Title: The Big Picture - Putting the Magnet Market Trends Together

Abstract: A common theme in the magnet industry is to attempt to forecast production and consumption of magnets within one or two applications, ignoring others. In one widely discussed market, for example, one can look at the transition from conventional ICE (internal combustion engines) to hybrid or full electric drive vehicles and the associated magnet requirements. Other markets of note include transportation electrification, stationary and mobile refrigeration systems, medical diagnostics, drones (many use motors!), robotics, etc. There is also a transition taking place from HDDs (hard disk drives) to SSDs which is likely to free up measurable amounts of neodymium. We'll look at these and other applications/industries, the growth trends within each and the combined demand-supply picture.

The following is text to support content of the slides presented at Magnetics 2018 in Orlando, Florida, February 8 and 9, 2018.

Slide 1: Thank you for the opportunity to speak with you about the market for rare earth magnets and especially for the market-leading NdFeB ("Neo") magnets.

Slide 2: We in North America still enjoy the largest GDP of any country. However, our population is only a small fraction of the world's total at 4.8% and is forecast to become a slightly smaller portion over the next 15 years.

This means that economic activity is very likely to shift to more populous regions, especially the 3rd world countries, as they develop a middle class, an improved infrastructure and stabilized political, health, legal and social issues. This is truly a global economy. To be successful today means traveling, learning foreign languages and familiarity with cultures of other countries.

Slide 3: Agenda.

Slide 4: Here is the short list of commercially available permanent magnets. Ferrite magnets continue to represent the largest volume sold on a weight basis. However, Nd-Fe-B magnets are a larger fraction based on dollars sold. Neo magnets are >six times more expensive than ferrite. Fractions of each type of rare earth magnet, in round numbers, is:

- NdFeB, sintered, fully dense: 90% of all rare earth magnets
- NdFeB, bonded magnets: about 5%
- SmCo, sintered, fully dense: 4%
- SmFeN, bonded either only SmFeN or hybrid magnets mixing SmFeN with ferrite: 1%

Slide 5: Production of permanent magnets has been tracked for many years by MMPA in the 1980s and 1990s, by industry experts such as Terry Clagett in the late 1990s and up to about

2010, Yang Luo of China in the early 2000s, the staff at Gorham Advanced Materials Institute, MMPA, and several others. As production and consumption has shifted to the Far East, mainly China, it has become very difficult to capture data. For example, there are (still) over 300 companies in China with capability to produce NdFeB magnets.

The data for 2010 has been vetted over several years and with several sources. It is believed to be as close to accurate as might be expected. Dividing total dollars by total weights to obtain average prices provides a crude verification of the data and these values appear to be reasonable. On the other hand, data for 2016, besides being quite recent, has not had the same level of scrutiny – therefore, please consider the numbers as being +/- 10% for the top half of the list and +/-15% for the bottom half.

In this summary of products, SmFeN is included in the “Other” category.

Slide 6: The USGS has tracked production of rare earth oxide for several decades and annually publishes the data it collates as supplied by producing countries. This graph shows a peak mine output in 2009 and 2010 followed by a reduction due to the issuance of mine production quotas by the Chinese government. By 2009, Molycorp had shut down its production operations and there was no major production outside of China.

Slide 7: The published amount of REO production was not adequate to sustain magnet production at the levels reported within the industry. This is indicated on the chart as point 1: Reported REO production and point 2: the inferred NdFeB magnet production. The inferred magnet production is smaller (~90,000 tons) than industry reports (105,000 tons).

Point number 3 indicates the chart line showing the magnet output reported by industry. Point 4 is at 105,000 for year 2016 (NdFeB only).

The process for producing NdFeB magnets is well-understood as are the production yields. It is possible with good accuracy to predict the amount of REO required to be mined, beneficiated and separated to provide the metals to produce the magnet quantities shown. Point 5 indicates the chart line of the REO quantities. Note we are talking about total REO, not just the magnet rare earths (Nd, Pr, Sm, Dy).

The difference between point 1 and points on the line (point 5) are provided by the black market, mostly within China. Size of the black market has been estimated between 10 and 60% of the total REO output. Since it is a black market, we can only infer its size.

Slide 8: There is only one large REO producer outside of China: Lynas. Lynas is an Australian company which mines and concentrates the ore at Mt. Weld in Western Australia then ships the concentrate to its LAMP facility in Malaysia (Lynas Advanced Manufacturing Plant). Production output has reached 16,000 tons per annum, a few thousand tons short of the ultimate objective – the original plan called for 22,000 tons per annum output at current levels of capital investment.

Conclusion: there may well be a continuing shortfall of magnet rare earths which will be exacerbated by robust economic activity globally and a crack-down on black market supply.

