aligned magnets, also need optimization.

(6) And additional alloys suitable for hot deformation from the as-cast state[29] can probably be developed.

(c) Developing the Magnet Manufacturing Technology

For magnets in the Fe-Cr-Co family, various processing techniques exploiting their ductility, methods for obtaining directional grain, for precipitate orientation by deformation aging, and magnet production by sintering were developed in the laboratory.[5] They are being slowly introduced into commercial production, but the economic incentive is low at present.

Again, there is much left to be done for the rare earth permanent magnets, especially the rare earth Fe versions. Generally, lower-cost mass production methods must now be developed, including the capability for making very large pieces, and also small, thin or intricate shapes economically. More attention must be paid to the uniformity of properties within the magnets and the consistency of product quality. The bonded-magnet approach is particularly well suited to meet some of these objectives. It also lends itself to the fabrication of "integrated magnetic circuits," subassemblies comprising permanent magnets, soft magnetic, and structural components. With the R/Q method of processing Nd-Fe-B, the hot-deformation step still needs much development work to produce grain alignment in various piece and flux geometries at competitive cost. The new hot-rolling method for as-cast Pr-FeB magnets needs to be developed to production maturity and its applicability to other alloys is being explored.

(d) Making Magnets More "User Friendly"

For the high-energy rare earth permanent magnet, practical problems exist with breakage in handling, the magnetizing of magnets after assembly, finish machining, surface corrosion, etc. The danger of magnets cracking, or even of personal injury due to strong attractive forces is especially great for large magnets and assemblies; machining is difficult for thin sections; and high charging fields are costly to produce and often difficult to apply, It is possible to make magnets that are less brittle (bonded magnets are much less fragile than sintered ones), and charging is facilitated by producing magnets with just enough coercivity for a given use. The development of corrosion protection coatings for Nd-Fe has high priority at the present time. Polymer coatings also reduce chipping.

Under this heading we might further mention the desirability of a much more detailed description of the properties and peculiarities of the different magnet types than is typically offered in manufacturers' product literature. Uniform industry standards, and stricter guidelines for writing specifications and for testing would also make the application engineer's life much easier. Efforts to develop these should perhaps be made within the IEEE.

B. Efforts to Find Completely New Magnetic Materials

The announcement in 1983 of Nd_2Fe_4B as an excellent new permanent magnet material was widely unexpected, It raised new hopes that there were indeed still other potential magnet alloys to be discovered and it invigorated a global scientific effort to find them. A ferromagnetic substance is of interest if it combines a sufficiently high Curie point with high saturation and a strong easy-axis-type crystal anisotropy; so these are the characteristics one must initially look for in such a search, However, they are only necessary conditions, To develop a high H_{ci} in a good candidate substance is still a difficult task and may not be possible, But even in the basic search for high-anisotropy compounds or alloys there is little theoretical guidance available. According to our present understanding, the best candidates are still alloys or compounds with a high 3d-metal content that provides the magnetic moment, combined with a rare earth that can impose high crystal anisotropy,

A rather systematic search for previously unknown or poorly characterized rare earth - TM-based ternary and quasi-ternary intermetallics has been in progress for the last few years in several laboratories, Buschow[55] has repeatedly reviewed such work in recent publications, The studies initially concentrated on modifications of $Nd_2Fe_{14}B$ having the same crystal structure, but with the Fe partly or fully replaced by Co and other 3d-metals, carbon taking the place of boron, and RE being any of the rare-earth elements. Then several new compound types were identified and studied, most of them Fe- or (Fe, Co)-based rare earth borides. The most interesting so far have the Th_2Mn_{12}-type crystal structure, are also Fe based (Mn moments couple antiparallel, leading to a low B_s), they have a RE in the Th position and some Ti or Si substituted for the Fe.[56] Metastable phases prepared by melt spinning and heat treating were also screened; only Fe_3B containing a few percent of Nd shows some promise. In all, several alloys have been found that might have been of interest before $Nd_2Fe_{14}B$, but which are definitely inferior to the latter in one or another important aspect.

The search has so far failed to reveal any real candidate for a still better permanent magnet. This does not prove that such a material does not exist, but it has considerably reduced the probability of finding one. Of course, a new material need not necessarily promise still higher energy product, coercive force, or even Curie temperature than the present rare earth permanent magnets. It would also be of great interest if it used cheaper and more plentiful raw materials while having somewhat better properties than the ferrites.

C. Theoretical Limits for Permanent Magnet Properties

The question is often asked: what is the highest conceivable energy product? It is not easy to give a simple quantitative answer. To discuss it, one must first ignore coercive force and anisotropy and assume that a way might be found to give a fairly high H_{ci} to any magnetic material. (rare eartch additions do a pretty good job of this in many transition-metal alloys.) This reduces the problem to the question: which magnetic material has the highest saturation? At normal room temperature, that is an Fe-Co alloy with about 40% Co; its B_s is ~24.5 kG and the associated limit for the energy product would be ~150 MGOe. A realistic limit is certainly somewhat lower, since any additions made to modify the crystal structure, anisotropy, and microstructure so that a high coercivity might be developed almost invariably reduce the saturation value. Of the real magnet materials with high saturation we have now — Alnico 5, 35% Co steel, $Sm_2(Co, Fe)_{17}$, and $Nd_2Fe_{14}B$ — all have B_s values between ~13 and ~16 kG, with corresponding theoretical limits of $(BH)_{max}$ of 42-64 MGOe. The search for new candidate compounds described above could conceivably yield a useful substance with still higher saturation, raising realistic hopes for magnets with energy densities above 64 MGOe.

