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A Case Study of the Evolving U.S.-Rare Earth Supply Chain

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I. Abstract

There is a growing concern among U.S. business executives and policy makers for the future use of rare earth elements in the United States. Up until 2012, The People's Republic of China mined 97% of the world's supply of these elements and has periodically restricted export quotas. This is expected to continue into the future, and will likely lead to the price of numerous products to skyrocket. The supply risks create not only unavoidable problems for supply chain managers and executive for several industries, notably green energy, but also shape the future and resiliency of the U.S. economy and security. There have been several recent efforts to reestablish rare earth mining in the United States, most notably the Molycorp Mountain Pass in California. As the Mountain Pass mine increases mining and production capabilities, the supply chain for several global industries can drastically evolve. This paper will try to answer the broad question, "how is the U.S. rare earth mining industry changing?" Ultimately, the results of this analysis will attempt to identify the most crucial factors for future success for a rare-earth mining enterprise.

In an attempt to provide accurate insights for the industry's future, this paper will investigate the mining and manufacturing processes of rare earth elements through an immersive review of current literature. This information will shape research questions that will culminate in an interview with a U.S. rare-earth expert.

By the end of the research, I intend to have compiled qualitative results valuable for various stakeholders within the rare earth supply chain. The intent is that these results, either directly or indirectly, will help mitigate rare-earth supply chain scarcity and vulnerability.

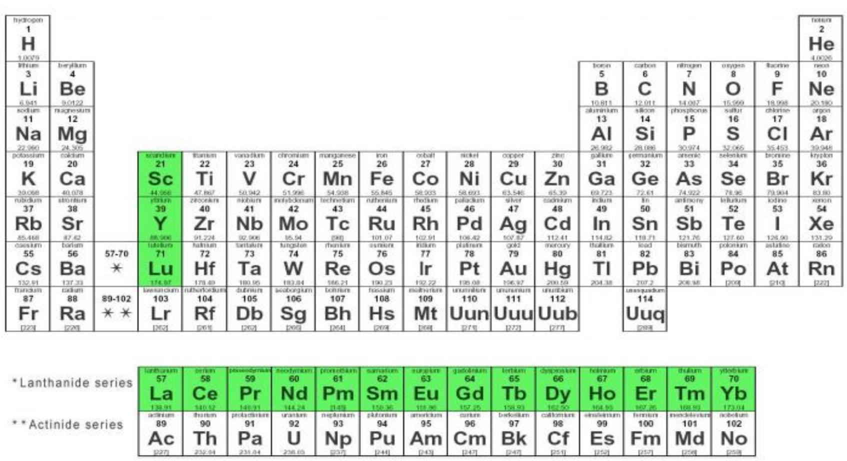
Initial Hypothesis

It is my belief that the U.S. rare-earth supply chain will face significant challenges from competitors and high barriers of entry (cost, production expertise, regulatory challenges, and customer demands) into the market. The complexity of the supply chain will be the deciding factor for a vertically integrated U.S. rare earth market.

II. Introduction

A. What are rare earth elements exactly?

To gain insight into rare earth supply chains, one must first have a general background to rare-earth elements. This term has generated buzz for several elements recently, but a common definition is necessary to frame the direction and research of this paper. There are 17 elements in the periodic table of elements known as Rare Earth Elements (REEs) that serve critical roles in the materials of many products, and these range from house lights to heavy-duty weapons. The term "rare earth" denotes the group of 17 chemically similar metallic elements, notably the lanthanide series including lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, along with lutetium, scandium, and yttrium.



So there are a lot of elements that fall into this category. Rare earth elements share similar atomic and chemical traits. However, distribution of the elements within the mineral deposits is not uniform; compositions vary greatly by geological formation, making mineral contents highly variable. Also, depending upon the deposit, some of these minerals have radiation exposure from the likes of Uranium and Thorium, which further complicate the extraction and refinement process. “The ores of rare earth elements are mineralogically and chemically complex and commonly radioactive.” [Headrick 5] Within the 17 elements, most of the focus will be upon three elements in particular: Neodymium, Terbium, and Dysprosium. This is largely due to their demand, strategic uses, and lack of substitution. In 2011, Department of Energy Secretary Steven Chu specifically cited all three elements the most critical with future supply challenges. [Chu 1-20] Additionally, Mark Smith, the CEO of Molycorp, has stated that all three elements are three of the four elements projected to be in short supply. (Eriksson)

B. Rare Earth Uses

The purpose and importance of this research, much like rare earth elements, is focused on practical applications. By becoming familiar with the wide spectrum of rare-earth applications, the reader can better understand why a reliable supply of such elements is critical to so many industries.

The most valuable quality of rare earth elements is that they are very reliable at high temperatures and they are widely considered the best source for permanent magnet components. These two attributes have a multiplier effect in the technology industry. Rare earths allow products to be smaller, but also reliable. Products heavily rely upon these elements particularly within high-quality magnets and batteries. (Boothroyd)

a. Green Energy Applications

The Toyota Prius, the world’s most popular hybrid energy vehicle, requires up to 22 pounds of rare earth elements, including significant amounts of Neodymium, Dysprosium, and Terbium for the vehicle’s permanent magnet motor (Eriksson). There are a myriad of uses for rare earth elements within wind turbines as well.

b. National Defense applications

The aerospace, defense, and weapons industries all heavily rely upon rare earth within their products. [Hedrick 4-8] Specifically, U.S. Joint Direct Attack Munitions (JDAM) aka “smartbombs”, rely heavily upon neodymium. Defensive countermeasures in several aircraft, dubbed “magic lanterns”, also rely upon Neodymium as well. Dysprosium is also used within stealth technology for helicopters. Avionic lighting systems rely heavily upon terbium and dysprosium for high quality displays. The list of uses in military applications is very large. An visual appendix (Appendix A) of rare-earth military applications is located is attached.

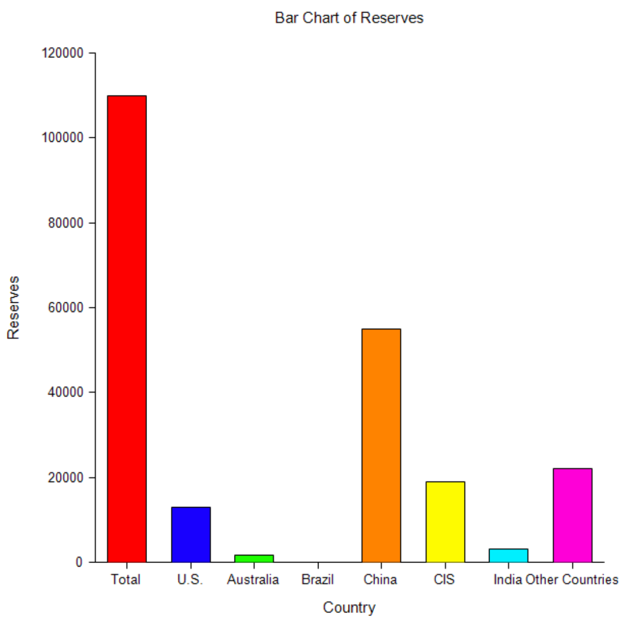
C. Global Distribution of Elements, Mining Operations, and Demand

Ironically, rare earth elements are not rare at all. The U.S. Geological Survey estimated in 2010 that world deposits for all rare-earth oxides to be 110 million tons. [McNutt]. These quantities are unevenly dispersed throughout the world across more than a dozen countries. However, the table below shows the distribution of rare earth deposits by country.

