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Trends and Problems in Research of Permanent Magnets for Motors – Addressing Scarcity Problem of Rare Earth Elements –

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1 Introduction

One of the fundamental technologies necessary for the creation of a low-carbon society, such as next-generation vehicles and energy-saving home electric appliances, is the neodymium magnet for motors. The urgent issue facing neodymium magnets, for which demand has increased dramatically, is resource risk. In particular, the resource problem concerning dysprosium (Dy) is serious. Dysprosium is used in magnets for the motors of next-generation vehicles, such as hybrid cars, plug-in hybrid vehicles, and electric cars, in which the motors are exposed to a high-temperature environment.

Increasing the strength of magnets is expected to promote green innovation, as it contributes to the development of smaller and lighter motors with higher-torque, leading to the advancement of energy savings in a range of consumer products such as home electric appliances. As a result, it reduces the power consumption of motors, which accounts for approximately 52% of total domestic power consumption, further reduces the carbon emissions of next-generation vehicles, and enhances the performance of wind generators. Since the invention of KS magnetic steel by Mr. Kotaro Honda in 1917, Japan has proudly and consistently led the world in the development, production and application of magnets. Amid calls for Japan to respond to resource risk and promote green innovation, influential individuals in the industrial world are expecting measures to be taken to develop human resources for the research and development of magnets in order to promote innovation by mobilizing all magnet researchers in industry, government and academia.

Based on this recognition, the “Tohoku Motor Magnet Innovation Strategy Council” was established on June 17, 2010.[1] This report discusses trends and problems in the research of permanent magnets for motors.

2 History of Permanent Magnets

2-1 Yearly changes in Energy Product of Permanent Magnets

Humans discovered natural permanent magnets long before the time of Christ; people were using naturally magnetized iron ores in 600 B.C. in a region of Greece called Magnesia.[2-4] However, the first artificial permanent magnet was invented and named KS steel by Mr. Kotaro Honda in 1917. Mr. Honda, a thorough experimentalist, invented KS steel by experimenting with all possible combinations of minerals in the spirit of perseverance and effort.

Figure 1 (History of Permanent Magnet Development) shows that permanent magnets are 60 times as strong as they were about 90 years ago. Strong permanent magnets that can be used in industrial applications were developed in the 20th century, and Japanese researchers and technologies have always played major roles in the history of the development of permanent magnets. Following the invention of KS steel, Mr. Kato and Mr. Takei invented the OP magnet in the 1930s, which served as a base for the ferrite magnet. In 1932, Mr. Tokushichi Mishima invented MK steel, which served as the starting point for the development of the AlCoNI magnet. The coercive force of MK steel was 2 to 3 times as strong as KS steel. In 1933, Honda, Masumoto and others worked together to invent new KS steel, whose coercive force is about 1.5 times as strong as MK steel.

The performance of permanent magnets made a big leap forward thanks to the advent of rare-earth samarium-cobalt magnets in the second half of the 1960s. The samarium-cobalt magnet was invented by the U.S. Air Force Research Laboratory in 1968 and its performance has improved thanks to the contribution made by Japanese researchers, including Mr. Yoshio Tawara. In 1983, Mr. Masato Sagawa invented the neodymium magnet, which has remained the strongest permanent magnet in the world ever since.

Among the "Ten Great Japanese Inventors" selected by the Patent Office in commemoration of the 100th anniversary of the Japanese industrial property system, two magnet-related inventors made the list: Kotaro Honda (Patent No. 32234: KS steel) and Tokushichi Mishima (Patent No. 96371: MK magnetic steel).[5] More than 10 kinds of magnets were invented in the 20th century. Revolutionary discoveries and inventions drawing public attention were made only once every 20 to 30 years, suggesting that they were the results of long-term, challenging research.

2-2 Serendipity in Permanent Magnet R&D[8,9]

In the research of permanent magnets, it can be said that revolutionary new materials have been invented through serendipity (a propensity for making fortunate and unexpected discoveries by accident).

The story behind the development of the MK magnet by Mr. Mishima in 1932 is as follows. In order to examine why the magnetic transformation point of Fe-(25 to 26%)Ni alloy differs greatly depending on over-heating or cooling, Mr. Mishima began experiments to narrow the gap in transformation points by using aluminum as an added element. When shaving an aluminum-added specimen to a prescribed size, Mr. Mishima accidentally discovered that the shavings did not drop and instead clung to the specimen. This led to the development of the MK magnet (Fe-Al-Ni alloy). Although Dr. Mishima is not an expert in the field of permanent magnets, he did not overlook the accident thanks to his extensive knowledge and scientific acumen.

In 1970, Matsushita Electric Industrial Co. (now Panasonic Corporation) began industrial production of manganese-aluminum-carbon magnets produced through hot extruding and hot casting methods by adding carbon to manganese-aluminum magnets, which were developed by N.V. Philips in 1960. That magnet has excellent workability, so it is still used for

