AN ENGINEERING PERSPECTIVE ON RARE EARTH ELEMENTS: A LITERARY INVESTIGATION OF MATERIALS TRANSFORMING CONSUMER TECHNOLOGY AND THE ENERGY INDUSTRY

by

Lindsey Nicole Elliott

Submitted in partial fulfillment of the

requirements for Departmental Honors in

the Department of Engineering

Texas Christian University

Fort Worth, Texas

May 7, 2018

AN ENGINEERING PERSPECTIVE ON RARE EARTH ELEMENTS:

A LITERARY INVESTIGATION OF MATERIALS

TRANSFORMING CONSUMER TECHNOLOGY

AND THE ENERGY INDUSTRY

Project Approved:

Supervising Professor: Robert R. Bittle MS, Ph.D.

Department of Engineering

Efstathios E. Michaelides MS, Ph.D.

Department of Engineering

Ken M. Morgan MS, Ph.D.

Department of Geology, Energy, & the Environment

ABSTRACT

From an engineering perspective, Rare Earth elements have the potential to transform technology in previously unprecedented ways. Their magnetic, luminescent, and electromechanical capabilities are allowing electronic devices to become more compact, reduce emissions, operate more efficiently, and cost less to produce and purchase. Such developments are proving beneficial to the economies of many developed nations because of their use in popular everyday consumer technologies as well as industries such as energy.

Along with this positive impact comes a political overlay that threatens the longevity of Rare Earth use. Presently, Rare Earths are expensive and dangerous to extract. This is largely due to the fact that they are not found together in large concentrations, so it is only economically feasible to extract them with another material, such as coal or minerals. The process of extraction is also hazardous and cumbersome; separating Rare Earths from other materials involves processes with high levels of emissions that may be dangerous to human beings if overexposure occurs. On the other hand, nations with more flexible safety and health regulations are investing in the development of Rare Earths and setting themselves apart as production leaders. Nations with more stringent health and safety regulations are becoming dependent on these nations to provide the Rare Earths for their applications. As a result, leaders in engineering industry can only benefit from Rare Earths if they optimize on the current supply economically.

The possibility of extracting Rare Earths through more efficient, safer processes is becoming recognized as a relevant topic of research. Additionally, investigation into alternatives to Rare Earths in some of the more common applications may allow for safer and less politically charged production methods for many 21st Century advancements.

ACKNOWLEDGEMENTS

The author would like to express gratitude and many thanks to Dr. Robert Bittle & Dr. Efstathios Michaelides for their tireless effort in supporting this project, their patience, their valuable feedback, their commitment to education, and their contagious passion for engineering as well as to Dr. Ken Morgan for the introduction to Rare Earth Elements in the beginning.

The author would also like to thank Texas Christian University, the John V. Roach Honors College, and the College of Science and Engineering for the opportunity and encouragement to perform undergraduate research.

TABLE OF CONTENTS

Wind turbines, hybrid electric vehicles, laptop computers, smart phones, solar panels, military munitions, and military aircraft: these key 21^{st} century technologies are linked not only by their importance in the everyday life of citizens of developed nations, but also by their current dependence on the materials that optimize their operation. Specifically, the materials in each of these systems referred to as Rare Earth Elements are known for having strong magnetic, luminescent, catalytic, optical, and/or electromechanical capabilities, and have positively contributed to the systems aforementioned in recent decades. These distinguishing characteristics of Rare Earth Elements are leading to their increased use in the production of electrical and mechanical systems and thus allowing these systems to become more compact, reduce emissions, operate more efficiently, and cost less to produce and purchase. As the economies of developing nations continue to grow, the demand for these and comparable technologies also increases. As a result, the demand for Rare Earth Elements increases. This demand has political, economic, and engineering implications. Further characterization of Rare Earth Elements and these implications will be addressed, political and economic with brevity, and supported with data in the following presentation/body of research.

The Rare Metal age has only emerged in recent decades. An average home 150 years ago was comprised primarily of materials from a nearby forest or quarry. By the 1960s, a home was comprised of roughly 20 different elements. Today, an Intel computer alone uses roughly 60 elements. As society evolves, the demand for a wider variety of elements increases. With rising world population, the quantities of all materials demanded also increases. Over the past 35 years alone, mining companies have produced four times the amount of Rare Metals than have been produced since the beginning of production. Materials scientists, metallurgists, and engineers have been developing new materials and new methods of using materials at a rapid rate. Key among these materials have been Rare Metals and a subset of Rare Earth Metals, which are also referred to as Rare Earth Elements. There are seventeen of these Rare Earth Elements that, as the name suggests, can be found on the Periodic Table of Elements. Three of the Rare Earth Elements are located on the far left side of the Transition Metal section of the table, and the other fourteen Rare Earth Elements comprise the entirety of the Lanthanide Series at the bottom of the Periodic Table. Appendix A displays the quantitative properties of Rare Earth Elements in a table by Periodic Table Symbol.

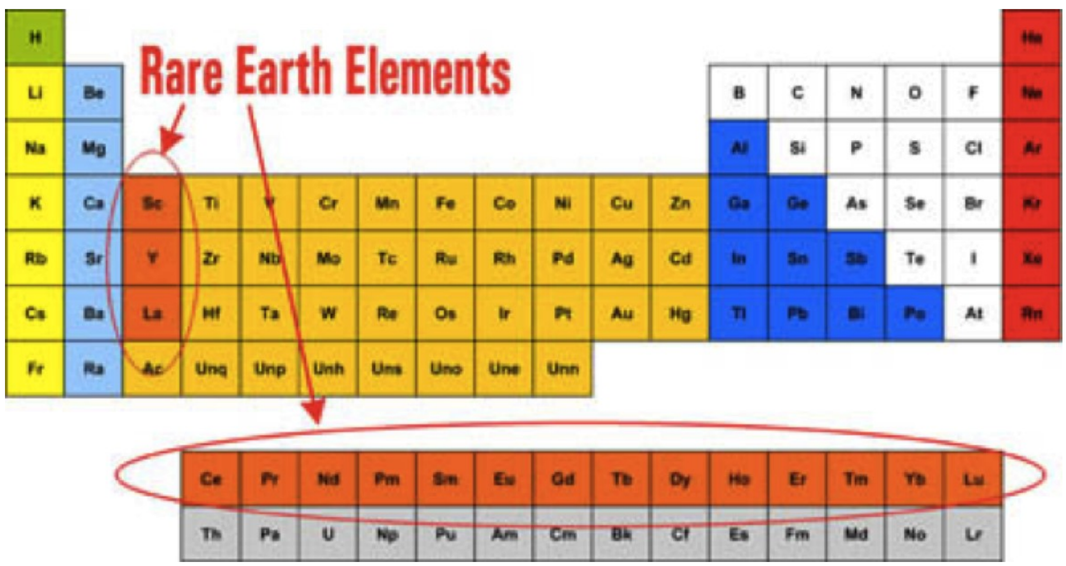

Figure 1: Location of Rare Earth Elements on the Periodic Table of Elements

Improvements in mining technologies have been key to the development and use of Rare Earth Elements, and 21st Century technology has developed a dependence on these elements for many new applications that improve quality of life for many consumers and increased success of a variety of industries.

