Production Status and Forecast

for the Availability of Rare Earth Materials (and Cobalt)

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Text to accompany slides of the presentation made at MS&T 2017, Pittsburgh, PA

The recent versions of Microsoft PowerPoint and Adobe Acrobat do not permit saving of the notes view. When printing in Notes view, the slide remains an image with the result that the file size is very large. Therefore, I am making two files available: the PowerPoint file with good resolution of the slide content and this text file which explains the content of the slides.

Slide 1: **Title**

Rapid changes to the market for technology products has had a pronounced affect upon permanent magnet raw material supply, magnet production and device design. This was evidenced in the "rare earth crisis" of 2011-12. Further supply and usage challenges are anticipated. Rare earth oxides, metals and alloys remain supplied from China at over 90% of the global total. Rare earths are consumed in increasing amounts for non-magnet applications such as glass dopants and catalysts. Cobalt, another critical element is required for samarium cobalt high temperature magnets and for improving NdFeB magnets. It is increasingly consumed by the lithium-ion battery market.

Slide 2: **Agenda: What's the big deal with magnets?**

Balance of supply and demand within the market and reducing the rapidity of changes are key to preventing disruptive pricing changes.

Slide 3: **Why are magnetic materials so important?**

Magnetic materials are important elements in the production, transmission and consumption of electrical energy. The major components of electricity generators are soft magnetic steel, copper windings, the electrical conditioning circuits and components, and the surrounding structure. Smaller generators utilize permanent magnets on the rotor to improve efficiency. This is particularly important for generators in portable and aerospace applications.

The transmission of electrical power requires a step-up transformer for power entering the transmission system and a step-down transformer at substations for the extraction of power for local consumption. Transformers utilize soft magnetic steels, especially silicon-iron.

Motors and other devices that convert electrical energy into mechanical require soft magnetic steel and copper windings. Efficiency is improved by utilizing permanent magnets.

Slide 4: **Energy Production and Consumption (USA)**

This San Key diagram from Lawrence Livermore National Laboratory is one of more than a hundred – one for each of the major countries of the world. The diagram shows sources of input energy into the USA by source type, end use for each type of energy and loss of energy. Data is presented as Quads (quadrillion BTU). Some facts: 37.54 of all energy input is used to produce electricity; 64.5% of electric power is lost - - only 35.5% reaches the end use; 68.3% of all input energy is lost – only 31.7% reaches the end use.

Slide 5: **Why are permanent magnets so important?**

Most importantly they are an enabling material – some devices such as HDDs and cell phone speakers would not be possible without extremely powerful rare earth magnets. Over 40, perhaps over 50% of electricity generated globally is consumed by motors. Permanent magnet motors are inherently more efficient. This is especially important when energy input is limited such as is an electrically powered vehicle with limited battery capacity.

Slide 6: **Agenda: Materials**

Slide 7: **Naturally Occurring Ferromagnetism**

Materials exist as collections of atoms – usually in a crystalline form.

The proximity of one atom to another causes an interaction of the electrons of each atom.

Heisenberg in 1928, using the quantum theory, explained that as atoms with partially filled electronic shells at large distances from each other move closer to one another their shells begin to overlap and quantum mechanical exchange forces arise between the incomplete shells. The corresponding energy appears in the mathematical formulation as an “exchange integral”.

When the exchange energy is positive, as it is for Fe, Co and Ni, ferromagnetic properties are exhibited. This occurs when the atomic spacing (a) is about 3-4 times the radius of the incomplete shell (r).

Additionally, some combinations of otherwise weak magnetic materials have strong magnetic characteristics. Examples are MnAlC and MnBi. Alloying modifies the atomic spacing between adjacent manganese atoms changing the exchange interaction for manganese, moving it from a negative value to positive and causing the material to exhibit ferromagnetism.

Conversely, when iron transforms into a FCC crystal structure, interatomic distances cause it (gamma Fe) to become anti-ferromagnetic.

Metallic gadolinium, a rare earth element, exhibits natural ferromagnetism.

Slide 8: **Slater-Pauling Curve**

The Slater-Pauling curve shows the calculated magnetization for several transition elements and binary combinations.

The highest magnetization is exhibited by a mix of iron and cobalt at approximately 2.4 Bohr magnetons.

The calculated value is very close to that achieved in products such as Supermendur and vanadium Permendur.

