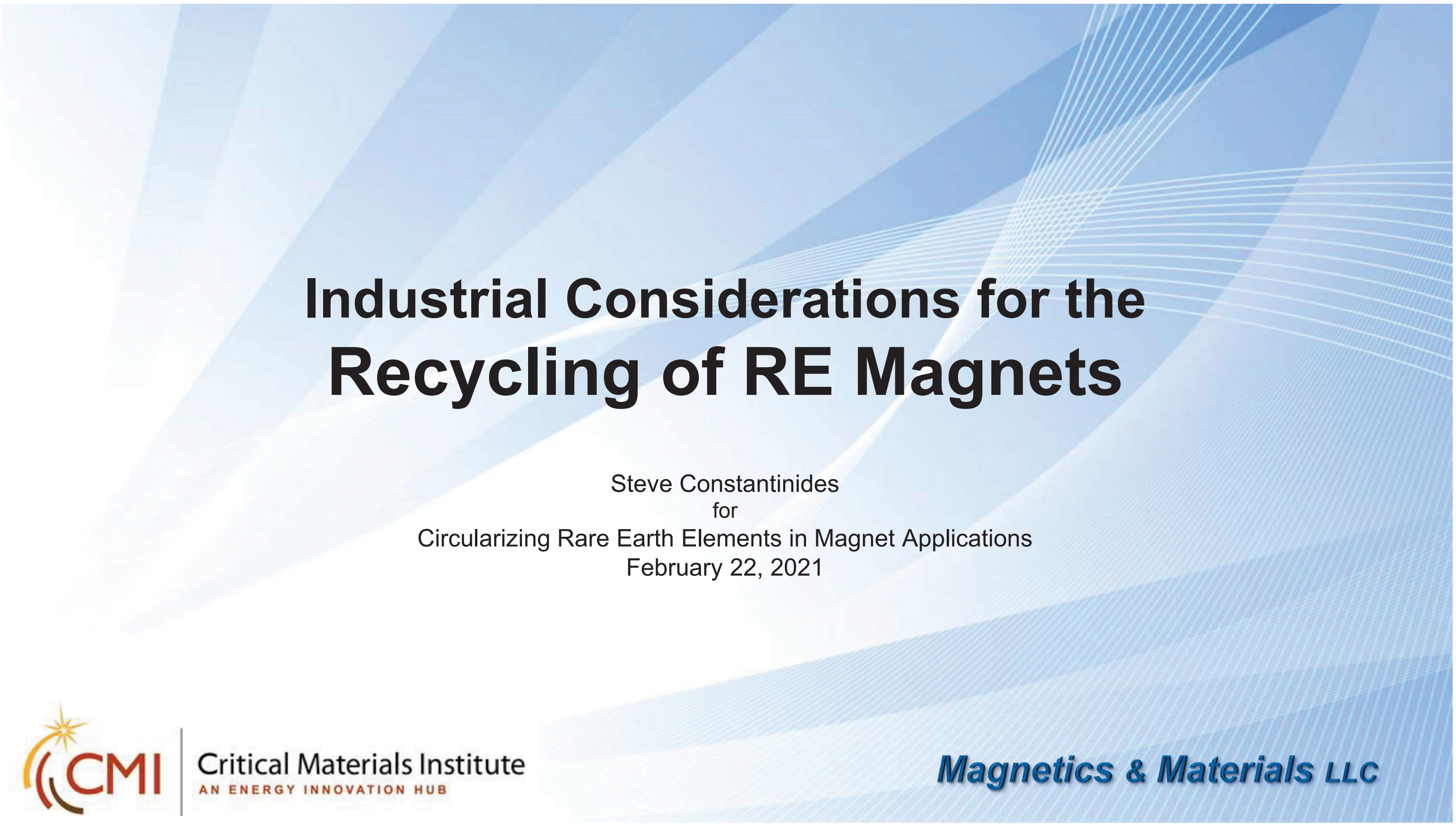


Industrial Considerations for the

Recycling of RE Magnets

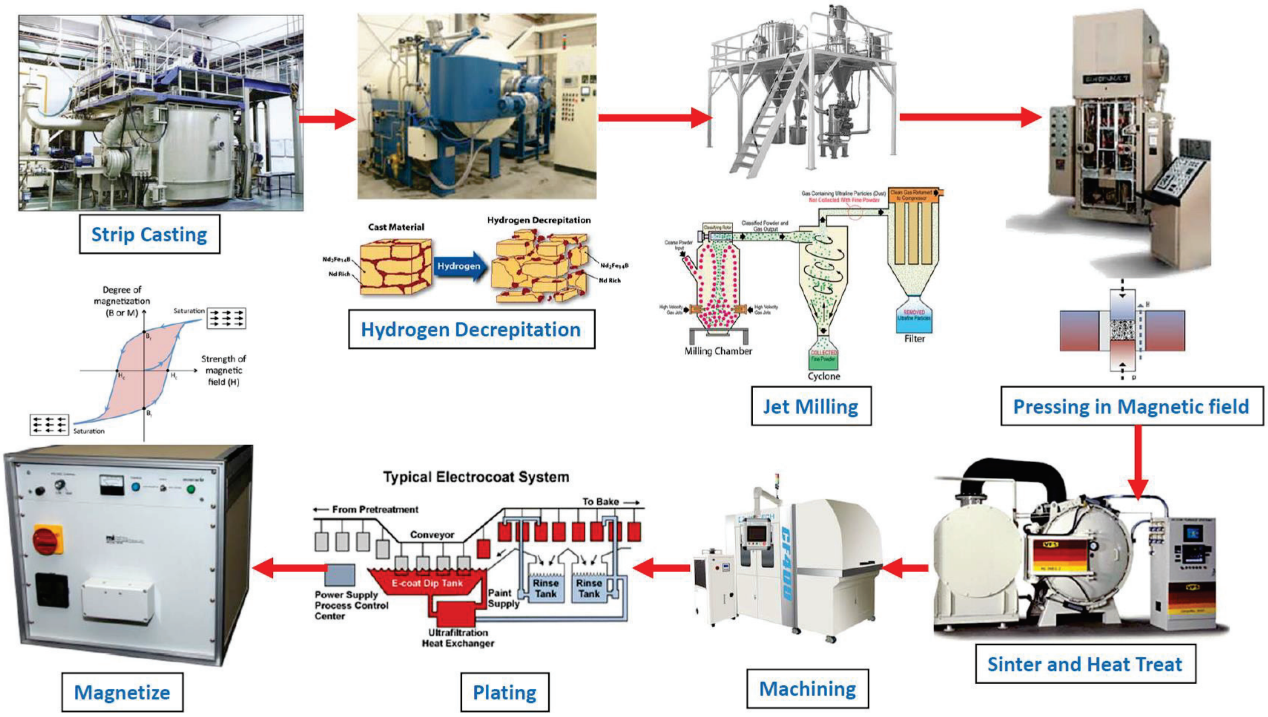
Steve Constantinides

Circularizing Rare Earth Elements in Magnet Applications

February 22, 2021

A presentation at the virtual (online) symposium on Circularizing of Rare Earth Elements, hosted by the Critical Materials Institute.

Sintered NdFeB Magnet Manufacturing Process



Reference: S. Constantinides & J. Ormerod

Slide 2: **Sintered NdFeB Magnet Manufacturing Process**

- This slide is presented to assist the viewer in appreciating the subsequent discussion of magnet manufacturing.
- Metal raw materials are melted together and strip cast into thin flakes. The flakes are treated with hydrogen to break them down into fine particles.
- The jet milling operation reduces particle size to about 3 microns.
- The milled powders are blended with additives and pressed in an orienting magnetic field to form a “green compact” which is placed into a furnace and thermally processed to full density.
- There is a 15 to 20% linear shrinkage during the thermal (sintering) process.
- Final dimensional size and tolerance is achieved using one or more machining processes including: EDM, diamond saw slicing, wire sawing, diamond abrasive wheel grinding, core drilling, etc.
- Since NdFeB is prone to corrosion, magnets are almost always coated. Coating options include spray epoxy, e-coat, and metallic plating such as electrolytic or electroless nickel, and aluminum IVD.
- Uncoated magnets and those with organic coating benefit from a pretreatment conversion coating such as zinc or iron phosphate.
- Although some product is shipped to customers unmagnetized, most require a final step of magnetizing.
- Magnetized NdFeB magnets generate strong magnetic fields which require careful handling and packaging.

