China's Rare Earth Elements Industry: What Can the West Learn?

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Introduction

China controls approximately 97 percent of the world's rare earth element market. These elements, which are not widely known because they are so low on the production chain, are critical to hundreds of high tech applications, many of which define our modern way of life. Without rare earth elements, much of the world's modern technology would be vastly different and many applications would not be possible. For one thing, we would not have the advantage of smaller sized technology, such as the cell phone and laptop computer, without the use of rare earth elements. Rare earth elements are also essential for the defense industry and are found in cruise missiles, precision guided munitions, radar systems and reactive armor. They are also key to the emergence of green technology such as the new generation of wind powered turbines and plug-in hybrid vehicles, as well as to oil refineries, where they act as a catalyst. (Note: for more in-depth information on the specific uses of rare earth elements, refer to Appendix A).

Over the past few years, China has come under increasing scrutiny and criticism over its monopoly of the rare earth industry and for gradually reducing export quotas of these resources. However, China is faced with its own internal issues that, if not addressed, could soon stress the country's rare earth industry.

This paper is designed to give the reader a better understanding of what rare earth elements are and their importance to society in general and to U.S. defense and energy policy in particular. It will also explore the history of rare earth elements and China's current monopoly of the industry, including possible repercussions and strategic implications if rare earth elements supply were to be disrupted.

Definition of Rare Earth Elements

According to the U.S. Geological Survey, rare earth elements comprise those elements that are part of the family of lanthanides on the periodic table with atomic numbers 57-71. Scandium (atomic number 21) and yttrium (atomic number 39) are grouped with the lanthanide family because of their similar properties.[1] Rare earth elements are separated into two categories, light rare earths and heavy rare earths. The light rare earth elements are lanthanum, cerium, praseodymium, neodymium, and samarium (atomic numbers 57-62), and they are more abundant than heavy ones. The heavy rare earth elements (atomic numbers 64-71 plus yttrium, atomic number 39) are not as predominant as light rare earths and are generally used in high tech applications.[2] For example: Erbium is used for fiber optics in communications. Europium and Terbium are used as phosphors. Gadolinium is used for in MRIs.

The term rare earth is actually a misnomer. They are not rare at all, being found in low concentrations throughout the Earth's crust, and in higher concentrations in numerous minerals. Rare earth elements can be found in

[1] James B. Hedrick, "Rare-earth Metal Prices in the USA ca. 1960 to 1994," *Journal of Alloys and Compounds*, 250, (1997): 471.

[2] The heavy rare earth elements sometimes will include europium.

almost all massive rock formations. However, their concentrations range from ten to a few hundred parts per million by weight. Therefore, finding them where they can be economically mined and processed presents a real challenge.

Rare earth elements can be found in a variety of minerals, but the most abundant rare earth elements are found primarily in bastnaesite and monazite. Bastnaesite typically contains light rare earths and a small amount of the heavies, while monazite also contains mostly the light, but the fraction of the heavy rare earths is two to three times larger. According to the U.S. Geological Survey, bastnaesite deposits in China and the U.S. make up the largest percentage of economic rare earth resources. Monazite deposits, found in Australia, Brazil, China, India, Malaysia, South Africa, Sri Lanka, Thailand, and the U.S. make up the second largest segment. Other examples of minerals known to contain rare earth elements include apatite, cheralite, eudialyte, loparite, phoshporites, rare-earth-bearing (ion absorption) clays, secondary monazite, spent uranium solutions, and xenotime.[3]

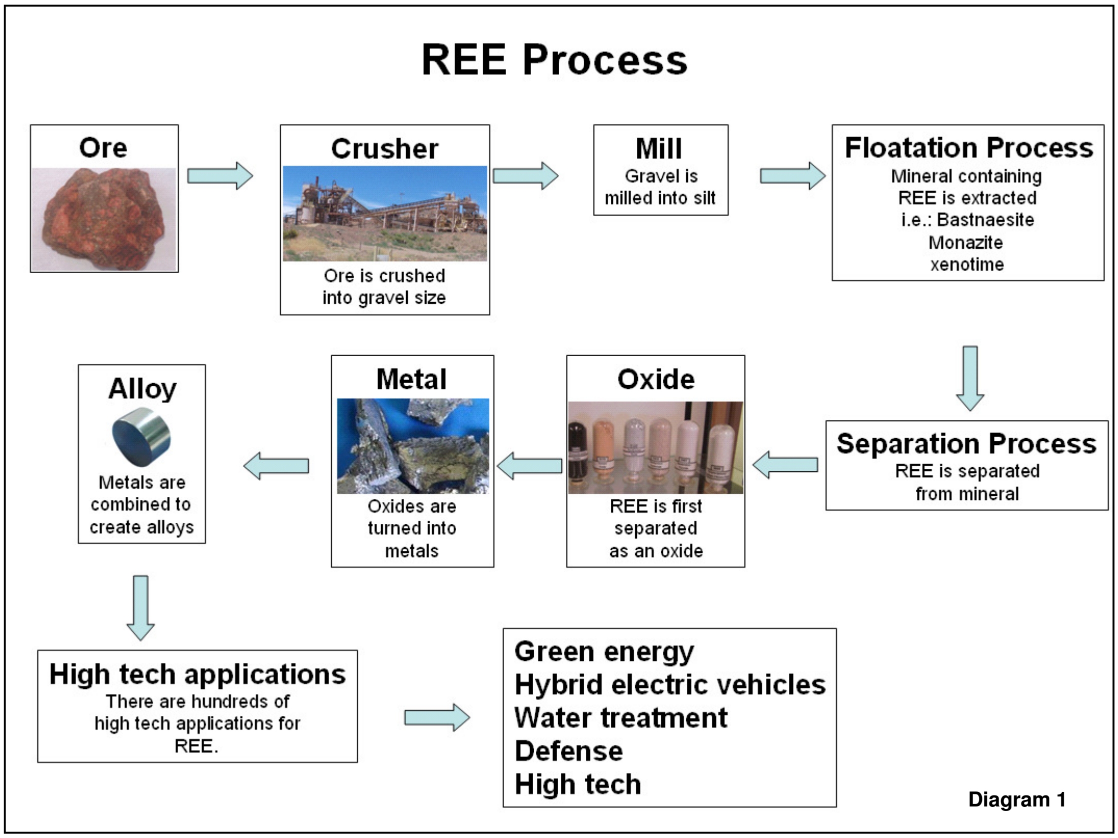
Producing Rare Earth Oxides: No Small Task

A better appreciation of rare earth elements and the difficulty in acquiring them is attained by examining how they are processed. Dr. John Burba, Chief Technology Officer at Molycorp Minerals, the company that runs the only rare earth mining operation in the U.S., pointed out that, "a lot of people don't quite understand why rare earth operations are different (from other mining operations)."[4] Mining gold, for example, is a much simpler procedure than mining rare earth elements. One method in processing gold ore, simply put, is to mix the ore with sodium cyanide. The gold is then leached right out.

Rare earth elements are far more complicated and costly to extract. (See Diagram 1 below) First, ore containing minerals (for this example, we will look at bastnaesite), is taken out of the ground using normal mining procedures. The bastnaesite must then be removed from the ore, which generally contains a number of other minerals of little value. The bastnaesite is removed by crushing the ore into gravel size, then placing the crushed ore into a grinding mill. Once the ore is ground down through a mill into a fine sand or silt the different mineral grains become separated from each other. The sand or silt is then further processed to separate the bastnaesite from the other nonessential minerals. This is accomplished by running the mixture through a floatation process. During the floatation process an agent is added and air bubbles come up through the bottom of the tank. Bastnaesite sticks to those bubbles and floats to the top of the tank as a froth, where it is then scraped off.

[3] *Mineral Commodity Summaries 2009*, U.S. Geological Survey, Washington, D.C.: U.S. Government Printing Office, 2009), 131.
[4] John Burba, interview by author, Mountain Pass, California, 8 July 2009.

The bastnaesite contains the rare earth elements, which must be further separated into their respective pure forms in a separation plant, using acid and various solvent extraction separation steps. Each element has its own unique extraction steps and chemical processes and at times, these elements will require reprocessing to achieve the ideal purity. Once the elements are separated out, they are in the form of oxides, which can be dried, stored, and shipped for further processing into metals. The metals can be further processed into alloys and used for other applications such as the neodymium-iron-boron magnet. These alloys and magnets are then assembled into hundreds of high tech applications. In total, the process takes approximately 10 days from the



point when the ore is taken out of the ground to the point at which the rare earth oxides are actually produced. The mining and processing of rare earth elements, if not carefully controlled, can create environmental hazards. This has happened in China.

China Steps Up Efforts in the Academic World

Since the first discovery of rare earth elements, by Lieutenant Carl Axel Arrhenius, a Swedish army officer, in 1787, there has been a great deal of interest in their chemical properties and potential uses. One could argue that the study of rare earth elements has mirrored the industry. Until the 1970s the Mountain Pass rare earth mine in California was once the largest rare earth supplier in the world. During that time, American students and professors were greatly interested in learning about the properties of these unique materials. Their efforts led to ground breaking uses for rare earth elements both commercially and militarily. Then, as China began to gain a foothold in the industry, U.S. interest seems to have waned, not due to a lack of resources, but to what Professor Karl Gschneidner, Jr., says is a student tendency to gravitate more toward “what’s hot.” There they can make the most impact both as students and later in their careers. As needs arise for new technologies, such as developing advanced biofuels, student interest tends to shift, remaining on top of the latest trends.

In China things are vastly different. There is a great amount of interest in both the industry and the academics of rare earths elements. In fact, nearly 50 percent of the graduate students who come to study at the U.S. Department of Energy’s Ames National Laboratory are from China and each time a visiting student returns to China, he or she is replaced by another Chinese visiting student.

China has long lagged behind the U.S. technologically. However, as of the early 1990s, China’s vast rare earth resources have propelled the country into the number one position in the industry. Hence, it is only fitting that Chinese student interest follow suit. The study of rare earth elements in China is still new and exciting. Additionally, China has set out on an expansive effort to increase its overall technological innovation, effort which includes the use of rare earth elements. China’s academic focus on rare earth elements could one day give the country a decisive advantage over technological innovation.

China first began its push for domestic innovation during the 1980’s. Two programs came about as a result of China’s desire to become a world leader in high-tech innovation. In March 1986, three Chinese scientists jointly proposed a plan that would accelerate the country’s high-tech development. Deng Xiaoping, China’s leader at the time, approved the National High Technology Research and Development Program, namely Program 863. According to China’s Ministry of Science and Technology, the objective of the program is to “gain a foothold in the world arena; to strive to achieve breakthroughs in key technical fields that concern the national economic lifeline and national security; and to achieve ‘leap-frog’ development in key high-tech fields in which China enjoys relative advantages or should take strategic positions in order to provide high-tech support to fulfill strategic objectives in the implementation of the third step of China’s modernization process.”[5] Rare earth elements are an important strategic resource in which China has a considerable advantage due to the massive reserves in the country. Therefore, a great deal of money has gone toward researching rare earths. Program 863 is mainly meant to narrow the gap in technology between the developed world and China, which still lags behind in technological innovation, although progress is being made.

Program 863 focuses on biotechnology, space, information, laser, automation, energy, and new materials. It covers both military and civilian

[5] Ministry of Science & Technology of the PRC, available from Internet; http://www.most.gov.cn/eng, accessed 4 November 2009.

projects, with priority going to projects that may be used for both civilian and military purposes.[6] The use of rare earth elements can be found in each one of the areas in which Program 863 focuses.

Eleven years later, in March 1997, China's Ministry of Science and Technology announced Program 973. It is the largest basic research program in China. Research projects supported by Program 973 can last five years and receive tens of millions of RMB (10 million RMB = $1.46 million). Program 973 is specialized to meet the needs of the country. An example of a research project that would fall under Program 973, and which involves the study of rare earth elements, would be more efficient oil refining processes.

There are other programs as well, such as the Nature Science Foundation of China (NFSC), which generally lasts three years. However, no other program is as significant to China's technological innovation, including the research and development of rare earth elements, as Programs 863 and 973.