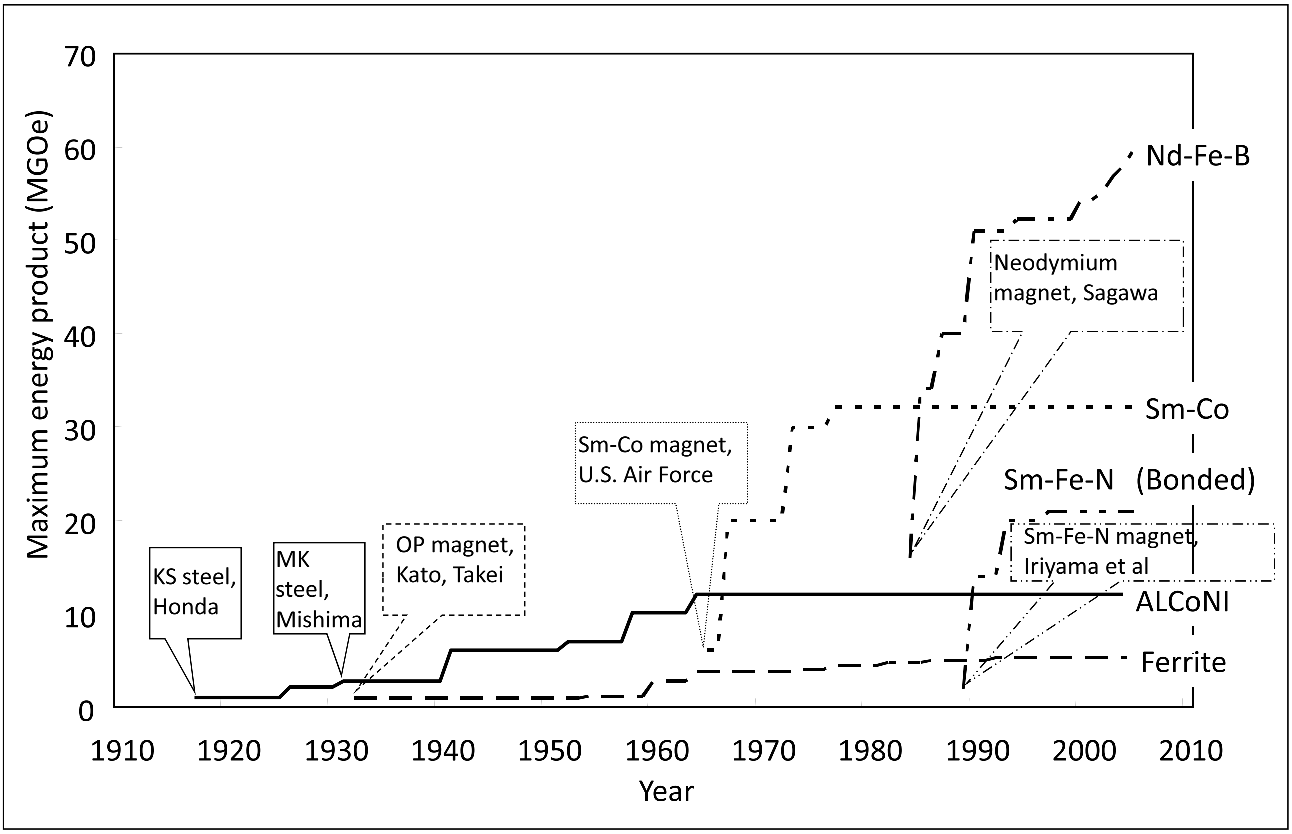

Figure 1 : Yearly changes in Energy Product of Permanent Magnets

Prepared by the STFC based on Reference[1,6,7] some purposes.[4] Since the manganese-aluminum magnet shows high crystal magnetic anisotropy, it was once touted as a potential candidate for a permanent magnet not containing cobalt. However, it has yet to be put to practical use. A group of researchers, led by Mr. Kubo of Matsushita Electric Industrial, once used an ordinary crucible to melt specimens during its research to put manganese-aluminum magnets to practical use. However, since impurities, such as Si, were mixed in with the melted specimens in the crucible, the group began to use a carbon crucible. As a result, the ingot mixed with carbon from the crucible and was powderized overnight. The powder was found to be a strong magnetic powder, leading to the development of the manganese-aluminum-carbon magnet.

The invention of the neodymium magnet by Mr. Sagawa in 1983 is said to have been prompted by a false hypothesis.[10] In 1978, Mr. Sagawa attended a study meeting titled “Rare-Metal Magnets: from Basics to Application” and was inspired to study magnets. Mr. Masaaki Hamano, in his speech at the meeting, explained that the reason R_2Fe_{17}, a compound of rare-metal R and iron (Fe), does not become a permanent magnet is that the ferromagnetic state of the intermetallic compound is unstable due to the too-small distance between the Fe atoms. Based on the fact that carbon in steel widens the distance between the Fe atoms in the steel, Mr. Sagawa hypothesized that the Fe-Fe atomic distance of R_2Fe_{17} can be widened, if it is alloyed with small-atomic-radius elements, such as C and B. Mr. Sagawa started experiments the next day, creating a variety of R-Fe-C and R-Fe-B alloys in an arc melting furnace, measuring their magnetism and examining their crystal structures. His research led to the invention of a neodymium magnet. Later, however, it became clear that the distance between the Fe atoms in $Nd_2Fe_{14}B$, the main phase of the neodymium magnet, is not very different from that in the B-free R_2Fe_{17} and that the improvement of the magnetic nature of Fe caused by B in $Nd_2Fe_{14}B$ was actually due to chemical interaction between Fe electrons and B electrons. Although Mr. Sagawa’s hypothesis at the beginning of his research was wrong, his research eventually resulted in developing the world’s strongest magnet thanks to his persistent efforts.

In 1990, a samarium-iron-nitrogen permanent magnet was invented by Mr. Iriyama and others of Asahi Kasei Corp. Mr. Iriyama had learned that a magnet can be invented by nitriding iron, after hearing a report by Mr. Minoru Takahashi that saturation magnetization improves if Fe is nitrided. Mr. Iriyama dissolved and nitrided Fe-30%mass%X alloy (with X being any available element in the periodic table), and eventually invented the Sm-Fe-N permanent magnet. Mr. Iriyama is also not an expert in the field of permanent magnets. If he was an expert in the field, he would not have thought of doing what he did. Since iron-nitrogen ($Fe_{16}N_2$) is soft phase, experts are inclined to think that even if saturation magnetization is increased by nitriding, the crystal magnetic anisotropy would not increase. This is another example of an outsider’s bold idea leading to the invention of a new chemical compound.

In this way, the invention of new permanent magnets has historically been brought about by bold interdisciplinary ideas, and passion and chance.

3 Current Status of Permanent Magnets for Motors

3-1 World’s Strongest Neodymium Magnet: Changing Motors around the World

Although electric magnets were previously used for rotating motors, neodymium magnetic plates have come to be used recently, especially for small motors, leading to a reduction in motor size and noise. Elevators were some of the first machines to use neodymium magnet motors. Then, neodymium magnets began to be used for washing-machine motors, increasing spin-dry power and reducing motor noise. Neodymium magnets are also now used in heavy machinery. Conventional hydraulic motors are noisy, as engines have to be kept rotating, but motors using neodymium magnets have made it easy to operate heavy machines in residential neighborhoods and at night.

In terms of numbers, neodymium magnets are most used in information equipment (Figure 2). A voice coil motor (VCM) is a linear motor that moves a voice coil placed in the magnetic field of a permanent magnet in proportion to electric current. VCMs are used as actuators for the head positioning of hard disks, for camera zooming, stopping down and shuttering, and for micromachinery. Neodymium magnets have also helped to make mobile phones thinner. The main challenge in making thinner mobile phones was to make speakers thin. By using an ultracompact neodymium magnet, it became possible to develop the world's thinnest speaker.

3-2 Neodymium Magnet: Trump Card for Energy Saving

In Japan, production of neodymium magnets mainly for use in information equipment has increased thanks to the spread of personal computers in the 1990s. In recent years, however, the proportion of neodymium magnets for use in motors has increased, so the production volume of neodymium magnets has increased sharply (Figure 3, Figure 4). The reason behind this is the fact that there are growing calls to reduce power consumption and increase the use of energy-saving equipment in order to cut CO_2 and other greenhouse gas emissions in line with the ratification of the Kyoto Protocol.

Thanks to neodymium magnets, the energy consumption of air conditioners has been drastically reduced. In air conditioners, electricity is mostly consumed by dive compressor motors.[12] Previously, AC induction motors were used for air conditioners, but inverter air conditioners were put on the market for the first time in 1981 and a highly-efficient brushless DC motor was developed in the 1990s. Following the enforcement of the revised energy conservation act in 1999 and the introduction of fuel efficiency standards under the act in 2003, all air conditioning manufactures started to improve their air conditioners and worked towards enhancing the performance of motors in order to drastically cut energy consumption. Most of the domestic air conditioning manufacturers adopted neodymium magnets in or after 2003 and have reduced the energy consumption of their products. Compared with conventional motors, new motors using neodymium magnets have reportedly improved their low-speed motor efficiency by approximately 30%.[13,14] However, non-inverter air conditioners are still more popular world-wide.