World Mine Production and Reserves:

	Mine production[e]		Reserves[6]
	2010	2011	
United States	—	—	13,000,000
Australia	—	—	1,600,000
Brazil	550	550	48,000
China	130,000	130,000	55,000,000
Commonwealth of Independent States	NA	NA	19,000,000
India	2,800	3,000	3,100,000
Malaysia	30	30	30,000
Other countries	NA	NA	22,000,000
World total (rounded)	133,000	130,000	110,000,000

Source: U.S. Geological Survey Minerals 2012 Commodities Report.



The United States currently has deposits upward of 13 million metric tons, roughly 11% of the total world supply. This represents the second largest amount by any single country. However, China dwarfs any other country, whose deposits account for 50% of the world's total supply. More impressively, China holds a virtual monopoly on rare-earth element mining. In 2012, 97% of global mining operations were in China. The reasons for this development will be discussed further in later chapters.

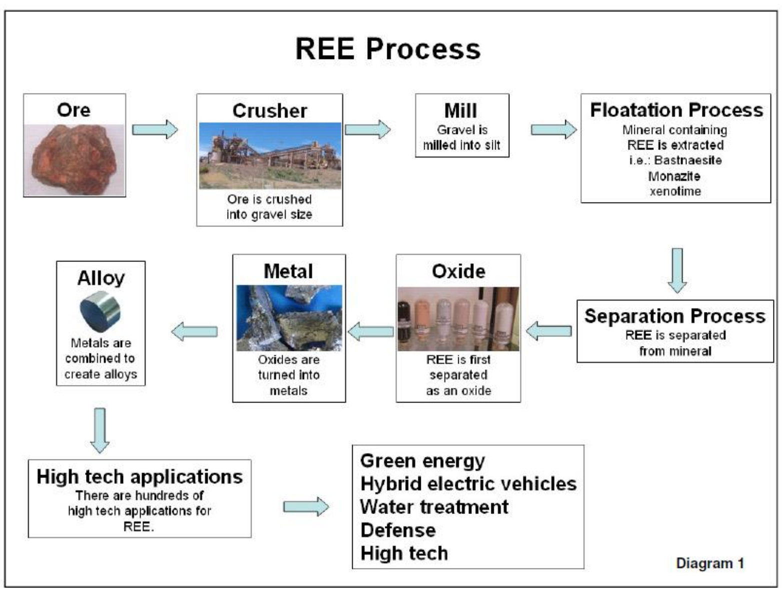
Despite having sizeable and concentrated deposits of rare elements, in 2011 the U.S. imported 100% of all its rare-earth needs. [McNutt] There is currently only one operational mine in the United States. The Mountain Pass mine in California has deposits in excess of 1 million tonnes. [Walters pg 24]. Rare earth materials are found throughout the world, but are often found in trace amounts uneconomical to mine. "A rare earth operation is a billion dollar investment that typically relies on three or four key people." [Frith]According to industry publications, rare-earth production can take up to 10 years to become fully operation; environmental regulation, obtaining proper permits, and facility development appearing to take the most time. (Hurst 24) With this in mind, the ROI for such projects should be considered in the longer term due to the substantial capital investment required.

Current forecasts estimate global demand will increase to 185,000 tons by 2015. [Humphries 2] With current capabilities, there is anticipated to be a shortfall in supply of 40,000 tons. [Hurst 28]

In 2012, the United States imported approximately $696 million worth of rare earth materials, marking a 430% increase from 2011. The increase does not reflect increasing demand, but rather increased price. [McNutt 129] This will be discussed further throughout the paper.

D. Vertical Integration and Supply Chain Complexity

Extraction, refinement, and processing of these elements is very complex and expensive. Each element has its own unique refinement process, and often times several depending upon customer needs. Because rare earths are chemically very similar, it is very challenging to separate the ore into different elements. [Dent 7]. These processes are much more complex than the refinement process, for example, of gold. Below is the refinement process for bastanite, the most common mineral in Mountain Pass. (Eriksson) 16]"Each element has its own unique extraction steps and chemical processes and at times, will requiring reprocessing to achieve ideal purity." (Hurst 5)



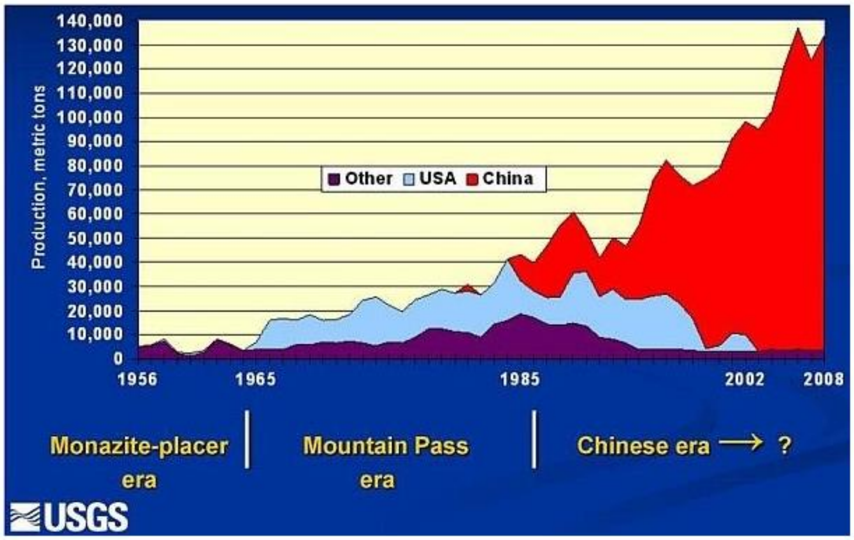
Source: Hurst5

It is important to note the complexity of each individual element and its respective supply chain requires for highly specialized (i.e. expensive) equipment and scientific expertise. [Hatch 27] This will be explored further in the paper. Not only does the vast majority of mining take place in China, but so does separation, refinement, and production. (Eriksson)

E. Rare-Earth Market, Substitutes, Projected Trends

In order to develop a full understanding of how the U.S. supply chain will be develop, it is important to examine the historical and geopolitical context for rare earth mining.

The United States, for decades, was the dominant global supplier of rare earth elements. The largest rare earth mine in the United States, the Mountain Pass mining operation currently owned by Molycorp (formerly the Molybdenum Corporation of America), was a dynamo in churning out rare-earth exports for a growing industry. The Mountain Pass mine, reaching peak production in 1990, mined 20,000 tons annually, before abruptly shutting down in 1992. [McNutt]. Currently, China produces more than six times the all-time high of Mountain Pass.



Source: U.S. Geological Survey

The scale of current mining operations in China has no precedent. China's dominance stems from the global explosion in demand for technology and consumer electronics. One example of increased demand is the rise of cellphone ownership. From 1990 to 2011, cell phone usage increased from 12.4 million to 5.6 billion. [Saylor 5] Such trends have fueled the market for rare earth elements. Rare earth elements are used across a variety of products, including virtually all cellular phones, computers, new batteries,etc . Particularly Neodymium is absolutely essential for these elements to operate effectively with a small form factor. [Hurst 32] The market for rare earth products in 2012 stands at $15 billion dollars.(People's Republic 1-6) As mentioned previously, this growth in demand is projected to continue into the future.