One cannot discuss the academics of rare earth elements in China without talking about Professor Xu Guangxian, who, in 2009, at the age of 89, won the 5 million yuan ($730,000) State Supreme Science and Technology prize, China's equivalent to a Nobel Prize. Xu was the second chemist ever to receive the prize.[7]

Xu, considered the father of Chinese rare earth chemistry, persisted in his academic research despite numerous political setbacks and frustrations. China credits Xu with paving the way for the country to become the world's primary exporter of rare earth elements. Xu attended Columbia University, in the U.S., from 1946 to 1951, where he received a Ph.D. in chemistry. After the Korean War broke out, Xu returned to China, and was hired as an associate professor at Peking University. At first, he researched coordination chemistry, focusing on metal extraction. In 1956, he is said to have switched his focus to radiation chemistry, supporting China's efforts to develop atomic bombs. His work focused mostly on the extraction of nuclear fuels. After the Cultural Revolution began in

[6] "PRC Acquisition of U.S. Technology," U.S. Government Printing Office, June 14, 1999.
[7] Hepeng Jia and Lihui Di, "Xu Guangxian: A Chemical Life," Royal Society of Chemistry, March 25, 2009, <http://www.rsc.org/chemistryworld/News/2009/March/25030902.asp>.

1966, Xu's department stopped its atomic research and he turned his focus to theoretical research. Three years later, however, he, and his wife Gao Xiaoxia, were accused of being spies for the former Kuomintang government. Xu and Gao were held in a labor camp until 1972, after which time Xu returned to Peking University. Xu then began to study the extraction of praseodymium from rare earth ores as laser material.[8] It was during this time that Xu made his greatest breakthrough. He applied his previous research in extracting isotopes of uranium to rare earth extraction and succeeded.

In the early 1990s, Xu, who chaired the chemistry sector of the National Natural Science Foundation of China, launched several research programs in rare earths. By 1999 he was still not satisfied with China's progress, pointing out that the country had failed to lead research on the application of rare earth metals in electronic parts and other high-tech industries. Xu pushed hard to further the rare earth industry.[9] Today, Xu is retired, but he continues to push for further progress in the rare earth industry.

In early 2000, Xu wrote, "Chemistry is thought to be too conventional to be important (in China); but this is because chemists are too humble to claim their great achievements. If the discipline's image as an 'archaic study' deters excellent students from entering the field, there will be a big problem." He also wrote, "Chemistry is not the accompanying science to physics and biology, but a central discipline. It will never disappear."[10]

There are two basic types of research – applied and fundamental. Prior to the 1990's, China focused on the separation of rare earths, which falls under applied research. Gschneidner, who is also a senior scientist at the Ames Laboratory, stated that 20 years ago, China focused too heavily on applied research. Applied research is the scientific study and research directed toward trying to solve practical problems.[11] China has since recognized this "weakness" and there is a bigger effort to conduct more fundamental research as well.

There are two state key laboratories in China, both established by Xu, that focus on rare earths. The State Key Laboratory of Rare Earth Materials Chemistry and Applications is affiliated with Peking University in Beijing. The State Key Laboratory of Rare Earth Resource Utilization is affiliated with the Changchun Institute of Applied Chemistry, under the Chinese Academy of Sciences and is located in Changchun.

The "Open Laboratory of Rare Earth Chemistry and Physics" was established in August 1987, at the Changchun Institute of Applied Chemistry with the approval of the Chinese Academy of Science (CAS). In 2002, it changed its name to the "CAS Key Laboratory of Rare Earth Chemistry and Physics." Then, in 2007, it became the "State Key Laboratory of Rare Earth Resource Utilization," falling under the Ministry of Science and Technology. There are currently 40 faculty members in the lab, including two CAS academicians and 20 professors.

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[8] Chinese reports point out that Xu Guangxian was dispatched to study the extraction of praseodymium and rubidium from rare earth as laser material. However, Rubidium is not a rare earth, nor is it typically found in rare earth ore.

[9] Hepeng Jia and Lihui Di, "Xu Guangxian: A Chemical Life."

[10] Ibid.

[11] Karl Gschneidner, interview by author, Ames, Iowa, September 23, 2009.

The lab primarily focuses on:

- *Rare earth solid state chemistry and physics*: Material defects and composites, rare earth luminescence and molecular engineering, thin films and interfaces, material simulation and design, rare earth light alloys, nano coatings and microstructure.
- *Bioinorganic chemistry and the chemical biology of rare earth and related elements*: Specific recognition between rare earth compounds and biomolecules, protein expression and nucleic acids chemistry, and the modulation of biomolecular confirmation and function.
- *Rare earth separation chemistry:* Clean techniques for rare earth separation, chemical and environmental issues of rare earth separation and the integration of the separation and the preparation of rare earth.[12]

The state key laboratory of Rare Earth Materials Chemistry and Applications made significant progress in the 1980s in the separation of rare earth elements. There are approximately 29 faculty members in the lab, including three CAS members, 13 professors, three senior engineers, and one administrative assistant.[13] Currently there are 55 Ph.D. graduate students, four masters graduate students, and 17 postdoctoral research fellows working in the lab.[14] The lab focuses on rare earth separation techniques, the exploration of new rare earth functional materials, and optical, electrical, and magnetic properties and materials of rare earth elements.

There are two other laboratories in China dedicated to rare earth elements. The Baotou Research Institute of Rare Earths was established in 1963. This organization has become the largest rare earth research and development institution in the world.[15] It focuses on the comprehensive exploitation and utilization of rare earth elements and on the research of rare earth metallurgy, environmental protection, new rare earth functional materials, and rare earth applications in traditional industry. The General Research Institute for Nonferrous Metals (GRINM) was established in 1952. This is the largest research and development institution in the field of nonferrous metals in China. The institute does not focus exclusively on rare earths, but also on many of the metals of the periodic table, other than iron.

While each of the four laboratories and institutes mentioned above complement each other, they each have different keystone research efforts. The State Key Laboratory of Rare Earth Resource Utilization focuses on applied research. The State Key Laboratory of Rare Earth Materials Chemistry and

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[12] CAS Key Laboratory of Rare Earth Chemistry and Physics, Chang Chun Institute of Applied, available from http://english.ciac.cas.cn; Internet; accessed November 1, 2009.
[13] "The State key Laboratory of Rare Earth materials Chemistry and Applications," A handbook about the lab.
[14] Peking University, College of Chemistry and Molecular Engineering: The State Key Laboratory of Rare Earth Materials Chemistry and Applications: History and Development, available from http://www.chem.pku.edu.cn/page/relab/english/history.htm; Internet; accessed October 28, 2009.
[15] According to Karl Gschneidner, Baotou Research Institute of Rare Earths has been the world's largest research organization of its kind for the past 30 years.

Applications focuses on basic research. Baotou Research Institute of Rare Earths and GRINM both focus on industrial applied research of rare earth elements.

In addition to having state run laboratories dedicated to researching and developing rare earth elements, China also has two publications dedicated to the topic. They are the Journal of Rare Earth and the China Rare Earth Information (CREI) journal, both put out by the Chinese Society of Rare Earths. These are the only two publications, globally, that focus almost exclusively on rare earth elements and they are both Chinese run.

Industrial Power: China Drives the U.S. Aside

The U.S., not so long ago, was the leader in both the innovation and trade of rare earth elements. The discovery of rare earth elements at Mountain Pass, California marks a particularly important moment for U.S. scientists. During the late 1940s, the Atomic Energy Commission was offering top dollar for uranium. The U.S. needed the uranium to counter the nuclear threat from the Soviet Union. Eager prospectors combed the Southwest in hopes of striking it rich.

In 1949, two such prospectors made their way to the Mountain Pass area, where they used a Geiger counter to try to locate radioactive material that would indicate a uranium deposit. There, the prospectors discovered an outcrop that had a radioactive signature associated with it. Within the outcrop, they found some brownish colored mineral. Thinking it was uranium the prospectors laid stake to their claim and sent samples to the U.S. Geological Survey for analysis. The ore was identified as the rare earth element flourocarbonate bastnaesite and the radioactive material that had been detected turned out to be mostly thorium with only minute traces of uranium.

While the discovery turned out to be worthless to the two prospectors, the discovery of bastnaesite and thus rare earth elements led to a claims-taking rush. The mine ended up in the hands of Molybdenum Corporation of America. In 1953, the company started producing the first mineral concentrate, bastnaesite.

The mining operation came at an ideal time. The Mountain Pass plant was designed initially around the separation of europium. Europium, used as red phosphor, was essential for the cathode ray tubes needed in color televisions, which were making their way into households across America. Mountain Pass used to produce approximately 100 pounds per day of separated europium, which was about 99.99 percent pure.

In time, the mine developed more efficient solvent processes to extract europium. Other rare earths were extracted as well, including lanthanum, cerium, neodymium and praseodymium. This increasing supply of rare earth elements allowed scientists to investigate new uses for them. Over the next few decades, Mountain Pass, which today is owned by Molycorp Minerals, was the primary source of rare earth elements for the world.[16]

[16] Scott Honan, Mountain Pass Mine presentation," Mountain Pass, Ca, 8 July 2008; and Harold Hough, "Domestic Mining – Mountain Pass Mine Reopens," *Miners News*, 2007.

Much earlier, in 1927, Ding Daoheng, a Chinese professor and well-known geologist, discovered iron deposits at Bayan Obo in Inner Mongolia, China. Seven years later, it was confirmed that the mine contained both bastnaesite and monazite. In the 1950s, after conducting a detailed geological survey, the mine was built and operated as the iron ore base of the Baotou Iron and Steel Company. In the late 1950s, China began recovering rare earths during the process of producing iron and steel.

Other rare earth deposits have been found in China as well. For example, in the 1960s, China discovered bastnaesite deposits in Weishan County, Shandong, and in the 1980s, more bastnaesite deposits in Mianning County, Sichuan. Today, rare earth elements are produced in Inner Mongolia (Baotou), Shangdong, Jiangxi, Guangdong, Hunan, Guangxi, Fujian and Sichuan, and other provinces and regions throughout China.[17]

Since the 1960s, China has placed great importance on establishing a plan to maximize the use of Bayan Obo. This plan included employing technical personnel throughout the country to research more efficient methods to recover rare earth elements. China also began efforts to promote the research and development of rare earth elements technologies. As the global consumption of rare earth elements increased, so too did China's production levels. Between 1978 and 1989, China's increase in production averaged 40 percent annually, making China one of the world's largest producers.[18]

Through the 1990s, China's exports of rare earth elements grew, causing prices worldwide to plunge. This undercut business for Molycorp and other producers, and eventually either drove them out of business or significantly reduced production efforts.

In a 1996 paper entitled *The History of China's Rare Earth Industry* authors Wang Minggin and Dou Xuehong, both from the China Rare Earth Information Center at the Baotou Research Institute of Rare Earth in Inner Mongolia pointed out, "China's abrupt rise in its status as a major producer, consumer, and supplier of rare earths and rare earth products is the most important event of the 1980s in terms of development of rare earths."[19]

Since 1992, when Chinese leader Deng Xiaoping made his famous proclamation, "There is oil in the Middle East; there is rare earth in China," the country's industry began moving at full throttle. That same year, the Chinese State Council approved the establishment of the Baotou Rare Earth Hi-Tech Industrial Development Zone. Seven years later, President Jiang Zemin wrote, "Improve the development and application of rare earth, and change the resource advantage into economic superiority."[20] This is precisely the direction China has been going.

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[17] China Magnet: Baotou Rare Earth Development and future Direction of (b)," available from http://www.citie168.com/en; Internet; accessed November 2, 2009.

[18] Wang Minnin and Dou Xuehong, *The History of China's Rare Earth Industry*. ed. C.H.Evans, "Episodes from the History of the Rare Earth Elements," (Netherlands, Kluwer Academic Publishers, 1996), 131-147.

[19] Ibid.

[20] Baotou National Rare-Earth Hi-Tech Industry Development Zone: Rare Earth-An Introduction, available from http://www.rev.cn/en/int.htm; Internet; accessed October 29, 2009.