At present, induction motors not utilizing permanent magnets are extensively used in industry. If they are replaced by neodymium permanent magnet motors, it would significantly reduce energy consumption and help reduce CO_2 emissions.[14] At present, approximately 52% of Japan's total domestic power consumption is accounted for by motors. It is estimated that a 1% improvement in the efficiency of electric motors would save power equivalent to the output of a 500MW thermal power station.[14]

The products in which neodymium magnets have increasingly been used in recent years are automobile motors. If neodymium magnets did not exist, hybrid cars would not have been developed. The production of neodymium magnets has increased sharply in line with the expansion of hybrid-car production. As the production of next-generation vehicles, such as hybrid cars and electric cars, is expected to increase in the future, the production of neodymium magnets is also expected to continue to increase.

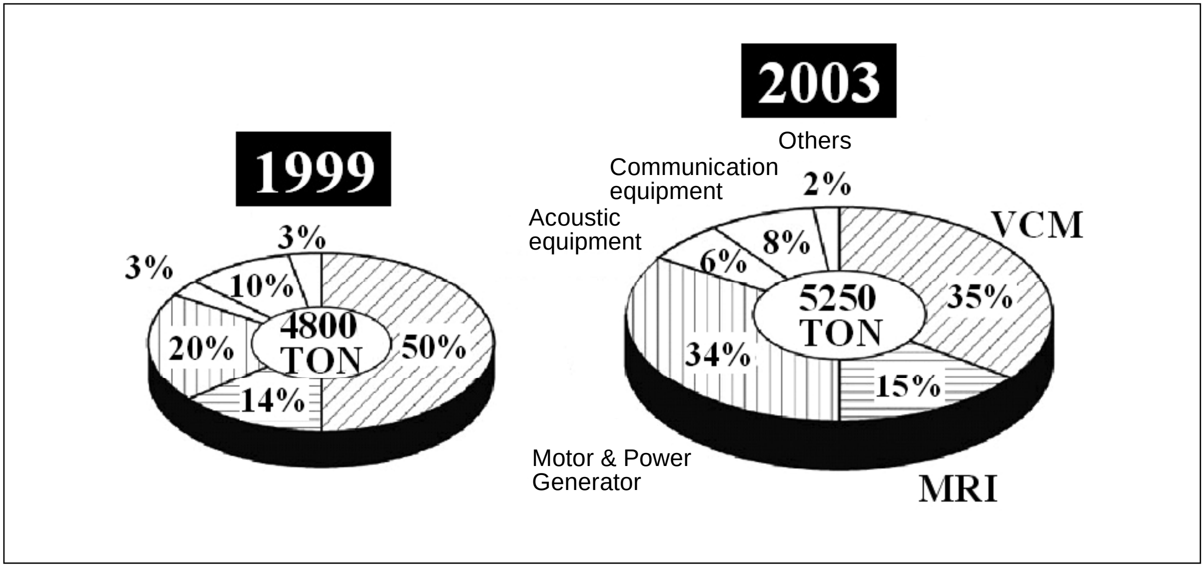

Figure 2 : Application of Neodymium Sintered Magnets in Japan

Source: Reference[2,11]

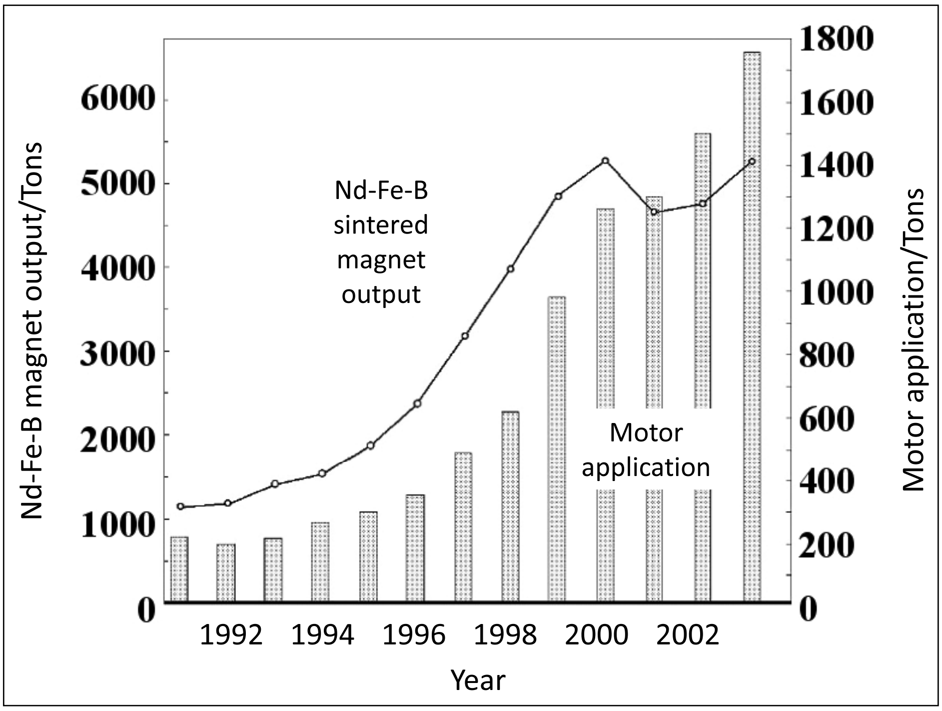

Figure 3 : Relationship between Neodymium Magnet Production and Motor Application in Japan

Source: Reference[2,11]

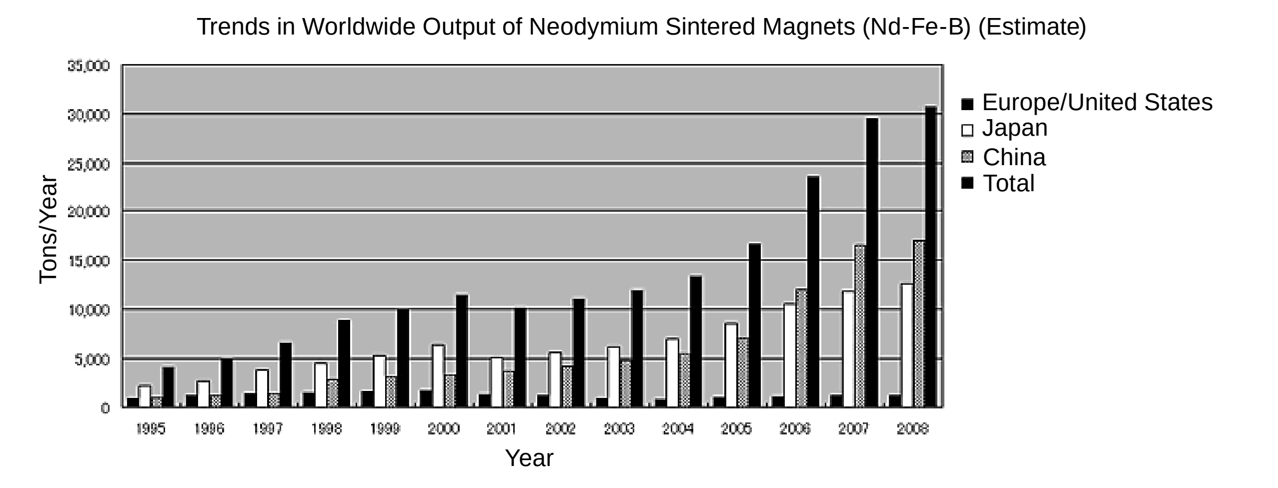

Figure 4 : Trends in Worldwide Production of Neodymium Sintered Magnets

Source: Reference[4]