If one considers some of the emerging industries for the future, particularly, alternative energy, rare-earth magnets are the lynchpin to developing dependable new reliable energy technologies. Without sacrificing quality or efficiency, there are not yet viable substitutes for rare earths.[Dent 5] As an example, Neodymium is by far the number one choice for magnets in both hybrid vehicle batteries and wind turbines, and there is no practical replacement for such an element. The effects of climate change and increasing global energy demands compound and require new, breakthrough solutions. It is imperative for government, industry, and consumers to leverage alternative energy technologies and expand their use.

Some developing countries, particularly China, have been investing heavily into the future of alternative energy technologies. Growth is anticipated for developed countries as well. With gasoline prices anticipated to increase in the future, hybrid vehicles will become a huge demand. It is estimated that by 2017, global demand for hybrid vehicles will reach 2,870,000. (Addison) For any promise of an affordable hybrid vehicle available to drivers, a reliable supply of rare earth batteries and magnets is essential.

It has long been an economic tradition of superpowers to develop most or all of their national defense infrastructure and weapons domestically. The U.S. military and Department of Commerce have raised foreign procurement concerns for more than two decades, but only through recent congressional hearings have such concerns been validated. [Botwin page 4]

However, many of the products that the U.S. military relies upon originate from the sands of Inner Mongolia, China. This realization left many in U.S. policymakers flatfooted, while some responded quickly. On July 11th, 2011, House Resolution 2011 launched the "National Strategic and Critical Materials Policy Act", vowing to establish a stronger, integrated U.S. supply chain of rare earth products in the United States. Also, the DoD continues to stockpile "strategic materials" at National Stockpile sites, but rare earths materials have yet to be included [Humphries 1-15 pg21]. Most recently, the Department of Energy has established a $120 million "innovation hub" for rare earth materials research and a focus on finding suitable substitutes. (United States)

F. Recent Mining Developments

Washington has become much more aware of China's rare earth mining dominance to China, and is drafting policies to redevelop the domestic mining industry. Confidence in Molycorp is rising as supply concerns begin to recede. "Provided Mountain Pass stays on track, this may be enough to sustain many of the domestic needs of the U.S." [Hurst 26]

Most recently the Molycorp Mountain Pass has been ramping up operations and are rolling out their "mines to magnets," initiative in phases. The goal of this project is to develop a vertically integrated, domestic rare-earth supply chain from mining to distribution. Creating a "one-stop shop" for all rare-earth demand is crucial for sustainability purposes for green energy, but is absolutely essential for U.S. military procurement.

G. Diminishing Export Quotas

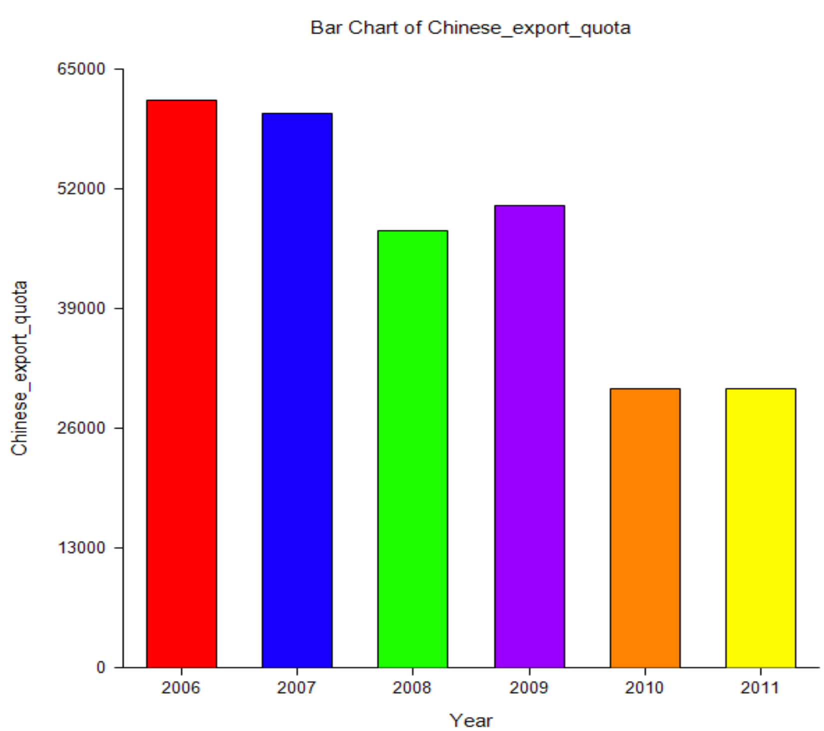
Most recently, Chinese export quotas have rapidly diminished. The table below indicates that 2011 export quotas represented a 50% drop from 2006 levels.

Table 3. China's Rare Earth Production and Exports, 2006-2011

	2006	2007	2008	2009	2010	2011
Official Chinese production quota	86,520	87,020	87,620	82,320	89,200	93,800
USGS reported production	119,000	120,000	120,000	129,000	130,000	112,500 (estimated by IMCOA)
Chinese export quota	61,560	60,173	47,449	50,145	30,259	30,246

Source: China Ministry of Land and Resources. U.S. Geological Survey. Ministry of Commerce of China.

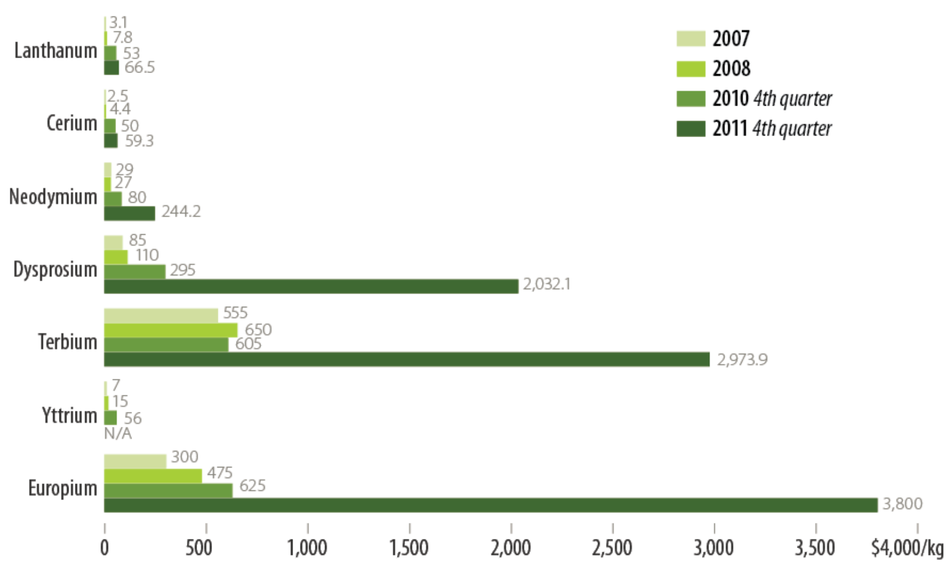
Note: USGS production data exceeded Chinese quotas, some of which is attributed to illegal mining.