Mfg Cost & Selling Price

- Raw Material Cost
- Conversion Cost
  - Labor
  - Equipment Operation
  - Consumables
- Overhead Burden
  - Capex and Depreciation
  - Factory & Office Maintenance
  - Taxes
  - Insurance
  - Regulatory Costs

The sum of all China costs are ~37% of US costs

In the following example (next slide) overhead is included in the conversion cost

Slide 3: **Mfg Cost & Selling Price**

- Most of the costs included in magnet production are shown here – at least in general terms.
- There are often large differences between these costs in various regions of the world.
- Differences between China and the US have diminished over time, but remain very large.

Mfg Cost & Selling Price

Key Points

- **Actual Raw Mat'l Cost**
- **HRE content**
- **Material Reclaim**
- **Profit Margin**

Example

Simplified calculations showing effect of material cost, manufacturing cost, and margin.

Cost Structure for NdFeB Sintered Magnets: China

Select grades; enter values in yellow and salmon cells; gray cells are calculated

Rmb exchange rate 6.9441 Rmb per USD on Date 8-Jan-20

Rare earth prices at 30% discount to published

Select Material: N45H

Material	Weight%	Raw Matl $/kg	$ per kg of alloy	% of Mat'l	Add'l Criteria	Comments
Nd	24.20%	36.96	8.94	48.2%	0%	
Pr	5.00%	36.96	1.85	10.0%	0%	From NdPr
Dy	2.80%	224.00	6.27	33.8%	0%	From Fe-Dy
Tb	0.00%	0.00	0.00	0.0%	0%	
Ce	0.00%	0.00	0.00	0.0%	0%	
La	0.00%	0.00	0.00	0.0%	0%	
Y	0.00%	0.00	0.00	0.0%	0%	
SubTot	32.00%		17.06	92.0%		
Fe	64.09%	0.44	0.28	1.5%	0%	Fe plus Fe-B
Co	1.00%	31.00	0.31	1.7%	0%	
SubTot	65.09%		0.59	3.2%		
B	1.05%	0.53	0.01	0.0%	0%	B from Ferro-Boron
C	0.01%	0.50	0.00	0.0%	0%	
SubTot	1.06%		0.01	0.0%		
Al	0.30%	1.77	0.01	0.0%	0%	
Cu	0.50%	6.15	0.03	0.2%	0%	
Ga	0.50%	135.00	0.68	3.6%	0%	
Nb	0.50%	36.00	0.18	1.0%	0%	
Ti	0.00%	0.00	0.00	0.0%	0%	
Zr	0.00%	0.00	0.00	0.0%	0%	
SubTot	1.80%		0.89	4.8%		
Other	0.05%		Contaminants such as >			Mn, O, S, etc
Total Mat'l	102.9%		$ 18.55	100.0%		Per kg material cost

Magnet Manufacturing Cost — **China Manufacturing**

Type of product:	Block, medium, P-t-S		
Material yield[1]:	86.6%		Includes hard reclaim
Magnet Mfg Cost (w/o Mat'l)[2]:	$ 2.40	$/kg	Cref: Conv. Cost Calcs.
Magnet Mfg Cost + Material:	$ 23.82	$/kg	
Raw Mat'l % of Mfg Cost[3]:	89.9%		
Selling Margin%:	10%		
Magnet Selling Price:	$ 26.47	$/kg	

