Rare earth elements and permanent magnets (invited)

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Rare earth (RE) magnets have become virtually indispensible in a wide variety of industries such as aerospace, automotive, electronics, medical, and military. RE elements are essential ingredients in these high performance magnets based on intermetallic compounds RECo5, RE2TM17 (TM: transition metal), and RE2TM14B. Rare earth magnets are known for their superior magnetic properties—high induction, and coercive force. These properties arise due to the extremely high magnetocrystalline anisotropy made possible by unique 3d-4f interactions between transition metals and rare earths. For more than 40 years, these magnets remain the number one choice in applications that require high magnetic fields in extreme operating conditions—high demagnetization forces and high temperature. EEC produces and specializes in RECo5 and RE2TM17 type sintered magnets. Samarium and gadolinium are key RE ingredients in the powder metallurgical magnet production processes which include melting, crushing, jet milling, pressing, sintering, and heat treating. The magnetic properties and applications of these magnets will be discussed. We will also briefly discuss the past, current, and future of the permanent magnet business. Currently, over 95% of all pure rare earth oxides are sourced from China, which currently controls the market. We will provide insights regarding current and potential new magnet technologies and designer choices, which may mitigate rare earth supply chain issues now and into the future. [doi:10.1063/1.3676616]

I. INTRODUCTION

In Japan, it has been said that oil is the "blood," steel is the "body," and rare earths are the "vitamins" of a modern economy. Rare earth elements are ubiquitous in many civilian, green energy, and military technologies. They have become imbedded in applications such as face-centered catalysts for efficient oil production, florescent light bulbs, hybrid electric vehicles, nickel metal hydride batteries, computer hard drives, glass additives, polishing powders, direct-drive high power wind generators, speakers, nuclear fuels, radar, most weapons systems, and over a thousand other uses. Several rare earth elements are essential ingredients in production of the highest performance magnets available in the world today, which has enabled vast miniaturization and the significant increase in power density in hundreds of applications.

China has become the dominant source of rare earth elements over the last two decades. Today, nearly 100% of the world's rare earth metals and more than 95% of the rare earth oxides come from China. China's near worldwide monopoly on the production of downstream materials such as rare earth oxides, metals, and magnets severely impacts the supply chain in this growing global market. The past decade has seen an unmistakable trend toward increased dominance in raw material production and manufacturing by China, and a steep decline in U.S. production capabilities, most notably in the neodymium iron boron (Nd-Fe-B) market where there is currently no domestic production. This Chinese dominance is further demonstrated with over 65% of hard ferrite and roughly half of aluminum nickel cobalt (Alnico) and samarium cobalt (Sm-Co) production in that nation.[1] In addition, China has imposed export quotas and export taxes of up to 25% for rare earth elements, arguably in violation of their covenants made with their protocol of accession to the Word Trade Organization. These export quotas have been decreasing steadily over the last several years in spite of rising global demand and were slashed by 72% in July 2010,[2] causing many recent news stories.

Practically, the aftermath of the quota reductions last year resulted in skyrocketing prices, long and uncertain deliveries, very fast payment terms with advance payments and fundamental questions about whether or not materials would be available at all at any price. The amount of stockpiled materials companies had going into the change had a big impact on how they responded. Companies found themselves pouring enormous amounts of money into raw materials in order to build inventories to ensure continuous operations and deliver their products to customers. In addition, due to the lack of availability of pure elemental forms of the rare earths, testing and evaluation of rare earth alloys took time and resources. Customers of products containing rare earths have been working to redesign systems using less rare earths, opting for lesser performing substitutes. This money would have been better deployed on capital equipment, adding employees, workforce training and facilities expansion to enhance international competitiveness. Instead, it sits in drums full of rare earth inventories and lost time and effort.