China is hedging for the future in anticipation of increasing domestic needs of rare earths. Three indiciations of such a trend are cell phones purchases,hybrid vehicles sales, and wind turbine demand. From July 2008 to March of 2009, demand for mobile phones in China increased by 70 million. Such demand is projected to increase over time.[Xinhua] Additionaly, by 2015, China will have more than 500,000 hybrid energy vehicles (Eriksson) From a co-study between Harvard and Tsinghua universities, it is estimated that by 2030, China wind energy capacity may reach 6.96 trillion kilowatt hours; equivalent to all of China's energy demands. (Fairly) Mark Smith, the CEO of Molycorp, noted that a single wind turbine magnet can require up to two tons of rare earth material. (Hurst 19) Both hybrid vehicles and wind turbines depend heavily upon Neodymium, Terbium, and Dysprosium.

H. Price Instability

Within the past 24 months of this paper, the price for rare earth minerals has skyrocketed. Particularly, the market for Terbium, Dysprosium, and Neodymium are increasingly volatile.



[Source: Humphries]

Molycorp, after its Initial Public Offering, has raised hundreds of millions of dollars towards their goal and has already forged strategic industry partnerships, including Arnold Magnetics, one of the only American processors of Neodymium Iron Boron magnets. [Arnold] Currently, Molycorp shows the most promise of any American mine for profitability. With generating a positive net income in 2012, the company and its CEO have very clear and strategic goals to gain rare earth market share. (Elmquist) Molycorp is also making a number of investments domestically and abroad. Most recently, Molycorp has purchased Neo-Materials, a Canadian leader in rare earth materials production. Molycorp has also purchased Silmet, an Estonian firm for their production prowess. (Eriksson) This aggressive strategy is the only one of its kind within an American mining company. Molycorp is also one of the only major mines in the world that specifically focuses upon rare-earth mining. Chinese counterparts mine rare-earths as a bi-product of other operations, particularly iron. (Eriksson)

I. Recent Research in Supply Chain Recycling

There is increasing evidence that reliance upon traditional supply chain models will not only prove costly, but ineffective in the near future. Many large firms are beginning to research new means to develop “closed loop supply chains” that include recycling efforts. [Bell] Specifically, The Honda Corporation is beginning the first rare-earth recycling plant. Given increasing cost for such products, new recycling initiatives will likely manifest across more industries. However, recycling for rare earths is particularly costly, given the chemical waste and materials associated with reprocessing. (Eriksson) Japan, as the industry leader in rare-earth magnet productions, is leading the charge for rare-earth recycling, Such recycling efforts for rare earth elements will shape the future industry and U.S. rare earth supply chain.

III. Methodology

Data for this research was collected in two methods: secondary source data from literature review and primary source data through a qualitative case study method via a recorded interview. The literature guided the direction of the case study, shaped case-study questions, and provided insight to the changing supply chain. Digging through scientific papers, business journals, Chinese and American government statements provided in-depth information about specific issues within their respective sectors. This knowledge helped to identify broader, underlying drivers of the United States rare-earth supply chain.

The perspective of this paper is an interdisciplinary approach to an issue concerning many sectors and industries . For the data collection process, I intend to use a mixed-method approach. This approach will begin by conducting an archival analysis of public information available about rare earth metals and the companies that use them. This content will serve to both provide comprehensive insight to my research questions as well as shape open-ended questions for a single-case study interview with a U.S. industry expert. For investigating the structure of the rare-earth supply chain for the mining industry, this mixed-method approach will help to capture several key phenomenons within a unique and complex context.

A. Archival Analysis—Publications focusing on rare-earth topics are abundant, with a diverse audience ranging from science, government, and business. However, the literature is often stratified and the content is narrow-focused on specific issues relevant to its audience. It is believed that taking a more comprehensive approach to the landscape of literature will help draw meaningful results to the research question.

B. Case Method- Because there are so few industry experts of this field within the United States, methods such as surveys would yield a very small response. The single-case study, by deeply investigating a single situation, can provide rich results and content for drawing generalizations. A well-regarded single-case study recognized for explaining the unique situations and drawing meaningful generalizations was Graham and Zelikow's study of the Cuban Missile Crises. (Yin 3-15)

The interview conducted will be with a rare-earth industry expert. The interview will begin by asking extremely open-ended and broad questions about their industry. Once some specific topics are discussed, the expert will be asked more refined follow-up questions. The purpose of this approach is to objectively collect content related to specific questions. Before this single-case interview was conducted, the method has been reviewed and approved by the University of Tennessee's Institutional Review Board.

C. Shaping Of Interview Questions

It has been through this initial research that the sub questions were formed for this paper. This background acts as a primer for the research questions and also guides the reader into gaining better understanding of the material and underlying issues. To answer the primary question, "How is the U.S. Rare Earth Supply Chain changing?," a series of sub questions will help to answer this question. The questions asked will further develop the research that will ensure an integrated supply chain in the United States. The case study method is an effective approach considering the scarcity of active mines in the United States. To date, there is only 1 large scale mine in production in North America. The qualitative data may also effectively aid rare earth mines and rare earth buyers in better understanding outlying issues that they face in the future. The questions for interviews include the following:

1. What are the most pressing factors according to industry experts?
2. What are the comparative advantages and opportunities for US mining?
3. What are the demands from industry for the products? What are the future trends?
4. How sophisticated are customer demands based upon their supply chain/ product/ mineral used?
5. Where will refinement for elements such as Neodymium, Terbium, and Dysprosium take place?
6. What kinds of extraction problems do you have with heavy rare earth elements and exposure to Uranium and thorium? Is radiation an issue?
7. Is there a current export strategy? What role does the Japanese magnet market play?
8. What kinds of regulatory challenges does an American firm face?
9. What is the role of technical training of employees and research conducted by firms?
10. What kinds of recycling measures are being considered within the supply chain?
11. What kinds of concerns does a U.S. firm face with global competition?

These questions precede an interview using open-ended questions from an industry leader; inquiring about their thoughts, concerns, and comments about the changing nature of the U.S. rare earth supply chain.

IV. Results

A. Initial Findings In Literature

This research endeavor focuses on how the U.S. rare earth supply chain is changing, and the following information helped to shape and transform the research questions presented in this paper.

A lot of the current literature has extremely valuable content and information, but it is often disjointed across industry-focus or target audience. There are very few interdisciplinary articles available that collectively address all of the following: scientific challenges, supply disruptions, network analysis, macro-economic trends, and geopolitical developments related to the rare earth industry. In addition, most of the current information are only concerned with supply scarcity and China's monopoly. Most articles on the topic share very generic analysis and content. Current publications about the topic tend to focus on only a few issues including:

potential supply problem for the U.S., Chinese export quotas, brief descriptions about rare-earth elements and use, and the resurgence of the Molycorp mine. However, very few publications take a deeper dive into the issues.

With Molycorp's momentum, as well as other new operations like Australia's Lynas Corp. mine in Malasyia, there are very promising solutions for current supply and sourcing concerns on the horizon. A number of American and Canadian firms have begun production and started selling metals. Several firms are anticipating full-capacity by the end of 2013 (Steinitz). The elements and chemicals produced will be the same demands necessary not only for green energy technologies, but also for national defense applications. The quantities that mining companies like Molycorp are capable of producing are more than sufficient for domestic demands. These conclusions are not reached by many papers, and accurately framing the issue is critical to solving the supply chain issues.