RAW MATERIAL COSTS

MAGNET

Cost Structure for NdFeB Sintered Magnets: Western

Rare earth prices at 10% discount to published

N45H

Material	Weight%	Raw Matl $/kg	$ per kg of alloy	% of Mat'l	Add'l Criteria	Comments
Nd	24.20%	47.52	11.50	49.1%	0%	
Pr	5.00%	47.52	2.38	10.1%	0%	From NdPr
Dy	2.80%	288.00	8.06	34.4%	0%	From Fe-Dy
Tb	0.00%	577.80	0.00	0.0%	0%	
Ce	0.00%	0.00	0.00	0.0%	0%	
La	0.00%	0.00	0.00	0.0%	0%	
Y	0.00%	27.00	0.00	0.0%	0%	
SubTot	32.00%		21.94	93.6%		
Fe	64.09%	0.44	0.28	1.2%	0%	Fe plus Fe-B
Co	1.00%	31.00	0.31	1.3%	0%	
SubTot	65.09%		0.59	2.5%		
B	1.05%	0.53	0.01	0.0%	0%	B from Ferro-Boron
C	0.01%	0.50	0.00	0.0%	0%	
SubTot	1.06%		0.01	0.0%		
Al	0.30%	1.77	0.01	0.0%	0%	
Cu	0.50%	6.15	0.03	0.1%	0%	
Ga	0.50%	135.00	0.68	2.9%	0%	
Nb	0.50%	36.00	0.18	0.8%	0%	
Ti	0.00%	0.00	0.00	0.0%	0%	
Zr	0.00%	0.00	0.00	0.0%	0%	
SubTot	1.80%		0.89	3.8%		
Other	0.05%		Contaminants such as >			Mn, O, S, etc
Total Mat'l	102.9%		$ 23.43	100.0%		Per kg material cost

Magnet Manufacturing Cost — **USA & Western World Manufacturing**

Type of product:	Block, medium, P-t-S		
Material yield[1]:	86.6%		Includes hard reclaim
Magnet Mfg Cost (w/o Mat'l)[2]:	$ 6.71	$/kg	Cref: Conv. Cost Calcs.
Magnet Mfg Cost + Material:	$ 33.77	$/kg	
Raw Mat'l % of Mfg Cost[3]:	80.1%		
Selling Margin%:	30%		
Magnet Selling Price:	$ 48.24	$/kg	

Slide 4

Slide 4: **Mfg Cost & Selling Price (Detail)**

- Magnet manufacturing costs are calculated in this graphic from part of an Excel spreadsheet.
- Actual material cost to the magnet manufacturer is a closed contract price with the supplier(s) and prices are almost always considerably less than published prices. Prices within China have been 25 to 35% below published while the few western material suppliers have been able to negotiate prices that are just somewhat lower than published prices.
- HRE content has a profound effect on material cost. In this example, a 2.8% Dy content results in HRE being 33.8% of the material cost. The total of all rare earth (TRE) content is 92% of the material cost.
- Process yield is the % acceptable product from 1st time manufacture.
- Some of the scrap associated with unacceptable product (e.g., cracked or dimensionally out of spec magnets) can be recycled within the manufacturing facility resulting in a material yield that is a considerably higher percentage.
- Some scrap is partially reacted fine powder which can be collected and sent for chemical reprocessing. Thus, these materials are reclaimed but not immediately available for re-use.
- Profit margins among the 300 Chinese manufacturers vary considerably. With many smaller companies, profit margins are squeezed and companies struggle to survive. A 10% margin is used in these calculations versus a 30% margin for US manufacture/sale.
- China taxes are also an issue. For example, there is currently a VAT rebate on exported magnet but not on rare earth raw material.

Recycling of Rare Earths

Magnet Producer

- Clean hard scrap
  - Immediately reprocessed
- Reacted fines
  - Require chemical reprocessing to separate REEs from other materials and to separate the REEs from each other