China Moves to Dominate the Magnet Industry

The individual rare earth elements have taken turns in their value to science as the markets have changed. In other words, during the early 1960s, lanthanum was used in the optical glass industry. Cerium was widely used to polish media.[21] Didymium, a mixture of the elements praseodymium and neodymium, was widely used in the glass industry for coloring. However, there was no market for samarium and europium and large stock piles of these materials grew. Then, as mentioned before, in 1965 the U.S. began to use europium as a red phosphor in color televisions. In the 1970s samarium became a key ingredient for a super magnet – the samarium cobalt magnet.

Today, permanent magnets dominate rare earth technology because of their ability to provide greater magnet power in vastly smaller sizes. Permanent magnets are magnets that, unlike electrical magnets, produce their own magnetic fields. Permanent magnets are what provide the ability to make computers smaller, for example.

Magnetic technology rates as the most important use of rare earth elements due to its many uses in energy and military applications. The two primary rare earth magnets are the samarium cobalt (SmCo) magnet and the neodymium-iron-boron (NdFeB) magnet. The SmCo magnet is able to retain its magnetic strength at elevated temperatures. Because of its thermo-stability, this type of magnet is ideal for special military technologies. These technologies include precision guided munitions – missiles and "smart" bombs and aircraft.[22]

The NdFeB magnet came about in the 1980s, when a scientist discovered that a LaTbFeB alloy had special properties. While attending a conference, the scientist reported that he had found some unusual characteristics in a 50:50 lanthanum:terbium and iron-boron mixture. Scientists from General Motors and Hitachi, who were in the audience, returned to their respective laboratories, found that NdFeB has superior permanent magnetic properties, and submitted applications for patents. A battle ensued and both companies came to an agreement that split the rights to the discovery. Hitachi agreed to take a "sintered" magnets patent and GM agreed to take the "rapidly solidified" magnets patent.

GM needed the magnets for its vehicles and in 1986 the company established a new division to produce the NdFeB magnets. They called the division Magnequench. In 1995 two Chinese groups, the Beijing San Huan New Materials High-Tech Inc. and China National Non-Ferrous Metals Import & Export Corporation, joined forces with Sextant Group Inc, a U.S. investment firm founded by Archibold Cox, Jr., and tried to acquire Magnequench. The purchase

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[21] Cerium dioxide (CeO2) is used as a polishing agent (medium). CeO2 is a highly effective agent for removing scratches and other imperfections from the surface of the glass. Many glass (i.e.: eyeglasses, TV glass plates, plus most optical objects and instruments, etc. are polished using CeO2. This method of polishing glass has been around for over 50 years and it is still the fastest and most effective polishing agent. Input by Karl Gshneidner, email, December 2, 2009.

[22] James B. Hedrick, "Rare Earths in Selected U.S. Defense Applications," Paper presented at the 40th Forum on the Geology of Industrial Minerals, Bloomington, Indiana, May 2-7, 2004.

was reviewed by the U.S. government and finally went through after China agreed to keep Magnequench in the U.S. for at least five years. Magnequench was located in Anderson, Indiana.

The day after China's deal to keep Magnaquench in the U.S. expired in 2002, the entire operation, along with all the equipment, disappeared. All employees were laid off and the company moved to China. At the time, it seemed that no one really cared. Today, however, "they are all sorry about that mistake," Gschneidner points out. "As the business went, technology went." Some critical military applications for the NdFeB magnets include lasers as rangefinders, target designators, and target interrogators; and communication systems such as traveling wave tubes (TWT) and klystrons, which are used in satellite communications, troposcatter communications, pulsed or continuous wave radar amplifiers, and communication links.[23]

In less than one decade, the permanent magnet market experienced a complete shift in leadership. According to John Burba, in 1998, 90 percent of the world's magnet production was in the U.S., Europe, and Japan. Japan manufactured approximately 70 to 80 percent of the world's fully sintered magnets. The U.S. and Europe manufactured the other 20 to 30 percent of fully sintered magnets. The U.S. also manufactured approximately 80 percent of the world's rapidly solidified magnets, with the remainder manufactured in Europe.

By September 2007 China had 130-odd sintered NdFeB large magnet manufacturing enterprises, with an annual capacity of over 80,000 tons. In 1996, their total output was approximately 2,600 tons. By 2006, the total output had grown to 39,000 tons. This is an average annual growth of over 30 percent.

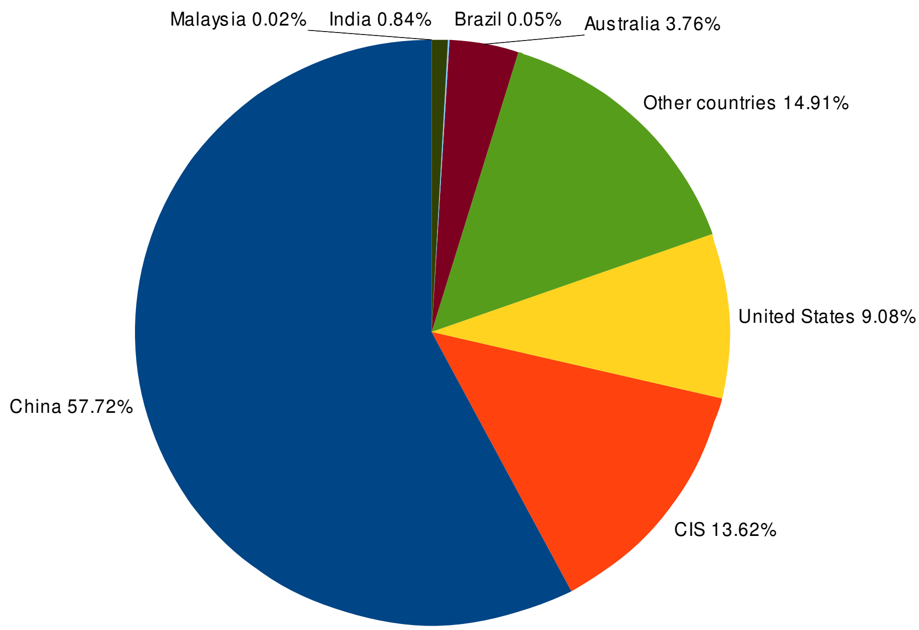
China Moves to Gain Total International Market Advantage

China's move to capture the market did not stop at magnet technology and Magnequench. At one point, the country almost acquired Molycorp, which owns the Mountain Pass mine in California, the only rare earth mine in the U.S. Molycorp purchased Mountain Pass in 1951. In 1978, Unocal purchased Molycorp. In 1982, Mountain Pass Mine began processing samarium oxide and in 1989, it began processing neodymium oxide, both critical components of two types of permanent magnets. In 2005, China National Offshore Oil Corporation (CNOOC) submitted an $18.5 billion cash bid for Unocal, outbidding Chevron by half a billion dollars. [24] CNOOC's bid raised a great deal of concern for U.S. energy security. While there was a media frenzy over these concerns, one issue received little attention – repercussions of China gaining control over Molycorp through CNOOCs purchase of Unocal. If the deal were to have gone through, China would have gained control over Mountain Pass and therefore the country would have had a complete monopoly over all the current major rare earth element resources in the world.

[23] Ibid.

[24] "China Oil Firm in Unocal Bid War," *BBC News*, June 23, 2005, <http://news.bbc.co.uk/2/hi/business/4121830.stm>, accessed October 20, 2009.

China has also pursued a stake in some of Australia's rare earth resources. In early 2009, Lynas Corporation, an Australian mining company, had plans to build a large rare earth mine at Mount Weld in southwestern Australia. In February, however, the company suspended construction of the project because of funding problems. In May 2009, China Non-Ferrous Metal Mining Co. was poised to invest $252 million to provide much needed debt funding in return for a 51.6 percent stake in Lynas. Before the deal could be finalized, the Australian government had to approve it following a review by the Foreign Investment Review Board (FIRB). Normally, the board has 30 days to decide. However, FIRB had requested at least three resubmissions, which suggested that the Australian government was carefully considering the full implications of the deal's impact on the world's supply of rare earth elements.[25] Finally, in September 2009, China backed out of the deal after Australia's Foreign Investment Review Board requested several alterations to the deal, "including a reduction of its stake to below 50 percent."[26]



Graph 1. 2008 Global Reserves of REEs. Source: U.S. Geological Survey

China has managed to invest in another Australian rare earth developer, Arafura Resources Ltd. In this case, Jiangsu Eastern China Non-Ferrous Metals investment Holding Co., now has a stake of no more than 25 percent of the company.[27]

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[25] Ross Kelly, "Australia Delays Ruling on China Rare-Earth Investment," *The Wall Street Journal*, September 4, 2009, <http://online.wsj.com/article/SB125195549768682359.html>.
[26] Alex Wilson, "Lynas Turns to Market for Funds After China Deal Sours," *Wall Street Journal*, September 30, 2009, <http://online.wsj.com/article/SB125421704377948759.html?mod=googlenews_wsj>.
[27] Ibid.

The question arises as to why China should need to pursue rare earth resources outside of its borders when it possesses the largest reserves, at 57 percent, in the world.[28] (See Graph 1)

The Issues China Faces

According to Zhao Shuanglian, Vice Chairman of Inner Mongolia's Autonomous Regions, "Rare earth is a unique treasure, and it is also Inner Mongolia's primary strategic resource."[29] While China possesses approximately 57 percent of the world's reserves of rare earth elements, the industry within China is plagued with disorderly development and poor management practices. The Chinese government fears that if the current poor mining practices and lack of regulation continue, China will "become a rare-earth poor country, or even a country without rare earth elements."[30] Other issues facing China's rare earth industry are smuggling and illegal mining activities, environmental damage due to poor mining practice, and the growing challenge of ensuring its own domestic needs of rare earth.

Smuggling

According to China Business News, due to the annual increased demand for rare earth elements, many buyers are resorting to smuggling rare earths out of China. In 2008, approximately 20,000 tons of rare earth were reportedly smuggled from the country.[31] Meanwhile, during that same year, according to official customs statistics, China exported 39,500 tons of rare earth oxide. This means that smuggling accounted for one-third of the total volume of rare earths leaving China.[32]

One aim of China's "Rare-Earth Industry Development Plan of 2009-2015" is to try to curb some of the smuggling by introducing regulations and policies to punish the smugglers.[33] Smuggling is potentially detrimental to China's rare earth industry because it keeps prices low and depletes resources quicker. Smuggling also indicates a severe lack of control over the industry and can lead to even greater repercussions such as more damage to the environment. Regulations on safe mining practice are nearly impossible to enforce in this type of environment. As it is, because of poor management practices and the large scale of the industry, China already has difficulty in enforcing regulations to improve safety and environmental measures in its rare earth industry.

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[28] Various other sources indicate that China possesses only 54 percent of global reserves.
[29] "The Tremendous Accomplishments of the Five Major Autonomous Regions Since the Founding of New China," Accessed on China's Human Rights Website [Chinese], translated by Scott Henderson, September 2, 2009, <http://www.humanrights.cn/cn/zt/xwgzrd/2009/20x/t20090902_493500.htm>.
[30] "Chinese Government Wins Initial Success in Fight to Protect Tungsten, Antimony, and Rare Earth Elements," *Chinese Government Net*, May 7, 2009.
[31] "China Mulls Plans to Curb Rare Earth Smuggling," *Xinhua*, September 14, 2009.
[32] Ibid.
[33] Ibid.

Severe environmental damage

A major concern surrounding China's practice of mining rare earth elements is the negative impact it has to the environment due to lax mining practices. There are a number of potential environmental implications to mining rare earth elements if not done properly. Unfortunately, because of the revenue potential, many rare earth mines have been operating illegally, with no regulation, causing severe environmental hazards, which exacerbates the problem.