Taking the next step to forming a self-sustaining supply chain in the United States, the question no longer is the feasibility of mining but the feasibility of value added processes like separation, refinement, and production taking place outside of China.

From initial research, there are three principals about the rare earth supply chain that must be emphasized. The first is the remarkable steps the Chinese government took to reach their ambitious goal and dominating the industry. The second is recent actions of Chinese firms in attempts to continually dominate the industry by pulling all downstream activities to China. Specifically, most separation, refinement, and production occur in China, and production costs in China are very low. Additionally, scientific and engineering knowledge of rare earth elements outside of China is very limited. (Eriksson). Because the domestic price of Chinese rare-earths is projected to be lower than global prices, many multi-national firms are shifting more downstream activities to China. The Molycorp purchase of Neo-materials has a number of operations within China. (Erikkson) The third is that the Chinese mining companies are planning an aggressive consolidation of mining operations and stockpiling, with a probability of further reduction in exports. [Hurst 20]

This trend is largely fueled by increased prices and production factors. Until mining and production of rare-earths outside of China becomes more efficient, it seems inevitable that some form of production within a firm's rare-earth supply chain will take place within China. [Johnson] Considering China's increasing appetite for rare earth consumption and accounting more for all global demand, this seems even more apparent. By 2015, China may account for almost 70% of total rare earth consumption. (REE)

There is a copious amount of academic research already dedicated to global outsourcing, particularly related to supply chain management contexts. Since the 1990s, virtually all rare earth industrial mining and services had been outsourced. [Fifarek] Much of the knowledge, expertise, and research belong to Chinese researchers working for Chinese firms. Fifarek suggests that offshoring stagnates innovation; this hypothesis has been supported within the United States regarding rare-earth elements. As the tides of change pull services and operations to the new shores of developing countries, the original country's accumulated knowledge and expertise drifts away and decays. Since rare-earth mining operations have moved abroad, America's two largest rare earth R&D centers have either closed or outsourced themselves. The Rare-Earth Information Center based in Ames, Iowa shut down due to lack of funding; while the former Raleigh based Magnequench Rare Earth R&D Center moved to Singapore in 2005. However, as noted earlier, a new Ames rare-earth center will be opening shortly thanks to DOE efforts. (United States)

In contrast to America's dearth of rare-earth scientists ,engineers, and supporting institutions, China has two separate industry publications dedicated to rare-earth news and scientific research. Additionally, there are four Chinese rare earth research laboratories, including the largest such facility in the world, each with its own narrowed research focuses. [Hurst 10]

There is also concern in the literature that demand for American products will be insufficient for mining firms to generate profit. However, American firms do possess a few key strategic advantages in the type of rare earth produced and creating strategic partnerships abroad. While current trade relations between China and Japan remain tense related to island disputes in the East China Sea, there is an opportunity for the U.S. to partner with the magnet-manufacturing base in Japan to export products. Japan hosts one of the largest bases of neodymium magnet refinement, and if relations remain sour with the Chinese, future investments into the country may be reconsidered, proving opportunistic for American miners. [Lifton 2] In this initial research, it is apparent that there are major disconnects between industry, scientific and government publications.

B. **Interview Discussion and Findings**

My interviewee is a high-level executive within the rare earth industry with an extensive background in green energy. The interview lasted forty minutes, and involved broad discussions of the industry and the unique landscape of rare-earth mining in the United States. Throughout the course of the interview, there were six broad themes that became apparent.

1) Supply will be more abundant in the near future

Two projects coming online, namely Molycorp and Lynas d, will undoubtedly change the global landscape for mining operations. After spending 14 years in preparation and more than $1 billion, Molycorp is capable of mining its rich ore deposits, extract and process elements, refine valuable minerals, and manufacture an array of highly specified chemicals and magnets all under one banner. Through a wide variety of acquisitions, Molycorp has a deep portfolio of products and services for the wildly varying customer demands. One of the most promising includes Molycorp's "Mines to Magnets" strategy. Also, strong partnerships with chemical distributors like Univar further support Molycorp's promise to deliver to customers.

Australia's Lynas Corp. has yet to reach full production and refinement capacity; this is largely due to political backlash from its newest constructed plant in Malaysia. However, industry analysts are optimistic in Lynas' long term potential.

2. Rare earth magnets are paramount for wind energy development and success

Permanent rare earth magnets are becoming more ubiquitous within wind turbine manufacturing.

> "Typically as they [wind turbines] get larger, two, three, five and even more megawatt per unit models and as they go offshore, why the industry hesitated to go to rare-earth magnets is availability and cost. In the last two years, that's been painful. So as more [mining] companies get online and increase the production of permanent rare-earth magnets, particularly neodymium iron boron magnets, and the cost, there's more visibility, there's more predictability, the supply chain is more reliable, more secure, I believe that the wind turbine generators are going to want to go to those magnets, assuming they believe they can afford them and have secure supply, because the benefits they deliver are overwhelming." (Interview)

Neodymium iron boron magnets require less maintenance and increase the efficiency of generators compared to ferrite magnets. The market U.S. wind turbines in 2012 is more than $7 billion and projected to grow.[Sherman] As more wind farms move offshore, the benefits for neodymium magnets are even greater.

3. The very small talent pool of U.S. rare-earth technicians, scientists, and engineers

Outside of China, there are only a handful of R&D centers or innovation hubs dedicated to rare earth research. This has limited the number of citizens with any formal study of the scientific applications for rare-earth elements.

> "For the most part, it just doesn't exist. Literally the talent, the chemical engineering expertise is very thin out there in terms of those who have any experience whatsoever in the extraction, separation, and purification of rare-earth elements. It is a unique set of chemical engineering skills and outside of China and Molycorp and Lynas, it's largely lacking in the world. So it's just a numbers game at this point." (Interview)

While the Department of Energy's January 2013 announcement of the reestablishment of rare earth research at Ames, there are still no marquee academic programs that cultivate future STEM careers in this industry. (United States) This labor shortage can lead to higher operating costs as well as productions delays.

4. Extensive vertical integration is (probably) the only profitable business model

There are only a few mines that have both highly concentrated mineral compositions and sufficient volume to be economically viable. The extraction and refinement process are so complex and customer specification requirements are so specific that a decentralized or multi-firm supply chain strategy is not feasible.

On a mine and being vertically integrated:

> "I've found is that as you go down that supply chain, going from oxides of rare-earth to metal, alright, to the metallic form and then from metal, creating rare-earth alloy, alloys, plural, and then finally specialty rare-earth alloys that get turned into value-added rare-earth magnets. For a business, the margins that you can make on those products increase pretty much as you go downstream. They can vary here and there. Sometimes the margin on alloy that you can make as a manufacturer is higher than the margin you can make on magnets. Sometimes it's reversed, but being able to supply customers at any point along that supply chain allows a company to maximize those margin opportunities across the supply chain." (Interview)

5. The supply chain has to be global, and must have a presence in the China market

The United States is the fourth largest industrial consumer of rare earth products, after China, Japan, and the European Union.

> "China is the dominant player in virtually all steps of the supply chain. So if you, as a company, want to be a global player, it's very difficult not to play a role in China's markets. China, first of all, consumes approximately 70% of all global rare-earth and 70% of the global market. So if you, as a producer, decide that you want to only play and sell products outside of China, then you're only addressing 30% or so of the global market. So you unnecessarily, in my view, handicap yourself as an enterprise doing that." (Interview)

Due to the high fixed costs of operating a production plant, companies must generate revenue by selling on volume and serving substantial proportions of demand. New rare-earth firms must court the Chinese market. Additionally, due to China's established expertise, institutions, and infrastructure, any firms supply chain will likely have to cross Chinese borders.