Each atom with unbalanced electrons and ferromagnetic properties produces a magnetic field. This field can be calculated and is expressed in Bohr magnetons, ⍰B. Bohr magnetons can be converted to Gauss or Tesla by the formula: 4 • Pi • emu / cm3 = gauss. What this curve shows is the magnetic strength in magnetons for each of the three transition metal elements (iron, cobalt, and nickel) and binary combinations of these elements with others. The strongest magnetic material is a combination of iron and cobalt. There are several soft magnetic materials that take advantage of this phenomena including Supermendur, Mu-Metal (Carpenter Technology), vanadium Permendur, and more.

Slide 9: **Elements in Existing Magnetic Materials**

This is a list of most of the commercially available magnetic materials, divided by type (soft, permanent, and other). Elements are listed starting with the largest content percentage, followed by second largest, etc. Note that columns 1 and 2 are mostly iron or cobalt. Nickel shows up mostly in columns two and three.

An exception is manganese which is not ferromagnetic as a unitary material (no other elements mixed with it), but which can become magnetic (usually ferrimagnetic) when mixed with other elements that affect the inter-atom distances so as to cause the exchange integral to become positive. (See slide 7).

Slide 10: **The Spectrum of Magnetic Materials**

Matt Willard, a professor at Case Western Reserve University created this excellent graphic that shows three characteristics of magnetic materials. The horizontal axis indicates a materials resistance to magnetization and demagnetization. The left vertical axis represents a materials ability to temporarily store magnetic energy. The size of the circle representing each material shows the saturation magnetization.

Soft, easily magnetized and demagnetized materials are located toward the bottom left of the chart and are suitable for flux carrying applications such as transformers and lamination steels in stators and rotors of motors and generators.

Materials in the upper right of the chart are difficult to demagnetize – these are permanent magnets. The materials in the extreme upper right are rare earth magnets.

Slide 11: **Rare Earth Magnets**

Rare earth magnets are divided into samarium cobalt of which there are two types – 1:5 and 2:17 – neodymium iron boron (NdFeB or "neo"), and samarium iron nitride (SmFeN). Neo magnets represent the largest portion at about 95% by weight of all the rare earth magnets.

Slide 12: **Sintered (Dense) Magnet Producers**

Downstream from the raw material supply are the magnet manufacturers.

This listing shows manufacturers of the four most common permanent magnet materials.

Chinese companies produce over 80% of each of the magnet materials and the Chinese economy consumes the greatest portion domestically, building the magnets into products for use within China and for export – products such as motors, appliances, and consumer electronics.

Although there are few manufacturers of permanent magnets in North America, there are many companies, specifically distributors, that purchase magnets and pass them on to customers in the US and Canada.

Magnet distributors typically just buy and resell while fabricators add value to the purchased magnets through secondary processing such as machining and assembly.

What quantity of magnets are purchased by these USA-located fabricators and distributors? We'll see a few slides from now.

Slide 13: **Global Sales of Permanent Magnets**

Data in this slide for year 2010 is well-established; data for 2016 is a close estimate.

The two most produced materials are ferrite and NdFeB with ferrite representing the largest weight percentage and NdFeB representing the largest sales in dollars. When the market sales dollars are divided by the weight sold, average sales per kg is calculated. The numbers in the table are self-consistent and agree closely with 3rd party price per kg information.

Keep in mind that selling price is greatly affected by size and shape of the magnet as well as country of production and country of the purchaser.

Slide 14: **Agenda: Supply**

We now know the materials of interest for rare earth (and ferrite) magnets. If we accept that rare earth magnets are very important for modern devices – are often required for these devices – then dependable supply at acceptable prices should be a major concern of industry.

Slide 15: **Rare Earth Oxide Production, USGS Data**

The United States Geological Society (USGS) solicits information of production of rare earths from foreign governments and producing entities. The compiled results are published annually in Mineral Commodity Summaries and posted on the USGS website (https://minerals.usgs.gov/minerals/pubs/mcs/).

The chart on this slide shows production of rare earth oxide (REO) from 1960 through 2016. (A 2nd order polynomial fit of the data has an R2 of >0.95). Production has increased considerably over the years. But has it kept up with demand?

Slide 16: **REO and NdFeB Magnet Production**

In the chart on this slide, point 1 indicates the line showing published and forecast production of NdFeB magnets in tonnes per annum (tpa). At point 5, we see magnet production indicated as ~105,000 tonnes.

Chart line indicated by point 2 is the REO production required to produce the magnet quantities shown by line 1. This can be calculated making assumptions about the fraction of magnet rare earths used to actually make magnets (90%) and processing yield of converting REOs into finished magnets.

So far, so good. But when we pace points representing actual REO product on the chart at point 3 and calculate the quantity of magnets that could be produced, point 4, we see a huge discrepancy between points 2 and 3 and between points 4 and 5.

How can this be?