4785 County Road 33 | Phone: 585-229-2187 | sc45@frontiernet.net
Honeoye, NY 14471 | www.magmatllc.com

Slide 9: While the sourcing of material may become problematic, what are some of the major applications and changes happening with them?

Slide 10: This is an introduction slide for a select group of applications. Current market size is indicated with some forecast data.

Slide 11: Now let's look at a few specific markets in more detail, starting with HDDs (hard disk drives).

Slide 12: Most of you are probably familiar with a shift that is occurring from traditional hard disk drive data storage to the use of flash memory – called solid state drives or SDDs. A thumb drive is a small example. Memory assemblages are now available that replace hard disk drives with capacities to multiple terabytes. SDDs are faster than HDDs and less prone to physical damage. They have been more expensive, but are quickly reaching price parity.

For large installations, they have a major advantage in that they consume less electrical energy, generate less heat and require less cooling. Lower energy consumption means lower operating cost over time.

Slide 13: After peaking in 2010, HDD production, in units, has been on a steady decline. Not shown in this chart is that the average size (storage capacity of the drives) has been increasing. Nevertheless, due to conversion to SSD, we can expect a continuing erosion of HDD quantities to take place.

Slide 14: In this slide, we show on the right axis units sold per year. Magnet tons required is indicated on the left axis. The magnets' weight includes the spindle drive motor bonded magnet and the voice coil motor sintered magnet. Tonnage also includes modest amounts of magnets that have been present in optical disk drives (ODDs) though many of these magnets are ferrite (including molded ferrite) instead of NdFeB.

Slide 15: The next market for us to examine is transportation – specifically cars and small trucks.

Slide 16: A reason for considering electric drive vehicles, aside from CO_2 emissions, is potential for improved efficiencies. Thomas Keim and John Miller prepared this illustration in 2008. It shows us four areas of high energy loss that can be dramatically reduced using an electric traction drive motor.

Slide 17: How large is the automotive marketplace? Developed countries have stabilized near 40 million units produced per year. Both emerging economies and China are growing rapidly. The sum of all markets in 2015 was 86 million vehicles.

Slide 18: Looking at the USA, we see that alternative drive vehicles represent about 3% of the US market of 17 million vehicles – ignoring diesel. This is only slightly better than 2016. Growth of the market has been slow due to relatively low gasoline prices and the premium cost of an electric drive vehicle.

Slide 19: Globally, the market for battery electric and plug-in electric drive vehicles reached 1.28% penetration compared with 1.04% in the USA.

Slide 20: One reason for the high cost of electric vehicles is the battery. To store adequate energy, it must be large and therefore costs a great deal. The cost per battery in the first Tesla model has been about $15,000, about 25% of the price of the vehicle.

Lithium ion batteries contain substantial amounts of cobalt which has doubled in price during 2017. Batteries now account for about 50% of all cobalt consumed each year. For comparison, the magnet industry consumes between 6 and 7% of the cobalt.

Slide 21: Several countries have announced the end of production for ICE vehicles (internal combustion engines) within the next 20 years. Each country has its own rationale for the termination of ICE production. However, several sources are predicting a much more moderate transition from ICE to EV. This includes Berkshire Hathaway and large automakers (per Bloomberg). The DOE and its International Energy Agency are far more sanguine regarding the speed of the transition. We'll see…

Slide 22: I've been so dismayed at overly optimistic forecasts that I've produced my own forecast as shown here. Since its creation the only large change I've had to make was 18 months ago reducing market penetration by diesel due to the emissions problems experienced by Volkswagen and Fiat-Chrysler.

Note that even in 2015, ICE represents about 80% of vehicles sold in the USA – per my forecast.

Slide 23: Using data from the previous slide and extrapolating forward to year 2050 calculations can be made to show magnet requirements – just for the traction drive system. Assumptions are shown on the slide. Large quantities of magnets would be required and new mines must be opened!

In the assumptions, market penetration of EVs by 2050 is shown as 50%.

Slide 24: Let's do wind power next.

Slide 25: Wind power is nothing new. Well, it was done a bit differently in 1888.

Slide 26: Wind power grew from small generators of 1 or a few kilowatts to large units of 8 megawatts or greater.

From 1 to 100 kW (kilowatts) is considered "small wind". Above 100 kW is utility-scale wind.

Induction generators spin at 1500 to 1800 rpm and are mostly now of the doubly fed type (DFIG). Speed of the large rotating blades is limited to about 10 to 12 rpm due to physical stress. To spin the generator at 1800 rpm requires a 3-stage step-up gearbox. This gearbox undergoes severe distortional stress as well as gear tooth stress. The result is rapid wear requiring frequent refurbishment - annually or more often. The gearbox also produces noise which may disturb neighbors.