4 Challenges of Permanent Magnet Motors and Research Projects

4-1 Challenges of Neodymium Magnets

Figure 5 shows the relationship between the application and composition of neodymium magnets. The temperature of a magnet, if used in a next-generation vehicle, reaches up to 200℃ while in use, but Neodymium magnets, in particular, are vulnerable to heat, while the coercive force of any magnetic material decreases as temperature increases. In neodymium magnets, the Curie temperature (the point at which magnetization falls to almost zero) of the $Nd_2Fe_{14}B$ compound is as low as 312 ℃ . Therefore, in order to increase the coercive force of neodymium magnets at high temperature, rare-earth dysprosium (Dy) is added. Figure 6 shows the product-by-product demand for dysprosium.

On the other hand, since the Dy that is added to $Nd_2Fe_{14}B$ substitutes for Nd and the magnetic moment of Dy causes it to be bound with Fe in an antiparallel manner, the magnetization of the magnet decreases due to the addition of Dy, and its maximum energy product (BH max) becomes small. Therefore, about 40% of the Nd in neodymium magnets currently used in next-generation vehicles is substituted by Dy in order to obtain a strong coercive force. As a result, the maximum energy product is about 40% smaller.

However, resource problems are more serious than the decrease in maximum energy product. Rare-earth metals have low dysprosium contents, with the ratio of its existence in rare-earth mineral ores to that of Nd being about 20%. Moreover, its origin is almost limited to China, raising concerns about a future supply shortage in view of an expected increase in demand for next-generation vehicles. For instance, the Next-Generation Vehicle Strategy Council, which is composed of the presidents of car manufacturers, has been strongly arguing that the research and development of Dy-free magnets through industry-academia-government collaboration is necessary.[17]

Furthermore, people in industrial and academic circles are calling for the development of more high-performance magnets. Since 25 to 30 magnets are used per vehicle, the development of more efficient magnets can lead to making vehicles lighter.[14,18] Enhancing magnet technology will also make motors for air conditioners more efficient.[19] Although the motor efficiency of Japanese home electric appliances is considerably high, the absolute number of motors is very high. As described in 3-2, motors account for 50 to 60% of the total domestic power consumption in Japan. Therefore, a 1% improvement in the efficiency of electric motors would reduce power consumption considerably. Moves to the use of electricity—from engines to motors and from hydraulic pumps to motors—have been progressing in various fields, as exemplified by next-generation vehicles. Therefore, the proportion of energy consumption accounted for by motors is expected to increase further in the future and this will increase the needs to enhance the performance of permanent magnets and motors.

4-2 Three National R&D Projects in Japan

With the aim of solving problems facing neodymium magnets, such as those described above, three national magnet R&D projects are now being implemented.

○ Rare Metal Substitute Materials Development Project, "Development of Technology to Reduce Dysprosium Used in Rare Earth Magnets"
  - Implemented by the Ministry of Economy, Trade and Industry (METI) and the New Energy and Industrial Technology Development Organization (NEDO)
  - Started in 2007
  - Project to deal with the urgent issue of Dy resource problems
  - Hereinafter referred to as "Technological Development for Dy-Saving Neodymium Magnets"

○ Element Science and Technology Project, "Project for High Performance Anisotropic Nanocomposite Permanent Magnets with Low Rare-Earth Content"
  - Implemented by the Ministry of Education, Culture, Sports, Science and Technology (MEXT)
  - Started in 2007
  - Project is aimed at enhancing the performance of magnets as well as dealing with Dy resource problems
  - Hereinafter referred to as "Nanocomposite Magnet Development"

○ Rare Metal Substitute Materials Development Project, "Development of New Permanent Magnets Substituting for Nd-Fe-B Magnets"
  - Implemented by the Ministry of Economy, Trade and Industry (METI) and the New Energy and Industrial Technology Development Organization (NEDO)
  - Started by using the supplementary budget (2nd) for 2009
  - Project is aimed at enhancing the performance of magnets as well as dealing with Dy resource problems
  - Hereinafter referred to as "Development of New Permanent Magnets"

In order to facilitate collaboration between the "Rare Metal Substitute Materials Development Project" by METI/NEDO and the "Element Science and Technology Project" by MEXT, a joint strategy council consisting of representatives from industry and academia has been established. The council sponsors a joint public symposium around February every year at the University of Tokyo to share research results and enhance collaboration.

4-2-1 Development of Technology to Reduce Dysprosium Used in Rare Earth Magnets (Technology Development of Dy-Saving Neodymium Magnets)

The project is designed to develop Dy-saving yet highly-coercive neodymium magnets for use in

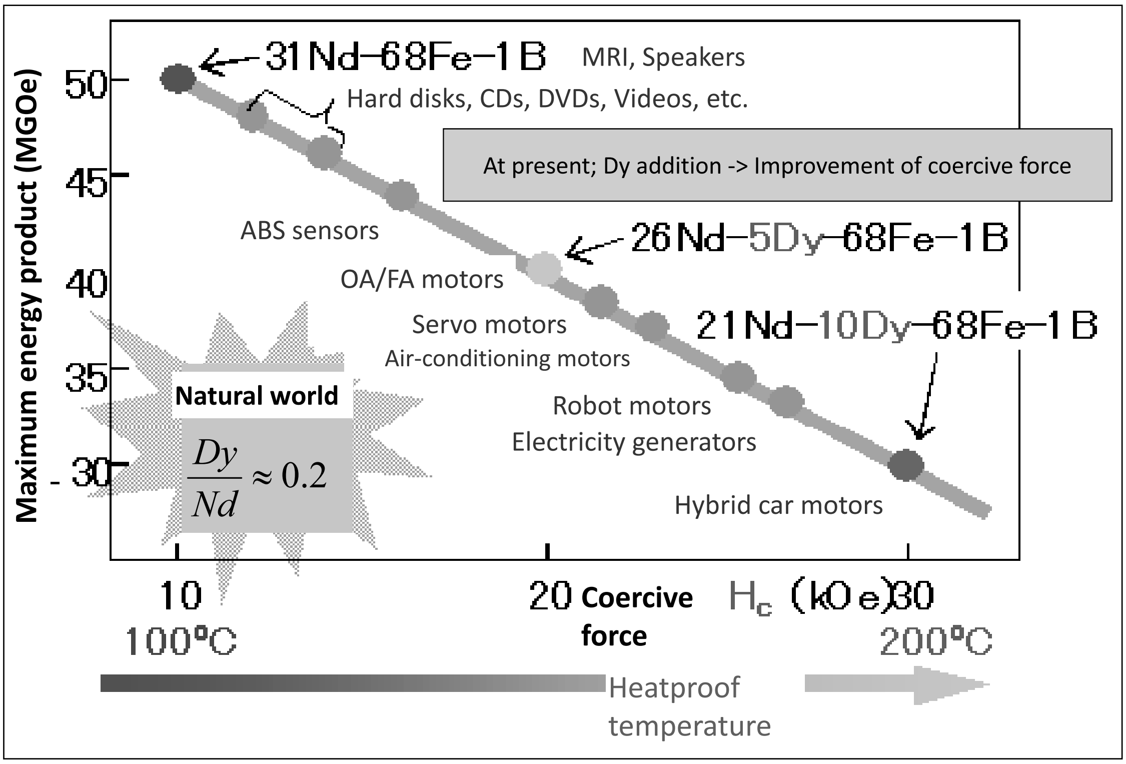

Figure 5 : Application and Composition of Neodymium Sintered Magnets

Prepared by the STFC based on Reference[15]