To this author it seems reasonable to assume that the best room-temperature energy products will never exceed ~100 MGOe. The present record value of 50.6 for Nd-Fe-B is then about 50% of this strictly intuitive but probably more realistic upper limit. This still leaves significant room for future gains, but not for the kind of revolutionary progress witnessed since 1970.

One can, of course, envision hypothetical materials with higher saturation than Fe-Co. One such "dream" is to create essentially a ferromagnetic and fully dense manganese metal.[57] Assuming the theoretical moment maximum of 5 Bohr magneton per Mn atom, this leads to an upper limit of B_s = 47,000 Gauss and B_{Hm} = 550 MGOe! Another dream of some of us in the 1960s involved forcing a parallel coupling of the high moments of the heavy rare earths with strongly magnetic 3d-atoms in rare earth - TM intermetallics.[58] But nature has been totally uncooperative with all attempts along these lines. It is extremely unlikely that such substances will ever be possible.

The situation is different at very low temperatures near 0°K. There, several HRE metals are ferromagnetic with the highest saturation values measured. Dysprosium, the "best," has a $B_s \approx 39$ kG. From this one calculates a theoretical $BH_m \approx 380$ MGOe. Again, the daring assumption is that Dy could be given a coercivity $H_{ci} > 20$ kOe without reducing its B_s. But a dysprosium compound, Dy_3Al_2 has indeed been shown to be a "supermagnet" at 4.2°K, with $H_{ci} \approx 20$ kOe, $B_r \approx 17$ kG and $BH_m \approx 70$ MGOe, an absolute record for the energy product.[59] This is, of course, of no practical use now. But it is conceivable that in some future engineering projects — in conjunction with superconducting devices that must be cooled with liquid helium, or in space-cryogenic permanent magnets may become useful. They could then also be combined with pole pieces of Dy or Ho that would carry 1.5 times as much flux as Fe-Co.

Publishing History

Manuscript received February 27, 1990; revised April 6, 1990. The author is Professor Emeritus of the University of Dayton, School of Engineering, and owner of KJ5 Associates, 1616 Hillrose Place, Fairborn, OH 45324-4017, USA.

Reformatted, color illustrations added, and references updated by Mark Duncan in September 2009.

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Workshop	Location	Year	Editors	Publisher
WS-1	Dayton, Ohio	1974	No proceedings were published	
WS-2	Dayton, Ohio	1976	Karl J. Strnat	University of Dayton
WS-3	San Diego, Calif.	1978	Karl J. Strnat	University of Dayton
WS-4	Hakone, Japan	1979	H. Kaneko and T. Kurino	Soc. N-T Tech.
WS-5	Roanoke, Virginia	1981	Karl J. Strnat	University of Dayton
WS-6	Baden, Austria	1982	J. Fidler	TU Wien
WS-7	Beijing, China	1983	X. Pan, W. Ho and C. Yu	China Acad. Publishers
WS-8	Dayton, Ohio	1985	Karl J. Strnat	University of Dayton
WS-9	Bad Soden, Germany	1988	C. Herget, R. Poerschke	Deusch Physics Ges.
WS-10	Kyoto, Japan	1989	T. Shinjo and T. Kurino	Soc. N-T Tech.
WS-11	Pittsburgh, Penn.	1990	S. G. Sankar	Mellon Institute

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Carnegie-Mellon University, Mellon Institute, 4400 Fifth Street, Pittsburgh, PA 15213-2683 (S. G. Sankar).

About the Author

Karl J. Strnat, the father of rare earth permanent magnets, died from a heart attack on May 1, 1992. In 1966, he with G. I. Hoffer, found that YCo_5 had an extremely large uniaxial magnetocrystalline anisotropy and a very large theoretical energy product, and suggested it would make an excellent permanent magnet. A year later, several groups including Strnat, showed that $SmCo_5$ was the best permanent magnet of the RCo_5 materials.

AFellow of the IEEE), he was born in 1929 and received degrees of Dipl. Ing. (M.S. Engineering Physics) and Dr. Techno (D.Sc.Electrical Engineering) from the Technical University of Vienna, Austria.

For 10 years beginning in 1958, he was a researcher and supervisory physicist at the US Air Force Materials Laboratory, Wright· Patterson AFB, Ohio. F. M. Tait Professor of Electrical and Materials Engineering from 1968 on, he taught at the University of Dayton, Ohio, directed its Magnetics Laboratory, conducted and managed magnetic materials R&D. Professor Emeritus since 1989, he still teaches there. He also owns and manages a consultation, instrumentation, and testing firm, KIS Associates, in Dayton.

He authored or co-authored over 100 papers, and 6 US and 36 international patents in the field of magnetics, and has traveled and lectured extensively. He organized two conference series, “International Workshops on Rare-Earth Magnets and Applications,” held 10 times in the USA, Europe, and Asia, and "Symposia on Magnetic Anisotropy and Coercivity," and edited six proceedings books. He pioneered the development of rare earth-cobalt magnets.

Dr. Strnat was a member of the IEEE Magnetics Society, chaired its Technical Committee on Permanent Magnets, was its Distinguished Speaker in 1984/1985, and served as a Society Fellow Evaluator. He was active in committees of Intermag and MMM Conferences and the National Materials Advisory Board. He was also a member of the ASTM and the Arbeitsgemeinschaft Magnetismus.

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