4785 County Road 33 Phone: 585-229-2187 sc45@frontiernet.net
Honeoye, NY 14471 www.magmatllc.com

To avoid these problems, permanent magnet direct drive (PMDD) generators were designed. The blades still turn at 12 rpm, but so too does the generator. To obtain high energy output requires frequent pole-switching within the generator. This is accomplished by making the outside diameter large and placing numerous magnets on the OD – more than 140 is common, each producing a pole reversal.

Size of offshore generators is especially large such as this D7 unit from Siemens illustrated with an Airbus A380 to show scale.

Slide 27: This data from GreenTechMedia shows the transition from small MW-rated towers to larger ones with orders for delivery starting in 2018 averaging close to 8 MW (megawatts).

Slide 28: A map of the USA shows a concentration of wind generators in the mid-west, extending from Texas up to Minnesota and east into Indiana. These are relatively near the industrial center of the country. Installing windfarms to the west will require grid infrastructure expansion. Installing more wind farms to the east will require more expensive leases and NIMBY rejections.

Slide 29: The Global Wind Energy Council published an outlook in 2016 containing this forecast – this table is the moderate growth scenario. What does this mean for the magnet industry?

Slide 30: Using their forecast and industry actual data for the percentage direct drive, magnet weight required per MW output per tower, rate of installation, percentage of re-powered towers, etc., this chart was prepared. We expect a peak in new installations (globally) sometime in the mid-2020s followed by a slowing. Simultaneously, a refurbishment of existing generators will accelerate. Generator design life is mostly 20 years. Some magnet structures may be reusable and some will require replacement.

In any event, magnet demand is expected to peak at over 40,000 tons per annum.

Slide 31: The next market is "cool".

Slide 32: Magnetic refrigeration is accomplished using a material's magnetocaloric characteristics. Discovered in 1880 and examined more closely in the 1920s, it was only considered a scientific curiosity until 1997 when Karl Gschneidner, Vitalij Pecharsky and associates discovered a giant magnetocaloric effect (GMCE) using a gadolinium alloy. Suddenly the race was on.

Slide 33: Conventional refrigeration has two major shortcomings. First, it uses materials that can have a harmful effect on the environment (Freon). Secondly, the compressor used in the Carnot cycle consumes large amounts of energy – as described here.

However, existing refrigerator compressor systems have been made in large quantities for many decades, the designs have been greatly refined and production has been made very efficient.

Slide 34: The market opportunities are huge! Even larger than automotive – and, by-the-way, most cars and trucks now come with an air conditioner.

Slide 35: A number of companies and laboratories are working on the final hurdles. The two main ones are: 1) the cost of the magnet and system is about 4x the cost of a comparable performance Carnot cycle refrigerator system; and 2) a fully acceptable GMCE material has not yet been vetted.

Slide 36: The illustration shows a mock-up assembly. Watch the YouTube video for a visually clear illustration. Note the size of the magnet assembly. It must produce as large a field as practical in the region of the GMCE material (>1.5 tesla is desired).

Either the GMCE material is moved into and out of the magnetic field or the magnet is cycled past the GMCE material.

Slide 37: Estimates – and they are just that – are made for the many market opportunities and calculations for magnet demand indicated.

Because of the huge numbers of systems and relatively large size of the permanent magnet, magnet demand is extraordinarily high. If all systems were converted (by 2050), annual magnet demand would be on the order of 900 thousand tons – about 9 times the 2016 production.

If a significant reduction in the required magnet weight is not possible, these systems may develop for specialty purposes only.

Slide 38: Or, wait a moment. What about alnico magnets? Might they be used? Perhaps. But recall they contain cobalt, nickel, and copper.

Slide 39: So, let's wrap this up.

Slide 40: This is a busy slide! Most of the applications using rare earth magnets are listed here. 2015 data is "reasonably" accurate (perhaps +/-10%). From that we forecast market growth (or shrinkage) in 5-year increments to 2050. These are just best estimates of market size. Many factors can change market size including new production techniques and yields, government mandates or quotas, discovery of additional resources, competing application technologies, etc.

For magnetic refrigeration, the assumption is made that it is a specialty system.

Slide 41: This is the Finger Lakes region of western New York State – in the summer time!

The breadth of the market and short time for this presentation has required limiting content. Not all application data is available, but there is substantial additional information for several markets in my files.

Please send questions, suggestions, or corrections to Steve Constantinides at: sc45@frontiernet.net.

Thank You!

4785 County Road 33
Honeoye, NY 14471
Phone: 585-229-2187
sc45@frontiernet.net
www.magmatllc.com