According to an article published by the Chinese Society of Rare Earths, "Every ton of rare earth produced, generates approximately 8.5 kilograms (18.7 lbs) of fluorine and 13 kilograms (28.7 lbs) of dust; and using concentrated sulfuric acid high temperature calcination techniques to produce approximately one ton of calcined rare earth ore generates 9,600 to 12,000 cubic meters

An aerial shot showing Bayan Obo, the world's largest rare earth mine, located north of Baotou, Inner Mongolia, China. Two massive mine pits can be seen in the upper center of the image. The mines are surrounded by iron and iron ore deposits. Rare earth elements are a secondary product of this mine.

Source: GoogleEarth

(339,021 to 423,776 cubic feet) of waste gas containing dust concentrate, hydrofluoric acid, sulfur dioxide, and sulfuric acid, approximately 75 cubic meters (2,649 cubic feet) of acidic wastewater, and about one ton of radioactive waste residue (containing water)." Furthermore, according to statistics conducted within Baotou, where China's primary rare earth production occurs, "all the rare earth enterprises in the Baotou region produce approximately ten million tons of all varieties of wastewater every year" and most of that waste water is "discharged without being effectively treated, which not only contaminates potable water for daily living, but also contaminates the surrounding water environment and irrigated farmlands."

The disposal of tailings also contributes to the problem. Tailings are the ground up materials left behind once the rare earth has been extracted. Often, these tailings contain thorium, which is radioactive. Generally, tailings are placed into a large land impoundment and stored. In the U.S. strict controls are put into place and permits are required to store tailings. According to Wang Caifeng, China's Deputy Director-General of the Materials Department of the Ministry of Industry and Information Technology, producing one ton of rare earth elements creates 2,000 tons of mine tailings. Wang said that China has sacrificed greatly in its extraction of rare earths.[34] While taking steps to solve the problem, China still has a long way to go before it achieves any semblance of control over the environmental damage that occurs from its mining and processing of rare earth elements. According to a representative of one Chinese factory in Baotou, Inner Mongolia, while companies will put some money toward more environmentally friendly mining processes, others opt to keep those expenses at a minimum to maintain their competitive edge in the market. The costs associated with environmental improvements are absorbed by the customers. Another factor within China's industry is that the land belongs to the government and not to the factories. Therefore, if a rare earth producer pays a large sum of money for machinery or processes which are more environmentally friendly that investment could be suddenly lost because the government can choose to take back the land for any number of reasons such as building a new road through the property. This reduces the incentive to meet any type of environmental standards. Furthermore, the Chinese government does not provide any financial support to help companies meet environmental standards. The ore mined in Bayan Obo is transported to Baotou via open railway carts, where it is then processed. Unfortunately, with old, outdated technology, equipment, and little oversight, the waste finds its way into the Yellow River, which passes by the south side of Baotou and travels about another 1,300 miles, through mountainous terrain as well as through heavily populated areas before finally dumping into the Yellow Sea.

In 2005, Xu Guangxian wrote that thorium was a source of radioactive contamination in the Baotou area and the Yellow River.[35] According to a local source, who asked not to be identified, "In the Yellow River, in Baotou, the fish all died. They dump the waste – the chemicals into the river. You cannot eat the fish because they are polluted." Some 150 million people depend on the river as their primary source of water.[36]

[34] Wang Caifeng spoke at the 2009 Minor Metals and Rare Earths Conference, Beijing, China, September 2-3, 2009.

[35] Xu Guangxian et al, "An Emergency Call for the Protection of Thorium and Rare Earth Resources at Baiyun Erbo and the Prevention of Radioactive Contamination of the Yellow River and Baotou," Chinese Academy of Sciences news site, October 20, 2005, <www.cas.ac.cn/html/Dir/22005/11/17/5793.htm>.

[36] Multiple sources claim figures between 150 and 180 million people. The largest part of this population is located on the eastern side of China, which is the direction in which the river flows.

Under traditional technology means, refining rare earth elements requires such chemicals as ammonium bicarbonate and oxalic acid. The potential health hazards of ammonium bicarbonate include: Irritation to the respiratory tract if inhaled, irritation to the gastrointestinal tract if ingested, redness and pain if it comes in contact with the eyes, and redness, itching, and pain if it comes in contact with the skin.[37] Oxalic acid is poisonous and potentially fatal if swallowed. It is also corrosive and causes severe irritation and burns to the skin, eyes, and respiratory tract, is harmful if inhaled or absorbed through the skin, and can cause kidney damage.[38] These and other chemicals often find their way into the Yellow River.

Safety standards in China are lax. “People in their 30s have died of cancer working around the mines, possibly from radioactive materials,” said one local source. “I visited a factory many times. When I visit a factory or workshop, I tell the director of the workshop, ‘would you tell the laborers to put their mask on when they are doing their job?’ He said, ‘Oh yeah. We do every time, but it’s too hot. They don’t want to keep their mask on.’ You can see that the air is dirty and they are breathing it all in.” The most common disease in Baotou is pneumoconiosis, better known as black lung. There are 5,387 residents in Baotou who suffer from black lung, which makes up more than 50 percent of the cases in the autonomous region.[39]

While China might have general pollution control standards, the country has never actually worked out pollutant discharge standards for the rare earth industry. As the rare earth industry in China has rapidly grown, there has been no effective way to control the usual pollutants such as ammonia, nitrogen, and thorium dust, which are emitted during the production phase. Furthermore, general health and safety regulations are often ignored for a number of reasons, including:

- The industry is large and challenging to monitor.
- People and companies are not being held accountable. For example, in Western society, if an employee dies or becomes ill, repercussions could include a lawsuit or life-long pension which the company is obligated to fulfill. This is not the case in China.

Domestic consumption is a priority

With 1.3 billion people and the fastest growing economy in the world, China is faced with the challenging task of ensuring it has adequate natural resources to sustain economic growth, while also trying to appease the international community, which has been protesting China’s cuts in rare earth export quotas.

[37] Tradezone: Qinhuangdao Sinochem Imp.&Exp.Co.,Ltd: Material Safety Data Sheet, available from http://www.tradezone.com; Internet; accessed October 30, 2009.
[38] JT Baker: Material Safety Data Sheet: Oxalic Acid, available from http://www.jtbaker.com; Internet; accessed October 30, 2009.
[39] “Rare Earth Industry Adjusts to Slow Market,” *Gansu Daily*, September 7, 2009, <http://english.gansudaily.com.cn/system/2009/09/07/011259782.shtml>.

According to Wang Caifeng, in 2008 China used 70,000 tons of rare earth elements. Global consumption was 130,000 tons. China exported 10,000 tons of rare earth magnets worth $400 million and 34,600 tons of other rare earth products worth $500 million.[40]

There are numerous examples that point to China's anticipated increase in rare earth consumption. For example, at the end of July 2008, China had 600 million cell phone users. Less than one year later, by the end of March 2009, China had 670 million cell phone users.[41] New technologies, such as the third-generation (3G) networks, have boosted the sale of cell phones, a trend which will likely continue as more and more Chinese citizens buy cell phones and others upgrade to the new technologies. Putting it into perspective, in China, approximately 50 percent of the population has cell phones. CTIA, the International Association for Wireless Telecommunications, reported in October 2008 that the U.S. (with a population of 304 million people as of July 2008) had more than 262 million wireless subscribers. This means that 86 percent of the entire U.S. population had cell phones.[42] If China were to follow the same technological growth patterns as the U.S., the country could one day have approximately 1.1 billion cell phones or more.

In another example, the use of solar and wind power are set to increase exponentially in China. Green energy technology is expected to become the largest consumer of rare earth elements in the future. According to Mark Smith, Chief Executive Officer of Molycorp Minerals, the company that owns and operates the Mountain Pass rare earth mine in California, "We've coined the term, 'the green elements.' because there are so many applications right now – hybrid electric vehicles, wind powered generation …permanent magnet generators, compact fluorescent light bulbs … Just to name a few. Rare earths are absolutely indispensable. They (green technologies) will not work without rare earths."[43]

In its 2007 energy strategy, the Chinese government had a target of 30 gigawatts capacity for wind-power. According to Fang Junshi, head of the coal department of the National Energy Administration, China will have 100 gigawatts of wind-power by 2020. "The annual growth rate will be about 20 percent," he said. As of 2009, China has about 12 gigawatts of wind-power capacity, and hopes to raise that to 20 gigawatts by 2010.[44] NdFeB magnets are a critical component for some models of the new generation wind-powered turbines. Mark Smith pointed out that in certain applications, *two tons* of rare earth magnets are required in the permanent magnet generator that goes on top of the turbine. "If

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[40] Wang Caifeng spoke at the 2009 Minor Metals and Rare Earths Conference, Beijing, China, September 2-3, 2009.

[41] "China's Cell Phone Users Top 670 Mln," *China View: Sci & Tech*, May 20, 2009, <http://news.xinhuanet.com/english/2009-05/20/content_11404515.htm>.

[42] "The Wireless Association Celebrates 25 Years of Mobile Communication," CTIA 10 October 2008, <http://www.ctia.org/media/press/body.cfm/prid/1781>.

[43] Mark Smith, "Rare Earth Minerals: The Indispensable Resource for Clean Energy Technologies," (Paper presented at the 2009 Minor Metals and Rare Earths Conference, Beijing, China, September 2-3, 2009).

[44] "China's Wind-Power Boom to Outpace Nuclear by 2020," *China Daily Online*, April 20 2009, <http://www.chinadaily.com.cn/bizchina/2009-04/20/content_7695970.htm>.

the permanent magnet is two tons, then 28 percent of that, or 560 lbs, is neodymium."[45]

China's consumption of rare earth elements is also expected to increase dramatically as more and more foreign companies move their production sites to China to take advantage of the lower cost of rare earths and therefore reduce their overall production costs. This is part of China's larger strategy to maintain a tight hold on the industry.

China Fights Back before it's too Late: Implications for the West

In 2005, Xu Guangxian called for protective measures in the rare earth industry, warning that rare earth and thorium resources at Bayan Obo were in "urgent need of protection and rational utilization." Xu pointed out that since Bayan Obo had started off exclusively as an iron ore mine, it did not properly consider ways to recover rare earths and thorium. Since 1958, when Baotou Iron and Steel Works began their mining operations, 250 million tons of ore had been mined at the main and eastern ore bodies, leaving a remaining ore volume of 350 million tons. At the rate that China was mining – 10 million tons of ore per year – Xu estimated that the main and eastern ore bodies would be completely depleted within 35 years.[46]

With so much emphasis placed on the importance of rare earth elements in modern day technology, maintaining strict control over this resource will help to propel China into a position of greater political, economic, and military power. Prior to 2009, according to Dai Xu, an expert on military issues, "China had been selling these precious rare-earth metals at a dirt-cheap price for 20 years."[47] This has both been stripping the country of one of its most important strategic resources and damaging the environment.

In an effort to try to protect its resources, the Chinese government has been clamping down on its domestic industry in several ways, including: restricting export quotas on rare earth elements; closing down smaller and illegal rare earth operations and consolidating larger ones in an effort to gain more control; trying to put into place increased environmental laws regulating rare earth mining; and stockpiling. Much of the developed world regards these measures as threatening.

Restricting export quotas

Of most concern to the international community, China has been restricting export quotas in order to have enough resources for its own industries and to regain control over its domestic operations. China currently restricts export quotas on dysprosium, terbium, thulium, lutetium, yttrium, and the heavy and scarcer rare earths. This reduction of export quotas has pushed up the

[45] Mark Smith, "Why Rare Earth Metals Matter," interview by Tom Vulcan, May 18, 2009.
[46] Xu Guangxian et al, "An Emergency Call for the Protection of Thorium and Rare Earth Resources at Baiyun Erbo and the Prevention of Radioactive Contamination of the Yellow River and Baotou.
[47] "Rare Earths Become Rare," *People's Daily Online*, September 11, 2009, <http://english.peopledaily.com.cn/90001/90780/91344/6754752.html>.

international price of key rare earths, including neodymium which is so critical for the neodymium-iron-boron permanent magnets.[48]

The Ministry of Land and Resources implemented a regulation stating that the 2009 export quota for rare earth ores would be set at 82,320 tons, 72,300 of which are light rare earth elements, the remaining 10,020 tons being heavy rare earth elements. These numbers were based on "controls of the total amount of extraction for" rare earth ore for 2008 and forecasts for market factors in 2009.[49] More cuts are expected in the future.