The trend in cultivation of materials and the corresponding innovation of Rare Metals and Rare Earth Metals is not unprecedented. The stone age, bronze age, iron age, and steel ages paralleled this development. Each of these ages is characterized by the discovery and development of a new material followed by its adoption and a resulting economic transformation. More specifically, development of new materials has shown to continually lead to enhancement of tools, improvement of existing products, and the creation of new products that stimulate the economy as a result. The Rare Metal age is similar. As the Rare Metal age continues to unfold, many products have been enhanced and created that are smaller, faster, lighter, denser, and cheaper than ever before.

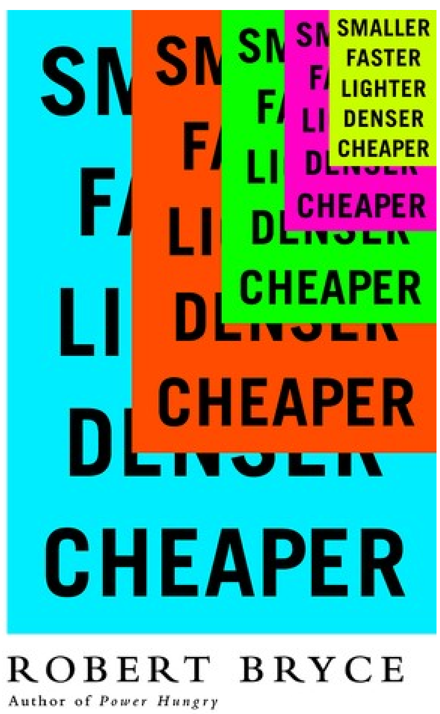

Figure 2: Smaller, Faster, Lighter, Denser, Cheaper by Robert Bryce Highlights the Trends of Performance Optimization and Physical Consolidation in 21st-Century Technology

As products are improved in the Rare Metal age, demand for Rare Earth Elements increases proportionally. Along with this impact comes a political overlay that threatens the time period available for Rare Earth Element use. Presently, Rare Earth Elements are expensive and dangerous to extract. Despite their designation as “rare,” Rare Earth Elements are actually very abundant in the Earth’s crust comprising roughly 150-220 parts per million where deposited. Rare Earth Elements deposits can be found in many international locations geographically, specifically China, Australia, Brazil, Canada, Greenland, India, Kyrgyzstan, Malaysia, Russia, South Africa, Sweden, and the US. Although these locations are documented as having substantial quantities of Rare Earth Elements, the exact locations and quantities of the Rare Earth Elements in their deposits is still unknown. Predictions can be calculated to approximate the amount of Rare Earth Elements present, but these predictions are no more accurate than those used to predict peak oil supply and demand. Similarly, predictions for Rare Earth Element demand in the future are equally unreliable and ever-changing. In January of 2013, the US Geological Survey estimated an international supply of roughly 110 million tons of REE reserves, but other organizations internationally present different predictions of Rare Earth Elements supplies. Changes in demand for Rare Earth Elements in the future may lead to issues when matched with a limited Rare Earth Element supply.

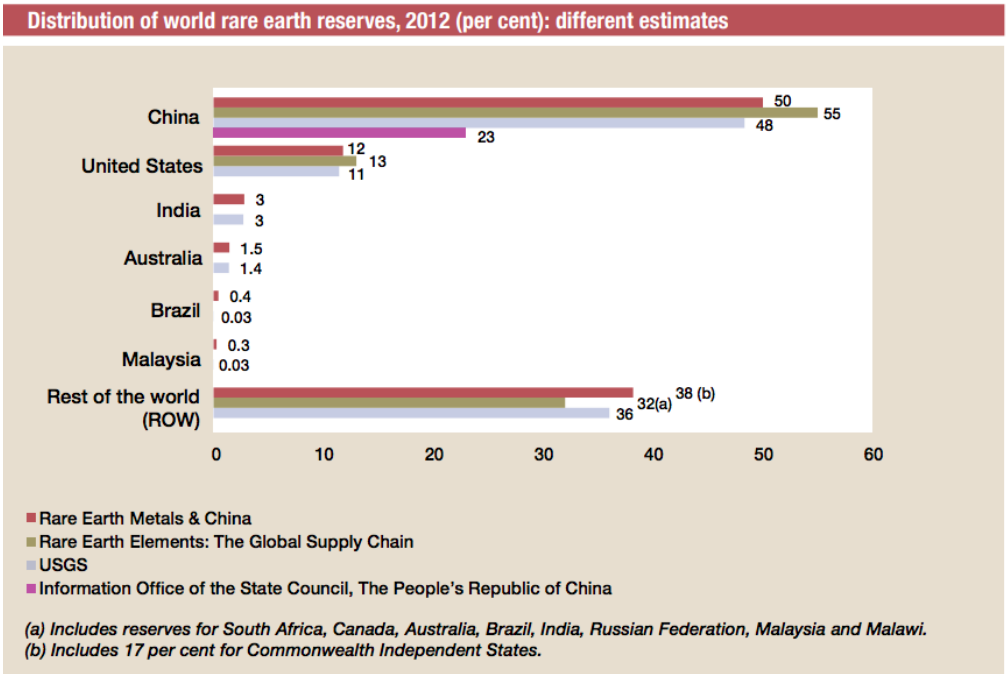

Figure 3: Different Predictions of International Rare Earth Element Supply; Predictions Vary by Predicting Organization

Although Rare Earth Elements are not technically scarce, they are not found together in large concentrations in the aforementioned deposits. Technically, Rare Earth Elements are found amongst minerals, often mineral impurities, in small concentrations but have to be separated, usually by mass, by magnetic capability, or by a chemical decomposition process, into their respective constituents from the raw mineral material. There are approximately 200 minerals presently suspected to contain Rare Earth Elements, but the three minerals from which Rare Earth Elements are most frequently extracted are bastnäsite, monazite, and xenotime.