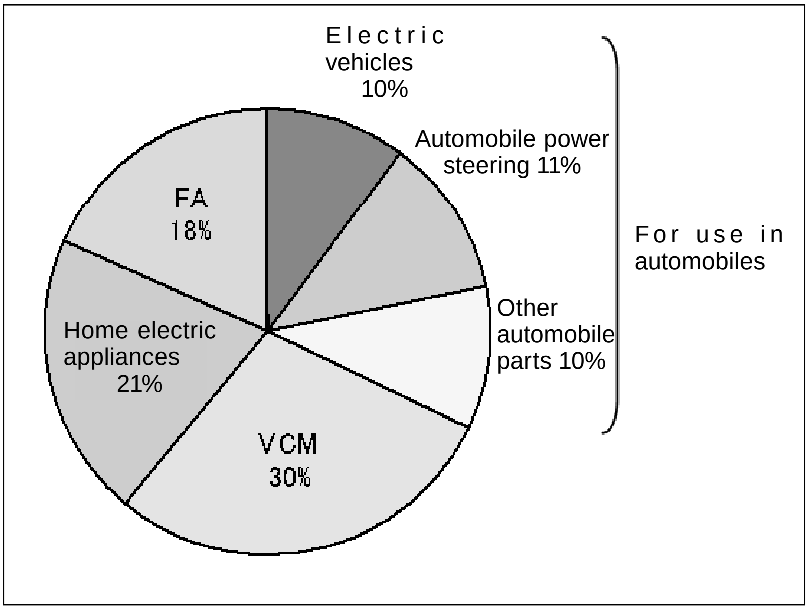

Figure 6 : Product-by-Product Demand for Dysprosium (Japan Market in 2004)

Source: Reference[16]

high temperature environments, aiming to reduce the amount of Dy consumed by such neodymium magnets by 30% in five years.

It is known that coercive force can be increased by reducing the probability of a reverse magnetic domain forming. It is thought that it is possible to do so by reducing the size of magnetic grains to single-domain grains (I in Figure 7) or by improving the coherency at interface of $Nd_2Fe_{14}B$, the main phase of the magnet (II in Figure 7).

The 7-I method is based on the knowledge that reducing the size of grains increases coercive force because it causes a relative reduction in the size of defects and an increase in the rate of crystal grains consisting of one magnetic domain (single-domain grain). Research and development is underway on production processes, including that of reducing crystal grain layer spaces of strip casting, which is an ingot production method, that of obtaining fine powder by operating jet mills at high speed, and that of developing a low-temperature sintering technique to curb grain growth at the sintering stage.[2] The process of miniaturizing crystal grains increases the surface area of grain, and thereby addresses the problems of controlling oxidation and increasing the homogeneous deposition of the Nd-rich phase on the surface at the same time. The 7-II method is designed to develop guidelines for process improvement by making model interfacial surfaces through thin-film technology and examining the best surface for increasing coercive force. So far, it has been found that, depending on the amount of oxygen melting in the Nd-rich phase (liquid phase) in deposits on grain boundaries, the interfacial situation changes and that an amorphous phase comes to exist on the surface. It has also been found that the coercivity of Nd-Fe-B magnets can be increased through high-field annealing.[20]

One of the features of this project is that production process technology development, like the 7-I and 7-II methods described above, is being promoted in a way to coordinate the acquisition of new guiding principles and the application development of automobile magnets. In order to find a new guiding principle, the project is trying to clarify the reasons that the current coercive force remains at about 10% of the theoretical value (90kOe) of the anisotropic magnetic field and that the coercivity of the grains decreases drastically when the size of crystal grains is reduced to a certain level, by analyzing the interface nanostructure of neodymium magnets and magnetization process. Furthermore, the project aims to obtain a guiding principle to enhance coercivity by using computing science and to pass the guiding principle on to production process technology development. Meanwhile, in the application development of automobile magnets, the project is examining the magnet durability assessment and the optimum shape of magnets that have been developed through the R&D of production processes in vertical collaboration with user companies and is passing the results of the examinations on to each R&D team.

A research evaluation committee made an interim evaluation of the results of this project study in October 2009. The committee said, “The project approaches the problem from two approaches based on the principle to increase magnetic coercivity, which enables reductions in dysprosium consumption: miniaturizing crystal grains and controlling the interfacial surface of grains. The project has cleared its intermediate target (achieved a 20% reduction in dysprosium consumption in FY2009). It will further strengthen Japan’s leadership in the field of ultra-strong magnets. The research papers announced are excellent in terms of their novelty.”[21]

4-2-2 Project for High Performance Anisotropic Nanocomposite Permanent Magnets with Low Rare-Earth Composition (Nanocomposite Magnet Development)

This Element Science and Technology project of the Ministry of Education, Culture, Sports, Science and Technology covers rather long-term research and

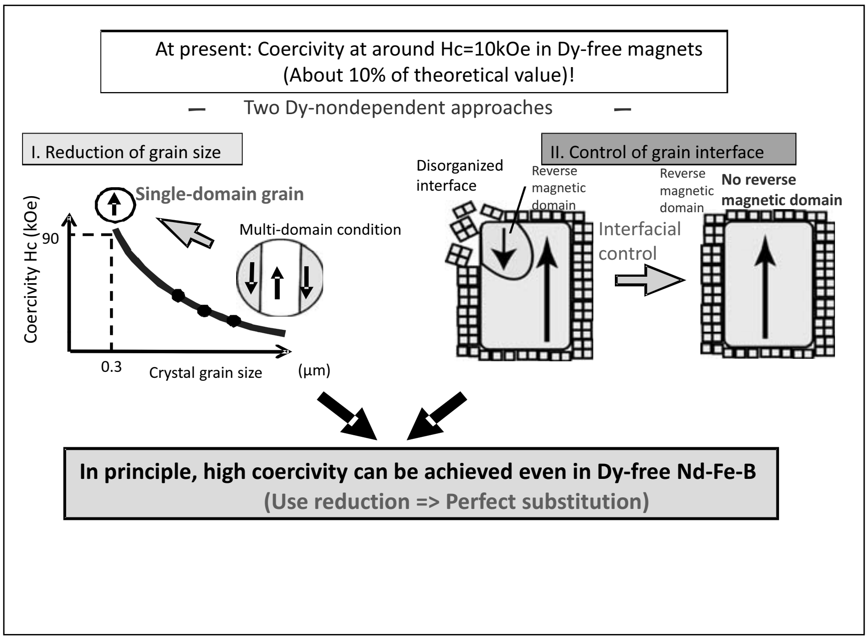

Figure 7 : Methods to Increase Coercivity of Neodymium Magnets

Source: Reference[15]

development projects.[22]

There are two approaches for enhancing the property of magnetic materials.[18] One of them is to find a completely new ferromagnetic compound that exceeds the $Nd_2Fe_{14}B$ compound. This approach is included in the project study objectives to be covered in the next section. The other approach is to form nanocomposites and it is being attempted in this element science and technology project.