On 2 September 2009, speaking at the annual Minor Metals and Rare Earth Conference in Beijing, Wang Caifeng tried to allay fears over China's reduction in export quotas of rare earths, pointing out that China would encourage the sales of finished rare earth products, but limit the export of semi-finished goods.

Of course, this brings about a new fear. China's control over rare earth elements has the potential to increase foreign dependence on China for finished goods. China has adopted various policies to further develop the rare earth industry at its roots. China's vision is to increase industrial utilization of rare earth elements in order to draw in more rare earth enterprises, both within and outside of China, to set up operations in Inner Mongolia in the area of rare earth applications. Zhao Shuanglian pointed out that Inner Mongolia wanted to control its rare earth resources so that it could become a major industrial base. Zhao also expressed an interest in attracting more domestic and international interest in Inner Mongolia to develop the rare earth industry.[50] This is an ideal scenario for China because it will give the country complete control over the industry and provide more job opportunities for Chinese citizens in the manufacturing industry. However, for those countries forced to move their production bases to China due to their dependence on rare earth elements, jobs are lost and, perhaps more critical to national security, proprietary and even critical technologies will likely be compromised.

Closing smaller operations and consolidating larger ones to gain more control

China is striving to cut back and consolidate the industry to gain more control over it. It is achieving this by closing down smaller, illegal operations and consolidating and merging larger producers. These steps will ultimately put complete control over Chinese rare earth elements into the government's hands, which will completely restrict any type of private enterprise exchange.

As far back as 1991, China's State Council listed rare earth ore as a specially designated type of ore for national-level protective extraction.[51] 2008 marked the peak in China's rare earth industry. However, in 2009, due to the

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[48] "China's Grip Tightens on Rare-Earth Metal Neodymium," *Asia Times*, June 29, 2009.
[49] "Chinese Government Wins Initial Success in Fight to Protect Tungsten, Antimony, and Rare Earth Elements," *Chinese Government Net*.
[50] "The Tremendous Accomplishments of the Five Major Autonomous Regions Since the Founding of New China," September 2, 2009.
[51] "Chinese Government Wins Initial Success in Fight to Protect Tungsten, Antimony, and Rare Earth Elements," *Chinese Government Net*.

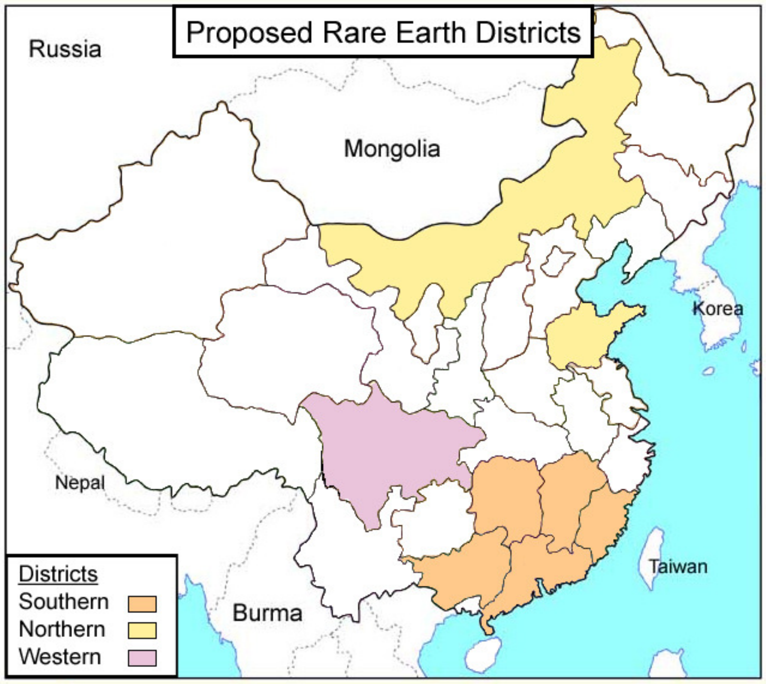
economic downturn, demand fell sharply. Prices fell due to oversupply on the international market and price wars among Chinese suppliers, in particular smaller players.[52] In 2008 and 2009, China began implementing regulations to place greater controls on the rare earth industry. For example, the Ministry of Land and Resources implemented a regulation (GuoTuZiFa Number 49) in 2009 that would "protect and make rational use of China's superior natural resources," in particular, tungsten, antimony, and rare earth ores. According to the regulation, the Ministry of Land and Resources is suspending any applications nationwide for survey or mining licenses for rare earth ores until 30 June 2010.[53] The goal for controlling the rare earth industry in China is "to prevent over-exploitation and blind competition, and to advance the effective protection and scientific, rational use of these superior mineral resources."[54]

The Inner Mongolian government openly hopes to control more of China's domestic rare earth resources and reduce exports. Part of this effort, according to Zhao Shuanglian, is to attract both domestic and foreign downstream users.[55] Zhao said, "We should by no means lay too much stress on raising the price of rare earth in the short-term. We are aiming to make Baotou in Inner Mongolia into a world-class rare earth industrial base."[56]

China's rare earth resources are widely distributed across 22 provinces and regions throughout the country. Because of the scattered distribution of rare earth resources, it is difficult to carry out efficient oversight of the industry. According to one source, a revised draft of the 2009-2015 Plans for Developing the Rare Earth Industry will simplify management of China's rare earth resources by "designating large districts."[57] The new plan will divide China's industry into three large districts – south, north, and west. The southern district is Jiangxi, Guangdong, Fujian, Hunan, and Guangxi; the northern district is Inner Mongolia and Shandong; and the western district is Sichuan. From 2009 to 2015, light rare earths will be the item of focus in Inner Mongolia and Sichuan, with some development in Shandong as needed. Medium and heavy rare earth mining will be the focus in Jiangxi, Guangdong, and Fujian. The Ministry of Industry and Information Technology will oversee the industry by creating an expert examination system for rare earth extraction. The system will include impromptu onsite visits and inspections to ensure national directive plans are being implemented and executed.

[52] "Rare Earth Industry Adjusts to Slow Market," *Gansu Daily*.
[53] "Chinese Government Wins Initial Success in Fight to Protect Tungsten, Antimony, and Rare Earth Elements," *Chinese Government Net*.
[54] ibid.
[55] "Inner Mongolia Govt Assisting Baotou Rare-Earth in Acquisitions in Western China," *China Mining and Metals Newswire,* September 3, 2009.
[56] "China's Inner Mongolia Regulates Rare Earth Export to Attract Investment, Official," *Xinhua General News Service,* September 2, 2009.
[57] "Ministry of Industry and Information Technology Draws Red Line for Rare Earth Exports; Elementary Materials Remain Prohibited for Export," *Sina.com* [Chinese], August 17, 2009.

On 10 December 2008, Baotou Steel Rare Earth set up the Inner Mongolia Baotou Steel Rare Earth High-Tech Co., a state-owned sole-proprietor company in the rare earths high-tech zone of Inner Mongolia; and Inner Mongolia



Baotou Steel Rare Earth High-Tech Co. was an eight-party, 700-million Yuan ($102.5 million) joint venture that included Baotou Huamei Rare Earth High-tech Co., Zibo Baosteel Lingzhi Rare Earth Hi-Tech Co., Inner Mongolia Baosteel and Rare-Earth Development Co. The new venture is supposed to be the controlling voice of the rare earth industry by using a new business model with a unified organization and production arrangement, unified purchasing, and unified sales. Prior to this, the state had promoted the idea of establishing two major rare earth groups, one in the north and one in the south. However, it was difficult to balance the interests between the two enterprises and the plan never came to fruition. The biggest advantage to having one enterprise in charge of the industry is easier central control of pricing.[58] Having a centralized enterprise should also facilitate turning the region into a rare earth "production of goods" zone.

New regulations to protect the environment

China does not have pollutant discharge standards for the rare earth industry. Environmental issues behind the mining of rare earth elements are a huge concern. The differences between Western mining efforts and those seen in China today are staggering. Aware of the problem, the local government is reporting to be trying to find ways to improve the situation.

In July 2009, the Ministry of Environmental Protection organized the "Rare Earth Industry Pollutant Discharge Standards." These new standards will

[58] "Ministry of Industry and Information Technology Vice Minister: Special Plans for Developing Rare Earth Industry Forthcoming," *Securities Daily* [Chinese], August 10, 2009.

hopefully “eliminate backward production abilities and promote the upgrading and updating of China’s rare earth industry.”

The Ministry of Environmental Protection set discharge standards for six types of atmospheric pollutants – sulfur dioxide, particles, fluoride, chlorine, hydrogen chloride, and sulfur trioxide. For water pollutants, discharge standards were set for 14 types of pollutants, including fluoride, total phosphorous, total carbon, total nitrogen, and ammonia nitrogen. In many southern regions with lakes, the new standards implement special discharge limits for ammonia nitrogen discharge concentrations. These new standards are split into two parts, one part for existing enterprises and the other part for newly built enterprises. Under the new standards, rare earth enterprises are required to increase their investment in environmental protection and improve production technologies and costs.

Of course, whether or not these new standards are ever successfully fully implemented remains to be seen. Based on China’s production of 150 tons of rare earth elements, the cost for producers to implement some of the environmental protection efforts would be 1.1 billion yuan ($161 million) and there would be additional annual environmental protection costs of about 280 million yuan ($41 million) for the concentration of water pollutants discharged industry-wide. This would add a cost of 1,000 to 1,500 yuan ($145 to $220) to production for every ton of product.[59] If producers believe their investments toward meeting these standards are not secure and the Chinese government does not provide some type of financial incentive, the Chinese government might be hard pressed to fulfill these standards.

Only time will tell if cleaning up the environment in China is achievable. China has a history of pressing forward in its economic ventures with no regard for the environment. China could easily create more stringent environmental regulations as a front to cover up its poor image. If China were to place environmental issues and regulations high on the priority list, it would mean higher costs to run the industry and less production. This could force the international community to push hard for alternatives, potentially hurting China’s superior status in the rare earth industry. China is able to operate its rare earth mines at one third the cost in part because of the country’s lax environmental standards. Additionally, efforts to clean up China’s environment will require government funding and increased oversight, and would likely cost billions of dollars. According to renowned Australian rare earths expert Dudley Kingsnorth, “I think it will be at least 10 years before China will match our standards.”[60]

Stockpiling

Xu Guangxian, China’s “Father of Rare Earths,” has been pushing to have China build up its strategic reserves of rare earths. According to Xu, “We (China) must set up a stockpiling system for rare earths and thorium (thorium for energy)

[59] Ibid.

[60] Lindsey Hilsum, “Chinese Pay Toxic Price for a Green World,” Timesonline, December 6, 2009.

and support leading domestic producers like Baogang, Minmetals, and Jiangxi Copper to implement the stockpiling."[61]

According to Xu, Japan and South Korea have built up stockpiles, which are enough for 20 years of consumption, by taking advantage of low market prices before 2008 when China began to restrict production, but China hasn't set up a stockpiling system yet.[62] (Japan currently imports the majority of its rare earth from China, importing nearly 90 percent in 2006.[63] Furthermore, according to the Times newspaper, Japan gets approximately 20 percent of its rare earth from China's black market.[64])

According to An Sihu, assistant director of the Rare Earth High-Tech Zone Management Committee, China has major plans to build a national rare earth resources strategic reserves base. The tentative plan is to store up the raw materials that were not used up from the annual excavation at Baosteel and use that to stabilize prices. Efforts currently are underway in Northern China to realize this goal. A new rare earth industry park began construction in July 2008 and is to be located in Northern China However, in order to be completely effective, all of China's rare earth regions need to consolidate their efforts toward the construction and use of this planned rare earth strategic reserve site.[65]

Xu continually warns about depleting rare earth reserves from over production.[66] Stockpiling rare earth elements will allow China to better regulate the pricing of rare earths as well as help ensure its own future supplies.