V. Conclusions

When combining the initial findings within the literature as well as the content of the interview together, some themes and patterns become clearer.

Global supply levels and price will stabilize in the near future

> "So as the supply becomes larger outside of China and more diverse, that should even out the price volatility that I've seen. It should increase the supply, diversity of supply, and that will, I believe, encourage greater demand" (Interview)

Although Chinese supply is decreasing, new firms with large capacities can fill the void. Alternative sourcing options are increasingly available, and China's market demand will be so large that foreign firms will be needed to provide extra materials. Should wind turbines continue to adopt neodymium boron magnets technology, both the rare-earth and wind energy industries will benefit.

There will probably be only a handful of competitors

The fixed costs are astronomically high, and the requirements for a fully operational firm are so vast that new entrants to the market will be an anomaly. Molycorp required nearly $900 million in investment capital to begin refining its deposits. Lynas' operation cost more than $800 million. Should more competitors enter the marketplace and increase supply, prices will likely drop. Molycorp began issuing public stock in 2010, when rare-earth prices reached all-time highs. (Kaiser) Once Molycorp and Lynas commenced production phases, global prices quickly stabilized.(Onstad) Investors are unlikely to fund such a new and expensive operation that does not promise large returns.

There is a very grave need to create new STEM education programs for this field.

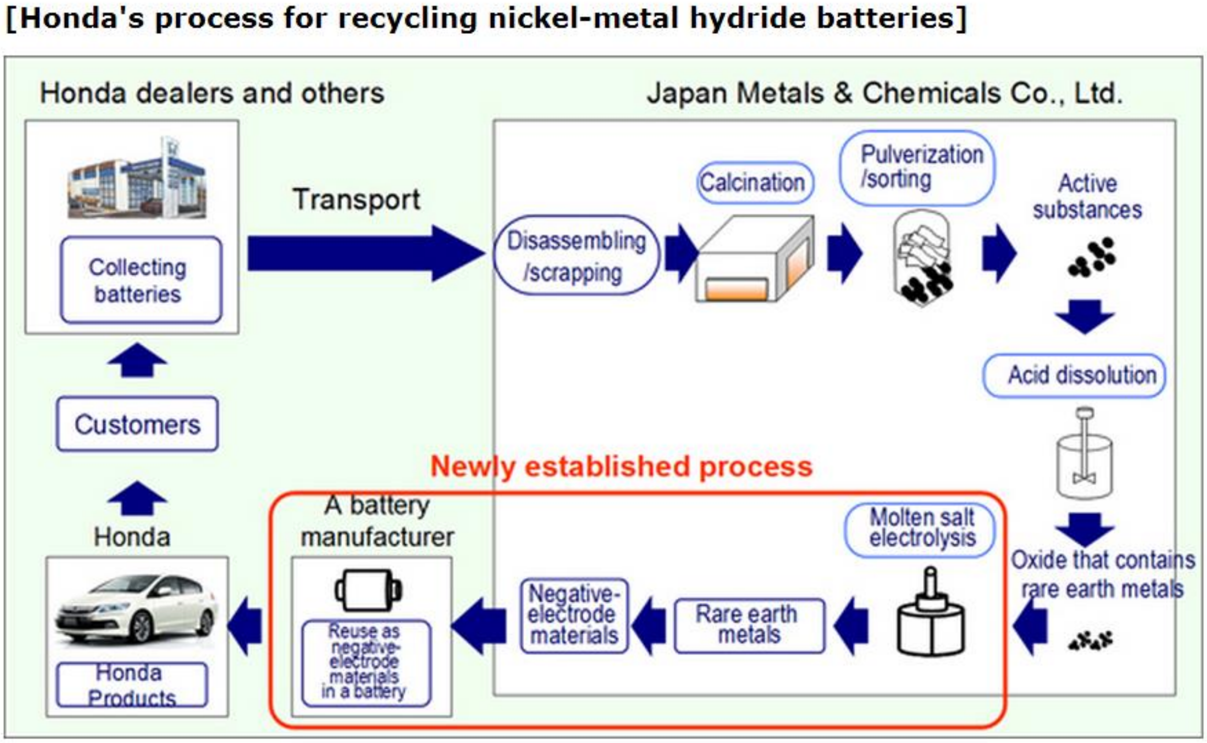
With so few workers capable of working in this field, any mining company will be pressed to find a steady supply of employees with such a background. Should any country, namely the United States, choose to have mining operations to compete with Chinese firms, there need to be educational curriculums and programs that attract students to pursue these fields. The dearth of technical knowledge outside of mainland China should cause concern for policy makers. If the U.S. military ever hopes to avoid rare-earth products with any foreign, namely Chinese, fingerprints, the government must take bold steps to increasing the number of American workers with the proper technical skills and education background.

Operational efficiency and innovative recycling efforts will be the game changer.

The main source of competitive advantage for companies in this industry is price. Optimizing production efficiency will ensure that operational costs are minimized. Additionally, any firm capable of large scale recollecting, recycling, and re-enriching rare-earth products will have a very distinct advantage. There are a handful of large-scale rare-earth recycling programs coming online in 2013. For various economic and geopolitical reasons, Japanese companies have been spearheading many of these pilot projects. Some companies already generating results from their recycling projects include Hitachi and Honda.

In 2010, Hitachi announced a breakthrough technology for recycling rare-earth magnets. The new technology can recycle magnets eight times more efficiently than conventional methods. (Hitachi)

In March 2013, Honda completed a 12-month implementation of a new recycling method that extracts the Lanthanum from old car batteries. The new method combines a creative recollection process with new re-enrichment techniques. Honda is using its dealership network as both a collection and re-distribution channel for customer batteries. Once centralized, new chemical techniques recover up to 80% of original purity levels, and recycled batteries are then redistributed back to the local level. Honda intends to make this recycling method commercially available once, “sufficient volume is secured”. (Honda)



Source: Honda

Scaling and commercializing these kinds of recycling programs offer unique challenges and opportunities for U.S. mines. Collaborative opportunities exist between Japanese companies and U.S. stakeholders like the Ames Critical Materials Hub and Molycorp. Combining Japanese recycling practices with new American supply can fundamentally alter the supply chain.

There will only be one firm in North America for the near future

Because of the enormous financial and time requirements to opening a new mine, there will not be any new U.S. producers for at least several years.. Behre Dolbear, a global advisory firm specializing in the minerals industry, publishes an annual report ranking each country's mining environment and potential. In Dolbear's 2013 report, although the United States ranked

6th out of 25 countries for overall mining, the U.S. scored the worst among the 25 for mining delays. The report explains:

> "Permitting delays are the most significant risk to mining projects in the United States. A few mining friendly states (Nevada, Utah, Kentucky, West Virginia, and Arizona) are an exception to this rule but are negatively impacted by federal rules that they are bound to enforce resulting in a 7- to 10-year waiting period before mine development can begin." (Wyatt)

Aside from Molycorp, only two other U.S. company are considering future production. Arkansas-based U.S. Rare Earth Inc. (USRE) owns 6 different properties (Idaho, Montana, and Colorado) that collectively may yield promising rare-earth deposits. In February 2013, USRE announced promising results from a preliminary drill and assessment of their Diamond Creek site (Montana). Exploratory drilling permits for other sites, including Lemhi Pass (Idaho), are pending approval. Another company, Rare Element Resources (RER), owns a large site in Bear Lodge, Wyoming. RER is still surveying their site and exploring the rare-earth deposits at Bear Lodge. (Udovich)

Assuming USRE's deposits are economically viable to extract, it will almost certainly be several more years until they can begin refining and selling to customers. It is not apparent that any other large operations are currently undertaking these steps.