The maximum energy product ((BH) max) of the current neodymium sintered magnet records a high of 60MGOe, approaching close to 64MGOe, which is the theoretical limit of the $Nd_2Fe_{14}B$ compound. Therefore, the magnet has only about a 10% margin left for enhancement. However, it may be possible to develop a neodymium magnet that exceeds the theoretical limit of $Nd_2Fe_{14}B$ by nanocompositing the hard magnetic materials for the $Nd_2Fe_{14}B$ compound and the soft magnetic materials with higher saturation magnetization, such as iron, and if the hard phase (hard magnetic phase) and the soft phase (soft magnetic phase) are magnetically connected.

The nanocomposite magnet is a concept discovered in the process of developing isotropic magnets by the liquid-quenching method. Around the same time that Mr. Sagawa invented a neodymium sintered magnet, Croat and others of General Motors Corporation developed a neodymium magnet as a bond magnet material, using the liquid quenching method.[18,23]

Magnetic materials used in industry are broadly divided into sintered magnets and bond magnets. Sintered magnets are anisotropic magnets in which the axes of easy magnetization of the crystal grains of the $Nd_2Fe_{14}B$ compound are oriented in the same direction. The maximum energy product of sintered magnets is high. On the other hand, bond magnets are isotropic magnets produced by liquid quenching nanocrystals of a magnetic compound and then solidifying them with resin. Therefore, their magnetic strength is about half that of sintered magnets. However, neodymium bond magnets are stronger than ferrite magnets and cheaper than neodymium sintered magnets and have shape flexibility.

Nanocomposite magnets consist of a nanoscopic hard phase and a nanoscopic soft phase but behave like single-phase magnets, as the two phases have exchange-coupling functions. Due to particle interaction, nanocomposite magnets produce higher remnant magnetization than the value theoretically expected from a completely isotropic microstructure. Since isotropic nanocomposite magnets have a lower Nd content than bond magnets, they are cheaper and more erosion resistant and are being commercialized as precursor powder for medium-property bond magnets.[18,24] Although isotropic nanocomposites have advantages in the sense that rare metals are scarce, they cannot be made stronger than sintered magnets due to their isotropic property. However, for more than 10 years some people have said that if nanocomposite magnets are made anisotropic by directionally controlling their axis of easy magnetization, it should be possible to obtain properties surpassing those of sintered magnets.

However, no researcher has yet to succeed in aligning crystal orientation on the nano scale. Moreover, there is another unsolved problem that nanocomposite magnets are unable to generate strong coercive force: the conventional research of neodymium magnets has failed to overcome the shortcoming that the coercive force of a neodymium magnet decreases sharply when the volume ratio of its soft phase is increased.[25] This is due to the deficient perspective of controlling the internal textures of materials for generating coercive force. Amid calls for reductions of dysprosium, increasing coercive force has become more urgent than increasing magnetization.

Therefore, in the development of high-performance anisotropic nanocomposite magnets with low rare-earth composition under the MEXT's Element Science and Technology Project, efforts are being made to develop highly-coercive basic magnetic powder and highly-coercive metallic nanoparticles, and to clarify their tissue growth and coercive force generation mechanism, while aiming at creating anisotropic nanocomposites of Fe and $Nd_2Fe_{14}B$ compounds and achieving a coercive force stronger than neodymium magnets without using Dy and concurrently with reducing the use of Nd.[26] The project study is designed to achieve technology to maintain the coercive force without using Dy but by making the size of crystals one-digit smaller than neodymium sintered magnets. Since the conventional method of miniaturizing easily-oxidizable $Nd_2Fe_{14}B$ compounds has its limits, the HDDR process is being experimented with in making powder particles with an anisotropic texture and high coercive force. The HDDR process is a process to break down singlecrystal particles to nanocrystals in high-temperature hydrogen and then make polycrystals with an anisotropic texture by removing the hydrogen. The HDDR process is an interesting process in that recombined crystals can be brought back roughly to their original orientation by subtly controlling reaction conditions. Their grain size is about one-tenth that of neodymium sintered magnets.

The project study is also designed to find a theory to increase coercive force without depending on the crystal magnetic anisotropy of rare earths, such as Nd. Even when crystal grains are miniaturized to reduce the use of Dy, the magnetic anisotropy of Nd and other rare earths still decreases sharply as their temperature is raised. However, since the magnetic anisotropy of iron is less dependent on temperature, if the crystal magnetic anisotropy of iron in rare-earth iron compounds can be utilized, the effect of temperature on the coercivity of magnets can be reduced. As for the hard phase, powder particles with anisotropic internal tissues are made. Although this technology was invented in the 1980s, few researchers have actually utilized it and there are only a few hypotheses concerning tissue growth. Meanwhile, regarding the soft phase, although there is technology to reduce the size of grains to 5 to 10nm, techniques such as those for judging the advisability of applying the technology to compounding processes and compounding the technology into the hard phase, have yet to be established. Therefore, there is a host of challenging issues, including the fact that the surface becomes easily oxidized in the process of producing nanoparticles.

Since there are many issues that have yet to be clarified or resolved in this research project, including the tissue growth mechanism, coercivity generating principle, and technology for producing anisotropic magnetic particles, the first thing to do is attempt to understand mechanisms by studying new magnetic domain observation means and conducting tissue analyses in microscopic areas. Since this research project involves challenging basic research, it is not designed to put technology to practical use by the end of the project period. Rather, its purpose is to ascertain at the end of the project period whether it is possible to industrially produce practical magnetic materials based on nanocomposite magnets in the future.

4-2-3 Development of New Permanent Magnets Substituting for Nd-Fe-B Magnets (Development of New Permanent Magnets)

In March 2010, "Rare Metal Substitute Materials Development Project: (I) Development of New Permanent Magnets Substituting for Nd-Fe-B Magnets and (II) Development of Yttrium Compound Materials for Ultra-Light, High-Performance Motors" was launched as a METI/NEDO project.[27] This project, which is designed to contribute to ensuring the stable supply of rare metals, such as Dy, was inaugurated as part of an emergency economic package (2nd supplementary budget for FY2009). It called for setting a detailed goal that can be achieved during the implementation period after consultation among the New Energy and Industrial Technology Development Organization (NEDO), theme leaders and adopters.