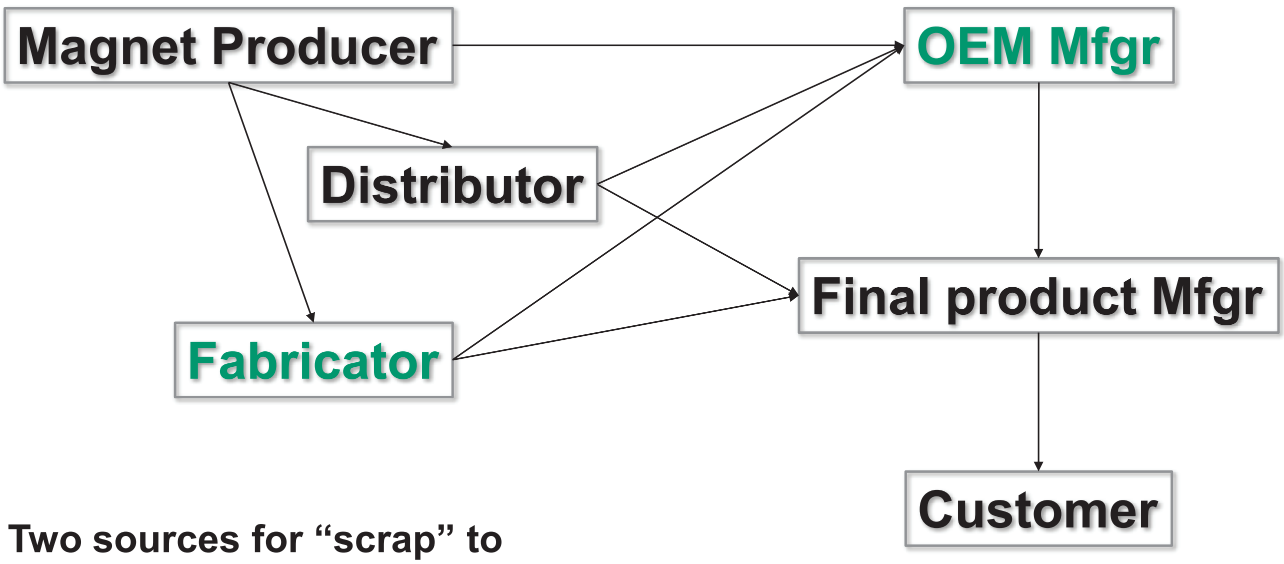
EOL Product

- Separated Magnets
  - Little opportunity for re-purposing
  - Crush and use as raw material at magnet producer site
- Chemically digested waste
  - Chemically separate REEs and re-enter production stream at raw material suppliers' sites

Slide 5: **Recycling of Rare Earths**

- Opportunities for the recycling of materials containing rare earths exist at the magnet producer and when the magnet is end-of-life.
- Magnet producer "hard scrap" is generated as dense alloy or magnet product. This material can be simply cleaned and immediately inserted back in the manufacturing process.
- The immediately recycled scrap raises the apparent production output. So we distinguish between process yield, which can be quite low, and material yield. Since the recycled clean hard scrap is immediately re-used, that has the effect of increasing material yield above that of process yield.
- Fine powder formed during processing and when the magnets are machined to finished size and shape is partially oxidized or chemically reacted. This powder requires chemical reprocessing to separate the rare earth elements (REEs) from the other alloying ingredients, contaminants such as processing coolants, from oxygen, and from other reactants and contaminants.
- Since this material has to go far back in the production cycle, it is not counted as an increase in material yield, but it does affect the amount of rare earth material above and beyond that which is first-time mined.
- As you are aware, end-of-life (EOL) products are many-and-varied. Larger magnets can be removed from the end product, crushed and re-introduced into a magnet production stream, with suitable additives to adjust chemistry, for use as a bonded magnet powder or to facilitate sintering of the material dense magnets.
- Many end-of-life products do not have easily separated magnets. In many of these cases, it may be advantageous to crush, pulverize and reprocess the product as if it were an ore from a mine. However, the rare earth element concentration must be high enough to justify the processing cost.

Magnet Supply Chain



Two sources for "scrap" to reprocess are in green text

Slide 6: **Magnet Supply Chain**

- We say magnets are used in devices, such as in motors, which are then used in applications, such as in HVAC, which serves a market, such as heating/cooling of office and residential buildings.
- Distributors and fabricators play an important role in getting magnets from the magnet producer to the manufacturer of the final product.
- The fabricator purchases bulk magnets and machines them to final shape and size. They may also build the magnets into sub-assemblies. The finished magnets and assemblies are then sold to OEMs or a company producing the saleable final product.

Fabricator and OEM Process Scrap

Hard Scrap

- Trim after removing usable magnet from block
- Cracked or off-spec magnets

Reacted Fines

- Partially chemically reacted fine particles from grinding, sawing, drilling, etc.

Material Sources

Domestic magnet fabricators

Examples: Adams Magnetic, Arnold Magnetic Technologies, Bunting, Dexter Magnetic Technologies, Electron Energy Corp., ITA, MCE, etc.