Since Rare Earth Elements are dispersed amongst raw mineral material and difficult to separate, the cost of mining and refining Rare Earth Elements is very high. In fact, it is only economically feasible to extract them with another material, such as coal or minerals that also have market value once refined. The process of extraction is also hazardous and cumbersome;

separating Rare Earths from other materials involves refinement processes with high levels of emissions that may be dangerous to human beings if overexposure occurs. Sometimes the mining and refining byproducts also include radioactive material. Increasing concern for residential areas adjacent to mines and the manual laborers working to produce Rare Earth Elements internationally has changed the perception of the value of Rare Earth Elements.

Furthermore, on a more political note, nations with more flexible health and safety regulations are investing in the development of Rare Earth Elements and setting themselves apart as production and supply leaders. Nations with more stringent health and safety regulations are becoming dependent on these nations to provide the Rare Earths for their applications. Since technological advancement is a key indicator of the development level of a nation, these more developed nations are demanding the most Rare Earth Elements, and their dependence on Chinese markets is increasing as a result.

The four regions most dependent on Rare Earth Elements currently include China, Japan, the US, and the EU. Of these, China currently produces the largest supply of Rare Earth Elements because, in addition to geographically possessing a predicted value of over 10% of the Earth's Rare Earth Element supply, China also has the most relaxed health and safety regulations of the four regions. In contrast to the US, the EU, and Japan, Chinese manual laborers are permitted to undergo harsher measures to mine Rare Earth Elements. Chinese labor is less costly, but also a dangerous endeavor. This allows China to quickly and efficiently refine raw materials to extract the small quantities of Rare Earth Elements included therein. There are other locations with proven Rare Earth Elements deposits, including the US, Japan, and the EU, however these nations are not able to produce enough Rare Earth Elements to be economically competitive with China presently. Manual labor regulations are more stringent in those regions and their respective governing bodies. In addition, the upfront capital costs to begin Rare Earth Element production alone are enough to cause many nations to hesitate on committing to the economic investment. These nations then become the main purchasers of China's Rare Earth Element supplies.

If it becomes economically feasible for these nations to invest in Rare Earth Element research and development themselves, then the US, Japan, and/or the EU may be more likely to find methods of harvesting Rare Earth Elements safely, economically, and via automation instead of human labor. This could bring healthy competition to the Rare Earth Element supply markets in China. For example, Mountain Pass, California, a region that once refined Rare Earth Elements domestically for the United States, may be able to go back to its development processes of the past, improve upon them, and provide the US with a supply of Rare Earth Elements as contingency to sustain its 21st Century Rare Earth Element dependent economy.

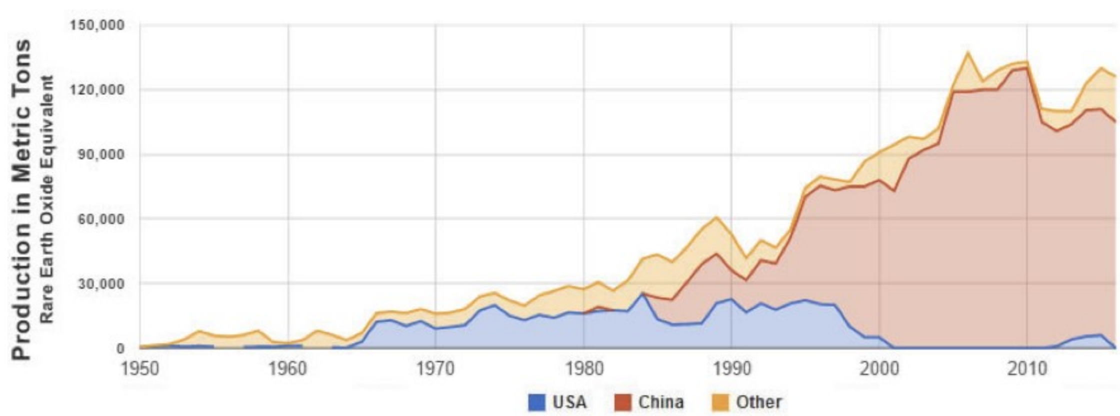

Figure 4: The USA, China, and Other Nations have Split the Production of Rare Earth Elements; The US Decreased Production of REEs in Mountain Pass, California in the Early 2000s, but have Since Started Domestic Production Again for Resource Security

Specifically, Molycorp has been the company leading the United States' development of Rare Earth production in Mountain Pass, California. This company, headquartered in both Greenwood Village, Colorado and Beijing, China, has recently changed ownership to Neo Performance Materials. Neo is attempting to reestablish the US Rare Earth Element market and provide materials for highly complex applications while simultaneously developing more Rare Earth Element applications. Lynas Corporation LTD is also responsible for the development of Rare Earth Elements in Mount Weld in Australia, another nation considered to be developed politically and economically. This region is also emerging as a key Rare Earth Element supplier/producer of the future. Furthermore, investigation into deposits of Rare Earth Elements on the ocean floor as well as the surface of the moon has been heightened in recent years to confirm the presence of deposits of Rare Earth Elements. Although these may not be the most easily accessible deposits of Rare Earth Elements, accumulating a comprehensive survey of all deposit locations will still aid in the prioritization of ultimate Rare Earth Element development.

China has also recognized its monopoly on the Rare Earth Element supply market and is taking responsibility to respond appropriately, as some of this responsibility ends up being in its favor. China has also been taking more responsibility for the cleanliness of its environment and the health of its citizens. Fewer licenses are being distributed to Rare Earth developers in China, and black market development of Rare Earth Elements is being increasingly targeted and put to rest. As a result, China has begun to decrease its overall exports of Rare Earth Elements and thus drive up the price of the exported commodities.