Possible Solutions, Policy Recommendations and Conclusions

The rest of the world was seemingly asleep as China grew to become a goliath in the rare earth industry. It took the rest of the world nearly 20 years to suddenly wake up to the realization that the future of high technology could be in the hands of this one supplier. While there may be ample rare earth elements in the earth's crust, the challenge is in locating reserves worth mining and putting into place the infrastructure and processes necessary to mine and process them. According to Scott Honan, a Manager at the Mountain Pass mine in California, "No one, that I'm aware of, could come in and start up another mining operation, say, next year." It is a time-consuming and highly complex process. After discovering a potential site and conducting a feasibility study, this type of mining operation requires permits, financing, building of infrastructure (including roads, railways, etc.), the acquisition of mining technology, transportation for the materials available, and so on. All of these steps could easily take up to ten years to accomplish.

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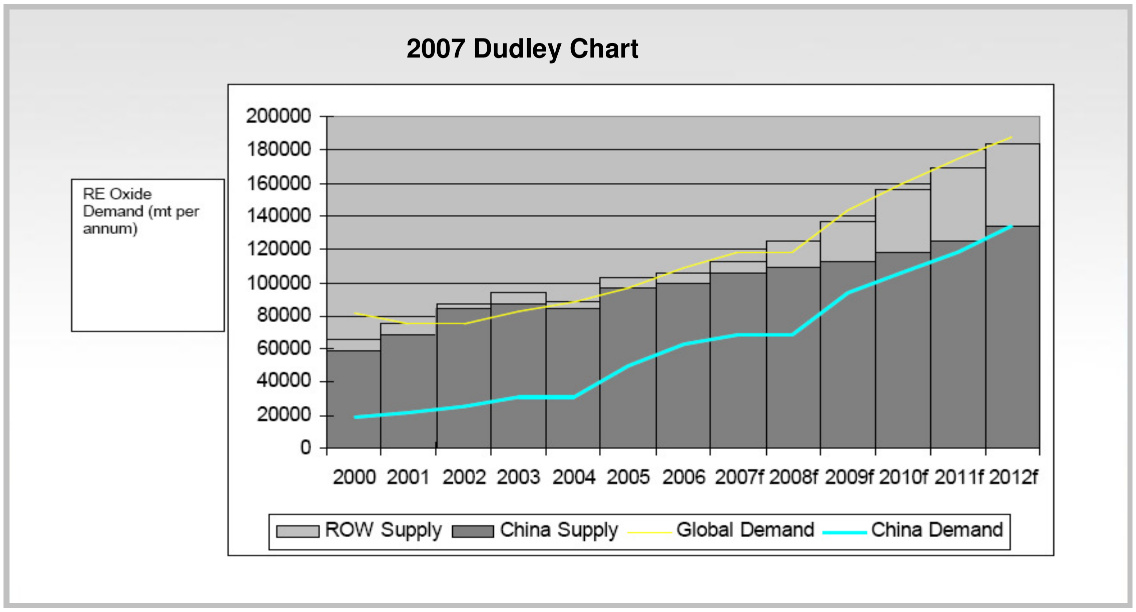
[61] "Chinese Rare Earth Expert Calls for Immediate Stockpiling," Metal-Pages, November 2, 2009.
[62] Ibid.
[63] Hikaru Hiranuma, "Securing Supplies of Rare Metals for Environmental Technology," The Tokyo Foundation, June 2, 2009.
[64] Paul Mason, "Rare Earth: The New Great Game," *BBC Newsnight*, November 18, 2009.
[65] "Ministry of Industrial and Information Technology Vice Minister: Special Plans for Developing Rare Earth Industry Forthcoming," *Securities Daily* [Chinese], August 10, 2009.
[66] "Chinese Rare Earth Expert Calls for Immediate Stockpiling," Metal-Pages.

Currently, outside of the U.S., there are several mines which have investors excited. Those mines are Thor Lake (owned by Avalon) and Hoidas Lake (owned by Great Western), both located in Canada; Mount Weld (owned by Lynas Corp), located in Australia; and Steenkampskraal (owned by Rareco, division of Great Western), located in South Africa. It will take years, hundreds of millions of dollars before production is possible. The reserves at Thor Lake are under water in a region that freezes over two to three months of the year. Hoidas Lake is located in remote northern Canada in Saskatchewan. Mount Weld is located in an isolated region in the south-west of Australia. Mount Weld is probably the most promising mine with its higher grade rare earth ore and easier accessibility compared to the two Canadian mines. Construction and operations have begun for Mount Weld, however there are still a number of hurdles to overcome. In addition, operations for Mount Weld will likely be costlier because the minerals will have to be transported to Malaysia, where they will be further processed into the separate rare earth elements. Steenkampskraal is a former operating rare earth mine, which has been restarted. The projected start-up dates are: 2010 - Steenkampskraal, 2011-12 – Mount Weld, 2012 – Hoidas Lake, and 2013 – Thor Lake. One potential threat is that, while China's reduction in export quotas is currently causing prices to go up, if China were to turn that around and bring prices back down, this could potentially put these and other companies out of business even before they become fully operational.

Mountain Pass California shows great promise due to its infrastructure already being in place and the fact that the mine was fully operational until 1998. By 2010, Molycorp Minerals expects to produce 3,000 metric tons (3,310 tons) of rare earth annually. By 2012, Molycorp expects to reach its peak production capacity, producing 20,000 metric tons (22,000 tons) of rare earths annually. Cerium, lanthanum, praseodymium, and neodymium are expected to comprise the main elements produced. However, Molycorp will also produce small amounts of other critical rare earths – samarium, europium, gadolinium, terbium, dysprosium, and erbium. Provided Mountain Pass stays on track, this may be enough to sustain many of the domestic needs of the U.S., but it will be extremely difficult for the U.S. to ever be able to compete with China as a global manufacturer of rare earth based products. To bolster its competitive edge, Molycorp is planning to reestablish domestic supply chains by partnering with domestic magnet producers. Currently, Molycorp has a letter of intent with Arnold Magnetics to produce NdFeB magnets using neodymium oxides produced from Mountain Pass. While this will hopefully improve the outlook for the U.S., increased global competition for rare earth resources needs to be considered. For example, Japan depends heavily on rare earth supplies for its manufacturing of high tech components, such as cell phones, computers, and hybrid vehicles.

In 2007, Dudley Kingsnorth put together a chart (See diagram 3) commonly referred to in the rare earth industry as "the Dudley chart." The chart depicts China's demand coming close to its production levels by the year 2012.



Source: Molycorp Minerals presentation slide during 2009 Minor Metals and Rare Earths Conference **Diagram 3**

Knowing that the chart was created prior to the current economic slowdown, Mark Smith asked Kingsnorth to redo the chart with the current global economic slowdown in mind. Kingsnorth's new projection pushed China's demand levels equaling the country's production levels only by two years to 2014. However, according to Smith, one thing not included in the chart is the use of rare earth elements in permanent magnet generators for the wind turbine industry. It was not included because in 2007, the wind turbine industry was just coming to bear in the market. Today, however, a rapid paced growth is occurring in the wind turbine industry. Therefore, according to Smith, "When you take the wind turbine industry into account and the economic recession into account, everything just comes right back to 2012."[67]

The future of rare earth elements is not necessarily bleak. It does, however, require careful analysis and monitoring. By 2014, global demand is expected to exceed 200,000 tons per year.[68] According to the U.S. Geological Survey, there are sufficient reserves of rare earth elements to sustain global consumption needs for many years. The challenge, though, is in finding these and putting into place the required infrastructure and procedures quickly enough while also ensuring the environment is not damaged.

In 2008, China produced some 139,000 tons of refined rare earth. By the middle of the next decade, China's output is expected to reach 160,000 tons per

[67] Mark Smith, "Rare Earth Minerals: The Indispensable Resource for Clean Energy Technologies."
[68] "China's Grip Tightens on Rare-Earth Metal Neodymium," *Asia Times*.

year. However, global demand is rising quickly and experts believe there will be a 40,000 ton annual shortfall by 2015.[69]

With so much at stake, it is imperative that the U.S. develop methods to acquire a secure, long-lasting source of rare earth elements. Other countries relying heavily on rare earth elements, such as Japan and Korea are scrambling to secure future supplies. Japan, as a huge manufacturing hub of high tech equipment, has been carefully monitoring the rare earth industry and trying to come up with solutions to protect its own needs. One Japanese expert outlined proposed policies for Japan that would secure rare earth metals. According to the expert, Japan should strengthen its relationships with current supply countries and also pursue new frontiers. The report points out that most mines in the world have already been "pioneered by the major resource enterprises." And indeed, in early 2009, Japan struck a deal to set up a rare earth mine in Vietnam. The mine will solely produce for Japan's vehicle manufacturers.[70] More recently, in November 2009, an article published by The Australian, reported that Japan is "increasingly looking to secure further resources supplies in Australia, with a focus on rare earths, to stem the dominance China has on the market." Tomio Harada, the Australian general manager of the government-backed Japan Oil, Gas & Metals National Corp, Jogmec, points out that there is a difference between transferring stake to a Japanese company and transferring stake to a state-owned Chinese company. Harada said that China's interest was driven by the need for control. Japan, on the other hand, is aware of the national interest concerns in Australia.[71]

The U.S. could use Japan as an example and pursue joint ventures with other countries with known rare earth reserves. The U.S. has much to learn and to pay attention to as it develops a strategy to ensure it has adequate resources of rare earths available to meet its future demands. There are a number of tools available that can facilitate this process. It would be to the U.S. advantage to provide sufficient support to Western companies specializing in the mining and development of rare earth elements and materials by offering support as needed and collaborating on research efforts. One of these efforts might be to seek alternative methods to obtain/extract rare earth elements. For example, the U.S. might invest in and promote the research and development of cost effective methods of recycling, because currently there are no cost effective ways to recycle rare earth elements from old equipment, such as computers, electric motors, and cell phones. The U.S. would also benefit if it could figure out how to extract the rare earth from tailings materials. Under the current technology, significant amounts of rare earth elements are left behind in these tailings materials. Some are simply not recoverable in the floatation process. Until we figure out how to maximize extraction efforts, much of the rare earth elements simply go to waste.

[69] "Huge Hold Holds Key to Future of Wind Farms, Hybrid Cars," *China Daily Online*, September 2, 2009.
[70] Paul Mason, "Rare Earth: The New Great Game."
[71] Sarah-Jane Tasker, "Japan comes Knocking for Rare Earth, Uranium Stakes," *The Australian*, November 2, 2009.

Because of the growing academic gap between the U.S. and China, with regards to the study of rare earth elements, it would be beneficial for the U.S. to strive to close that gap by having Congress and military commands place more emphasis on education and awareness of rare earth elements and other critical resources. This could be accomplished by ensuring that the study of rare earth elements, on both a strategic level, and a research and development level, are consistently included in the curriculum of key military and other U.S. government institutes. Because of the growing strategic importance of rare earth elements, the U.S. might want to consider setting up one or more national research and development centers. These centers would address the country's needs, develop solutions to these critical problems, and train students, scientists, and engineers to form a technical infrastructure to reclaim interest and maintain the U.S.' leadership in rare earth research and development. It would also be in U.S. interest to more closely study China's rare earth strategies.

Finally, building a strategic stockpile of critical rare earth elements capable of sustaining the country for 20 years or more would greatly increase security of supply. Perhaps this is the most important thing the U.S. can do in the near future.

Without taking any steps, the U.S. and other developed, as well as developing, nations could find their resources of rare earths and therefore many of their high tech capabilities, threatened in the not so distant future.

Glossary

Alloy: A compound that consists of two or more metals, or metals with a non-metal.

Applied research – Scientific study and research directed toward trying to solve practical problems.

Atomic fission - The process in which large atoms break apart, releasing smaller atoms and large amounts of energy. The smaller atoms are called **fission products**.

Atomic number – The number of protons in the nucleus of an atom determines the atomic number of the element. The elements on the periodic table are in order by their atomic numbers.

Atomic weight – The average mass of an atom of an element.

Bastnaesite – A yellowish to reddish-brown mineral that is a source of rare earth elements.

Bioinorganic Chemistry – Applications of principles of inorganic chemistry to problems of biology and biochemistry.