Prices have moved by over an order of magnitude since June, 2010, and the gap between internal to external Chinese

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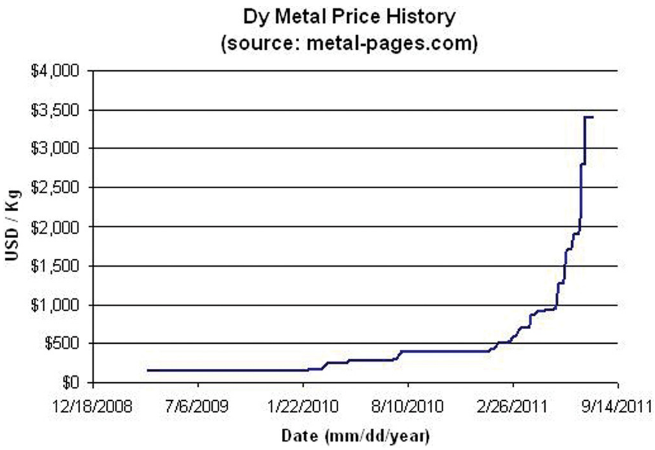

FIG. 1. (Color online) Dysprosium price history 2009 to 2011.

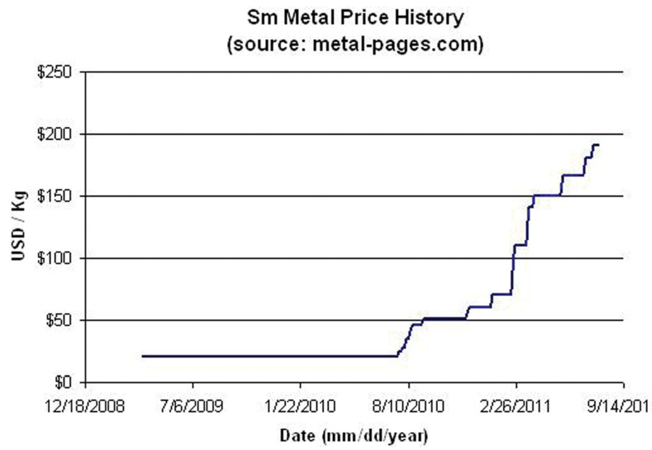

FIG. 3. (Color online) Samarium price history 2008 to 2011.

prices has widened.[3] Dysprosium metal has moved to nearly \$3500/kg, up from \$170/kg within the past two years (Fig. 1). Neodymium metal has moved from \$30/kg to over \$470 (Fig. 2) and samarium metal from \$21/kg to \$200/kg (Fig. 3). Prices have increased in China, but not nearly to the extent experienced outside of China, where the export quota was reduced by 40% of 2009 levels for 2010 and 2011. The difference in the price of rare earths between the domestic Chinese price and FOB China is significantly over \$100/kg for the rare earths. This makes the price differential range from a few percent on the most expensive rare earths such as terbium and dysprosium, to more than 600% for less expensive rare earths such as cerium or samarium.

II. RARE EARTH PERMANENT MAGNET OVERVIEW

Up through the 1960s, most permanent magnets were based on iron in combination with other transition metals such as cobalt and nickel. The dominant magnet material by tonnage comprising 89% of worldwide magnet sales is ferrite, which is essentially a form of iron oxide. Non-rare

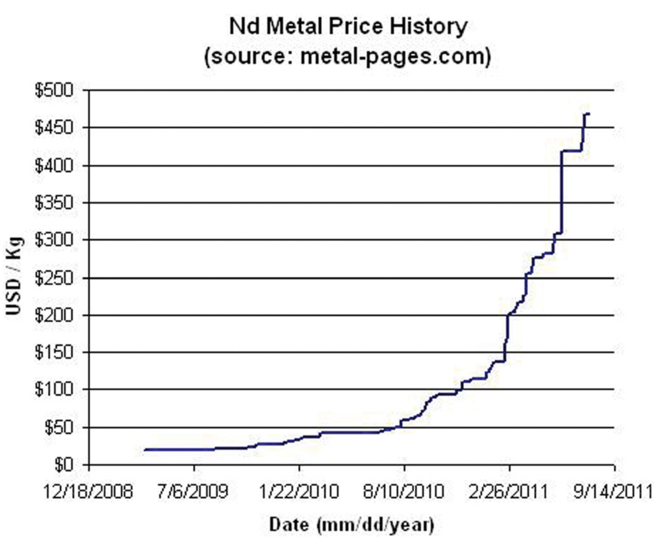

FIG. 2. (Color online) Neodymium price history 2008 to 2011.

earth magnets have been available for decades in the form of ferrites and Alnico.