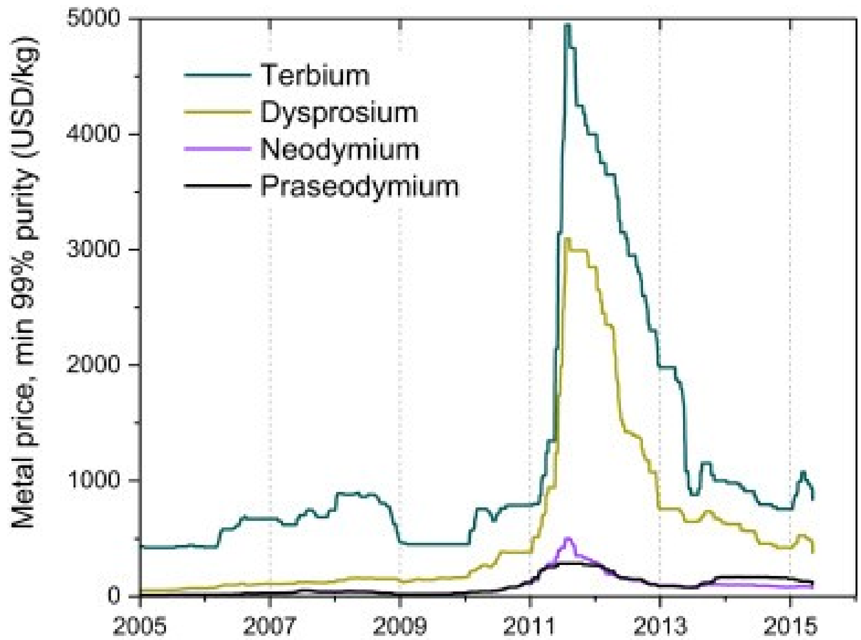

Figure 5: Rare Earth Element Price Increases by Percent for 4 Different Elements as a Result of China’s Actions to Reduce Exports

This is not only in recognition of China’s current monopoly on the economy of Rare Earth Elements, but also on the reality that Rare Earth Elements are nonrenewable resources in finite amounts. Preserving the domestic Chinese resources is a priority as is encouraging other nations to begin to develop some of their own domestic deposits for international resource sustainability. Economically, Chinese Rare Earth Element prices will hit a maximum threshold where it will be economically desirable for other nations to develop their own deposits of Rare Earth Elements instead of importing them. This is set to drive international development and production of Rare Earth Elements, and the Chinese are predicted to only occupy about 75% of the Rare Earth Element supply market as opposed to the previously reported 90-95%.

With increased development and enhancement of products also comes development of many products considered waste as they are phased out of everyday life, businesses, industries, and the economy. This is especially prevalent in what is referred to as a disposable society of today. For example, the average consumer disposes of a cellular device to acquire a new one roughly every 2-3 years. The disadvantage of this wastefulness is the amount of time it takes for many materials used in manufacturing and production of products today, including Rare Earth Elements, to decompose. The rate of waste accumulation is much faster than the rate of material decomposition, as is the case with cellular devices. As an alternative to decomposition, recycling initiatives are often suggested, however little to no successful initiatives have been implemented for the recycling of Rare Earth Elements currently. Again, research and development efforts could be encouraged in developed nations with high levels of Rare Earth Element disposal. Rare Earth Element recycling in general would also recirculate Rare Earth Elements back into the international or national supplies, and thus aid in alleviating the current international shortage and production limits. Dr. Doris Schuler proposes an innovative solution to the development of recycling technologies for reduction of Rare Earth Element waste in the EU.

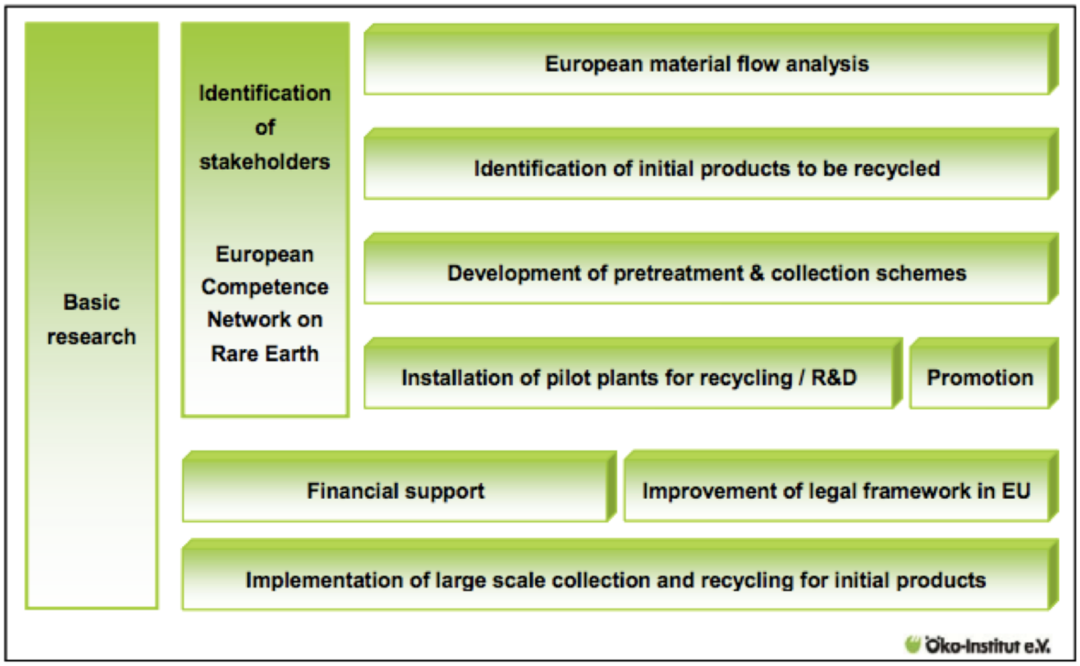

Figure 6: The European Union has Attempted to Create a Structure for Rare Earth Element Recycling; It is to be Implemented as Soon as Possible

When observed from an engineering perspective, the European Union's proposed system for recycling Rare Earth Elements can be improved to increase efficiency. The addition of a feedback loop into the proposed system may allow for a more modular, iterative process of development that could result in a comprehensive, cohesive solution faster. The feedback loop was selected to provide feedback from the end of the cycle to near the beginning of the cycle so that new/more products could be identified for recycling and the current infrastructure for recycled products could be improved.