Cathode ray tubes – A vacuum tube in which a hot cathode emits a beam of electrons that pass through a high voltage anode and are focused or deflected before hitting a phosphorescent screen.

***Cerium** - The most abundant of the rare earth elements. Cerium is critical in the manufacture of environmental protection and pollution-control systems, from automobiles to oil refineries. Cerium oxides, and other cerium compounds, go into catalytic converters and larger-scale equipment to reduce the sulfur oxide emissions. Cerium is a diesel fuel additive for micro-filtration of pollutants, and promotes more complete fuel combustion for more energy efficiency.

***Dysprosium** – A widely used rare earth element that helps to make electronic components smaller and faster.

***Erbium** – A rare earth element with remarkable optical properties that make it essential for use in long-range fiber optic data transmission.

***Europium –** A rare earth element that offers exceptional properties of photon emission. When it absorbs electrons or UV radiation, the europium atom changes energy levels to create a visible, luminescent emission. This emission creates the perfect red phosphors used in color televisions and computer screens around the world. Europium is also used in fluorescent lighting, which cuts energy use by 75% compared to incandescent lighting. In the medical field, europium is used to tag complex biochemical agents which helps to trace these materials during tissue research.

Fission Products – The smaller atoms released during the process of **atomic fission**.

Functional materials – Functional materials use their native properties and functions to achieve an intelligent action. Their physical and chemical properties are sensitive to changes in the environment, such as temperature, pressure, electric field, magnetic field, optical wavelength, absorbed gas molecules and the pH value.

Fundamental research – Research efforts focused on increasing one's knowledge on a topic.

***Gadolinium** - A rare earth element with unique magnetic behavior. Thus this element is at the heart of magneto-optic recording technology, and other technology used in handling computer data.

Geiger counter – A portable device that detects and measures radiation.

***Holmium** – An exceedingly rare and expensive rare earth element. Hence it has few commercial uses.

Incandescence – light from heat energy (i.e.: when a stove heats up, it turns red. This is incandescent light).

Inorganic – A substance in which two or more chemicals elements, other than carbon, are combined.

Ion Exchange Process – A reversible chemical reaction between an insoluble solid and a solution during which ions may be interchanged.

Isotope – One of two or more atoms with the same atomic number that contain different numbers of neutrons.

Klystrons – An electron tube used to amplify or generate ultrahigh frequency by means of velocity modulation.

Lanthanides – Also known as rare earth elements. The lanthanide series is the group of elements in which the 4f sublevel is being filled. No other element in the periodic table has these properties.

***Lanthanum** – A rare earth element that comes from the mineral bastnaesite, and is extracted via a method called "solvent extraction." Lanthanum is a strategically important rare earth element due to its activity in catalysts that are critical in petroleum refining. By one estimate, lanthanum "cracking-agents" increase refinery yield by as much as 10%, while reducing overall refinery power consumption.

Luminescence – “cold light” that can be emitted at normal and lower temperatures. In luminescence there is an energy source that kicks an electron of an atom out of its lowest energy “ground” state into a higher energy “excited” state. The electron then returns the energy in the form of light so that it can fall back to its “ground” state.

***Lutetium** – The last member of the Lanthanide series is, along with thulium, the least abundant rare earth element. It is recovered, by ion-exchange routines, in small quantities from yttrium-concentrates and is available as a high-purity oxide. Cerium-doped lutetium oxyorthosilicate (LSO) is currently used in detectors in positron emission tomography (PET).

Metallurgy – The science of extracting metals from their ores, purifying and alloying metals and creating useful objects from metals. The study of metals in bulk and at the atomic level.

Mischmetal – A complex alloy of rare earth metals, often used as flint in lighters.

Minerals – The building blocks of rocks. Geologists define a mineral as: A naturally occurring, inorganic, solid, crystalline substance, which has a fixed structure and a chemical composition that is either fixed or that may vary within certain defined limits.

Monazite – A reddish-brown phosphate mineral that contains rare earth elements.

Nano coatings – A coating on the nano-scale.

***Neodymium**- A rare earth element that is a critical component of strong permanent magnets. Cell phones, portable CD players, computers and most modern sound systems would not exist in their current form without using neodymium magnets. Neodymium-Iron- Boron (NdFeB) permanent magnets are essential for miniaturizing a variety of technologies. These magnets maximize the power/cost ratio, and are used in a large variety of motors and mechanical systems.

NdFeB Permanent Magnets – Neodymium-iron-boron magnets.

Nonferrous metals – Anything (metal, alloy, compound, etc.) that does not contain iron.

Ore - A mineral/rock that contains metal that is valuable enough to be mined.

Organic Chemistry – The scientific study of the structure, properties, composition, reactions, and preparation of chemical compounds that contain carbon.

Oxide – An oxide is any compound of oxygen with another element or radical.

***Praseodymium** – This rare earth element comprises only 4 percent of the lanthanide content of bastnaesite, but is used as a common coloring pigment. Along with neodymium, praseodymium is used to filter certain wavelengths of light. So praseodymium finds specific uses in photographic filters, airport signal lenses, welder's glasses, as well as broad uses in ceramic tile and glass (usually yellow). When used in an alloy, praseodymium is a component of permanent magnet systems designed for small motors. Praseodymium also has applications in internal combustion engines, as a catalyst for pollution control.

Pyrophoric alloy – An alloy that emits sparks when struck or scratched with steel; used in lighter flints.

Rapidly Solidified magnets – NdFeB magnet materials, which when in the molten state, the liquid alloy is dropped on a rapidly spinning Cu wheel and the alloy solidifies very rapidly in the form of fine (thin) ribbons. These ribbons are broken up into small pieces and held together with a molten plastic binder which then is cooled to room temperature - these are called the "bonded magnets". About half (dollar wise) of the rare earth magnets sold are bonded magnets; volume wise these amount to approximately 2/3 of the market.

Rubidium – An element classified as a metal. It is number 37 on the periodic table. It is not a rare earth element.

***Samarium** - A rare earth element that has properties of spectral absorption, making it useful in filtering glasses that surround neodymium laser rods.

Scandium – While scandium is not classified as a lanthanum, it is considered a rare earth element and falls on the periodic table as element number 21. It is used to produce high performance materials in both the aerospace and sporting goods industries. It is also used in lighting, lasers and consumer electronics.

Sintered magnets – Magnets formed by heating metal powders without melting.

SmCo – Samarium cobalt permanent magnet.

Tail Warning Function – A defensive system that uses a pulsed Doppler radar to detect missiles approaching the aircraft from behind and dispenses defensive countermeasures to defeat the attack by jamming them with electronic counter measures (ECM).

Tailings – The materials left over after the process of separating the valuable fraction from the worthless fraction of an ore.

***Terbium** – A rare earth element used in energy efficient fluorescent lamps. There are various terbium metal alloys that provide metallic films for magneto optic data recording.

Theoretical physics – The description of natural phenomena in mathematical form.

Thorium – A soft silvery-white tetravalent radioactive metallic element, isotope 232, that is used as a power source in nuclear reactors. Thorium can be found in monazite and, in smaller quantities, other minerals.

***Thulium** – the rarest of the rare earth elements. Its chemistry is similar to that of Yttrium. Due to its unique photographic properties, Thulium is used in sensitive X-ray phosphors to reduce X-ray exposure.

Traveling Wave Tube (TWT) – an electronic device used to amplify radio frequency signals to a higher power.

Ytterbia - A colorless compound (Yb_2O_3) that is used in certain alloys and ceramics.

***Ytterbium** – A rare earth element that resembles Yttrium in broad chemical behavior. When subject to high stresses, the electrical resistance of the metal increases by an order of magnitude. Therefore, ytterbium is used in stress gauges to monitor ground deformations caused, for example, by earthquakes or underground explosions.

***Yttrium** – A rare earth element. Almost every vehicle on the road contains yttrium based materials that improve the fuel efficiency of the engine. Another important use of yttrium is in microwave communication devices. Yttrium- Iron-Garnets (YIG) are used as resonators in frequency meters, magnetic field measurement devices, tunable transistors and Gunn oscillators. Yttrium goes into laser crystals specific to spectral characteristics for high-performance communication systems.

Appendix A

Uses and Sources of the Rare Earth Elements

La Lanthanum 57

Uses: Lanthanum is strategically important due to its use as a catalyst to create fuel for vehicles and aircraft. It is also used in alloys needed as part of fuel cells and batteries. Lanthanum is the key to modifying glass crystal structure and the refractive index, which makes it easier for optical lens designers to create their lenses. Lanthanum is used in night vision instruments. Lanthanum is also used as a compound in carbon arc lamps, color television sets, cigarette lighter flints, and optical fibers. It's phosphors are used in X-ray films and certain lasers to help reduce the dose of radiation to patients by up to 75%. There is current interest in hydrogen sponge alloys containing lanthanum. These alloys take up to 400 times their own volume of hydrogen gas, and the process is reversible. Each time they take up gas, heat energy is released. Hence, these alloys have possibilities in an energy conservation system.

Abundance earth's crust: $3.9x10^{1}$ milligrams per kilogram.

Abundance Ocean: $3.4x10^{-6}$ milligrams per liter

Sources: Found in rare-earth minerals such as cerite, monazite, and bastnaesite. Lanthanum and other rare earths have become more available in recent years. The metal can be produced by reducing the anhydrous fluoride with calcium.

Ce Cerium 58

Uses: Cerium has many uses. It is used for catalytic converters in automobiles to reduce emissions. It is used as a catalyst in petroleum refining and in metallurgical and nuclear applications. As an oxide, it is used in glass polishing agents. Along with other rare earths, cerium is used in carbon-arc lighting, especially in the motion picture industry. It is also used in self cleaning ovens. As part of a Mischmetal, it is used to manufacture pyrophoric alloys for cigarette lighters. A cerium based conversion coating is non corrosive and may have significant military applications.

Abundance earth's crust: $6.65x10^{1}$ milligrams per kilogram

Abundance Ocean: $1.2x10^{-6}$ milligrams per liter

Sources: Cerium is the most abundant rare-earth metal. It is found in allanite (aka: orthite), monazite, bastnasite, cerite, and smarskite. Monazite and bastnasite are most predominant. There are large deposits of monazite on the beaches of Travancore, India, and in Brazilian river sands. Alanite can be found in the western United States. Bastnaesite is in Southern California.

Pr Praseodymium 59

Uses: Praseodymium is used as an alloying agent with magnesium to create high-strength metals used in aircraft engines. It is also used in a Misch metal compound (5%) for the flints in lighters. Praseodymium forms the core of carbon arc lighting, used in the motion picture industry. It is added to fiber optic cables

as a doping agent where it is used as a signal amplifier. Praseodymium salts give color to glasses and enamels. It is also a component of didymium glass, used to make various types of welder's masks.
Abundance earth's crust: 9.2 milligrams per kilogram
Abundance Ocean: $6.4x10^{-7}$ milligrams per liter
Sources: Monazite and bastnaesite are the two primary commercial sources of Praseodymium.

Nd Neodymium 60
Uses: Modern day technology, such as cell phones, portable CD players, computers and sound systems would be vastly different without the use of strong permanent magnets made from neodymium. The Neodymium-Iron-Boron (NdFeB) permanent magnets are so strong that they are ideal for the miniaturization of a variety of technologies. Neodymium based permanent magnets are also at the heart of anti-lock brakes, air bags, anti-glare automobile light glass and mirrors. Neodymium oxide can be added to CRT glass to enhance picture brightness by absorbing yellow light waves. The oxide also has a sky-blue color and is used to produce various coloring pigments for ceramic tile, artistic glass, and others. Neodymium compounds help stabilize electrical properties in ceramic capacitors. Many solid state lasers use neodymium due to its optimal selection of absorption and emitting wavelengths. Neodymium lasers are used in material processing, drilling spot welding/marking and medicine, where the neodymium light laser is used for non-evasive surgical procedures. MRIs also use the neodymium magnet. Neodymium is also used in Misch Metal (18%) for the flint in lighters.
Abundance earth's crust: $4.15x10^{1}$ milligrams per kilogram
Abundance Ocean: $2.8x10^{-6}$ milligrams per liter

Pm Promethium 61
Uses: Promethium is not found naturally on earth. Promethium is used as a beta source for thickness gages and can be absorbed by a phosphor to produce light. It can be used as a nuclear powered battery by capturing light in photocells which convert it into electric current. Such a battery, using 147Pm would have a useful life of about 5 years. Promethium shows promise as a portable X-ray source. It might also be useful as a heat source to provide auxiliary power for space probes and satellites. Promethium can be used to make lasers that can be used to communicate with submerged submarines.
Abundance earth's crust: Not applicable
Abundance Ocean: Not applicable
Sources: It now seems that Pm is missing from the earth's crust.