In the 1960s, researchers at Wright Patterson Air Force Base discovered a new class of magnets based on the rare earth metal samarium and the transition metal cobalt. Hence, rare earth magnets were born. In the 1980s, neodymium iron boron, another rare earth-transition metal magnet, was developed in Japan and the United States.

The American magnet industry reached its peak in the late 1980s and early 1990s. At the time, roughly 6000 people were employed producing magnets in the United States. Today the U.S. magnet industry now employs roughly 600 people. There are now three Alnico producers, one independent hard ferrite producer, two Sm-Co producers, and no NdFeB producers, even though NdFeB is now the largest seller and most recent type of permanent magnet material.[4] Worldwide magnet sales topped \$8 billion in 2010, with U.S. manufacturing capacity a tiny portion of the total. Sales in permanent magnets overall are projected to double by the end of this decade.

Rare earth magnets owe their superior properties of high induction and coercive force to the unique combination of elements with unfilled "d" and "f" orbitals, in other words a transition metal and a rare earth. The combination of these elements and others allow the electrons in the alloy structure to align with one another anisotropically and obtain a much higher residual induction (B_r) with a much higher resistance to being demagnetized or intrinsic coercivity (H_c) than previous material systems.

In the samarium cobalt system, the predominant rare earth used is samarium, and the primary transition metal is cobalt, which is often used along with iron, zirconium, and copper. The rare earth content in the Sm-Co system is typically in the range of 25–35% by weight. Some specialty grades for near zero change in residual induction over a wide temperature range utilize the rare earth gadolinium. As temperature rises, the residual induction of Sm-Co decreases, while for Gd-Co, the residual induction increases, although from a much lower initial value. A combination of Sm-Co and Gd-Co allows producers to offer high stability magnets with as low as 10 ppm change in magnetic induction per