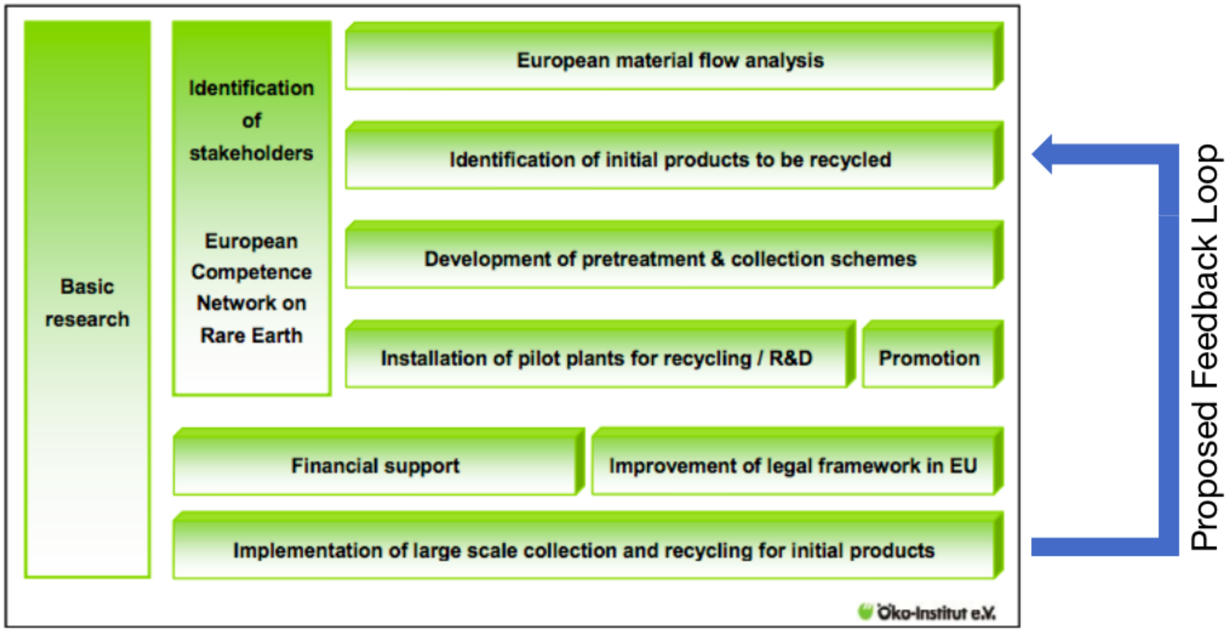

Figure 7: Proposed Addition of a Feedback Loop to the EU's Proposed Rare Earth Element Recycling System will Likely Expedite the Iterative Process of Improving the Recycling System (Note: This Feedback Loop is Recommended by the Author)

Presently, few Rare Earth Element recycling initiatives have been proposed and even fewer have been implemented. A few beginning to emerge include Osram AG in Germany, the Solvay Group in France, and AERC Recycling Solutions and Global Tungsten & Powders in the US. Each of these groups is recycling the Rare Earth Elements commonly used in fluorescent light bulbs. Ames Laboratory in the US is also researching ways to recycle neodymium and dysprosium, as are a number of organizations in Japan. Ideally, successful recycling initiatives for Rare Earth Elements will develop and be implemented as production and use of Rare Earth Elements also develop. On another note, the build-up of many Rare Earth Elements that are unable to be decomposed is environmentally detrimental, so the rapid development of successful recycling initiatives for Rare Earth Elements is paramount.

In order to maximize the impacts of a successful recycling initiative, it is logical to prioritize recycling methods for the most commonly discarded, and often the most commonly used, Rare Earth Elements. In order to do this, it is key to first take an inventory of the discarded Rare Earth Elements and determine which one(s) are the best investment to implement in recycling processes. There are certainly some Rare Earth Elements that are used more commonly than others. The top five most commonly used Rare Earth Elements are neodymium, dysprosium, yttrium, terbium, and europium in no particular order. These materials are specifically valued for their unprecedented magnetic capabilities or luminescent capabilities. Since they are the most commonly used Rare Earth Elements, it is suspected that they are also the most prevalent in landfills and the highest in demand in the supply markets. Respectively, they are also some of the best materials for development of a recycling program.

In addition to Rare Earth Elements' contributions to a green society through demands for rapid improvements to international recycling infrastructure, many Rare Earth Elements are also being used to enhance the operation of machines used in the renewable/green energy industry. In one of the most common examples, the magnetic properties of neodymium, dysprosium, terbium, and praseodymium are being used to enhance the generators located in the nacelles of wind turbines. Using a lightweight, magnetic Rare Earth Element to replace, in many cases, hundreds of turns of copper wire in a generator improves the strength-to-weight ratio of the device as well as the efficiency. Using Rare Earth Elements in the design of wind turbines also allows for the machines to last longer under the mechanical impacts of creep and fatigue, thus making them more durable than their predecessors.

As mentioned previously, some US and Japanese companies are making an effort to begin recycling Rare Earth Elements in commonly used fluorescent lightbulbs. This is because lightbulbs are one of the most common applications of Rare Earth Elements. Luminescent materials are also commonly being used to provide the backlight to screens such as those of plasma televisions, laptop computers, or smartphones. Some of the Rare Earth Elements commonly used to make phosphors, or synthetic fluorescents, are yttrium and europium. Since these Rare Earth Elements surpass their competitors in luminescent capabilities, they are sought after for providing exceptionally clear and bright images on television screens. Their brightness is also valued by civil engineers for the design of street light systems to enhance the safety of major infrastructural systems.

Figure 8: An Array of the Many Uses of Rare Earth Elements Divided into Categories

Rare Earth Elements also have the potential to transform the future of healthcare. One company in particular, Hendo, has been using the exceptionally strong magnetic capabilities of Rare Earth Elements to develop hover board technology. This technology is likely to be appreciated not only by skateboard enthusiasts, but also by future hospital patients. Hendo's hover board technology is able to function via opposing magnetic forces acting against each other. This repulsion force is able to lift the magnetically polarized hover board off of an oppositely magnetically polarized surface on cue. Through the use of electromagnets, this magnetic polarization can be turned on and off with the flip of a switch. A proposed use of this technology is in hospital operating rooms. If, for example, seismic activity is detected during an operation, hover technology can be activated so that key equipment in the operating room, including the operating table securing an unconscious patient, can be lifted from a magnetically polarized floor and not shaken by the seismic activity. This would entail installation of the technology on the identified key equipment beforehand, but it could potentially save lives at critical moments during surgery.

In terms of alternatives for Rare Earth Elements, some research has been performed in labs by materials scientists and engineers to replicate the impurities found in minerals that can be mined and refined into Rare Earth Elements for use. Unfortunately, these efforts have not been met with substantial success to date. There is also a lapse in the literature on alternatives for Rare Earth Elements regarding direct material replacements. Technically, Rare Earth Elements are considered critical materials, or materials whose supply condition or status is in critical need of reform. For example, Tesla Motors has also been developing motors with permanent magnets on their rotors that are not Rare Earth Element dependent. These motors are predicted to outlast previously used copper wire motors, similarly to the Rare Earth Element types, but they will also be recyclable and made from more commercially available non-critical materials. In the interim of developing Rare Earth Element alternatives, it is also a best practice to use the Rare Earth Elements necessary as efficiently and scarcely as possible. Aside from Tesla's initiatives, there is limited success and literature on direct replacements of Rare Earth Elements with non-critical materials. Continual research and development investment may help lead to advancements in not only alternatives to Rare Earth Elements as lab-produced synthetics or non-critical material replacements, but also in environmentally friendly processes that can be used to extract Rare Earth Elements with fewer chemicals and hazardous byproducts.