Review of Interview Questions

Both the literature and expert interview provided some insight into many of the 11 original interview questions. Several questions were addressed that related to broad industry trends, future developments in the U.S., recycling programs, the role of government regulation, , customer demands, and workforce recruitment and training. However, questions related to the mining of specific elements (Neodymium, Dysprosium, and Terbium) as well as examining the extraction process and any radiation issues were unanswered.

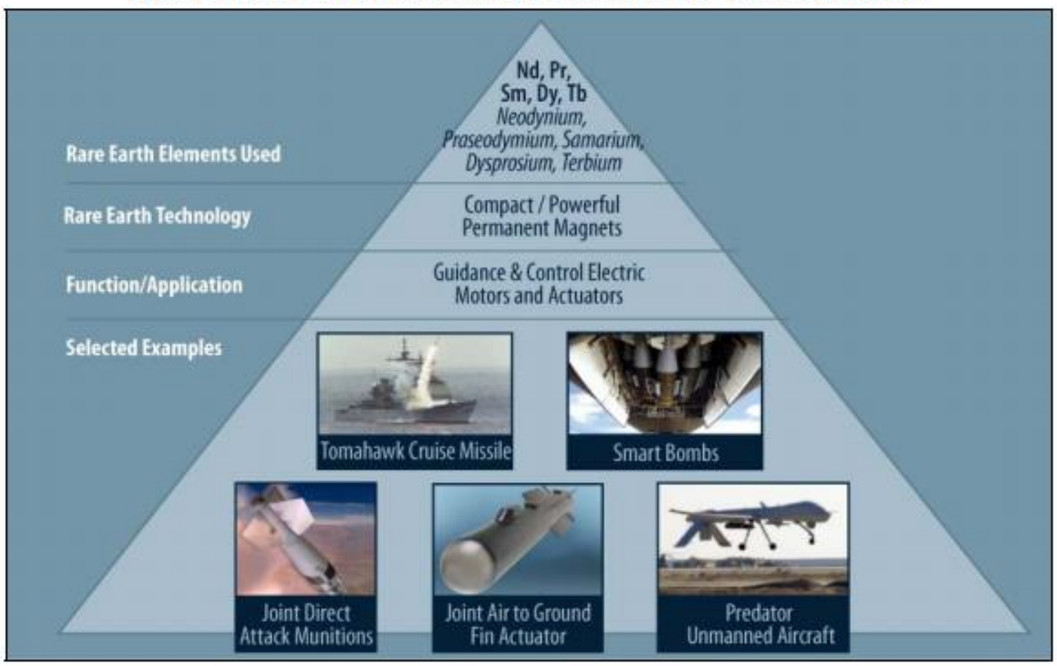
Further Research Needed on Individual Elements and Minerals

In the exploratory phases of this research, a number of elements were identified as being of particular economic importance. The applications for Dysprosium, Terbium, and Neodymium are so vast that further research should be dedicated to either viable substitute materials or potential recycling programs for these elements. Another subject that can be researched further is the impact of radioactive materials on rare-earth mining processes. Because primary data came from only one industry expert, the results of this research are limited. A number of mining firms that can be explored further include: Molycorp (U.S.), U.S. Rare Earth. , Rare Element Resources (U.S.) Lynas Corp. (Australia), Great Western Minerals Group (Canada).

Appendix A

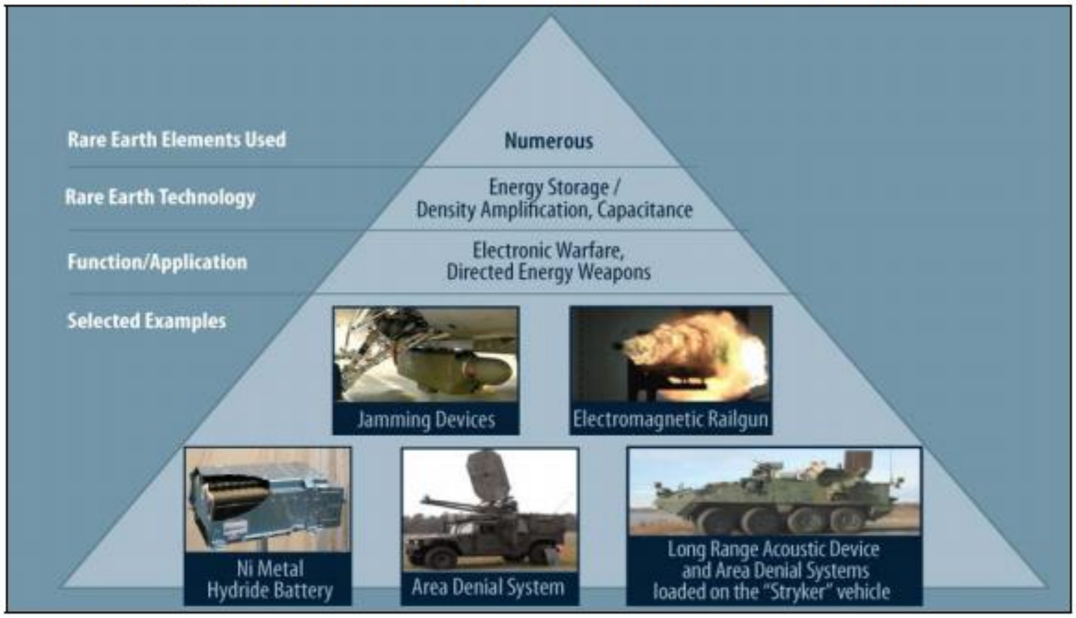
All visuals graphics presented in this sections were taken from 2012 Congressional Research Service report "Rare Earth Elements in National Defense; Background, Oversight Issues, and Options for Congress" [Grasso]