Large OEMs

Examples: GM, Ford, Chrysler & auto parts manufacturers; ABB, Moog, Raytheon, etc.

Slide 7: **Fabricator and OEM Process Scrap**

- In addition to EOL magnets, there is waste available for recycling by collecting from magnet fabricators and large OEMs.

Available Domestic Process Scrap

- Total Metal Magnet imports: <$400 million
- Estimate for NdFeB: between $250 and $325 million
- Existing import statistics from the Census Bureau and ITC are conflated
  - Multiple products per single shipment statistic
  - "Permanent magnet" includes other metal magnetic materials (semi-hard and possibly even soft magnetic materials)
  - Incorrect assignment of magnet material type

- Using NdFeB import quantity of $300 million and an average import value for NdFeB of $70 per kg, the kgs of imported NdFeB is 430 tons - - less than 0.3% of global production (155 ktons in 2019).
- A much larger quantity of magnets is imported within finished products.
- Estimated material scrap of 30% during fabrication yields a potential of 130 tons to be recycled
  - Combination of clean hard scrap and chemically reacted fine particles

Slide 8: **Available Domestic Process Scrap**

- As we purchase more-and-more finished products from China and other low cost manufacturing regions, less-and-less intermediate materials such as rare earth materials and magnets are needed.
- Re-establishing a domestic supply chain requires creating a market for the finished domestically made products.
- Without a thriving domestic production, opportunities for in-process recycling will be limited.

EOL Product Availability – some comments

Sources of Magnets

- HDDs
- EVs
- Wind Power
- Motors (Industrial)
- Cell Phones

Costs of Recycling

- Collection
- Magnet removal from device
- Use options
  - Re-purpose
  - Fragment, treat and bond
  - Reprocess into dense magnet

Product Design for Re-use

To facilitate EOL magnet removal

Slide 9: **EOL Product Availability – some comments**

- HDDs:
  - HDD magnets have gotten smaller – both the VCM magnet(s) and the spindle drive bonded magnet. The VCM magnets have shrunk from a few hundred grams in the mid-1980s to currently less than 7 grams in 3.5" drives and less than 4 grams in 2.5" drives.
  - Although data storage is growing dramatically, due to increased areal density, the number of drives is going down.
  - Increasingly cost competitive SSDs are now replacing HDDs in all but the most demanding applications, e.g., cloud data storage.
- EVs
  - EVs still represent a small percentage of all new vehicles - in the US less than 3%.
  - With a design life of 100,000 miles (7 years), large quantities of traction drive motors will only become available for recycling in the 2030s.
- Wind Power
  - China has utilized permanent magnet direct drive (PMDD) generators at better than 50% of new installations of commercial wind. In Europe the percentage is <5% and in the US it is <3%.
  - PMDDs are more commonly used in offshore wind and this is a growth area in Europe and the US.
  - Design life of the generators is 20 years, so EOL PMDD generators won't be available in measurable quantity until ~2040.
  - However, as existing induction generators reach EOL, they are likely to be replaced with PMDD generators.
- Motors, generators and magnetic separation
  - Motor failure is primarily due to two issues: shorted copper windings and bearing wear.
  - Larger motors are rebuilt, not thrown away.
  - Design life of large motors is 20 years or more, with interim refurbishment expected.
  - Magnet recycling from motors is not well-defined and may take two or more decades to resolve.
- And a general comment: a permanent magnet is permanent – unless it becomes physically compromised through physical damage or corrosion. This will influence the recycling strategy.

Transportation

- Cost of shipping
  - Magnet producer to export location, processing fees for on-boarding
  - High seas, airline, truck transport
  - Port-of-entry off-loading and processing fees
  - VAT tax (and refunds), import tariffs
- Time-in-transit
  - Inventory carrying charges – especially important for ocean shipments of six weeks or more
  - Extended production forecast times
  - Time between production and consumption delays feedback regarding problem detection and correction
- Other issues
  - Potential for shipping disruption such as damaged or missing containers
  - Delays at ports of shipping and ports of entry
  - Costs associated with inability to re-use shipping containers