In conclusion, the unprecedented material properties of Rare Earth Elements are allowing for cutting-edge development of 21st Century technology, but the Rare Earth Element industry is still in need of further development. In addition to verifying and securing the locations of Rare Earth Element deposits internationally, the mining and refining processes of Rare Earth Elements that remain dangerous and hazardous need improvement industry-wide. With investment in further Rare Earth Element research and development, improvements to these processes as well as synthetic lab-developed alternatives for Rare Earth Elements and/or direct substitutes for Rare Earth Elements may be identified. Furthermore, rapidly improving Rare Earth Element recycling infrastructure and limiting use of Rare Earth Elements to only those absolutely necessary may aid in securing a short term supply of Rare Earth Elements. From an engineering perspective, Rare Earth Elements will be key to developing new technology and improving standards of living in the future, but engineers will also be largely responsible for maintaining the safety and sustainability of the international Rare Earth Element supply.

WORKS CITED

"A Framework for Evaluating the Accessibility of Raw Materials from End-of-Life Products and the Earth's Crust." Egyptian Journal of Medical Human Genetics, Elsevier, 16 June 2017, www.sciencedirect.com/science/article/pii/S0956053X17303963?via%3Dihub#b0155.

Abraham, David S. The Elements of Power Gadgets, Guns, and the Struggle for a Sustainable Future in the Rare Metal Age. Yale University Press , 2017.

"Bear Lodge Project." Rare Earth Elements, Rare Element Resources LTD, 2016, www.rareelementresources.com/bear-lodge-project#.Wuzy8VMvx-U.

Bryce, Robert. Smaller Faster Lighter Denser Cheaper: How Innovation Keeps Proving the Catastrophists Wrong. PublicAffairs, 2016.

"Company." Neo Performance Materials, www.neomaterials.com/company/.

Doris , Doris, et al. "Study on Rare Earths and Their Recycling." Jan. 2011, http://www.ressourcenfieber.eu/publications/reports/Rare%20earths%20study_Oeko-Institut_Jan%202011.pdf

Editors, AccessScience. "Rare-Earth Elements: Recycling or Replacement." Access Science, McGraw-Hill Education, 2014, www.accessscience.com/content/rare-earth-elements-recycling-or-replacement/BR0113142.

Fisher, Travis, and Alex Fitzsimmons. "Big Wind's Dirty Little Secret: Toxic Lakes and Radioactive Waste."IER, 23 Mar. 2013, www.instituteforenergyresearch.org/analysis/big-winds-dirty-little-secret-rare-earth-minerals/.

Graedel, T. E., et al. "On the Materials Basis of Modern Society." PNAS, National Academy of Sciences, 19 May 2015, www.pnas.org/content/112/20/6295.

"Impact of Materials on Society (IMOS) - Rare Earth Elements." YouTube, Materials Research Society, 2 Mar. 2016, youtu.be/C-b1NacN3lY.

Klinger, Julie M. "Rare Earth Elements: Development, Sustainability and Policy Issues." Egyptian Journal of Medical Human Genetics, Elsevier, 5 Jan. 2018, www.sciencedirect.com/science/article/pii/S2214790X17302472.

Lin, et al. "Recovery of Rare Earth Elements from Coal and Coal Byproducts: What Have We Learned from the USGS CoalQual Database?" American Journal of Human Genetics; (United States), ASM International, Materials Park, OH, 1 Aug. 2016, www.osti.gov/servlets/purl/1342507.

McGuinn, Jack. “For Some Industries, Rare Earth Elements Becoming Rarer Still.” A Look at Belt, Chain and Gear Drive Technology | Power Transmission Blog, Randall Publications LLC, 2018, www.powertransmission.com/newsletter/0212/rare.htm.

“Mission 2016: Strategic Mineral Management.” The Future of Strategic Natural Resources, MIT, web.mit.edu/12.000/www/m2016/finalwebsite/index.html.

Nesbit, Jeff. “China's Continuing Monopoly Over Rare Earth Minerals.” U.S. News & World Report, U.S. News & World Report, 2 Apr. 2013, 5:10, www.usnews.com/news/blogs/at-the-edge/2013/04/02/chinas-continuing-monopoly-over-rare-earth-minerals.

“OUR COMPANY.” Lynas, Lynas Corporation LTD, 2018, www.lynascorp.com/Pages/Mt-Weld-Concentration-Plant.aspx.

Paul, Justin, and Gwenette Campbell. “Investigating Rare Earth Element Mine Development in EPA Region 8 and Potential Environmental Impacts.” National Service Center for Environmental Publications, United States Environmental Protection Agency, 15 Aug. 2011, nepis.epa.gov/Exe/ZyNET.exe/P100FHSY.txt?ZyActionD=ZyDocument&Client=EPA&Index=2011%20Thru%202015&Docs=&Query=&Time=&EndTime=&SearchMethod=1&TocRestrict=n&Toc=&TocEntry=&QField=&QFieldYear=&QFieldMonth=&QFieldDay=&UseQField=&IntQFieldOp=0&ExtQFieldOp=0&Xm.

Pavel, Caludiu C, et al. “Substitution Strategies for Reducing the Use of Rare Earths in Wind Turbines.”Egyptian Journal of Medical Human Genetics, Elsevier, 4 May 2017, www.sciencedirect.com/science/article/pii/S0301420717300077.

Rare Earth Elements-End Use and Recyclability. USGS Science for a Changing World, 2011, pubs.usgs.gov/sir/2011/5094/pdf/sir2011-5094.pdf.

“Rare Earth Elements (REE): Why Are They Strategically Important? - Clear IAS.” ClearIAS.com, ClearIAS, 16 Mar. 2017, www.clearias.com/rare-earth-elements-ree/.

“Rare Earth Elements: What Confluence? | Sean Dudley | TEDxBozeman.” YouTube, TEDxTalks, 24 May 2016, youtu.be/tgS8hgvo1nk.

“REE - Rare Earth Elements and Their Uses.” Geology, Geology.com, 2018, geology.com/articles/rare-earth-elements/.