Sm Samarium 62
Uses: Samarium is combined with cobalt to create a permanent magnet with the highest resistance to demagnetization of any material know. Because of its ability to take continuous temperatures above 250 degrees, it is essential in both aerospace and military applications. Precision guided munitions use samarium-

cobalt permanent magnet motors to direct the flight control surfaces (fins). Samarium-cobalt can be used as part of stealth technology in helicopters to create white noise to cancel or hide the sound of the rotor blades. These permanent magnets are also used as part of the aircraft electrical systems. They also are used to move the flight control surfaces of aircraft, including flaps, rudder, and ailerons. Samarium is used in both missile and radar systems' traveling wave tube (TWT). Samarium-cobalt magnets are used in defense radar systems as well as in several types of electronic counter measure equipment, such as the Tail Warning Function. Samarium is also used as carbon arc lighting for the motion picture industry. Samarium oxide has been used in optical glass to absorb the infrared. It is used in infrared absorbing glass and as a neutron absorber in nuclear reactors.
Abundance earth's crust: 7.05 milligrams per kilogram
Abundance Ocean: 4.5×10^{-7} milligrams per liter
Sources: Found in minerals such as monazite (2.8%) and bastnaesite, which are commercial sources.

Eu Europium 63
Uses: There are no commercial uses for europium metal. However, europium has been used to dope some types of plastics to make lasers. Europium is the most reactive of the rare earth elements. It is being studied for possible use in nuclear reactors. Europium oxide is widely used as a red phosphor in television sets and as an activator for yttrium-based phosphors. Europium-doped plastic has been used as a laser material.
Abundance earth's crust: 2.0 milligrams per kilogram
Abundance Ocean: 1.3×10^{-7} milligrams per liter
Sources: Identified spectroscopically in the sun and certain stars. 17 isotopes are now recognized.

Gd Gadolinium 64
Uses: Gadolinium has unique magnetic behavior, which allows it to form the heart of magneto-optic recording technology used for handling computer data. Magnetic resonance imaging (MRI) systems use materials that contain Gadolinium to enhance the images created. Gadolinium is also the most efficient element used to detect power plant radiation leaks. Gadolinium is used with yttrium to form garnets that have microwave applications. Gadolinium can be alloyed with certain metals, such as iron and chromium, to improve their workability and resistance to high temperatures and oxidation. Gadolinium compounds are also used to make phosphors for color televisions.
Abundance earth's crust: 6.2 milligrams per kilogram
Abundance Ocean: 7×10^{-7} milligrams per liter
Sources: Found in several other minerals such as monazite and bastnaesite, both of which are commercially important.

Er Terbium 65

Uses: Terbium with zirconium dioxide can be used as a crystal stabilizer in fuel cells that operate at high temperatures. It is used in energy efficient fluorescent lamps and metal alloys that provide suitable metallic films for magneto-optic recording of data.

Abundance earth's crust: 1.2 milligrams per kilogram

Abundance Ocean: 1.4×10^{-7} milligrams per liter

Sources: Found in cerite, gadolinite and other minerals along with other rare earths.

Dy Dysprosium 66

Uses: Dysprosium, which is critical to improve the coercive force of high efficiency, high performance motors used in next-generation vehicles, energy-conserving home electronics, and wind power generation, is difficult to find a substitute. The metal, which has natural high oxidizing properties, is also difficult to store. Dysprosium is essential for Japanese technology, making electronic components smaller and faster. At this point, Japan is wholly dependent on China for a stable supply of this REE. It can be an additive to enhance the coercivity in neodymium-iron-boron magnets. It has been used to make laser materials.

Abundance earth's crust: 5.2 milligrams per kilogram

Abundance Ocean: 9.1×10^{-7} milligrams per liter

Sources: Dy occurs with other rare-earth elements in a variety of minerals such as xenotime, fergusonite, gadolinite, euxenite, polycrase, and blomstrandine. Monazite and bastnasite are the most important sources though.

Ho Holmium 67

Uses: Holmium is one of the least abundant rare earth elements. It has no commercial uses. However, it possesses unusual magnetic properties that could be exploited in the future.

Abundance earth's crust: 1.3 milligrams per kilogram

Abundance Ocean:2.2×10^{-7} milligrams per liter

Er Erbium 68

Uses: Erbium is used as an amplifier for fiber optic data transmission. Erbium has also been introduced in lasers for medical and dental uses because they are suited to energy delivery without thermal build up in human tissue. Erbium is used to color glass. It is the only pink colorant truly stable in glass melts. It is used in sunglasses and decorative crystal glassware. Erbium has also been finding uses in nuclear and metallurgy. For example, adding erbium to vanadium lowers the hardness and improves workability.

Abundance earth's crust: 3.5 milligrams per kilogram

Abundance Ocean: 8.7×10^{-7} milligrams per liter

Sources: Found in the same metals mentioned under Dy.

<u>Tm Thulium 69</u>

Uses: Thulium is the rarest of the rare earths. Its chemistry is similar to yttrium. It can be used in sensitive X-ray phosphors to reduce X-ray exposure. However, it is very expensive and therefore has few practical applications.

Abundance earth's crust: $5.2x10^{-1}$ milligrams per kilogram

Abundance Ocean: $1.7x10^{-7}$ milligrams per liter

Sources: Tm occurs in small quantities along with other rare earths in a number of minerals. It is obtained commercially from monazite, which contains about 0.007% of the element. Tm is the least abundant of the REEs. New sources, however, have been discovered and now it is considered as rare as silver, gold or cadmium.

<u>Yb Ytterbium 70</u>

Uses: When subject to very high stresses, ytterbium increases its electrical resistance by an order of magnitude and is used in stress gauges to monitor ground deformations caused, for example, by nuclear explosions. Ytterbium might have some use in improving the grain refinement, strength, and other mechanical properties of stainless steel.

Abundance earth's crust: 3.2 milligrams per kilogram

Abundance Ocean: $8.2x10^{-7}$ milligrams per liter

Sources: Occurs with other rare earths in a number of rare minerals. Commercially recovered mostly from monazite sand (0.03%).

Handling: Has a low-acute toxic rating

<u>Lu Lutetium 71</u>

Uses: Stable lutetium nuclides emit pure beta radiation after thermal neutron activation. Therefore, it can be used as catalysts in cracking, alkylation, hydrogenation, and polymerization. Cerium-doped lutetium oxyorthosilicate (LSO) is currently used in detectors in positron emission tomography (PET).

Abundance earth's crust: 8x10-1 milligrams per kilogram

Abundance Ocean: 1.5x10-7 milligrams per liter

Sources: Lu occurs in very small amounts in nearly all minerals that contain yttrium. In Monazite, it is present about 0.003% of the time (commercial source). The pure metal has been isolated only in recent years.. It is one of the most difficult to prepare.

Handling: Lu is radioactive.

<u>Y Yttrium 39</u>

Uses: Yttrium oxide is the most frequently used oxide. Every vehicle uses yttrium based materials to help improve the efficiency of fuels and eliminate pollution. Yttrium is also used in microwave communication devices for the defense and satellite industries. Yttrium iron garnets are used as resonators for use in frequency meters, magnetic field measurement devices, tunable transistor s and Gunn oscillators. Yttrium with garnets are used in cellular communications devices. Yttrium and other lanthanides have many high-tech and defense uses, such as stabilizers for exotic light-weight jet engine turbines and other parts and

as a stabilizer material in rocket nose cones. They can also be formed into laser crystals specific to spectral characteristics for military communications. Yttrium ceramics can be used as crucibles for melting reactive metals and as nozzles for jet casting molten alloys. Cars contain oxygen sensors composed of yttrium based ceramic materials. Yttrium is also widely used to give the red color in color television tubes.
Abundance earth's crust: 3.3×10^{1} milligrams per kilogram
Abundance Ocean: 1.3×10^{-5} milligrams per liter
Sources: Y occurs in nearly all of the rare-earth minerals. There has been found high Y content on lunar rocks. Y is recovered commercially from monazite sand (3%) and from bastnaesite (0.2%).

Sc Scandium 21

Uses: There are two primary uses for scandium. First, due to its luminescence and electrical conductivity properties, scandium is used in lighting, lasers and consumer electronics. Second, it is used as an alloy in aluminum to produce high-performance materials in the aerospace and sporting goods industries. There are currently no substitutes for scandium in its applications to lasers and the illumination industry. However, titanium/aluminum alloys and carbon fiber can be used to replace scandium/aluminum alloys in some cases, especially in the sports equipment industry.
Abundance earth's crust: 2.2×10^{1} milligrams per kilogram
Abundance Ocean: 6×10^{-7} milligrams per liter
Handling: Little is known about toxicity.
Sources: More abundant in the sun and certain stars than on earth. It is widely distributed on earth. It occurs in very minute quantities in over 800 mineral species. Found in Scandinavia and Malagasy. Most Sc today is recovered from thortveitite or is extracted as a by-product from uranium mill tailings.

Appendix B

The Discovery of Each Rare Earth Element

Element	Atomic Number	Discovered by	Discovery Date
Lanthanum	57	C.G. Mosander	1839
Cerium	58	M.H Klaproth & J.J. Berzelius	1803
Praseodymium	59	C.A. von Welsbach	1885
Neodymium	60	C.A. von Welsbach	1885
Promethium	61	J.A. Marinsky L.E. Glendenin, & C.D. Coryell	1947
Samarium	62	Lecoq de Boisbaudran	1879
Europium	63	Sir William Crookes	1889
Gadolinium	64	J.C.G. Marignac	1880
Terbium	65	C.G. Mosander	1843
Dysprosium	66	Lecoq de Boisbaudran	1886
Holmium	67	P.T. Cleve & J.L. Soret	1879
Erbium	68	C.G. Mosander	1843
Thulium	69	P.T. Cleve	1879
Ytterbium	70	J.C.G Marignac	1878
Lutetium	71	G. Urban & C.A. von Welsbach	1908
Yttrium	39	Johan Gadolin	1789
Scandium	21	Lars Fredrick Nilson	1879

Origin of Each Name

Lanthanum: Derived from the Greek word *lanthanein*, which means hidden or concealed.

Cerium: Derived from a newly sighted asteroid called Ceres.

Praseodymium: Derived from the Greek words *prasios* and *didymos*, meaning green twin. It is one of two major components of didymium (refer to glossary).

Neodymium: Derived from the Greek words *neos* and *didymos*, which means new twin.

Promethium: Derived from the Greek mythology name *Prometheus*, who stole fire from heaven and give it to man.

Samarium: Named after a Russian mine official, Colonel M. Samarski.

Europium: Named after the continent of Europe.

Gadolinium: Named after the Finnish chemist Johan Gadolin.

Terbium: Terbium was originally called erbium. It was confused with erbium. The name of this element is derived from the town of Ytterby, Sweden.

Dysprosium: Derived from the Greek word *dysprosilos*, which means difficult to get to. It was one of the last rare earth elements discovered.

Holmium: Derived from the Latinized world for the city of Stockholm, *Holmia*.

Erbium: Derived from the village of Ytterby, Sweden.

Thulium: Named after *Thule*, the ancient name of Scandinavia.

Ytterbium: Named after the village of Ytterby, Sweden.

Lutetium: Named after the ancient name of Paris, *lutetia*.

Yttrium: Named after the town of Ytterby, Sweden.

Scandium: Named after the Latin word “Scanda,” which means Scandinavia.