The theme adopted for Project (I) is in essence developing new permanent-magnet materials by using iron-nitrogen compounds. By using readily-available iron and nitrogen as the main raw materials, studies are being made to explore high saturation magnetic flux and high magnetic anisotropic magnets with properties potentially exceeding those of current neodymium magnets. Specifically, it is planned to obtain technical guidelines for synthesizing a desired phase of iron nitride and to build technology to produce bulky R-Fe-N through the analysis of nano-level microstructures and their formation process, and through evaluation of their magnetic characteristics, focusing on iron nitride materials and rare-earth R-Fe-N. The ultimate goal is to contribute to the realization of a low-carbon society by developing new permanent magnets for use in electric and hybrid car motors.

Project (II) is not for the research and development of permanent magnets. Rather, it is designed to develop yttrium (Y) compound materials in order to realize next-generation motors that can replace current motor parts.

4-3 Overseas Production and R&D Status[28]

As Figure 4 shows, neodymium sintered magnets are currently produced mainly in Japan and China. In the 1990s, Japan was the largest producer, while China's and Western countries' production levels were about the same. Then, production in Japan and China increased, but in 2006 China surpassed Japan as the world's largest producer of the magnets. Although Japanese-made neodymium sintered magnets are reputed to be the best in the world in terms of magnetic property, China has become the world's largest producer of the magnets, backed by low cost and abundant resources. Asian countries, including China, South Korea and Taiwan, have intensified their magnet research activities.

Although the number of Japanese-made neodymium sintered magnets used in hard disks and other information equipment has increased as described in Chapter 3, information equipment's share of total neodymium sintered magnet production has decreased due to the effect of smaller and lighter information equipment. On the other hand, the shares of neodymium sintered magnets used in air conditioners and automobiles have increased. In China, about 29% of the neodymium sintered magnets produced in the country was accounted for by use in such products as electric bicycles, VCMs and MRIs, about 44% by such products as speakers and magnetic separators, and about 20% by low-grade applied products, according to 2004 statistics. Chinese-made neodymium sintered magnets have yet to be used in such fields as next-generation car engines in the country. For products requiring high-performance magnets, Japanese-made magnets have been mainly used.

In the 1960s, the U.S. magnet industry was the strongest in the world, but now it has almost disappeared. The United States has not produced neodymium sintered magnets since 2005, after producing about 100 tons in 2004. Most recently, however, concerns have been raised from some quarters, including the military, about the fact that the United States relies completely on China and Japan for its supply of electromagnetic conversion-related devices. This has prompted some researchers to try to revive the country's magnet research. For instance, a group of 44 researchers from industry, academia and government, led by Prof. George C. Hadjipanaysis of the University of Delaware, hosted "The Future of High Performance Permanent Magnets in the U.S.A.," a workshop aimed at revitalizing the research of advanced magnetic materials in the country.

In Europe, although well-known magnet makers are still in business, their production of neodymium sintered magnets in 2007 was about 800 tons, two orders of magnitude smaller than Japan's and China's. Magnets imported from China have increased in European markets. However, since Europeans still think that researching permanent magnets is one of the important components of a sustainable society, European motor manufacturers have begun to contact Japanese magnet researchers actively.

5 Future Approach to Basic and Generic Research in Permanent Magnets

With the trends and problems in the research of permanent magnet motors discussed above in mind, I would like to make my recommendations on how to promote basic and generic research of permanent magnets in the future.

Researching permanent magnets is a challenging project requiring a long period of time. At the same time, however, most of the groundbreaking inventions and discoveries have been put to practical use, producing a major impact on green innovation. Therefore, the input of public funds into basic and generic research aimed at contributing to green innovation, like the national R&D projects described earlier, should be increased and continued.

Table 1 shows the number of participants in recent academic conferences and the number of presentations made at the conferences. Although these numbers alone do not show it clearly, the activities of magnet-related academic societies in Japan have begun to show signs of being reactivated since 2007, when agenda-set national projects concerning the R&D of permanent magnets were inaugurated. The recognition that this area of research has come to be reactivated was shared at a meeting of the Tohoku Motor Magnet Innovation Strategy Council held on June 7, 2010, with a total of 219 industry, academia and government representatives in charge of magnets and the regional economy attending.

It would be meaningful to shed light on important objective basic research for solving green innovation issues, including the R&D of permanent magnets, and to promote such research in a top-down manner. Assuming that the investment efficiency of research and development is constant, if investment in a research and development project is increased and the number of researchers participating in the project also increases, the time required for making a groundbreaking invention or discovery is expected to be shortened.

Needless to say, it is necessary to strive to increase R&D investment efficiency, not to mention the investment amount. Since neodymium magnets are extremely high-quality finished magnets, it is hard to achieve a breakthrough in material composition exploration without a guiding principle. The research of magnets so far seems to have been pursued by industry, guided by experience and intuition. However, such an approach has come to its limits and universities are being asked to come up with a new guiding principle. Fortunately, great progress has been made with measuring technology. For instance, by using such techniques as multiscale analysis, NMR measurement and neutron line diffraction, it has become possible to measure what could not be measured before. Also, the progress made in computer science based on first-principle calculations is expected to advance new theoretical analyses, contributing to material development. For example, in the “Technology Development of Dy-Saving Neodymium Magnets,” which was discussed earlier, progress has been made in clarifying the interrelation between grain-boundary composition/structure and coercivity/internal construction, and in shedding light on the relationship between a microparticle’s anisotropy and its surface by measuring the magnetic property of the microparticle group. In this way, by combining structure and mechanism analysis utilizing advanced measuring techniques with theoretical analysis utilizing computing science, a new guiding principle for material development should be established in order to find new chemical compounds and organize magnetic alloys (Figure 8). This type of teamwork research has already been tested in some national R&D projects, for example, “Technology Development of Dy-Saving Neodymium Magnets.” It is desirable to continue and expand such efforts.

At the same time, however, the invention of new permanent magnets has been historically brought about by bold interdisciplinary ideas, passion and chance, as described in 2-2. Researching magnets requires a variety of expert knowledge: physics and metallurgy for the research of magnetic materials, electromagnetic engineering for the development of magnets, and machine engineering and electronics for their application. Magnets are important material elements to connect electric energy and machine motion in order to convert energy into movement and vice versa. However, as described in 4-2, there are many phenomena that have yet to be theoretically explained. Hence, the participation of researchers in various specialized fields is required. For instance, it is necessary to promote the participation of researchers not only in the department of engineering but also in the department of science. This raises the necessity of promoting proposal-based research, based on the free thinking of individual researchers. As a bottom-up approach to promote the participation of researchers in different fields, it would be beneficial to establish a kind of competitive research funding that encourages agenda-set development competition.[29]

It would be useful to develop the style of Scientific

Table 1 : Trends in the Number of Participants in Magnet-Related Academic Conferences and the Number of Presentations

Magnetics Society of Japan, Hard Magnetic Materials Study Group

Calendar Year	1984	1987	1988	1991	1994	1996	1998	2001	2003	2005			2008
										First	Second	Third	
Number of participants	192	178	144	118	111	63	96	98	64	75	38	68	46

Japan Institute of Metals

Year	2006		2007		2008		2009		2010
	Spring	Autumn	Spring	Autumn	Spring	Autumn	Spring	Autumn	Spring
Number of presentations on hard magnetic materials	12	4	9	5	14	19	33	25	16

(Note); The 9 cases in the spring of 2007 include one symposium and the 33 cases in the spring of 209 include 27 symposiums.