Spedding, and Frank H. “Rare-Earth Elements.” Access Science, McGraw-Hill Education, 2014, www.accessscience.com/content/rare-earth-elements/573400.

UNCTAD. “Special issue on rare earths.” Commodities At A Glance, no.5. UNCTAD, 2014, https://statistical.proquest.com/statisticalinsight/result/pqpdocumentview.pqppanelgroup_1.gispanelfour:pdfLinkUri?pdfLinkUri=%2Fftv2%2F4c4e000001e8b24e.pdf&docUri=%2Fcontent%2F2014%2F4050-S52.1.xml

Wang, Shanshan, et al. “Distribution and Source of Rare Earth Elements in PM2.5 in Xiamen, China.”Environmental Toxicology and Chemistry, Wiley-Blackwell, 18 Aug. 2017, setac.onlinelibrary.wiley.com/doi/full/10.1002/etc.3902.

“60 Minutes: Rare Earth Elements.” CBS News, 19 July 2015.

FIGURE SOURCES

Figure 1: McGuinn, Jack. "For Some Industries, Rare Earth Elements Becoming Rarer Still." A Look at Belt, Chain and Gear Drive Technology | Power Transmission Blog, Randall Publications LLC, 2018, www.powertransmission.com/newsletter/0212/rare.htm.

Figure 2: "Smaller Faster Lighter Denser Cheaper: How Innovation Keeps Proving the Catastrophists Wrong by Robert Bryce." Goodreads, Goodreads, 13 May 2014, www.goodreads.com/book/show/18210818-smaller-faster-lighter-denser-cheaper.

Figure 3: UNCTAD. "Special issue on rare earths." Commodities At A Glance, no.5. UNCTAD, 2014, https://statistical.proquest.com/statisticalinsight/result/pqpdocumentview.pqppanelgroup_1.gispanelfour:pdfLinkUri?pdfLinkUri=%2Fftv2%2F4c4e000001e8b24e.pdf&docUri=%2Fcontent%2F2014%2F4050-S52.1.xml

Figure 4: "REE - Rare Earth Elements and Their Uses." Geology, Geology.com, 2018, geology.com/articles/rare-earth-elements/.

Figure 5: Klinger, Julie M. "Rare Earth Elements: Development, Sustainability and Policy Issues." Egyptian Journal of Medical Human Genetics, Elsevier, 5 Jan. 2018, www.sciencedirect.com/science/article/pii/S2214790X17302472.

Figures 6 & 7: Doris , Doris, et al. "Study on Rare Earths and Their Recycling." Jan. 2011, http://www.ressourcenfieber.eu/publications/reports/Rare%20earths%20study_Oeko-Institut_Jan%202011.pdf

Figure 8: Lin, et al. "Recovery of Rare Earth Elements from Coal and Coal Byproducts: What Have We Learned from the USGS CoalQual Database?" American Journal of Human Genetics; (United States), ASM International, Materials Park, OH, 1 Aug. 2016, www.osti.gov/servlets/purl/1342507.

APPENDIX A

Properties of Rare Earth Elements by Periodic Table Symbol

TABLE 1. Properties of the rare-earth metals

Symbol	Transitions	Transition temperature, °C (°F)	ΔH transition, cal	Lattice parameters, Å a	Lattice parameters, Å c	c/a	Ionic radius RE^{3+}, nm
Sc	hcp (ABAB)	—	—	3.3088	5.2680	1.592	0.0732
	bcc	1335 (2435)	958	—	—	—	—
Y	hcp (ABAB)	—	—	3.6482	5.7318	1.571	0.0893
	bcc	1478 (2692)	1189	4.08	—	—	—
La	dhcp (ABAC)	—		3.7740	12.171	1.6125*	0.1061
	fcc (ABC)	310 (590)	67	—	—	—	—
	bcc	865 (1589)	753	4.26	—	—	—
Ce	fcc (ABC)	—	—	4.85	—	—	—
	dhcp (ABAC)	−178 (−288)	—	3.68	11.92	1.619*	0.1034
	fcc (ABC)	~100 (heating) (212)	—	5.160	—	—	Ce^{4+}
		−10 (cooling) (14)	—	—	—	—	0.0092
	bcc	726 (1339)	700	4.12	—	—	
Pr	dhcp (ABAC)		—	3.6721	11.832	1.611*	0.1013
	bcc	795 (1463)	760	4.13	—	—	Pr^{4+} 0.090
Nd	dhcp (ABAC)	—	—	3.6583	11.7966	1.612*	0.0995
	bcc	863 (1586)	713	4.13	—	—	
Pm							0.0979
Sm	hcp (nonprimitive)	—	—	3.6290	26.207	1.605	0.0964
	bcc	926 (1699)	744	—	—	—	Sm^{2+} 0.111
Eu	bcc	—	—	4.5827	—	—	0.0950 Eu^{2+} 0.109
Gd	hcp (ABAB)	—	—	3.6336	5.7810	1.59	0.0938
	bcc	1238 (2255)	935	4.05	—	—	—
Tb	hcp (ABAB)	—	—	3.6055	5.6966	1.580	—
	bcc	1289 (2352)	1203	—	—	—	0.0923 TB^{4+}
		—	—	—	—	—	0.084
Dy	hcp (ABAB)			3.5915	5.6501	1.573	0.0908
	bcc	1381 (2518)	955	—	—	—	—
Ho	hcp (ABAB)	—	—	3.5778	5.6178	1.570	0.0894
Er	hcp (ABAB)	—	—	3.5592	5.5850	1.569	0.0881
Tm	hcp (ABAB)	—	—	3.5375	5.5540	1.570	0.0869
Yb	fcc (ABC)	—	—	5.4848	—	—	0.0858
	bcc	795 (1463)	418	—	—	—	Yb^{2+} 0.093
Lu	hcp (ABAB)			3.5052	5.5495	1.583	0.0848

*The values are the author's opinion of the best average values. The actual values vary slightly in the original literature, depending on the investigator and the purity of the metal at hand. Most of the values were obtained on 99.8–99.9% pure metal, the principal impurities being hydrogen, oxygen, nitrogen, carbon, and tantalum. Some of these values will change slightly as purer metal are produced.