Slide 17: **Illegal Trade in Rare Earths**

China admittedly has a problem with production of off-record (black market, illegal trade) REOs. In the early 2000s, this production was limited. As the price of REOs increased so too did illegal production. The production is "illegal" as China has had a production quota system.

Estimates of illegal production have ranged from as low as 30% of legal production to as high as 60%. The chart data suggests that illegal production equaled legal output in 2015-16.

This chart provided by Arafura is only for NdPr ("Didymium") and indicates about a 40% illegal trade in China. Much of the illegal REOs are produced in southern China from the ion adsorption clays which contain significant amounts of heavy rare earths.

Slide 18: **China Production of REO**

China's production of REOs has been consolidated from over 40 companies into six "umbrella" companies for improved reporting accuracy and control of production.

Outside of China there are over 400 companies attempting to develop a rare earth mining business. We cannot speak to more than a few and their presence in this presentation is not an endorsement and the absence of one of these entities does not constitute a criticism.

Slide 19: **Lynas Production of REO**

Outside of China, the USGS reports production from several countries/companies. At present the single largest producer is Lynas with a mine in Australia (the Mount Weld mine) and separation facilities in Malaysia (the Lynas Advanced Materials Plant, LAMP).

The Mount Weld mine contains the highest recognized ore grade at about 14% REO. The ore is monazite, a phosphate ore.

Lynas has improved operations with FY 2017 sales and profits reaching new highs.

Slide 20: **Lynas Production of REO (cont.)**

Lynas also has a mine location in Malawi, but the Mount Weld mine is satisfying all current needs.

Slide 21: **Lynas – CondiSoil®**

An issue with all the mining activity is that once the desired elements are extracted, it is necessary to discard the left-over, unwanted "dirt". Lynas had recognized that the remaining mineral content might be useful as a soil amendment and they are developing a soil additive with the name CondiSoil®.

Slide 22: **Mountain Pass Rare Earth Mine - Update**

The Mountain Pass mine in California has the second highest ore grade at 6 to 9% depending on dig location. The ore body contains both Bastnaesite and Monazite. Due to the thorium content of the monazite, Molycorp concentrated on use of the Bastnaesite ore.

In efforts to establish a mine-to-market strategy, Molycorp succeeded in acquiring several assets including a rare earths processor in Estonia (Silmae), a metals and alloys processing facility in Tolleson, Arizona, and most importantly, Neo Materials Technology.

Neo Materials Tech consisted of 1) a REO-to-metal processing facility in China, 2) REO sales network supplying globally, and 3) Magnequench, an operating division that produces NdFeB powder for bonded magnets.

With the bankruptcy of Molycorp, the Magnequench business and associated assets were separated into a going business and renamed Neo Performance Materials.

Slide 23: **Mountain Pass Rare Earth Mine – Update (cont.)**

After spending well over $1 billion to install ore and REO processing equipment, a chlor-alkali recycling facility and on-site electric power generation, continuing processing difficulties coupled with a high processing cost prevented Molycorp from reaching profitability. Negative cash burn eventually forced the company into bankruptcy.

A consortium led by Shenghe Resources made the winning bid of $20.5 million – about 2% of the installed capital cost!

It is not yet known if the US government review will approve or deny the purchase.

Slide 24: **Alkane Resources Ltd.**

Alkane Resources, an Australian company, has two active projects. The rare earth project is for the processing of the gangue from the Dubbo Zirconia Project (DZP). Thus, the primary mine output is slated to be Zirconium, Hafnium and Niobium. Rare earth processing and output is a secondary, beneficial output material.

Slide 25: **Alkane Resources Ltd. - DZP**

Rare earth output at about 6,700 tpa is about 26% of total tonnage output.

Importantly, mine life at annual output is rated at 80 years.

Capital cost for material processing is a conventional $50 million per 1,000 tpa output.

Slide 26: **Alkane Resources Ltd. – DZP (cont.)**

This slide shows the REO fractions. Note that the ore is high in yttrium but has more-or-less conventional amounts of HREEs (heavy rare earth elements).

Slide 27: **Arafura Resources Ltd. - Nolans**

Another Australian company, Arafura, is developing the Nolan's mine. Annual output of 14,000 tpa is reasonably high, but the anticipated mine life is only 23 years.

Project development at this point involves a Korean operation for final processing (OCI Co. Ltd.).

Slide 28: **Greenland Minerals and Energy Ltd. - Kvanefjeld Project**

The Greenland Minerals' Kvanefjeld project is a lower grade resource but huge in overall quantity. It also contains measurable amounts of uranium. It is being developed in conjunction with Shenghe Resources (remember Molycorp…).