Institute of Electrical Engineers of Japan, Division A meeting (Magnetic materials, etc.)

Year	2007	2008	2009
Number of participants	192	178	144

Prepared by the STFC based on academic societies’ data

Research on Priority Areas consisting of planned and proposal-based research in the Grants-in-Aid for Scientific Research under the collaboration of industry, academia and government. In other words, we need a system designed to promote both planned research at centers of excellence under industry-academia-government collaboration and proposal-based research following agenda set by project leaders of planned research under said collaboration. Figure 9 illustrates the problems involved in the development of permanent magnets and R&D approaches to solve them.

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This report is based on speeches by the members of the Tohoku Motor Magnet Innovation Strategy Council and their discussions at Strategy Council meetings. Among the speakers are Yoshikazu Goto, councilor at the Ministry of Economy, Trade and Industry, Katsuhiko Ito, deputy governor of Miyagi

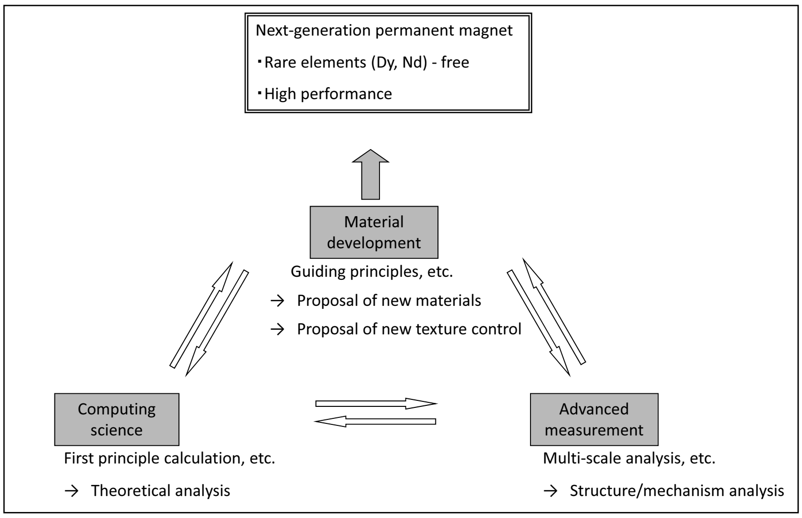

Figure 8 : Approach to Basic and Generic Research of Permanent Magnets for Motors (Teamwork-type planned research)

Prepared by the STFC

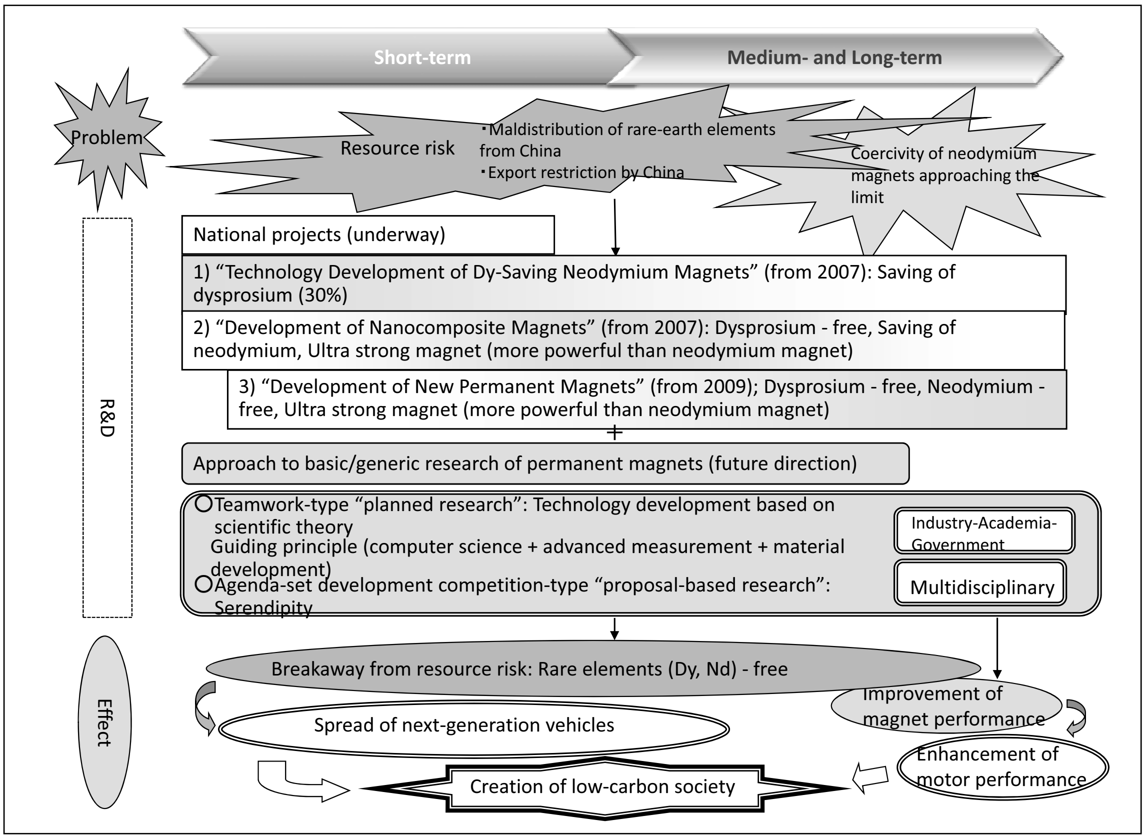

Figure 9 : Problems with Permanent Magnets and Approach to Basic/Generic Research

Prepared by the STFC

Prefecture, Yoshio Endo, executive director of the Tohoku Economic Federation, Masataka Muramatsu, Toyota Motor Corp. director, Hideki Harada, chief executive officer of the Japan Association of Bonded Magnetic Materials, Yasuo Iida, program manager at the New Energy and Industrial Technology Development Organization, Takeshi Nishiuchi, senior researcher at Hitachi Metals Ltd., Masato Sagawa, president of Intermetallics Co., Kazuhiro Hono, fellow at the National Institute for Materials Science, Hiroshi Kazui, chief of the Tohoku Bureau of Economy, Trade and Industry, Ko Kumagai, president of Tohoku Innovation Capital Corp., Satoshi Kawakami, operating officer at Tokyo Electron Ltd., Akihisa Inoue, chancellor of Tohoku University, Satoshi Sugimoto, professor at Tohoku University, Ken Takahashi, professor at Tohoku University, Masuo Okada, professor at Tohoku University, and Akira Miyamoto, director at the Industry Creation Hatchery Center. I would like to take this opportunity to extend my deepest gratitude to each of them.

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Profile

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