Melting point, °C (°F)	Boiling point, °C (°F)	Heat of vaporization ($\Delta H_{v,0}$), kcal/g-atm	Density 25°C, g/cm³	Molal volume 25°C, cm³/g-atm	Radius metal atom, nm	Electrical resistivity (4.2 K), ohm-cm 10^{-6}	Residual resistivity (4.2 K), ohm-cm 10^{-6}	Compressibility, cm²/kg 10^{-6}
1541	2831 (5128)	89.9	2.9890	15.041	0.1640	52	3	2.26
1522	3338 (6040)	101.3	4.4689	19.894	0.1801	59	2	2.68
921 (1690)	3457 (6255)	103.1	6.1453	22.603	0.1879	61–80	Super-conductor	4.04
799 (1470)	3426 (6199)	101.1	6.672	21.001	0.1820	70–80	10	4.10
931 (1708)	3512 (6353)	85.3	6.773	20.805	0.1828	68	1	3.21
1021 (1870)	3068 (5554)	78.5	7.007	20.585	0.1821	65	7	3.0
1168 (2134)	2700 (est.) (4892)	—	—	—	—	—	—	(2.8)
1077 (1971)	1791 (3256)	49.2	7.520	20.001	0.1804	91	7	3.34
822 (1531)	1597 (2907)	(41.9) $\Delta H° = 29$	5.2434	28.981	0.1984	91	1	8.29
1313 (2395)	3266 (5911)	95.3	7.9004	19.9041	0.1801	127	1	2.56
1356 (2473)	3123 (5653)	93.4	8.2294	19.3119	0.1783	114	4	2.45
1412 (2574)	2562 (4646)	70.0	8.5500	19.0058	0.1774	100	5	2.55
1474 (2685)	2695 (4883)	72.3	8.7947	18.7533	0.1766	88	3	2.47
1529 (2874)	2863 (5145)	76.1	9.066	18.4499	0.1757	71	3	2.39
1545 (2813)	1947 (3537)	55.8	9.3208	18.1244	0.1746	74	3	2.47
819 (1506)	1194 (2181)	36.5	6.9654	24.8428	0.1939	28	2	7.39
1663 (3025)	3395 (6143)	102.2	9.8404	17.7808	0.1735	60	2	2.38

Appendix A Source:

Spedding, and Frank H. “Rare-Earth Elements.” Access Science, McGraw-Hill Education, 2014, www.accessscience.com/content/rare-earth-elements/573400.

SUPPLEMENT A

Rare Earth Element Research Poster as presented at the 2018 American Society for Engineering Education Gulf-Southwest Section Annual Meeting on April 5, 2018

Rare Earth Elements

Lindsey Elliott

Texas Christian University
2901 Stadium Drive Fort Worth, Texas 76129, USA
L.N.Elliott3764@tcu.edu

From an engineering perspective, Rare Earth elements have the potential to transform technology in previously unprecedented ways. Their magnetic, luminescent, and electromechanical capabilities are allowing electronic devices to become more compact, reduce emissions, operate more efficiently, and cost less to produce and purchase. Such developments are proving beneficial to the economies of developed nations because of their use in popular everyday consumer technologies as well as industries such as healthcare and education.

Along with this positive impact comes a political overlay that threatens the longevity of Rare Earth use. Presently, Rare Earths are expensive, inefficient, and dangerous to extract. This is largely due to the fact that they are not found together in large concentrations, so it is only economically feasible to extract them in conjunction with another material, such as coal. The process of extraction is also hazardous and cumbersome; separating Rare Earths from other materials involves processes with high levels of emissions that may be dangerous to human beings if overexposure occurs. On the other hand, nations with more flexible safety and health regulations are investing in the development of Rare Earths and setting themselves apart as industry leaders. Nations with more stringent health and safety regulations are becoming dependent on these nations to provide the Rare Earths for their applications.

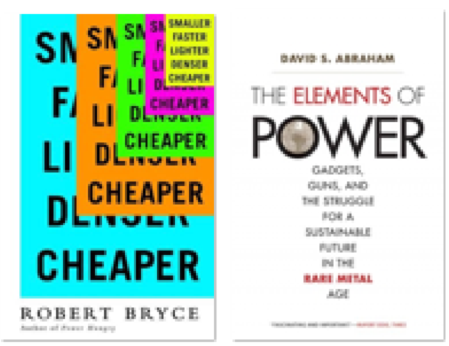

Image 1A & 1B: Literary References Highlighting Current Energy Industry Trends (Image Source 1A: https://www.amazon.com/Smaller-Faster-Lighter-Denser-Cheaper/dp/1610392051) (Image Source 1B: https://www.amazon.co.uk/Elements-Power-Gadgets-Struggle-Sustainable/dp/0300196792)

Many engineers support the efforts that make Rare Earths readily available in order to stay competitive in today's market. Rare Earths have also been a part of research and development regarding devices that will improve the safety and security of populations. For example, engineers are experimenting with the magnetic capabilities of Neodymium, a Rare Earth, to lift furniture and valuables off of the ground during earthquakes to minimize harm or damage to both humans and property. Once irregular seismic activity is recognized in immediate area(s), the magnetic polarity of magnets is adjusted so that similar poles reject each other with enough strength to force objects off the ground. This technology alone could make a life changing impact in locations such as operating rooms.

In the near future there will be much conversation regarding the tradeoff between the benefits and risks that arise as a result of utilizing Rare Earths. The decisions from these conversations will likely have strong political implications but also continue to aid in increasing efficiency across the technological & energy industries.

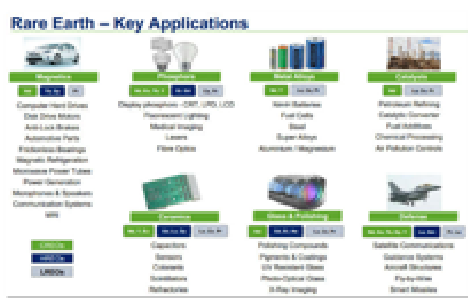

Image 3: Key Applications of Rare Earth Elements (Image Source 3: https://steemit.com/education/@malay11/rare-earth-material-and-it-s-application-and-extruction-process-and-new-technology-to-extruction-from-coal-ash)

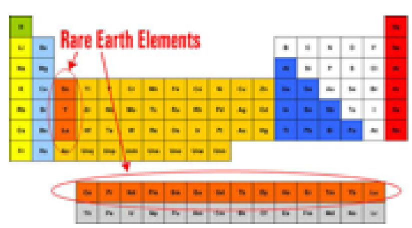

Image 2: Location of Rare Earth Elements on the Periodic Table of Elements (Image Source 2: https://www.powertransmission.com/newsletter/0212/rare.htm)

SUPPLEMENT B

Rare Earth Element Research Poster as presented at TCU's The Michael and Sally McCracken Annual Student Research Symposium 2018