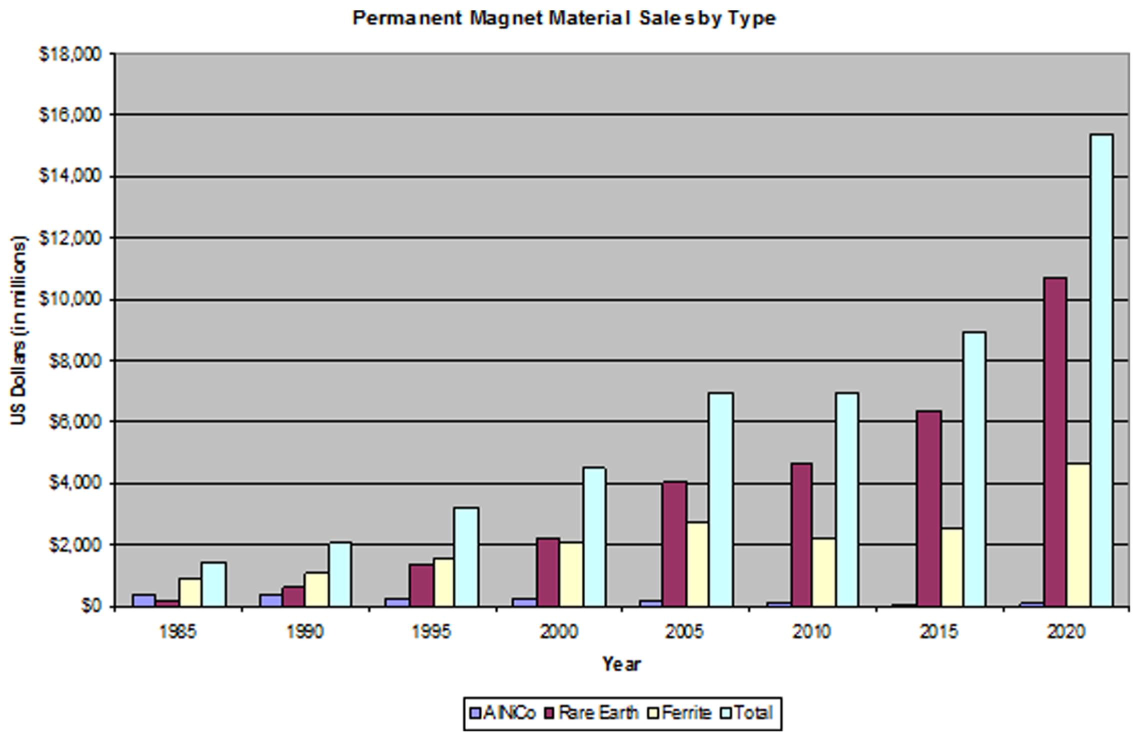

FIG. 4. (Color online) Permanent magnet sales by type by revenue worldwide.

degree Celsius. This is useful in some of the many applications of samarium cobalt magnets, which include motors and generators, actuators, medical devices, oil exploration, microwave communications, guidance systems, and many others.[5] The most common customer requirements are typically for higher temperature and higher stability with high performance and high resistance to demagnetization.

In the neodymium iron boron system, neodymium is the predominant rare earth element employed. The transition metal of predominant use is iron with some cobalt used in some grades. The weight percentage of total rare earths is approximately 31%. The rare earth praseodymium is often used as a significant partial substitution for neodymium, generally to reduce costs in its pure form or as a mixture with neodymium. For higher temperature applications, neodymium is partially substituted by the rare earth dysprosium levels well beyond 5% by weight and in some grades terbium is utilized to increase the Hc or resistance to demagnetization. Increasing coercive force comes at the expense of remanance.

This need for dysprosium is of particular importance in the emerging applications of the Nd-Fe-B magnets used in hybrid electric vehicles in the transmissions for their motors and generators, which give these vehicles their combustion engine-electric motor dual functionality. Permanent magnets offer the higher torques over the broad temperature range needed when compared to induction machines. This engine environment requires Nd-Fe-B with higher temperature grades, which must have substantial amounts of dysprosium in order to increase H_{ci}.

One can see the trend over time in the development of higher energy product magnets which has been transferred into commercial acceptance as well. Around the year 2000 rare earth magnets eclipsed non-rare earth magnets in dollar volume of sales worldwide even though they can be 5–20 times more expensive per kilogram than non-rare earth alternatives (Fig. 4). The primary reason for this shift is due to higher magnetic flux per unit mass. This not only reduces magnet sizes but also reduces system costs by enabling surrounding components to get smaller. This helps to miniaturize the devices and therefore expand uses and broaden market penetration.

The main reason why rare earth permanent magnets have garnered so much attention in the discussions on Chinese rare earth dominance is that Nd-Fe-B magnets drive much of the worldwide demand. The rare earth elements employed for magnets comprise just over 20% of the demand by tonnage but between 30 and 50% of the demand by total value of the materials.[6] That value varies highly due to the recent dramatic fluctuations in price; nonetheless, magnet applications are the largest market sector in commercial value.

The 17 elements, which comprise the rare earths, include the elements lanthanum through lutetium and the elements scandium and yttrium since they are generally found together. Some deposits also contain the radioactive element thorium. Rare earths are not truly rare in the earth's crust since they have a relative abundance comparable to cobalt and nickel[7] (Fig. 5). It is important to note that relative abundance in nature does not necessarily lead to commercially successful mining and processing operations. Each ore body has its own unique distribution of rare earth elements ranging from the "light" to "heavy" rare earths, which can vary significantly due to the nature of the deposits found worldwide. When they are mined, all of them are obtained together in various concentrations whether there is demand for all of what is obtained or not. The "light" rare earths, which typically comprise the elements lanthanum up through