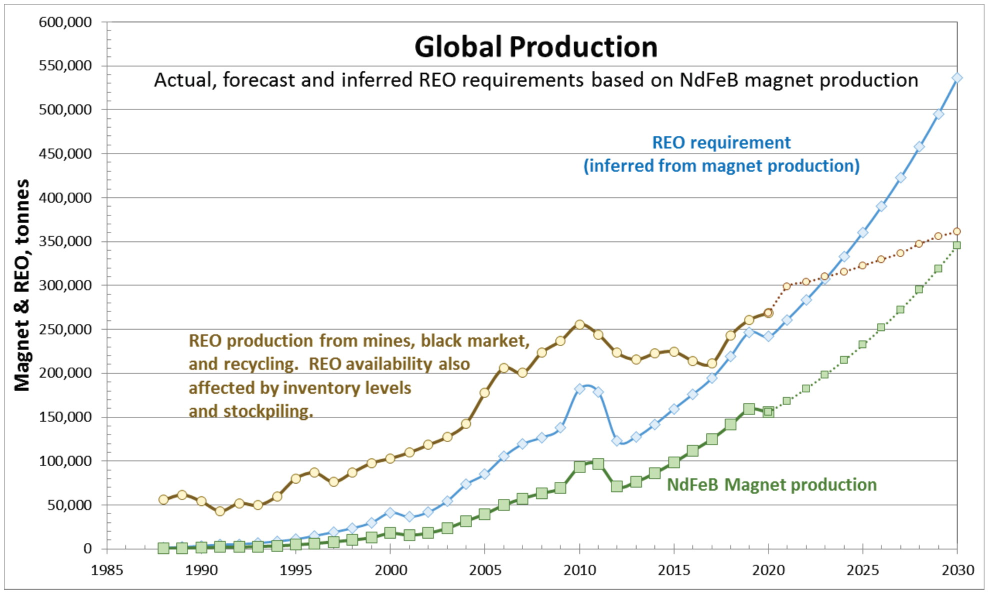
Slide 10: **Transportation**

- When the Producer and the User are located far apart, especially if they are across national boundaries, shipping becomes for a logistics and financial issue.
- Costs are incurred at numerous locations in the supply route.
- There are VAT charges and/or refunds and import tariffs to account for and pay.
- Inventory is expensive to have and shipping by sea is a lengthy process. Delivery from China to a factory in the US, door-to-door, typically takes seven weeks (>13% of a year). Invoices are issued at time of shipping. Thus the customer, that is the "user", owns the product for seven weeks before it is available for use.
- The User must forecast demand considering this 7-week lag time.
- If there is any issue with product quality or performance, discovery is delayed by at least that 7-week period and resolution of the problem is similarly delayed.
- For industries attempting just-in-time delivery, a worker strike at a port of entry is catastrophic to the User.
- Re-use of shipping containers is probably not feasible. New containers must always be available for use and old containers must be disposed of. Local manufacture makes container re-use practical.

RE Magnet Raw Material Supply & Demand

Factors that make estimating REO from magnets a challenge include:

- Alternate use for magnet REEs
- Intermittent stockpiling
- Increasing, but variable use of Ce and La in RE bonded and sintered magnets
- Unspecified size and nature of black market (HREEs vs LREEs)
- Inconsistent government policies affecting REO production and magnet usage – market perturbations



Preliminary data from market study to be published July 2021

Slide 11: **RE Magnet Raw Material Supply & Demand**

Note: at time of publication, this chart was still in development.

- Magnet production is expected to continue to grow exponentially due to several factors.
  - Increased EV production
  - Expansion of off-shore wind power PMDD generator production
  - Economic growth in developing countries including India, Malaysia, Indonesia, South America and Africa.
- REO production can be approximated from magnet production.
  - REO has by-and-large met the demand for magnet manufacture due in large part to a black market that, at its peak, represented >50% of total apparent REO output.
  - Expansion of mining activity in Australia and the US has recently contributed to growth in REO availability.
- There are no large-scale REO production projects available to contribute to supply in the next 5 years and planned projects experience funding uncertainty.
- With no change in political policies and private investment, a shortfall in REO is likely in the mid-2020s.

For information on the recently completed (June 2021) investigation and report on the **Global Permanent Magnet Market** visit:
www.MagnetReport.com

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Honeoye Lake in the Finger Lakes region of western New York - - in summer