Slide 29: **Greenland Minerals and Energy Ltd. - Kvanefjeld Project (cont.)**

Large areas of southern Greenland have been free of ice/snow coverage for large fractions of the year.

Slide 30: **Ucore Rare Metals**

Ucore Rare Metals has been developing the Bokan Mountain asset for several years. While it has interesting amounts of Dy and yttrium, the size of the ore body is limited providing an 11-year mine life while only producing 2240 tpa.

On the other hand, Ucore is attempting to market processing of rare earth ores/oxides using the SuperLig® Process (Molecular Recognition Technology, MRT), a process developed by IBC Advanced Technologies, Inc..

Slide 31: **Recycling of REE-Containing Products**

Recycling has garnered a great deal of attention for what it offers in reducing scrap going into solid waste as well as "rescuing" valuable elements that are difficult to access in mining and processing.

That more recycling has not already occurred represents difficulties, a few of which are shown on this slide.

The last item, Design for Recycling, is meant to simplify the act of reclaiming materials..

Slide 32: **Recycling of Magnets: Example**

The recycling of magnet materials already occurs during the production process – at least for clean hard scrap.

Partially reacted powders ("fines") require a more sophisticated treatment and several companies have developed methods for so doing – only a few are shown here.

Slide 33: **Organizations Engaged in Recycling Efforts**

If one were to Google "rare earth recycling" over 1.5 million hits result.

This is a major activity in terms of organizations and technologies and, again, only a few are shown here.

The review, shown at the bottom of the slide, written by Binnemans et al. is an excellent paper and highly recommended.

Slide 34: **Raw Material Sourcing – Comparing REEs & Cobalt**

Diversity of material supply is important.

Why did REEs experience such an increase in pricing in 2011 while cobalt did not? Perhaps the answer lies in the supply chain's ability to react to market needs.

Converting REO to metal is a constraint-point in the REE supply chain.

There are few facilities outside China with the capability of processing rare earths on a commercial scale and none that can do it as inexpensively.

On the other hand, cobalt is widely available – not to say that a disruption in the Republic of the Congo (ROC) wouldn't have an impact on supply and pricing, but the market would be able to adjust relatively more quickly and effectively than for the current rare earth metal supply where China capacity is 83+ percent of the world total.

Slide 35: **Raw Material Sourcing – Comparing REEs & Cobalt (cont.)**

On the other hand, cobalt is mined in large percentage in the Democratic Republic of the Congo (Zaire, Belgian Congo) at about 50% of all mined cobalt. Additional quantities are mined in 19 other countries.

On the other hand, 50% of cobalt processing takes place in China. This percentage has grown in recent years and would be higher except that refining has also increased in other countries.

Slide 36: **Material Prices - Cobalt**

Cobalt is a key ingredient of several magnetic materials including: alnico, SmCo, Fe-Cr-Co, Vicalloy, Supermendur, 2V-Permendur, and others.

The magnetics industry consumes between 6 and 7% of the annual production of cobalt.

Other major uses include specialty steels and batteries.

Looking at a chart of cobalt prices in current dollars suggests that there is an overarching upward trend and that the price today is far higher than it was in the first half of the 20th century and potentially moving higher.

But the US dollar today is does not have the value it had 80 or even 30 years ago. So looking at the data adjusted for inflation as shown on this next chart…

Slide 37: **Material Prices - Cobalt, Inflation Adjusted**

When the inflation-adjusted prices are plotted, we see that the price of cobalt today is about the same as it was 80 years ago and is only oscillating around the long-term average.

The red chart also indicates that, although there is moderate price volatility of late, there does not appear to be an upward trend in real pricing, though there is no guarantee against this.

Note also that the major peak in 1978, caused by political unrest in the Belgian Congo (ROC), was only an 6.5x rise over the base, similar in magnitude to the other commodity price swings we've been reviewing.

Slide 38: **Agenda: Consumption**

Slide 39: **Populations and Markets, by Region**

In North America we are generally very inwardly focused forgetting that, despite having the largest GDP of any nation, that we represent only about 7% of the world's population.

The 93%ers are moving up the economic ladder – purchasing more and enjoying an improving standard of living.

While salaries and benefits may lag the western economies, they will also move upward.

We must think more globally!

Slide 40: **Where are Rare Earths Used?**

When we speak about consumption of rare earths, especially magnets, we should ask where all the rare earths are used.

Many of the magnet rare earths have secondary usages which compete with the REE usage in magnets.

Slide 41: **Rare Earth Oxide Consumption by Application**

2015 estimate of 45,000 tons magnet REO equates to 92 ktons of magnets at 82% REO to metal yield and 75% magnet manufacturing yield.