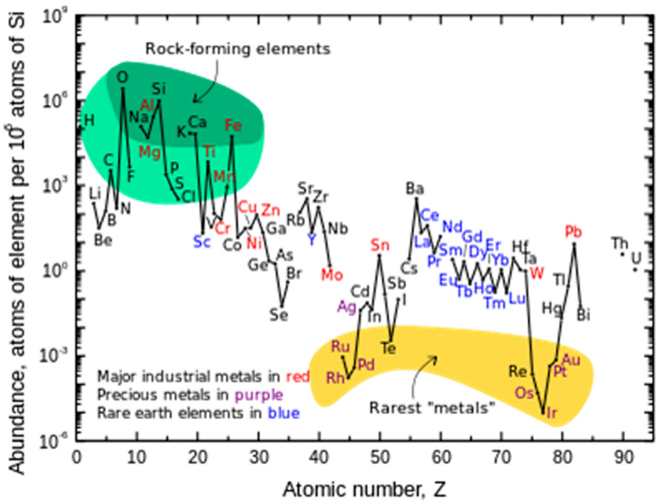

FIG. 5. (Color online) Relative abundance of elements worldwide.

samarium, are much more abundant than the "heavies." The "heavy" rare earths are comprised of the elements europium through lutetium and have more limited number of ore bodies in the world which contain them. In addition, heavy rare earth elements account for roughly one to two percent of the reserves of all of the 300 or more potential rare earth deposits identified in the world.

Neodymium along with lanthanum to a lesser extent are the key drivers of demand for the light rare earths. Neodymium has been historically up to several times the price of the other light rare earth elements. The demand for neodymium is very tight compared to available supply and will continue to be so until after substantial non-Chinese mining separation and down stream production may come on line by the end of 2012.[8] Praseodymium, samarium, and gadolinium on the other hand have been in oversupply, which is still anticipated to be the case even with new mining operations coming on-stream. The supply of samarium has been estimated at roughly three times the demand. In 2009, there was so much extra samarium that there are a number of claims that, along with cerium, were being dumped back into the mining tailings in China.

Of the heavy rare earths, dysprosium is of very high interest due to the high price and relatively higher market tonnage required. The rare earth terbium, historically the highest price of all rare earths which also has a lower annual demand tonnage, has primary application as a phosphor in florescent lighting with modest, but important amounts used in magnets. In addition, dysprosium has perhaps the longest time ahead of it where it is slated to be in deficit between supply and demand which could last until the end of this decade. One can therefore see that due to permanent magnet industry needs for neodymium and dysprosium, these elements have a substantial influence in the overall rare earth element mining and downstream supply chain.

Strategies developed to ease rare earth use in permanent magnets could have a big impact on the supply chain. Core technical strategies to reduce usage of rare earths in magnets are the areas of mitigation, elimination or replacement, and recycling. All of these approaches will require substantial technology development and are fraught with inherent risks. Although such measures may prove helpful in the medium to long term, due to the growth in demand for rare earths and magnets, development of new production sources of rare earths and downstream supply chain capacity outside of China is an inescapable reality.

Mitigation strategies are ones which reduce the usage of rare earths and include incremental production process improvements through the development of novel magnet systems. Just a few such strategies and technologies will be briefly touched on here.

In Slovenia in September of 2010 at the biannual Rare Earth Permanent Magnet workshop, it was evident that development of technology to mitigate rare earths usage in magnets is an area of extremely heavy emphasis by Japan on dysprosium.[9] The Japanese government at the instigation of Toyota beginning around 2005 started to invest substantially in technology development to reduce rare earth content and has invested over $500 million in rare earths. Areas of research to reduce dysprosium content include efforts such as improved grain refinement, and interfacial control, helium jet milling, and reduction of the amount of dysprosium in individual grains through development of magnet particles with shell "rich" and core "light" concentrations.