Figure 1. Rare Earth Elements in Guidance and Control Systems



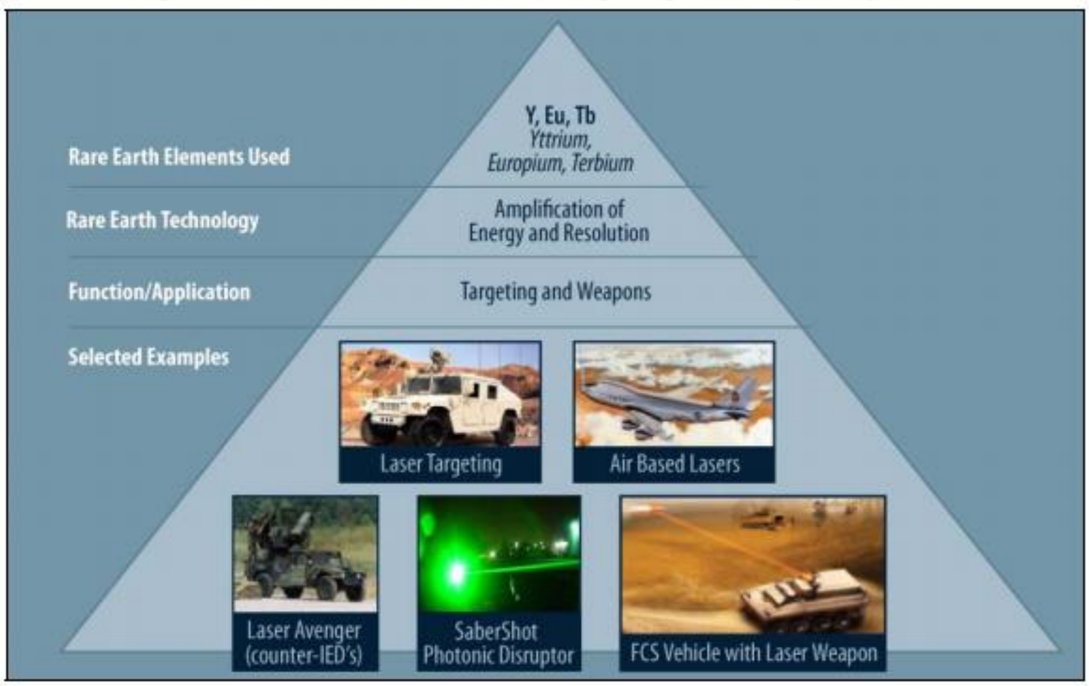
Source: Compiled from presentations by the Rare Earth Industry and Technology Association, the United States Magnet Manufacturing Association, and David Pineault, "Global Rare Earth Element Review," Defense National Stockpile Center, Spring 2010.

Figure 2. Rare Earth Elements in Defense Electronic Warfare



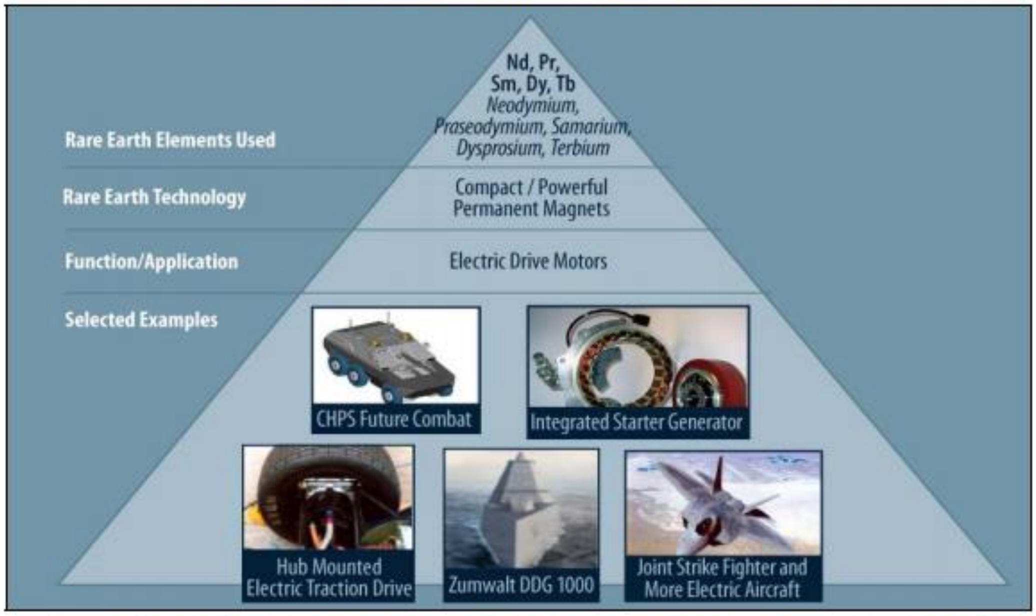
Source: Compiled from presentations by the Rare Earth Industry and Technology Association, the United States Magnet Manufacturing Association, and David Pineault, "Global Rare Earth Element Review," Defense National Stockpile Center, spring 2010.

Figure 3. Rare Earth Elements in Targeting and Weapon Systems



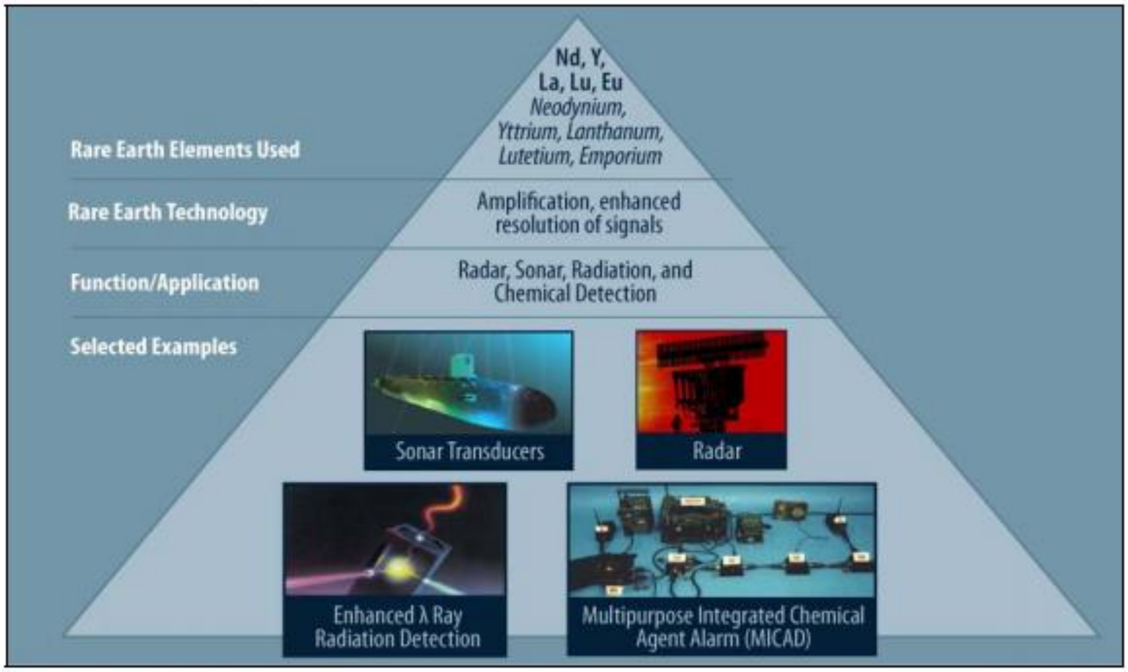
Source: Compiled from presentations by the Rare Earth Industry and Technology Association, the United States Magnet Manufacturing Association, and David Pineault, "Global Rare Earth Element Review," Defense National Stockpile Center, spring 2010.

Figure 4. Rare Earth Elements in Electric Motors



Source: Compiled from presentations by the Rare Earth Industry and Technology Association, the United States Magnet Manufacturing Association, and David Pineault, "Global Rare Earth Element Review," Defense National Stockpile Center, spring 2010.

Figure 5. Rare Earth Elements and Communication



Source: Compiled from presentations by the Rare Earth Industry and Technology Association, the United States Magnet Manufacturing Association, and David Pineault, "Global Rare Earth Element Review," Defense National Stockpile Center, spring 2010.

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