2020 estimate of 65,000 tons magnet REO equates to 133 ktons of magnets at 82% REO to metal yield and 75% magnet manufacturing yield.

Dudley Kingsnorth has published for many years regarding production and consumption of rare earths. In these two tables we see magnets accounting for 31-33% of the consumption of all rare earths.

Where are all these magnets used?

Slide 42: **Major and Developing Uses of Neo Magnets**

Historically about 70% of all magnets (NdFeB, SmCo, and ferrite) are used in motors/generators and that percentage is expected to continue.

This slide highlights six applications that use large amounts of rare earth magnets (mostly NdFeB).

Every one of these applications is a form of motor.

It's beyond the scope of this paper to explain in depth what the markets are – let's focus on just a couple.

Slide 43: **Alternative Powertrain Types**

The first market we'll look at is transportation…

There are many "alternative drive" types.

This list shows most of them including one or more examples of each that are in production.

All use permanent magnet traction drive motors except for the Tesla model S which uses an induction motor. Permanent magnet motors are inherently more efficient.

Slide 44: **2017 Sales Data based on Sales through July**

Hybridcars.com tracks sales within the USA by drive type and manufacturer – 2017 data through July and annualized is shown here.

EREVs (Chevy Volt) are included in the PHEV column in this table.

Although Diesel is not an electric drive vehicle, it represents an alternative to conventional gasoline engines.

For year 2017, all these alternate power sources represent only 3.7% of USA sales of new cars and small trucks.

This is well below market forecasts and is due at least in part to lower gasoline prices.

In the USA, hybrid and plug in hybrid vehicles lead with about 4x the sales of BEVs.

Slide 45: ***Steve's* Forecast - USA Market, Sep 2017**

In response to overly optimistic forecasts, opinions have been sought regarding the development of the transportation industry and this chart is my attempt to show a consensus of the development of alternate drive systems by type and over time.

Reasons why ICE (including clean diesel) will remain the primary source of tractive power, at least through 2025, are the technological advances being made to provide ever more efficient ICE drive systems at modest price increase and using existing fuel distribution infrastructure with simultaneous "light-weighting" of the vehicles.

Expansion in use of any type drive depends upon a range of factors including economic (e.g., gas prices), political (e.g., CAFÉ standards), and technical (e.g., greatly improved battery performance/cost).

Slide 46: **Magnet Requirements for EVs**

But what will a switch to EVs mean regarding NdFeB magnet demand?

This table shows estimated sales in the USA and globally through 2040, assumptions have been made regarding percentage EVs and quantities of magnets calculated based on assumptions shown.

Recall that magnet product in 2016 was about 105,000 tonnes.

If China, France, California and other governments have their way forcing a complete conversion to EVs, we will need a global output of about 416,000 tonnes per year NdFeB magnets in addition to other application needs!

Slide 47: **Wind Power - Types and Locations**

This graphic shows the size of different wind systems. Commercial wind, now typically 2.5 MW towers or larger, is approaching cost parity per kWh with conventionally produced electricity. On-shore towers are typically about 2.5 MW but may be as large as 6 MW. Off-shore towers are usually larger to take advantage of the consistent wind while minimizing maintenance cost per MWh produced.

Siemens, for example, has produced a design at 3 and at 6 MWs per tower with both induction and permanent magnet generators. This permits the wind farm operator to select the type of generator based on trade-offs in capital versus on-going operation expenses.

Superconducting generators have been proposed and designed but remain too expensive and undeveloped.

Slide 48: **Global Wind Power Generation: Total and PM**

Use of permanent magnet generators has been slow to be adopted in the west (north America and Europe) with less than about 1% adoption in the west versus more than 50% adoption on new towers in China.

On a global basis only 15% are permanent magnet type generators.

Direct drive and hybrid drive permanent magnet generators represent less than 1% of generators in North America and the UK (England and Scotland) and only a slightly higher percentage in Europe.

Slide 49: **Direct and Hybrid Drive Generator: Magnet Requirements**

Consumption of permanent magnets per MW generator size has dropped from >650 kg/MW to about 550 kg/MW. Some hybrid generator designs have been produced and consume between 165 and 250 kg/MW but require a 2-stage gearbox.

Magnet requirements to meet the installation forecast is approximately 9,000 tonnes in 2016 increasing to 10,500 tons in 2020 at which point it may stabilize.

Slide 50: **Agenda: Summary Comments**

Slide 51: **Summary**

This slide speaks for itself.

Be sure to check other papers/presentations on the Magnetics & Materials website (www.magmatllc.com).

Please contact me with questions, suggestions or corrections at sc45@frontiernet.net

Thank you!