Next generation magnets, which in theory could double the performance of current rare earth permanent magnets, are under development at several research institutions and companies around the world. Meta materials are nanocomposite magnets which take "hard" magnetic particles Nd-Fe-B or Sm-Co on the nano scale and combine them with a “soft” magnetic material, iron. When the hard and soft magnetic phases are combined at the nanoscale, they act as one system. The key physical principle is that there is an exchange coupling between the soft phases and the hard magnetic phase. Nanocomposite magnets take the advantage of high saturation magnetization of the soft magnetic phase and benefit from the high intrinsic coercivity of the hard magnetic phase. Development of these anisotropic high energy permanent magnets are focused in the areas of nano particle production and developing approaches, which will allow the interaction of the hard and soft phases to consistently achieve

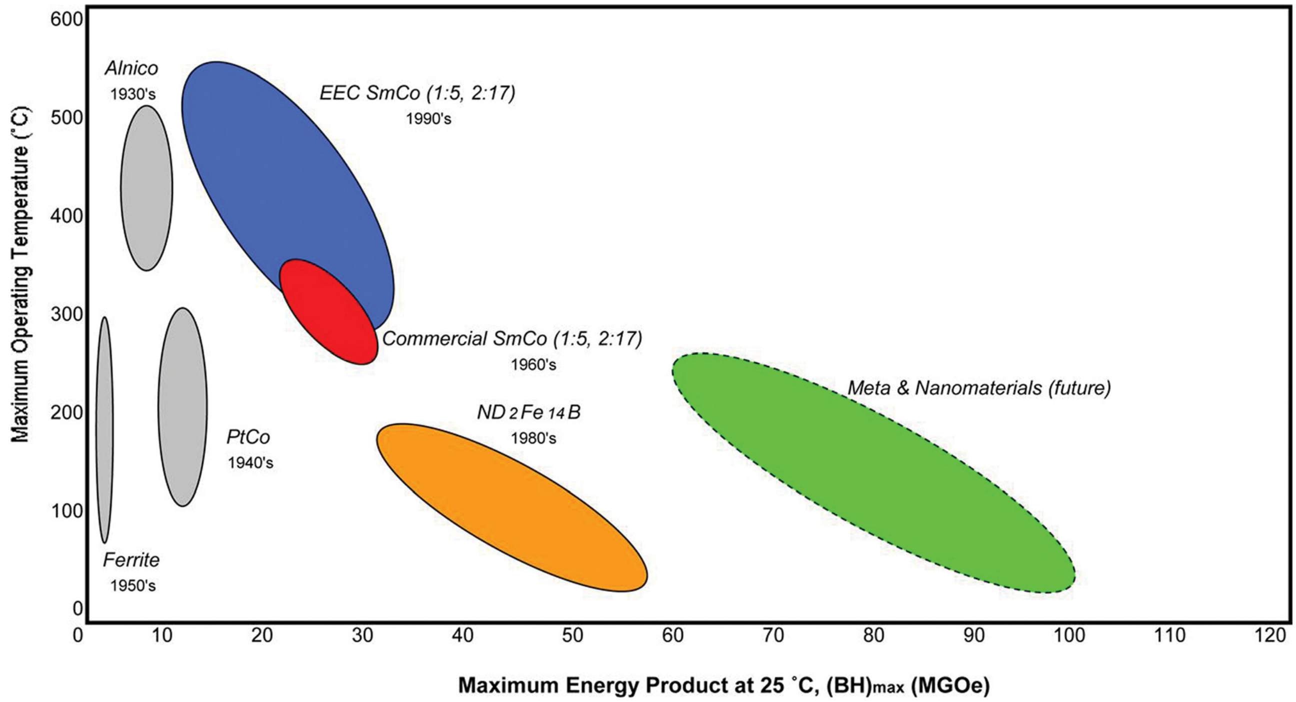

FIG. 6. (Color online) Comparison of magnet type by maximum energy product and maximum operating temperature.

the high induction and coercivity.[10] In addition, consolidation techniques, which are employed for rare earth magnets, i.e., sintering at high temperatures, will not work for these new systems due to adverse grain growth. Lower temperature processes such as die upsetting and hot pressing or others need to be developed for these new materials.

Nanocomposites represent an opportunity to reduce rare earth usage in two fundamental ways. First, the performance is enhanced since the total mass of the magnet to obtain a desired magnetic flux is reduced substantially. In addition, the rare earth content will be diluted due to the addition of iron in amounts, which could be as much as 30%. Such a new breakthrough material could offset this mitigation of rare earths by increased demand for such magnets by enabling further miniaturization and new customer applications.

Non rare earth magnet systems have been and are still topics of increasingly intense investigation. In the last century, a wide variety of systems have been thoroughly investigated significantly limiting the potential for new systems to be discovered. In addition, some such non rare earth systems may not perform as well as current rare earth magnets. However, the hope is that these systems could offer considerable customer benefits in cost and decrease the large gap in performance between non rare earths and Nd-Fe-B and Sm-Co thus creating substantial new opportunities in the marketplace. Although there are some magnet systems which could theoretically be developed, there are enormous fundamental challenges which need to be overcome. Such efforts in new materials could provide some answers to the rare earth supply chain issues; however, one must recognize the very high risk. Also, potential benefits from successes will not be realized in magnet production in the short term or even medium term.

Some customers are currently re-designing and qualifying systems by replacement of higher cost, higher dysprosium Nd-Fe-B magnets with samarium cobalt magnets whose properties in some cases can be very similar or even exceed performance of the original material (Fig. 6). Although samarium is impacted by the supply chain issues, the longer term potential for reasonable pricing and availability is quite good. Also, ferrite and alnico magnets can offer customers choices; however, the gap between their performance and Nd-Fe-B is higher. This may cause issues with customers on overall magnet system performance, size, weight, and cost. In addition, for motor and generator applications, use of coil wound induction machines in lieu of permanent magnet machines can provide alternatives. All such efforts require substantial time, money, and effort to develop.

Recycling of rare earths is an area of strong interest at present around the world. The high prices of rare earths at present make it more attractive to recoup value from scrap and other sources than in the past. Current recycling practices in the Nd-Fe-B production have been predominantly to return minor amounts of scrap material and re-melt it along with new alloy. The downside of such an approach is that it usually reduces overall magnetic properties. In samarium cobalt, some of this remelting activity occurs, but often only the cobalt is recycled into new material from waste streams. Organic contaminants from machining processes and adhesives used in securing magnets into assemblies are impediments to recycling. In addition, the common practice of nickel coating onto Nd-Fe-B magnets for corrosion protection is not only a chemical contaminant but also nickel's magnetic properties can pose additional issues in attaining desired magnetic performance. Rare earth magnets are brittle intermetallics, which are deeply imbedded into other products, thereby physical extraction often yields a small return on substantial effort to recycle end of life products.

Rare earths are chemically very similar, which causes a high challenge in separation from ore bodies of known input compositions. Mixed recycle input streams of rare earths from many sources will require even greater effort to separate the rare earths into re-sellable compositions. Some success is being reported in Japan in Nd-Fe-B magnet recycling from end of life products in air conditioning compressor motors and elsewhere. In spite of these challenges, very worthwhile efforts and interest to ramp up development of cost effective and innovative recycling technologies are being pursued.

III. CONCLUSION

Although a broad variety of issues have been covered here in response to the current situation with China's dominance of rare earth elements, there are tremendous opportunities for technology development and commercial success. Rare earths in the short to long term will continue to be the materials of choice for many growing applications for which replacements will be very challenging if not impractical. Fortunately, the news headlines have infused much cash into non-Chinese rare earth mining and downstream supply chain development and production interests, which are moving forward with vigor in the United States, Canada, Australia, Asia, and South Africa. In addition, the U.S. government is engaged in collaborating with industry and academia in re-invigorating the international rare earth supply chain. This is a great area of business and technology to participate in through the balance of this decade.

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